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RADON CONCENTRATIONS AND INFILTRATION IN HOMES

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ABSTRACT

Radon concentrations, averaged over the heating season, were measured using passive, integrating detectors. Occupied homes representing a range in design for energy efficiency, lifestyle of occupants, use of mechanical ventilation (e.g. air-to-air heat exchangers), and effective leakage areas as measured by "blower door" tests were included in the study. This study and results which have appeared in the literature indicate that building ventilation is a less important factor than source of entry of radon. It is more effective to prevent radon from entering than to attempt to remove excess radon by ventilation.

INTRODUCTION

Indoor Air Pollution. Rising fuel costs and concern that non-renewable energy resources may be exhausted in the not too distant future are prompting increasing numbers of people to weatherize existing buildings and to construct new energy-efficient buildings. A prime consideration in energy conservation for buildings is the reduction of air exchange or infiltration (the exchange of indoor air with outdoor air). The air exchange rate for typical homes constructed before the 1970s was one or more air changes per hour. That is, for most buildings in use today, the indoor air is exchanged with outdoor air on the average once each hour or more frequently.

Older buildings which have been weatherized by adding insulation, caulking, and weatherstripping, and new energy-efficient homes (super-insulated, envelope, earth-sheltered, etc.) may have air exchange rates that are much lower than "typical" buildings. The air exchange rate in some well-sealed buildings may be as low as one air exchange each ten hours (see Figures 3 & 4). This reduction in air exchange is usually quite effective as an energy conservation measure because air exchange often accounts for one-third or more of a building's heat loss.(1) However, restriction of exchange of indoor and outdoor air may solve a heat loss problem only to create a new problem of indoor air pollution.(1)

Radon, a naturally occurring radioactive gas, is one of several indoor air pollutants. Formaldehyde (mostly from building materials), carbon monoxide and nitrogen oxides (mostly from unvented gas flames), particulate matter (from smoking and wood burners) and even excessive moisture which may lead to mold and mildew are increasingly receiving attention as indoor air pollutants.

Radon. Uranium, and of lesser importance thorium, undergoes radioactive decay through a series of radioactive products which includes among them radon. Since uranium occurs in trace amounts in many minerals and rocks and in most soils, radon is ubiquitous. Radon is a noble gas, that is, a relatively chemically inert gas. Like air and water vapor, radon is transferred from place to place with relative ease unless an impervious barrier is present.

Radon undergoes radioactive decay to produce other radioactive products called radon progeny or radon daughters. The radon progeny, isotopes of lead, bismuth and polonium, are not noble gases and quickly become attached to particulate matter in the air or plate-out on, i.e. are deposited on, solid surfaces.

Radon and its progeny are known to cause lung cancer in people (e.g. uranium miners) who breathe air which contains radon concentrates substantially above the normal background level.(2,3,4,5) Radon concentrations frequently (as will be done in this paper) are expressed in picocuries per liter (pCi/L). One pCi/L of radon in air corresponds to a concentration of radon which produces about 63 radioactive decays per minute in one cubic foot of air. Outdoor radon concentrations are usually less than one picocurie per liter. Radon concentrations in the range of one to two picocuries per liter have been found in many typical homes.(6,7,8, 9,10) Table I lists standards and guidelines for radon concentration. The Environmental Protection Agency standard of 4 pCi/L is a widely used reference level for radon in homes and commercial buildings. That is, occupied space in a building which has an average radon concentration greater than 4 pCi/L is usually considered unsafe and action to reduce the radon centration warranted.

TABLE I RADON STANDARDS AND GUIDELINES

Agency	Radon Concentration
United States Mine Safety and Health Administration (Regulation for miners)	16 pCi/L
National Council on Radiation Protection and Measurement (Recommended action level for general population)	8 pCi/L
Bonneville Power Administration (Action level for residential weatherization program)	5 pCi/L

Environmental Protection Agency (Indoor limit in homes built on sites contaminated by uranium processing)	4 pCi/L
American Society of Heating, Refrigeration and Air Conditioning Engineers (Recommended level in commercial buildings and residences)	2 pCi/L

