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FIELD STUDY COMPARISONS OF CONSTANT CONCENTRATION AND PFT INFILTRATION MEASUREMENTS

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SYNOPSIS

The accuracy of tracer gas measurements of building air infiltration rates has been a widely discussed topic. One question that has often come up at past AIVC conferences is the ability of passive methods, such as the Perfluorocarbon Tracer (PFT) method, to accurately measure fluctuation air flow rates. A series of field studies is being conducted to compare the air infiltration measurements of the constant concentration tracer gas (CCTG) and PFT methods and provide recommendations for their proper implementation in the field.

The field studies include side-by-side measurements of multi-zone air infiltration rates using the CCTG and PFT methods. The results are reported from two tests in an unoccupied single-family house and eight tests in an occupied house. Test periods varied from one to three weeks. The measurements from the unoccupied house showed that there were no major discrepancies between the two methods. The PFT measurements in the occupied house were consistantly lower than those by the CCTG method. Warm weather periods with substantial, periodic airing resulted in the PFT method producing underprediction errors greater than 30%. During the cold weather periods when the fluctuation in the infiltration rate was due to weather changes and a small amount of airing, the underprediction error ranged from 5 to 29%.

1.0 INTRODUCTION

The Perfluorocarbon Tracer (PFT) approach, as developed by Dietz et al[1] at the Brookhaven National Laboratories (BNL), is a efficient method for field measurements of multi-zone air flow rates and studies of indoor air pollutants. Questions have been raised about the accuracy of the method since it relies upon natural air movement in the zones for tracer mixing and some of the equipment used is presently unfamilar to much of the air infiltration research community. It has also been recognized that due to an approximation in the development of the air flow rate computation, the technique will generally underestimate the average air infiltration when the infiltration rate is not steady.

The purpose of this study is to evaluate the accuracy of field air flow measurements using the PFT technique. The initial portion of the study analyzes the expected error in the flow measurements resulting from inaccuracies in the PFT equipment. Simultaneous PFT and constant concentration tracer gas (CCTG) field measurements are then conducted to judge the actual performance of the method. These measurements are performed in unoccupied and occupied single family houses under various weather conditions.

2.0 DESCRIPTION AND ACCURACY OF SYSTEMS

2.1 Constant Concentration System

The constant concentration tracer gas system measures the air infiltration rate in separate zones of a multi-zone building by keeping the concentration of a single tracer gas constant at a target level in all the zones. This is accomplished by varying the tracer injection rate in each zone according to the concentration measurements and estimated air infiltration rates in the zones. Using this method, the air infiltration is approximately equal to the tracer injection rate for the zone divided by the target concentration.

The CCTG measurements were performed using two different 10 zone systems developed at Princeton University[2,3]. Both use sulphur hexaflouride (SF_6) as a tracer gas with target concentrations ranging from 50 to 350 parts per billion (ppb). Each system measures the concentration of SF_6 using a gas chromatograph (GC) with an electron capture detector (ECD). The original system has an aluminum oxide column and operates with a 60 second sample time. The most recent model, system two, uses a moisture trap, molecular sieve columns, and a backflushing arrangement to achieve a reduced sample time of 30 seconds (if necessary the sample time can be reduced to 15 seconds). Both systems have been modified to provide hourly adjustment for GC drift, on site graphic display of data, and remote access of on-going and past data via telecommunications.

Errors in the infiltration rates measured by the CCTG technique are the result of nonuniform mixing in a zone, fluctuations in the flow rates, and uncertainty in the injection flow rate, concentration measurement, concentration of the injection gas, and concentration of the calibration gas. For typical system operating conditions, a high degree of intrazone mixing, and adequate physical divisions between zones, the uncertainty in the air infiltration measurement is approximately 5%[4]. Since the unoccupied house had a large open staircase between the downstairs and upstairs the uncertainty in the air infiltration measurements is assumed to be 10%. The uncertainty of the measurements in the occupied house are also assumed to be 10% because no mixing fans were used and there were sometimes large fluctuations in the flow rates due to the opening and closing of windows (i.e. airing).

2.2 Perfluorocarbon Tracer System

The PFT method is a passive, constant emission tracer gas technique which can be used to measure average infiltration and interzone air flow rates in a multi-zone building. The measurements are performed by placing a constant source (or emitter) of a different type of tracer gas in each zone of the building and recording the average concentration of each gas in each zone.

A detailed description of the equations used to compute the multizone air flow rates is presented in Dietz et al[1]. A discussion of the development of these equations for a single zone case is presented here to illustrate the underprediction problem of passive methods. For a single zone building when the testing period is sufficiently long (greater than two to four days), the tracer emission rate is equal to the product of the concentration and the infiltration rate. Given a relatively constant emission rate, the average infiltration rate is equal to the product of the emission rate and the average of the inverse of the concentration. Because it is not practical to measure the average inverse concentration, the inverse of the average concentration is used instead. The two quantities are identical when the infiltration rate is steady but the inverse of the average is smaller for fluctuating infiltration rates. The effect of using the inverse average concentration on the underprediction of infiltration rates is discussed in the results section.

The passive sources and Capillary Adsorption Tube Samplers (CATS) used in these tests are the same as those developed at BNL[1]. The CATS are small glass tubes about the size of a cigarette. During sampling one of the two caps on the ends of the tube is removed allowing the tracer gases to diffuse into the tube where they are adsorbed by a charcoal-like material (Ambersorb) located near the center of the tube. The gas adsorbed in the CATS is driven off by heating the tube to 400-450°C in a desorbsion rack and the sample is sent to the GC. The GC measures the volume of tracer gas contained on the CATS. By knowing the tracer diffusion rate and exposure time of the CATS, the tracer gas volume can be converted to an average concentration. Experiments performed in our test chamber show that the standard deviation of the measured volume of a group of 10 CATS exposed for one day was 2.4% of the mean. Since this deviation is less than or equal to the accuracy of the GC, the precision of the CATS is assumed to be 2%. The passive CATS volume measurements were compared to samples taken directly from the test chamber and analyzed on the GC. The data from the tests indicate that volume measurements by the two methods were not statistically significant. Thus, the accuracy of the CATS sampling process is assumed to be 2%.

