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THE USE OF MODIFIED CONSTANT CONCENTRATION TECHNIQUES TO MEASURE INFILTRATION AND INTERZONE AIR FLOW RATES.

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SYNOPSIS

The constant concentration tracer gas (CCTG) technique is typically used to measure air infiltration rates in mulitzone buildings. The measurements are performed by injecting metered amounts of a tracer gas into each zone so as to keep all the zones at a target concentration. One drawback to this method is that no information is gained about the level of interzone flow rates in the building.

Modified constant concentration techiques are described which allow selected infiltration and interzone air flow rates to be estimated. These techniques differ from the typical operation in that there are certain zones where no tracer gas is injected. One approach, described as discontinued injection, is useful for measuring interzone flow rates between two sections of a building when the air flow rates are relatively constant. The tracer gas injection in one of the sections is stopped at a certain point in time, but the concentration measurements are continued. The increase of tracer gas injection in the other section and the drop in concentration in the "starved" section are used to estimate the air flow rates between the sections.

Field measurements using the modified CCTG methods are presented for experiments in single family and multifamily buildings. The results are compared to those obtained by passive, multiple tracer gas tests.

1.0 INTRODUCTION

The constant concentration tracer gas (CCTG) technique has proven to be useful for real time measurements of infiltration rates in multizone buildings. One of the advantages of the method is that it requires only a single tracer gas (TG) to measure infiltration in a large number of zones of a building. It accomplishes this by injecting the amount of tracer gas into each zone that is required to keep the concentration of the tracer gas constant and at the same level in all of the zones. This allows the infiltration flows into each zone to be measured reguardless of the flows between the zones. Unfortunately, with the typical operation of the CCTG system no information is obtained of the interzone air flow rates.

In many cases the infiltration rates are the only, or most important, flow rate of interest and the CCTG method provides the necessary measurements. There are cases when interzone measurements are also necessary. This is true for studies of nonuniform pollution sources such as the entry of radon into the lower level of buildings and measurement of adequate ventilation rates. For example, a companion paper in this conference[1] presents CCTG measurements in a single family house where infiltration levels in upstair bedrooms are well below present ASHRAE standards[2]. It is hypothesized that the abundance of infiltration air in the downstairs could often provide the necessary "fresh air" if the interaction between the zones is adequate. This paper presents a modified form of the constant concentration technique, called <u>discontinued injection</u>, that measures not only infiltration rates but also air flow rates between the zone where injection is discontinued and the rest of the building.

Our CCTG systems and those developed by other research groups have the ability to operate in ten separate zones. While this is sufficient for most single family houses, it is often inadequate for large, complex structures such as office buildings and multifamily buildings. Two other modifications of the CCTG method have been developed in order to measure air flow rates in these types of buildings. The first, called guarded-zone, "isolates" a zone or set of zones from the rest of the building so that infiltration measurements can be made in these zones. The second, called surrounded sampling, keeps a constant concentration in a zone or set of zones in order to measure infiltration and other incoming air flows into those zones. In addition, the relative amount of air moving from those zones to the surronding zones is also measured.

This paper presents the type of system operation, equations, and analysis needed to perform the three modified CCTG measurements. A set of results are presented from field tests of the guarded-zone and surrounded sampling methods applied to a six-story multifamily building. The results from tests using discontinued injection in an unoccupied single family house during summer-fall and winter conditions are also presented. The uncertainties are discussed and these short term (two hour) results are compared to those from simultaneous long term average measurements using a passive multiple tracer gas system (PFT).

2.0 GUARDED-ZONE

The guarded-zone method is used to measure infiltration flows in a selected area of a building where it is not possible to implement the system in all sections of the building. In this method, all 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[3]:

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

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 outdoors ($c_n = 0$)

If the concentration in a zone is kept constant at a level c_t then equation 1 reduces to:

$$c_t \cdot F_{jT} = \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (2)$$

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

For the guarded zone $c_k = c_t$ and equation 2 reduces to:

$$F_{ng} = S_g / c_t \qquad (3)$$

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 1 includes the effect of these deviations in the computation of F_{ng}[4].

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 in those zones, c_p, is negligible):

$$S_s / c_t = F_{ns} + \sum_p (1 - c_p / c_t) F_{ps} \qquad (4)$$

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

Our measurements were conducted using the constant concentration tracer gas (CCTG) system[5]. 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, remote access via telecommunications, 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 site for these 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. 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.

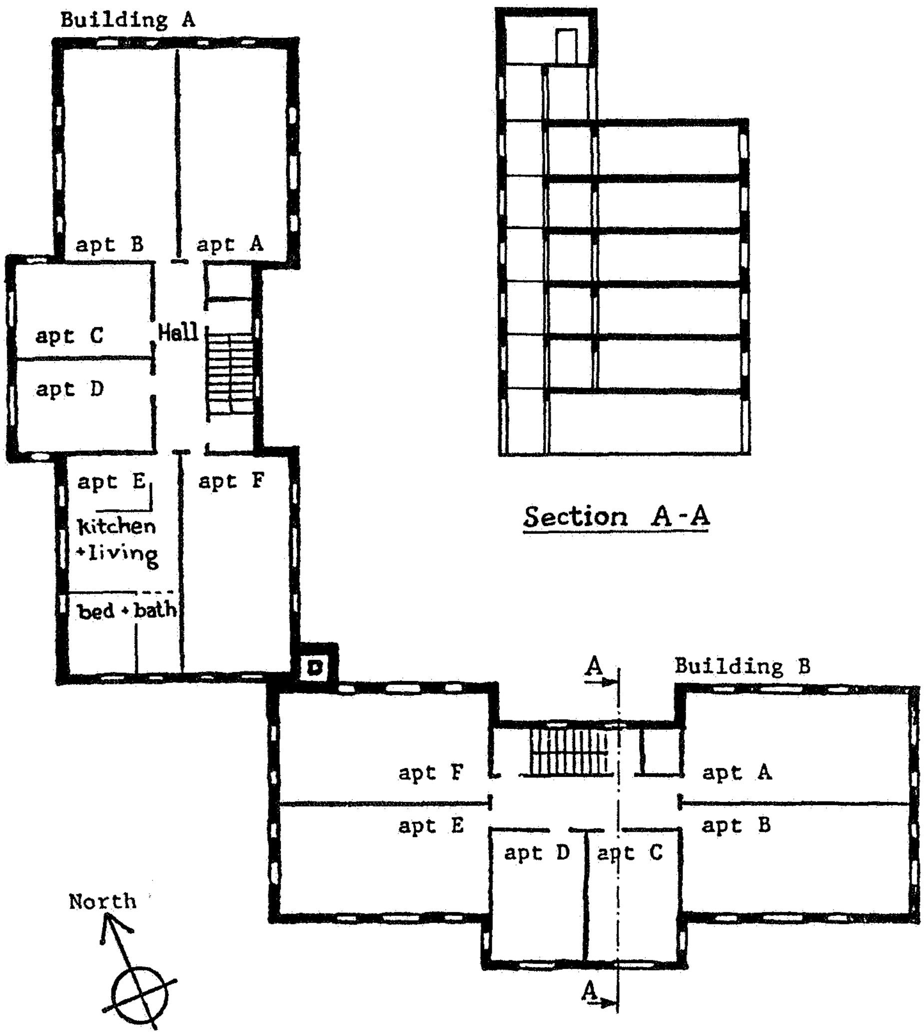

Figure 1. Floor plan and elevation of multifamily test building.

