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Measured Air Exchange Rates and Indoor Air Quality in Multifamily Residences

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SUMMARY

Measurements of air exchange rate and indoor air quality were taken in three occupied units in three separate buildings of a multifamily complex at the Naval Submarine Base in Bangor, (State of) Washington, over 5 - 6 consecutive days in November 1983. These three identically-sized all-electric units were located in two-story, four-unit buildings that had been constructed in 1978. One unit was on the ground floor; the other two units were on the second floor.

Pollutants monitored indoors included radon, formaldehyde, carbon monoxide, particulate matter, and nitrogen dioxide. Indoor and outdoor temperature and wind speed were also recorded. Outdoor formaldehyde and nitrogen dioxide were also measured. The air exchange rate was measured using a constant release of perfluorocarbon tracer; the airborne tracer concentration was collected automatically over continuous sampling periods of 6 - 8 hours.

The average air exchange rate for a 24-h period ranged from 0.24 air changes per hour (ach) in the ground-floor unit to 0.91 air changes per hour in an upstairs unit. The mean air exchange rate for the entire monitoring period ranged from 0.29 ach in the downstairs unit to 0.71 ach in an upstairs unit.

Indoor pollutant concentrations were generally low except for particulate matter in the units occupied by smokers. The particulate matter in these two units was two to four times higher than that measured in the unit occupied by nonsmokers. Levels of carbon monoxide were also slightly elevated in one of the smoker-occupied units compared to those in the unit with no smokers.

INTRODUCTION

One consequence of increasing the energy efficiency of buildings through installation of "tightening" measures is a reduction in natural ventilation. Thus, interest in improving the energy performance of federally constructed and maintained buildings is accompanied by concern that pollutants normally found in the indoor environment may build up to unacceptable levels that could lead to health problems for building occupants.

As part of an assessment to set new conservation standards for the design of U.S. government residential construction [1], Pacific Northwest Laboratory researchers measured the air exchange rates and indoor pollutant concentrations in a sample of recently constructed multifamily government dwellings. The results were then used to estimate any potential changes in indoor air quality that might occur in similar residences constructed according to the new U.S. Department of Energy standards.

This paper describes the residential building sample, the instrumentation and methodology used to quantify air exchange rates and indoor pollutant concentrations, and the measurements obtained. The implications of the findings for modifications to federal construction standards are then discussed.

BUILDING SELECTION AND DESCRIPTION

Measurements for this study were obtained from dwellings clustered in a residential development at the Bangor Naval Submarine Base in Bangor, Washington. Bangor is located on a peninsula across the Puget Sound water-

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way to the west of Seattle. The area experiences much the same maritime climate as does Seattle.

With assistance from the base's Housing Division, three individual dwelling units were selected to participate in the study. These units were located in the most recently constructed (1978) base housing development, which comprises 25 two-story four-plex buildings. The three units studied were all in different buildings. One unit was on the ground floor; the other two were second-floor units. All three units were occupied by Navy servicemen and their families.

All three study units have identical floor plans (see Fig. 1) of 87.3 m^2, with 2.4-m ceilings and a volume of 213 m^3. The first-floor units share a common wall with a garage. Construction is wood frame with concrete slab-on-grade for the first floor unit and a 5-cm concrete floor for the second-floor units. Each unit has a patio with a sliding glass door off the family room. Each unit has its own clothes dryer, vented to the outside, as well as kitchen and bathroom vents to the outside. All units are about 75% carpeted. The units have zoned baseboard heating with no combustion appliances or wood-burning facilities. The electricity is included as part of the rent for the units; therefore, the charge for electricity is independent of amount used. Consequently, all the occupants in the study tended to keep all rooms heated at temperatures above approximately 21 °C, even at night.

Unit #1 is a second-floor upstairs unit, occupied by two adults (one a smoker) and a young child. Unit #1 was monitored from Monday, November 7, until Saturday, November 12, for air exchange rate and all pollutants except radon. Monitoring for radon continued until December 7.

Unit #2 is a first-floor (ground level) unit occupied by two adults (both smokers), two children, and one medium-sized dog. Unit #2 was monitored from Tuesday, November 8, through Saturday, November 12, for air exchange rate and for all pollutants except radon. Monitoring for radon continued until December 9.

Unit #3 is a second-floor upstairs unit, occupied by two adults and a teenager (all nonsmokers). This unit was monitored from Monday, November 14, until Saturday, November 19, for air exchange rate and all pollutants except radon. Monitoring for radon continued until December 19.

