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CONTRIBUTION OF WATERBORNE RADON TO HOME AIR QUALITY

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ABSTRACT

The American Water Works Association Research Foundation (AWWARF) initiated a study to determine the contribution of waterborne radon to radon levels in indoor household air. The project required selection of three communities with waterborne radon levels in the ranges of 500 to 2,000 pCi/L; 2,000 to 10,000 pCi/L; and greater than 10,000 pCi/L and required the concurrent measurements of airborne and waterborne radon in selected homes. The main objective of the project is to perform a controlled experiment to explore the effect of a centralized water system on indoor radon levels in three communities with widely variant waterborne radon contamination levels.

Various processes, such as diffused bubble aeration, granular activated carbon (GAC), and packed tower aeration (PTA) for removal of radon were reviewed. Various advantages and disadvantages of each treatment system were identified. Capital costs and annual operating costs for PTA systems for radon removal from water were evaluated.

Improvement in indoor air quality resulting from treatment of waterborne radon in two communities was small. However, in one community a large indoor air radon reduction was achieved by reducing the waterborne radon concentration using a PTA treatment system.

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BACKGROUND

RADON OCCURRENCE IN PUBLIC GROUNDWATER SUPPLIES

The occurrence of radon in drinking water supplies originates from groundwater sources. The radon content in groundwater may range from around 100 pCi/L to occasionally over 1,000,000 pCi/L (Longtin 1990). In order to develop regulations for radon in drinking water, the U.S. Environmental Protection Agency (USEPA) conducted a survey to develop a nationwide distribution of radon in public groundwater supplies. The survey included a sample of 1,000 sites, which were divided into four population categories. A minimum reporting level (MRL) of radon of 100 pCi/L was used in this survey. The maximum concentration of radon found in this survey was 25,700 pCi/L. Only 27.4 percent of the sites reported concentrations of radon less than the MRL of 100 pCi/L.

Population-weighted averages of radon in groundwater were calculated. It was found that the states of Maine, New Hampshire, and Rhode Island had the highest levels of radon in the nation. The population-weighted average for radon in water was 194 pCi/L for populations greater than 1,000. For populations less than 1,000, the average was 602 pCi/L; whereas the overall national average was 249 pCi/L.

INDOOR RADON OCCURRENCE

Radon enters into a home through cracks and other openings in the walls and floors that are in contact with the soil. A nationwide survey of radon concentrations in indoor air was conducted by Cohen (1989) at the University of Pittsburgh. This study, with over 100,000 measurements of indoor air radon concentrations, found that the indoor radon levels in a given geographic area is log normally distributed, with a geometric standard deviation of about three. Average radon levels in main living areas have been found to be 40 percent higher in winter than in summer. Also, this study showed that radon levels in rooms below ground level are twice as high as in rooms above ground level. The nationwide mean radon level in living areas was found to be 1.76 pCi/L. The data in this study showed that North Dakota and Colorado had the highest levels of indoor radon.

It has been estimated that about 10 percent of all homes in the United States have radon levels exceeding the USEPA corrective action level of 4 pCi/L (Skrable 1991). A major portion of these homes had radon concentrations in the range of 4 to 20 pCi/L.

RADON TRANSFER FROM WATER TO AIR

When water is exposed to the atmosphere, some of the dissolved radon in water will diffuse into the air. In general, the quantity of radon and the rate at which it is released from water depend on the waterborne radon concentration, water temperature, and water usage (i.e., the degree of agitation to which water is subjected). Thus, the largest releases of waterborne radon in the home are due to those activities and appliances that spray or agitate heated water, such as taking showers and washing dishes or clothes.

Gesell and Prichard (1978) conducted a field test on the number of dwellings served by water containing 1,500 to 2,000 pCi/L of radon. They found that the ratio of radon concentration in air to the water concentration ranged from 5×10^{-5} to 2×10^{-4} and averaged 1×10^{-4}. Hess, Weiffenbach, and Norton (Hess et al. 1982) made more extensive measurements of the radon water-to-air exchange in 85 houses. The ratio of the concentration of radon in air to that in water was found to be 1.07×10^{-4}, which is in good agreement with Gesell and Prichard (1978).

RADON-IN-WATER HEALTH RISK

Radon itself, being chemically inert, is not hazardous at environmental concentrations. The major health effect associated with radon arises from the inhalation of its short-lived decay products, which are chemically reactive and may lodge on the lining of the lungs (Nero 1990). Alpha particle emissions from polonium-218 and polonium-214 damage tissue near the deposition site. This is the main mechanism that increases the risk of lung cancer associated with exposure to radon and its decay products. Traditionally, airborne radon is considered to be a much greater risk than ingested radon in daily life (Crawford-Brown 1991). As a result, the health risk of waterborne radon currently is based on the diffusion of radon from water to indoor air.