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 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 (71 m^3) and the other of the bedroom and bathroom (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 in the 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 2 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 airflow rates directly. However, 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 (2.5 to 6.0 air changes per hour at 50 Pa).

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[4]. 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[4,5]. 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). The high degree of window opening in the occupied apartments of this building is discussed in reference 6.

The guarded zone experiments were also conducted when all the windows in the test and A3D apartments were opened a linear distance of 50mm and then 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 50mm 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).

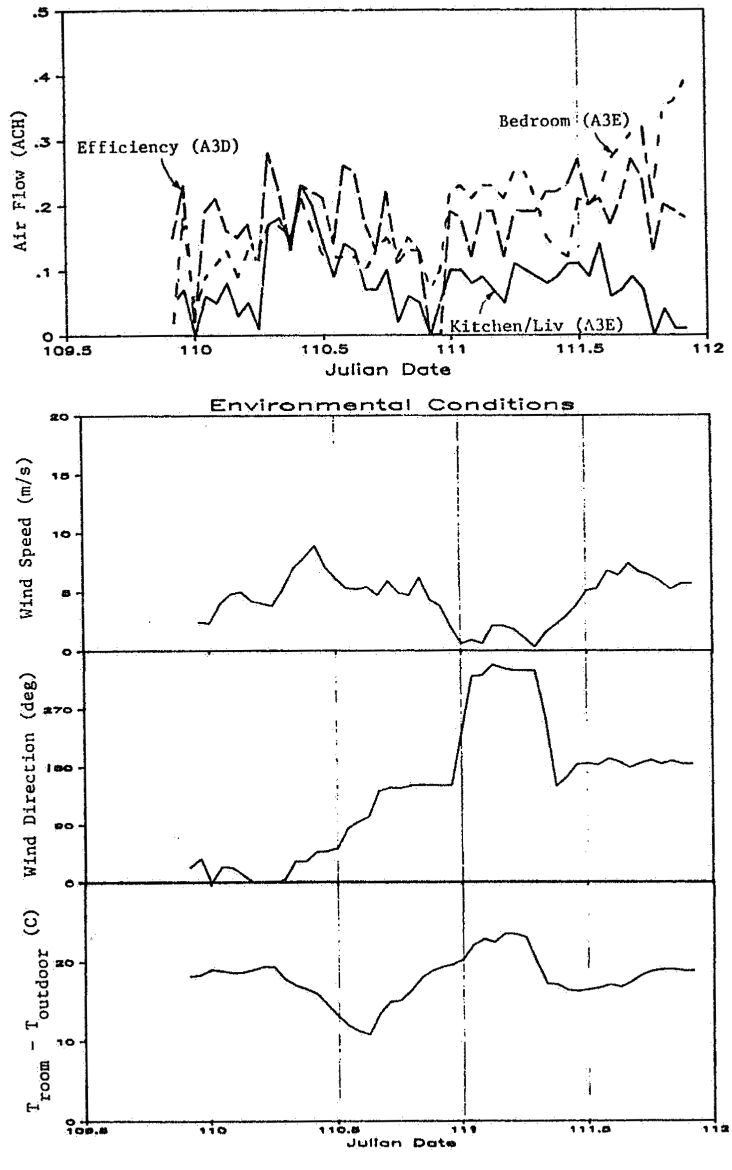

Figure 2. Airflow into an unoccupied efficiency apartment and infiltration into the two zones of the test apartment when windows are closed. Below: environmental conditions.

TABLE 1

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

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

Day : 110
Tin : 28.0 ±0.7 [°C]
Wind Speed : 5.0 ±1.7 [m/s]
c_t : 40 ppb

A3E and A3D windows closed
Tout : 11.4 ±3.0 [°C]
Direction : 5 ±2 [degrees clockwise from noon]

TABLE 2

Apartment Airflow Rates under Various Window-Opening
Conditions: One Day Averages
(Standard Deviation in Parenthesis)

Window Position	Airflow [ACH] A3E K&L	A3E Bed	A3D	Wind Spd [m/s]	Dir [deg]	Tin [°C]	Tout [°C]
Closed	**0.09** (0.06)	**0.13** (0.03)	**0.16** (0.07)	**5.0** (1.7)	**5** (2)	**28.0** (0.7)	**11.4** (3.0)
All Open 50mm	**3.8** (2.0)	**3.2** (1.6)	**2.5** (0.4)	**2.1** (1.1)	**338** (83)	**24.7** (0.8)	**13.4** (1.2)
All Wide Open	**32** (26)	**66** (47)	**14** (2)	**4.7** (2.3)	**165** (69)	**19.7** (0.6)	**16.9** (2.0)

3.0 SURROUNDED SAMPLING

This method is used to measure incoming air flow rates in a selected set of zones and the relative magnitude of the flow from these zones to the surrounding zones. In this method the tracer concentration is kept constant at c_t in a single zone (x) and is sampled in the surrounding zones (s). By keeping the concentration at c_t, the equation for the TG concentration in zone x is:

$$c_t \cdot F_{xT} = \sum_s c_s \cdot F_{sx} + S_x \qquad (5)$$

By applying the continuity equation (i.e. $F_{xT} = F_{nx} + \sum_s F_{sx}$), this equation is further simplified to:

$$S_x/c_t = F_{nx} + \sum_s (c_t - c_s) F_{sx}/c_t \qquad (6)$$

If the concentration in the surrounding zones is small relative to c_t, then S_x/c_t is approximately equal to the total airflow entering that zone (F_{Tx}). Combined with infiltration airflow rates measured by the guarded CCTG 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), $c_s/c_t = F_{xs}/F_{Ts}$. Although this does not specify an absolute airflow rate, it does indicate where incoming flows are originating and their relative magnitudes.

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 3 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 2 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.

