VENTILATION TECHNOLOGY - RESEARCH AND APPLICATION

8th AIVC Conference, Überlingen, Federal Republic of Germany
21 - 24 September 1987

POSTER P1

MEASUREMENT OF SEASONAL AIR FLOW RATES IN AN UNOCCUPIED SINGLE FAMILY HOUSE

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SYNOPSIS

For more than four years air infiltration measurements have been made on two nearly identical side-by-side test houses in Gaithersburg, Maryland, USA. This testing of the complete seasonal weather influence on air infiltration has, in the past two years, included constant concentration tracer gas measurements (CCTG). These multi-zone air infiltration measurements have added further detail on the response of air infiltration into the house to weather changes and the variation of air infiltration between different house locations. Time series data point out the minimal infiltration rates that occur during certain periods. Seasonal data displayed in frequency and three-dimensional plots illustrate the regularity of air infiltration and its relation to delta temperature and windspeed. Regression analysis is then applied to the data sets to reveal the influence of individual parameters such as delta temperature, windspeed and direction. The results show that a simple additive model of delta temperature and windspeed explains most of the air infiltration variations ($r^2 \sim 0.75$) and that more sophisticated models add little to the accuracy of the prediction.

1.0 INTRODUCTION

Our ventilation standards attempt to establish the levels of ventilation air which are required to avoid adverse health effects to human occupants.[1] The amount of air mandated has varied somewhat over the years as our knowledge of the subject has increased. Levels of carbon dioxide, for example, have now been limited to 1000 ppm so as to avoid human discomfort. CO_2 is viewed as a surrogate for other air constituents, including odor. The more one looks into the question of minimum ventilation for acceptable indoor air quality, the more questions arise. In our larger buildings we ask what is the value of ventilation efficiency, ie., is the outside air entering the building actually reaching the occupants or does one have to supply still more air to make certain every occupant is satisfied? When variable air volume systems are in use, and flow rates drop because the local temperature conditions are satisfied; are the local occupants being supplied at least the minimum amount of "fresh air"?[1,2] Such questions aimed primarily at mechanical ventilation systems must also be asked of our residential buildings. This paper seeks to add additional information on one aspect of residential ventilation: what are the seasonal air infiltration variations due to weather factors? The site of this investigation is the control house of the pair of nearly identical test houses operated by GEOMET Technologies just outside Washington, D.C.

For more than four years air infiltration information has been gathered on a regular basis for each of the two test houses.[3] The measurements were made using the tracer dilution method. The gas chromatographic equipment is situated in a mobile laboratory parked between the test homes. Plastic tubing and an air transfer pump allow air infiltration measurements of the upstairs and downstairs zones of each test house. These locations are shown as X and Y on Fig. 1. The control house has been used for the complimentary, more detailed, air infiltration measurements obtained by the constant concentration tracer gas (CCTG) equipment.

As indicated in Fig. 1, CCTG infiltration measurements were conducted in five separate upstair zones and a single downstair zone. This figure also indicates the locations of the sample and injection points along with the positions of the small mixing fans that were used during the CCTG measurements. Under many circumstances natural room air circulation patterns can prove sufficient to mix the room air, thereby allowing one to eliminate the small air mixing fans used in this study. Studies in this house showed that even without the fans the deviation in the concentration increased only slightly.

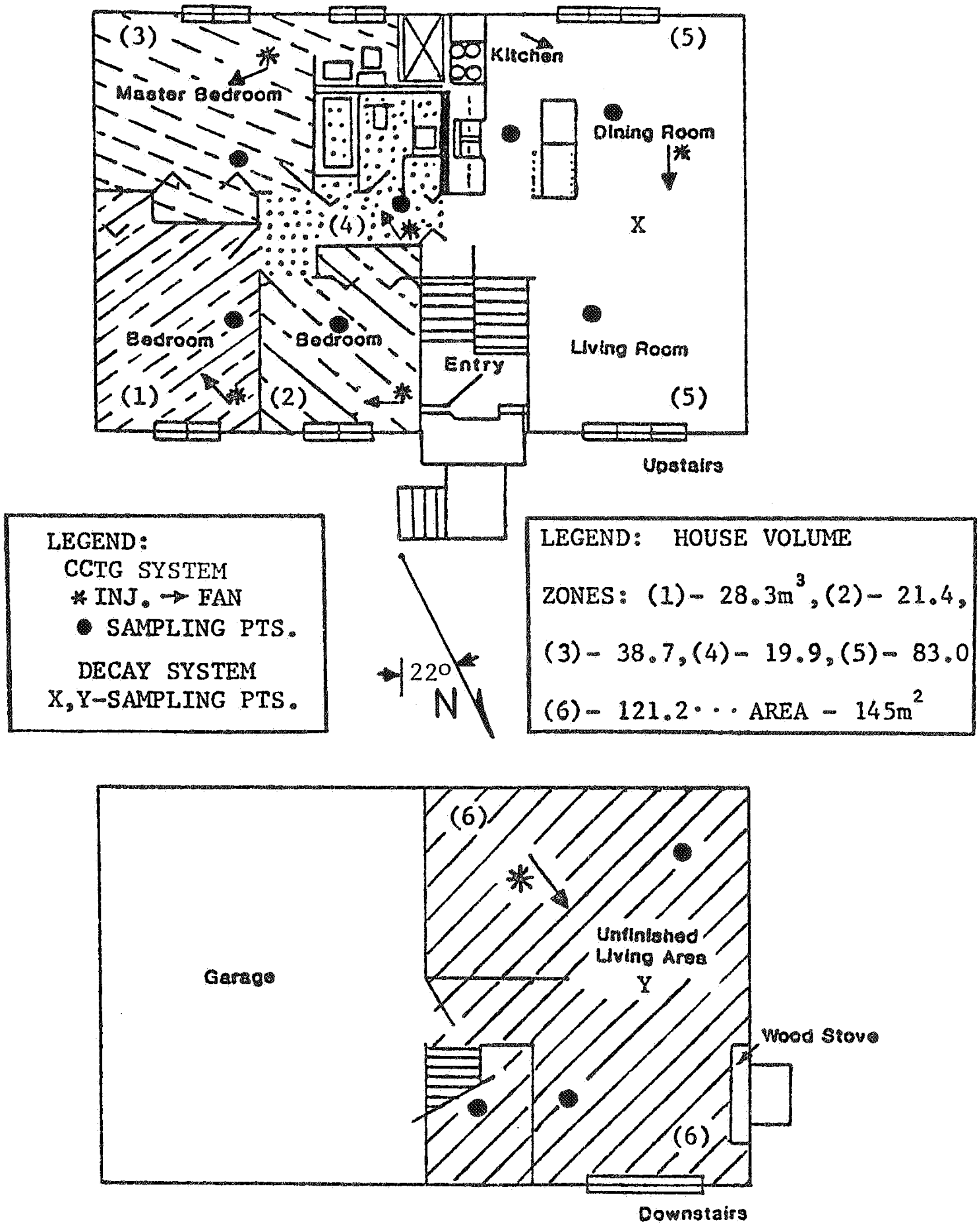

Fig. 1. Floor plans, sampling points & fans, and volumes & floor areas of control house. Six zones evaluated for air infiltration by the constant concentration method are numbered.

