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Impact of Energy Conservation Measures on Radon and Radon Progeny Concentrations: A Controlled Study

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ABSTRACT

The effects of retrofitting for building tightness, air-to-air heat exchangers, and HVAC circulation fans on radon and radon progeny levels were investigated using two matched test houses. One test house was retrofitted for tightness and outfitted with an air-to-air heat exchanger. The two houses were unoccupied; selected occupant-related activities were simulated in a controlled manner. Retrofit for tightness reduced the annual average air infiltration rate by 24% and increased radon and radon progeny concentrations by a similar amount. The air-to-air heat exchanger reduced radon and radon progeny concentrations commensurate with mechanical ventilation. Increased mixing from the furnace circulation fan equalized the upstairs/downstairs concentrations. Extended use of the circulation fan reduced radon progeny levels similar to those obtained with the heat exchanger (about 50% reduction). Seasons had considerable impact on indoor radon and radon progeny; higher levels were found in the summer and fall seasons.

INTRODUCTION

Whether viewed in terms of energy consumption or in terms of indoor air quality, the indoor environment is affected by a complex interplay of outdoor conditions and indoor factors. Air exchange, particularly natural infiltration, which is the uncontrolled air leakage across the building envelope, has an important influence on energy consumption and indoor air quality.

Lower air exchange rates decrease energy requirements for heating and cooling but tend to increase indoor pollutant levels if significant sources are present. Nevertheless, energy conservation strategies for new buildings and retrofitted structures often concentrate on reducing air exchange. Potentially adverse indoor air quality is sometimes offset by air-to-air heat exchangers that boost air exchange while recovering part of the energy that would be lost from the additional air exchange.

Energy conservation, air exchange, indoor air quality, and control options such as air-to-air heat exchangers have been studied (Harrje and Mills 1980; Yocum 1982; Fisk et al. 1981), but many critical relationships remain at the qualitative stage.

In a major study sponsored by the Electric Power Research Institute, we systematically examined relationships among air exchange rates, energy consumption, and indoor air quality (Nagda et al. 1985). This paper summarizes measured results for radon and radon progeny under the influences of normal and contrived HVAC operation, operation of an air-to-air heat exchanger, and energy conservation measures aimed at reducing natural infiltration.

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STUDY ELEMENTS

To gain a reasonable degree of experimental control, two houses of identical design and orientation were constructed in adjacent lots. The floor plan is shown in Figure 1. The houses were monitored for several weeks. One of the houses, the experimental house, was then retrofitted for tightness and equipped with an air-to-air heat exchanger. The other house was maintained in its original condition to serve as a control.

Six basic settings (Table 1) that varied environmental conditions within the houses were used for week-long periods. The measuring program was conducted through the summer, fall, and winter. The test houses were unoccupied; occupancy factors were simulated in a controlled manner.

The measuring strategy involved four indoor zones covering the upstairs and downstairs in each house plus a single outdoor zone. Measurements included air exchange, energy consumption, air quality, and environmental parameters as summarized in Table 2. Pollutants examined included carbon monoxide, oxides of nitrogen, formaldehyde, inhalable particulates, radon, and radon progeny.

Radon gas concentrations were measured on a continuous basis using techniques developed by Thomas (1977). The principal components of the system are shown in Figure 2. Filtered sample air is continuously drawn through a scintillation cell that is optically coupled to a photomultiplier/pulse scaler. Alpha activity within the cell activates the scintillation phosphor, producing photons that are intercepted by the photomultiplier and converted to a pulse train by the scaler. A signal conditioner converts the accumulating pulse counts to an analog voltage for data logging (0 to 4000 counts = 0 to 4000 mV).

Alpha activity within the cell is attributable to radon as well as its alpha-emitting progeny, polonium-218 (RaA) and polonium-214 (RaC′). When a radon atom decays within the cell, the recoil atom, RaA, may deposit on the cell walls or it may be swept out of the cell with the sample airstream. Thus, over a given time interval, the number of alpha disintegrations (counts) depends on (1) the average radon concentration over the current time interval, (2) the fraction of radon progeny that deposits on the cell walls, (3) alpha activity from previously deposited progeny, and (4) counting efficiency of the system.