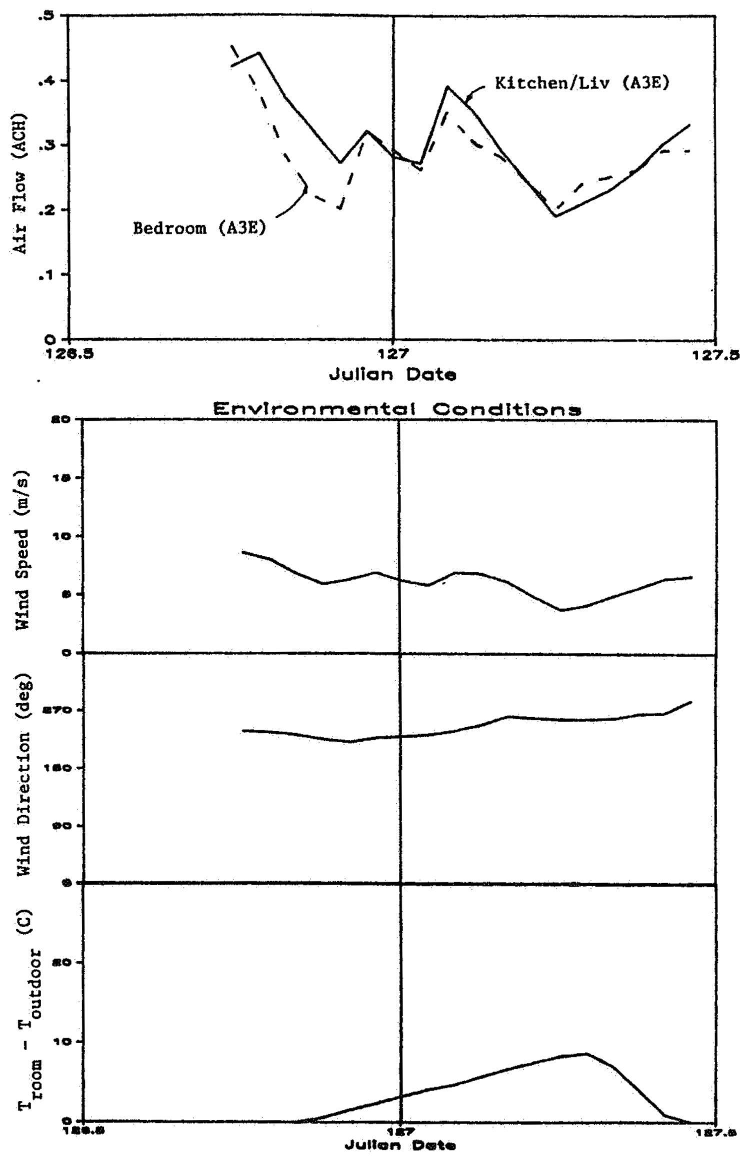

Figure 3. Airflow into the test apartment and environmental conditions during "surrounded sampling".

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

A3F	: 1.2 ppb	A3D (eff)	: 9.7 ppb
A2E	: 0.0 ppb	Hall	: 22.5 ppb
A4E	: 0.0 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. However, if it is assumed that the total air flow rate into these apartments is 3.0 ACH (or 36 m^3/h) the most the flow from the test apartment to these apartment could be is 1.4 m^3/h. This indicates that apartment A3E interacts little with its neighbors.

4.0 DISCONTINUED INJECTION

The discontinued injection technique is used to measure the absolute magnitude of the flows between a single zone and the rest of the zones in the building. The following analysis is performed for a building with the CCTG system operating in all the zones. An analysis of the method applied to a multifamily building is presented in reference 7. A experiment starts with all the zones being kept at a constant concentration - i.e. the typical operation of the constant concentration system. At some point in time, the tracer injection into one of the zones is discontinued. During the following transient period the equation governing the TG concentration in the zone where injection was discontinued (zone d) is given by:

$$V_d \cdot dc_d/dt = -c_d \cdot F_{dT} + c_t \cdot \sum_i F_{id} \qquad (7)$$

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

$$c_d(t) = c_t \cdot \frac{F^*_{id}}{F_{dT}} + \left[c_t - c_t \cdot \frac{F^*_{id}}{F_{dT}} \right] \cdot \exp\left[\frac{-F_{dT}}{V_d} \cdot t \right] \qquad (8)$$

where $F^*_{id} = \sum_i F_{id}$, which represents the air flow from the other zones in the building to zone d.

Using equation 8 as a model, a regression technique can be used to solve for F^*_{id} and the total flow leaving zone d (F_{dT}). By applying the continuity equation to zone d, the infiltration in zone d is found to be the difference of F_{dT} and F^*_{id}.

With the concentration constant at the target level in the injection zones, the equation for the TG concentration in each i zone is given by:

$$c_t \cdot F_{jT} = c_d \cdot F_{dj} + c_t \cdot F^*_{ij} + S_j \qquad (9)$$

where zone j is one of the injection zones
F^*_{ij} is the flow from the other i zones

By applying the continuity equation (i.e., $F_{jT} = F_{nj} + F_{dj} + F^*_{ij}$), this equation is further simplified:

$$S_j/c_t = F_{nj} + F_{dj}(1 - c_d/c_t) \qquad (10)$$

If it is possible to estimate the infiltration flow in the i zones then equation 10 can be used with the injection and concentration data to estimate the flows from zone d to the i zones:

$$F_{dj} = (S_j/c_t - F_{nj})/(1 - c_d/c_t) \qquad (11)$$

The sum of these flows can be used in the continuity equation of zone d to estimate the exfiltration rate of zone d:

$$F_{dn} = F_{dT} - \sum_j F_{dj} \qquad (12)$$

By summing together the continuity equations for all the i zones the following equation is obtained:

$$\sum_i F_{ni} + \sum_i F_{di} = \sum_i F_{id} + \sum_i F_{in} \qquad (13)$$

Given estimates of the infiltration rates in the i zones, equation 13 can be used to compute the total exfiltration rate ($\sum F_{in}$) from the i zones. Thus, the discontinued injection method provides estimates of the infiltration, exfiltration, and total incoming flows of the discontinued injection zone, the flow to and from that zone to the other zones of the building, and the total exfiltration flow of the other zones.

The test building for this portion of the study is an unoccupied, bi-level, single family house located northwest of Washington D.C.. The house is heated with a heat pump warm air system. There are supply vents in each upstair zone and in the downstair zone. The two return vents are located in the upstairs. Infiltration measurements in this structure have been described in previous AIVC publications, including a companion paper in this conference[1,8]. Figure 4 displays the floor plan of the house and includes the location of the mixing fans and the sample and injection lines. The CCTG system was installed to provide measurements in the downstairs and five separate upstairs zones. The system operated with a sample time of 60 seconds. This resulted in a six minute interval between concentration measurements in a single zone.

The tests were conducted over two separate time periods. The first period began August 21st, 1986 and ended September 9th. The second period began January 14th, 1987 and ended January 22nd. For both periods the system was programmed to stop injection in the downstairs zone every second day starting at 12 midnight and continuing for five hours. At the end of each test the system resumed its normal operation. During a five hour test the system kept the concentration constant in the five upstairs zones and the concentration was measured in the downstairs zone. In addition, a separate data acquisition system recorded the indoor and outdoor temperatures and the wind velocity and direction at each half hour. The results from four different discontinued injection tests from the first period (julian dates 239, 241, 247, and 251) and three from the second period (julian dates 16, 18, and 22) are presented in this section.