The passive sources consist of a small metal tube half the size of a cigarette containing the liquid tracer gas with a silicone rubber plug on one end. The tubes are filled with 0.4 mL of a individual tracer and last for two to seven years. A drawback to this type of emitter is that the emission rate is strongly temperature sensitive. The variation in temperature is approximately 5% per degree celsius and is described by the following relation[5]:

$$S_1 = S_2 \exp(-4000(1/T_1 - 1/T_2)) \qquad (1)$$

where S_i = steady state source rate measured at T_i (K)

The response of the emission rate to changes in temperature is not immediate - the steady-state rate is reached after 10 to 14 days. Thus, as long as there is not a steady trend in the indoor temperature during the measurement period, under typical conditions it is reasonable to use the average temperature over the test period to adjust the emission rate and to assume that the emission rate is constant. In our measurements it is assumed that the temperatures of the emitters are known to an accuracy of 2°C which yields an accuracy of 10% for the source rate.

The gas chromatograph used in the study is similar to the BNL two-trap atmospheric model[6]. Although it can provide direct ambient measurements, for this study the system was used only to analyze CATSs from the field. The CATSs are analyzed by placing them in a desorbsion rack where they are individually heated to drive the adsorbed gases onto one of the two GC traps. The GC trap is flash heated to 400°C to send the gases through a palladium catalyst, nafion drier, 15cm pre-column, 91.5cm analytical column, and a ECD. Backflushing through the catalyst, drier, and pre-column is provided at the proper time to prevent heavier gases from entering the analytical column. The desorbsion of a CATS and analysis is completed in nine minutes. A chromatogram of the three gases presently used by our group (perfluoromethylcyclopentane (PMCP), perfluoromethylcyclohexane (PMCH), perfluorodimethylcyclohexane (PDCH)) is displayed in figure 1. The desorbsion rack and GC are connected to a microcomputer-based data acquisition and control system. The software for the system, developed at Princeton University, provides automated analysis of a full (23 position) rack, system calibration, and storage of the measurements in a disk file. The disk file can be read directly into a multi-zone air flow rate computation program.

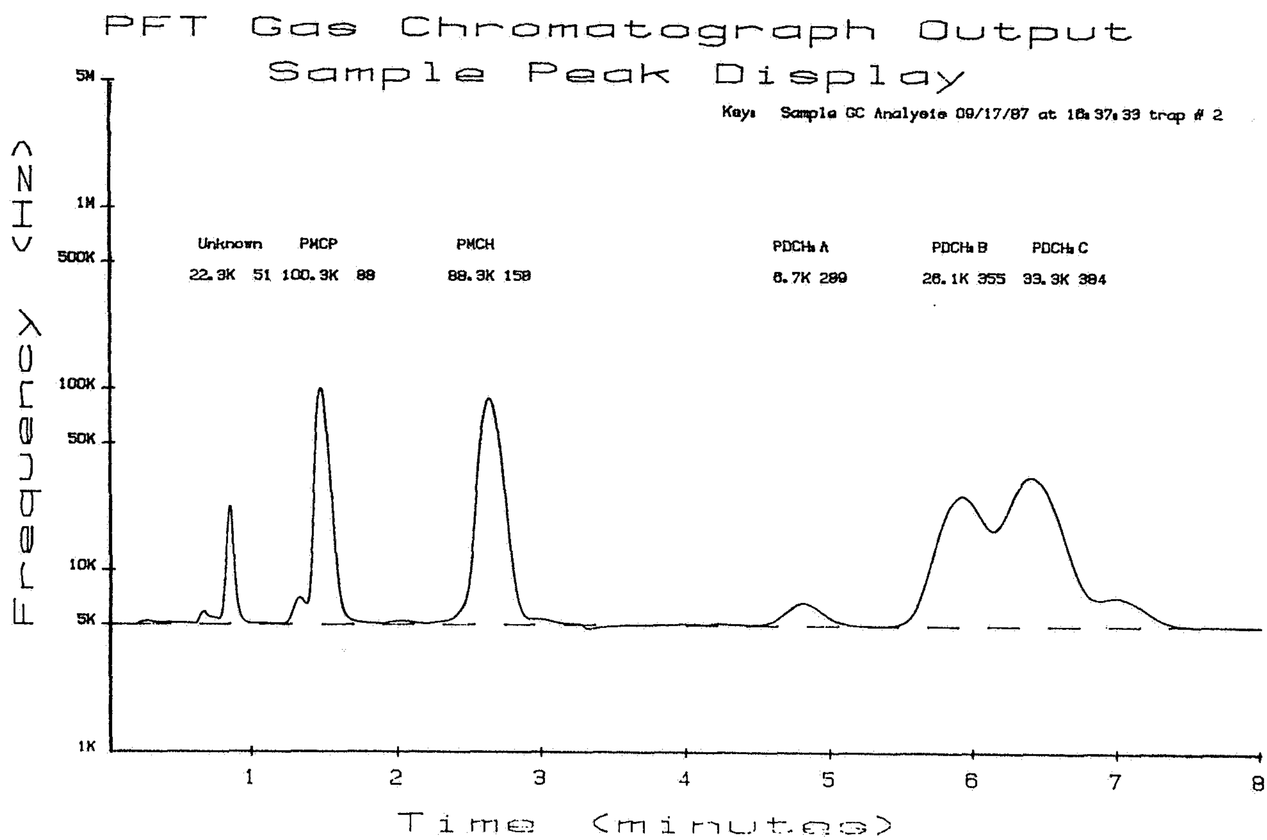


Figure 1. Sample chromatogram showing peaks from three different PFT gases: PMCP, PMCH, PDCH.

