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APPROACHES TO ESTIMATING AIRFLOWS IN LARGE MULTIFAMILY BUILDINGS

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ABSTRACT

Air infiltration can account for a significant part of the heat loss in multifamily buildings. Its magnitude, however, is difficult to determine. In the absence of a central ventilation system, pressurization tests of the whole building are virtually impossible and one-chamber tracer gas measurements become inapplicable. Heating-season-average air infiltration rates can be estimated indirectly by comparing energy consumption data with engineering models of heat loss. However, a large uncertainty is associated with this estimate.

We describe various pressurization and tracer gas techniques for characterizing airflows in large multifamily buildings. We applied a number of these techniques to a six-story apartment building. Single and multizone fan pressurization methods enable the measurement of leakage areas of apartments to the outside and to other interior spaces. Single-zone fan pressurization at the apartment building showed that the apartments were relatively tight, with leakage areas dominated by the building's many open windows. Constant-injection tracer gas techniques allow measurement of airflows in the building's vertical shafts, which are likely to be stack dominated. Constant-injection measurements were used to estimate leakage areas in the stairwell. Three variations of the constant-concentration tracer gas technique can be used to measure outside airflows into individual apartments and allow certain interzone airflows to be estimated. These techniques applied to the apartment building showed that apartments exchange air primarily with the outside at rates depending heavily on window openings.

INTRODUCTION

In comparison to single-family houses, the shared walls and floors in multifamily buildings reduce conductive heat losses, leaving air infiltration to be a larger part of overall heat losses. A house can often be characterized as a single, uniformly mixed zone exchanging air with the outside. In multifamily buildings, airflow paths connect each apartment to one or more adjoining apartments and sometimes with enclosed common spaces such as hallways and stairwells as well. Hallways connect the building horizontally, while stairwells, elevator shafts, incinerator shafts, etc., provide vertical airflow paths. It is the outside airflow into apartments and other conditioned spaces that contributes to ventilation and energy use, while airflow among the interior spaces affects moisture and odor transport and the spread of fire within the structure. In order to understand these relationships, we need to ask: what are the major airflow paths in the building and what is the magnitude of the flows?

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The overall air infiltration rate of the building may be estimated from the total (measured) space-heating energy use, if the conductive heat losses and the efficiency of the heating system can be estimated. This paper includes a discussion of how the air infiltration rate can be inferred, even when heating system efficiency is not known.

Airflows are caused by pressure differences across openings and the magnitude of airflows can be calculated if the pressure differences and the size of openings (called leakage areas) are known. The pressure differences are induced by temperature differences (stack effect) and by the wind. The airflows for the whole building are expressed in terms of the leakage areas between the zones and the pressure distribution in the building. A number of multizone airflow models have recently been developed (Feustel and Kendon 1985). Application of the models, however, generally requires empirical parameters such as leakage areas and wind-induced pressure differences specific to the building. The difficulty of measurement has limited the determination of these empirical parameters and have made it difficult to validate the models.

In this paper we present a number of experimental approaches for estimating the magnitudes of airflows in a large apartment building. Using actual measurements in a multifamily building, we discuss the usefulness of a variety of techniques, such as pressurization and constant-concentration and constant-injection tracer gas techniques. We also discuss additional approaches that we have not yet tried, such as multizone guarded pressurization and multiple tracer gas techniques. These techniques provide estimates of leakage areas and leakage distribution, parameters that might be used in multizone airflow models. A better understanding of airflows in multifamily buildings will help to reduce energy use and fire hazards and improve air quality. An intermediate goal would be the development of techniques to facilitate building diagnostics. The research described here is a small step in this direction.

The site of our measurements is a 60-unit, six-story apartment building for senior citizens located in Asbury Park, New Jersey. The floor plan and one elevation of the building are shown in Figure 1. The ground floor has offices in one wing and common areas in the other. The apartments are located, six per floor per wing, on the next five floors. The windows are casement type with interior storms, except in the bathrooms where there are no storms. Every apartment has windows on at least two different faces of the building. The apartments on each floor share a hallway, which is connected to a pair of stairwells and an elevator shaft. Both stairwells (for each wing) have outside doors on the ground floor, and one of them also has a door at the top for roof access.

INFERRING AIR INFILTRATION

An estimate of the seasonal-average air infiltration rate for the whole building is adequate for calculating the heating load. Such an estimate can be obtained from the monthly energy consumption billing data. The billing data are first analyzed using PRISM (Fels 1986), which relates building energy use to outdoor temperature and characterizes the building in terms of three parameters -- a base level consumption, a heating slope, and a reference temperature (degree-day based). The weather-normalized annual energy consumption (NAC) of the building is then given by:

$$NAC = \alpha + \beta H_o(\tau) \qquad (1)$$

where α = base level consumption

β = heating slope

H_o = normal year heating degree days for the given reference temperature

τ = reference temperature

DeCicco extended the PRISM model by factoring the heating slope (β) and reference temperature (τ) in terms of additional physical parameters (DeCicco et al. 1986):

$$\beta = (L_i + L_t)/\eta \tag{2}$$

$$\tau = T_{in} - Q/(L_i + L_t) \tag{3}$$

<u>where</u> L_t = transmission heat loss rate

L_i = average air infiltration heat loss rate

η = heating system efficiency

T_{in} = average indoor temperature

Q = intrinsic heat (gain from the sun, appliances, and people)

The parameters L_i and η can be calculated from Equations 1 to 3 using PRISM estimates of NAC, α, and β, measurement of T_{in}, and engineering estimates of L_t and Q.

Analysis of monthly gas use data (June 1982 to June 1983) for the building yields the following estimates (standard errors in brackets):

α = 6.4 [3.5] MBtu/day (79 [43] kW)

β = 0.81 [0.14] MBtu/F.day (18 [3] kW/°C)

NAC = 6990 [424] MBtu/yr (7260 [440] GJ/yr)

Interior temperature was estimated from spot measurements to be 79 F (26°C); L_t and Q were estimated to be 0.32 MBtu/F.day (7.0 kW/°C) and 6.1 MBtu/day (75 kW), respectively (DeCicco et al. 1986). The simultaneous solution of L_i and η is shown graphically in Figure 2 as the intersection of two lines (representing constant NAC and constant β) and yields the values L_i = 0.22 MBtu/F.day (4.8 kW/°C) (corresponding to 1.6 ACH) and η = 68%. Given the measured steady-state boiler efficiency of 77% and the large number of open windows observed at the building (DeCicco and Kempton 1986), the estimates appear reasonable. A rigorous error analysis is complicated because of the nonlinearity of the equations and because the parameter estimates are not independent. Figure 2 suggests that the uncertainty of the air infiltration rate could be as large as the estimate itself.

If η is known from other measurements, then L_i can be estimated directly from Equation 2. For typical errors in η, β, and L_t, this method gives only a rough estimate of the building's air infiltration rate. For instance, if it is assumed that the error in estimating L_t is 20% of the value and the error in estimating η is 0.05, then the error in computing L_i is approximately 50% of the computed value. It should also be mentioned that, given a PRISM estimate of τ, a value of L_i can be computed from Equation 3 that is not dependent on η. However, for this case, the error in (T_{in} - τ) is too great to yield a reliable estimate of the average air infiltration heat loss rate.

Another drawback to this method is that the heat losses are assumed to be made up of handbook values of transmission losses and air infiltration only. For example, the building envelope may have thermal anomalies (convective loops, thermal bridges, construction defects, etc.) that would increase transmission losses above their handbook estimate. For this case, the above procedure would yield an estimate of the air infiltration rate that is higher than its correct value. At the apartment building, no significant thermal anomalies were observed in infrared thermography, so that this problem is not anticipated. Finally, the nature of the computation leads to only a heating-season-average infiltration rate for the entire building. No information is obtained about the weather dependence or spatial variation of air infiltration in the building.

Houses and other small buildings can frequently be pressurized by a single device such as a blower door. Some large buildings, with central air distribution systems for heating, cooling and/or ventilation, can be pressurized using the buildings' circulation fans (Harrje et al. 1982). This building, like many other multifamily buildings, does not have central air distribution and has too many interior partitions to be uniformily pressurized by a transportable fan. Nevertheless, pressurization measurements in parts of the building can yield useful information in buildings such as these. Frequently, individual apartments and other regions can be pressurized separately. These single-zone measurements yield data on the relative leakiness of apartments and can also be used to estimate components of air leakage in the building. A precise separation of the component of air leakage to the outside, from the leakage to other parts within the building, requires multizone measurements involving several pressurization devices. The measuring techniques and types of data that can be obtained are outlined below.

Single-Zone Pressurization

We assume that the pressurization device used is a blower door, which is a calibrated fan that can be mounted in a doorway. If the apartment has a doorway open directly to the outside, then the blower door can be mounted in this door to pressurize or depressurize the apartment. If the apartment door opens into a hall, then the same effect can be created by leaving open several windows and/or doors between the hallway and the outside.