Radon In Buildings. Radon concentrations in buildings may become unacceptably high if the rate at which it is removed, chiefly through exchange of indoor air with outdoor air, is substantially less than the rate at which radon enters the building. Either a low ventilation rate, a strong source of radon or both are usually associated with elevated radon concentrations. Since all soil contains traces of radon-producing uranium and thorium, the gas trapped in pores within the soil has a radon concentration much greater than the air above the soil. Cracks or pores in basement slabs and walls, slab-footing joints, mortar joints, loose fitting pipes which penetrate the slab or basement walls, exposed soil in a sump or unfinished crawlspace and weeping tile may all be routes of entry of radon into homes. Some well water contains high concentrations of radium, the parent of radon. Homes in which such well water is used may receive substantial radon as it is released when the water is used, especially in showers. The Environmental Protection Agency publication "Radon Reduction Techniques for Detached Houses" gives a brief, but readily understandable, discussion of radon entry routes as well as methods for radon control in existing homes.(11)

Study Design. Two factors were of prime concern in the design of this study: (1) The homes monitored were "real," occupied homes, not test homes and (2) radon concentrations were averaged over a heating season. While specially designed test homes have the advantage that variables such as infiltration rate or indoor temperatures may be accurately controlled and measured, the results of studies on such homes may not correlate well with the conditions to which people are exposed in their homes. Radon concentrations in buildings may vary substantially over times of a few days as weather conditions or the activities of home occupants change. Using passive, integrating Track-Etch radon detectors from October through April, averages these relatively short term variations and gives a more representative measure of exposure to radon.(12,13) Detectors were placed in the basement, on the ground floor (usually in the kitchen) and on the second floor (usually on a bedroom wall). A very small number of carbon canister detectors were used to obtain a quick check on some mitigation efforts. In climates less severe than that of Northeastern Wisconsin, it might be appropriate to also include the "air conditioning" season. During the 1985-1986 heating season several characteristics of the houses and occupant behavior were measured. Hydrothermographs were placed in the kitchen or family room of each house to continuously record temperature and relative humidity over a four to ten week period. These data and data from the Green Bay Weather Service Office were used to estimate the absolute humidity difference between the house interior and the outdoors (see Figures 1 & 2). The air tightness of the houses was measured using the fan pressurization/depressurization method. Two Green Bay contractors were used: Energy Experts and Community Builders, Inc. For two houses, the effective leakage area was measured by both contractors. Their results agreed within about ±10%. As one measure of occupant behavior which might influence radon concentrations, automatic mechanical counters were used to monitor the number of times entrance doors were opened and closed per week over a several week period.

RESULTS

General Survey. During the 1981-1982 heating season 17 sites were monitored and during the 1985-1986 heating season 9 sites were studied. Table II summarizes the results of these general surveys. The difference in the average outside radon concentrations for the two heating seasons may be due to differences in weather conditions (depth of frost, snow cover, etc.) or it may be due to the fact that the design of the outdoor detectors was different for the two sets of measurements. Both values are within the range usually considered as normal for outside radon concentrations. The typical houses, that is, houses built using the standard construction techniques and without any special or unusual energy saving schemes, fall in the expected 1-2 pCi/L range. Basements, as might be expected since they are the location of the principal entry routes for radon in most homes, have a significantly higher radon concentration. As the data in Table II indicate, it is not surprising that energy-efficient homes, that is passive solar, super-insulated, earth sheltered, etc., in which special care is usually taken to reduce infiltration also have a significantly higher radon concentration than typical homes. The detailed data on which the averages in Table II are based are given in reference (14).

TABLE II AVERAGE RADON CONCENTRATIONS (pCi/L)
[ARITHMETIC MEAN ± STANDARD ERROR OF THE MEAN
(NUMBER OF VALUES AVERAGED)]

	1981-1982	1985-1986
Outside	0.82 ± 0.16 (8)	0.13 ± 0.02 (6)
Basements	3.10 ± 0.26 (10)	3.93 ± 0.75 (9)
Energy-efficient homes	3.24 ± 0.59 (12)	5.34 ± 1.90 (6)
Typical homes	1.29 ± 0.23 (11)	1.95 ± 0.22 (14)

For the 1981-1982 heating season, the average radon concentrations for basements and energy efficient homes are both significantly greater than those for the outside and typical homes (t-test at 95% confidence level). Typical homes are not significantly higher than outside in 1981-1982. The outside values for that season included seven values less than 0.9 pCi/L and one value of 1.88 pCi/L, which resulted in a rather high average and large standard error of the mean. For the 1985-1986 heating season the typical homes are significantly higher than outside. Except of the outside sites, the averages for the different types of sites for the two heating seasons are not significantly different.

