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AIR EXCHANGE RATES BASED UPON INDIVIDUAL ROOM AND SINGLE CELL MEASUREMENTS

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SYNOPSIS

For more than two years a series of detailed air infiltration measurements have been conducted over the complete yearly weather cycle on two identical side-by-side test houses in Gaithersburg, Maryland, USA. These measurements have been part of a broad study of the interaction of air infiltration, indoor air quality and energy in tightly constructed, well-insulated homes. The standard method of collecting air infiltration data throughout the study has been tracer gas decay. Operation of the duct air circulation fans has transformed each house into a single well-mixed cell. Natural air mixing in the upper and lower floors, with the fan operated occasionally, results in two cell behavior. The present phase of the air infiltration portion of the study has been to use constant concentration tracer gas equipment to study the air infiltration in six individual zones. This has allowed comparisons between the two methods as well as looking at the air infiltration profile in a much more detailed way. For example, the average infiltration rates for the control house using the two measurement methods are quite similar, but detailed information is now available on individual zone air infiltration rates and the effects of mechanical systems and weather influences on the zones. This paper compares the air infiltration measurement method results in the well-documented control house.

1.0 INTRODUCTION

In determining the air infiltration levels in our housing stock, in many countries we are evaluating our primary sources of ventilation. In any building situation where quantification of these important air infiltration values is desired, there is a wide choice of measurement methods with an associated degree of measurement complexity and detail in the information provided.[1] Examples include single location, tracer gas decay measurements or perhaps an interpretation of pressurization information on the building, as the simplest ways to estimate air infiltration values. At the other end of the information and complexity scale are constant-concentration tracer gas (CCTG) systems which can sample each zone in the house or larger building. In addition, multiple tracer gases may be employed to document interzone air flows to complement the individual zone air infiltration/ventilation rates provided by the CCTG system.

Is important detail on the air infiltration/ventilation rates being missed because of the choice of a simple measurement approach? The physics of the air movement within the house can greatly aid in making even the simplest air infiltration/ventilation measurements representative. Natural mixing of the air within the house is one factor that aids the investigator in collecting pertinent information. When we are dealing with more than one floor or where zones are separated by significant distances and/or closed doors, one can anticipate variations in the AI measurements depending upon location. Air exchange rates based upon individual zones (cells) and those based on limited cell measurements will be discussed in this paper.

Air infiltration was studied over a complete yearly cycle as part of an ambitious study into the interrelationships between energy use and indoor air quality (IAQ) in tight, well insulated residences.[2-6] The study, funded by the Electric Power Research Institute, followed a strategy using side-by-side identical houses which were closely monitored for indoor air quality, energy, local weather and air infiltration from a centrally located instrumentation trailer as shown in Figure 1. In addition, as part of the total experimental plan, the research included detailed testing of such other factors as: building envelope tightness over the seasons, insulation performance evaluated by infrared scanning, testing of passive detection methods to evaluate IAQ, and additional methods to measure the air infiltration rates in the individual zones of the houses. This paper discusses the results of the constant-concentration tracer gas measurements evaluating air exchange rates in six zones and how they relate to the extensive study of air infiltration in these houses using one or two cell tracer gas decay methods.

Figure 1. Test Site Showing Experimental and Control Houses with Mobile Laboratory.

The house floor plan is shown in Figure 2 indicating floor area and volumes. One path of communication between the various rooms and floors is the duct system that is used to distribute conditioned air in the heating and cooling seasons and can be operated continuously or intermittently ("auto setting"). Further details of the various aspects of the research conducted in these houses can be found in References 2-6. In many respects, the extended test period of more than two years has transformed the houses into valuable research laboratories for GEOMET Technologies. This was considered to be an ideal location to demonstrate the ability to evaluate individual zone air infiltration rates using the CCTG measurement system developed at Princeton University with funding from the U.S. Department of Energy.