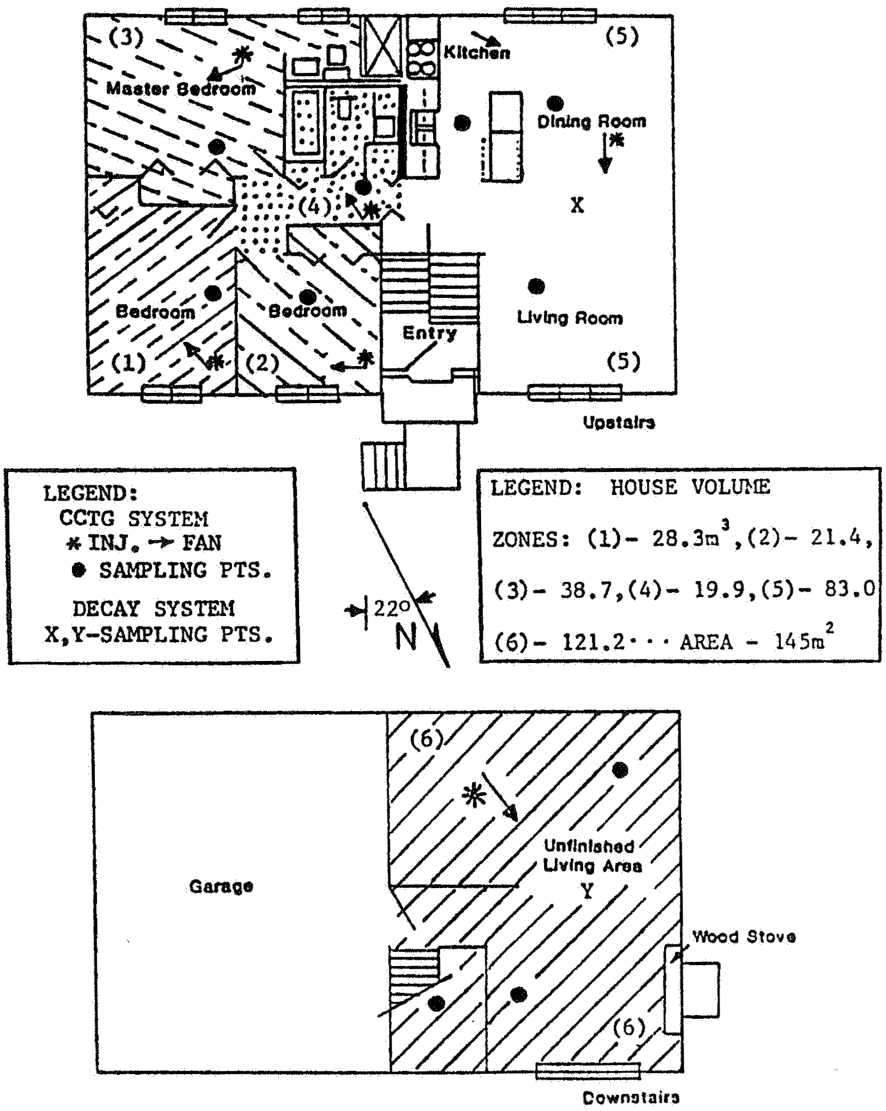

Figure 4. Floor plans of unoccupied test house. The zone volumes and the location of the injection and sampling points, as well as mixing fans are included.

Figures 5 and 6 display the measured concentration in the downstairs and the total normalized injection rate (the SF_6 injection rate divided by the zone volume) in the upstairs for the tests on julian days 18 and 241. For the initial part of the analysis the five upstair zones are grouped together and considered as a single zone. The downstairs concentration and upstairs injection rate respond as expected to the injection being discontinued. The concentration curves from both days show an exponential decrease and the injection rate simultaneously increases. During the test of day 18 the average upstairs concentration was only 3.0% below the target and had a rms deviation about the target of 3.8%. This low deviation from c_t indicates that, even with the downstairs concentration dropping rapidly, the system responds quickly enough to keep the upstairs concentration sufficiently near c_t. When the downstairs injection was started at the end of the test the system typically took one hour to return to stable operation. Thus, the complete test interrupted the normal operation of the CCTG system for six hours. However, as will be shown later, the test period could be reduced to two hours which will reduce the interruption time to three hours.

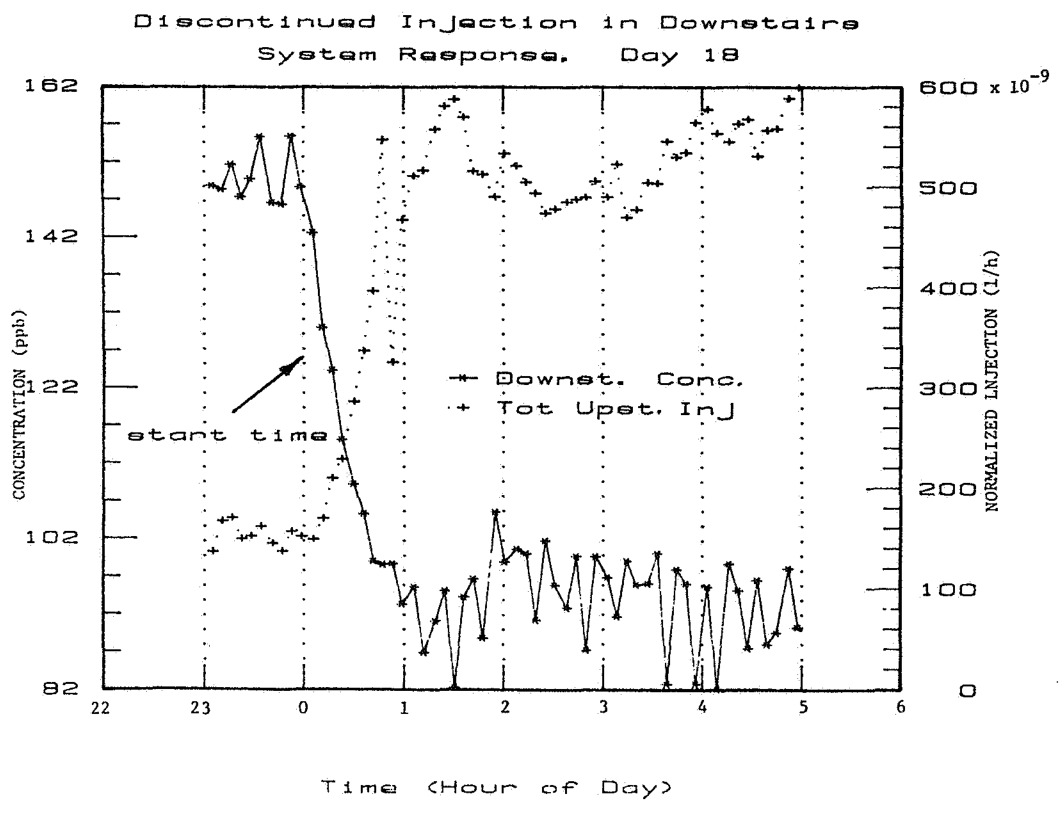

Figure 5. Response of downstairs concentration and upstairs injection rate to discontinued injection downstairs: Day 18.