The USEPA proposed a regulatory standard limiting the concentration of radon in drinking water supplies. The proposed maximum contaminant level (MCL) of radon is 300 pCi/L in public drinking water supplies serving more than 25 residences. Considering the normal water use and ventilation conditions in an average home, and considering that the ratio of radon in air to radon in water is 1×10^{-4}, the proposed MCL of 300 pCi/L in water is expected to contribute 0.03 pCi/L to the average indoor radon concentration (Skrable 1991). Skrable (1991) also mentioned that the proposed limit of 300 pCi/L of radon in water may cause a false sense of safety to occupants of homes if the radon concentration in water is reduced when in fact the major source of airborne radon is infiltration from the soil. Water supplies with high radon concentrations tend to occur in areas where significant radon entry occurs via soil gas (Tanner 1988).

The USEPA (1986) risk assessment of radon in drinking water is based on inhalation from radon released during water-related activities as the major exposure pathway. This assessment of risk estimated that a water radon concentration of 10 pCi/L would produce a lifetime risk of 1×10^{-6} (i.e., there is a chance of 1 death in 1 million population during a life span of 70 years due to lung cancer).

There can be two significant sources of radon that contribute to the indoor home radon concentration. These sources are soil gas and drinking water. The pathway for health effects from soil gas radon is inhalation, resulting in lung cancer. The pathways for health effects due to radon in drinking water may be inhalation and ingestion, resulting in lung and stomach cancers. For lung cancer from radon in drinking water, the critical pathway is inhalation, whereas for stomach cancer the critical pathway is ingestion. Extensive studies have been conducted to determine the health risk of indoor air radon. Studies have shown that the effect of 300 pCi/L of radon in water on indoor air radon will be negligible, compared with the 4 pCi/L indoor air concentration as an action level. There will be little reduction in the health risk of lung cancer by reducing the waterborne radon concentration from 1,000 pCi/L to 300 pCi/L, when the indoor air radon contribution from soil gas is 3 pCi/L in the air.

RESEARCH STUDY OUTLINE

The American Water Works Association Research Foundation (AWWARF) initiated a project to study the contribution of waterborne radon to radon levels in indoor household air. The project entailed the concurrent measurements of airborne and waterborne radon in selected homes in three small communities before and after the installation of waterborne radon removal systems on community water supply systems.

The selection of these three communities for this study was based on their documented waterborne radon levels in the ranges of 500 to 2,000 pCi/L, 2,000 to 10,000 pCi/L, and greater than 10,000 pCi/L.

The objectives of this study are to perform a controlled experiment aimed at exploring the effect of a centralized water treatment system on indoor radon exposures in three communities with widely variant waterborne radon contamination levels, and to produce empirical data regarding radon water-to-air transfer coefficients in the home environment.

COMMUNITY SELECTION

In order to develop statistically significant measurements based on different waterborne radon concentrations, it was necessary to carefully identify and select the communities. Three communities were selected that have groundwater with documented radon concentrations in the following ranges: one with 500 to 2,000 pCi/L; one with 2,000 to 10,000 pCi/L; and one with greater than 10,000 pCi/L. Each of the communities are served by a centralized public groundwater supply system. This would allow installation of centralized radon removal equipment. All three communities are located in southern New Hampshire, within a 15-mile radius of each other, and served by small groundwater systems owned and operated by the SNHW Company. These communities have been designated as Community A, B, and C to comply with the confidentiality agreement made with the homeowners.

RADON MEASUREMENTS

This study had not only to generate valid water and air radon measurements, but also to successfully establish a waterborne radon removal system and data base, where differences in pre- and posttreatment indoor air radon concentrations could be attributed to the pre- and posttreatment waterborne radon contribution.

Airborne Radon Measurements

Airborne radon measurements were made using electret-passive environmental radon monitors, (E-PERM). The E-PERM is a device that uses an electrostatically charged Teflon disc, called an electret, to measure the radon concentration in air. Once activated, the electret surface, which has a positive charge, attracts negative ions produced by the alpha particles generated from decaying radon. The radon enters a filtered ionization chamber housing the electret, and negatively charged ions are drawn to the surface of the electret, thereby reducing its surface voltage. The resulting electret surface voltage is read using a portable digital meter (surface potential electret reader, or SPER) before and after exposure to radon. The resulting differential voltage is then used to calculate the average radon concentration present during the exposure period. For a 7-day exposure period, the lower level of detection (LLD) of airborne radon measurements using E-PERM is about 0.3 pCi/L (USEPA 1989). Airborne radon tests were performed in accordance with the USEPA radon measurement protocols (USEPA 1989).