The constant concentration system and control algorithm used in this study has been described in detail in previous AIVC conference proceedings.[4,5] The method consists of injecting the proper amount a dilute mixture of the tracer gas (SF6 at typically 0.15% concentration in air) into each zone so that the concentration is kept constant at the target in all the zones. By keeping the concentration constant, the air infiltration rate into each zone is simply equal to the tracer injection rate for the zone divided by the target concentration. While the CCTG system normally measures infiltration rates, intermittent measurements of certain interzone rates are possible by discontinuing injection in selected zones. These types of measurements are not included here but are discussed in another paper presented at this conference.[6]

In order to keep the concentration at the target level the system measures the tracer gas concentration, calculates the rate of injection needed for each zone, and injects the tracer gas at a variable rate - all on a time scale that allows adequate control of the tracer concentration. The system consists of an electron capture gas chromatograph, a series of ten sample and injection lines, valve control electronics, and a microcomputer-based data acquisition system. The concentration measurement takes approximately 30 seconds to complete. Injection begins at the start of the cycle and can continue until the last half second of the cycle.

It is important to note that, instead of performing only a single injection in a zone between samples of the zone, the system performs an injection into every zone during each 60 second cycle. This method more closely approximates constant injection. At the end of each hour of operation the average concentration, rms deviation in the concentration from the target, and the estimated average infiltration rate are stored to a disk file. Recent modifications to the system allow the user to interactively graph this data on the screen or access the data via modem communications from a remote location while continuing the normal operation of the system. In addition, the system records hourly measures of the concentration of a reference tank to adjust for the drift of the gas chromatograph. Also, the most recent version of the CCTG system utilizes an improved version of the gas chromatograph with molecular sieve columns and backflushing which provides reduced measurement and cycle times of 10 and 30 seconds.

Weather data, which are an important part of the information set, are supplied from the between-house mobile laboratory and includes: outside temperature, wind speed, and wind direction.

The infiltration measurements were conducted during three separate periods of time: in the spring from March 21 to April 2 of 1985, in the summer/fall from August 20 to September 9 of 1986, and in the winter from January 14 to 22 of 1987. The final data set includes 120 observations from the spring, 301 from the summer/fall, and 137 from the winter period.

2.0 TIME SERIES DATA

As was previously described in Ref. 4, the individual rooms and zones in the control house experience a wide variety of air infiltration rates. Typical of such recently collected data is the plot in Fig. 2