Deposition factors and counting efficiency were routinely verified with a calibrated radon gas source. Hourly average radon concentrations were calculated from the general algorithm developed by Thomas (1977):

$$C(T) = \frac{1}{E} AY_T - BY_{T-1} - CY_{T-2} \qquad (1)$$

where

$C(T)$ = average radon concentration over the hour ending at time T (nCi/m^3)
E = counting efficiency (cpm/dpm)
Y_T, Y_{T-1}, Y_{T-2} = net counts accumulated during the current, previous, and next previous hours
A, B, C = factors that account for deposition and radioactive decay.

Working levels (WLs) of radon progeny were measured on a continuous basis using techniques developed by Marley and Geiger (1977). The principal components of the system are shown in Figure 3. Airborne particulate matter (carrying radon progeny) are collected continuously on a membrane filter. Simultaneously, the gross alpha activity of the accumulating sample deposit is continuously monitored by a detector that is permanently and precisely positioned over the entry side of the filter. The filter holder contains lateral slots along its crown to provide for sample air entry while positioning the detector. Detector output is conditioned by a pulse scaler to provide an analog voltage for data logging (0 to 1500 cpm = 0 to 1500 mV, nominal).

WL is defined in terms of alpha energy from the ultimate decay; 1 WL corresponds to any combination of radon progeny in a liter of air that ultimately emits 1.3×10^5 MeV of alpha energy. The two nuclides of interest are RaA (6.0 MeV) and RaC′ (7.68 MeV). Marley and Geiger (1977) found that the simplifying assumption of a single average energy (6.84 MeV) allows calculation of WL from gross alpha counts to no more than a 5% error even at extremes of disequilibrium.

Hourly average WL was calculated using the general algorithm developed by Marley and Geiger (1977):

$$WL = \frac{KY_T}{EV} \qquad (2)$$

where

Y_T = number of counts during the hour ending at time T
K = 5.6×10^{-5} WL/α per liter of air
E = counting efficiency
V = sample air volume.

Detector efficiency was verified periodically using a calibrated disk source that could be positioned to precisely reproduce the sampling geometry. Biases with respect to the calibrated source were evaluated by colocating monitors.

RESULTS AND DISCUSSION

Effect of Seasons

Hourly concentrations of indoor radon were low but a seasonal trend of higher indoor radon concentrations during the summer and fall and lower concentrations in the winter was observed. As shown in Table 3, weekly average radon concentrations in the control house under normal HVAC operation in winter were approximately half as high as those in summer and fall. With similar outdoor concentrations, the summer and winter radon concentrations differed by a factor of 2, while air exchange rates differed by a factor of 4. Likewise, summer and fall concentrations were similar, but air exchange rates differed by a factor of 2. Differences between the fall and winter could largely be attributed to higher air exchange rates in the colder seasons. Radon entry rates from the soil appeared to have been approximately equal during the fall and winter and lower during the summer.

Effect of Retrofit

Retrofitting the experimental house increased indoor radon concentrations by an amount consistent with the reduction in air exchange. During periods of normal HVAC operation (Table 4), average concentrations in the experimental house were slightly lower than in the control house prior to retrofit. Following retrofit, concentrations increased markedly in the experimental house, while concentrations in the control house remained near preretrofit levels for the summer and fall.

This relationship did not hold for the winter case. Concentrations were relatively low in both houses during winter. This is attributable to lower radon entry rates and higher air exchange rates in the winter than in the other seasons. Nonetheless, the lack of difference between the two houses could not be explained except that the radon concentrations were generally very low.

Pre- and postretrofit radon progeny levels and their variations with seasons are consistent with radon concentrations.

Effect of Air-to-Air Heat Exchanger and Circulation Fan

Operation of the air-to-air heat exchanger at high, medium, and low settings increased air exchange by 0.45, 0.33, and 0.16 ACH, respectively, over natural infiltration. Mechanical ventilation effectively removed both radon and radon progeny. However, the removal effectiveness for radon was much stronger than for radon progeny (Figure 4). Simply running the HVAC fan constantly (air exchange rate of 0.26 ACH) competed favorably with the heat exchanger for radon progeny removal.