Air flowing through the fan into an apartment being pressurized may leave directly to the outside or into adjoining conditioned spaces within the building. Only the former affects energy use and ventilation. The leakage flow rate through the fan thus gives an upper bound to the apartment's (outside) leakage. Several apartments were pressure tested in this way. The leakage flow, expressed as apartment volumes per hour at an inside-outside pressure difference of 0.2 inches of water (50 Pa), ranged from 2.5 to 6 air changes per hour (ACH) (Harrje et al. 1983; present study). Even if all this leakage were to the outside, the leakage rates would make the apartments very airtight. Several of these apartments would meet the standards for airtightness in Sweden's new single-family houses. Most houses in the U.S. range from 10 to 20 ACH at 0.2 inches of water (50 Pa) with relatively few below 6 ACH.

Apartments in other buildings whose tightness data we have seen are much leakier. For instance, a number of apartments in New York City ranged in leakiness from 10 to 43 ACH. Blower door data before and after leakage sites are temporarily sealed can be used to determine their relative leakiness. This method has been used to determine the components of air leaks in single-family houses (Caffey 1979; Harrje and Born 1982; Reinhold and Sonderegger 1983). In apartments, it can be useful to divide the leakage into inside and outside components.

Many residents at the apartment building keep one or more windows open throughout the year (DeCicco and Kempton 1986). The blower door was used to quantify the leakage through open windows. One efficiency apartment was pressurized in steps, with one or more windows open by various amounts. Figure 3 shows leakage flow as a function of window-opening area. With windows closed, at a 0.2 inches of water (50 Pascal) pressure difference, the leakage flow is 102 ft^3/m (174 m^3/h) for this 269 ft^2 (25 m^2) apartment. However, unlike most houses, window leakage dominates the overall apartment leakage, even at small window-openings. The linear relationship between leakage flow and window opening area corresponds to flow through an opening with a discharge coefficient of 0.73, which is between the extremes of 0.61 for sharp-edged orifices and almost one for smooth nozzles. These results have several major implications for the airflow pattern. First, with windows open, the leakage area between the apartment and other spaces within the building is relatively small. We would expect the apartment to exchange air almost exclusively with the outside. Second, since the windows dominate air leakage, the leakage area of the exterior of the building can be calculated from visual observations of the window positions. Window positions have been recorded over an extended period of time (DeCicco and Kempton 1986), and these data may be usable with airflow modeling and tracer gas information to estimate air infiltration levels in the building.

With each apartment acting as an individual zone exchanging air almost exclusively with the outside, the airflow pattern can be characterized by Figure 4. The hallways and stairwells together can be treated as another zone, since the doors connecting them at each floor are kept propped open by the residents. In principle, this zone can also be pressure tested; however, this large volume could not be adequately pressurized by a single blower door.

Multizone Pressurization

Constant Pressure Method. Most buildings are not as airtight as the one studied, and individual apartment pressurization is less useful in separating inside and outside leaks, as noted above for the New York City buildings. In such cases, multiple blower doors can be used to obtain additional information. Researchers have used six blower doors to test a six-apartment building in Minneapolis (Modera et al. 1985). First, each apartment was pressurized using a single blower door, and its gross leakage was measured. Next, all the apartments were pressurized simultaneously so that each apartment was at the same pressure. In this condition there is no flow between apartments, and all the flow passing through the fan in or out of the apartment is outside leakage. This technique provided a breakdown between inside and outside leaks. The researchers used these measurements with their multizone model to calculate air infiltration into each apartment.

Guarded Pressurization. Balancing the pressures in the apartments becomes difficult as the number of apartments increases, even if an adequate supply of blower doors can be located. Nevertheless, two or more blower doors can provide useful data in larger buildings. As before, a single blower door measurement gives the gross leakage of the apartment. Pressurizing a neighboring apartment to the same pressure gives approximately the gross leakage less the leakage between the test apartment and its neighbor. Other leakage components can be determined using additional blower doors. If all adjacent zones to the test apartment can be pressurized, then the net leakage from the test apartment to the outside can be determined. This is analogous to the constant pressure method, except that only the values for the interior "guarded" zones are determined.

TRACER GAS MEASUREMENTS

Individual Apartment Airflows

Ideally, we would like to measure the dominant airflows in the entire building over an extended period of time. In most cases, each apartment can be considered to be a single well-mixed zone. Even with this simplification, the building consists of many interconncected zones where any zone may communicate with as many as six neighbors. In the case studied, there are more than 30 separate zones in each wing with most zones having five adjoining zones. Present tracer gas (TG) systems are not capable of measuring the flow rates in the entire building. Dilution of a single TG has been applied to a building separated into two zones, constant injection of multiple TGs to a four zone building, and constant concentration of a single TG to a ten zone building (Harrje et al 1985). In this section we describe three variations of the constant-concentration (CC) technique adapted for the complex flow environment of multifamily buildings: guarded-zone CC, surrounded-sampling single-zone CC, and discontinued-injection CC. The first method is mainly useful in measuring infiltration airflows, while the second two provide information on interzone flows.

Guarded-Zone Constant Concentration. In this method, all building zones adjacent to the test zone (or set of zones) are kept at the same constant concentration as the test zone. Measuring the rate of tracer addition to the "guarded" test zone (g) then yields the rate of the outside air infiltration into the zone. The coupled set of first order differential equations that govern the level of tracer gas in a multizone building is (Sinden 1978):

$$V_j \frac{dc_j}{dt} = -c_j \cdot \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (4)$$

where V_j = volume of zone j

F_{ji} = airflow from zone j to i

c_j = tracer gas concentration in zone j

S_j = rate of tracer gas injection into zone j

n = number of zones in building + 1

the n^{th} zone is the outside air ($c_n = 0$)

If the concentration in a zone is kept constant at a level c_t then Equation 4 reduces to:

$$c_t \cdot F_{jT} = \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \tag{5}$$

where F_{jT} = total flow out of zone j

For the guarded zone $c_k = c_t$ and Equation 5 reduces to:

$$F_{ng} = S_g/c_t \tag{6}$$

where F_{ng} is the flow of outside air (zone "n") into the guarded zone.

Thus, the infiltration flow into each guarded zone is approximately the rate of TG injection into the zone divided by the target constant concentration. In practice, the concentration deviates from the target level. An analytical procedure adapted from Equation 5 includes the effect of these deviations in the computation of F_{ng} (Bohac 1986).

For the surrounding "unguarded" zones (s), the tracer injection rate can be used to estimate the sum of the infiltration airflow rate plus the rate of air flowing in from zones where there is no injection (assuming that the concentration is negligible in those zones):

$$S_s/c_t = F_{ns} + \sum_p F_{ps} \tag{7}$$

where the p zones are those in which there is no injection.

Our measurements were conducted using the constant concentration tracer gas (CCTG) system (Bohac 1986). The system uses sulphur hexafloride (SF_6) as a tracer gas with a detectable range of 10 to 300 parts per billion (ppb) and can inject and sample in 10 zones. Recent modifications provide hourly adjustment for detector drift and monitoring of an on-site weather station. At present, we record the wind speed, direction, outdoor and indoor temperature each minute, and their average values each hour.

The test apartment for the guarded zone studies was an E unit on the third floor of building A (designated A3E - see Figure 1). It is a one-bedroom apartment with a volume of 4238 ft^3 (120 m^3) and was unoccupied during the tests. All of the surrounding apartments, except the adjoining efficiency unit (A3D), were occupied. The test apartment was considered as two separate zones - one consisting of the kitchen and living room (2507 ft^3 (71 m^3)) and the other of the bedroom and bathroom (1730 ft^3 (49 m^3)). A single TG injection line was placed in each zone with its output placed in the airstream of a fan to help mix the injected gas with room air. An additional mixing fan was placed in each zone and the sample was taken from a blend of two locations in the zone. A single sample line and an injection line were placed in each of the surrounding apartments. In general, the input of the sample line was placed near the center of the zone, and the output of the injection line was placed on a uninsulated steam riser to aid dispersement of the gas. A single mixing fan was used in the unoccupied efficiency unit, but none in the occupied zones.

The tracer gas measurements were conducted for about 25 days, using the guarded zone method about half that time. The purpose of the experiment was to estimate infiltration flows in winter with various window openings and to study the ability of the CCTG system to keep the concentration at a target level. The brief duration of the experiment did not allow detailed examination of the dependence of air infiltration on weather conditions or window openings in the rest of the building.

Figure 5 displays the measured airflow of A3D and the two zones of the test apartment and the environmental conditions over a two-day period when the windows of the two apartments were closed. The CCTG method measures airflows rates directly, but for easier interpretation, the flow rates are divided by the volume of the zones and expressed as air change per hour (ACH). The measured flow for the test apartment is the infiltration flow, while for apartment A3D the measurement includes airflows from its other neighbors as well. Over the two days of tests, the airflows in these zones varied between 0 ACH and 0.35 ACH. These results seem reasonable given the tightness of the apartments indicated by the blower door tests.