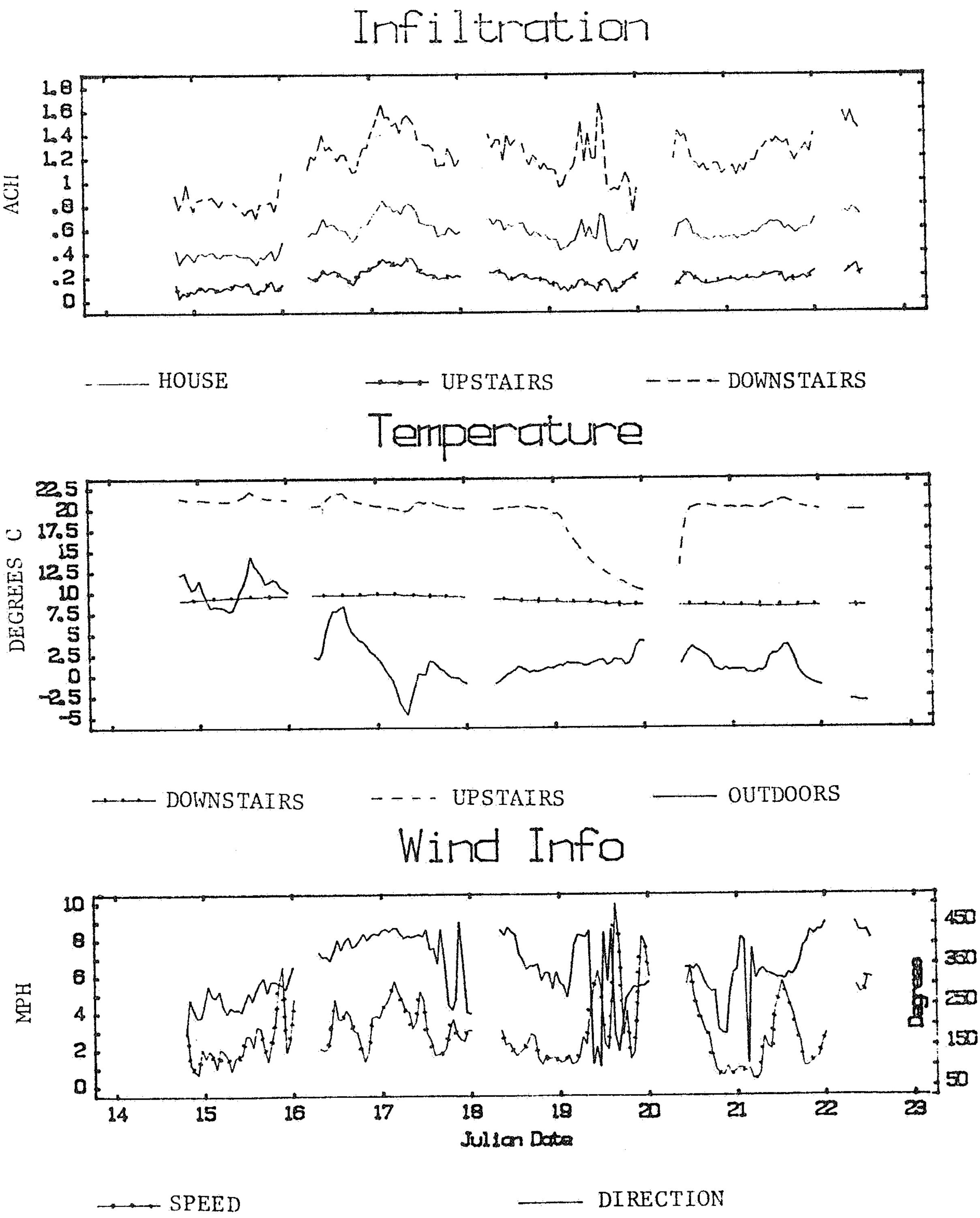

Fig. 2. Time series air infiltration data from the winter data set. Five upstairs zones plotted as "upstairs" in this figure.

which displays the winter data of the whole house, downstairs, and upstairs air infiltration over time, as well as the downstairs, upstairs, and outdoor temperatures, together with wind speed and direction. The upstair infiltration rate is an aggregate of the five upstair zones. The air infiltration variation points out the source of concern as to whether or not ventilation rates are consistantly sufficient to satisfy indoor air quality requirements in all areas of the house. Although the basement levels for air infiltration frequently exceed 1 ach, the upstair levels (and those for the individual upstair zones) often fall below 0.1 air change per hour (ach) and thus internal air circulation may be required to meet ventilation standards.

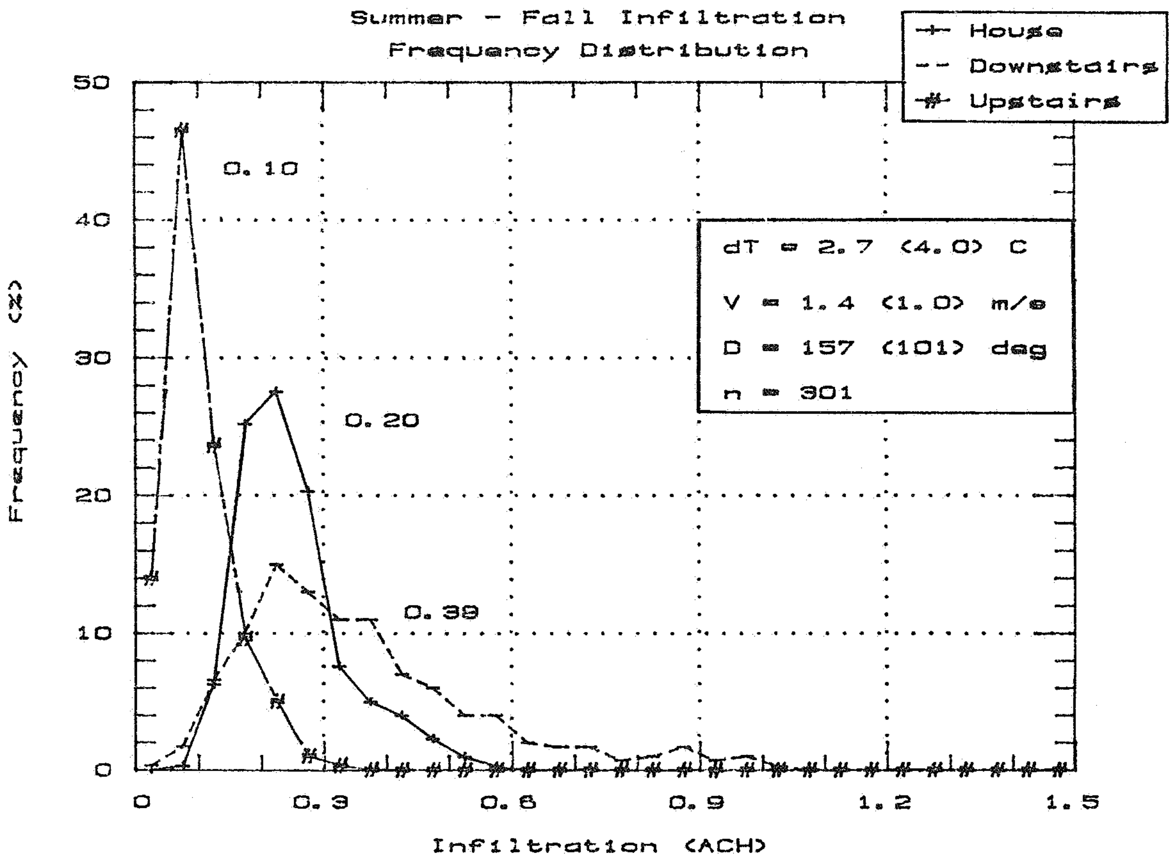

Fig. 3a. Typical frequency distribution plot based upon summer-fall data set. Three plots are for total house, upstairs and downstairs.

3.0 SEASONAL AIR INFILTRATION VARIATIONS

3.1 Frequency Plots

It is also useful to plot the seasonal air infiltration data for the upstairs, downstairs, and whole house based on frequency of occurrence. These relatively short-term test results, as shown in Figures 3a, 3b, and 3c illustrate the same characteristic profiles as described in Ref. 3 (also shown in Ref. 2) for longer term tracer gas decay studies. Each of the frequency plots provides information on the average and standard deviation of the delta temperature, wind velocity, wind direction, and number of data points. The infiltration frequency and weather data allow examination of the percentage of time ventilation standards are met and under what weather conditions they are met.