A rough estimate of some of the flows can be obtained by a quick scan of the data. For example, from equation 8 it is evident that the time constant of the decrease in the downstairs concentration is equal to the total flow entering the downstairs divided by the downstairs volume and the steady-state concentration (c_{ss}) divided by c_t is equal to F^*_{id}/F_{dT}. Figure 5 shows that during the cold winter weather (indoor-outdoor ΔT of 17.6 °C) of day 18 the downstairs reached a c_{ss} of about 95 ppb in approximately one hour. Since c_{ss} is reached in about 3 time constants, the total incoming flow is about three ACH or 360 m³/h. Also, the ratio of c_{ss} to the target (0.6) indicates that about 60% of the air entering the downstairs came from the upstairs. Finally, the roughly three-fold increase in the upstairs injection rate after injection is discontinued suggests that the air flow from the downstairs to the upstairs is much greater than the upstairs infiltration. In contrast to the winter period, the mild weather data displayed in figure 6 shows a longer decay time and lower c_{ss}. This indicates a lower incoming flow in the downstairs and that less of the incoming flow came from the upstairs. Also, the relatively smaller increase in the upstairs injection rate suggests a smaller flow from the downstairs to the upstairs.

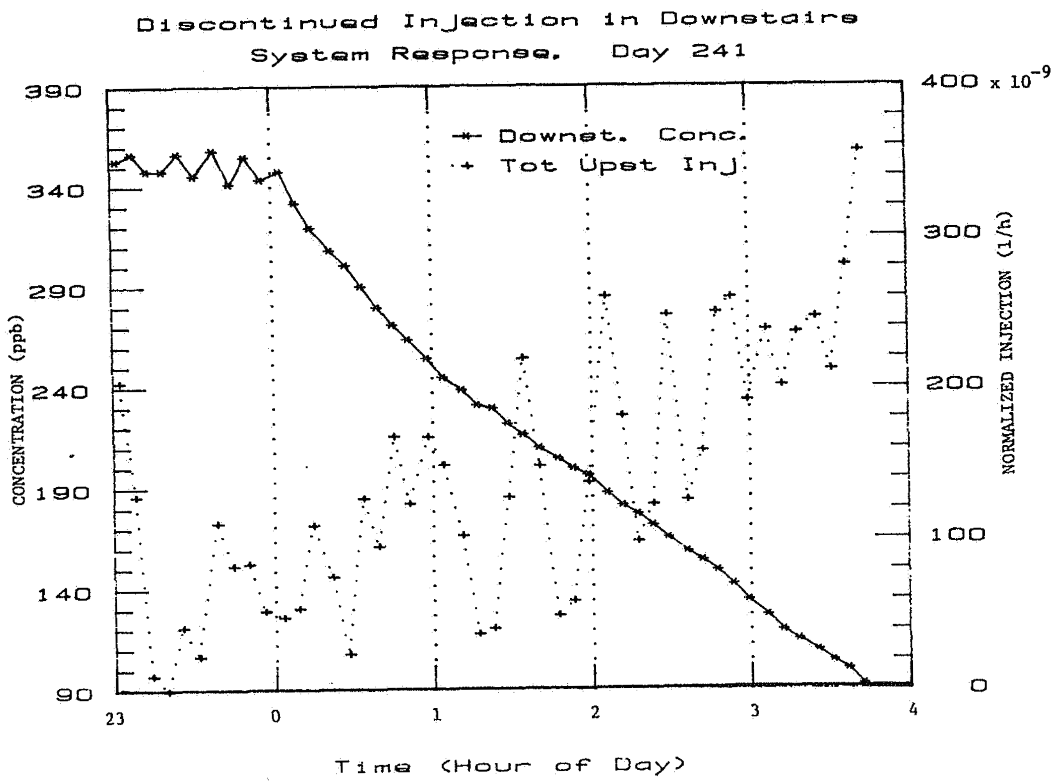

Figure 6. Response of downstairs concentration and upstairs injection rate to discontinued injection downstairs: Day 241.

A rigorous, quantitative analysis of the data can be performed in a number of different ways. The first step of the analysis is to estimate the airflows in equation 8. For this process a choice must be made of which parameter identification method will be used and the length of time over which the analysis is performed. Two different least square regression techniques were studied. The first is a nonlinear method developed by Marquardt[9] that is available in a commercial statistics program. For this method the form of the equation is identified as:

$$c_d = c_t \cdot P_1 + c_t \cdot (1 - P_1) \cdot \exp(-P_2 \cdot (t - t_o)) \quad (14)$$

where $P_1 = F^*_{id}/F_{dT}$
$P_2 = F_{dT}/V_d$
t_o = the start time of the test

The columns of c_d and t are input to the program to yield the estimates and standard errors of P_1 and P_2. Figures 7 and 8 display the first two hours of concentration data and fitted curve from the regresssion for days 18 and 241. The results show good agreement between the fitted model and the measured concentration with low standard errors for the estimate. As expected from the qualitative analysis performed earlier, the decay is more rapid for day 18 than for day 241 (a time constant of 2.76 compared to 0.58) and the relative value of c_{ss} is higher.