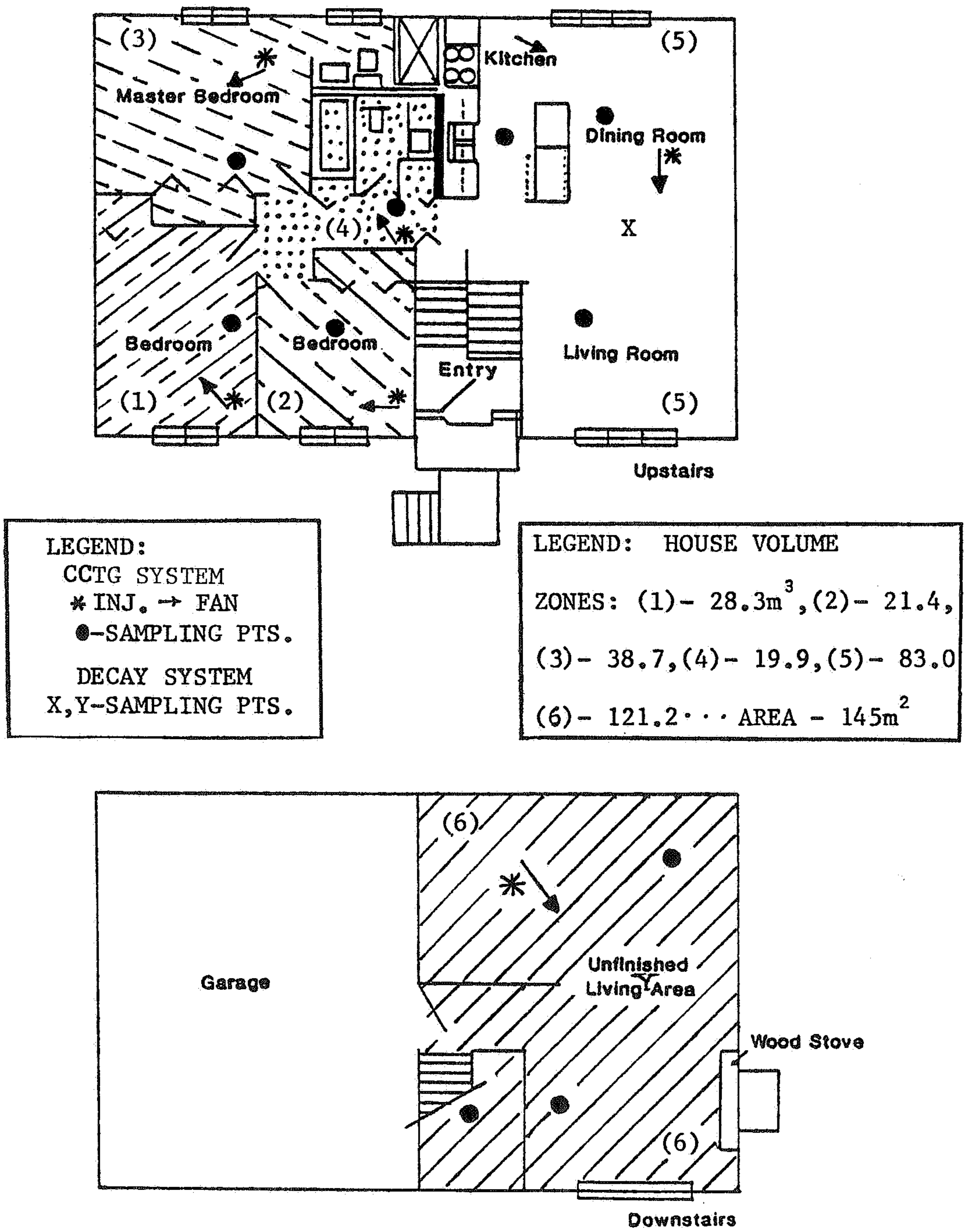

Figure 2 -
Floor plans, sampling points & fans, and volumes & floor areas of control house. Six zones evaluated for air infiltration by the constant concentration method are numbered.

Table 1

CONSTRUCTION CHARACTERISTICS OF STUDY HOUSES

GENERAL CHARACTERISITICS:

Exterior

Overall Dimensions	40 ft 5 in x 26 ft 8 in (12.3 x 8.1 m)
Foundation Wall	8 in cinder block extending 4 ft below grade
Exterior Walls	Aluminum siding above foundation knee wall
Windows	Metal frame, double-glazed
Sliding Door	Insulated glass
Doors	Steel with polyethylene foam core, doorsills with adjustable weather-stripping
Attic	Soffit vents and continuous ridge vent
Roof	Conventional asphalt shingle

Interior

Floor Area	1400 ft^2
Vertical Distance	16 ft 3 in (top of floor slab to main floor ceiling)
Walls	Wood studs placed 16 in on center, faced with gypsum board drywall

INSULATION/INFILTRATION BARRIER:

Attic	8 in of loose-fill between ceiling joists, R value equal to 30
Sill Sealer	Polyurethane foam between sill plate and floor surface
Walls	Unfaced 3.5 in glass fiber batts between joists, R value equal to 11
Vapor Barrier (Polyethylene)	From floor plate to ceiling, around windor and door openings, applied to ceiling joists extending 4 in from walls, overlapped at seams.

HVAC SYSTEM:	Rating
Air Conditioning--Electric Heat Pump	
Heat Pump Fan	1.2 A
Heat Pump Compressor	11.9 A
House Design Cooling Load	20,000 Btu/h
Heating--Electric Furnace	
Dual Circuits	40 A, 24 A
House Design Heating Load	24,500 Btu/h

2.0 THE HOUSES

The bi-level houses used in this study were built during the fall of 1982 as part of a new subdivision approximately 35 kilometers northwest of Washington, DC in Gaithersburg, Maryland. Two identical houses were constructed to somewhat relaxed building standards so that later retrofitting efforts could be made to improve the tightness of the building envelope. Table 1 summarizes important features of that construction. One of the houses, the experimental house, was subsequently retrofitted to achieve six air changes per hour (ACH) leakage rate at 50 pascals differential pressure, whereas the control house remained at 10 ACH @ 50 Pa throughout the period of testing.