Figure 6 displays the measured airflows of the three other adjoining apartments over the same period of time. The data show periods of abrupt changes in the airflow rates that do not appear to be related to changes in the weather. The magnitude of these flows and the large number of observed window openings indicate that the changes are due to occupants opening or closing windows. Note that even when the indoor/outdoor temperature difference is greater than 27F (15°C), occupants are opening windows to an extent that causes airflows to exceed 5 ACH.

The CCTG system records the measured airflow, average concentration, and rms deviation in the concentration from the target for all of the zones on an hourly basis. The average concentration and rms deviation give an indication of how well the concentration was kept near the target. Table 1 displays the average and standard deviation of these three values over one day of data for each of the seven zones. The three unoccupied zones, with mixing fans and closed windows, had average concentrations within 0.1 ppb of the target and rms deviations of about 0.5 ppb or 1.25% of the target. These results are as good or better than those obtained in single-family houses and indicate proper operation of the CCTG system (Bohac et al 1985). An error analysis of the CCTG system operating in single-family houses indicates that this level of concentration fluctuation corresponds to an uncertainty of approximately 5% in the estimated airflow rates (Bohac 1986; Kvisgaard et al 1985). The concentration deviation for the other apartments is much greater - varying between 6.3 to 18.8 ppb from the target of 40 ppb. The increase in the deviation is most likely due to the absence of mixing fans and the high airflows (i.e., open windows). In order to examine which of these two factors is the greater contributor to the larger deviations, the average concentration deviation of apartment A3F, during the same day of testing, was computed for the hours when the airflow was less than 1.0 ACH (the average for the entire day was 1.6 ACH). The average deviation was found to be 2.4 ppb - much less than the 6.3 ppb deviation for the entire day. This indicates that for moderate airflows, the concentration can be kept close to the target without mixing fans. However, large airflows (> 1.5 ACH) appear to result in large concentration deviations and, consequently, larger uncertainty in the estimated airflow rates.

The guarded zone experiments were also conducted when all the windows in the test and A3D apartments were opened a linear distance of 2 inches (50 mm) and also opened wide. Table 2 shows the average flow rates over one day for these window openings. Although the weather conditions for these three sets of data do not allow direct comparisons, the results do indicate the expected order of magnitude of the flow rates for diferent window openings. The data show that opening the casement windows 2 inches (50 mm) increases the flow rate by more than an order of magnitude (0.1 ACH to 3 ACH) and opening the windows fully further increases the flow rate by another order of magnitude (39 ACH).

Surrounded Sampling. In this method the tracer concentration is kept constant at c_t in a single zone (g) and is sampled in the surrounding zones (s). By keeping the concentration at c_t, the equation for the TG concentration in zone g is:

$$c_t \cdot F_{gT} = \sum_s c_s \cdot F_{sg} + S_g \tag{8}$$

By applying the continuity equation (i.e., $F_{gT} = F_{ng} + \sum F_{sg}$), this equation is further simplified to:

$$S_g/c_t = F_{ng} + \sum_s (c_t - c_s) F_{sg}/C_t \tag{9}$$

If the concentration in the surrounding zones is small relative to c_t, then S_g/c_t is approximately equal to the total inflow of air into that zone (F_{Tg}). Combined with infiltration airflow rates measured by the guarded CC technique under similar weather conditions, we can estimate the magnitude of flow coming from neighboring zones.

In addition, this method gives information about the airflows into the surrounding zones. Assuming that the concentration is steady in an adjacent zone (s), $c_s/c_t = F_{gs}/F_{Ts}$. Although this does not quantify a specific airflow rate, it does indicate where incoming flows are originating.

The experimental setup was similar to that used for the guarded zone method. The TG concentration was kept constant in the two zones of the test apartment (A3E) and its level sampled in the surrounding zones. The concentration was held at a higher level (250 ppb) than for the earlier tests so that lower airflows from the test apartment could be measured. For a c_t of 250 ppb and a lower detection limit of 10 ppb, flows from A3E to an adjacent space that were greater than 4% of the total incoming flow could be measured.

Figure 7 displays the airflow data for the test apartment and the environmental conditions over an 18-hour period. This brief period of data does not allow an in-depth comparison with earlier infiltration data. However, a comparison of these data with that displayed in Figure 5 indicates that the infiltration flow is of the same order of magnitude as the total incoming flow. We can conclude that the infiltration flow in the test apartment is a significant portion of the total incoming flow when the windows are closed.

The average tracer gas concentrations over the test period are (note that the concentration of a sample that is below the detection limit of about 10 ppb is considered to be 0):

A3F : 1.2 ppb

A2E : 0.0 ppb

A4E : 0.0 ppb

A3D (eff) : 9.7 ppb

Hall : 22.5 ppb

The results indicate that very little of the flow into apartments A3F, A2E, and A4E came from the test apartment. This could have been a result of either high total incoming flows in those apartments or that only a small amount of the air leaving the test apartment traveled to those apartments. The tracer concentrations also indicate that apartment A3E is poorly connected to spaces above or below, relative to its neighbors on the same floor. Thus, the stack effect in the apartment is small, determined by the apartment height and not by its position in the building. The concentration in the hall and earlier estimates of the outside flow into the hall give an indication of the airflow path from the test apartment. The average concentration in the hall establishes that about 9% of the flow into the hall came from the test apartment (one of the two doors connecting hallway and stairwells was open during these measurements). Guarded CC measurements show that the airflow into the hall typically ranges from 180 to 1081 cfm (306 to 1,836 m^3/h), which gives a range of 16.5 to 97 cfm (28 to 165 m^3/h) for the flow from A3E to the hall. Since the average flow entering/leaving the test apartment over the 18 hours was 20.9 cfm (35.5 m^3/h), it appears that most of the air leaving A3E traveled into the hall. This is consistent with the wind data, which show that (neglecting the stack effect) A3E would have been pressurized relative to the stairwell/hall area.

Discontinued Injection. This technique incorporates both methodologies of the two CC methods discussed previously. An experiment starts with a test zone (g) and all surrounding zones (s) being kept at a constant concentration -- as is used for the guarded zone method. During this initial period, the tracer injection rate into zone g is used to estimate the infiltration flow rate in the guarded zones (Equation 6) and S_s is used to compute the infiltration rate plus the flow rate from the zones where there is no injection into the surrouding zones (Equation 7). At some point in time, the tracer injection into one (or more) of the surrounding zones is discontinued. During a transient period, the equation governing the TG concentration in the zone where injection was discontinued (zone d) is given by:

$$V_d \cdot dc_d/dt = -c_d \cdot F_{dT} + c_t \cdot \sum_i F_{id} \tag{10}$$

where the zones in which injection is being performed are signified by i. This solution to Equation 7 is:

$$c_d(t) = c_t \cdot \frac{F^*_{id}}{F_{dT}} + \left[c_t - c_t \cdot \frac{F^*_{id}}{F_{dT}} \right] \cdot \exp\left[\frac{-F_{dT}}{V_d} \cdot t \right] \tag{11}$$

where $F^*_{id} = \sum_i F_{id}$

The asymptotic steady-state value of c_d and a log-linear regression yields the first term on the right-hand side of Equation 11 and the time constant for the concentration decay. The latter leads to an estimate of F_{dT}. The sum of the flows from zones i to zone d is given by:

$$\sum F_{id} = \frac{c_d}{c_t} \cdot F_{dT} \tag{12}$$

In addition, the tracer injection in zone g is related to F_{ng} and F_{dg} as given by Equation 9 (except s is replaced by d). From this equation and knowing F_{ng} from the initial period, F_{dg} can be computed. Thus, the discontinued injection method provides estimates of the total flow into a surrounding zone, d, the flow from that zone to the guarded zone, and from the zones in which injection is provided to zone d.

Experiments were conducted using this method for each of the surrounding zones of the test apartment. From the limited tests conducted, we were able to conclude that the flows from the test apartment to the one below and to the laterally adjoining apartments were relatively small (< 2.9 cfm (5 m^3/h)). The flow from the test apartment and hallway area was estimated to be between 32 to 45 cfm (55 to 77 m^3/h).

Vertical Shaft Flows

In tall buildings, the vertical airflow in shafts is usually a dominant airflow path. The vertical shafts in the test building are the two stairwells, the elevator shaft, the incinerator shaft, and three shafts for mechanical ventilation. The flow through each of these shafts has been examined independently.

Airflows through the two mechanical ventilation shafts in building "A" (for the windowless bathrooms of the efficiency apartments) were measured using an anemometer. The flow through these exhaust vents was found to be approximately 500 cfm (850 m^3/h). The exhaust fan for ventilating the hallways was not operable and could not be tested.

A smoke gun was used to identify major vertical airstreams and estimate their relative magnitudes. For example, we found very little air movement at the elevator shaft with the elevator door open. Openings to the incinerator shaft are small and relatively well sealed to prevent odors from entering the living spaces. In contrast, the flow up the stairwells appeared to be relatively large -- possibly the dominant vertical airflow in the building.