Radon Control. Two of the homeowners whose energy-efficient houses had radon concentrations greater than 4 pCi/L in the living space installed air-to-air heat exchangers (AAHX) between the 1981-1982 and 1982-1983 heating seasons.

TABLE III RADON CONTROL

Site	Change	average radon concentration (pCi/L) 1981-1982	1982-1983
M	AAHX	5.86	4.30
H	AAHX	6.07	3.57
Q	ESAC	3.15	6.43
I	NONE	1.88	1.80
O	NONE	1.13	1.25

The use of the air-to-air heat exchanger reduced the radon concentration, but at site M the concentration remained above 4 pCi/L and neither site was reduced to the 1-2 pCi/L level of typical homes. Attempts to monitor the use of the air-to-air heat exchangers did not succeed. Reliable information on the dilution to be expected by the use of the AAHX is therefore not available. At site Q an electrostatic air cleaner (ESAC) was installed between the 1981-1982 and 1982-1983 heating seasons. The radon concentration appears to have increased by a factor of more than two. This result is consistent with expectation. When the surface area available for plate-out of radon progeny is reduced by removing particulates from the air, the radon progeny preferentially plate-out on the walls, floor, ceiling and detector, thus giving a "false" high reading. The detectors are only calibrated for "typical" home particulate concentrations. Sites I and O, for which no radon reduction measures were taken, were monitored in 1982-1983 to be sure that the general radon level had not changed from the 1981-1982 heating season.

Moisture, Radon and Building Tightness. Excessive moisture, i.e. very high relative humidity is often a symptom of inadequate air exchange for a building. Of course, excessive moisture might also be related to an excessive source of water vapor such as a damp basement or clothes dryer vented indoors. In order to gain insight into the relationships among radon concentration, relative humidity and air change rate for a building, fan pressurization air change rates and relative humidity were measured at most sites. Figure 1 shows the % relative humidity measured at four sites in the fall (November-December 1985) and figure 2 for three sites in the spring (February-April 1986). The general trends, decreasing humidity in the fall and increasing humidity in the spring are the expected responses to weather conditions. The comparatively low relative humidity at site B appears to be associated with the lifestyle of the occupants. Site B is a home of typical construction occupied by a family with children and several pets. The exterior doors in site B are opened and closed much more frequently than in other homes in this study. Monitoring with an automatic counter on the doors indicated less than 200 opening/closings per week for houses other than site B but more than 400 opening/closings per week for site B. The substantial effect on indoor air quality of the lifestyle of occupants, that is frequency of opening and closing doors is also suggested by the radon data for the 1981-1982 heating season. The buildings were classified as open (high air exchange due to usage or closed (low air exchange due to usage). Homes with children, commercial buildings, and other lifestyles or usage factors which result in many openings and closings of outside doors each day were classified as "open." Homes occupied only by working adults or other usage patterns which result in few openings and closings of outside doors each day were classified as "closed." The average radon concentration for the open buildings was 1.64 pCi/L compared with 3.55 pCi/L for the closed buildings. These data clearly show a correlation between the frequency of opening and closing of doors and radon concentration. However, cause and effect is not shown. It is reasonable to assume that opening and closing doors might increase ventilation enough to reduce radon concentration, but the needed measurements to demonstrate have not as yet been made.

Site W (Figure 1) is a very tight, passive solar home and site V (Figure 2) is a superinsulated home. Both sites V and W have air-to-air heat exchangers. Since the relative humidities of sites V and W are comparable with (or slightly lower than) the relative humidities at other sites, it appears that the air-to-air heat exchangers are controlling moisture.

The tightness of the houses studied was measured using commercial fan pressurization ("blower door") methods. A calibrated fan placed in an outside doorway is used to pressurize or depressurize the house. Measurement of the indoor/outdoor pressure difference as a function of the volume rate at which the fan is moving air into or out of the house allows estimation of the air exchange rate (air changes per hour - ACH). The air change rate at 50 Pa pressure difference was used as a relative measure of the leakiness of a house. Figures 3 and 4 use the reciprocal of the air change rate (1/ACH) as a relative measure of the tightness of a building. The horizontal axes in figures 3 and 4, 1/ACH, may be interpreted as the time in hours required to completely exchange the indoor air for outdoor air (at 50 Pa pressure difference). In figure 3 the difference in absolute humidity inside the house and that outside the house is plotted as a function of the reciprocal air change rate. The effect of the air-to-air heat exchanger (AAHX) for sites V and W is obvious in figure 3. The absolute humidity gradients for the homes with AAHX is within and below the range of absolute humidity gradients for all the other homes measured, but as measured without the AAHX in operation, the AAHX homes are twice as tight (both > 0.4 hr for 1/ACH) than the other homes (all < 0.2 hr for 1/ACH). For the homes without air-to-air heat exchangers there is no correlation between humidity and tightness (correlation coefficient = 0.50). It seems that lifestyle and moisture sources are at least as important in determining humidity as tightness of the house.

