THE IMPLEMENTATION AND EFFECTIVENESS OF AIR INFILTRATION STANDARDS IN BUILDINGS

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CONTAMINANT BUILD-UP IN HOUSES

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SYNOPSIS

The relation between air infiltration rate and indoor concentrations of radon gas, radon daughters, and formaldehyde has been investigated for both summer and winter conditions in a number of Toronto houses with low rates of natural ventilation. Air infiltration rates obtained by the fan depressurization method and the sulfur hexafluoride tracer gas dilution method are compared. Formaldehyde levels were monitored using both the revised NIOSH impinger sampling method and badge dosimeters. Levels of radon gas and daughters were determined by a grab sampling technique and by film dosimeter as well for radon daughters.

Average air change rates in air-conditioned houses were lower over the summer months (0.12 - 0.40 ach) than over the winter period (0.21 - 0.66 ach). The average summer indoor formaldehyde concentration for air-conditioned houses was 0.076 ppm as compared with an average of 0.038 ppm in winter. The average radon and radon daughter concentrations for air-conditioned houses were higher by 44% and 32%, respectively, during the summer months than during the winter months.

1. INTRODUCTION

Prolonged exposure to low concentrations of indoor air contaminants can under certain circumstances be a serious threat to the health of building occupants. In recent years considerable attention has been focussed on formaldehyde gas emissions from urea formaldehyde foam insulation and, in areas of high natural radioactivity, on particulate airborne radioactivity (radon daughters) resulting from radioactive decay of radon gas. With the increasing demand for improvement in air-tightness of the building envelope as an energy conservation measure, the potential for such contaminants to be present at an unacceptable level, even in the absence of significant sources, has increased. Formaldehyde gas, for example, can be traced to sources such as synthetic fabrics, wood products, and products of combustion. Radon gas, a decay product of naturally-occurring nuclide radium-226, can be found to some extent in most soils throughout the world. Radon emanates from earth-derived building materials and can enter a building by transport from surrounding soil through cracks and openings in foundations.

This paper presents a summary of the results of a monitoring program designed to examine the relation between infiltration rate and indoor concentrations of radon, radon daughters and formaldehyde in houses having relatively low rates of natural ventilation. It also compares air infiltration data obtained by the fan depressurization and tracer gas dilution methods. Twelve houses in Metropolitan Toronto were tested weekly during the winter heating season from November to March 1982. Ten of them were tested also during the summer from July to September 1982; eight of the ten used their central air-conditioning systems extensively.

2. DESCRIPTION OF TEST HOUSES

Electrically heated houses with forced warm-air systems were selected for the test program because their air exchange is not augmented by a furnace chimney. Two-storey, single-family dwellings with basements and no urea formaldehyde foam insulation were studied; their volumes, including basements, ranged from 555 to 948 m^3. All were frame construction with brick siding, ten years old or less, with central air-conditioning and fireplaces.

Selection of the twelve test houses from a pool of eighteen was based on low natural ventilation rate, characterized by the overall air leakage properties assessed by the fan depressurization method (CGSB Interim Standard 149-GP-10, "Determination of Air Tightness of Buildings by the Fan Depressurization Method"). It gives the tightness of a building enclosure by exhausting air from the structure and measuring the airflow rate and corresponding pressure difference across the enclosure. A portable commercial exhaust fan unit developed by Orr and Figley[1] was used.

3. MONITORING AND ANALYTICAL TECHNIQUES

Weekly air sampling consisted of taking grab samples for radon/radon daughters and formaldehyde analysis and concurrent measurements of air exchange rate using the tracer gas dilution method. Thermohygrographs were installed in the living room to measure indoor temperature and relative humidity. Outdoor environmental conditions, including temperature, relative humidity, wind speed and direction, and atmospheric pressure were recorded at the time of sampling. Door and window openings and occupant activities (vacuuming, smoking, etc.) were noted for each sampling period.

3.1 Air Infiltration

In the tracer gas dilution method the infiltration rate can be determined from the exponential decay rate of the tracer gas concentration with respect to time. If the natural logarithm of the concentration is plotted against time, the measurements should fall on a straight line provided the air change rate remains constant. A scatter of points is expected and a straight line best fit can be calculated using the least squares method.

The air change rate is given by

$$S = \frac{\ln C_1 - \ln C_2}{t_2 - t_1}$$

where

C_1 = concentration of tracer gas at time t_1
C_2 = concentration of tracer gas at time t_2
S = air change rate per unit time.

