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Radon Measurements in Houses in Eastern and Central Iowa

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Radon concentrations in air in main floor areas of 213 houses in Central and Eastern Iowa were measured with alpha track detectors integrating over periods of five months to one year. Forty-two houses in Central Iowa had significantly higher radon concentrations (lognormal distribution with geometric mean 2.1 pCi/L, geometric standard deviation 2.2, and arithmetic mean 2.75 pCi/L) than 171 houses studied in Eastern Iowa (geometric mean 1.6 pCi/L, geometric standard deviation 2.2, arithmetic mean 2.1 pCi/L).

Significant differences in radon levels were found among different categories of houses with regard to ventilation rate, basement construction, and cracks and openings in basements. Almost every category with more than a few houses in it contained houses with annual average main-floor radon levels over 4.0 pCi/L. Liquid scintillation measurements of radon in the water supplies of the houses showed, for 50 private wells: high 1700, average 490, and geom. mean 350 pCi/L, with geom. st'd. dev. 2.8; and for 21 public supplies: high 740, average 210, and geom. mean 130 pCi/L, with geom. st'd. dev. 3.1. Radon in the water supplies was not correlated with radon in the air in the houses. A method for measuring radon in the soil gas was developed and with it the soil-gas radon was measured near 40 of the houses in Central Iowa. Soil gas radon levels ranged from 40 to 1200 pCi/L, with average 380 and geom. mean 290 pCi/L, and geom. st'd. dev. 2.2. Radon in soil gas was not correlated with radon in air in the houses.

INDEX DESCRIPTORS: Environmental Radon, Radon Measurements, Environmental Radon Sources

Radon-222, with a 3.8-day radioactive half life, is an inert gas occurring in the radioactive decay series of uranium-238. If the decay products of radon (isotopes of polonium, bismuth, and lead, with radioactive half-lives of from less than a second to tens of minutes) are inhaled after being produced by radon in air, they can adhere to the airways of the lung, where alpha radiation from subsequent decays in the series bombards the bronchial epithelium. There is a large body of epidemiological data for uranium miners indicating the risk of lung cancer from radon decay products (National Research Council, 1988).

The average exposure to radon has been accepted (U.S. Environmental Protection Agency (EPA), 1986a) as a useful indicator of the cancer risk due to its decay products because long-term measurements of radon concentrations are more easily and reliably obtained than long term measurements of radon decay products, and because risk factors can be estimated once radon concentrations are known (Vanmarcke, Berkvens and Poffijn, 1989). Many variable factors (the concentrations of the radon decay products, concentrations and size distributions of the airborne aerosols to which the radon decay products attach, and individual genetic or other predispositions to cancer) may be important if more precise estimates of lung cancer risks are desired in particular circumstances.

The lifetime risk of lung cancer from radon for an individual is estimated (National Research Council, 1988; EPA, 1986b) to be between 0.7 and 3 percent for exposure to an average radon level of 2.0 picoCuries per liter (2.0 pCi/L) in the areas of buildings in which people spend their time indoors for most of their lives. This level is typical for many buildings. For other radon levels, the risk is estimated to be proportional to the radon level and the time spent breathing the air with that radon level.

The EPA doesn't presently regulate radon, through it does suggest guidelines by which homeowners may assess whether and when to consider efforts at reduction of radon levels in their homes. At present, the lowest EPA radon guideline is that owners of houses with year-round average radon levels over 4.0 pCi/L in the living areas of the houses should take mitigation action to try to lower the levels as much as practicably possible within a few years; for houses over 20 pCi/L mitigation action should be taken within a few months, and for houses over 200 pCi/L action should be taken immediately (EPA, 1986b). As radon measurement and mitigation technologies progress, maximum acceptable radon levels may be reduced to 2 pCi/L or lower.