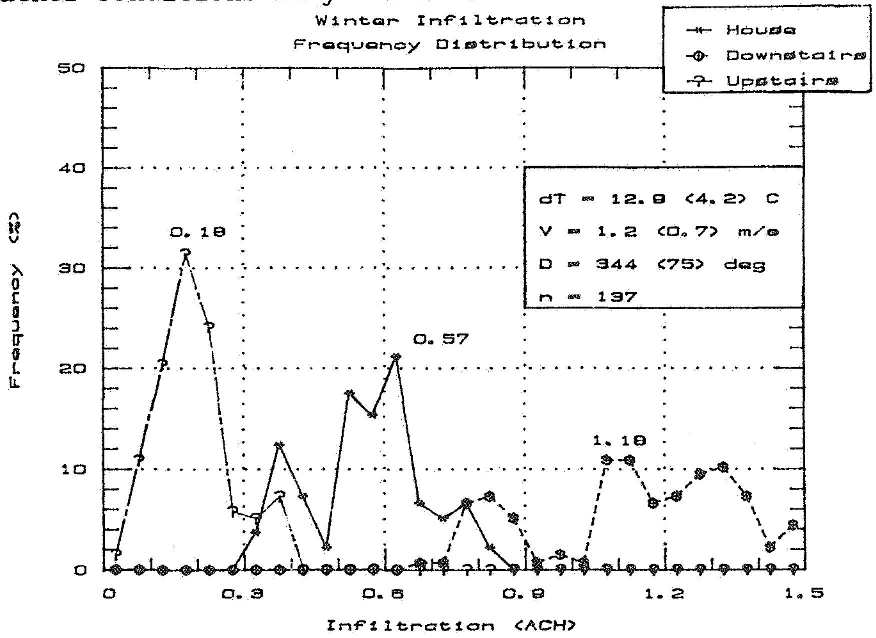

Fig. 3b. Typical frequency distribution plot for winter data set.

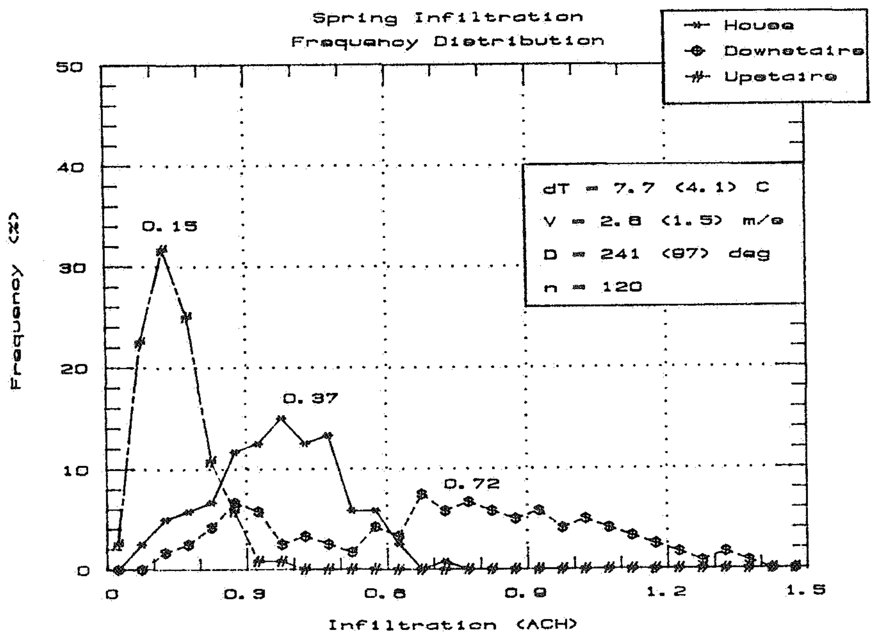

Fig. 3c. Typical frequency distribution plot for spring data set.

For this house ASHRAE standard 62[1] specifies a minimum ventilation of 0.44 ach for the whole house and 0.53 ach for just the upstairs rooms. The proposed standard revision, 1987, specifies a minimum of 0.35 ach for the house and individual rooms. For the summer - fall period (Fig. 3a) only 1 hour of the 301 hours whole house measurements equals or exceeds 0.5 ach and only 20% exceeds 0.25 ach. The winter data presents a much improved air exchange rate, where 75% of the time 0.5 ach is exceeded and there are no periods less than 0.25 ach. Finally, the spring data indicates 15% above 0.5 ach and 20% less than 0.25 ach. These results indicate that the closed house infiltration rates do not meet minimum standards over all the seasons.

The frequency plots show that the minimum ventiltation standard of 0.53 ach for the upstairs is never met for any of the recorded data. The 1987 proposed standard of 0.35 ach is met less than 1% of the time in the spring and winter and not at all in the summer - fall. However, during the winter the air flow from the higher ventilated downstairs may provide adequate ventilation air depending on the degree of mixing between the two areas. During the two other periods the ventilation air from the downstairs would seldom be sufficient.

3.2 3-Dimensional Displays

One method we have found to be useful in interpreting the air infiltration data for the test house during the various seasons is a three-dimensional display. Figures 4, 5 and 6 indicate displays for spring, summer/fall, and winter data. Looking at the temperature