The PFT analysis system is calibrated by measuring the peak height response of each of the gases over a range of gas volumes. Calibrations are presently performed for volumes from 5 to 500 pico liters. If necessary the range could be expanded or shifted down by a factor of 40. A typical calibration curve for the three gases is displayed in figure 2. The data are fit to a third order polynomial equation using a weighted least squares regression technique. The difference between the sample volume and that computed from the calibration equation is seldom greater than 3%. The calibration of the system typically drifts a few percent from day to day. To adjust for this drift three CATSs, with known volumes of tracer gas (reference CATS), are analyzed with each rack of field CATS. The difference between the known and assumed volumes are used for a linearly proportional adjustment of the calibration curves. Our tests have shown the drift to be proportional over the entire calibration range.

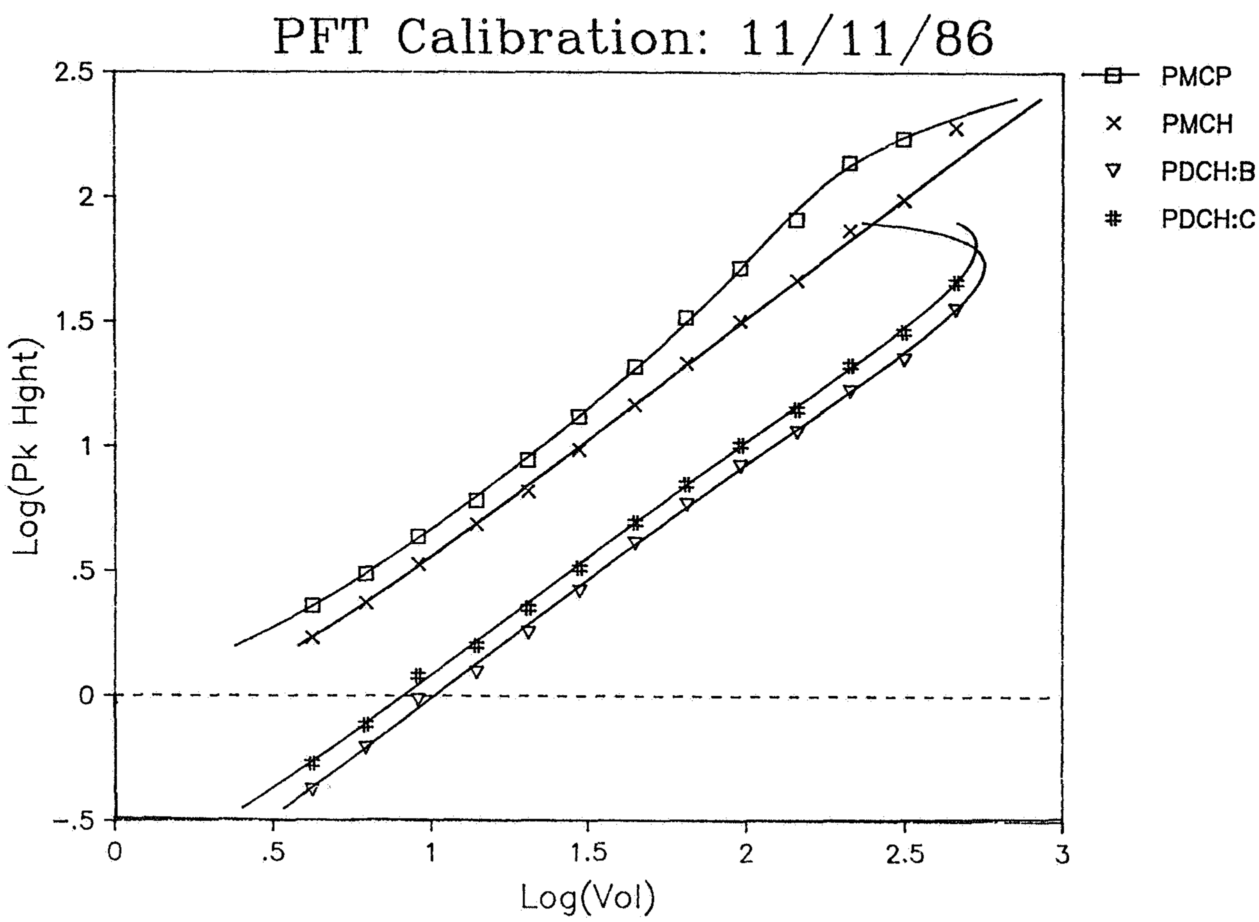


Figure 2. Typical calibration curve for PFT gases. The curve fit is a third order polynomial.

The calibration samples and reference CATS are constructed by flowing a calibration gas of known concentration through a CATS for a specified time at a known rate. The accuracy of the timing mechanism and flow measuring device is less than or equal to 1%. Unfortunately, commercially produced calibration gases of high accuracy are not available. In order to establish the PFT gas concentrations in the calibration cylinder, a series of calibration gas exchanges have been conducted with BNL. Additional standards were made at Princeton using the gas emitted by sources located in a sealed flask placed in a constant temperature bath. The standards were produced by flowing air through the flask at a constant, measured rate and collecting the air in a sample bag. With this method, the concentration of the sample bag is equal to the tracer gas source rate divided by the air flow rate. The GC measurements from the BNL gas, the sample bags, and the calibration cylinder have been compared to determine the concentration of the cylinder. From the range of values obtained in this process, it is belived that the accuracy of the PFT gas concentrations in the cylinder is approximately 8%.

This section has presented the errors associated with each piece of equipment of the PFT system. In addition to these errors there is also an error due to the nonnuiformity of the concentration in the zone. This error is chosen to be either the standard deviation of the CATS measurements in the zone or 5% - whichever is greater. Given the uncertainties of the variables in the flow equation, the uncertainty of the each air flow rate can be approximated by the Euclidean summation of the uncertainty due to each variable in the flow rate equation[7]. Using this method the uncertainty of the infiltration rates in the occupied house ranged from 15 to 20% for the downstairs, 17 to 55% for the upstairs, and 14 to 24% for the whole house.

3.0 DESCRIPTION OF TEST HOUSES

3.1 Unoccupied House

The unoccupied house is a bi-level, single-family residence located northwest of Washington, D.C.. The house is heated with a heat pump warm air system. There are supply vents in each zone of the house and the two return vents are located upstairs. Infiltration measurements in this structure have been described in previous AIVC publications, including a companion paper in this conference[8,9]. The CCTG system was installed to measure infitration in the downstairs and five separate upstair zones. For the purposes of this study the flow rates in the five upstair zones have been added together and are designated as the single upstair zone.