To get some perspective on the significance of the radon problem, it can be compared to the situation with water pollutants. For pollutants regulated by the EPA, lifetime individual cancer risks at EPA regulated maximum contaminant levels are in the range of 5×10^{-5} to 10^{-6} (Cothern, Lappenbusch and Cotruvo, 1983). For these low risk levels, epidemiological studies are generally not possible because the population exposure would not be expected to produce enough cancer cases to allow statistically significant conclusions. By contrast, with lifetime lung cancer risks from radon for residents of many houses expected to exceed several times 10^{-2}, epidemiological studies of lung cancer and radon in air are possible, and it should be possible to verify or disprove the current risk estimates for radon at levels below 10 pCi/L in houses within the next few years (Toohey, 1987). In the meanwhile, conservative risk estimates are as relevant for radon in air as they are for environmental agents with far lower risks, especially since there exists abundant epidemiological evidence for the ability of radon at levels near those at which it is found in houses to cause lung cancer.

METHODS

Selection of Houses

In Central Iowa the 42 houses, surveyed in 1984, were sought by personal contacts so as to be distributed, rurally and in towns, over the region indicated in Figure 1. The counties included, with numbers of houses studied, were: Polk (13), Jasper (7), Story (8), Poweshiek (5), Dallas (4), Marion (3), Tama (1), and Green (1). There was no cost to the homeowners for the measurements. In Eastern Iowa, 123 homeowners in Linn County (including Cedar Rapids) enrolled in the survey in 1986, and 48 homeowners in Scott County (including Davenport) enrolled in the survey in 1987, by contacting the county health departments after becoming aware of public announcements that radon measurements would be available from them at a cost of $25.

It is not known whether the houses that were studied are representative of the housing stock in these regions of Iowa. Because of the $25 fee in the Eastern Iowa study, participation by low-income homes may have been lower than their proportion in the population. Low-income homes may tend to be less tightly sealed against unwanted ventilation in the winter, and therefore may tend to have lower radon levels than the houses that were studied. Only 17 of the 213 homes in

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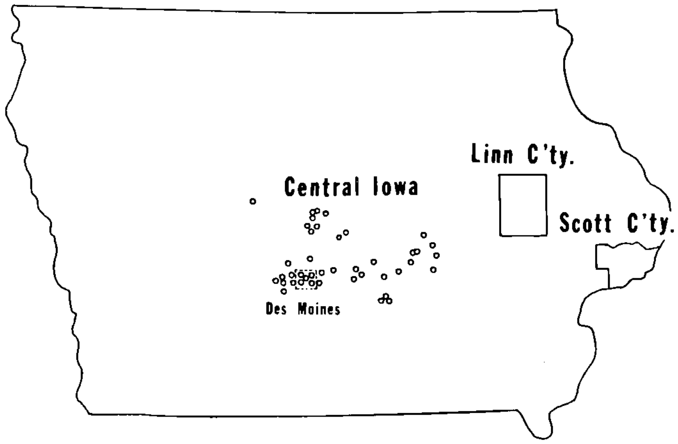

Fig. 1. Locations of houses studied.

the survey were classed as drafty by their owners. Factors influencing participation were the environmental interest and the chain of personal contacts that found willing participants in Central Iowa. In none of the houses had radon measurements been made previously. The houses that were studied are probably representative of a large number of homes in Iowa even if some types of structures are underrepresented.

Measurements of Radon in Air

An alpha-track detector, Terradex type SF or type F (Alter and Fleischer, 1981), was placed for one year (except in the Central Iowa group) on the ground floor of each house. These are passive detectors, consisting essentially of a plastic alpha-track detecting strip in a plastic cup or cylinder covered with a filter to permit gasses to enter but prevent particulates and radon daughters from entry. Since radon concentrations can vary significantly with seasonal and weather patterns, the one-year average is the best representation of the radon concentration to which residents are exposed in a house (Nero, Schwehr, Nazaroff, and Revzan 1986). One year averages permit health risks from radon to the residents of the houses to be estimated. These measurements also allow comparison of the radon level with the EPA 4 pCi/L mitigation action guideline, which refers to year averages in living areas (nominally the main floors) of houses.

The houses the Central Iowa Region had the alpha-track detectors in them for periods ranging from five to nine months, all ending in November, 1984. These do not include the coldest months December, January, and February, when radon levels have generally been observed to be highest: annual levels in houses in four regions of the United States with northern climates averaged 80% of winter levels (Nero, Schwehr, Nazaroff, and Revzan, 1986). The measurements in this Central Iowa group of houses, then, may be estimated to be as low as 80% of the one year averages that would be obtained, but are unlikely to overestimate them.