The stairwell itself has a certain leakage area to the outside. From our measurements, we estimated (1) an equivalent leakage area associated with the stairwell alone, (2) the increase of airflow in the stairwell due to air leaking through the closed stairwell doors, and (3) the increase in airflow when all these doors are opened. With the leakage area determined and given a good model, we should be able to predict the air infiltration under different weather conditions.

Airflow Measurements. For the tracer gas airflow measurements, it is assumed that, on average, the air moves up the stairwell. The flow rate gradually increases from that at the bottom floor as air enters from outside the stairwell. This continues until the neutral plane level (NPL) is reached. Above the NPL there is only flow out of the stairwell, so the airflow rate decreases higher up the building. Tracer gas is injected at a constant rate at the bottom floor and is diluted as it travels up the stairwell. Assuming that the concentration in the stairwell is at steady state, the airflow rate at the NPL is given by:

$$Q = q_i \cdot C_i / C_{NPL} \tag{13}$$

where q_i = injection flow rate of tracer gas

C_i = concentration of injection gas

C_{NPL} = concentration of tracer gas at NPL

Since the flow is only out of the stairwell above the NPL, the concentration is not diluted further.

The CCTG system was used for injection and sampling of SF_6 in the stairwell. A constant flow of tracer gas was injected in the bottom of one of the stairwells using a fan to help mix the tracer with stairwell air. The concentration of tracer gas was measured on every floor of the building. An air sample is obtained with a manifold of six short sampling tubes of equal length evenly distributed over a vertical cross section in the stairwell. Our experiments were conducted from midnight to six a.m. so that the changes due to tenant behavior would be minimal. Table 3 summarizes the configuration of the stairwell for each of the measurements. Wind speed and direction as well as the average outside and stairwell temperatures were recorded.

In all tests we found that the concentration of tracer gas decreased up to about the third floor. Above, the concentration stayed the same or decreased slightly. This is consistent with our assumption of upward flow in the stairwell and agrees well with the smoke gun indication of the NPL at about the third floor. The time required to reach a quasi-steady-state condition (assuming ambient conditions to be constant) was about 40 minutes for the smallest measured airflow rate and 1.5 minutes for the largest.

Table 4 shows the results of six experiments. The difference in flow rate between tests 1 and 2 shows that there is little air moving from the halls through the closed doors to the stairwell. The stairwell behaves almost as a separate zone with an infiltration flow rate of 77.1 cfm (131 m^3/h) or about 1.5 ACH for the stairwell volume. In test 3, opening the stairwell windows on every floor by a linear distance of 2 inches (50 mm) (an area of 116 square inches per window (75000 mm^2/window)) increases the flow rate about sixfold.

In test 4 the doors to the hall were opened wide and the flow rate increased again about threefold. The increment approximately reflects airflow from the apartments to the hall and stairwell, not counting for any change in flow in other shafts, and the relatively small change in ambient conditions. The total airflow up the stairwell with hall doors closed corresponds to an air infiltration rate of 0.22 ACH for the entire "A" wing volume. When hall doors were opened, the flow increased to 0.67 ACH. This suggests that, for the typical operating condition of open doors, the stairwell airflow is a dominant flow path and that much of the flow up the stairs comes through the apartments.

In test 5 we checked the effect of replacing the six-tube air-sampling manifolds on the second and fourth floors by a single tube mounted near the wall. We found that, under these flow conditions, the air is well mixed throughout the height of the stairs. Replacing the manifold with a single sample line probably would have had little effect on the accuracy of the measurements. Finally, test 6 measures the effect of opening the outside door of the stairwell. This is often observed during the daytime, when maintenance personnel and occupants leave the doors propped open so they do not to have to walk around the building to enter it. Opening the door increased the flow rate by about 20%.

A second series of tests were conducted about a week later to test the repeatability of the first set of experiments (test 7) and to measure the flow rate in the second stairwell (test 8). The hourly average concentrations at each sample location, wind conditions, and the stairwell/outside temperature difference are displayed in Figure 8 and the computed NPL airflow rates are shown in Table 5. The distribution of TG concentration was similar to the previous experiments. The concentration decreased until the third floor (the measured location of the NPL); after this point, it did not decrease appreciably. Since the weather conditions for tests 2 and 7 were slightly different, the flow measurements cannot be directly compared. However, the flows are of the same order of magnitude, and the higher flows for test 7 are consistent with the comparatively lower outside temperatures at that time. The window positions for the building were recorded at the time of each of the tests. The data show that the area ratio of apartment window opening from tests 2 to 7 was 2.4. This indicates that the magnitude of window opening appears to have little effect on the flow in the stairwell when the stairwell/hall doors are closed.

The tests also showed that the flow in the second stairwell was consistently higher -- averaging 25% greater over the six hours of measurements. This was expected, since the second stairwell leads to the roof and is therefore one story (17%) higher than the other. It also has two additional windows and a door to the roof.

Computed Leakage Areas. More can be learned if we fit the data to an approximate airflow model of the stairwell. The airflow under stack effect is given by (ASHRAE 1985):

$$Q = 10360\ A \sqrt{h\ (T_i - T_o)/T_o} \qquad (14)$$

where Q = airflow (m^3/h)

A = free area of inlet or outlet (m^2)

h = height from lower opening to NPL (m)

T_i = average temperature of indoor air in height h (K)

T_o = temperature of outdoor air (K)

The constant includes a discharge coefficient of 0.65. Since we are dealing with a number of leakage sites, we use a formula appropriate for uniformly distributed leaks. If A' is the leakage area per unit height and H is the total height of the stairwell, then:

$$Q = 10360\ A' \int_0^{H/2} \sqrt{h\ (T_i - T_o)/T_o}\ dh \qquad (15)$$

$$= 10360\ A'(H/6)\sqrt{2H\ (T_i - T_o)/T_o} \qquad (16)$$

Equations 14 to 16 assume that there is no restriction to airflow in the vertical shaft. Assuming further that the leakage area is equal above and below the NPL, the experimentally measured airflow rate can be used to determine a leakage area. The calculated leakage areas for the eight tests are listed in Table 6. Note that these are the equivalent areas of openings with an assumed discharge coefficient of 0.65. They are different from the Equivalent Leakage Areas (ELA) defined by LBL, which assume a discharge coefficient of 1.0 at a pressure difference of 0.016 inches of water (4 Pa).

The leakage area estimated from measurements can be compared with values calculated from dimensions of physical openings. For example, the window openings in the stairwell in test 3 increased the actual physical leakage area by about 581 in^2 (0.375 m^2), while the calculated area increased by 732 in^2 (0.472 m^2). Part of the discrepancy is possibly due to the assumed value of 0.65 for the discharge coefficient (C_d). A C_d of 0.73 was derived from apartment pressurization data (see section on single-zone pressurization). With this value there is only an 11% difference between the actual window opening area and the computed leakage area. Another example was the opening of the stairwell outer door in test 6, where the actual leakage area increased by about 326 in^2 (0.21 m^2), and the calculated area increased by 713 in^2 (0.46 m^2). Here, the assumption of uniformly distributed leakage area in the stairwell was certainly at fault. The door opening (the equivalent of three window openings) was at the farthest point from the NPL and, thus, at the greatest indoor/outdoor pressure difference. To provide the same flow as a single opening far from the NPL, uniformly distributed leaks must have a much larger total opening. This is consistent with the larger computed leakage area and shows the importance of the assumption of distribution of the openings.

In addition to estimating stairwell leaks, the constant-injection method is applicable to determining the general behavior of airflows in the building. When the doors from the stairwell to the halls were opened in test 4, the flow rate increased by about 1180 cfm (2000 m^3/h), corresponding to a leakage area increase of 1,420 in^2 (0.914 m^2). The observed window leakage area of all the apartments was estimated (from a window survey conducted just before sunrise that same night) to be 1.21 ft^2 (13 m^2). Under these conditions, the airflow into the apartments from the outside occurred relatively easily (i.e., a relatively small pressure drop existed across the exterior envelope). The greatest resistance to airflows through the apartment to the stairwell probably were the doors between the apartments and hall. Dividing the calculated increase in leakage area 1420 in^2 (0.914 m^2) by the crack length of all the doors involved, we obtain an average crack width of about 4 mm -- a number that is quite realistic.

MULTIPLE TRACER GASES (PFT)

The guarded concentration method allow the measurement of the airflow from the outside to the apartment, and some information on airflows among apartments can be determined from variations in procedure such as surrounded sampling and discontinued injection. More direct, concurrent measurement of air infiltration and inter-apartment airflows requires the use of multiple tracer gases. The most convenient of the multitracer systems is based on the perfluorocarbon tracer method (Dietz and Cote 1982). Passive tracer sources and passive samplers make the field units inexpensive and allow for long-term-average measurements. In principle, a different tracer gas is required for each zone of the building, and researchers have successfully used the method to measure airflows among the attic, living space, and crawl space of a house and the outside (Dietz et al. 1986). Large apartment buildings have many more zones than the three or four different PFTs available. However, not all zones communicate with one another. In one protocol, each floor was assumed to be a single well-mixed zone, and communication between nonadjacent floors was neglected. Tracers 1, 2, 3, 1, 2, etc. would be deployed on successive floors. In another approach, a core apartment was tagged with one PFT tracer, all its neighbors on the same floor with a second tracer, and the apartments below and above with two other tracers. The second approach was more practical and some airflow measurements were made in three five-story apartment buildings in New York City (Dietz et al. 1985).