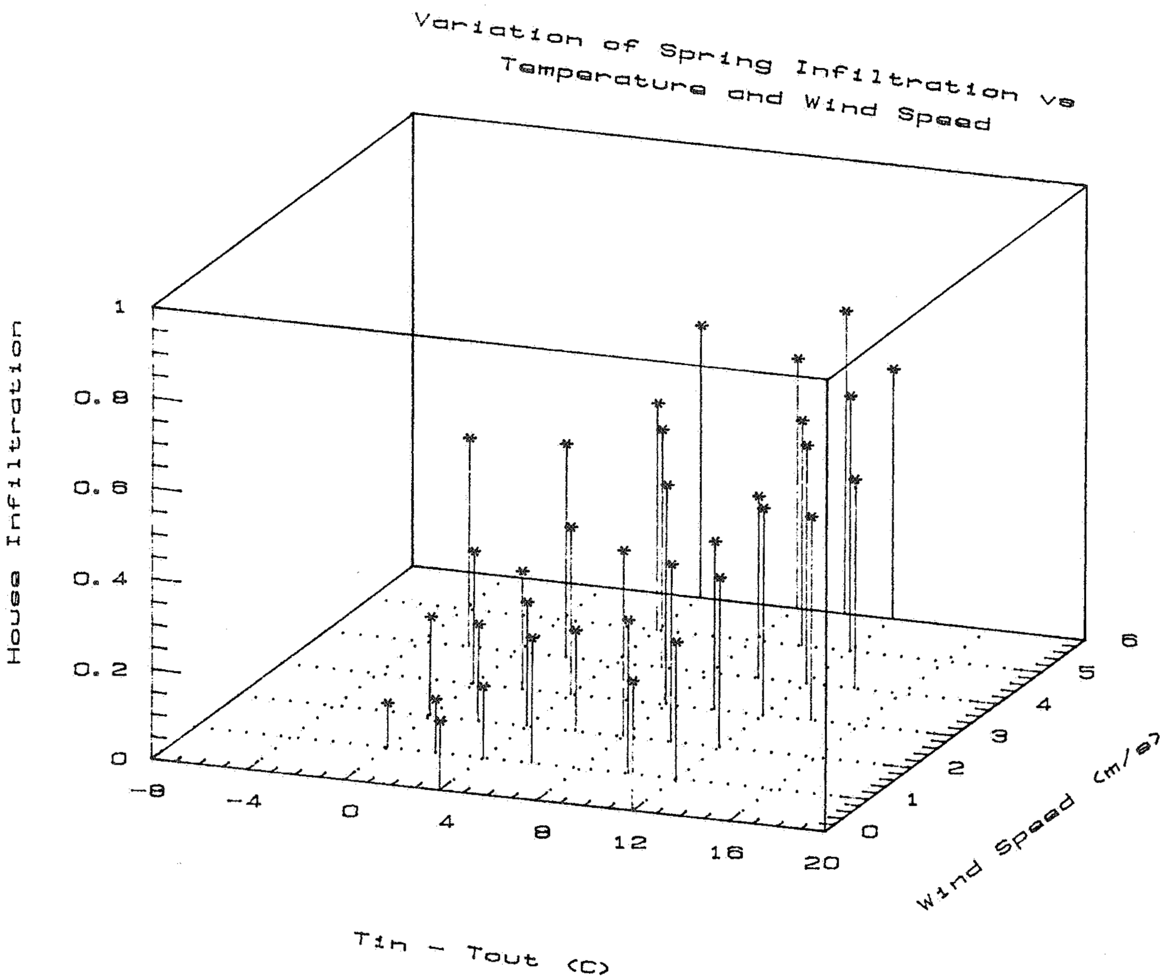

Fig. 4. Three-dimensional data display for the spring data set.

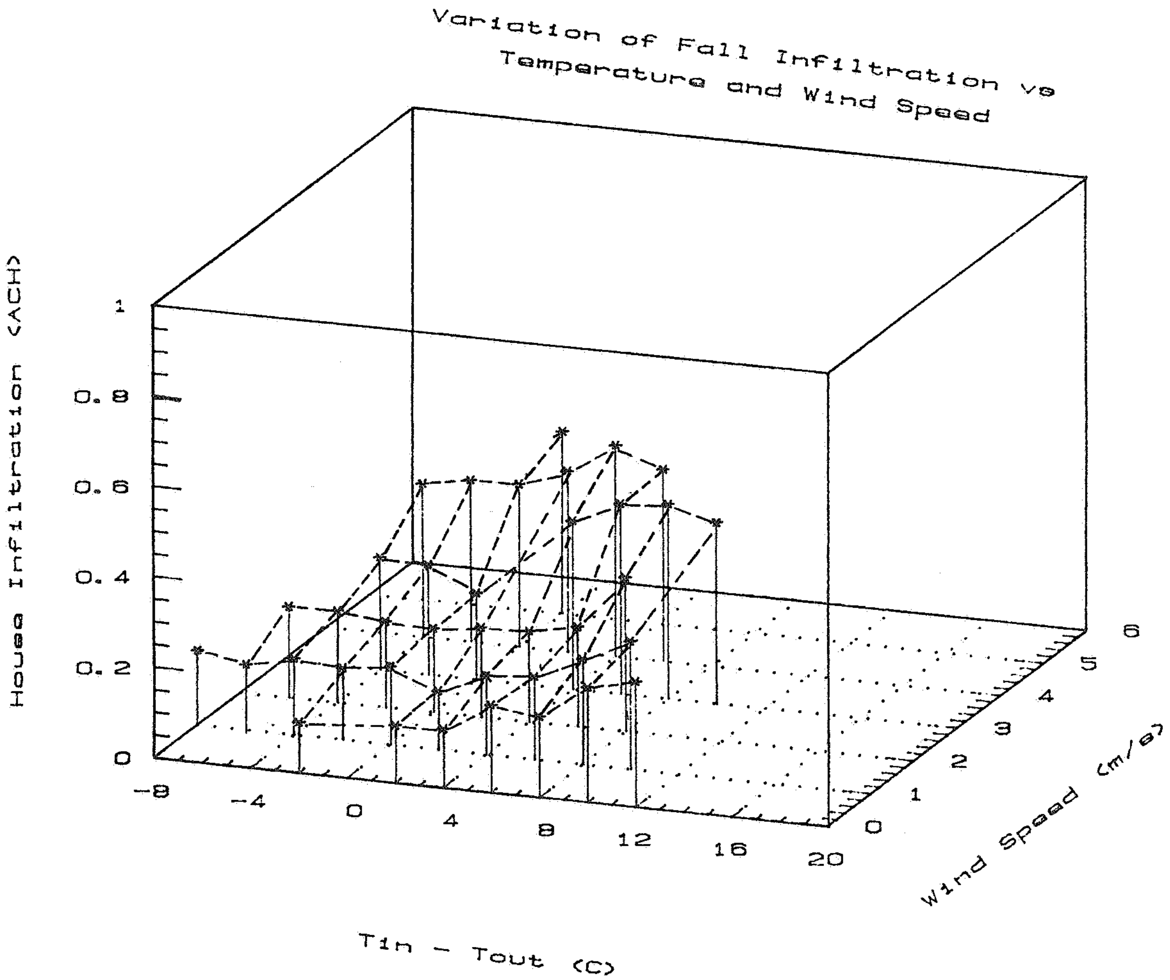

Fig. 5. Three-dimensional data display for the fall (late summer) data set.

windspeed matrix, the fall data are seen to cover a similar windspeed range (0-4 m/s) when compared to the winter data but, as expected, a different delta temperature range (-8 to +12°C versus 2 to 20°C). The spring data occupies an intermediate range of delta temperature (0 to 12°C) covering the overlap of the fall and winter delta temperature data, but in addition extends over a wider range of windspeeds, to 6 m/s. Contours for constant windspeed and for constant temperature difference are illustrated in the fall air infiltration data, in Fig. 5. Unfortunately, the extremes of temperature and wind conditions for the various seasons in the Washington, D.C. area did not take place during the intervals when the CCTG equipment was in place. The extremes in delta temperature can reach 35°C in winter, and -15°C in summer in that area, and winds to 10 m/s are not unusual.