The places on the main floors where the detectors were installed included kitchens, hall-ways, and living rooms. When each house was visited to deliver and install the radon dector, information was recorded on a survey form about the basement construction and condition, ventilation (tight, average, or drafty, estimated by the owners), heating and air conditioning system, topographic location, detector location, and any special features of the house.

To minimize detector storage time, batches of detectors were returned to Terradex weekly as they were collected. As controls, two detectors, that had been kept unopened for the year were opened and placed with one batch as it was gathered. The results for both of these controls were reported as 0.0 pCi/L for one year "exposures". Three detectors were installed outdoors for a year, one in Cedar Rapids and two in Mount Vernon, in protective inverted coffee cans attached about two meters above the ground to trees.

In ten houses, two detectors were installed within a few centimeters of each other. These duplicates were submitted as blind samples to the detector processing laboratory by recording different names on the reporting records.

Uncertainties in the alpha-track detector results were reported by Terradex Corporation to range from 12% at 6 pCi/L, 14% at 4.0 pCi/L, and 20% at 1.0 pCi/L, to 30% at 0.2 pCi/L. The results of the ten sets of replicate measurements with two detectors per house were: (3.5, 3.2); (3.3, 3.2); (2.7, 2.3); (2.4, 1.8); (1.8, 0.9); (1.6, 1.5); (1.1, 1.0); (1.1, 0.5); (0.9, 0.6); and (0.6, 0.4) pCi/L. A X^2 analysis of the variance in these duplicates shows it is well accounted for by the standard deviations reported by Terradex. In more extensive studies (Nelson, 1987; Nyberg and Bernhardt, 1983) of the variation in replicate measurements with this kind of detector under field conditions, it has been found that the coefficient of variation is typically 40% to 60% higher than Poisson counting statistics alone would indicate.

The calibration precision for types F and SF detectors has been determined by Terradex Corporation to be better than 5% for one standard error in the mean (Taylor and Oswald, 1986).

With these considerations, the overall experimental uncertainty in the data from the alpha-track detectors in these Iowa studies is estimated to be, for one standard deviation, about 20% at 4.0 pCi/L, slightly smaller than that at higher concentrations, and increasing for results below 1 pCi/L as characterized by Terradex.

Measurements of Radon in Soil Gas

The soil gas was sampled by a method involving driving a 2.2-cm diameter steel rod 90 cm into the ground, removing it, and taking a gas sample into a scintillation cell through a polyvinyl-chloride tube extended down into the bottom of the hole after the rod was removed. A rubber squeeze-bulb pump was used to bring the soil gas through the tube up to the valve of an evacuated scintillation cell which was then opened.

The scintillation cells used were constructed from black methylmethacrylate plastic tubing of 5 cm diameter with a clear methylmethacrylate window epoxied on one end. The interiors were coated with ZnS(Ag) scintillator. They were calibrated by sampling radon from a sealed 140 liter drum with a radium-chloride standard solution (from the EPA Environmental Monitoring Systems Laboratory in Las Vegas) in equilibrium with the air in the drum. The radium solution had been bubbled with nitrogen to remove the radon from it before installation in the drum. Because the monitoring of the relative radon concentration in the drum as a function of time showed a radon buildup curve well fit by the 3.8-day characteristic, the drum was shown to be not leaking radon. The calibration factors for the fifteen scintillation cells that were constructed were found to have a 10% standard deviation from the mean.

Several variations in the technique for sampling the soil gas were investigated in the course of developing the method. The procedure used was found to yield higher measured soil-gas radon concentrations than a procedure periodically sampling the radon that built up over several weeks in a pipe driven to the same depth. When the rod is pulled out of the ground, a partial vacuum develops in the hole, drawing in the soil gas, some of which was displaced when the rod was driven into the ground. The filling of the hole with soil gas as the rod is removed may involve the soil porosity in the concentration of radon in the hole. The ability of the radon to flow through the soil is also an important factor in the migration of radon into basements, along with the radon concentration in the soil gas. Pulling the rod half-way out of the ground and waiting for from 5 minutes to 1 hour before removal made no difference in the radon concentration found after the rod was removed. Five minutes after removing the rod completely, the radon concentration in the gas in the bottom of a hole