One of the major benefits of using the E-PERM is that it can be used in areas of high humidity and temperature (e.g., laundry rooms, bathrooms, and kitchens), which are not normally recommended for radon testing. This characteristic made the E-PERM well suited for use in this study. These rooms were important for this study because they are most likely to have radon in air contributed from waterborne radon.

The airborne testing program was based on the premise that if factors with the greatest potential to affect radon measurements can be kept identical in the pre- and posttreatment testing phases, then any statistically valid differences between pre- and posttreatment results can be attributed to differences in the waterborne radon concentration.

The measurements were conducted between February and April, 1990. Except for a few unusually mild days, during which no testing was done, the temperatures were typical for southern New Hampshire for that time of year. These conditions for indoor radon can be considered a worst case scenario.

Airborne radon monitoring was conducted over a 7-day period (the time period between readings) to measure the average home air quality conditions and to cover at least one weekly cycle of household activities contributing to waterborne radon releases. Every house tested had a clothes and a dish washer. Water usage was monitored by taking water meter readings before and after the test.

The concentration of radon in indoor air is generally less than its equilibrium value. As a result, radon will move from water into the air according to Henry's law. Radon has a high Henry's coefficient, which indicates that radon will easily diffuse from water to air. Release of waterborne radon to indoor air depends on waterborne radon concentrations, water temperature, and the degree of agitation of water. Thus, the largest releases of waterborne radon in the home are due to activities such as taking showers and washing dishes or clothes.

Radon monitor locations were selected to best differentiate between airborne radon contributions from the soil and from the household water. The air radon contribution from domestic water should be the highest in areas or rooms where household activities would cause radon/water separation. Radon monitors were placed within each house in areas with varying potentials for radon/water separation. These areas included the following:

Area 1: Areas of high potential for release of radon from water and high potential for airborne levels from soil gas (e.g., basement laundry rooms)

Area 2: Areas of low potential for release of radon from water but with high potential for airborne levels from soil gas (e.g., basement family rooms)

Area 3: Areas of high potential for release of radon from water and low potential for airborne levels from soil gas (e.g., first floor kitchens or bathrooms and second floor laundries)

Area 1 (high water and high soil) was chosen to be the laundry rooms located in the basements in Communities B and C. The habitable portions of the typical basement were divided into a family room, a work or storage room, and an enclosed laundry room. The enclosure of laundry rooms helped to isolate them from the rest of the basement.

Basement family rooms were selected as Area 2 (low water, high soil). These areas are typical locations recommended in the USEPA radon measurement protocols for screening tests (USEPA 1990). They have the same potential for soil gas as the enclosed laundry rooms. However, the effect of waterborne radon would likely not be as significant as in the enclosed laundry rooms.

Rooms on an upper floor have a lower potential for elevated radon concentrations due to soil gas because of remoteness from soil gas sources. However, kitchens or bathrooms on the first floor and laundries on the second floor were chosen as Area 3 (high water, low soil), based on the premise that they would be affected mostly by waterborne radon resulting from either dish washing or showering.

For each selected house, E-PERMs were placed in each of the three areas discussed above for a continuous 7-day period before and after the installation and operation of the community-wide radon removal water treatment systems. A 7-day period for indoor air radon measurements was selected to cover the weekly cycle of household water-related activities in a house. In accordance with the USEPA radon measurement protocols, monitors were placed: at breathing height, between 4 and 6 feet above the floor; away from walls, air-moving equipment, registers, and furnaces; and in unobstructed areas.

In keeping with the intent to maintain test conditions consistent in both pre- and posttreatment phases of the testing program, a sketch of each house floor plan was prepared showing the exact locations of the radon monitors as they were placed in the pre-treatment testing phase. The plans were then used to replace the monitors in the same locations for posttreatment testing.

Water Sample Collection and Analysis

Samples of household water were collected for radon analysis concurrently with the placement of the airborne radon monitors for both the pretreatment and posttreatment testing phases. Water samples were collected only at the time monitors were placed. A total of 242 regular water samples and 51 duplicate water samples, for QA/QC purposes, were collected. Water samples were taken from the cold-water system, using the submerged vial method. Except for a few houses that had iron removal systems in operation, none of the houses had point-of-entry or point-of-use water treatment systems in operation. Samples were collected following the USEPA (1983) protocols.