In figure 4, the average radon concentration for a site is plotted as a function of the reciprocal air change rate. There is a general trend of increasing radon concentration with increasing tightness of the building and a very weak correlation (correlation coefficient = 0.85). The effect of the air-to-air heat exchangers is not obvious in figure 4. In fact, site W which has an air-to-air heat exchanger that makes the effective air change rate greater than that for many other homes included in this study has the highest radon concentration observed in a living space. This suggests that the strength of the source of radon, as well as the building air exchange rate, is very important in determining the indoor radon concentration.

Strong Radon Source. The radon concentration in the crawl space of site W was monitored in 1985-1986 and found to be 96.88 pCi/L. Site W is a passive solar home with an air-to-air heat exchanger. Outdoor air from the air-to-air heat exchanger enters the crawl space, which acts as a very large duct to transfer fresh air to the living space and then back through the heat exchanger to the outside. The very large radon concentration in a well ventilated space - the air-to-air heat exchange provides about one half air change per hour - appears to be due to a very strong input rate for radon. A drain in the crawl space seemed to be the most likely source. Table IV summarizes the radon concentrations found before and after sealing the crawl space drain with duct tape. The July 1986 measurements were made using charcoal absorption detectors over a one-week period.(15)

TABLE IV SITE W RADON CONCENTRATIONS (pCi/L) BEFORE AND AFTER SEALING CRAWL SPACE DRAIN

	crawl space west	crawl space east	living room	utility room
Winter average (Oct. 85-Apr. 86)	96.88	---	10.14	7.48
July before (One week)	0.8	1.3	0.7	---
July after (One week)	0.3	0.6	0.3	---
Winter average (Oct. 86-Apr. 87)	16.7	---	17.1	15.3

Since the air change rate in July was very large because windows and doors were open during much of the sampling time, the radon concentrations are low, but all are greater than the winter outdoor average of 0.2 pCi/L. The radon concentration at the east end of the crawl space near the drain being higher than at the west end and the decrease by about a factor of two after sealing the drain suggest that the drain might be the chief source. During the 1986-1987 heating season, tracketch detectors were placed in the same locations as the detectors used in 1985-1986 (last line of Table IV). These results are consistent with the high air change rate (as measured using SF_6 tracer gas methods) between the crawl space and living space (about two and one-half air changes per hour for the crawl space and one exchange per hour for the living space). The observed air change rates are expected to result in approximately equal radon concentrations for both the crawl space and living space. The ratio of the radon concentration in the crawl space to that in the living space for 1985-1986 is not constant with the air change rates. Although re-reading of the track etch detector used in the crawl space in 1985-1986 verified the value listed in Table IV, there must be some doubt about its validity. The 1986-87 results also suggest that the effort to reduce the entry of radon by sealing the drain was not successful. Further investigation, particularly of pressure differences between the inside and outside of the house when a wood stove is in use are in progress.

CONCLUSIONS

Implications of Results. The results above and data in the literature(7,8,9,10,11) suggest three general conclusions with respect to the radon concentrations in buildings.

(a) The lifestyle of occupants may have a significant effect on indoor radon concentrations and indoor air quality in general. The frequency of opening and closing windows and doors or the frequency of use of bathroom and range fans (vented to the outside) may change the air exchange rate of buildings substantially. The use of wood stoves and fireplaces, because of the large volume of combustion air they require, may cause a lower pressure within the house than the pressure of the surrounding soil gas thus causing an increase in the inflow of radon.

(b) The installation and use of an air-to-air heat exchanger or other forced ventilation does not assure a low radon concentration. Air-to-air heat exchangers were developed primarily as moisture control devices and to provide sufficient ventilation to insure adequate indoor air quality while not drastically increasing energy use; many are operated with humidistats. While they may perform satisfactorily in controlling humidity, there is no guarantee that they will also adequately reduce radon to acceptable levels. The only sure way to know that radon has been reduced to below some desired concentration is to monitor specifically for radon.