In each of the test houses 50 cc of SF_6 (as a tracer gas) was injected upstream of the fan into the return-air plenum of the forced-air heating system. Samples were drawn at the same location for subsequent analysis of SF_6 concentration 30, 45, 60 and 75 min after injection. During the sampling period the furnace fan was switched to manual mode in order to achieve thorough and continuous mixing of air within the structure. Connecting doors, closet doors, registers, etc., were opened to allow free circulation of air. Windows, exterior doors and fireplace dampers were closed.

Tracer gas injection and sample extraction from the return-air pleneum was achieved using a hypodermic syringe. The transfer of SF_6 from a gas cylinder to the 50-cc syringe was accomplished outside and downwind of the test house. A clean 50-cc syringe and needle were used to draw sample air from the return-air plenum for injection into a 20-mL evacuated glass tube for temporary storage and subsequent analysis in the laboratory with an electron-capture dectector/chromatograph.[2]

3.2 Formaldehyde

Formaldehyde levels were monitored following the revised NIOSH (National Institute for Occupational Safety and Health) impinger sampling method developed by R.R. Miksch at the University of California, and using a 1-h sampling period. Samples were taken in the living room or dining room of each house, with the sampling train located approximately 1 m above floor level. A calibrated constant-flow pump was used to draw air at 1 L/min through a midget impinger containing sodium bisulfite absorbing solution for subsequent analysis in a spectrophotometer.

For comparison, formaldehyde badge dosimeters containing sodium bisulfite solution were used to collect samples over a seven-day period. Badges were suspended approximately 1 m above the floor in the living room and in one of the bedrooms in each house.

3.3 Radon/Radon Daughters

Simultaneous radon/radon daughter samples were collected from the basement area of each house using a grab sampling technique. All measurements were taken approximately 1 m above the floor. For radon gas sampling, several changes of basement room air were drawn through a zinc sulphide-coated flow-through scintillation cell after passing a glass fibre filter to exclude daughter particles. The radon gas collected inside the cell was allowed to decay for approximately 4 h (seven half-lives of short-lived daughter chain), at which time the daughters were virtually at equilibrium with the parent radon. The cell was then placed inside a light-tight castle containing a photomultiplier tube connected to a scaler/counter. The alpha particles resulting from radioactive decay interact with the zinc sulphide coating of the cell to produce the scintillations observed by the counting system. Calibration of each cell counter system against a known radon source yields a count per minute to pico curie per litre (pCi/L) conversion after subtracting the predetermined background count for the cell.

Radon daughter concentrations were determined by means of the modified Kusnetz method.[3] A high-volume air pump with a capacity of 30 L/min was used to draw air through a glass fibre filter for 10 min. The particulate radon daughters collected on the filter were then counted with a portable alpha counter incorporating a photomultiplier tube detector.

For comparison with grab sampling data, three radon dosimeters were exposed in each house (two in the basement, one on the main floor) over a four-month sampling period. Alpha particles from the decay of radon gas and daughters bombarding an alpha-sensitive plastic film detector (mounted on a card) leave radiation tracks. Analysis of the dosimeters was carried out by the manufacturer.

4. DATA ANALYSIS

4.1 Air Infiltration

Figure 1 shows the average air change of each house for both winter and summer months, obtained by the tracer gas dilution method and the air change rate for each house; this ranged from 3.9 to 7.9 air changes per hour (ach), obtained by the fan depressurization method at a pressure difference across the building envelope of 50 Pa. From a best fit line drawn through the points, the ratio of air infiltration rates measured by the tracer gas method and fan depressurization method was 1/14 for winter and 1/20 for summer.

Figure 2 shows the average infiltration rate of each house, determined by the SF_6 tracer gas method for both periods of