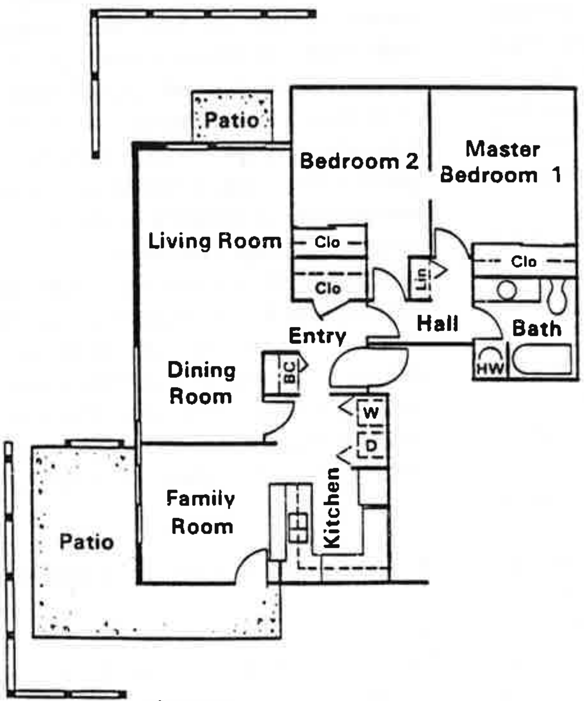

Fig. 1. Floor plan of each study unit. All three units were identical but located in different buildings.

INSTRUMENTATION

Real-time measurements of indoor concentrations of carbon monoxide and particulate matter were taken every day in one residence, and nearly every day in the other two residences. Week-long integrated measurements of indoor and outdoor formaldehyde and nitrogen dioxide and a month-long integrated measurement of radon were also taken. Air exchange rates were measured using perfluorocarbon tracer sampled by a programmable atmospheric tracer sampler (PATS). A portable weather station was used to measure outdoor temperature, wind speed, and wind direction. Indoor temperature was measured using a thermistor and a bimetallic thermometer in each unit. The instruments used to measure these parameters are described in the Appendix.

The air exchange rate was measured using perfluorocarbon tracer (PFT) gas. The principle and techniques of PFT deployment and capture for air exchange rate measurement are described elsewhere [2 - 4]. The airborne perfluorocarbon was captured using a Gillian* Programmable Atmospheric Tracer Sampler (PATS) deployed in each residence. The PATS units were programmed to capture the tracer gas over intervals of approximately 6 - 8 hours in each residence, so the air exchange rate was measured continuously for time periods of 6 - 8 hours during the monitoring period.

MEASUREMENT PROTOCOL

In each unit, the active instruments for monitoring CO and particulate matter and for capturing the PFT gas were placed in the main living area near an inside wall, away from windows and outside doors. Inside passive pollutant monitors for formaldehyde, nitrogen dioxide, and radon were hung from the ceiling in the main living area of each unit. The inside temperature sensor was placed in the hallway, and an additional temperature probe (bimetallic thermometer) was placed near the active instruments in the main living area. The outdoor monitors for formaldehyde and nitrogen dioxide were placed on the weather station.

The weather station, which measured wind speed, wind direction, and outdoor temperature, was placed behind the building being monitored. The data logger for the weather station was placed next to the building, and all sensor leads were run to the logger. After the experiments were concluded, we discovered that the logger had not recorded the indoor and outdoor temperatures. Hence, these outdoor temperature data were lost. However, inside temperatures were recorded from the bimetallic thermometer readings, and outside temperatures used were obtained from the nearest reporting weather station (at the naval base).

Unit #1

Two sources of the perfluorocarbon tracer were placed in Unit #1 24 hours prior to the start of the air sampling with the PATS unit. One PFT source was placed in the family room (see Fig. 1), and the other was attached to the thermistor in the hallway. The PATS was programmed to sample the airborne tracer gas every eight hours, beginning at 20:00 on November 7. Daily activity records were kept by the occupants beginning on November 8.

Particulate matter was monitored on every day, except on November 8, because only one instrument was available to monitor Units #1 and #2 (both monitored during the same time period). The second particulate matter instrument scheduled to be used was too noisy (according to the occupants). Therefore, the remaining instrument was shuttled between Units #1 and #2, monitoring in each unit for part of the day (see Table 1). In addition, the carbon monoxide monitor malfunctioned sometime between Thursday night and Friday morning (November 8 and 9), so those data were lost.

Unit #2

Two PFT sources were deployed in Unit #2 24 hours before the PATS was activated. One was placed in the hallway near the bedrooms, and the other was located on the temperature sensor placed between the family and dining rooms. Particulate matter was monitored every day, except for November 12. The instrument was shared with Unit #1, so monitoring was not done for an entire 24-h period every day (see Table 2). Carbon monoxide was not sampled on Saturday, November 11; the instrument malfunctioned on Friday, November 10, and the data were lost. Tracer gas concentration was sampled every 6.3 hours from November 8, at 20:00 until 12:00 on November 12. Daily activity records were kept by the residents beginning on November 9.