This phenomenon can be explained through use of equilibrium factors. The equilibrium factor is the ratio of the equivalent concentration of radon progeny to the concentration of radon. The equilibrium factor without mechanical ventilation was near 0.6 with the circulation fan cycling automatically (Figure 5). Operating the heat exchanger increased the equilibrium factor to near unity, even though radon concentrations and WL were reduced. Thus, while the heat exchanger can reduce radon concentrations, the plateout of free progeny and deposition of attached progeny are hampered by the operation of the heat exchanger. On the other hand, constant running of the circulation fan decreased the equilibrium factor to approximately 0.4 by enhancing plateout and deposition of progeny.

Recirculating air through the house ductwork magnifies the opportunities for plating out free progeny and depositing attached progeny; dilution also occurs from natural infiltration. Heat exchanger operation provides for dilution only.

Figure 6 shows equilibrium factors for different levels of circulation fan activity. Equilibrium factors for the fan-off condition were between 0.8 and unity, indicating relatively minor losses to plateout and other removal mechanisms. With the circulation fan constantly on, equilibrium factors dropped to approximately 0.5, indicating stronger removal. The relationship is nonlinear. Polynomial regression revealed the following expression (index of correlation = 0.91):

$$F = -7.77 \times 10^{-3}X + 3.75 \times 10^{-5}X^2 + 0.9 \qquad (3)$$

where

F = equilibrium factor
X = percent of time that the fan is active.

CONCLUSIONS

Radon and radon progeny were affected by the retrofit. Relative to the control house, radon concentrations were 25% to 30% higher in the experimental house during the summer and fall. WLs of radon progeny were increased by 35% in the summer and 20% in the fall. During the coldest part of winter, radon and radon progeny levels were much lower in both houses; no effect of retrofit was observed.

The heat exchanger reduced radon gas concentrations by as much as 50% and reduced WLs by as much as 40%. However, it was found that constantly running the central circulation fan, which did not markedly alter the air exchange rate, reduced WLs equally well.

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TABLE 1
Experimental Conditions Defined According to Circulation Fan and Heat Exchanger Settings

Experimental condition	Fan setting (both houses)	Heat exchanger setting (experimental house)
1	Off constantly	Off
2	On constantly	Off
3	Auto[a]	Off
4	Auto	Low
5	Auto	Medium
6	Auto	High

[a] Auto is the normal operating mode, which responds to heating/cooling demands.

TABLE 2
Measurement Parameters

Air exchange

- -- Air leakage rates under pressurized and depressurized conditions (blower door)
- -- Air exchange rates under naturally occurring conditions (tracer gas decay)

Energy consumption

- -- Total house consumption
- -- Heating/cooling consumption
- -- On/off status of individual appliances
  - Central air circulation fan
  - Water heater
  - Clothes washer and clothes dryer
  - Dishwasher
  - Refrigerator compressor and defroster
  - Bathroom and range exhaust fans
  - Air-to-air heat exchanger
  - Wood stove

Air quality

- -- Carbon monoxide
- -- Oxides of nitrogen
- -- Formaldehyde
- -- Inhalable particulates
- -- Radon gas
- -- Radon progeny

Environmental

- -- Temperature
- -- Windspeed
- -- Relative humidity
- -- Solar radiation
- -- Barometric pressure

Other parameters

- -- Thermal integrity of building
- -- Door opening frequencies
- -- Heat exchanger flow rates
- -- Volume of natural gas consumed during range operation

TABLE 3
Indoor Radon Concentrations in the Control House: Weekly Average Values and Standard Deviations for Normal Fan Operation

Period	Upstairs (nCi/m^3)	Downstairs (nCi/m^3)	Outdoors (nCi/m^3)	Air exchange rate (ACH)
Summer (August 26 to September 2)	1.05 ±0.36	1.44 ±0.74	0.23 ±0.19	0.15 ±0.07
Fall (October 21 to October 28)	0.96 ±0.39	1.19 ±0.37	0.14 ±0.10	0.29 ±0.09
Winter (December 23 to December 30)	0.59 ±0.26	0.53 ±0.25	0.22 ±0.27	0.61 ±0.15