(c) The radon source strength is more important than the ventilation rate. For example, site W discussed above had a radon concentration of about 10 pCi/L in the living space and an air change rate of about 0.5 ACH provided by an air-to-air heat exchanger. In order to reduce the radon concentration to below 4 pCi/L by increasing the ventilation with the source constant, it would require about a threefold increase in the air change rate to about 1.5 ACH.(11) It is usually more cost effective to reduce the entry of radon than to remove it by increased ventilation.

Design Considerations. It is more efficient to design a building which does not have high radon concentrations than to reduce the radon level after the building is in use. The following design considerations will help minimize radon in buildings.

(a) Avoid "negative" indoor air pressure, especially in basements and crawl spaces. That is, maintain the indoor air pressure nearly equal to the soil gas pressure so as to reduce the flow of radon into the building. (Positive pressure may have the undesirable effect of forcing moisture into walls and other building components.)

(b) Avoid routes of easy radon entry. For example, minimize cracks and loose joints in the basement and cover the sump and drains.

(c) Provide adequate, porous gravel under the slab and around basement walls so that radon will tend to migrate to the exterior rather than interior of a building. Proper venting of sub-slab soil gas has been demonstrated to be the most effective method of radon reduction.(11)

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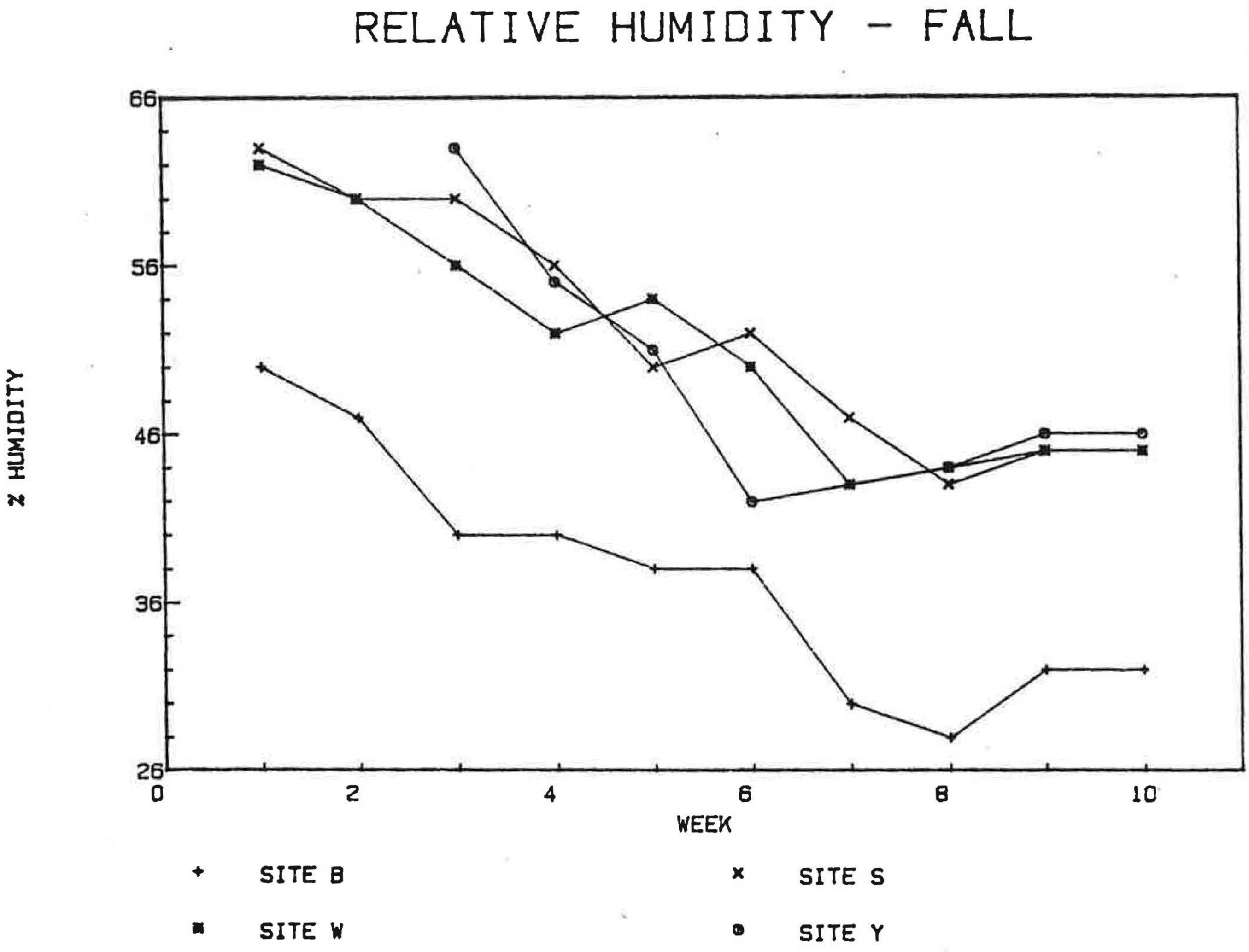