SUMMARY

The seasonal-average air infiltration rate of an entire multifamily building may be estimated from a calculation of transmission losses and analysis of billing data. However, the estimate depends on regression parameters that are not well determined. For the test building, an air infiltration rate of 1.6 ACH was estimated but with an uncertainty almost as large as the estimate.

Direct measurements of air infiltration rates are not possible in many large apartment buildings because of the multizone nature of their airflows. Such a building needs to be divided into zones and measurements applied to individual zones or groups of zones.

Individual apartments were pressurized using a blower door and were found to be relatively airtight. The building is typically operated with a significant number of open windows. Pressurization tests of an apartment showed that the leakiness would be dominated by the open windows, with two major consequences: (1) with open windows, each apartment will exchange air primarily with the outside and inter-apartment airflows are negligible; (2) the leakage area of the building can be determined from visual inspection of window positions.

Various tracer gas techniques were used to characterize airflow. The guarded-zone constant-concentration technique worked well and yielded the outside airflow rate into the guarded zones. The air infiltration rate was quite small with windows closed--about 0.1 to 0.2 ACH--but increased rapidly as the windows were opened--2.5 to 3.8 ACH with a 2 in (0.05 m) opening and 14 to 66 ACH with wide-open windows. These results confirm our projections based on pressurization measurements of the importance of the open windows. Surrounded-sampling tracer measurements showed that inter-apartment airflow is small compared with airflow between the apartment and the outside, and that the airflow between apartment and hall was significant. The discontinued-injection tracer method allowed some of these inter-apartment flows to be better quantified. Downward and lateral flow between apartments was negligible (< 2.9 cfm (5 m^3/h). Upward flow from the test apartment and hallway to the one above was slightly larger (32 to 45 cfm (55 to 77 m^3/h)).

A constant injection tracer gas technique was used to measure airflows in the stairwell under a variety of conditions. With stairwell-hall doors closed, the stairwell upward airflow is equivalent to 1.5 ACH of stairwell volume. With hall doors open and stairwell windows slightly open (typical of the test building) the flow was 18 times as high. The stairwell airflow is a dominant airflow path, equivalent to 0.67 ACH for the volume of the entire A wing of the building. Flow measurements obtained by the constant-injection technique were used to compute leakage areas using a simple flow model.

CONCLUSIONS

For building diagnostics, the seasonal-average air infiltration and associated heat losses can be inferred from billing data but with large uncertainty. Relative leakage areas of zones can be determined using pressurization techniques and are independent of weather. Tracer gas techniques allow the determination of actual airflow rates for prevailing weather conditions. Short-term tracer-gas measurements, such as those reported here, provide detailed, real-time measurements of some airflow rates, but do not permit the determination of seasonal-average infiltration rates because of changing leakage characteristics of the building, e.g., door and window openings. Passive devices for injecting and sampling tracer gas, such as the PFT system, left in the building for weeks or months, may be applicable to measuring long-term-average infiltration rates. Measuring techniques described in this paper help to identify major airflow paths and spaces that can be considered as single zones and to determine the relative leakiness among these zones and the outside. Based on this information, the building owner or operator can be advised on how to reduce infiltration heat losses and/or improve indoor air quality.

Pressurization techniques are inexpensive and somewhat less intrusive than constant-injection and constant-concentration tracer gas methods, which require the introduction of injection and sampling tubes to a number of apartments. These tracer-gas techniques are more likely to be used as research tools. The passive nature of the PFT technique makes it less intrusive, and inexpensive, and it may find wide applications.

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TABLE 1

Guarded-Zone Constant Concentration Tracer Gas Data:
Average of Hourly Values for One Day (Standard Deviations in Parenthesis)

	A3E K&L	A3E Bed	A3D	A3F	A2E	A4E	Hall
Air-flow h^{-1}	0.09	0.13	0.16	1.6	4.2	2.3	17.2
	(0.06)	(0.03)	(0.07)	(1.0)	(2.8)	(1.7)	(7.2)
Avg. Conc. ppb	40.1	40.0	40.1	38.8	38.0	40.2	38.8
	(0.3)	(0.1)	(0.5)	(3.4)	(9.9)	(7.4)	(6.8)
RMS Dev Conc ppb	0.5	0.3	0.6	6.3	18.8	11.1	12.0
	(0.2)	(0.1)	(0.3)	(5.0)	(7.8)	(14.0)	(6.7)

Day : 110
Tin : 82.4 ±1.3 (F)
Wind Speed : 11.2 ±3.8 (mph)
c_t : 40 ppb

A3E and A3D windows closed
Tout : 52.5 ±5.4 (F)
Direction : 5 ±2 (degrees clockwise from noon)

TABLE 2

Apartment Airflow Rates under Various Window-Opening Conditions: (One Day Averages)

Window Position	Airflow (1/h)			Wind Spd (mph)	Dir (deg)	Tin (F)	Tout (F)
	A3E K&L	A3E Bed	A3D				
Closed	0.09	0.13	0.16	11.2	5	82.4	52.5
	(0.06)	(0.03)	(0.07)	(3.8)	(2)	(1.3)	(5.4)
All Open 5 cm	3.8	3.2	2.5	4.7	338	76.5	56.1
	(2.0)	(1.6)	(0.4)	(2.5)	(83)	(1.4)	(2.2)
All Wide Open	32	66	14	10.5	165	67.5	62.4
	(26)	(47)	(2)	(5.1)	(69)	(1.1)	(3.6)

TABLE 3

Stairwell Test Configurations for Constant Concentration Tests

Test	Date	Configuration
1	May 1	all doors between stairwell and hall closed, windows and door to outside closed.
2	May 1	as test 1, but all doors between stairwell and hall sealed with masking tape.
3	May 1	as test 2; all windows in one stairwell opened 2 in.
4	May 1	same as test 3, but all doors between stairwell and hall wide open.
5	May 1	same as test 4; checking sampling mechanism (see text).
6	May 1	same as test 4; door between stairwell and outside opened 3 in.
7	May 10	same as test 1, different night.
8	May 10	same as test 1, other stairwell.

TABLE 4

Upward Airflow Rates in Stairwell at Neutral Pressure Level and Weather, Tests 1 - 6.

Test	Airflow Rate (cfm)	Average Air Temp. in Stairwell (F)	Outside Temp. (F)	Wind Speed (mph)	Wind Direction (degree)
1	88.4	79.3	57.0	7.6	267
2	77.2	79.0	55.4	6.5	268
3	567	71.2	53.8	6.0	274
4	1743	76.1	52.9	4.9	274
5	1720	76.1	52.2	3.6	268
6	2091	71.1	52.3	4.5	282

TABLE 5

Airflow Rates in Stairwell at Neutral Pressure Level and Weather, Tests 7 - 8.

Time a.m. (hour)	Airflow Rate test 7 (cfm)	Airflow Rate test 8 (cfm)	Average Air Temp. in Stairwell (F)	Outside Temp. (F)	Wind Speed (mph)	Wind Direction (degree)
0	104	142	80.1	51.6	1.6	218
1	104	133	79.5	47.7	2.2	267
2	115	142	78.8	46.4	1.1	308
3	121	148	77.5	45.0	3.1	39
4	124	151	76.6	44.8	3.4	357
5	127	153	75.2	45.3	4.7	353

TABLE 6

Calculated Stairwell Leakage Areas

test	leakage area (in^2)	test 7 time (hour)	leakage area (in^2)	test 8 time (hour)	leakage area (in^2)
1	115	0	135	0	170
2	99	1	124	1	147
3	831	2	134	2	154
4	2247	3	138	3	156
5	2247	4	141	4	159
6	2960	5	145	5	162