TABLE 4
Indoor Radon and Radon Progeny (Volume-Weighted Averages) for Periods of Normal Operation

	Control			Experimental			Outdoors	
	Radon (nCi/m^3)	Radon progeny (WL)	Air exchange (ACH)	Radon (nCi/m^3)	Radon progeny (WL)	Air exchange (ACH)	Radon (nCi/m^3)	Radon progeny (WL)
Preretrofit	1.11 ±0.30	0.0038 ±0.0012	0.30 ±0.21	1.00 ±0.32	0.0039 ±0.0012	0.30 ±0.12	-- --	-- --
Postretrofit								
Summer	1.19 ±0.64	0.0075 ±0.0044	0.15 ±0.066	1.61 ±0.53	0.0103 ±0.0045	0.11 ±0.05	0.23 ±0.19	0.0047 ±0.0023
Fall	1.04 ±0.37	0.0077 ±0.0020	0.29 ±0.093	1.44 ±0.97	0.0094 ±0.0043	0.22 ±0.08	0.14 ±0.10	0.0010 ±0.0010
Winter	0.57 ±0.15	0.0035 ±0.0014	0.61 ±0.15	0.50 ±0.11	0.0033 ±0.0014	0.46 ±0.13	0.22 ±0.09	0.0018 ±0.0006