Figure 1. Relative Humidity - Fall. The percent relative humidity in four homes in the fall. Week one is the first week of October 1985.

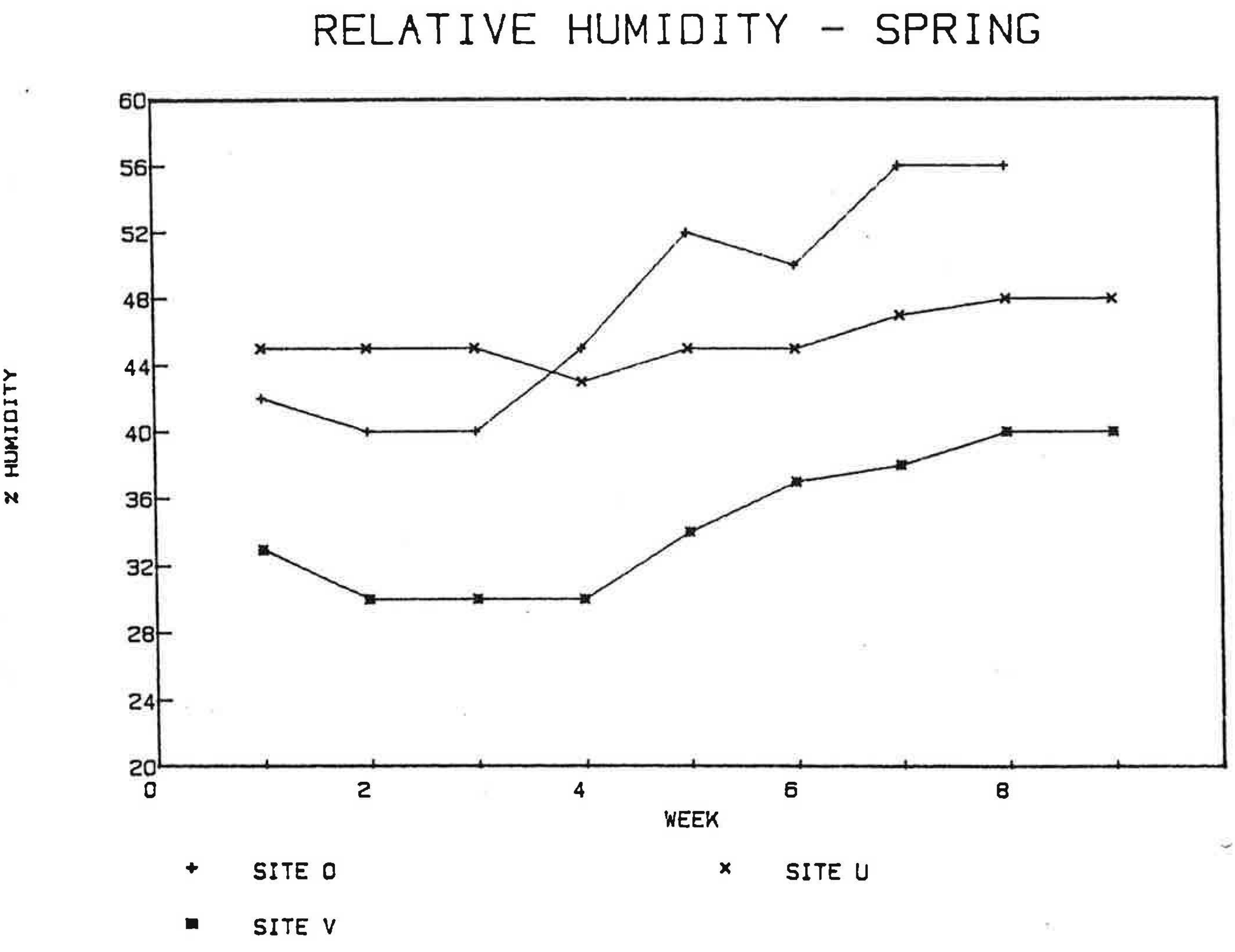

Figure 2. Relative Humidity - Spring. The percent relative humidity in three homes in the spring. Week one is the third week of February 1986.