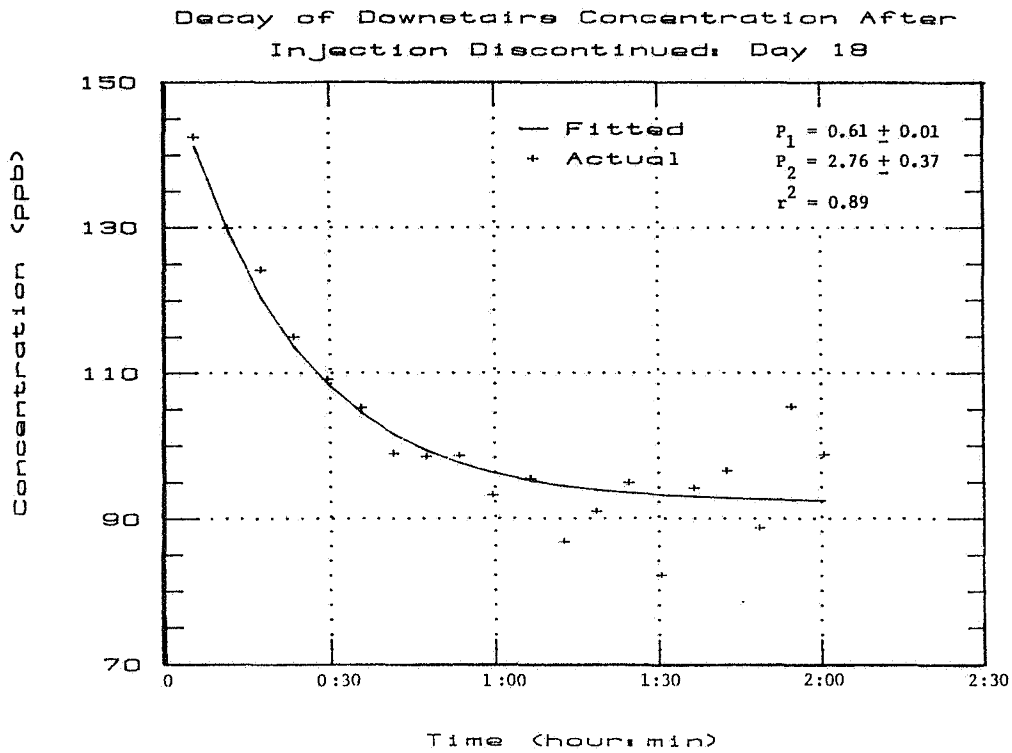

Figure 7. Results of nonlinear regression analysis of the downstairs concentration: Day 18 - two hours.

A second type of regression technique was applied to the concentration data. For this method, c_{ss} is estimated to be the average of the measurements after the concentration appears to be steady. With this value, a log-linear regression of the downstairs concentration minus c_{ss} versus time is performed to yield the time constant of the decay. For the winter data the results from this technique were similar to those from the nonlinear method. However, since the concentration for the summer/fall tests did not reach a steady value by the end of the five hour test, the technique could not be applied to those data sets. This points out one of the drawbacks of this method: a

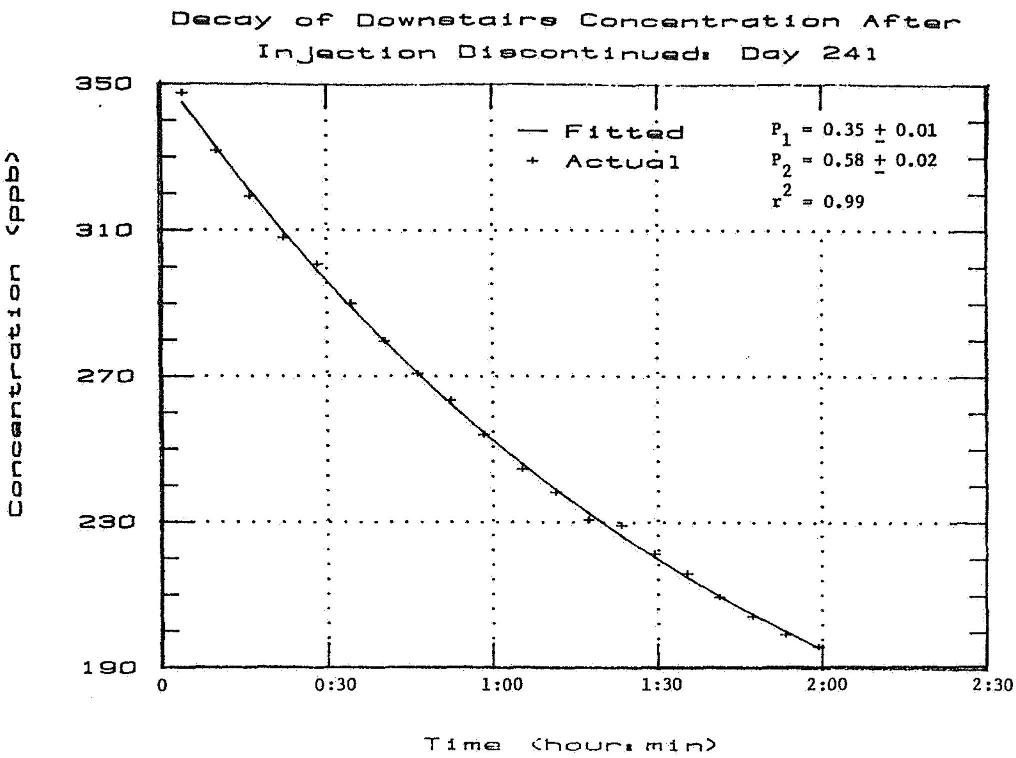

Figure 8. Results of nonlinear regression analysis of the downstairs concentration: Day 241 - two hours.

prohibitively long test period may be required to achieve a steady concentration in the discontinued injection zone. Futhermore, it is not possible to include concentrations in the regression analysis which are lower than c_{ss}. When the steady-state value is approached quickly and there is a moderate amount of scatter, such as occurs on day 18, measurements below c_{ss} are encountered early in the test. If the analysis period is halted when a measurement below c_{ss} is encountered, the analysis period may be too brief. Including only the values above the steady level would result in biased estimates. Because of these drawbacks and the easy implementation of the nonlinear method, the nonlinear method was chosen as the preferred technique.

Another variable in the analysis process is the length of time over which the analysis is performed. In general, there must be enough concentration data for the regression technique to properly determine F_{dT} and F_{nd}. The degree of scatter in the data due to measurement error, nonuniform mixing, and short term fluctuations in the flow rates determines how much data are required to achieve the desired accuracy of the estimates. However, the time period must not be chosen to be so long that some of the assumptions of the model are invalidated. For example, the solution of equation 7 assumes that the flow rates F_{dT} and F^*_{id} are constant. If there is a random fluctuation of these flows then the regression technique will properly estimate their average value but a steady shift in either flow during the analysis period could bias the results. A third consideration is the desired time resolution of the measurements.

The nonlinear regression technique was performed on the data from the seven test days using the first two hours and the entire five hours of data. The estimates and standard errors of the downstairs infiltration and upstairs to downstairs air flows from the two hour analyses are displayed in table 3. The relatively low standard errors (11 to 18% - except for one high percent error that occurred for a low interzone flow) indicate that the 20 values from a two hour period are sufficient to provide good accuracy while maintaining a short enough period to insure approximately stable flows and good resolution. The assumption of steady flows does not always hold for longer periods. Figure 9 displays nearly four hours of the measured concentration and fitted regression curve for day 241 (the measurements went off scale after four hours). Although the fit is good, the regular deviations of the measured values away from the curve indicate that the flows were not constant. As a result, the relative errors of the two parameters are larger than for the two hour analysis and the estimated value of parameter one is physically impossible. In addition, a five hour period was not necessary for the winter periods since the steady concentration was reached during the second hour. Thus, it appears that a two hour analysis period provides good accuracy and adequate time resolution.