Unit #3

Only one source of PFT was deployed in Unit #3, 24 hours in advance of sampling by the PATS. The source was placed in the hallway. The tracer was sampled using the PATS every eight hours beginning at 22:00 on November 14 and ending at 09:00 on November 19. Carbon monoxide and particulate matter were continuously monitored during the same period. A daily activity record was kept by the residents beginning on November 14.

*Gillian Instrument Corporation, Wayne, New Jersey.

TABLE 1

Summary of the measurements recorded in Unit #1, a second-floor apartment occupied by two adults (one ı smoker) and a young child

Day/Date	Time	Parameter	Average values	Notes/Significant activities
Monday 11/07 (November 7)	14:00 - 24:00	Temperature difference	Not noted	
	00:00 - 24:00	Wind speed	0.5 m/s	
	14:00 - 18:30	Particulate matter	< 10 μg/m³	
	15:00 - 18:00	Carbon monoxide	< 1 ppm	None
	20:00 - 04:00 (11/08)	Air exchange rate	0.26 ach	
Tuesday 11/08	00:00 - 24:00	Temperature difference	13.9 °C	
	00:00 - 24:00	Wind speed	0.7 m/s	
	00:00 - 16:00	Particulate matter	Missing	Child played with equipment
	07:00 - 16:00	Carbon monoxide	Missing	Child played with equipment
	16:00 - 24:00	Carbon monoxide	< 1 ppm	7 cigarettes smoked during evening
	04:00 - 04:00 (11/09)	Air exchange rate	0.30 ach	
Wednesday 11/09	00:00 - 24:00	Temperature difference	14.4 °C	
	00:00 - 24:00	Wind speed	0.9 m/s	
	16:00 - 24:00	Particulate matter	35 ± 8 μg/m³	5 cigarettes smoked during evening
	01:00 - 24:00	Carbon monoxide	1.8 ± 0.5 ppm	
	04:00 - 04:00 (11/10)	Air exchange rate	0.28 ach	
Thursday 11/10	00:00 - 24:00	Temperature difference	12.8 °C	
	00:00 - 24:00	Wind speed	1.6 m/s	
	00:00 - 15:00	Particulate matter	< 10 μg/m³	No cigarettes smoked during day
	00:00 - 16:00	Carbon monoxide	< 1 ppm	
	16:00 - 24:00	Carbon monoxide	Missing	Instrument malfunctioned
	04:00 - 04:00 (11/11)	Air exchange rate	0.52 ach	
Friday 11/11	00:00 - 24:00	Temperature difference	13.9 °C	
	00:00 - 24:00	Wind speed	1.2 m/s	
	11:00 - 24:00	Particulate matter	32 ± 30 μg/m³	4 cigarettes smoked during evening
	00:00 - 11:00	Carbon monoxide	Missing	
	11:00 - 15:00	Carbon monoxide	< 1 ppm	Instrument malfunctioned
	04:00 - 20:00	Air exchange rate	0.52 ach	
Saturday 11/12	00:00 - 12:00	Particulate matter	41.5 ± 27 μg/m³	8 cigarettes smoked
	00:00 - 24:00	Wind speed	2.5 m/s	
11/07 - 11/11		Air exchange rate	0.38 ± 0.1 ach	
11/07 - 11/12	(120 h)	Nitrogen dioxide (inside)	< 0.003 ppm[a]	
11/07 - 11/12	(120 h)	Nitrogen dioxide (outside)	< 0.003 ppm[a]	
11/07 - 12/07		Radon	1.8 pCi/ℓ[b]	
11/07 - 11/12	(169 h)	Formaldehyde (inside)	0.089 ppm[c]	
11/07 - 11/12	(169 h)	Formaldehyde (outside)	0.01 ppm[c]	

[a] ±20%.
[b] ±12.5%.
[c] ±15%.

RESULTS

The monitoring results for Unit #1 (second floor), Unit #2 (first floor) and Unit #3 (second floor) are summarized in Tables 1, 2, and 3, respectively. Mean concentrations and standard deviations are given for each pollutant, for each day and hourly period monitored. Daily mean air exchange rates in air changed per hour (ach) are also given. Indoor and outdoor concentrations of formaldehyde, nitrogen dioxide, and radon shown are average concentrations for the time period indicated.