The PFT gases were released by placing two PMCH emitters in the downstairs and five PDCH emitters in the upstairs. The concentration measurements were obtained using three CATS in the downstairs and six to seven upstairs. The temperature in the upstairs and downstairs was measured and recored on a separate data acquisistion system. The average temperatures over the sample period are used to adjust the tracer emission rates.

3.2 Occupied House

The occupied house is a single story ranch house with basement located in central New Jersey. It is heated with a heat pump, oil furnace backup, warm air system. The basement is unfurnished and not purposely heated, i.e., all supply and return vents are located upstairs. The total volume of the two levels is 767 cubic meters. The house is part of a seven-home radon study[10] and is designated as house #5 in the figures. As part of the radon study, side-by-side CCTG and PFT air flow measurements have been conducted for nine consecutive months.

The CCTG system has been installed to measure infiltration in seven upstair zones and two downstair zones. Similar to the unoccupied house, the separate zones in the upstairs and downstairs have been combined and infiltration measurements are reported for these two zones of the building. For the PFT measurements the house was also treated as a two zone building. PMCH was released in the basement using three emitters and three PDCH emitters were distributed upstairs. The concentration measurements were carried out using three CATSs upstairs, three downstairs, one replicate downstairs, and one blank (i.e. unexposed) downstairs. The temperatures in the two zones were recorded on a separate data acquisition system and the average temperatures over the sample period are used to adjust the tracer emission rates.

4.0 FIELD TEST RESULTS

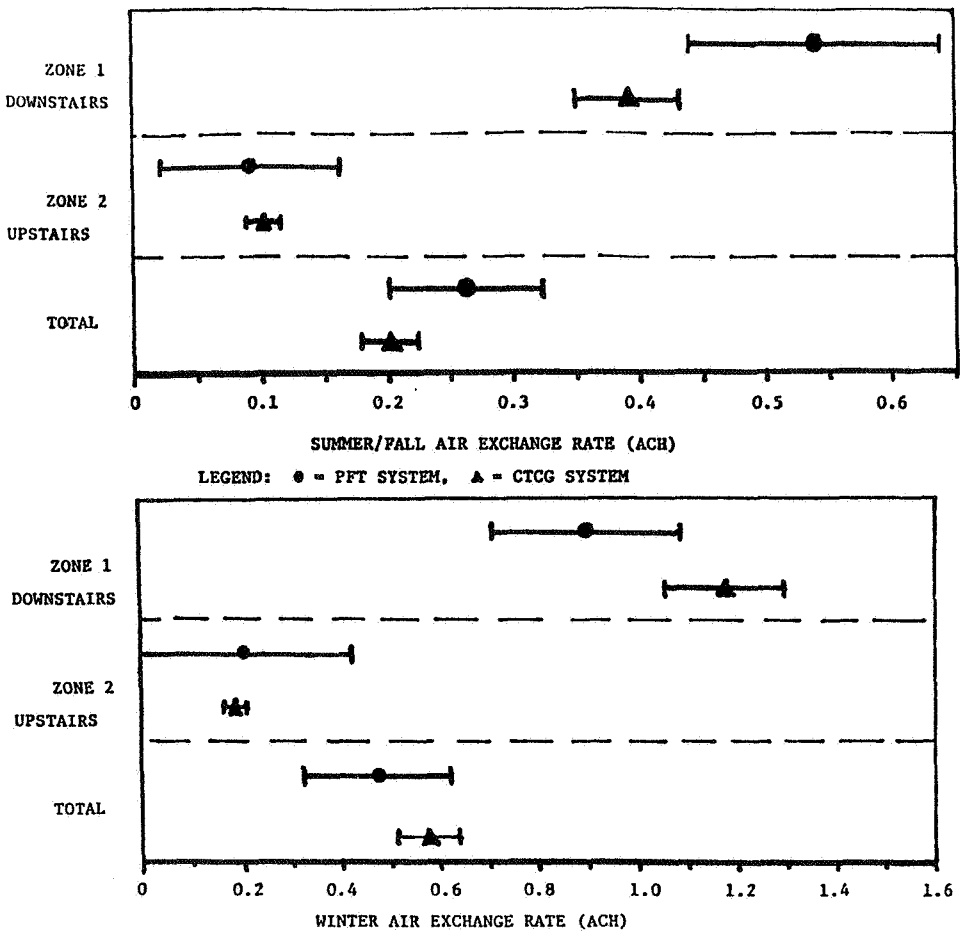
4.1 Unoccupied House

The simultaneous PFT and CCTG measurements were performed on two separate occations. The first test was conducted from August 21st, 1986 to September 9th. The second test started January 14th, 1987 and ended January 22nd. Since the CCTG system was interrupted every second day to perform interzone tests and the GC was not always functioning properly, the CCTG data does not span the entire time of the PFT measurements. For the first period the CCTG measurements cover 66% of the total time and they cover 77% of the second.

A comparison of the CCTG and PFT data for both time periods is displayed in figure 3. The measured average infiltration rates for the two separate zones and whole house are shown along with the corresponding uncertainties. For all of the values the uncertainties of the two methods overlap. This indicates that there are no major discrepancies between the two methods. From this limited data set (with incomplete coverage by the CCTG method), it is difficult to draw any conclusions about the tendency of the PFT method to measure lower values than the CCTG method.

4.2 Occupied House

The PFT measurements from November 1986 to May 1987 have been analyzed. These 15 tests span time periods from one to three



PFT/CCTG COMPARISON FOR UNOCCUPIED
TEST HOUSE

Figure 3. Results of the CCTG and PFT measurements for the two test periods. The error bars indicate the uncertainties of the measurements.

weeks. The CCTG system was operating in the house for 10 of the test periods. The results reported here include eight periods when the CCTG system was operating for at least 85% of the period. On average, the CCTG data covers 93% of the PFT period.

