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THE MEASUREMENT OF AIR EXCHANGE RATES IN RESIDENTIAL AND COMMERCIAL BUILDINGS IN THE NORTHWEST: TECHNIQUES AND RESULTS

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ABSTRACT

In a study of air exchange rates in commercial and residential buildings, several techniques were employed to measure the air exchange: analysis of sulfur hexafluoride tracer gas decay using a portable gas chromatograph; analysis of carbon monoxide decay using a continuous infrared analyzer; analysis of nitrogen oxides decay using a continuous oxides of nitrogen analyzer; and analysis of perfluorocarbon tracer (PFT) gas using a programmable automatic sampler, and a passive capillary tube sampler.

Using sulfur hexafluoride tracer gas with real-time chromatography was the most labor-intensive method, requiring constant attention for several hours; whereas, analyzing the decay of PFT tracer gas using small capillary tubes required little setup time and virtually no attention. However, the analysis of tracer gas captured by the capillary tubes was difficult and was performed using special analysis equipment.

The air exchange rate measured in the commercial buildings ranged from 5 to 0.04 air changes per hour (ACH) depending on the type of heating, ventilation, and air conditioning (HVAC) system. Air exchange in the residential structures ranged from about 1 ACH to about 0.3 ACH.

INTRODUCTION

For the past several years, Pacific Northwest Laboratory has been involved in field studies to measure air exchange rates in commercial and residential structures in the Pacific Northwest. These measurements have been used to support environmental assessments of new building standards; support modeling studies; establish baseline air exchange rates; and assess the effects that residential tightening measures, occupancy, wood combustion, and air-to-air heat exchangers have on air exchange rates and energy use.

A short review of techniques for measuring air exchange in buildings is presented. This is followed by a comparison of the techniques and the air exchange rates measured in commercial buildings and in residential buildings.

AIR EXCHANGE MEASUREMENTS REVIEW

Two basic techniques are used to measure air exchange rates in structures. One approach is using a tracer gas to measure the infiltration of outside air into a structure; the other approach is artificially pressurizing the building to measure the air flow rate induced in the structure. Each approach gives different information about the leakiness of a building. The tracer gas method gives a direct measure of the 'natural' air exchange rate during the climatic conditions at the time of the measurement. The pressurization method normally is performed at pressures above ambient pressure, and the measurements are independent of the climatic conditions.

The technique using tracer gas involves releasing a small volume of a selected tracer gas into a structure, making sure the volume is well mixed with the air inside the building, and then measuring the decay (or dilution of the gas with fresh air) in concentration of the tracer gas over a known time period.

The concentration of the tracer gas at any given time period can be determined from the equation:

$$Vdc/dt + QC = 0$$

where V = volume of the structure (m^3)
Q = air exchange rate (m^3/s)
C = concentration of the tracer gas in the structure
t = time (s)

Integration of this equation yields the following equation

$$C = Co \exp(-qt/V)$$

where Co = measured tracer gas concentration after decay
q = total air flow rate
t = time
V = volume

Rearrangement of the equation gives

$$\ln(C) = -I(t) + \ln(Co)$$

where I = Q/V in volume changes per unit time

A plot of the best fit line of ln(C) versus time is normally used to determine the infiltration rate, which is the slope of the line. An example of this type of plot is shown in Figure 1. Many different gases and measuring techniques have been used in studies of air exchange in structures.[4,5] A tracer gas is required to be essentially inert, detectable at very low concentrations (parts per billion range), nontoxic, and inexpensive. One of the most popular tracer gases is sulfur hexafluoride (SF_6),[1] and more recently perfluorocarbons (PFT) have been used.[2,3] Instruments to measure the decay of these gases must be highly sensitive because low concentrations of tracer gas are used. These instruments can either be real-time instruments that instantaneously measure airborne concentration of the tracer gas, instruments that give a short-time integrated measurement of the airborne concentration (such as infrared absorption), or instruments that instantaneously detect concentrations of the airborne gas captured in a medium (absorbent) or in plastic bags over known time periods in a structure.