For the 3-D display to be useful one must group the data in bins sufficiently coarse so that one can recognize the nature of the "data forest" and not have general trends obscured by the individual "data trees." The figures 4, 5, and 6 use bin widths of 1 m/s for windspeed and 2 °C for delta temperature. These figures show the expected positive relationship between delta temperature and windspeed to house infiltration. However, a quantitative analysis is required to better evaluate the relationship between these variables.

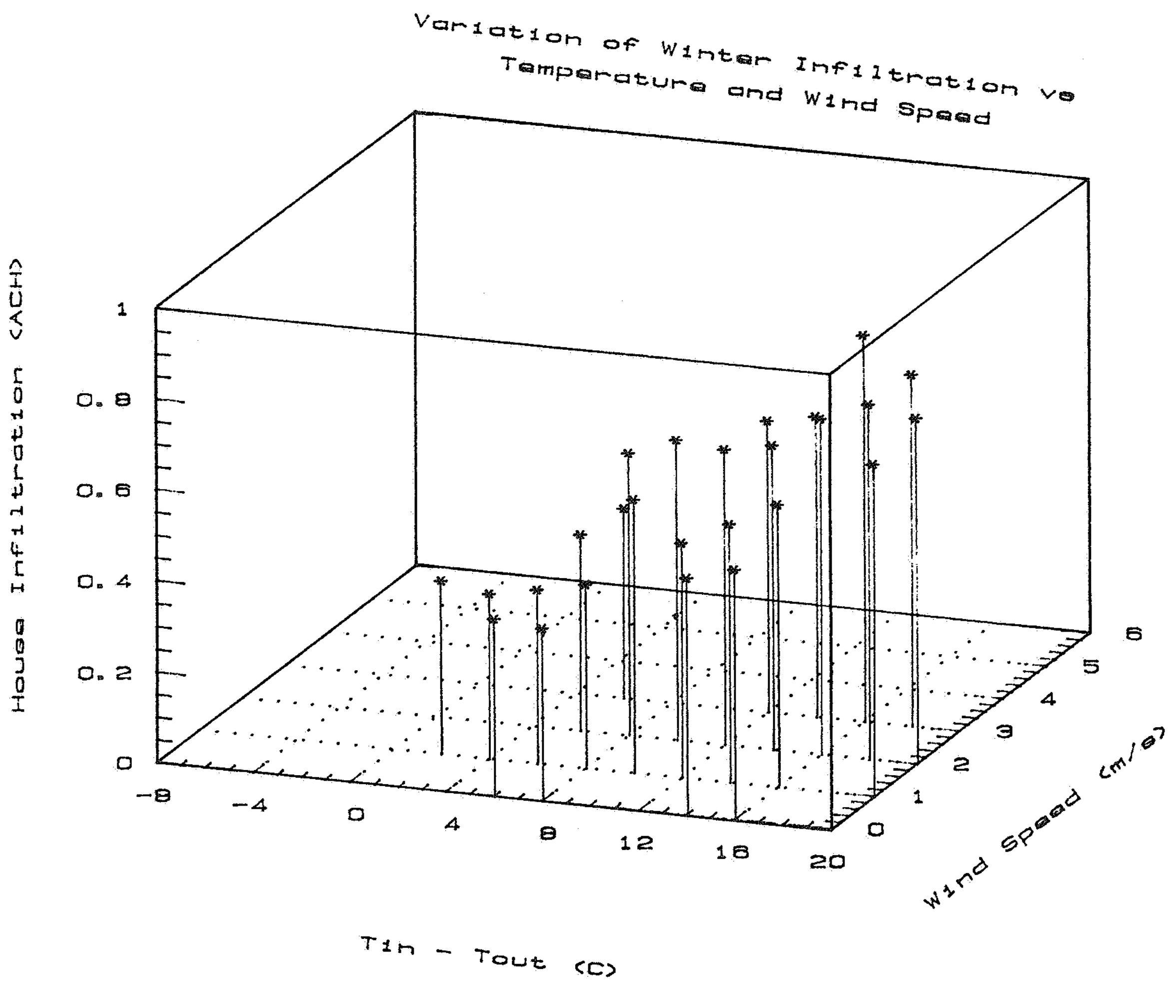

Fig. 6. Three-dimensional data display for the winter data set.

4.0 REGRESSION ANALYSES

Traditionally the model of air infiltration (AI) for an individual house has often taken the form of a regression relationship:[7]

$$AI = A + B*\Delta T + C*V$$

where a constant value A adds to a linear relationship of delta temperature and a third term relating wind speed. Variations have added an exponent to the windspeed term or sometimes wind directional information has been added.[8,9]

The origins of the model variations are that the air flow through adventiuous openings in the envelope of the building can generally be approximated by the equation: $Q = K \cdot (\Delta P)^n$, where K is the flow coefficient, n the flow exponent and ΔP the pressure difference across the opening.[10] The pressure difference from wind impinging on a surface is proportional to V^2, and is influenced by the impingement angle. The pressure difference from stack action is related to:

$$P_s = \rho_o \, g \, 273 \, h \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right]$$

which is proportional to $\Delta T/T_{ext}$ (K), where ρ_o is the air density at 273K and ambient pressure, h is the vertical distance between openings, and T_{ext} and T_{int} refer to the exterior and interior temperatures.[11] If it is assumed that the total building pressure from both the wind velocity and stack effects is equal to the sum of the pressures from the two effects acting alone, then the flow rate from both effects is given by:[12]

$$[a\Delta T^{1/n} + bV^{1/n}]^n$$

The regression results for the three seasonal data sets and the three data sets combined are summarized in Tables 1 and 2. The regression

Table 1

RESULTS OF REGRESSION ANALYSIS FOR VARIOUS MODELS

	Model	r^2 Value			
		Fall/ Summer	Winter	Spring	Total
(1)	$P1 + P2\Delta T$	0.113	0.623	0.293	0.666
(2)	$P1 + P2V$	0.377	0.317	0.656	0.135
(3)	$P1 + P2\Delta T + P3V$	0.710	0.852	0.780	0.790
(4)	$P1 + P2\Delta T^m + P3V^k$	0.725	0.859	0.790	0.813
(5)	$P1 + P2\Delta T + P3V + P4V\lvert\cos(\theta-\theta_o)\rvert$	0.740	0.875	0.829	0.817
(6)	$P1 + [(P2\Delta T)^\alpha + (P3V)^\alpha]^{1/\alpha}$	0.718	0.858	0.789	0.800

approach begins with simple constant and single variable models with ΔT and windspeed (V) and gradually increases the model complexity. The third model is a linear additive relation with ΔT and V. The fourth model uses variable exponents of m and k for the ΔT and V terms and is used to examine the preferred exponents of the stack and wind terms. The fifth is the linear model with a windspeed direction term ($\lvert\cos(\theta - \theta_o)\rvert$) added and studies the effect of wind direction. The absolute value of the cosine of the wind direction minus a reference direction was used because the house is sheltered by houses on both sides and is relatively open on the front and back sides. Finally, the sixth is a complex addition of terms, P1 + [(P2ΔT)^α + (P3V)^α]^1/α and is equivalent to the above flow equation for wind and stack effects. It examines the preferred value of n (here, $\alpha = 1/n$).