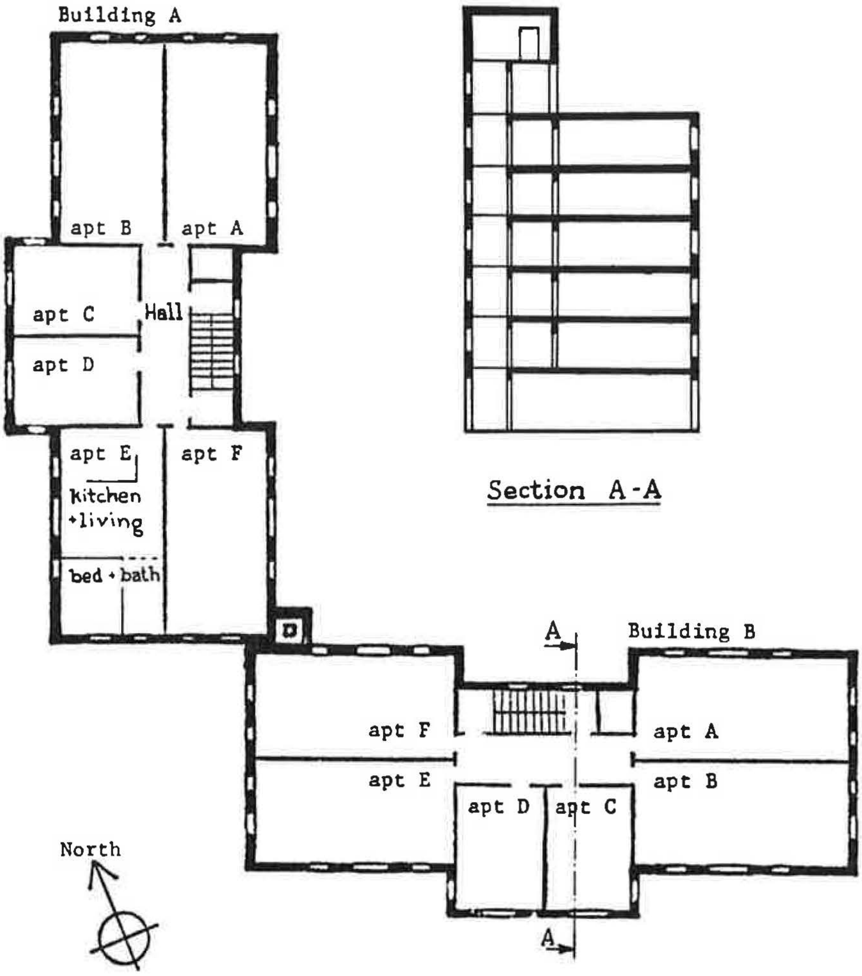


Figure 1. Lumley Homes floor plan and elevation

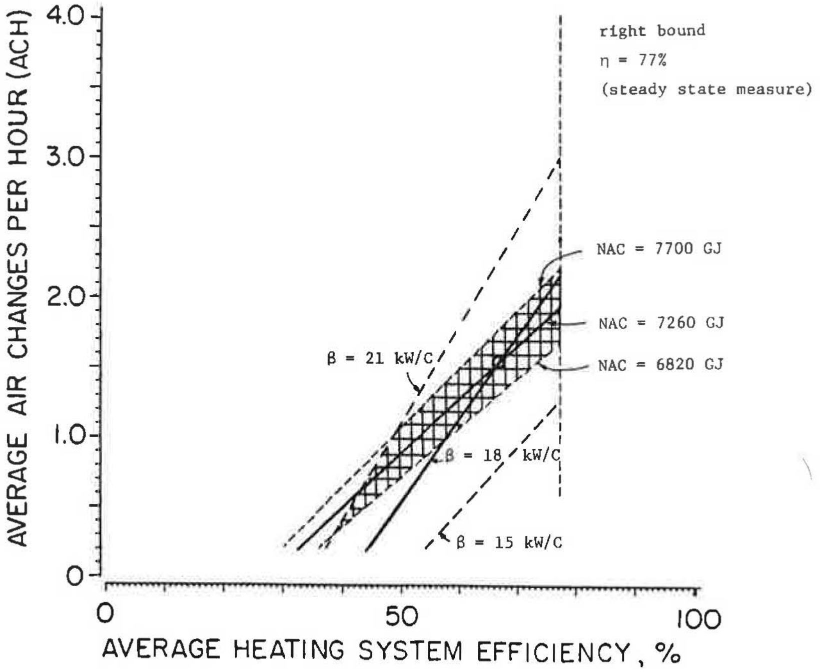


Figure 2. Combination of possible infiltration rate and heating system efficiency corresponding to PRISM estimates of NAC and β. The shaded area corresponds to solutions within one standard error of NAC and β. (Redrawn from DeCicco et al. 1986; used with permission from Energy and Buildings, Lawrence Berkeley Laboratory)

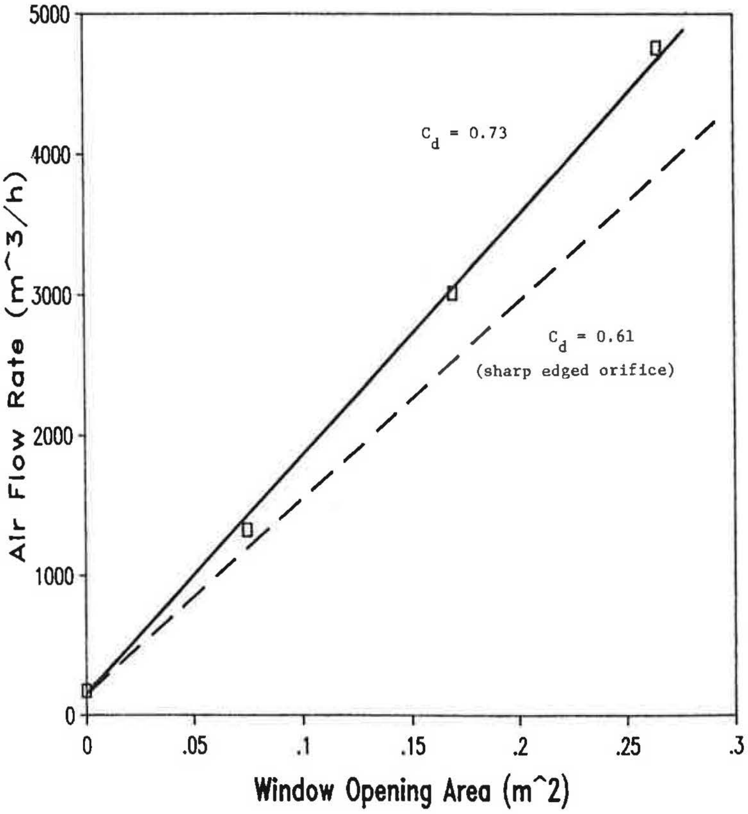


Figure 3. Blower door airflow rate vs. window opening area for a casement window

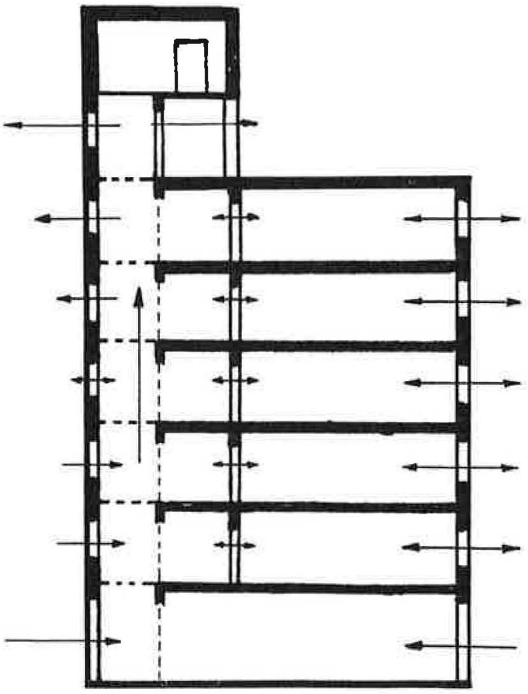


Figure 4. Illustration of typical airflow paths in Lumley Homes under predominantly stack conditions. Apartments are almost isolated zones