TABLE 3

Estimated Air Flow Rates From Discontinued Injection Method
(Uncertainties in parenthesis)

	Weather		Air Flow Rate [m^3/h]					
Day	dT[°C]	V[m/s]	F_{01}	F_{02}	F_{12}	F_{21}	F_{10}	F_{20}
239	4.2	2.4	69 (9)	14 (4)	5 (14)	28 (4)	92 (18)	-9 (15)
241	13.9	0.4	46 (5)	5 (1)	31 (12)	25 (3)	39 (14)	12 (12)
247	3.9	1.6	78 (14)	14 (4)	16 (11)	26 (5)	88 (17)	4 (12)
251	6.0	1.1	92 (10)	11 (3)	33 (11)	4 (2)	63 (15)	4 (11)
16	10.3	1.5	130 (27)	34 (6)	179 (36)	162 (33)	112 (55)	52 (49)
18	17.6	1.4	129 (23)	40 (6)	269 (46)	206 (37)	65 (72)	103 (59)
22	17.1	1.1	170 (28)	44 (6)	288 (63)	257 (42)	139 (90)	75 (76)

Note: F_{ij} is the flow from zone i to j.
zone 0 is outdoors, 1 is downstairs, 2 is upstairs

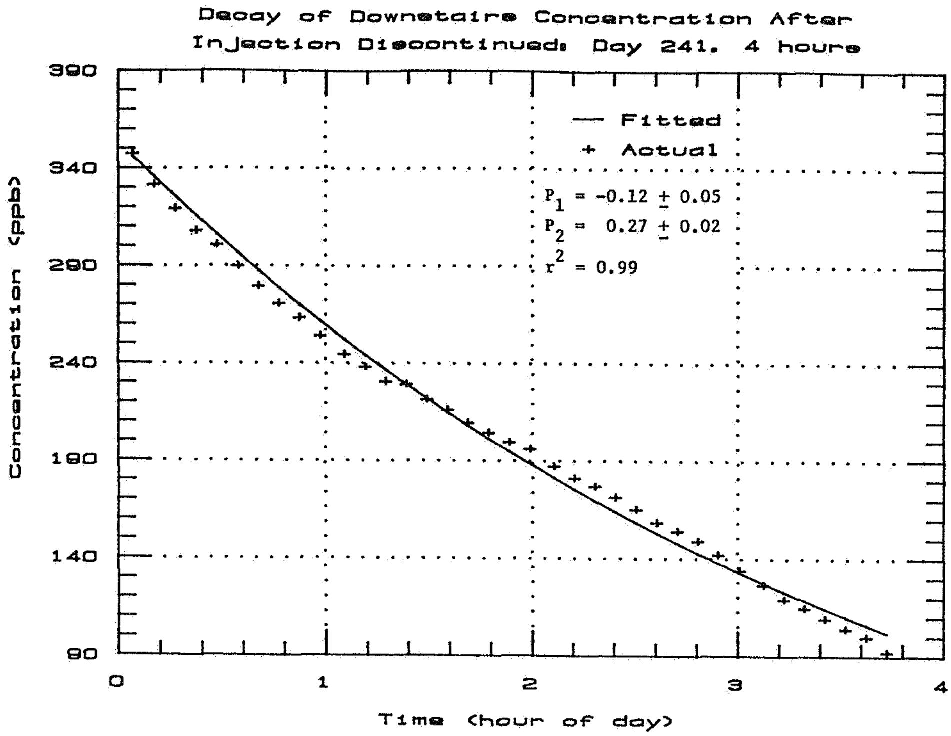

Figure 9. Results of nonlinear regression analysis of the downstairs concentration: Day 241 - four hours.

The solution of the remaining flows begins with using equation 11 to solve for the flows between the discontinued injection zone and the other zones. As stated earlier, the solution of this equation requires an estimate of the infiltration in the other zones. This could be obtained from either the value measured immediately before injection was discontinued, from a separate, simultaneous tracer gas measurement, or from a model of the air flows. A separate measurement would be the most accurate approach but it eliminates the advantages of the single tracer system. An estimate from the previous measurement is the simplest approach but it could be in error if there are significant changes in the weather during the test (the tests are conducted in the early morning to reduce weather variations and occupant effects). The third approach is to use an empirical model relating infiltration to weather variables (and possibly heating system use) that is generated from CCTG measurements in the same building. This method does account for variations in the infiltration due to weather changes, but the amount of data needed for an accurate model is often prohibitive. In most cases, the previous measurement will be preferred since it is readily available and provides reasonable accuracy.

Empirical models of the infiltration rates for the two separate test periods (days 16 to 22 and 235 to 251) were available from a companion study of CCTG measurements in the test house[1]. This model was used for the winter period since the regression fit was relatively good ($r^2 = 0.79$). However, the fit to the summer-fall data was unsatisfactory ($r^2 = 0.36$). For the tests during this period the infiltration measurement immediately before the injection was discontinued is used to estimate the upstairs infiltration.

The estimated infiltration rate and average injection rate (S_j) in an injection zone and average concentration in the discontinued injection zone (c_d) are inserted into equation 11 to solve for the average flow from the discontinued injection zone to the injection zones. This relationship is accurate if the flows are relatively constant. The sum of these flows and the total flow leaving the discontinued injection zone are used in equation 12 to compute the zone d exfiltration rate. Equation 13 is then used to compute the total exfiltration flow from the injection zones.

The computational procedure described above was applied to the seven test periods to achieve the air flow rates reported in table 3. The results from days 18 and 241 verify the qualitative analysis discussed earlier. In general, the air flows from the winter tests are much higher than those from the summer-fall (s/f) tests. This is expected since the weather is more severe and the operation of the heating system should increase the mixing between the two zones. For the winter tests the ratios of the average interzone flows divided by the downstairs infiltration were 1.3 to 1.9 while they were much less for the s/f tests: 0.2 to 0.6. This indicates that there will be a greater degree of vertical stratification of indoor pollutants in milder weather. During the winter tests the downstairs to upstairs flows were 1.1 to 1.3 times higher than the upstairs to downstairs flows. This result suggests that the mixing between zones due to the heating system operation overwhelms the expected stack flow from the downstairs to the upstairs. The results also show that, because of the stack effect and the large leakage areas in the downstairs[8], there is consistantly greater infiltration in the downstairs than the upstairs. It is interesting to note that the exfiltration is also greater in the downstairs than the upstairs. This is most likely due to the large downstairs leaks.

A pertubation type error analysis was applied to the air flow equations. Given the uncertainties of the variables in the flow equations, the uncertainty of each air flow rate can be approximated by the Euclidean summation of the uncertainty due to each variable in the flow rate equation[10]. For this error analysis the standard errors from the regression analysis were used to compute the uncertainties of F_{dT} and F^*_{id}. The uncertainty of the downstairs volume measurement was assumed to be 10%. For the winter measurements the uncertainty of the upstairs infiltration was chosen to be the standard error of the estimate for the model - 0.03 ACH. For the summer-fall period it was set equal to 25% of the estimated value. The uncertainty of the concentration measurements and tracer gas injection rate were assumed to be 5 and 10%. These uncertainties were used with the pertubation method to compute the air flow uncertainties shown in parentheses in table 3.