Table 1 summarizes the results of the correlation coefficient for the three seasonal data sets as well as the combined data set for the six models. The results from the first two models show the effect of the weather pattern during the periods. For the winter period, when the stack effect dominates, much of the variation in the data ($r^2 = 0.623$) can be explained with only the ΔT term. During the spring the wind has a greater effect on the infiltration level and the data is better explained with the windspeed term. Using the additive model of the two terms yields values of r^2 from 0.71 to 0.85. This range of correlation is similar, although slightly lower, to those reported by Nagda et al in Ref. 3. A scatter plot of the predicted versus measured house infiltration rates for the combined data set is displayed in Fig. 7. This plot shows the agreement between the predicted and measured infiltration rates ($r^2 = 0.79$) for the 480 observations.

Table 2

Estimated Parameters From Regression Analysis (see models Table 1)

Data Set	m	k	θ_o	α
Summer/Fall	1.23 (0.17)	1.42 (0.16)	14.8 (6.0)	1.35 (0.16)
Winter	0.65 (0.23)	0.71 (0.22)	31.1 (4.6)	0.57 (0.20)
Spring	0.49 (0.27)	0.89 (0.19)	38.7 (3.3)	1.85 (0.38)
Total	1.45 (0.09)	0.45 (0.14)	32.6 (2.9)	1.77 (0.19)

Table 2 displays the estimated parameters (m, k, θ_o, and α) obtained from the regression analysis of models 4 - 6. The results for m and k range from 0.45 to 1.45 and show little consistancy. Along with the small increase in r^2 from the linear additive model (3), this indicates that coefficients of 1.0 for the two terms are as reasonable as any others. The value of θ_o obtained from the wind direction term in model 5 is relatively consistant - varying from 15 to 39°. Since the house faces 22° East of North, this result is consistant with the greater degree of sheltering that exists on the sides of the house. However, the addition of the wind direction term typically increased the r^2 by only 0.03 (see Table 1) from model 3, indicating a weak dependence of the house infiltration to wind direction. The results from the sixth model show one estimate of the exponent α below 1.0 (0.57 for the stack dominated winter period) with the rest above 1.0. α for the combined data set was estimated to be 1.77 or n = 0.57. Given the wide variation in the estimates of α and the very small improvements in the r^2 from the additive model (3), no conclusive value of α can be determined. It appears that the linear model ($\alpha = 1$) performs as well as a square root of the sum of the squares ($\alpha = 2$) model.

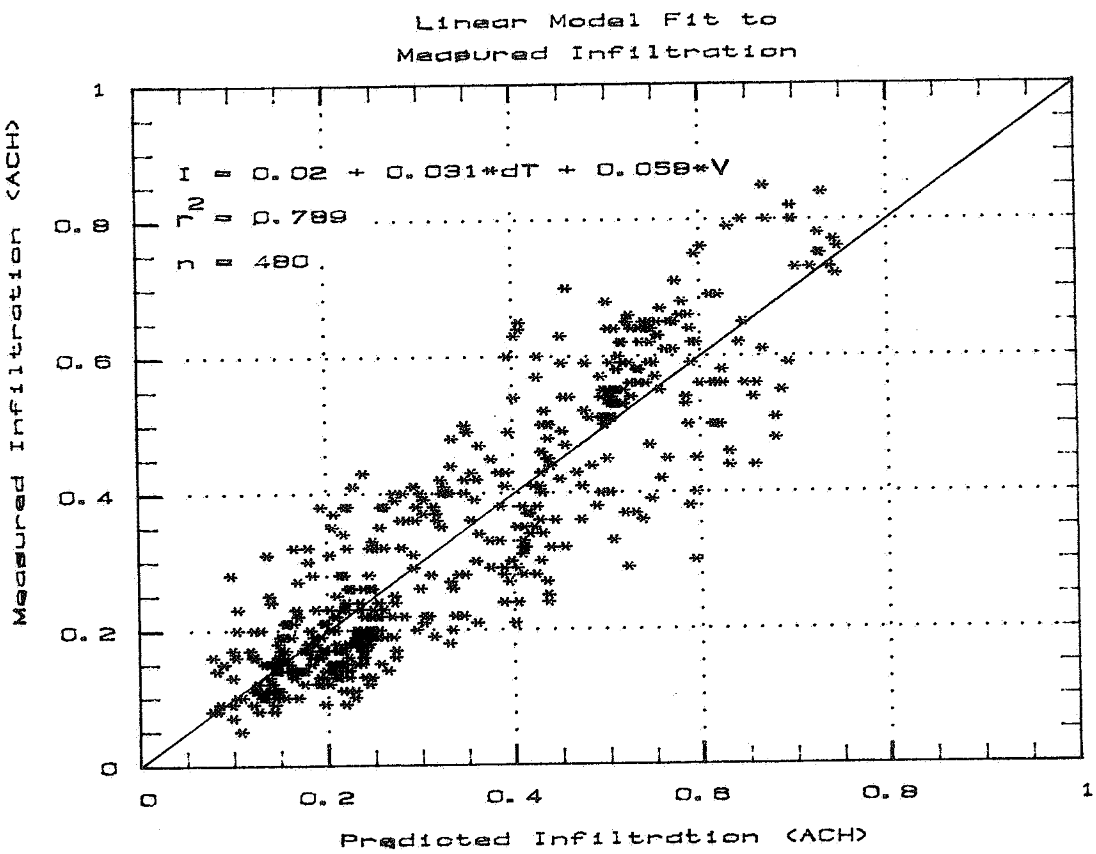

Fig. 7. Scatter plot of the total data set illustrating the agreement between predicted and measured air infiltration rates.