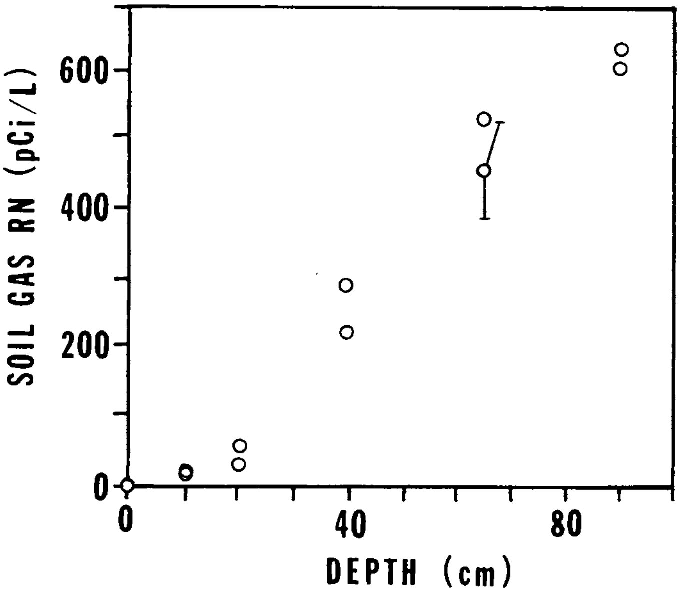

Fig. 2. Radon in soil gas versus depth in soil.

had dropped by approximately 50%.

The variation of radon in soil gas with depth, measured with this method, shows an increase with depth (Figure 2). The method may create some averaging of the sample over the depth of the hole, as would most other methods. Radon concentrations at depths greater than 90 cm which were not studied may have continued the increase with depth shown in the figure. A depth of 90 cm was the standard for subsequent studies to characterize and compare soil gas radon concentrations in various locations.

The radon concentrations in soil-gas samples taken more than two or three meters apart typically disagreed by large factors, 50% and more, even though the surface appearance of the region in which the samples were taken appeared homogeneous. These differences reflect significant variations in radon concentrations in soil gas over these distances.

Some evidence of the consistancy of the method was provided by six samples from the same depth, taken within a 30 minute period and within a 30-cm circle. They agreed to within 15% of the mean. Ten percent is the error associated with the scintillation cell calibration and counting error alone. With these considerations, the experimental error associated with this method for soil gas radon measurements is estimated to be one standard deviation of 15%

Figure 3 shows the variation over a period of several days for the radon in daily duplicate soil gas samples taken within a circle of 50 cm radius. The big drop in radon after the first duplicate samples may be due to ventilation of the soil by the first hole, which was not filled, or may be due to weather and soil moisture variables which were not controlled at this outdoor site.

For a systematic study of the radon concentrations in soil gas near 40 of the houses in the Central Iowa survey, the samples were taken from 90-cm holes located one meter away from the house foundations on two, usually opposite, sides of each house.

Measurements of Radon in Water

Radon activity concentrations in the water supplies of 100 of the houses were measured by the liquid scintillation method (Pritchard and Gesell, 1978). These covered all public or private water supplies serving the 213 houses in the survey. Water samples were taken from the kitchen taps after running the water for five minutes. The measurements were calibrated with standards of radon in quilibrium with radium-226 in various activity concentrations produced by successive diluation of an aqueous radium-chloride calibration standard sample obtained from the EPA Environmental Monitoring Systems Laboratory in Las Vegas. Liquid scintillation counting machines at Grinnell and Cornell Colleges were used.

RESULTS AND DISCUSSION

Radon in Air

The distribution of the radon concentrations for the 213 houses is shown in Figure 4. Hypotheses that the concentrations do not differ significantly between various regions or between various categories of house characteristics can be tested with the assumption that the frequency distributions of the radon concentrations are lognormal. Figure 5, showing the distributions for two regions on logarithmic probability paper, suggests lognormality, as has been found in most