WATERBORNE RADON REMOVAL SYSTEMS

In a study for the USEPA, Kinner et al. (1990) evaluated radon removal systems for small community water systems, using granular activated carbon (GAC) and adsorption, diffused bubble aeration, and packed tower aeration (PTA). The performance of GAC units may be impaired by accumulation of iron, manganese, and particulates. Furthermore, a GAC system may require periodic backwashing. Kinner et al. (1990) also mentioned that retention of radioactive materials in the GAC bed may cause the GAC to be classified as a low-level radioactive waste. Lowry et al. (1987) indicated that GAC is able to absorb a new radon atom on its surface once the radon atom previously absorbed decays to its progeny. Kinner et al. (1990) did not observe any breakthrough, and regeneration was not required. Lowry et al. (1991) analyzed data from 121 point-of-entry GAC units from 1981 to 1989 and indicated no loss of efficiency of units over 2 to 6 years of monitoring. It is, believed, therefore, that a GAC bed should theoretically remove radon from drinking water for extended periods. Kinner et al. (1990) concluded that the issues of fouling, gamma exposure, disposal of used GAC, and potential desorption of radon progeny should be considered before GAC is used for radon removal. The levels of Pb-210 and its progeny in the treated water should also be a concern when using GAC units (Lowry et al. 1991).

Kinner et al. (1990) also tested a diffused bubble aeration system for radon removal. The diffused bubble aeration system consisted of polyethylene tanks with plastic diffusers located at the bottom of the tanks. Aeration was provided by a blower. Water was pumped directly from the wells to the diffused bubble system and then pumped to pressure tanks. Air to water (A:W) ratios of more than 5:1 yielded radon removal efficiencies of 90 percent to 99.6 percent. Diffused bubble aeration systems, however, will have potential air pollution problems in addition to iron and manganese precipitation.

Kinner et al. (1990) found that the packed tower aeration (PTA) system was very efficient in removing radon from water (90 to 99 percent removal). Cummins (1988) also found that PTA was highly efficient. Lenzo (1990) conducted some full-scale pilot studies and found 96.5 percent removal at 10 feet packed depth. Untreated water is pumped to the top of the tower and evenly distributed over the packing of plastic materials, while air is blown from the bottom upward through the packing. The greater the contact time between the air and water, the greater the opportunity for transferring the volatile contaminant from the water into the upward-flowing air (Lenzo 1990). In the present study, the PTA system was used to remove radon from water in the three communities.

DATA MEASUREMENT

A total of 119 homeowners in the three communities participated in the pre- and posttreatment radon measurements. Community A participated with 19 homes, Community B participated with 85 homes, and Community C participated with 15 homes.

Airborne Radon Data

Airborne radon concentrations in both pre- and posttreatment periods primarily were measured in three locations in each house: the basement family room, the basement or second floor laundry, and the first floor kitchen. In addition, airborne radon was measured in the first floor bathrooms in two homes. A total of 60 pairs of airborne radon data (pre- and posttreatment measurements) were obtained in Community A, 256 pairs in Community B, and 45 pairs in Community C. All of these data were entered into the data base.

A summary of the airborne radon concentrations is shown in Table 1. This table shows high, average, and low airborne radon concentrations broken down by community and by the location in the house. The average radon concentrations in each community was reduced after treatment. These reductions for Communities A, B, and C were 0.1, 0.2, and 2.9 pCi/L, respectively. Low-level detection (LLD) of the E-PERM method of indoor radon measurement is about 0.3 pCi/L.

Because previous measurements of indoor airborne radon have been log normally distributed (c.f., Longtin 1988), the airborne data collected in this study also were assumed to be log normally distributed. A statistical analysis of airborne radon data by community and by each location was conducted.

Waterborne Radon Data

Waterborne radon for each house during pre- and posttreatment periods were collected. The household waterborne radon concentrations were entered into the waterborne radon data base.

The reduction of average household water radon concentrations

TABLE 1

Household Airborne Radon Concentration*

			Pretreatment			Posttreatment	
Community	Location	Maximum	Average	Minimum	Maximum	Average	Minimum
A	SL	1.6	0.6	0.0	1.5	0.5	0.0
	BF	9.2	4.1	0.5	7.2	3.7	0.6
	FK	1.3	0.5	0.0	1.4	0.5	0.0
	Overall		1.8			1.7	
B	BL	3.0	1.1	0.1	3.8	0.9	0.0
	BF	7.1	1.3	0.0	6.0	1.2	0.0
	FK	2.1	0.8	0.0	2.2	0.5	0.0
	FB	0.7	0.7	0.7	0.4	0.3	0.1
	Overall		1.1			0.9	
C	BL	8.8	4.9	1.1	5.8	1.7	0.0
	BF	7.5	4.1	0.9	5.5	1.6	0.0
	FK	7.8	3.6	1.8	2.9	0.6	0.0
	FB	7.8	6.8	5.7	5.0	3.3	1.5
	Overall		4.3			1.4	