TABLE 2

Summary of the measurements recorded in Unit #2, a first-floor apartment occupied by two adults (both smokers), two children and a medium-sized dog

Day/Date	Time	Parameter	Average values	Notes/Significant activities
Tuesday 11/08 (November 8)	16:00 - 24:00	Temperature difference	14.4 °C	Activity record not completed
	00:00 - 24:00	Wind speed	0.7 m/s	
	16:00 - 24:00	Particulate matter	31 ± 13 μg/m³	
	12:00 - 24:00	Carbon monoxide	1.4 ± 0.8 ppm	
	20:00 - 02:00 (11/09)	Air exchange rate	0.31 ach	
Wednesday 11/09	00:00 - 24:00	Temperature difference	13.3 °C	
	00:00 - 24:00	Wind speed	0.9 m/s	
	00:00 - 16:00	Particulate matter	21 ± 12 μg/m³	6 cigarettes smoked
	00:00 - 15:00	Carbon monoxide	1.2 ± 1.6 ppm	Clothes dryer used 2 h
	02:00 - 03:30 (11/10)	Air exchange rate	0.37 ach	
Thursday 11/10	00:00 - 24:00	Temperature difference	14.4 °C	
	00:00 - 24:00	Wind speed	1.6 m/s	
	15:00 - 24:00	Particulate matter	46 ± 14 μg/m³	10 cigarettes smoked during day
	15:00 - 22:00	Carbon monoxide	2.6 ± 0.7 ppm	
	22:00 - 00:00	Carbon monoxide	Missing	
	03:30 - 04:00 (11/11)	Air exchange rate	0.24 ach	
Friday 11/11	00:00 - 24:00	Temperature difference	12.2 °C	Dryer used 1 h
	00:00 - 24:00	Wind speed	1.2 m/s	
	00:00 - 10:00	Particulate matter	24 ± 19 μg/m³	9 cigarettes smoked during day
	00:00 - 24:00	Carbon monoxide	Missing	Instrument malfunctioned
	04:00 - 24:00	Air exchange rate	0.29 ach	Kitchen exhaust fan used
Saturday 11/12	00:00 - 24:00	Wind speed	2.5 m/s	
	00:00 - 12:00	Air exchange rate	0.22 ach	
11/08 - 11/12		Air exchange rate	0.29 ± 0.06 ach	
11/08 - 11/12	(96 h)	Nitrogen dioxide (inside)	< 0.004 ppm[a]	
11/08 - 11/12	(120 h)	Nitrogen dioxide (outside)	< 0.003 ppm[a]	
11/08 - 12/09		Radon	2.9 pCi/ℓ[b]	
11/07 - 11/12	(169 h)	Formaldehyde (outside)	0.01 ppm[c]	

[a] ±20%.
[b] ±9.7%.
[c] ±15%.

Tables 1, 2, and 3 also summarize mean daily temperature difference (outside-inside) and daily average wind speed. Also noted are significant activities recorded on the daily activity forms that could have an effect on pollutant levels (e.g., number of cigarettes smoked) or on air exchange rate (e.g., window openings, clothes dryer use).

The average pollutant concentrations for the monitoring period in each unit are summarized in Table 4. The average air exchange rate for each unit, corresponding average inside-outside temperature difference, and wind speed for the monitoring period are shown in Table 5.

Figures 2, 3, and 4 are histograms of the measured air exchange rates for Units 1, 2, and 3, respectively. The average air exchange rate was measured over 8-h intervals in Units #1 and 3, and for 6.3-h intervals for Unit #2. Mean air exchange rate for approximately 24-h periods in each unit are noted on Figs. 2, 3, and 4.

DISCUSSION

All three units had daily average air exchange rates less than 1 ach, ranging from a low of 0.24 ach in Unit #2 to a high of 0.91

TABLE 3

Summary of the measurements recorded in Unit #3, a second-floor apartment occupied by two adults and a teenager, all nonsmokers