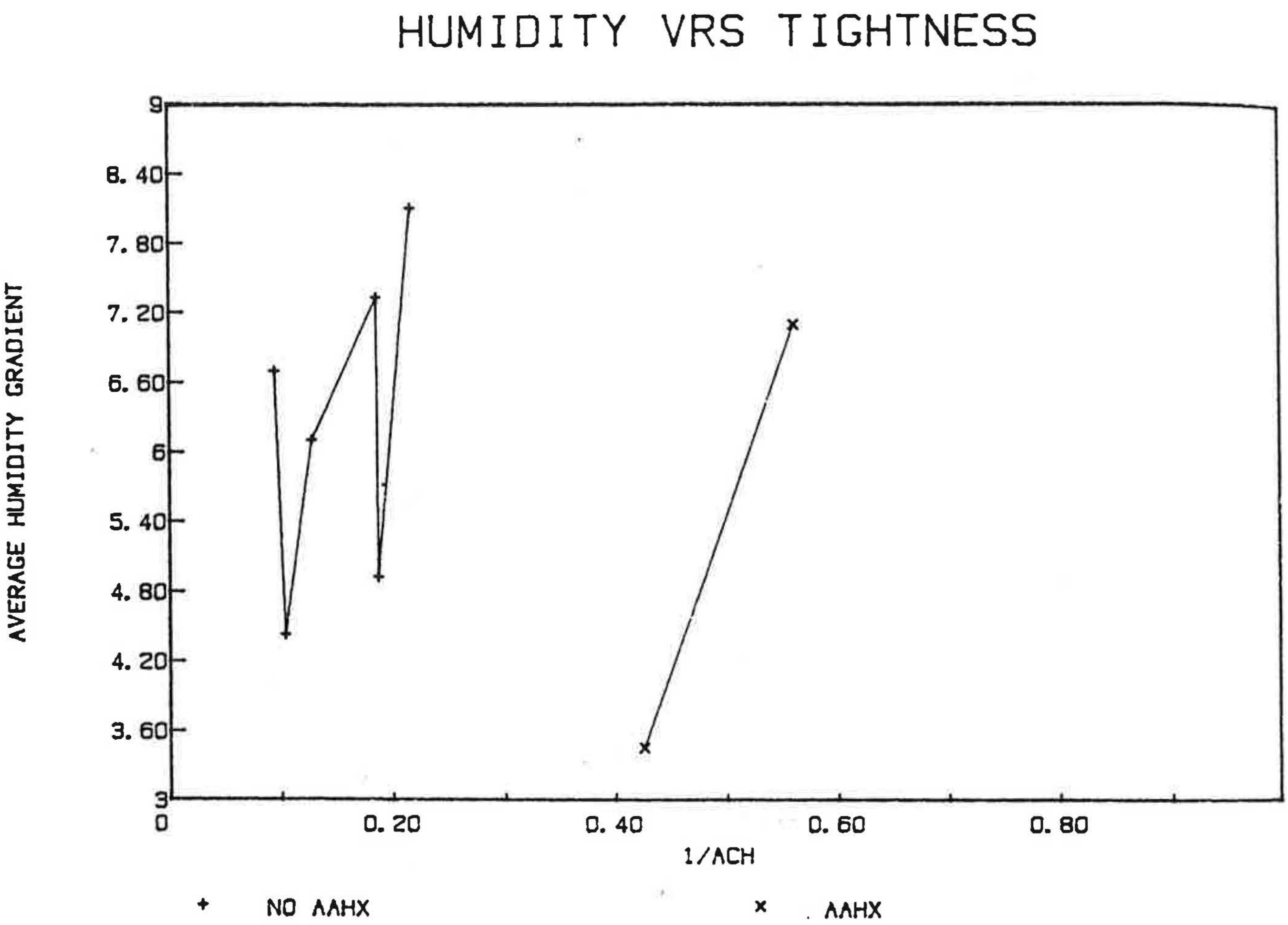

Figure 3. Humidity versus Tightness. The average absolute humidity gradient in torr (see text) versus the reciprocal of the air changes per hour at 50 Pa as a measure of the air tightness of a house. The horizontal axis, 1/ACH, is the number of hours per air change.