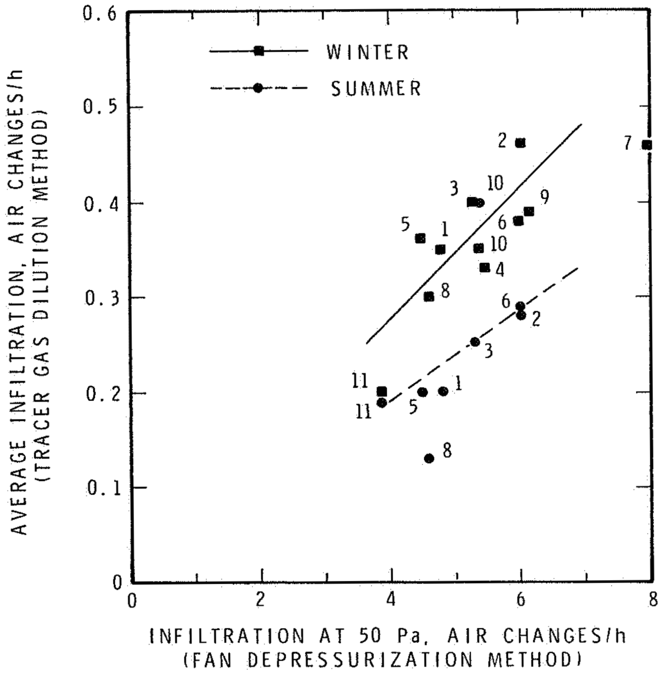


Figure 1 Comparison of air infiltration rates determined by the tracer gas dilution and the fan depressurization methods

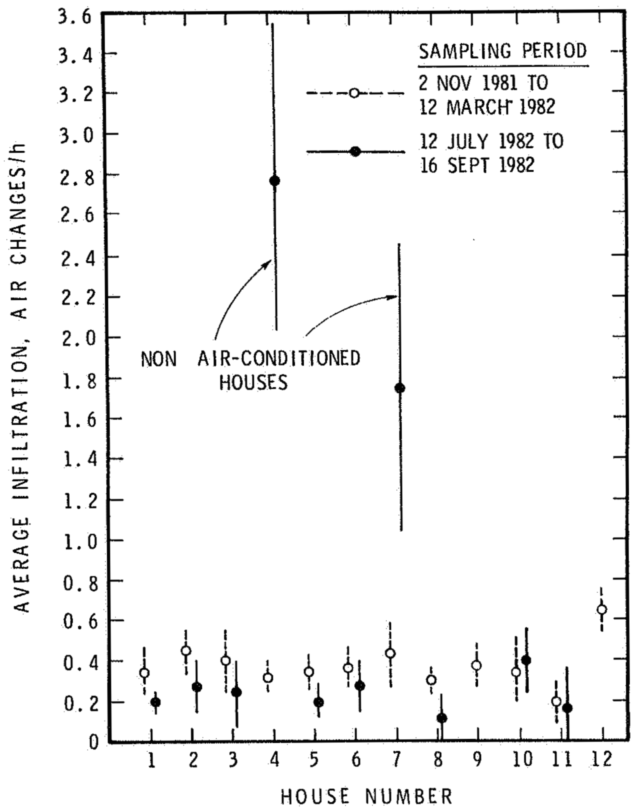


Figure 2 Average air infiltration rates (tracer gas dilution method) (with range of two standard deviations)

testing. Infiltration rates for air-conditioned houses over the summer months (0.12 - 0.40 ach) were lower than those over the winter period (0.21 - 0.66 ach). In two houses in which air conditioners were not used and windows were open the air change rates were much higher (1.75 ach for House No. 7, and 2.78 ach for House No. 4). The apparent relatively high air change rate in House No. 10 in summer may be related to air circulation, inasmuch as only one of two furnace fans is used for circulation of cooling air in summer. The gradual diffusion of SF_6 into uncirculated areas would give the effect of more rapid decay of tracer gas concentration, resulting in an incorrectly high apparent air exchange rate.

Figure 3 presents average air changes, wind speeds, and heating/cooling degree-days for eight air-conditioned houses in the summer months and for twelve houses in the previous winter. Air change rates were significantly less in the summer months than in the winter months when there are greater indoor/outdoor temperature differentials.