AIR EXCHANGE MEASUREMENTS IN COMMERCIAL BUILDINGS

Air exchange rates were measured in four types of commercial buildings during the winter heating season. Building 1 is a single-story office building built in 1978 of about 6,000 ft^2. The building is heated and cooled by electric heat pumps mounted on the roof. The HVAC system is divided into four zones and is never shut down. Automatic air dampers control fresh air intake and are adjusted continuously as a function of outside air temperature.

Building 2 is a two-story accounting office with a full basement. The office was built about 1974 and was built to be 'energy efficient' with tight construction and a few nonopening windows. The first and second floors are office areas and are central open bays with individual offices around the perimeter. The building is electrically heated and cooled through a central HVAC system (one system for

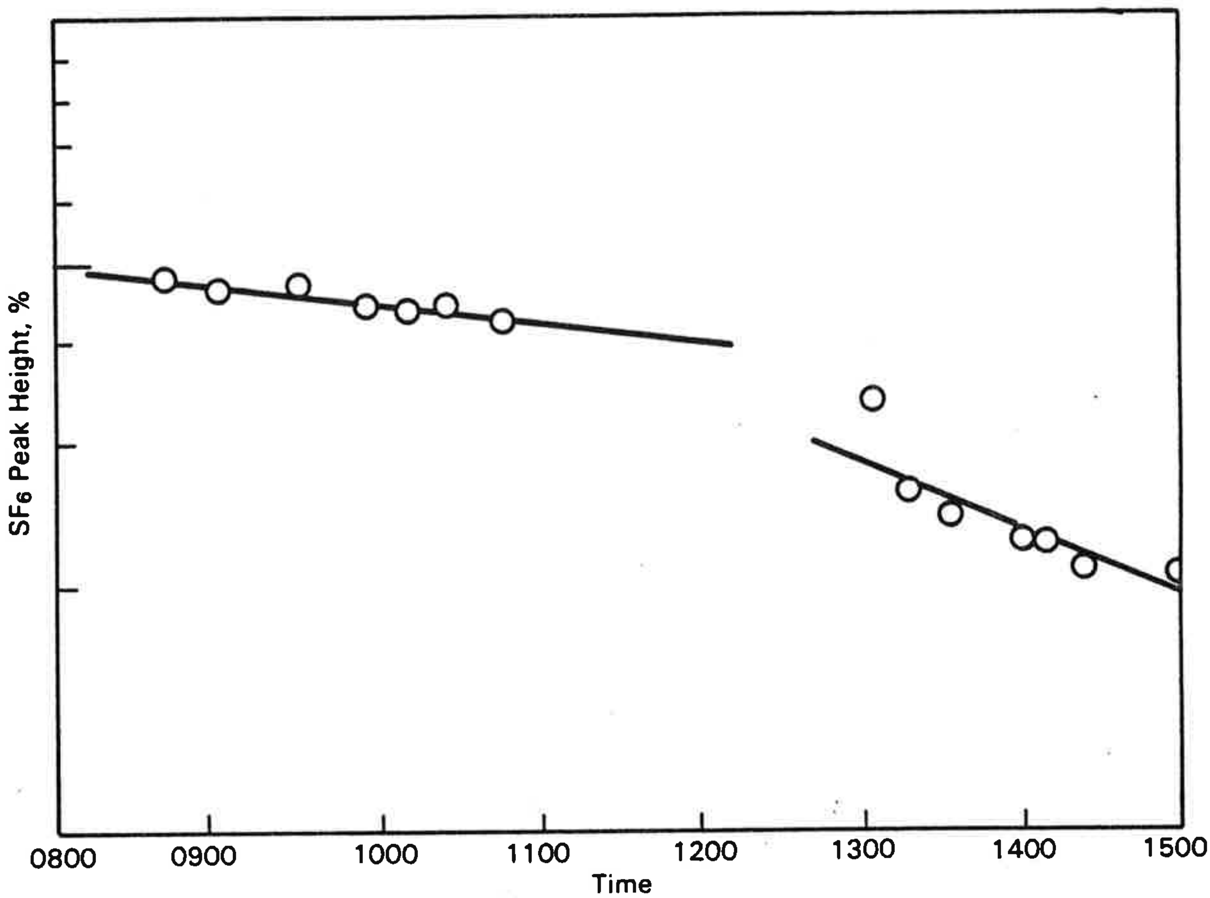

FIGURE 1: SEMILOG PLOT OF SF_6 TRACER DECAY VERSUS TIME

the basement and first floor, one system for the second floor with roof-mounted air intakes). Both HVAC systems are turned on at 6 a.m., shut down at 5 p.m. on weekdays, and turned off on weekends and holidays. Fresh air intakes are adjusted (dampered) automatically according to outside temperature.

Building 3 is a machine/wood shop connected to building 2, but separated by a firewall. The shop area is about 20,000 ft^2. The shop does not have a central HVAC system and is heated by overhead electric resistance heating. General ventilation is through 12-ft x 25-ft bay doors located on two of the four walls of the building, and local exhaust ventilation is provided for welding or metal stripping. All access doors from the shop to the accounting office are self closing and normally are closed during the day.

Building 4 is a single-story warehouse of approximately 100,000 ft^2. The warehouse is heated by overhead forced air electric heaters, but has no central HVAC system. Cooling is via several roof-mounted mechanically opened vents. The warehouse contains several 12-ft x 25-ft bay doors at either end of the building. During a working day, these doors are normally open and one or two receiving doors on the west side of the building are opened periodically to receive or to move shipments.

Air Exchange Measurements

The air exchange rate in each building was measured using SF_6 tracer gas and gas chromatography analysis. This type of air exchange measurement was possible because large (6 ft x 6 ft) areas inside were unoccupied and accessible where the equipment could be set up and analysis performed.