The results of the error analysis show that the flows determined from the regression analysis (F_{01} and F_{21} - where zone 0 is the outdoors, 1 is the downstairs, and 2 is the upstairs) have uncertainties less than 20% of the estimated values. For the winter tests the uncertainties of the flow from the downstairs to the upstairs were also about 20%. However, the relative uncertainties for the small flows of the s/f tests were much higher - 40 to 100%. In general, the exfiltration flows have the greatest relative uncertainty. This occurs because these flows are computed from the difference of other flows. This results in uncertainties for the downstairs exfiltration which vary from 20 to 90%. The uncertainties for the upstairs exfiltration flows are even higher: 60 to 300%. Thus, the discontinued injection method gives an uncertainty of about 20% for the downstairs infiltration, upstairs to downstairs flow, and large downstairs to upstairs flows. However, the uncertainties of the exfiltration flows can be as large as the estimated values.

In addition to the uncertainty analysis, the accuracy of the discontinued approach can be examined by comparing the measurements with those from other techniques. One possiblity is to compare the downstairs infiltration measurement from that obtained by the empirical models. Since the models for both the winter and s/f periods had high correlation coefficients (r^2 = 0.90 and 0.83) and the uncertainty of the measurements are about 20%, it is expected that the difference between the two values should be less than 40%. For the winter and s/f tests the downstairs infiltration measurements differed by 13% and 49% from those predicted from the empirical model. Thus, there is good agreement for the winter conditions but poor agreement for the mild weather conditions. The results from mild weather could be due to an inherent difficulty with measurements under those conditions or simply that there was not enough measurements to make a fair comparison. Further studies are needed to properly explain this result.

The CCTG discontinued injection tests in this house were supplemented with simultaneous passive, multi-tracer measurements. These tests were conducted using the PFT method developed by Brookhaven National Laboratory[11]. The analysis of the capillary adsorption tube samplers and computation of the air flow rates was conducted at Princeton. These measurements, described in more detail in a companion paper in this conference[12], provide average infiltration, exfiltration, and interzone flow rates for the downstairs and upstairs zones. A comparison of the PFT measurements and the average of the discontinued injection tests for the two measurement periods is presented in table 4. This comparison provides some indication of the agreement of the two methods. However, it is important to note that the PFT measurements are average values over the entire operation of the CCTG system. In contrast, the average of the discontinued injection measurements includes only a few flows from two hour periods. The results show good agreement between the two methods for all the infiltration measurements. In addition, there is good agreement between the winter period downstairs to upstairs and s/f period upstairs to downstairs measurements. There are large differences in the other measurements. Further tests are required to determine whether the differences are due to the limited number of measurements using the discontinued method or if there is a consistant difference between the two methods.

TABLE 4

Comparison of Discontinued Injection (DI) and PFT Methods
(Uncertainties in parenthesis)

Test Period		Air Flow Rate [m^3/h] F_{01}	F_{02}	F_{12}	F_{21}	F_{10}	F_{20}
Winter	DI -	143 (26)	39 (6)	245 (48)	208 (37)	105 (72)	77 (61)
	PFT -	109 (23)	39 (41)	273 (88)	72 (23)	-92 (50)	240 (48)
Summer	DI -	71 (10)	11 (3)	21 (12)	21 (4)	71 (16)	3 (13)
/Fall	PFT -	65 (12)	17 (13)	85 (27)	29 (10)	9 (22)	74 (16)

Thus far the analysis has considered the upstairs to be a single zone. However, the tracer gas measurements were conducted in five separate zones of the upstairs. This data can be used in equation 11 to compute the flows from the downstairs into each of these zones. The results of the computations for the seven test periods are reported in table 5. The discrepancy between the total flow and that in table 3 occurs because the infiltration in each upstairs zone is obtained from the previous measurement and not that predicted from the model. The results show that during the s/f tests little, if any, air flows from the downstairs directly to the bedrooms. Instead, it appears that the flow between the downstair and upstairs moves up the large, open staircase and into the kitchen, livingroom, and diningroom area (K,L&D). In contrast, during the winter period the air moves fairly uniformly from the downstairs to the upstairs zones. In fact, if the volume of each zone is considered, the relative amount of flow to each upstairs zone is nearly equal. This indicates that the heating system does an adequate job of mixing the air in the house. Further tests could be performed to evaluate the flows between the upstair zones by discontinuing injection in individual upstair zones.

TABLE 5

Estimated Air Flow Rates From Downstairs
to Individual Upstair Zones

	Air Flow Rate [m^3/h]					
Day	Bed 1	Bed 2	M Bed	Hall	K,L&D	Total
239	-2	-2	-3	1	12	5
241	1	0	4	4	22	31
247	-4	-1	-2	4	19	16
251	2	0	2	4	25	33
16	32	19	39	30	80	200
18	49	37	54	21	114	275
22	41	29	49	51	113	284

The discontinued injection method is extremely useful in indoor air quality studies. As shown in another study of this house, the infiltration flow rate in the bedrooms is much less than that recommended by ASHRAE standards[1]. However, the air entering the downstairs could often provide adequate ventilation of the upstairs if there is good communication between the two areas. These studies indicate that during the winter months when the heating system is operating there is good communication between the downstairs and the bedrooms. In mild weather conditions the communication is poor and the downstairs infiltration can not be counted on to provide ventilation in the bedrooms. With night setback one would also anticipate poor communication just when sleeping occupants would most desire bedroom ventilation.

5.0 CONCLUSIONS

The results show that the modified CCTG techniques are useful extensions to the typical multi-zone infiltration measurements. A series of guarded zone and surrounded sampling tests were conducted to measure infiltration and interzone flows in a 60-unit multifamily building. During the guarded zone tests the system was able to keep the concentration near the target level. The results showed that the infiltration to an apartment with closed windows was typically below 0.35 ACH. Opening the windows a linear distance of 50mm increased the infiltration rates by about a factor of 10 and wide open windows gave another factor of ten increase. The interzone measurements indicated that there is little direct communication between the apartments and that the total incoming flow is of the same order of magnitude as the infiltration flow.

A series of seven discontinued injection tests were successfully performed in a unoccupied single family house. The tests provided measurements of the average downstairs and upstairs infiltration, exfiltration, and interzone flow rates for two hour periods. As expected, the winter flows were much greater than those during mild weather. The operation of the heating system during the winter conditions appeared to provide adequate mixing in the house. In contrast, the upstairs bedrooms had little, if any, communication with the downstairs in mild weather. The results suggest that there may be indoor air quality problems in the upstairs bedrooms during mild weather. The error analysis indicates that the discontinued injection method gives an uncertainty of about 20% for the downstairs infiltration, upstairs to downstairs flow and large downstairs to upstairs flows. However, the uncertainties of the exfiltration flows can be as large as the estimated value. Comparisons of the results with those from empirical models and PFT tests show agreement for some of the flows and poor agreement for others. Further tests are required to properly compare the methods.

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