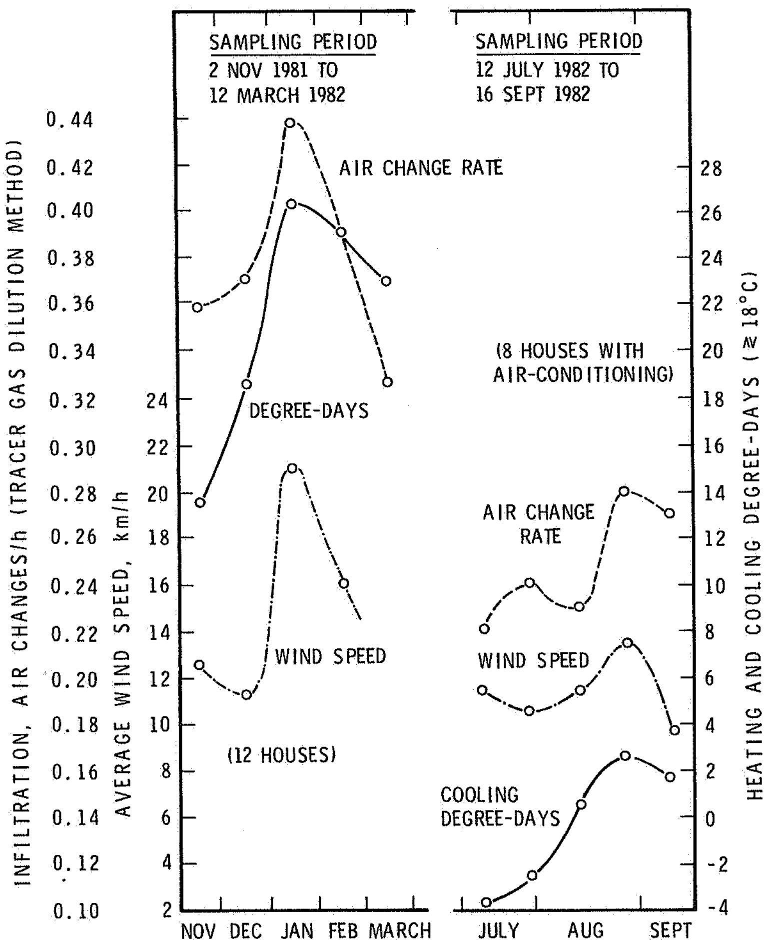


Figure 3 Average period air infiltration rate, wind speed and degree-days

It is expected that during the summer when the temperature differentials are low the air change rate will be due mainly to wind. There appears to be a positive correlation between air change rate and wind speed for several of the eight air-conditioned houses. Increased indoor relative humidity causes increased air tightness during the summer months and may also be a factor in the decreased air change rate[4]; winter averages of relative humidity ranged from 34 to 47%, and summer averages ranged from 56 to 65%.

4.2 Formaldehyde

The mean indoor formaldehyde concentrations obtained from 1-h NIOSH measurements in each of the houses are shown on Figure 4. In general, there was good agreement between the weekly dosimeter (7-day exposure) and 1-h NIOSH results over the winter sampling period, as shown graphically in Figure 5. Agreement was poor when they were compared on a weekly basis for each house. The higher indoor formaldehyde levels in air-conditioned houses appear to be related to a lower air change rate during the summer months. The average indoor concentration for the air-conditioned houses was 0.076 ppm, which is twice the winter average of 0.038 ppm. The levels of formaldehyde concentration indoors appear to be affected, as well, by those outdoors. Measurements during the summer tests indicated that outdoor levels near a highway and a major road (distance of 25 to 120 m) varied from 0.014 to 0.022 ppm, and near minor roads from 0.006 to 0.008 ppm. Outdoor levels are affected by traffic density since automobile exhaust contains significant concentrations of formaldehyde and other aldehydes.

At present the accepted indoor level of formaldehyde is 0.10 ppm (ASHRAE Standard 62-81, Ventilation for Acceptable Indoor Air Quality). In three of the test houses this level was exceeded in 70% of the indoor measurements made during the summer months. Over the winter months the same three houses also had the highest formaldehyde concentrations, but the maximum acceptable concentration was exceeded in less than 10% of the measurements.

4.3 Radon/Radon Daughters

Figure 6 shows averaged radon concentrations and Figure 7 averaged radon daughter concentrations for the two measurement periods. Average radon concentrations over the winter period ranged from 0.3 to 2.2 pCi/L; over the summer period they ranged from 0.37 to 2.26 pCi/L. Average radon daughter concentrations over the winter period ranged from 0.0007 to 0.0065 working level (WL); corresponding summer data ranged from 0.0011 to 0.007 WL. Comparison of summer and winter data for the eight air-conditioned houses shows that, on average, the radon gas and radon daughter