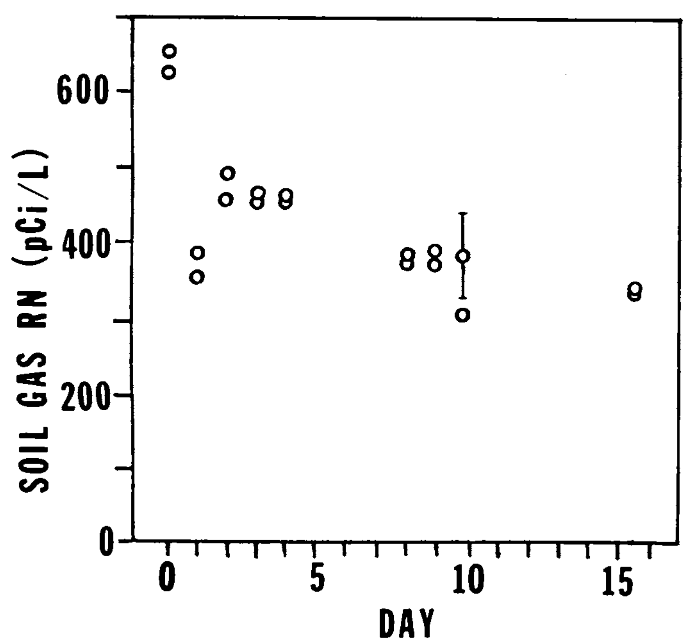

Fig. 3. Variation with time for radon in soil gas at 90 cm depth.

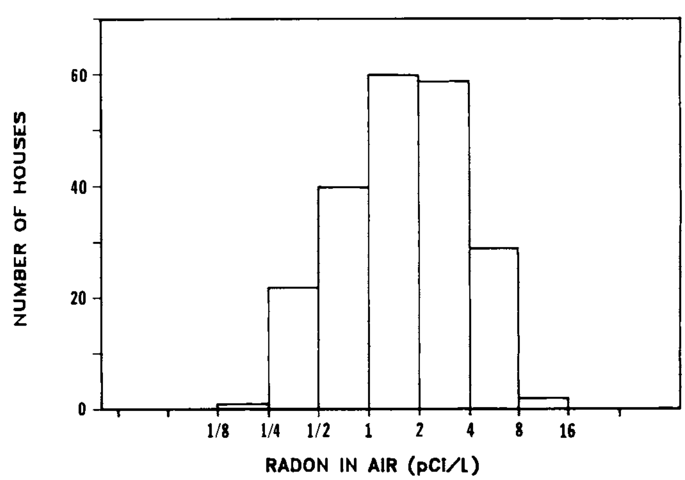

Fig. 4 Frequency distribution of radon levels in air in houses in Central and Eastern Iowa.

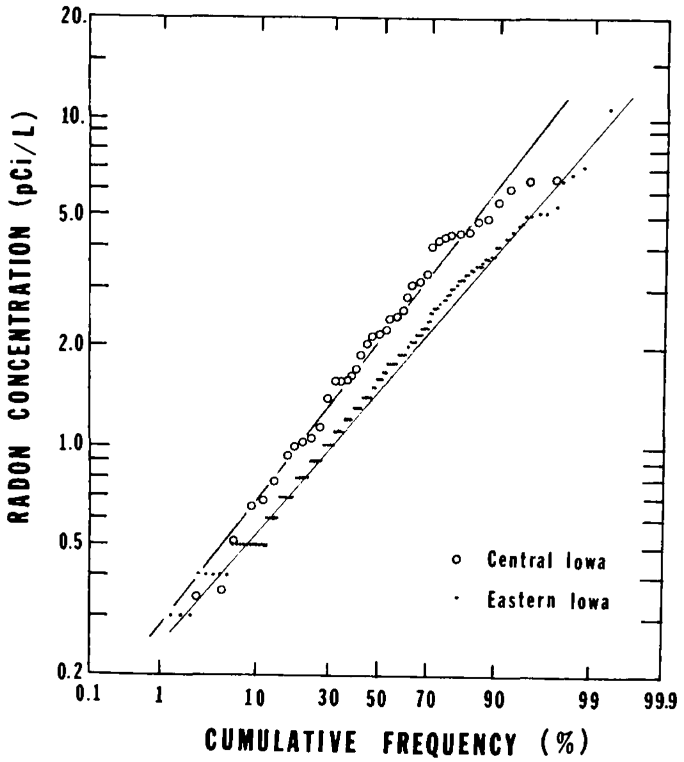

Fig. 5. Cumulative frequency distribution for radon levels in air in houses in Central and Eastern Iowa.

other surveys of annual average radon concentrations (Nero, Schwehr, Nazaroff and Revzan, 1986).