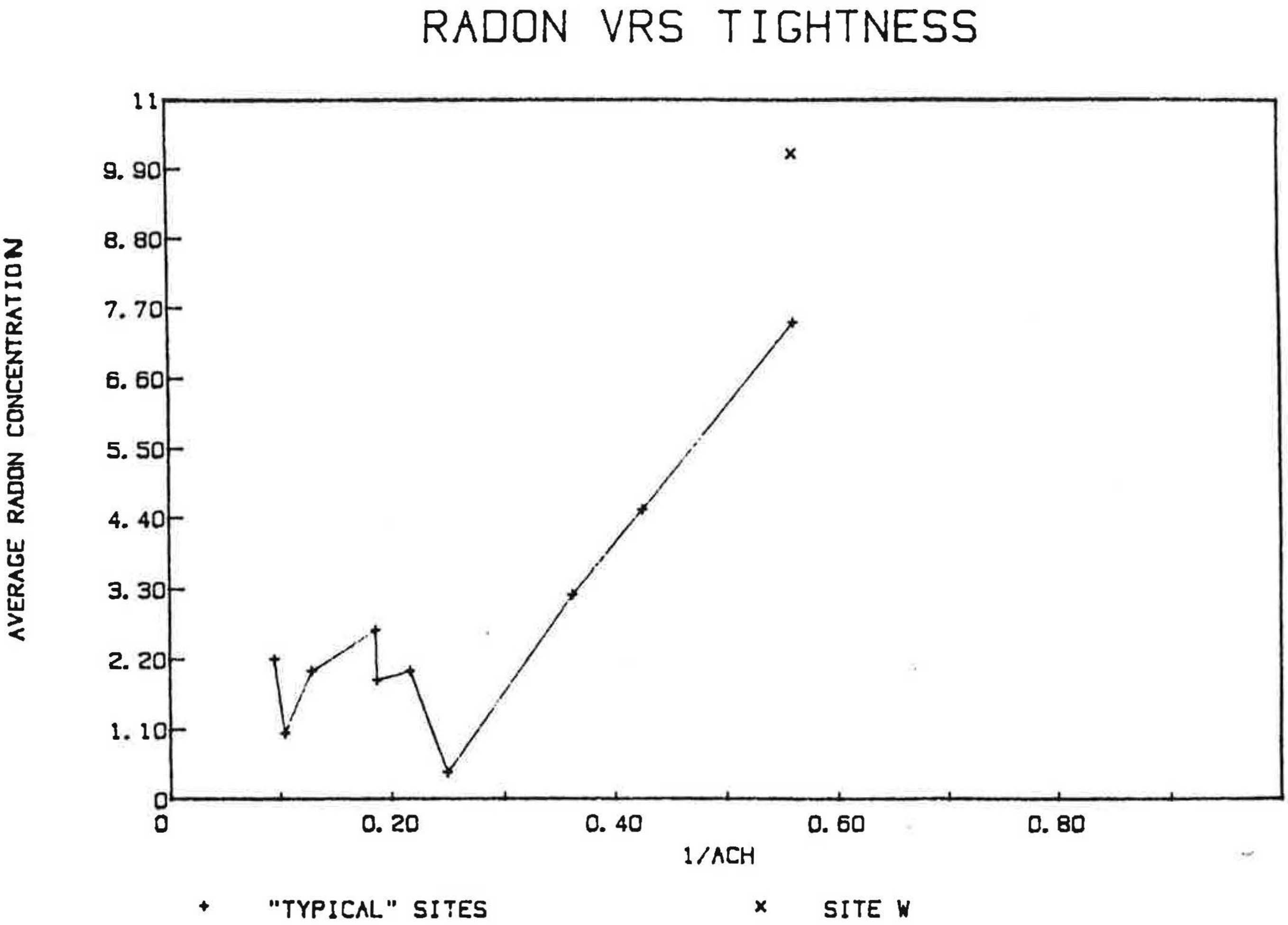

Figure 4. Radon versus Tightness. The average radon concentration in pCi/L versus 1/ACH (see Figure 3).