If the building did not have a central HVAC system, a small amount of SF_6 gas was released from plastic storage bags into the building at several locations. The gas was released by opening the plastic bag or by drawing samples from the bag using a sampling syringe. The SF_6 was released into the fresh-air intake in buildings with an HVAC system.

The amount of SF_6 released depended on the estimated volume of the building and the estimated percent fresh air intake. In the shop and warehouse, the SF_6 was released the night before air exchange was measured to allow for complete mixing. For the office buildings (1 and 2) the air exchange rate was measured while the HVAC system was off and the building was unoccupied (nonworking hours); in the shop and warehouse, the air exchange rate was measured during working and nonworking hours.

Sulfur hexafluoride was sampled manually several times during an hour using a very large gas-sampling syringe and was then injected into the analysis instrument. Samples were taken from several locations within the buildings to determine the degree of mixing of the SF_6 and to acquire an average of the indoor concentration. Fans may need to be used in structures to ensure proper mixing unless adequate time is allowed for natural mixing (as was the case in the shop and warehouse).

We were also able to determine air exchange rate in the warehouse by measuring carbon monoxide (CO) and nitrogen oxides (NO_x) decay, and in the shop by measuring NO_x decay. Because of the vehicular traffic (with combustion engines) and as a result of welding in the shop, these two pollutants were naturally present in very low but detectable concentrations in the warehouse and NO_x were present in the shop. After the working day was over, the decay in these pollutants was measured using real-time monitoring instruments. We were able to set up these instruments inside the buildings because there was adequate amount of open space that did not interfere with the workers and the noise from these instruments did not cause any disruptions.

The NO_x were measured with a commercial real-time nitrogen oxides analyzer. This instrument can detect 0.5 parts per billion NO_x. It requires a supply of bottled gas and a working area of about 4 ft x 4 ft to set up and use. The pump operating in the analyzer is somewhat noisy (too noisy to set directly in an office for instance). Analyses are recorded on a chart recorder.

Carbon monoxide was measured using a single-beam infrared continuous analyzer. The instrument was programmed to scan the infrared absorbence wavelength of CO and to automatically print out the concentration of CO every 34 min on a self-contained tape. The minimum detectable concentration of CO is 0.2 parts per million. This instrument requires no external bottled gas or recorder, but does require a pump. It is less noisy than the NO_x analyzer and requires an area of about 3 ft^2 to operate.