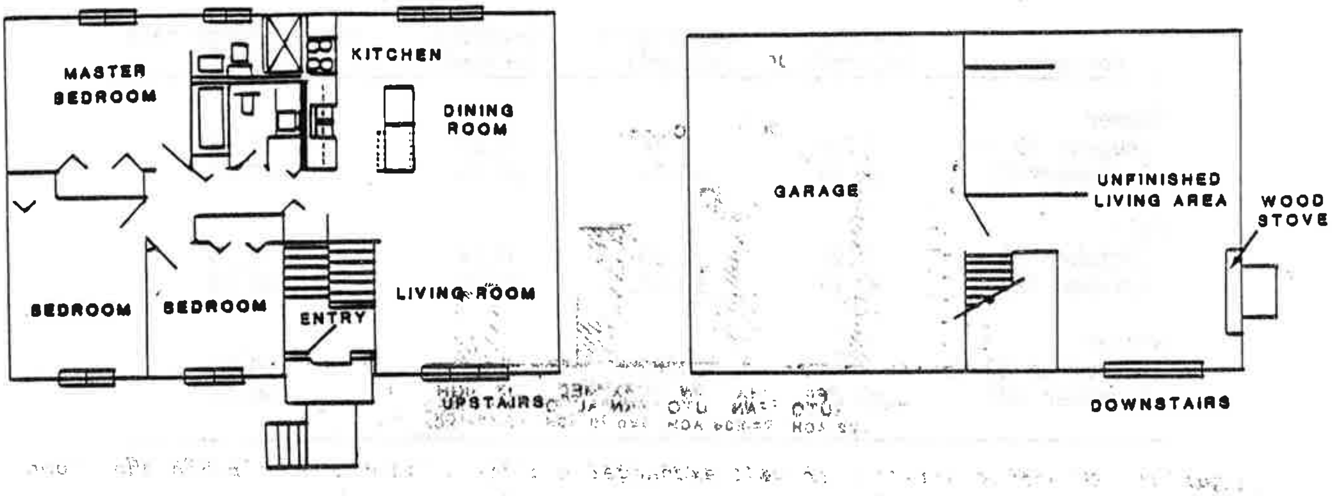

Figure 1. Floor plans for the test houses

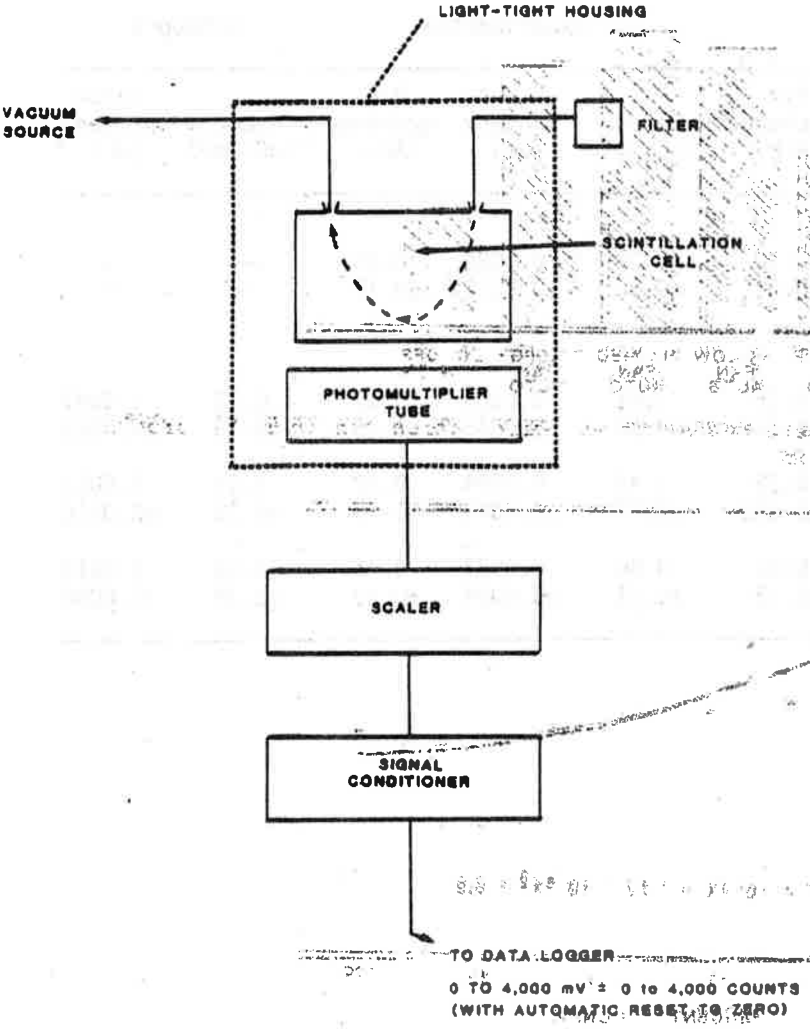

Figure 2. Continuous radon gas monitor components

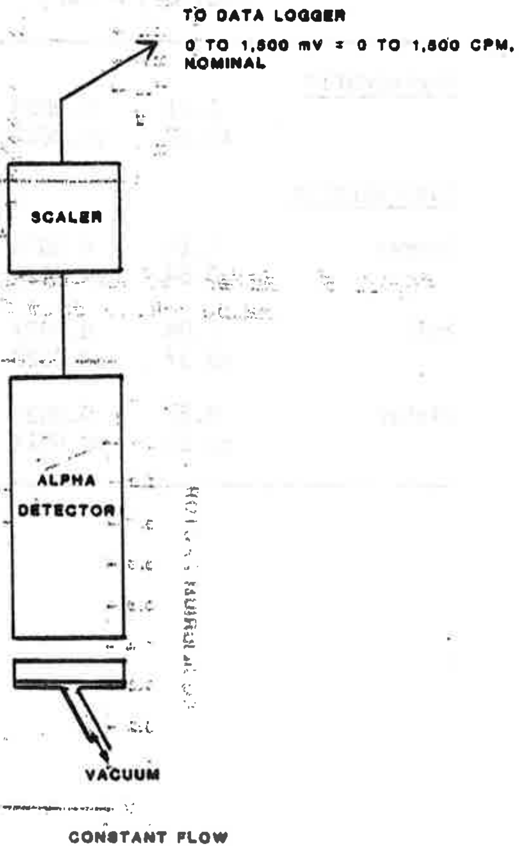

Figure 3. Major components of the continuous radon progency monitor

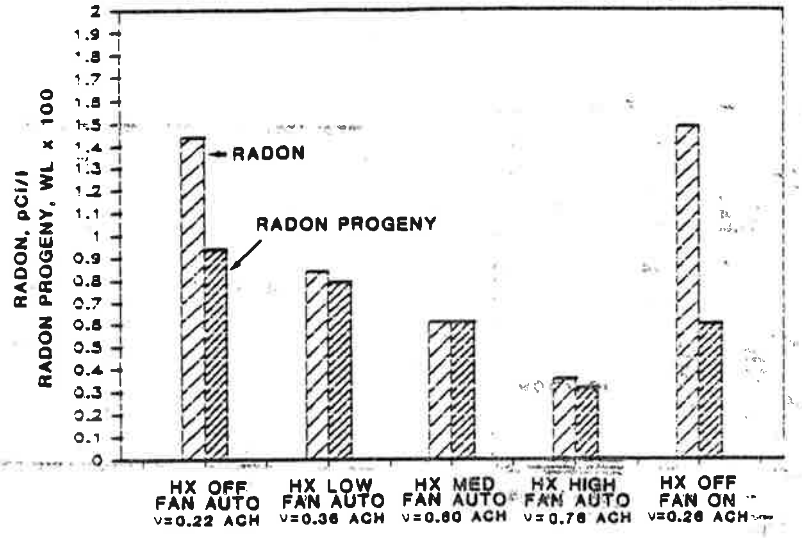

Figure 4. Effect of air-to-air heat exchanger and circulation fan on radon and radon progeny concentrations