Day/Date	Time	Parameter	Average values	Notes/Significant activities
Monday 11/14	11:00 - 24:00	Temperature difference	12.8 °C	Vacuum cleaner used 1 h
(November 14)	00:00 - 24:00	Wind speed	6.6 m/s	
	11:00 - 24:00	Particulate matter	13 ± 6 $\mu g/m^3$	
	11:00 - 24:00	Carbon monoxide	< 1 ppm	Kitchen fan used 1h
	22:00 - 06:00 (11/15)	Air exchange rate	0.69 ach	Clothes dryer used 1h
Tuesday 11/15	00:00 - 24:00	Temperature difference	12.2 °C	
	00:00 - 24:00	Wind speed	6.7 m/s	
	00:00 - 24:00	Particulate matter	< 10 $\mu g/m^3$	
	00:00 - 24:00	Carbon monoxide	< 1 ppm	Bath vent used 30 min
	06:00 - 06:00 (11/16)	Air exchange rate	0.75 ach	
Wednesday 11/16	00:00 - 24:00	Temperature difference	13.3 °C	Windows open 3 h
	00:00 - 24:00	Wind speed	6.0 m/s	
	00:00 - 24:00	Particulate matter	< 10 $\mu g/m^3$	
	00:00 - 24:00	Carbon monoxide	< 1 ppm	Bath vent used 1 h
	06:00 - 06:00 (11/17)	Air exchange rate	0.91 ach	Clothes dryer used 3 h
Thursday 11/17	00:00 - 24:00	Temperature difference	15.6 °C	
	00:00 - 24:00	Wind speed	3.5 m/s	
	00:00 - 24:00	Particulate matter	< 10 $\mu g/m^3$	Bath vent used 2 h
	00:00 - 24:00	Carbon monoxide	< 1 ppm	
	06:00 - 06:00 (11/18)	Air exchange rate	0.28 ach	
Friday 11/18	00:00 - 24:00	Temperature difference	14.4 °C	Activity record not completed
	00:00 - 24:00	Wind speed	2.8 m/s	
	00:00 - 24:00	Particulate matter	< 10 $\mu g/m^3$	
	00:00 - 24:00	Carbon monoxide	< 1 ppm	
	06:00 - 06:00 (11/19)	Air exchange rate	0.31 ach	
Saturday 11/19	00:00 - 09:00	Carbon monoxide	< 1 ppm	
	00:00 - 09:00	Particulate matter	< 10 $\mu g/m^3$	
11/12 - 11/19		Air exchange rate	0.62 ± 0.35 ach	
11/12 - 11/19	(120 h)	Nitrogen dioxide (inside #1)	< 0.003 ppm[a]	
11/12 - 11/19	(120 h)	Nitrogen dioxide (inside #2)	< 0.003 ppm[a]	
11/10 - 11/19	(164 h)	Nitrogen dioxide (outside)	< 0.002 ppm[a]	
11/14 - 12/19		Radon	1.42 pCi/ℓ[b]	
11/12 - 11/19	(119 h)	Formaldehyde (inside)	0.124 ppm[c]	
11/12 - 11/19	(119 h)	Formaldehyde (outside)	0.005 ppm[c]	

[a]±20%.
[b]±13.1%.
[c]±15%.

ach in Unit #3 for a 24-h period. These exchange rates are within the values reported for similar age multifamily complexes that have not received any special retrofit tightening measures [5, 6].

These air exchange rates are less than those typically found in detached structures in the Pacific Northwest [6]. However, these air exchange rate data indicate only the rate of exchange (or dilution) of the air inside the units with tracer-free air. Tracer-free air infiltrates not only from the outdoor air, but also can enter the unit from other adjacent units (vertical and horizontal as well as diagonal) [5].

The outdoor air exchange can be determined only by using a technique that deploys and captures multiple unique tracers in each

TABLE 4

Average pollutant concentrations over the monitoring period

Location	Particulate matter ($\mu g/m^3$)	Carbon monoxide (ppm)	Formaldehyde (ppm)	Nitrogen dioxide (ppm)	Radon (pCi/ℓ)
Unit #1 (second floor, 1 smoker)	25	< 1	0.089	< 0.003	1.8
Unit #2 (first floor, 2 smokers)	31	1.7	Lost	< 0.004	2.9
Unit #3 (second floor, no smokers)	10	< 1	0.124	< 0.003	1.4

TABLE 5

Week-long average air exchange rates, temperature difference and wind speed for each apartment

Location	Average air exchange rate (ach)	Inside-outside temp. diff. (°C)	Wind speed (m/s)
Unit #1 (second floor)	0.38 ± 0.1	13.8	1.0
Unit #2 (first floor)	0.28 ± 0.06	13.6	1.4
Unit #3 (second floor)	0.62 ± 0.35	13.7	5.1

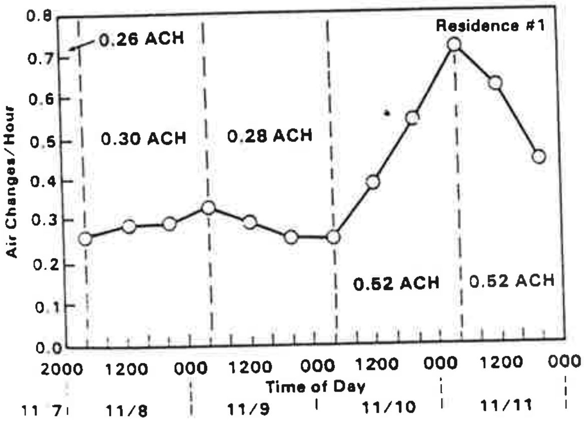

Fig. 2. Histogram of the measured air exchange rates for Unit #1.