A comparison of the infiltration measurements of the two methods is displayed in figure 4. The data show that the PFT measurements are consistantly lower than those by the CCTG method. Figure 5 displays the same comparison for the whole house data with error bars indicating the uncertainty of the measurements (note - one of the data points is off scale and has the value: CCTG - 1.30, PFT- 0.21). Unlike the results from the unoccupied house, in only one of the eight measurements does the uncertainty explain the difference between the two methods.

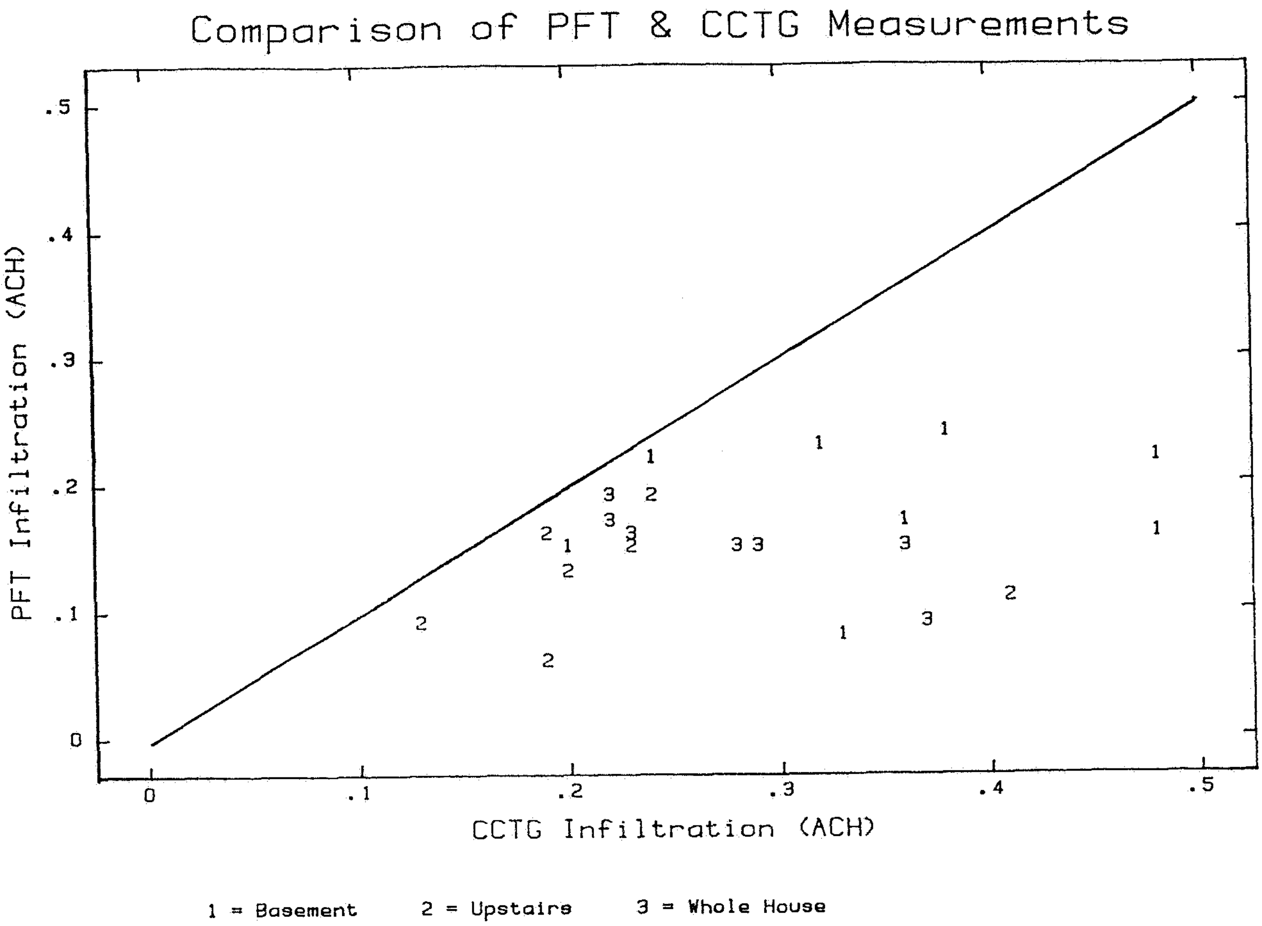


Figure 4. Results of the CCTG and PFT measurements for the eight test periods. The data include the infiltration measurements for the basement, upstairs, and whole house.

A possible explanation for this difference is that the occupants of house #5 are causing large fluctuations in the infiltration rate during some of the periods. Figures 6 and 7 display the time history of the CCTG measurements in house #5 for the eighth and twelfth periods. During the twelfth period there appears to be a fairly regular pattern of airing each afternoon. At these times the infiltration in the basement often increases by a factor of ten over its normal value (note - data above 1.0 are not shown on the graph). In comparison, the infiltration values shown in period eight do not fluctuate as strongly or as regularly.

From the analysis presented in section 2.2, it is expected that the relative magnitude of the fluctation will effect the level of underprediction of the PFT method. For the following analysis the standard deviation of the infiltration rate divided by the mean (normalized standard deviation - NSD), as computed from the CCTG data, is used as a measure of the fluctuation. This variable is plotted against the percent underprediction of the PFT method (the