RESULTS OF MEASURING AIR EXCHANGE IN COMMERCIAL BUILDINGS

The rates of air exchange measured using different gases and analysis techniques are given below for the four commercial buildings. Also given are the difference in inside and outside temperature and the average windspeed during the measurement period, if recorded.

Building 1

Air exchange rate was measured during the working hours on two days and on a nonworking day. The HVAC system operated during all measurement periods. The results are presented in Table 1.

Building 2

The air exchange rate in Building 2 was measured during one evening when the HVAC system was off and during two working days. All measurements were made for the first and second floors, which were served by two separate HVAC systems. The measured concentration levels of SF_6 on each floor indicated that there was good mixing of the air between floors. However, spot sampling of SF_6 in the basement indicated that air from the basement was not readily exchanged. The measured air exchange rates are summarized in Table 2.

Building 3

Air exchange was measured using SF_6 on only one day in the shop. The measurement period began when the shop was unoccupied and all outside doors were closed, and continued 2 hr into the work day when the bay doors were opened periodically. This ensured that one measurement was taken of air exchange resulting from natural leakage through the building shell. The air exchange rate was also determined from NO_x decay after the working day was over on two separate days. The results of these measurements are given in Table 3.

Building 4

The air exchange rate was measured using SF_6 tracer gas in the warehouse during the working hours on a Tuesday morning and afternoon (3/29). Both the NO_x decay and CO decay were measured on a Saturday and Sunday (3/26-27) and on a Monday (3/28) and early Tuesday during nonworking hours. The CO and NO_x were both introduced into the structure from the combustion engines of the vehicles used to move merchandise. The decay of CO on Monday and Tuesday is shown in Figure 2 and the decay of NO_x during these measurement is shown in Figure 3. Table 4 is a summary of the air exchange analyses.

AIR EXCHANGE MEASUREMENTS IN RESIDENTIAL STRUCTURES

Air exchange rates were measured in both multifamily and in two occupied and one unoccupied single-family residences. The multifamily complexes were three units of three separate four-plexes (two units upstairs, two units downstairs) located within two blocks of one another. These units were built about 1978 and have identical floor plans of about 940 ft^2 each. The units are all heated by baseboard electric heat, and all were occupied during the measurements.

The single unoccupied residence (house 1) is a single-story wood-framed house of about 1300 ft^2, built about 1972, with an addition that was added about 1974. The house is heated by

TABLE 1: AIR EXCHANGE RATE MEASUREMENTS IN BUILDING 1

Date	Air Exchange Rate (ACH)	Average Difference in Inside and Outside Temperature (°C)	Average Windspeed (mph)	(m/s)
2/3 (Thurs)	1.1 ± -0.2	18	2	0.9
2/4 (Fri)	0.67 ± -0.1	21	0.5	0.2
2/5 (Sat)	0.89 ± -0.1	21	1	0.4

TABLE 2: SUMMARY OF MEASUREMENTS OF AIR EXCHANGE RATES IN BUILDING 2

Date	Time	Air Exchange Rate (ACH)	Average Difference in Inside and Outside Temperature (°C)	Average Windspeed (mph)	(m/s)
3/21	1500-1900	0.39 ± -0.6	9	2.5	1.1
3/22	0900-1400	0.26 ± -0.4	5	3.6	1.6
3/22	1400-1700	0.59 ± -0.9	7	6.7	3.0
3/23	0900-1300	0.45 ± -0.7	8	3.7	1.6

TABLE 3: SUMMARY OF AIR EXCHANGE RATE MEASUREMENTS IN BUILDING 3

Date	Time	Air Exchange Rate (ACH)	Average Difference in Inside and Outside Temperature (°C)	Average Windspeed (mph)	(m/s)
3/23	1700-2200	0.07 (NO_x decay)	-	-	-
3/24	1700-2200	0.11 (NO_x decay)	-	-	-
3/25	0600-0800	0.12 (SF_6)	7	<2	<1
	0800-1000	5.5 (SF_6)	-	<2	<1