Note:
BL = Basement Laundry
BF = Basement Family
FK = First Floor Kitchen
SL = Second Floor Laundry
FB = First Floor Bath
* = All values given in pCi/L

due to the treatment system for Communities A, B, and C were 1,166, 2,170, and 20,775 pCi/L, respectively. Waterborne radon removal efficiencies of radon treatment systems installed at the well locations of all communities were measured by analyzing samples for waterborne radon concentration collected from the influent and effluent of the treatment systems. Treatment system efficiency ranges from 95 percent to 96 percent.

ANALYSIS OF DATA

The objective of this analysis was to determine the effect of household waterborne radon on household airborne radon levels under various waterborne radon concentrations. The average household waterborne radon concentrations measured during this study were 1,292 pCi/L for Community A, 2,411 pCi/L for Community B, and 21,295 pCi/L for Community C. If the reduction in airborne radon, due to the reduction in waterborne radon, is low and within the diurnal and other fluctuations of indoor radon concentration, it will be difficult to accurately identify the contribution of the reduction in airborne radon due to the reduction in waterborne radon. This is particularly true when the background indoor radon concentration, due to the soil gas and other sources, is high in comparison with the contribution of waterborne radon to indoor radon.

STATISTICAL ANALYSIS

The data entered into the data base have been analyzed using the following methods:

- Matched pair statistical analysis.
- Statistical analysis of the reduction in airborne radon concentrations with respect to the reduction in waterborne radon concentrations.
- Comparison of the cumulative distribution of pre- and posttreatment airborne radon concentrations.

Matched Pair Analysis

In studies involving data consisting of two samples where one cannot assume that the two samples are independent of each other, the data can be analyzed as an ordered pair. Samples of pretreatment household airborne radon measurements and posttreatment airborne radon measurements taken in the same house at the same locations can be paired together. The paired data are not independent of each other. Each observation (data point), consisting of pre- and posttreatment airborne radon concentrations at the same location, will be treated as a matched pair. These matched pairs can be plotted, and the difference in the slope of a linear regression line, passing through the origin, from a slope of 1.0 will indicate the degree to which the pre- and posttreatment data differ. A regression line with a slope not significantly different from 1.0 indicates that the pretreatment and posttreatment data are not significantly different. The statistical hypothesis for this regression model is that the slope of the regression line is not significantly different from 1.0. If this is not the case, then a conclusion can be reached that the pretreatment data are significantly different from the posttreatment data.

Figures 1, 2 and 3 show that the slopes of these lines for Communities A, B, and C are 1.11, 1.03, and 1.87, respectively. Slopes significantly greater than 1.0 indicate a reduction of the airborne radon concentration due to the reduction of waterborne radon concentration, whereas slopes less than 1.0 indicate an increase in the airborne radon concentration. The slopes of the regression lines for all communities are greater than 1.0 indicating a reduction between pre- and posttreatment average airborne radon concentration. The slopes of the regression lines for Communities A and B are 1.11 and 1.03, respectively. The slope of the regression line for Community C is 1.87.

The average household waterborne radon reductions were: Community A, 1,166 pCi/L (from 1,292 pCi/L o 126 pCi/L); Community B, 2,170 pCi/L (from 2,411 pCi/L to 241 pCi/L); and Community C, 20,775 pCi/L (from 21,295 pCi/L to 520 pCi/L).

Data Analysis by Location

The relative effect of the location within the household on the airborne radon concentration was evaluated by matched pair data of airborne radon concentrations segregated for each community by the three household locations. These locations are the basement family room (BF), the basement laundry (BL), and the first floor kitchen (FK) for Communities B and C, and the basement family room (BF), second floor laundry (SL), and the first floor kitchen (FK), for Community A. In addition, the first floor bathroom (FB) was used for locations in two houses each in Communities B and C.