Since the CCTG system provides infiltration measurements for not only the whole house but also individual zones, the analysis of the relationship of weather parameters to infiltration can also be performed for the individual zones. It is expected that the individual zones will respond differently than the whole house to certain factors such as the windspeed and direction. For example, while the wind direction has been shown to have a small effect on the house infiltration because of the local sheltering, it should have a more significant effect on the individual zones since the outside walls of a zone typically face only one or two directions.

To study this hypothesis, regression analyses are performed for the downstairs zone for the fall period. The linear additive model (3) applied to this data set results in a r^2 of 0.737. The wind direction effect is examined by adding a term ($\cos(\theta-\theta_o)$) to the model. This term differs from that used in model (4) above since the cosine of the direction and not the absolute value of the cosine is used. This form is used because the zone should be sheltered by the rest of the house on one side and exposed to the outside on the other. The results of the regression analysis with the direction term show an increase in the r^2 to 0.830. Thus, the direction term is able to explain 35% of the deviation of the data about the model that was not explained by the linear model. The value of θ_o is estimated to be $34^o \pm 5^o$. This direction corresponds to a wind impinging nearly perpendicular to the front of the house. This is a reasonable value since the only windows downstairs are located on the front wall, the side walls are sheltered by a house to one side and the attached garage on the other, the back wall is sheltered somewhat by the rear deck, and the effect of the wind on the front wall could be increased by the front landscaping that is sloping up to the house. A scatter plot of the predicted versus measured downstairs infiltration rates the the fall period is displayed in Fig. 8. This plot shows the agreement between the predicted and measured infiltration rates ($r^2 = 0.83$) for the 229 observations.

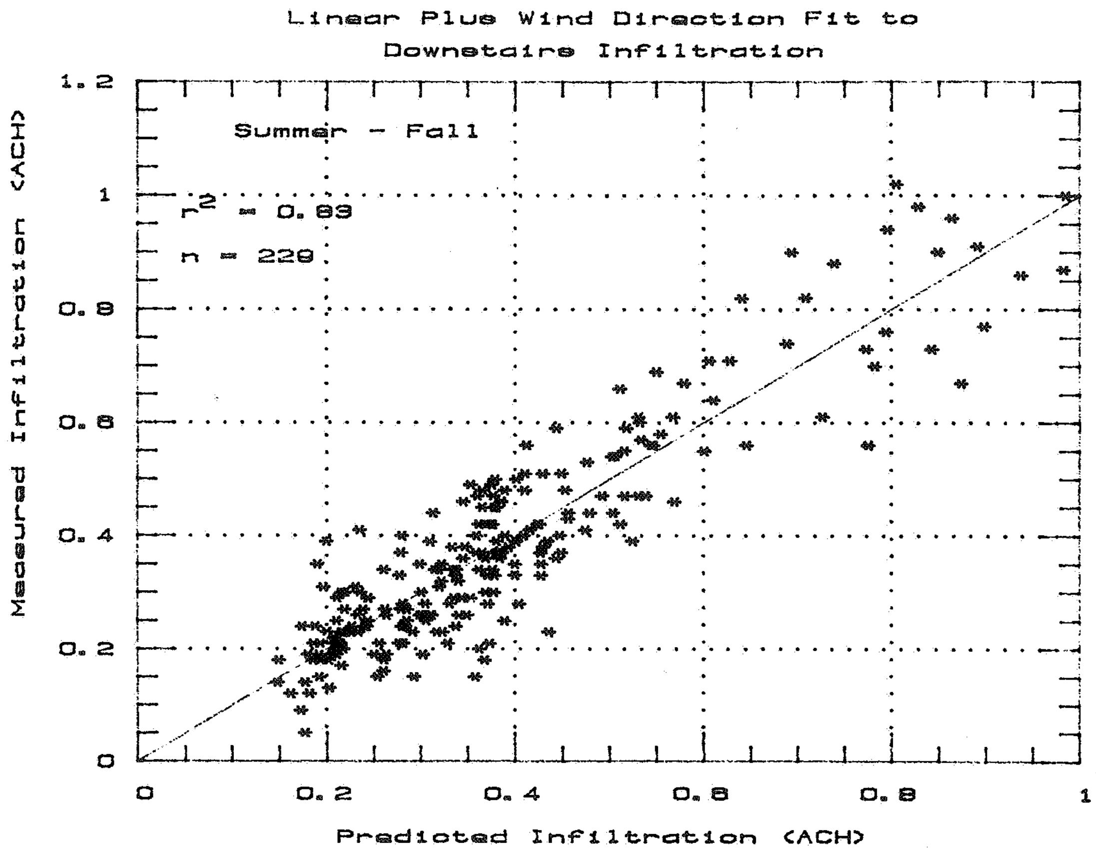

Fig. 8. Scatter plot of the measured air infiltration versus the predicted air infiltration using downstairs data and the linear model with wind direction.

5. CONCLUSIONS

This paper has presented a number of ways of viewing seasonal air infiltration data as collected by constant concentration tracer gas methods. The data clearly point out the variability of ventilation provided by air infiltration due to both weather and house location. The data show that the infiltrtion in the upstairs never reached the minimum level recommended by standard 62 and that the whole house infiltration often did not reach the minimum. To fulfill ventilation requirements use of window openings or mechanical ventilation would appear to be necessary to supplement or substitute for the inadequate air infiltration during certain portions of the year. From a modelling standpoint, the ability to look at details of where the air infiltration is taking place in the house, as well as the seasonal weather information, adds to the capabilities of generating an appropriate physical model for the air infiltration events. The regression analysis indicates that the infiltration is accurately predicted with a additive model of delta temperature and windspeed. More complex models which included the effect of wind direction and more sophisticated combinations of the parameters added little to the predictive capability of the model.

6. ACKNOWLEDGEMENTS

The study in the GEOMET research houses in Gaithersburg, Maryland is supported by the Electrical Power Research Institute under contract number RP2034-1. The research relating to air infiltration measurement methods and advancements in CCTG technology is supported by the U.S. Department of Energy, Building Systems Division through Lawrence Berkeley Laboratory.

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