A summary of the results for the houses in three regions is given in Table 1. These distributions appear to be somewhat higher than typical for the United States. The distribution for the annual average radon concentrations to which residents are exposed in 817 houses in 22 regions of the United States, reported in a survey (Nero, Schwehr, Nazaroff and Revzan, 1986) summarizing the results of many studies, has geometric mean 0.9 pCi/L, arithmetic mean 1.5 pCi/L, and geometric standard deviation 2.8.

The annual average radon concentrations in significant numbers of houses (about 25% of the houses in the Central Iowa study and about 10% of the houses in the Linn County and Scott County studies) were over the 4.0 pCi/L EPA guideline for recommending remedial action.

When the distributions for the Central Iowa group of 42 houses and the Eastern Iowa group of 171 houses are compared, a statistical t-test shows the Central Iowa group to be significantly higher in radon ($P=0.01$). The radon levels in Linn County do not differ significantly from those in Scott County.

A similar result (Gillette, 1988) has been obtained with short-term (3 to 7 day) measurements of radon in air in below-ground levels of houses, largely basements, with the houses sealed for low ventilation as in winter, to produce the highest possible radon concentrations. In that study, Polk, Jasper, Poweshiek, Marion, and Greene counties were among those with significantly higher levels than the state average, Dallas and Tama counties were near the state average, and Linn and Scott counties were among those with significantly lower levels. Due to the differences in detector location and conditions of exposure, the mean radon levels found in that study were two to four times higher than the main floor mean levels of the present study.

If the occurances of high-radon houses are assumed to have log-normal distributions represented by the fits of the lines to the data in Figure 5, it can be predicted by extrapolating the lines to 20 pCi/L that between one-half and one percent of the houses in Central Iowa will have annual average main-floor levels over 20 pCi/L, and in Linn County and Scott County about 0.1% or fewer of the houses will be over 20 pCi/L. However, the Central Iowa data distribution in Figure 5 shows a tendency to fewer high-radon houses than the log-normal distribution would predict. Only one of the 213 houses in this study, the one reported at 15 pCi/L, would have been over 20 pCi/L (below 30 pCi/L) for the annual average had mitigation to reduce the level not been applied before the year's exposure of the alpha-track detector was completed, after grab samples and short-term followup radon measurements showed levels consistantly over 20 pCi/L.

Radon Versus House Characteristics

Table 2 summarizes the data for annual average radon levels in air in the different categories of house characteristics. Information on house characteristics, other than the owner's estimates of ventilation rates, was recorded only for the houses in Eastern Iowa.

There are some houses with over 4.0 pCi/L for the year average in almost every category with more than a few houses in it.

The distributions of annual average radon in air in the various categories have been compared with the t-test, assuming lognormal distributions in each category, to search for significant differences. The geometric standard deviations are similar for all categories with more than a few houses, indicating that the assumption of equal variances necessary for applicability of the t-test is not unreasonable. The t-tests were single-ended, with the assumption that the most probable underlying reasons for the differences observed can be used to rule out differences of the opposite signs, as interpreted below.

Results for significant differences are summarized in the sixth column of Table 2, where categories between which statistical differences exist are indicated, along with the probability that the difference is random, due to statistical fluctuation. Differences with associated probabilities less than 0.05 are considered significant, and are italicized.

That tightly sealed houses show significantly more radon than average or drafty houses is understandable because outdoor air diluting the indoor radon has very low radon levels. The three alpha track detectors exposed outdoors for a year in this study recorded concentrations of 0.1, 0.2, and 0.4 pCi/L.

The differences observed for main-floor radon concentrations among houses with different basement characteristics imply the entry of radon into basements from the surrounding soil. Radon is found in soil gas at concentrations of hundreds of pCi/L. Basements usually have more radon in air than main floors above basements (Cohen, 1985). Because of factors that reduce the air pressure in basements relative to the pressure of outdoor air and soil gas, the entry of soil gas into basements through large cracks and openings is often enhanced by pressure driven flow (Bruno, 1983).