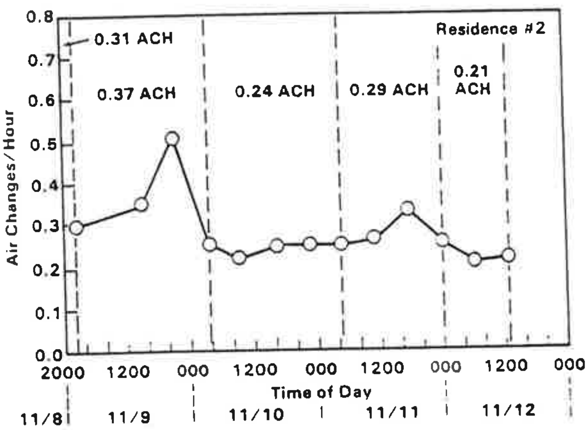

Fig. 3. Histogram of the measured air exchange rates for Unit #2.

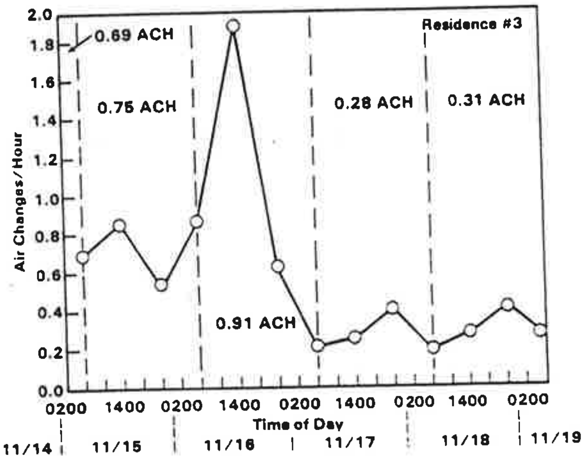

Fig. 4. Histogram of the measured air exchange rates for Unit #3.

adjacent unit, considering each adjacent unit as a single well-mixed zone [5]. Multizone deployment and capture of tracer gas would likely indicate that the actual outdoor air exchange rate in each unit would be less than that measured in this study. (As much as 20 - 30% of the air exchange rate in a unit can be attributable to air flowing between units.) This technique was not available at the time of this study, and its use would have required cooperation from the other three residents in each of the buildings where the monitored units were located.

Insufficient on-site wind speed and temperature data were recorded (the data logger failed several times during the monitoring periods) to enable the application of any empirical model that explains the air exchange rate in terms of the principal driving

TABLE 6

Indoor air quality guidelines[a]

Pollutant	Criterion value	Source
Radon	2 pCi/ℓ	American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). Recommended exposure level in commercial buildings and residence
	5 pCi/ℓ	Bonneville Power Administration "Action" Level for weatherization program
Formaldehyde	120 mg/m^3 [b]	American Society of Heating, Refrigeration, and Air Conditioning Engineers Standard, *ASHRAE 62-1981*[c]
Particulate matter	75 μg/m^3 [d]	Primary standard (for protecting the public health) of the National Ambient Air Quality Standard for outdoor air (*40 CFR 50.4-7*) — enforced by the EPA
Carbon monoxide	5500 μg/m^3 [b] (5 ppm)	*ASHRAE 62-1981* (see above)
Nitrogen dioxide	0.05 ppm[f]	Primary standard *40 CFR 50.4-7* (see above)

[a]For the purpose of evaluation, maximum permissible concentrations or "Guidelines" were selected for the pollutants. Each guideline value represents a highly restrictive standard or code for a specific pollutant.
[b]Maximum long-term average exposure.
[c]Adopted from West German and Dutch guidelines.
[d]EPA annual average limit (outdoor air) total suspended particulate matter.
[e]EPA 24-h limit (outdoor air).
[f]Annual mean.

forces of temperature difference and wind speed.

None of the units had indoor air pollutant concentrations exceeding the selected indoor air quality guidelines given in Table 6, even in periods during which air exchange rates were very low (below 0.5 ach). As with the case of air flow between units affecting the air exchange rate, the air flow between units can also affect the pollutant levels in the units. Not only can pollutants "migrate" from one unit to another (especially from lower units to upper units as a result of the stack effect), but the outside air infiltration is reduced by the presence of the adjacent unit(s), causing a longer residence time for the pollutants. There was, however, no way to absolutely distinguish the sources of the pollutants measured.