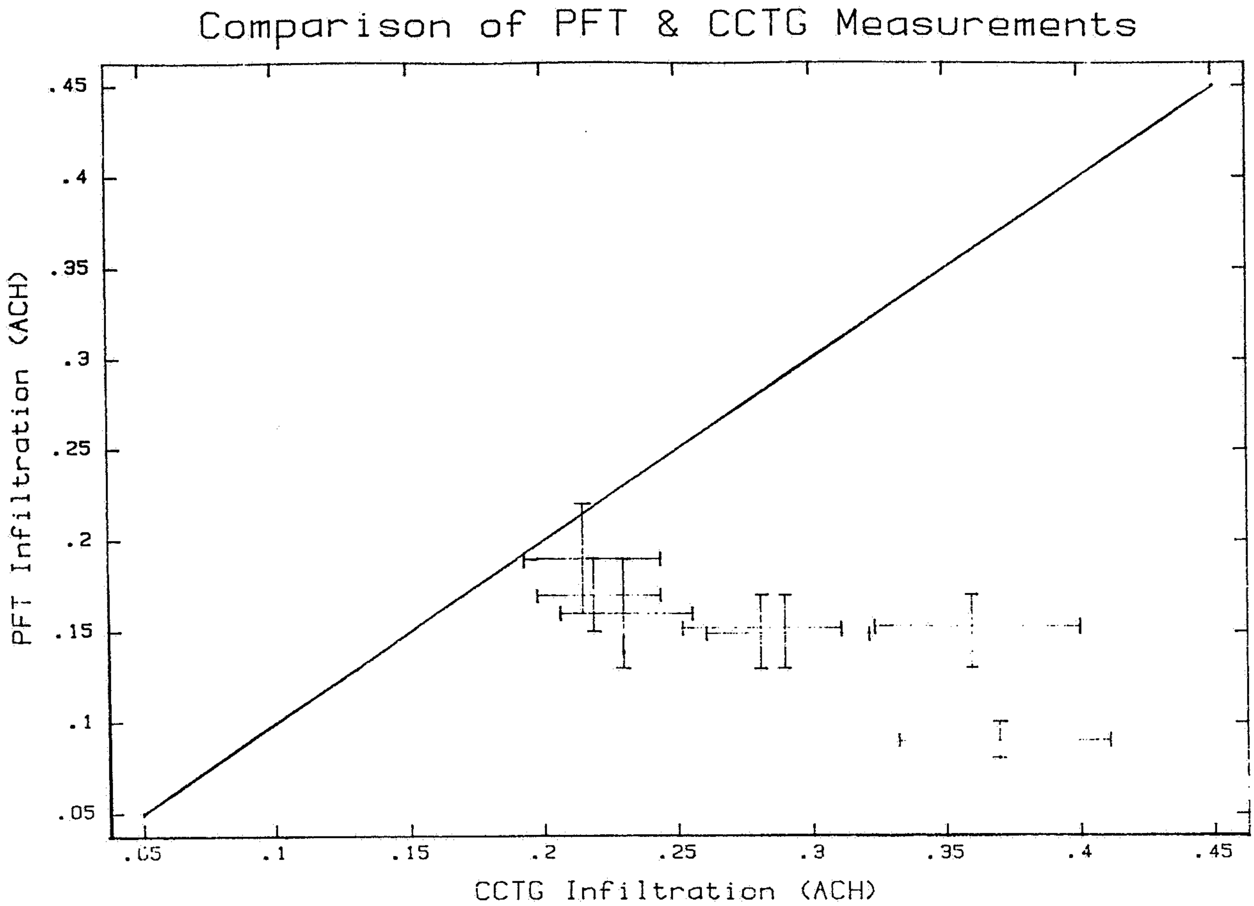


Figure 5. A comparison of the two methods for the whole house data. Error bars are included as a representation of the uncertainty of the measurements.

measurement by the CCTG method minus that by the PFT method divided by that by the CCTG - all multiplied by 100) in figure 8. The results show that there is a general trend of greater underprediction with larger deviations in the flow rate. However, there is quite a bit of scatter in the data that is not explained by the NSD.

The expected magnitude of the underprediction error can be more accurately determined from the CCTG time history data. These data are used with the single zone tracer gas equation to simulate the tracer concentration for the PFT method. The simulation is performed using the whole house data and treating the house as a single zone with one tracer gas being emitted. A two zone simulation is not possible since the CCTG system does not typically measure interzone flow rates. The constant tracer source rate is divided by the average simulated concentration to compute the simulated PFT measurement. The simulations were performed using the CCTG data from the eight measurement periods. A comparison of the percent underprediction of the measured PFT flow rate and those from the simulated rates is displayed in figure 9. The plot shows that there is a good correlation between

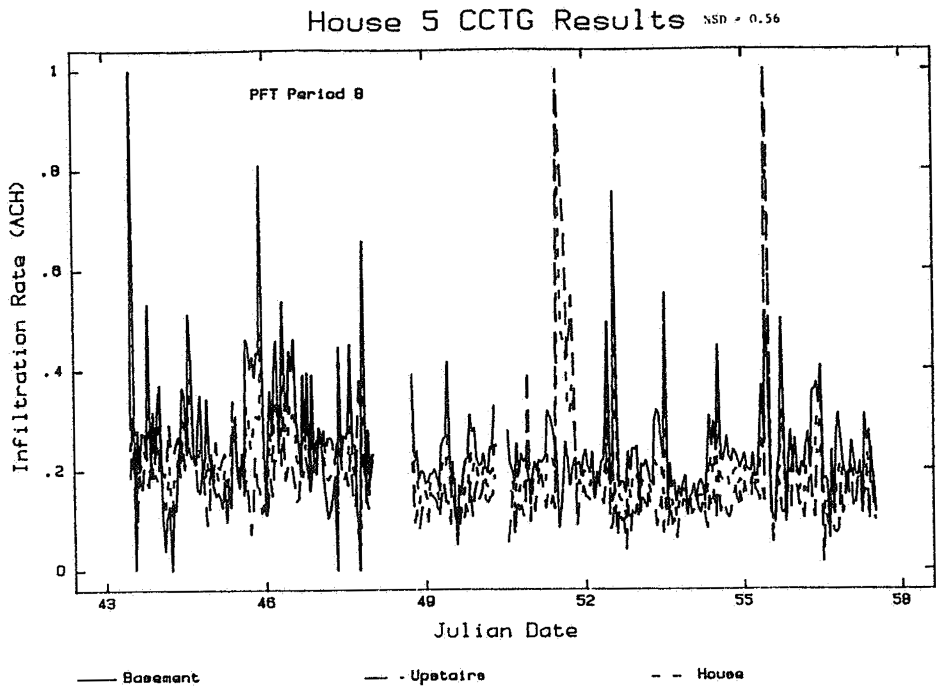


Figure 6. CCTG measurements of the infiltration during a winter measurement period. This period had the lowest NSD (0.56).