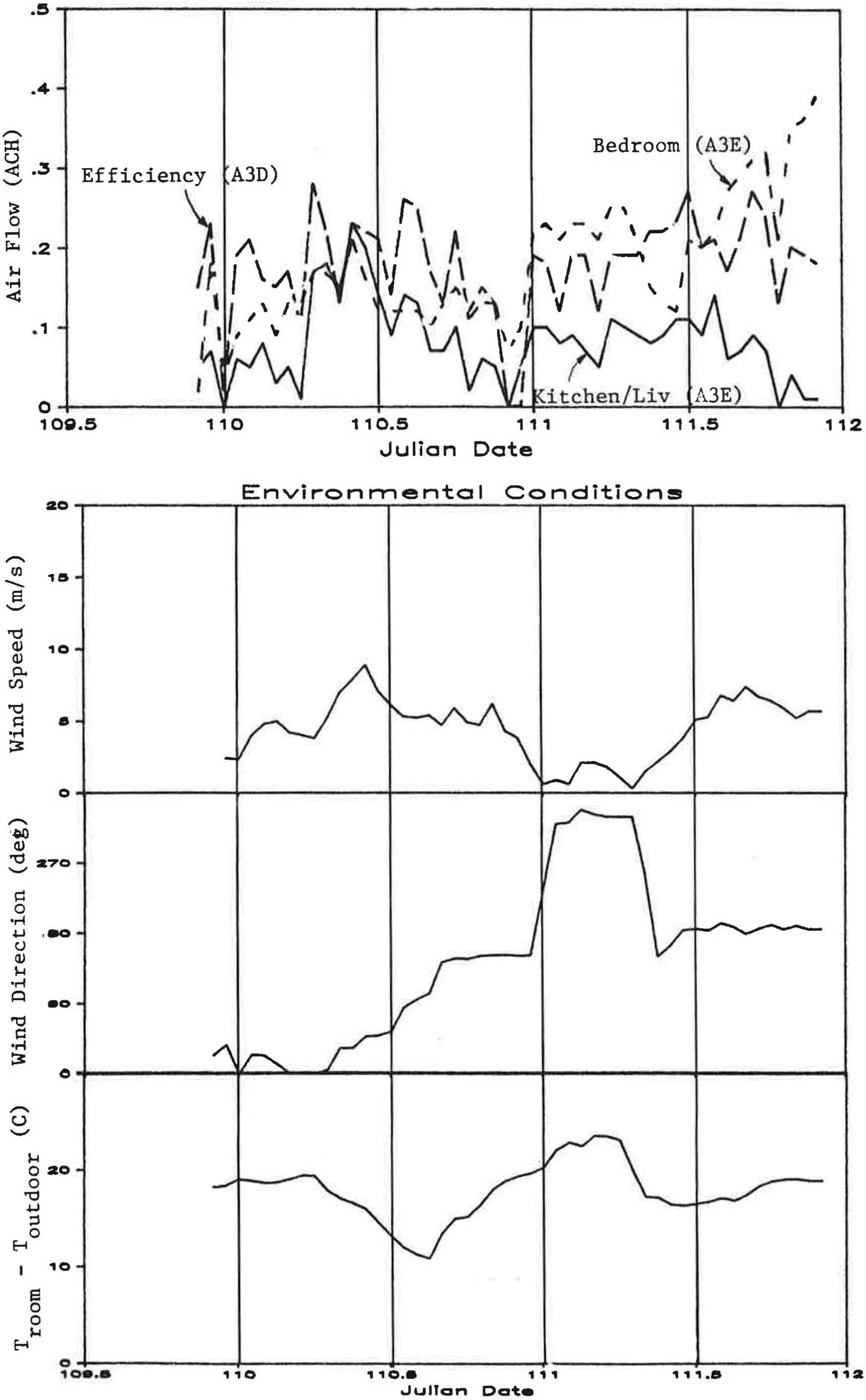


Figure 5. Airflow into an unoccupied efficiency and infiltration into the two zones of the test apartment when windows are closed. Below: environmental conditions

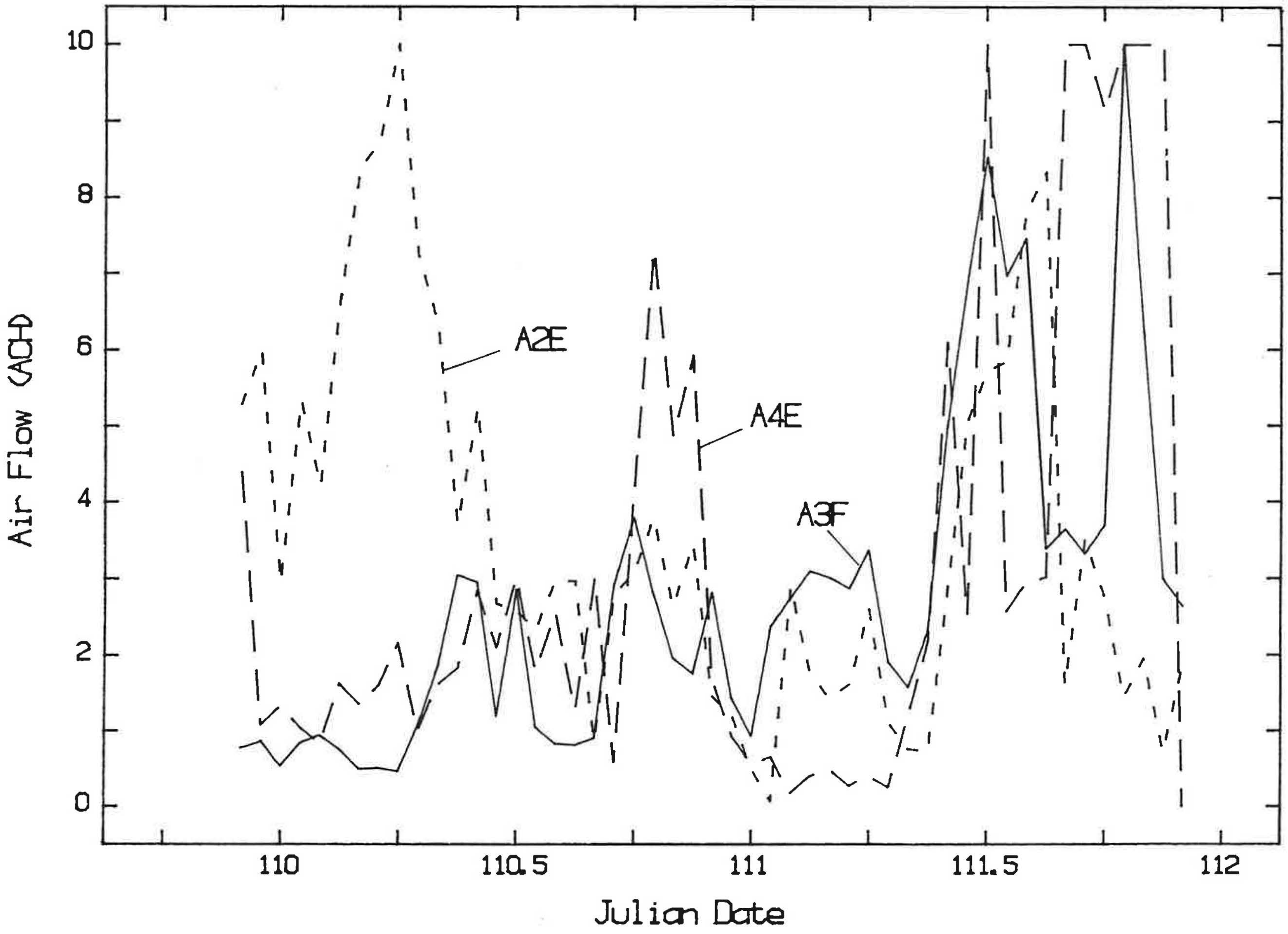


Figure 6. Airflow into adjoining, occupied apartments with tenant control of opening and closing windows. Environmental conditions as in Figure 5