The remaining discussion focuses on the monitoring results for each unit and the potential impact that tighter construction standards or retrofitting measures could have on the indoor air quality in these or similarly constructed residences.

Unit #1

The daily air average exchange rate in this second-floor unit ranged from 0.26 to 0.52 ach with the least variation in air exchange rate of the three units (see Fig. 2). The week-long average air exchange rate (0.38 ach) ranked between Units #2 and #3. All pollutant levels were well below the selected guidelines (Table 6), except for particulate matter. The particulate matter levels in this unit generally corresponded with the smoking activity (as recorded on the activity records), and approached one-half the annual average guideline (75 μg/m^3) on November 9 and 11. The continuous monitoring (raw) data for particulate matter (not shown) do show several short-term (<5-min) excursions throughout the waking hours exceeding this guideline.

The average air exchange rate on November 8 was about one-half the air exchange rate on November 11, yet the particulate matter levels were nearly the same. This may indicate either uneven distribution of the particulate matter (which is likely to occur with low air exchange rates), an error in air exchange rate determination because of poor or uneven distribution of infiltrating air in the residence caused by outdoor wind shifts during these days, or infiltration of particulate matter from outside or an adjacent apartment that cannot be distinguished in these measurements.

In any event, tightening of this unit or units similarly constructed (with smokers occupying the dwelling) by retrofitting or through more stringent construction standards would likely result in particulate matter levels approaching or exceeding the 75 $\mu g/m^3$ guideline for particulate matter.

Unit #2

This downstairs unit had the lowest average week-long air exchange rate (0.29 ach) of the three units sampled. This may be explained by the fact that downstairs units do not experience the inevitable stack effect typical of upper units or upper floors of a single family residence. The daily variation in temperature differences and wind speed (see Table 2) was not significant, which may contribute to the lack of variation in the daily air exchange rate. There was no activity (or lack of activity) as recorded on the activity records to suggest unusual occupancy patterns that would contribute to the low week-long air exchange rate in this unit.

Like Unit #1, this residence was occupied by smokers. Elevated levels of particulate matter (21 - 46 $\mu g/m^3$, average of 31 $\mu g/m^3$) and carbon monoxide (1.2 - 2.6 ppm, average of 1.7 ppm) were noted on November 8, 9, 10, and 12. However, these values are below the selected guidelines. The radon concentration (2.9 ρCi/ℓ) was above the ASHRAE exposure level of 2 ρCi/ℓ, possibly because of the radon from the soil combined with the concrete slab-on-grade construction and concrete ceiling. These sources of radon combined with the low average air exchange rate can account for the elevated radon concentration in this ground floor unit. However, the radon level was below the BPA action level (5 ρCi/ℓ) for residential weatherization. The level of nitrogen dioxide was well below the guideline, due to the absence of combustion sources.

The tightening of this unit (with smokers) either through modified construction standards or by energy conservation measures would probably result in increased radon levels and possibly result in approaching or exceeding the guideline (75 $\mu g/m^3$) for particulate matter. Additional monitoring for radon would be needed before any final conclusions can be drawn. Replicate monitors would need to be placed at more than one location in the unit and left for up to six months, to better characterize indoor radon levels.

Unit #3

This upstairs unit had the greatest week-long average air exchange rate (0.62 ach) and greatest variation in daily air exchange rate (0.28 - 0.91 ach) (see Fig. 4). This can be attributed to the variable and high average wind speed for the monitoring period, the more frequent use of vent fans in the unit, and the opening of doors and windows on one day (November 16) (i.e., occupancy effects), combined with the stack effect on this upstairs unit.

There were no smokers in this unit. When combined with the observed elevated air exchange rates, this resulted in pollutant levels well below the guidelines. The residence could probably be tightened without significant increases in pollutant levels, primarily because of the lack of pollutant sources. However, the effects of occupancy on the air exchange rates are unknown. Different occupants with different habits could create conditions in the unit similar to those in Unit #2. Tightening of this unit under these conditions could result in elevated levels of pollutants, especially particulate matter.

CONCLUSIONS

This study demonstrated that air exchange rates in apartments can vary significantly over short time periods (6 - 8 hours) and that average week-long air exchange rates can likewise vary significantly among apartments in the same complex. Several factors influence the air exchange rates in these apartments, including orientation, wind speed, and most notable, occupancy (opening windows, use of vent fans, etc.).

The use of PFT gas with automatic capture of the tracer for several periods of 6 - 8 hours over the monitoring study was a useful tool for measuring air exchange rate. The system could be deployed at the beginning of the study and recovered at the end of the study without unnecessary disturbance to the residents.