The overall results of this analysis showed that there is little reduction (less than 10 percent) of posttreatment airborne radon at all locations in Community A and at locations BF and BL in Community B. In Community C, indoor mean air radon concentrations under pretreatment condition were high at all locations ranging from 3.6 to 5.0 pCi/L. The slopes of the regression lines from the matched pair analysis vary from 1.74 to 2.41 indicating reductions of indoor air radon concentrations at

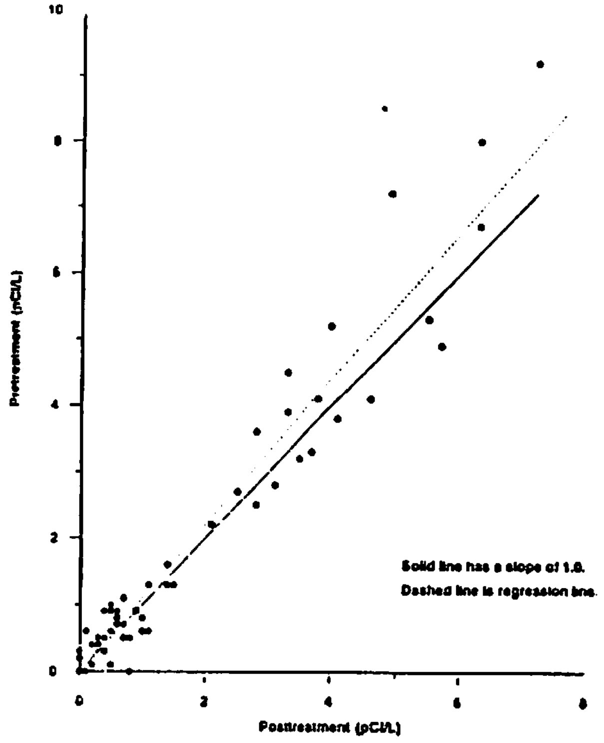

FIGURE 1 Matched Pairs Analysis, Community A, Summary

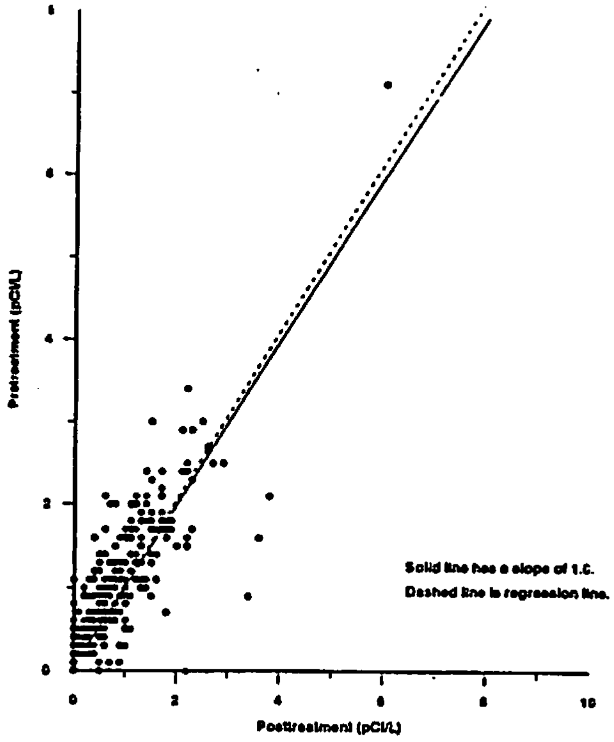

FIGURE 2 Matched Pairs Analysis, Community B, Summary

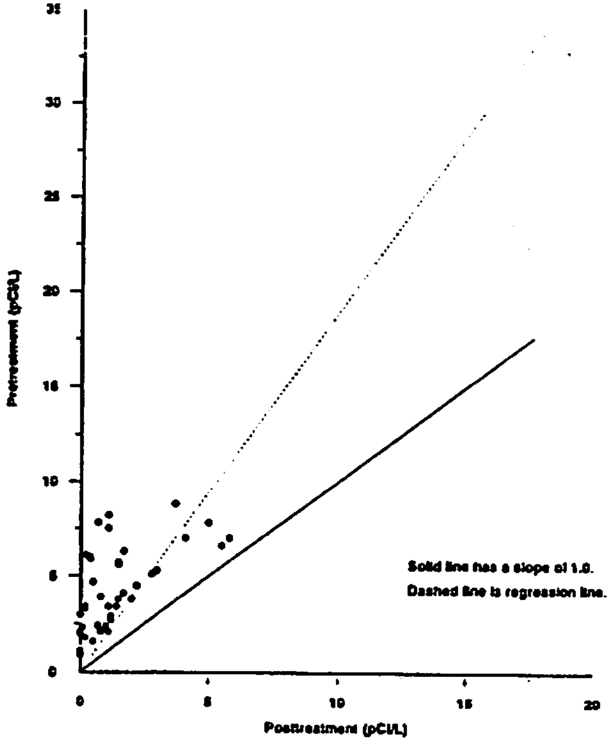

FIGURE 3 Matched Pairs Analysis, Community C, Summary

all locations. A range of reduction of 42.5 to 58.5 percent of airborne radon was achieved at locations in Community C.