The difference between houses built on concrete slabs (without basements) and houses with basements can be understood if the main floors of slab houses tend to be equivalent to basements with regard to

Table 1. Summary of Data for Radon Levels in Air by Region

	Central Iowa	Linn County	Scott County	All
N, houses	42	124	47	213
mean, pCi/L	2.75	2.0	2.3	2.2
geom. mean, pCi/L	2.1	1.5	1.6	1.6
geom. st. dev.	2.2	2.2	2.2	2.2
high, pCi/L	6.8	7.1	15.0	15.0
N>4.0 pCi/L	12	11	4	27

Table 2. Annual Average Radon in Air versus House Categories

Categories	N	N> 4.0 pCi/L	Geom. Mean (pCi/L)	Geom. St'd. Dev.	Categories differing
Ventilation					
a.) tight	88	16	1.9	2.0	*a,b) p=0.025*
b.) average	103	11	1.5	2.3	*a,c) p=0.005*
c.) drafty	17	1	1.2	1.8	b,c) p=0.10
Heat					
a.) forced air	148	12	1.6	2.1	a,c) p=0.08
b.) convection	6	1	1.5	2.3	
c.) hot water	12	1	1.2	2.3	
Air Conditioning					
a.) yes	133	14	1.6	2.2	a,b) p=0.07
b.) no	38	1	1.3	1.9	
Location					
a.) hillside	42	6	1.8	2.2	a,d) p=0.07
b.) plain	62	5	1.6	2.2	a,e) p=0.08
c.) hilltop	27	3	1.4	2.0	
d.) near hilltop	23	1	1.3	2.4	
e.) valley	13	0	1.3	1.9	
House Type					
a.) apartment	1	0	(2.9)	—	
b.) split-level	30	2	1.6	2.0	
c.) two-story	48	3	1.6	1.9	
d.) ranch	72	7	1.4	2.3	
e.) three-story	2	0	1.4	—	
f.) 1½ story	13	1	1.3	2.1	
Foundation					
a.) slab, no basement	4	1	3.9	1.2	*a,c) p=0.02* *a,d) p=0.01*
b.) crawl space	1	0	2.9	—	
c.) basement plus crawl space	7	0	1.7	1.8	
d.) basement	155	13	1.5	2.2	
Basement Walls					
a.) stone	6	0	2.3	1.7	*a,d) p=0.025*
b.) cement block	18	1	1.6	2.1	a,c) p=0.10
c.) poured concrete	108	11	1.5	2.2	b,d) p=0.15
d.) clay block	7	0	1.1	1.7	
e.) cinder block	1	0	0.5	—	
Basement Condition					
a.) tile sump	62	10	1.8	2.3	*a,d) p=0.01*
b.) no tile sump: openings	25	2	1.8	1.9	a,c) p=0.13 *b,d) p=0.02*
c.) no openings: cracks	17	1	1.4	1.9	
d.) none of above	61	1	1.2	2.1	

direct radon entry with soil gas through joints, cracks, or openings in the slab.

The difference between houses with stone basement walls and those with clay (tile) block basement walls can be understood in terms of openings for the entry of soil gas offered by the stone walls, usually of old construction with loose or missing mortar, while clay tile walls would be expected to be newer, and far less permeable to radon or soil gas.

The higher radon levels for the groups of houses with basement drain-tile sumps or major openings to the soil, compared with the group with no major basement cracks or openings, can also be understood in terms of paths available for the entry of soil gas.

Radon in Soil Gas

The radon levels in soil gas, sampled at 90 cm depth on opposite sides and one meter from the foundation of each of 40 houses in the Central Iowa survey, ranged from 40 to 1200 pCi/L, with mean 375 pCi/L, geometric mean 290 pCi/L, and geometric standard deviation 2.2. The frequency distribution was lognormal, except for an excess of lowest radon levels, between 50 and 90 pCi/L. Levels at the two different sides of each house often differed by factors of as much as two or more, while samples from holes separated by only a few tens of cm agreed quite well.

There was no correlation between the radon levels measured in the soil gas and the long-term radon levels measured in air with alpha track detectors on the main floors of these 40 houses.