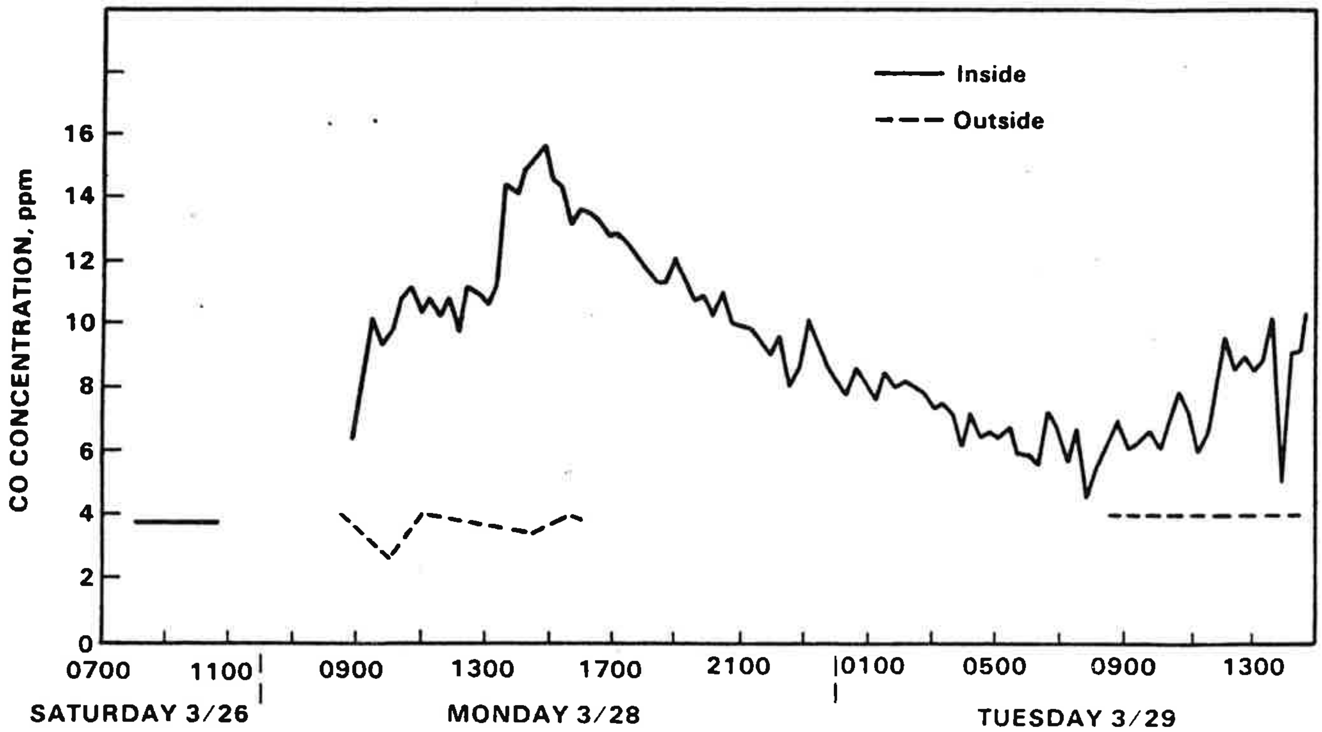

FIGURE 2: DECAY OF CO MEASURED IN BUILDING 4

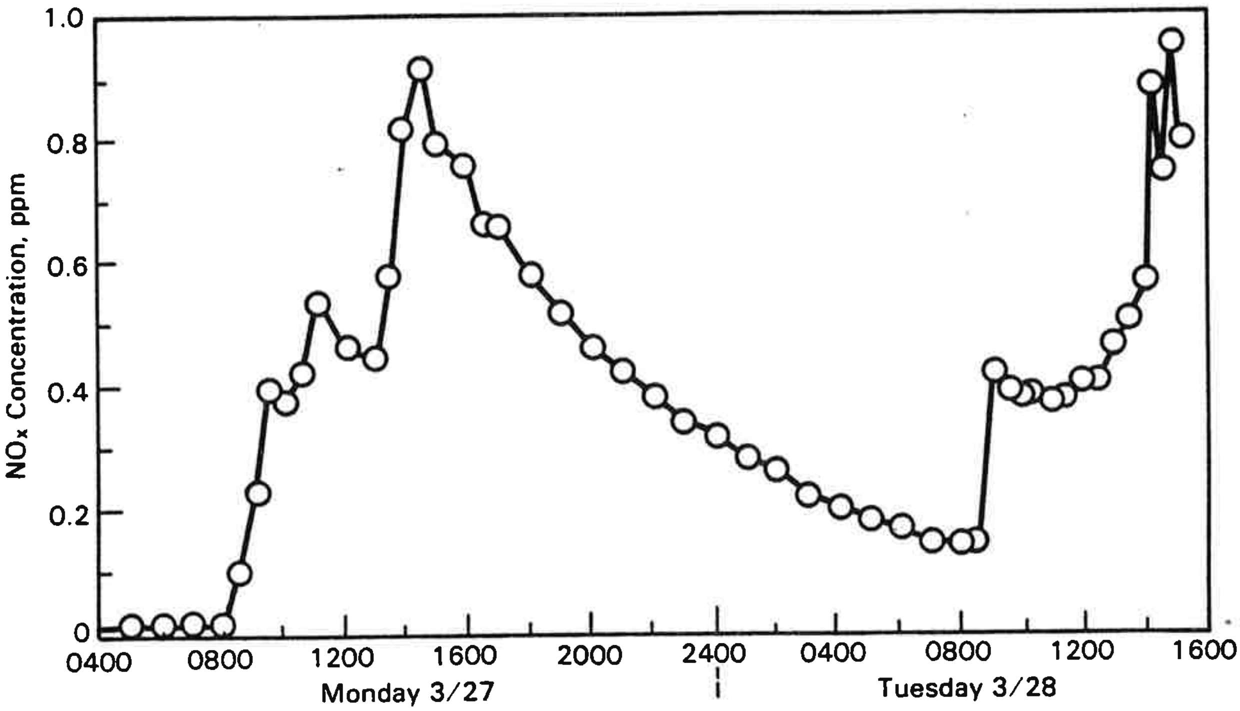

FIGURE 3: DECAY OF NO_x MEASURED IN BUILDING 4

TABLE 4: SUMMARY OF AIR EXCHANGE RATE MEASUREMENTS IN BUILDING 4

Date	Time	Air Exchange Rate (ACH)	Average Difference in Inside and Outside Temperature (°C)	Average Windspeed (mph) (m/s)
3/26-3/27 Sat-Sun	0300-0700	0.04 (NO_x decay)	-	calm
3/28-3/29	1700-0700	0.05 (CO decay)	-	calm
3/28-3/29	1600-0600	0.08 (NO_x decay)	-	calm
3/29	0800-1100	0.05(SF_6)	3	3.4 1.5
	1200-1500	0.2 (SF_6)		9.6 4.3

baseboard electric resistance heat, which operated during the measurements.

One of the occupied homes (house 2) was built in the early 1970s and is single-story wood-framed house with a crawl space and attic. Total square footage is about 900 ft^2. The house is heated with electric baseboard heat and supplemented with a fireplace with a heatalator/blower. The fireplace was used extensively during the air exchange measurements (more than 6 hr/d). The house was occupied by three people.

The other occupied residence (house 3), which was built in 1982 to be energy efficient, is 2 x 8, wood-framed with insulated sheathing down to the footing. The single-story house is approximately 1800 ft^2 with a crawl space and vaulted ceilings and a stone tromb wall as part of a solarium to act as a solar storage medium. It was also constructed with a poly-wrap vapor barrier. It is heated by a forced-air electric furnace, which was seldom on during the air exchange measurements. The house is occupied by two adults. Each of the single-family houses was equipped with a complete weather station and indoor and outdoor sensors to measure temperature, windspeed, and wind direction. A portable weather station and data logger were set up at the multifamily complexes to measure windspeed, wind direction, and indoor and outdoor temperature.