However, these air exchange rate data were limited because of the inability to distinguish the source of the tracer-free air that infiltrates the individual units. This air could be air from adjacent units (multiple connected zones) as well as air from the outside. Multiple tracers placed in the adjacent units would be required to determine the source of the infiltrating air and to assess the potential impact of pollutant sources in adjacent units on the pollutant levels in each unit.

The measured pollutant concentrations were within levels expected in these residences, given the air exchange rates, sources of pollutants (indoors and outdoors), and age and geographical location of the residences. As in the air exchange rate measurements, the sources of the pollutants measured could not be specifically identified. It is assumed that all sources were inside the units themselves. However, pollutants can migrate into the units from adjacent units, carried along by the infiltrating air from adjacent units. Even fine particulate matter (such as cigarette smoke, which is composed of particles of less than 0.5 μm aerodynamic equivalent diameter) present outdoors or in adjacent units has been shown to migrate into structures due to the insignificant deposition velocity of the particles relative to the air infiltration rate [7].

Indoor particulate matter concentrations appear to depend primarily on the number of cigarettes smoked and on the air exchange rate. Unit #1 showed elevated levels of particulate matter that were associated with cigarette smoking as indicated by the activity records. Average air exchange rate in Unit #2 was nearly half that of Unit #1 and, correspondingly, the highest average concentration of particulate matter was measured in Unit #2. Unit #3 had no smokers and no significant levels of particulate matter.

The levels of carbon monoxide in Unit #2 were elevated, but were not elevated in Unit #1 (both units had smokers). The elevated CO levels in Unit #2 may be caused by the combination of low average air exchange rate and smoking (a source of carbon monoxide). More data are needed for further conclusions.

The elevated level of radon in Unit #2 may be attributed to the combination of radon sources (soil, concrete slab-on-grade and concrete ceiling) and the low air exchange rate. However, further long-term monitoring would be necessary to evaluate other factors (e.g., ground moisture) that can influence the source strength of radon.

Insignificant levels of formaldehyde and nitrogen dioxide were found in all units monitored, possibly due to the age of the few sources of formaldehyde (particle board, carpets) and the absence of combustion appliances that would be a source of nitrogen dioxide. No significant levels of formaldehyde or nitrogen dioxide were found outside.

Modifying federal construction standards for residences such as these to "tighten" and render them more energy efficient could reduce the air exchange rates to unacceptable levels. In residences where occupants smoke the particulate matter levels could exceed the guideline and cause serious risks of health effects — especially for children [6]. In residences with significant sources of radon or residences built in areas with higher natural background radon, the occupants could experience increased risk of lung cancer [6]. Some mitigation measures may be necessary for increasing the air exchange rate or for reducing the number or strength of pollutant sources.

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Appendix

INSTRUMENTS USED IN MEASUREMENTS

Particulate matter — measured with a Real-Time Aerosol Monitor, Model RAM-1[a]. The RAM-1 measures aerosols ranging from 0.1 to 20 μm aerodynamic equivalent diameter. The continuous readout of particulate matter concentration was recorded on a chart recorder.

Carbon monoxide (CO) — measured using a direct indicating continuous digital readout electrochemical analyzer[b]. The instrument is capable of detecting carbon monoxide as low as 1 ppm with an accuracy of 10% of the reading. The continuous readout of carbon monoxide level was recorded on a chart recorder.

Formaldehyde — measured indoors and outdoors using a passive integrated monitor model PF-1[c]. The monitor is capable of detecting formaldehyde concentrations as low as 0.01 ppm over a 7-day exposure period.

Nitrogen dioxide (NO_2) — measured using a Model 530 passive sampler[d]. The sampler collects NO_2 according to the principles of molecular diffusion of NO_2 onto a coated disk built into the sampler. The amount of NO_2 is analyzed colormetrically. Exposure can be measured reliably within 10% accuracy.

Radon — measured by deploying a single Track Etch® radon detector inside the house. The Track Etch detector is designed to be left in the measurement area for 30 or more days and can measure concentrations as low as 0.2 pCi/ℓ for an exposure time of 1 - 3 months.

Indoor/Outdoor temperature — measured using thermistors and recorded on a battery-operated data logger. Inside temperature was also recorded using a bimetallic thermometer located near the instruments. The outdoor thermistor was shielded.

Wind direction/Wind speed — measured with a portable cup anemometer and wind vane set on the ground. The unit extended 3 m (10 ft) above the ground and was set on a tripod. Data were recorded by a battery-operated data logger.

[a] GCA Corporation, Bedford, MA.
[b] General Electric Company Aircraft Engine Group, Cincinnati, OH.
[c] Air Quality Research, Inc., Berkeley, CA.
[d] MDA Scientific, Inc., Glenview, IL.
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