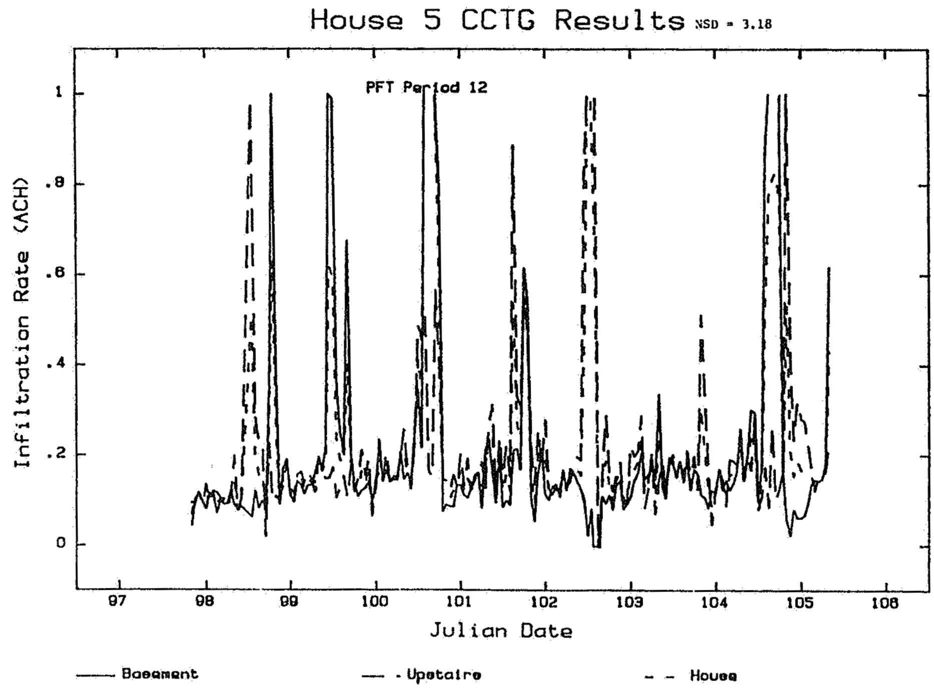


Figure 7. CCTG measurements of the infiltration during a warm weather measurement period. This period had the highest NSD (3.18) and the most evident airing.

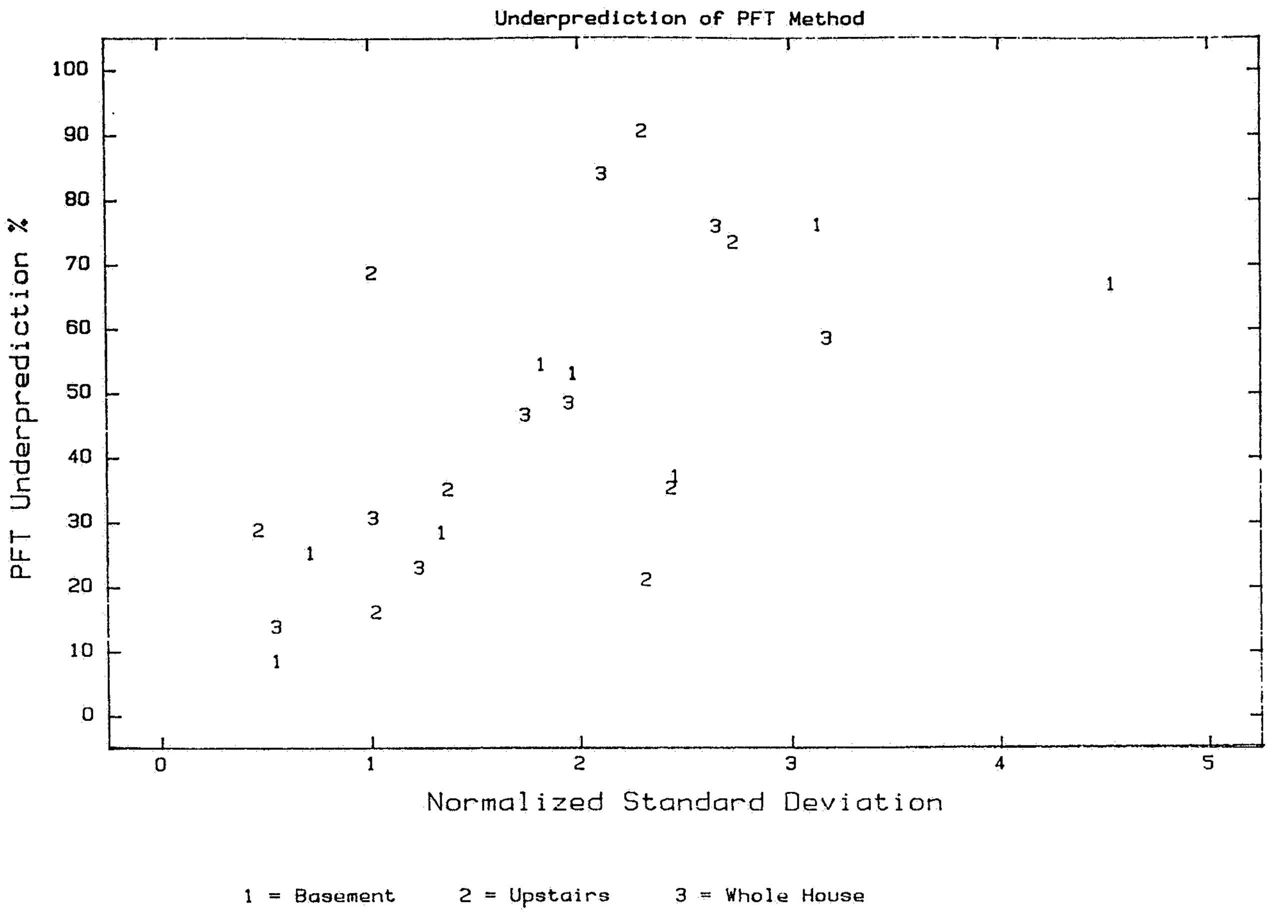


Figure 8. Variation of the percent underprediction of the PFT method with the relative magnitude of the infiltration rate fluctuation. The fluctuation is measured by the normalized standard deviation of the infiltration as reported by the CCTG method.

the measured and simulated underprediction. The strong relationship between the measured and simulated values indicates that the variation in the flow rate is responsible for much of the underprediction of the PFT method. However, the measured error is consistantly greater than the simulated error. This bias could be due to either the simplified nature of the simulation (one zone instead of two with interzones flows) or a bias in the two measurement systems.