To study soil gas radon levels more closely at two houses, samples were taken from five holes made at widely spaced positions around the foundations, including all four sides of the houses. For one house, the results were 550, 200, 180, 80, and 300 pCi/L; and for the other house, 380, 260, 250, 500 and 490 pCi/L. The variations among measurements for a given house are well outside the estimated 15% experimental uncertainty associated with the method. These results indicate that a few samples usually will not adequately characterize the soil gas radon content for the purpose of estimating its effect on radon levels in a house.

The range of radon concentrations found in soil gas in these measurements is comparable to the 20 to 600 pCi/L range reported in a study in Minnesota (Steck, 1986). It is somewhat less than the range (Luetzelschwab, Helweick and Hurst, 1989) of 540 to 1760 pCi/L measured in situ and up to 30,000 pCi/L determined indirectly for Central and Eastern Pennsylvania, where there are many homes with higher radon levels in indoor air than found in the Iowa homes studied here.

Radon in Water

Measurements of the activity concentrations of radon in the water at the kitchen taps were made for all the houses with private wells and for one or more houses on each public water supply serving houses in the survey. The 21 public water supplies had levels from less than 30 to 740 pCi/L, with arithmetic mean 210 and geometric mean 130 pCi/L, and geometric standard deviation 3.1. Radon levels in private water supplies ranged from less than 30 to 1700 pCi/L, with mean 480 and geometric mean 350 pCi/L, and geometric standard deviation 2.8. These results are consistant with earlier surveys of radon in water supplies in Iowa, in which the geometric mean for 85 public ground water supplies was 220 pCi/L (Hess, Michel, Horton, Prichard and Coniglio, 1985).

There was no correlation between radon in the water supplies and annual average radon in air for the houses. This indicates that radon in the water supplies is neither a significant direct source nor an indicator of other sources for the radon in the air.

It would be expected (Hess, Weiffenbach and Norton, 1982) that about 0.8 pCi/L in the air would come from radon outgassed from water in typical household uses if the water were at 10,000 pCi/L and the ventilation rate of the house were 1.0 air change per hour, corresponding to an average or slightly drafty house. With water radon levels ranging to 1700 pCi/L, this would produce a maximum of 0.28 pCi/L radon in air for a typical low-ventilation house (at 0.5 air change per hour), and an average amount of less than 0.1 pCi/L in air due to the radon in the water supplies of all of these houses.

The risk of cancer from drinking water with radon in it is estimated to be about one tenth of the risk of lung cancer from breathing the average amount of radon that escapes from the water supply into the air in a house with water usage (Cross, Harley, and Hofman, 1985). With less than 0.3 pCi/L in the air due to the water supplies, and lung cancer risk 0.7% to 3% for 2 pCi/L in the air (linearly dependent on radon concentration), the lifetime individual risk of cancer (primarily stomach cancer) due to the drinking of water with the radon levels found in this study is less than 0.05%, not of concern compared to the lung cancer risk from radon from all sources in the air.

CONCLUSIONS

In Central and Eastern Iowa, residents in houses with a wide variety of characteristics are exposed to radon at levels over 4 pCi/L in air for the year average on the main floor. From the characteristics of the log-normal distribution for radon levels in the houses studied, it would be expected that very few (<0.1%) houses will be found to have over 20 pCi/L on the main floor for the annual average in eastern Iowa, but that significantly more (0.5% to 1.0%) will be found in Central Iowa.

The soil gas around house foundations is at high enough radon levels to be the most-important source of the radon in air for the houses. The dependence of the radon levels on the presence of various paths through which soil gas can enter basements supports the view that soil gas is a major source. The water supplies have low enough radon levels that they are only sources of an insignificant fraction of the radon in the air in any of the houses.

Since from 10% to 25% of the houses studied had air radon levels over 4.0 pCi/L for the annual average, there is a large number of houses in Iowa for which radon mitigation should probably be applied. Because the ways in which radon enters houses in Iowa are similar to those found in other regions of the country, the dissemination of information on radon measurement methods and radon mitigation techniques that have proved effective in other parts of the country should result in significant health benefits for the residents of many homes in Iowa.

In view of these results, the Linn County Health Department has recommended that county residents measure for radon in air regardless of house type, and take mitigation action if annual average main floor levels are near or over 4.0 pCi/L.

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