In order to assess the effects of waterborne radon on indoor air radon, it was necessary to estimate the concentration of the average background indoor air radon concentration of each community. Estimated background airborne radon concentrations in the three communities shows that Community A had a relatively high background radon concentration, whereas Community B and C each had indoor background radon concentrations of 1.0 and 1.6 pCi/L, respectively, which are lower than the national average living area indoor radon concentration of 1.7 pCi/L (Cohen 1989).

Analysis of Radon Reduction Data

All posttreatment household airborne radon data were subtracted from the corresponding pretreatment radon data to determine the reduction in airborne radon at each location due to reduction in waterborne radon. An analysis of radon reduction data by community and by location was conducted. These results show that, for communities A, B, and C, average airborne radon reductions of 0.09 pCi/L, 0.19 pCi/L, and 2.92 pCi/L were achieved due to average waterborne radon reductions of 1,166 pCi/L, 2,170 pCi/L, and 20,775 pCi/L, respectively. Indoor radon reduction values can not be fully attributed to the reduction of waterborne radon concentration. Other variables that will contribute to these differences are diurnal radon variations, time lag of measurements, and accuracy of measurements.

Analysis of Distribution of Data

In order to obtain an overall, community-wide distribution of airborne radon concentration reduction due to reduction of waterborne radon for each community, a cumulative distribution analysis of pre- and posttreatment airborne radon concentrations was conducted. Cumulative distributions of measured airborne radon concentration values (both before and after treatment) for communities A, B and C are shown in Figures 4, 5 and 6 respectively.

This analysis shows that there was essentially no difference in airborne radon concentration due to water treatment in Community A, there was a small reduction of radon in Community B, and in Community C a large reduction of airborne radon was achieved. The cumulative distribution analysis does not consider matched pair data and does not represent the effect of the reduction of waterborne radon on airborne radon at a particular location within a house.