The results of the simulations show that the underestimation error of the PFT method is large when there are strong fluctuations in the flow rate. However, in some instances the error is as low as 5%. The four periods with the largest simulated percent underprediction (32 to 78%) occurred during the spring when the average outdoor temperatures varied from 12 to 20°C. The high levels of NSD (1.8 to 3.2) and large, periodic excursions in the infiltration (see figure 7) indicate occupant airing during this warm weather. Thus, variation in the infiltration as a result of

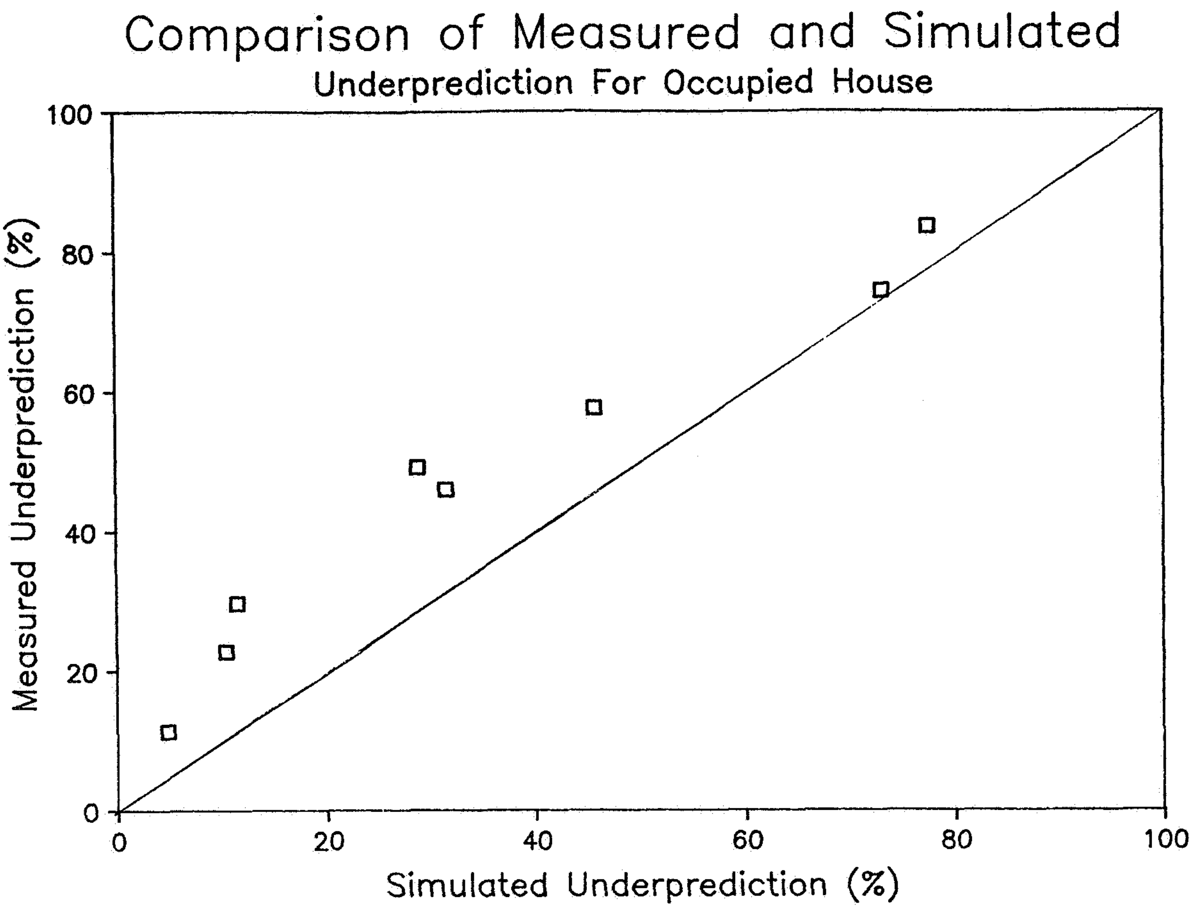


Figure 9. A comparison of the measured to simulated percent underprediction for the eight test periods.

occupant airing, and not changes in the weather, is causing large errors in the PFT measurements. The periods with the smallest error (5 to 29%) occurred during the winter when the average outdoor temperature varied from -1 to 5°C. The lower NSDs (0.6 to 2.0) and fewer infiltration excursions (see figure 6) indicate that airing is still present, but to a lesser degree, in the cold weather. The reduced airing corresponds to underprediction errors less than 30%. In summation, the data show that regular occupant airing can result in PFT underestimation errors greater than 30% but that infiltration fluctuations due to weather with only small amounts of airing result in errors between 5 to 30%.

5.0 CONCLUSIONS

The PFT approach has proven to be an efficent way to conduct field measurements of air infiltration rates in multi-zone buildings. Multiple measurements can be performed in many houses relatively easily. The laboratory analysis equipment is complex, but after the system became operational it operated reliably. The inherent errors of the PFT equipment and non-uniform mixing in a building corresponded to uncertainties ranging from 14 to 24% for the whole house infiltration measurements in the occupied house. The substantial, periodic airing that occurred during warm weather resulted in the PFT method producing underprediction errors greater than 30%. During periods when the infiltration fluctuation was due to weather changes and small amounts of airing the underprediction error ranged from 5 to 29%.

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