Multifamily Complexes

The air exchange rate in the multi-family complexes was measured using perfluorocarbon tracer (PFT). The airborne perfluorocarbon was captured using a Gillian Programmable Atmospheric Tracer Sampler (PATS) deployed in each residence. The PATS units are about 14 in. x 9 in. x 9 in. and were placed in the living area of the house on a table and programmed to capture the tracer gas by pumping room air through capture tubes for approximately 6 to 8 hr per tube for about 5 to 7 d. The pulse pump in the PATS was somewhat noisy.

Tracer gas was released into the residence continuously via diffusion through the rubber cap of a small 1/4-in.-diameter x 1-in.-long metal capsule containing perfluorocarbon liquid. The tubes were placed in the residence for the duration of the monitoring. One capsule was used per 500 ft^2 of floor area. The temperature of the PFT sources must be known to determine the airborne concentration for the measurement period.

The deployment of the tracer gas was not noticed by the resident. The only difficulties experienced during the measurement in the three units were malfunction of the printing of the time and pump stroke information on the paper tape of the PATS units. If this information is missing or not readable, the air exchange rates are difficult to analyze. Once all the tubes in the PATS were used to capture the PFT in the units, they were submitted for analyses. Because only two places in the country have the equipment to perform low-level PFT analyses, it can take several months to receive results.

Single-Family Residences

Air exchange rate in the unoccupied home was measured using SF_6 tracer and the PFT tracer with PATS sampler as well as passive capillary atmospheric tracer samplers (CATS). The CATS are small 1/8-in.-diameter x 3-in.-long glass capillary tubes that contain an adsorbent (the same as used in the PATS tubes) and that passively (without a pump) capture airborne PFT.

The CATS are useful for determining long-term (a week or more) average integrated air exchange rates. The CATS were placed at several locations in the house, uncapped, and left to capture the PFT released from the sources for a predetermined time period. At the end of the measurement time, the CATS were sealed and sent away for analyses similar to that performed for the PATS tubes. The CATS require no attention or moving parts and can be left in a residence for months with little notice from the residents. These can be recovered by the resident and mailed to the investigator if necessary. Little can go wrong with this system. As with the PATS, the temperature of the PFT sources must be known to determine the airborne concentration of the PFT during the measurements. Analyses of CATS measurements also take several weeks to months.

We were able to use the same technique for the SF_6 analyses as described for the commercial buildings in this residence because it was unoccupied and plenty of room was available to set up equipment. We did not have to ask permission or make arrangements to perform the measurements. Otherwise, this equipment (size and amount) and the disturbance would probably be unacceptable to most occupants.

Air exchange rates in the two occupied homes were measured using PFT and the PATS and CATS capture systems. In these homes the PFT had be placed in the house at least 24 hr before measurement to allow the PFT to disperse and become well mixed. This meant a return trip to place the CATS samplers or to uncap the CATS samplers unless the homeowners agreed to do so. On the other hand, the PATS sampler could be left in the home at the same time that the PFT was deployed and be programmed to begin taking samples in 24 hr automatically.

Neither homeowner complained about the floor space taken up by the PATS, or about the noise from the PATS, although the noise was somewhat disturbing to one homeowner when the TV was turned off and the house was quiet. On the other hand, the PATS units shut off automatically, and the units were recovered at a later date. The CATS samplers were silent and were easily deployed and recovered. In one instance, the homeowner capped one of the CATS tubes at our request because we were delayed in arriving to recover the tube.

RESULTS OF RESIDENTIAL MEASUREMENTS

The air exchange rates measured in each of the single-family residences are not yet available. However, the air exchange rates in the multifamily units are given below. Air exchange rates were measured each 24-hr period in the three multifamily units for 4 to 5 consecutive days in each unit.