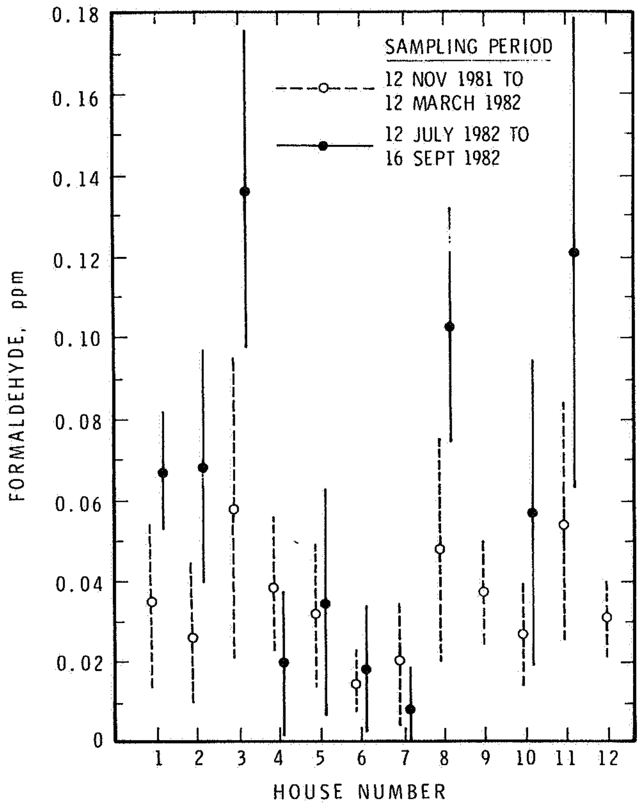


Figure 4 Average 1-h NIOSH formaldehyde concentrations (interior) (with range of two standard deviations)

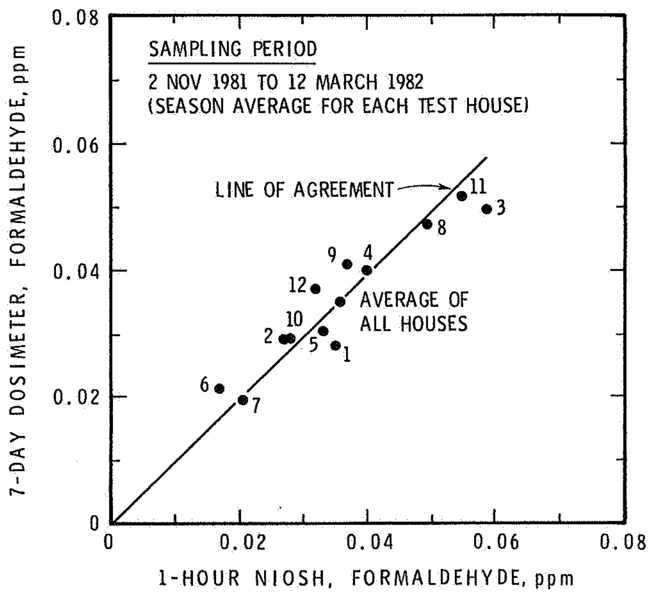


Figure 5 Comparison of average 1-h NIOSH and 7-day dosimeter formaldehyde measurements

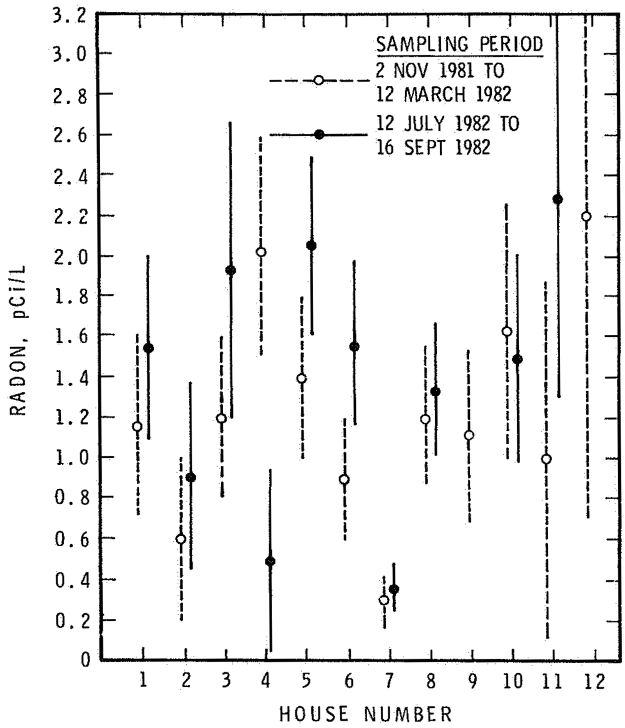


Figure 6 Average daily radon concentration (with range of two standard deviations)