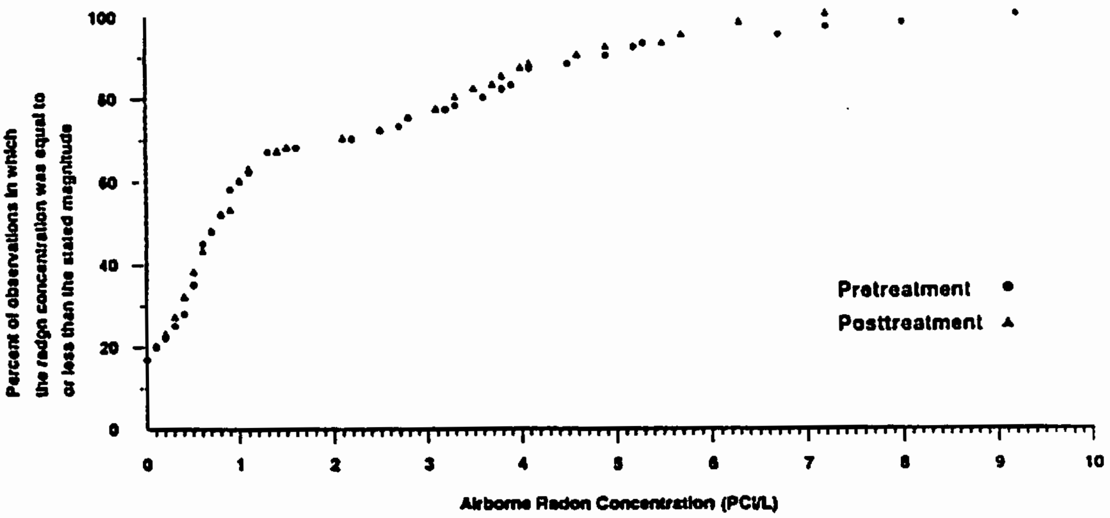

FIGURE 4 Airborne Radon Cumulative Distribution, Community A, Summary

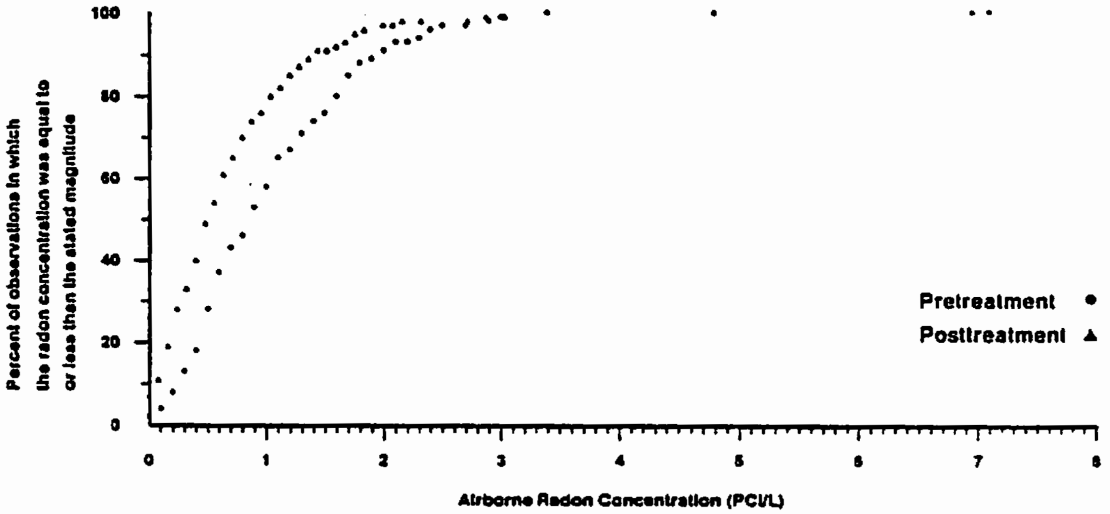

FIGURE 5 Airborne Radon Cumulative Distribution, Community B, Summary

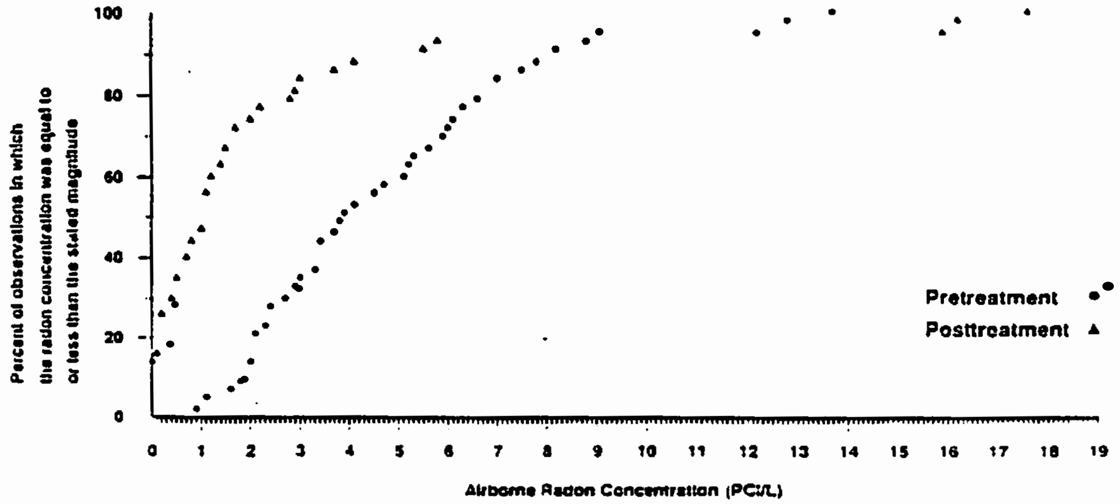

FIGURE 6 Airborne Radon Cumulative Distribution, Community C, Summary

CONCLUSIONS

The findings identified in this section lead to the following conclusions:

1. In Community A, contribution of waterborne radon to indoor air radon is small relative to the contribution from soil gas and other sources. Thus, water treatment system for radon removal has little effect on indoor air radon in Community A.

2. In Community B, average pretreatment indoor air radon concentrations in all locations are low and also the small difference in pre- and posttreatment indoor air radon concentration indicated a small contribution of waterborne radon to indoor air radon.

3. In Community C, a relatively large reduction of indoor air radon between pre- and posttreatment measurements at all locations indicated a large contribution of waterborne radon to indoor air radon and the effectiveness of water treatment system in indoor air radon reduction.

4. The effect of reducing waterborne radon on reducing indoor air radon has been found to be a reduction of 1 pCi/L of waterborne radon will reduce 1.3×10^{-4} pCi/L of indoor air radon.

5. Installation of water treatment systems for radon removal in water for Communities A and B containing radon concentration up to 2,400 pCi/L did not produce any significant improvement in indoor air quality.

6. Before conducting any studies of waterborne radon reduction and installation of waterborne radon removal system, it is advisable to conduct indoor air radon measurements to estimate the relative contributions of soil gas and waterborne radon to indoor air radon.

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