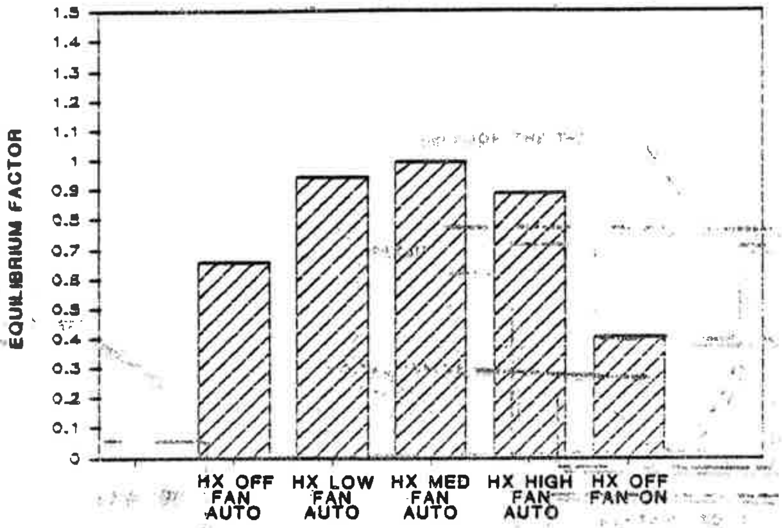

Figure 5. Effect of air-to-air heat exchanger and circulation fan on radon progeny/ radon equilibrium factor

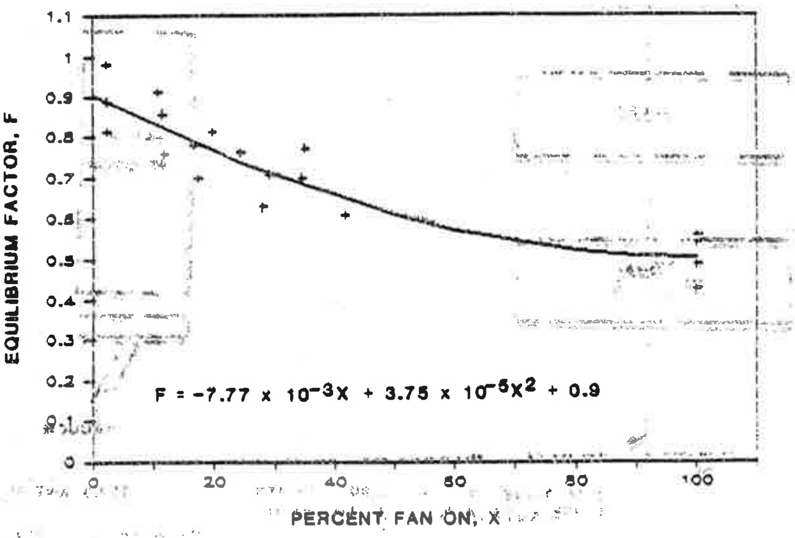

Figure 6. Observed relationship between the equilibrium factor and percent of time circulation fan was in operation

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INTRODUCTION

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