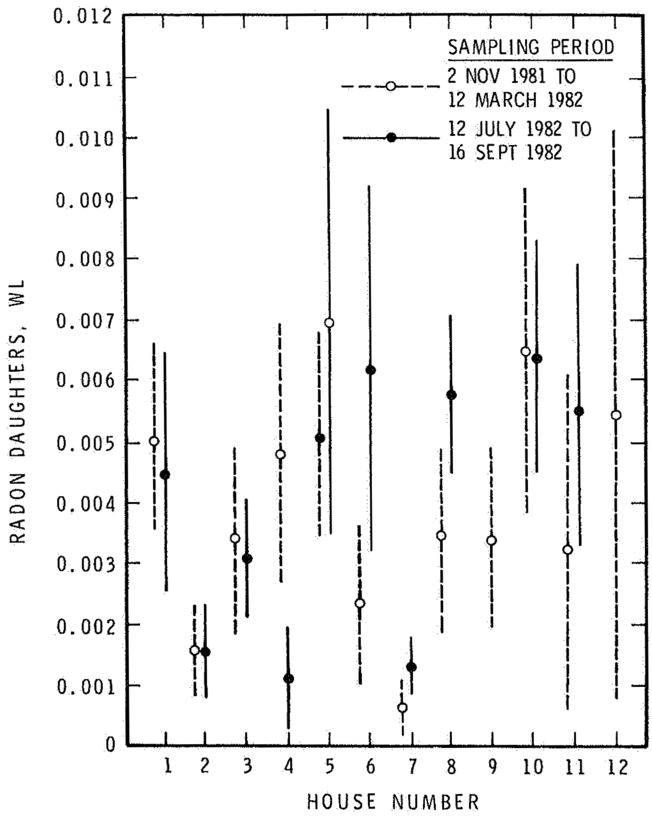


Figure 7 Average daily radon daughter concentrations (with range of two standard deviations)

concentrations were greater for the summer months than for the winter months by 44 and 32%, respectively. The acceptable limit for radon daughters is 0.01 WL (ASHRAE Standard 62-81). The radon/radon daughter data showed expected variations in individual samples taken at the same house on different sampling days. It can be explained, at least in part, by the effects of various meteorological factors shown in other studies to be statistically significant in affecting the emission rate of radon gas from soil. These include barometric pressure, air and soil temperature, relative humidity, and wind speed.

The average equilibrium factor (the ratio of measured radon daughters to the potential radon daughter concentration that could occur when in complete equilibrium with the parent radon) did not change significantly from winter (0.33) to summer (0.30) in the eight air-conditioned houses. Figure 8 provides a comparison of average radon and radon daughter measurements for each house, using a grab sampling technique with data obtained from the film dosimeters exposed over the winter sampling period. Agreement between the two sets of data can be considered fairly good. Figure 9 suggests that concentrations of both formaldehyde and radon gas tend to decrease as the air change rate increases and vice versa.