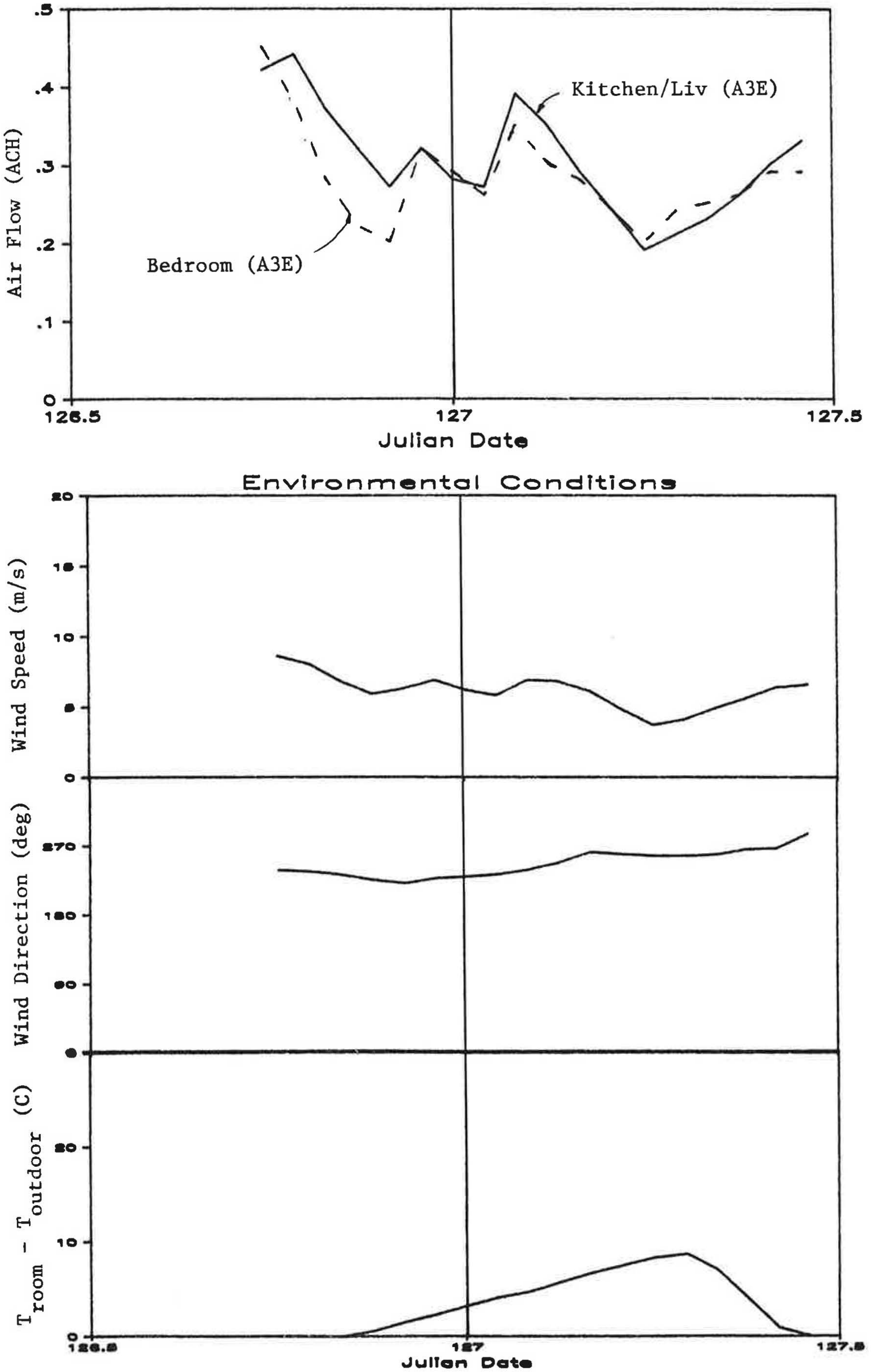
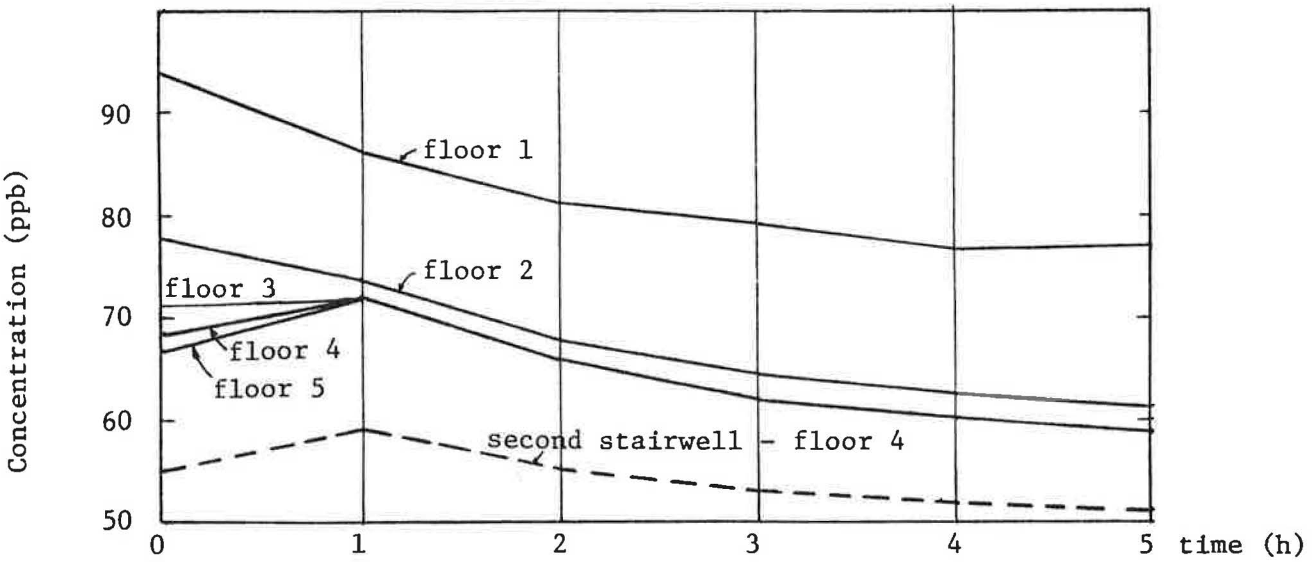


Figure 7. Airflow into the test apartment and environmental conditions during "surrounded sampling"



Environmental Conditions

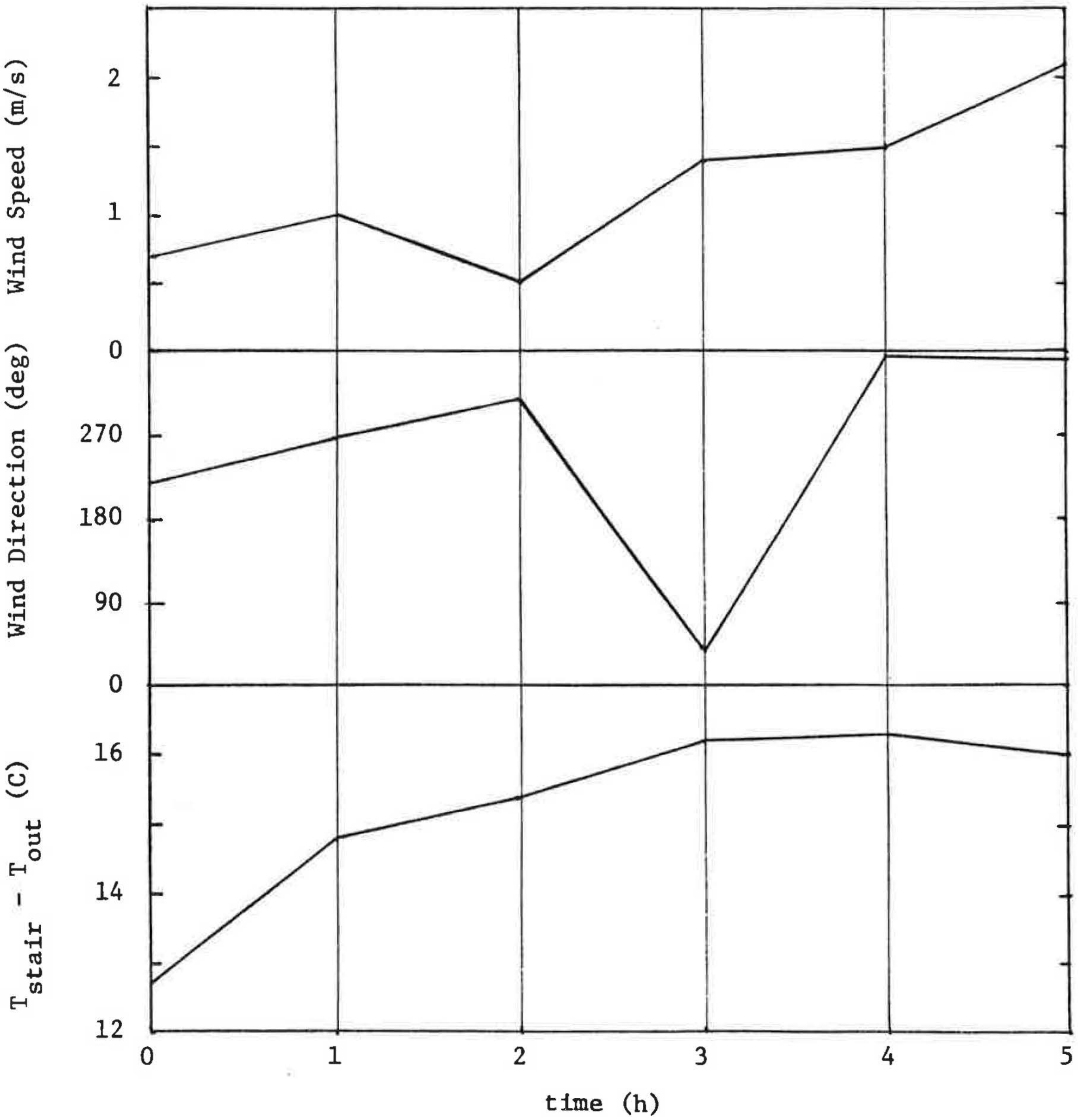


Figure 8. Vertical distribution of tracer gas concentration in the stairwells during predominantly stack conditions

Discussion

J.L. DOBB, John L. Dobb and Assoc., Toronto, Ontario, CANADA: What steps were taken to eliminate or reduce the heating system outdoor reset control in overheating the space and which causes occupants to use window openings to control space conditions with consequent dramatic effect on airflow through the building? Estimates of infiltration in such conditions are of doubtful value.

D.L. BOHAC: In 1984, the steam pressure and outdoor reset controls were reduced with a resultant weather-normalized annual energy savings of 30% to 40%. The effects of the reductions also included a measured 2 F drop in indoor temperature and an estimated 40% reduction in average infiltration based on uncertainties attached to the infiltration estimates for buildings such as this one. Nevertheless, we find the gross estimates are valuable for understanding the factors that influence energy use and comfort in multifamily buildings having outdoor reset control and for providing an empirical basis for a qualitative analysis of the effects of retrofits.

Our tracer gas studies enabled us to further document the airflows in this building under a wide range of conditions. Our studies in occupied apartments revealed the high infiltration rates that ocur in this overheated building. In addition, the data from the test apartment and stairwell (where the window openings were under our control) determined the level of airflow rates that occur with varying degrees of window and hallway door openings. This information is useful in understanding the impact of reducing the number of open windows and doors on energy use and indoor air quality.