The daily average air exchange rate over the measurement period is given in Table 5. Also given in Table 5 are the temperature difference and average windspeed during the measurement period if recorded. The daily record of air exchange measured in the multifamily units can be found in Parker, Wilfert and Dennis.[6]

OBSERVATIONS AND CONCLUSIONS

Our experiences in measuring air exchange rates in commercial and residential structures led to the following observations and conclusions.

The use of SF_6 as a tracer gas combined with onsite analysis is a sensible approach to measuring air exchange in small- to medium-sized commercial buildings, especially if the building has a central HVAC system. Adequate room must be provided to set up the analysis equipment where it is isolated from occupants and occupant activity. The use of SF_6 is well-known and highly accurate. Onsite analysis provides a same-day determination of the air exchange rate.

A central HVAC system provides a mechanism to introduce the SF_6 into the structure in a manner that allows quick and complete mixing. Introducing SF_6 into buildings without a central HVAC system requires careful planning to introduce the gas into the structure in plenty of time to allow adequate mixing. Access to the building during nonworking hours may be necessary to perform these measurements and to measure air exchange during times when the HVAC system is off. Access during nonworking hours is sometimes difficult to arrange.

The use of either NO_x and CO to determine air exchange rates requires source or a highly controlled release of these chemicals. Both chemicals can be toxic above certain concentrations and continuous exposure is not

TABLE 5: AIR EXCHANGE RATE MEASUREMENTS IN MULTIFAMILY UNITS

Dates	Unit	Number of Occupants	Air Exchange Rate (ACH)	Average Difference in Inside-Outside Temperature, (°C)	Average Wind (m/s) (mph)
11/07-11/11	#1(up)	3	0.38 ± -0.1	25 ± -2	2.2 ± -0.9 1.0 ± -0.4
11/08-11/12	#2(down)	4	0.28 ± -0.06	24 ± -1.7	3.1 ± -1.5 1.4 ± -0.7
11/14-11/18	#3(up)	3	0.59 ± -0.28	25 ± -2.4	11.5 ± -4.1 5.1 ± -2

recommended. The use of these gases in the warehouse was only possible because of the 'natural' source that was present. Comparing the air exchange rates measured using SF_6, CO, and NO_x shows that air exchange rates measured by analysis for each gas were similar for this structure. This was observed even though both NO_x and CO tend to be reactive and decay not only from dilution from the outside air, but also through chemical transformation.

The best use for CO and NO_x tracer gas would be in an unoccupied structure. Special analysis equipment is also required, which must be located in isolated or nonworking areas. The advantage of using these gases and analysis equipment is that these are well-suited to automatic monitoring. That is, the equipment can be left unattended (as in the overnight monitoring of the warehouse). As with the SF_6, air exchange rates can be derived soon after decay measurement.

The use of PFT tracer gas and PATS seems particularly well-suited for measuring air exchange in residences. The PFT gas is easily deployed and fairly inexpensive. The PATS can be programmed to capture tracer gas for several minutes or several hours over a time period of up to a week. The units are mechanical, however, and are subject to mechanical failure (e.g., not turning on or off at the programmed time or failing to advance the paper tape). The PATS is also somewhat noisy and can be a disturbance in a 'quiet' household. The only major drawback to the PATS is that the time required for analysis can be up to several months.

Using the CATS in combination with PFT was most helpful in to determining long-term average air exchange rates in the residences. The CATS can also be used to determine short-term (<24 hr) air exchange rates. They are small, silent, easily deployed and transported, and were nearly unnoticed by the residents. The only potential difficulty is ensuring that the PFT sources are deployed in the residence at least 24 hr before deploying the CATS. An involved and interested resident can be helpful in uncapping, capping, and mailing the CATS. As with the PATS, the analysis time can be several months.

Although not used in our studies in commercial buildings, the PFT/CATS combination appears to be well-suited for such an application if adequate PFT can be dispersed into the building and the CATS can be strategically placed.

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