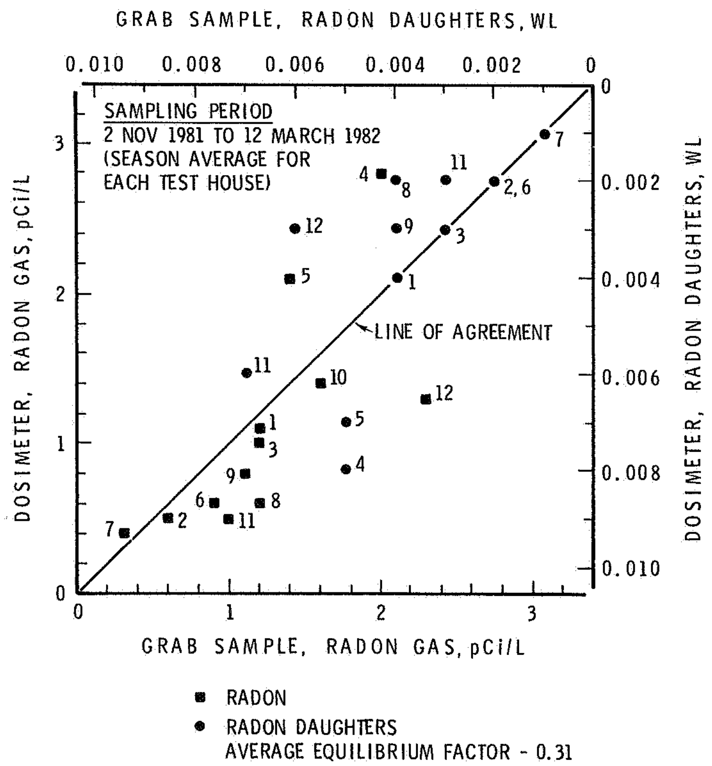
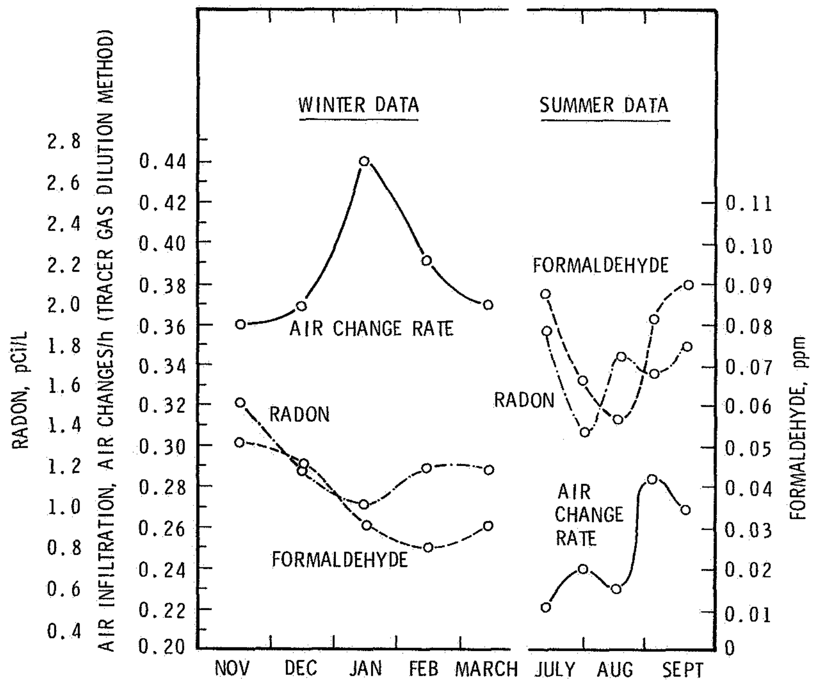


Figure 8 Comparison of grab sample and film dosimeter measurements of radon and radon daughter concentrations



NOTE: HOUSES 4 AND 7 WERE EXCLUDED FROM AVERAGES FOR JULY, AUGUST AND SEPTEMBER BECAUSE OF "OPEN" SAMPLING CONDITIONS EXPERIENCED

Figure 9 Average monthly air infiltration rate and formaldehyde and radon concentrations

5. SUMMARY

The possible correlation between air infiltration rate and indoor concentrations of radon, radon daughters, and formaldehyde in houses having relatively low rates of natural ventilation has been examined.

1. Air change rates measured by the fan depressurization method varied from 3.9 to 7.9 air changes per hour at a pressure difference of 50 Pa. Averaged infiltration rates obtained by tracer gas measurements over the summer study period (for air-conditioned houses) ranged from 0.12 to 0.40 air changes per hour; over the winter months the rates were higher at 0.21 to 0.66 air changes per hour. These measurements represent 1/20 and 1/14, respectively, of the air change rates as measured by the fan depressurization method at a pressure difference of 50 Pa.

2. The averaged indoor concentration of formaldehyde for all air-conditioned houses, as measured by the 1-h NIOSH method, was 0.076 ppm (ranging from 0.019 to 0.136 ppm) during the summer months, and 0.038 ppm (ranging from 0.015 to 0.059 ppm) for the winter months.

3. The averaged radon gas concentrations for all air-conditioned houses during the summer months ranged from 0.37 to 2.26 pCi/L; for the winter months they ranged from 0.30 to 2.2 pCi/L. The averaged radon daughter concentrations for all air-conditioned houses during the summer months ranged from 0.0011 to 0.007 WL; for the winter months they ranged from 0.0007 to 0.0065 WL.

4. Measurements indicate that concentrations of formaldehyde, radon, and radon daughters are affected by infiltration rate.

6. REFERENCES

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