3.0 DEPLOYMENT OF THE CCTG SYSTEM

The details of the constant-concentration tracer gas measurement system as used in these tests are to be found in Reference 7 and in the companion paper in this conference.[8] In order to make full use of the capabilities of the CCTG system it was necessary to carefully plan how it would be deployed in the control house at Gaithersburg. As Figure 2 points out, zones were assigned in the upper and lower levels of the house. Each of the six zones contained one sulphur hexafluoride tracer gas injection point (centrally fed by a plastic tube) located close to a small mixing fan necessary to circulate the air within that zone. Sampling in the smaller volume zones required only single sampling locations (as shown), whereas the larger zones such as the living room, dining room, kitchen zone (zone (5)) and the basement (zone (6)) required multiple point sampling. In each case, a single 1/8 inch diameter plastic tube was used to convey the zone air sample from the particular zone to the central control point of the CCTG system, but in the larger zones the tubing branched out to multiple sampling point locations. An additional fan was used in the larger zone (5) as noted in Figure 2.

The success of the operating CCTG system can be determined from its ability to maintain tracer gas concentrations within narrow bounds and thereby eliminate one zone from influencing the tracer gas concentration in adjacent zones. Table 2 is a printout of six hourly summaries of typical data recorded from the individual zones. The zones were actually sampled every six minutes

Table 2

HOURLY SUMMARIES OF CCTG DATA

```
Julian Day + fraction
20.9,12.2          Zone(1)              Zone(2)              Zone(3)              Zone(4)
89.4062,0.09, 150.1, 2.63,0.14, 149.9, 2.58,0.16, 150.1, 1.62,0.23, 150.6, 3.38,
0.08, 150.5, 3.53,1.00, 150.8, 3.17,0.46,5.7<-Wind Speed(mph)
20.8,12.3 Zone(5)          Zone(6)          ^----- AIave.(ACH)
89.4479,0.07, 150.5, 2.68,0.13, 150.0, 1.04,0.16, 150.0, 2.22,0.26, 149.6, 2.79,
0.08, 150.7, 3.26,1.03, 149.7, 3.10,0.47,6.8
20.6,12.2
89.4896,0.04, 154.7, 5.92,0.06, 151.6, 7.13,0.10, 150.9, 6.37,0.37, 149.9, 5.37,
0.04, 151.7, 6.28,1.03, 150.0, 7.45,0.45,6.1
20.5,12.1
89.5312,0.14, 149.1, 5.37,0.21, 149.6, 5.09,0.21, 149.9, 6.11,0.23, 151.5, 4.74,
0.13, 151.2, 6.34,1.12, 148.9, 4.06,0.54,7.1
20.3,12.0
89.5729,0.09, 150.8, 1.99,0.15, 150.6, 3.40,0.16, 150.6, 3.32,0.25, 149.8, 2.58,
0.08, 151.1, 3.34,1.10, 150.4, 5.98,0.50,6.4
20.2,12.0
89.6146,0.03, 152.0, 4.19,0.03, 153.3, 5.82,0.09, 153.7, 5.47,0.23, 152.2, 4.33,
0.02, 152.6, 4.22,0.89, 151.5, 5.23,0.38,5.2
```

Note Zone data includes:
AI rate (ACH), Concentration (ppb), Variation (ppb)

throughout each hour. The variation in tracer gas concentration, in hourly average, was held within approximately ±0.6% of the desired 150 ppb SF_6 concentration based upon a review of typical data, and over the hour the maximum tracer gas concentration excursion was approximately ±2.5%. These tracer gas concentration values insure a proper operation of the overall CCTG system based upon detailed error analyses. Again for additional CCTG system details see Refs. 7 and 8.

4.0 WIND AND TEMPERATURE DIFFERENCE PLOTS

The standard method of collecting air infiltration data in the two houses was through the use of SF_6 decay. Measurements were repeated every 15 minutes in each of the central locations upstairs and in the basements of both houses.[6] The locations X and Y are noted in Figure 2. It was observed that the magnitudes of the resultant air exchange measurements at the two locations tended to merge if the circulation fan in the air duct system was run continuously. This point will be discussed later.

To aid in the interpretation of the house air infiltration average data, the measurements were binned in narrow intervals of wind speed and velocity.[6] In all cases, as shown in Figures 3 and 4, a strong linear relationship between AI and the variables is apparent for both houses. The infiltration rate for the tighter experimental house is seen to be consistently lower than that of the control house.

To these original data plots has been added the information gathered using the CCTG system where the AI average is based upon volume averaging the individual air infiltration rates from the six zones. Comparing the results we observe that:

- The house AI average data, using the CCTG system, agrees closely with the infiltration rates for the control house using two zones and the SF_6 decay method.

- When the data sample sizes were comparable, the AI data scatter is noticeably reduced in the six zone averaging method with the CCTG system. Such comparisons, however, cannot be made in many of the bins because the March-April test window for the six zone testing was limited in temperature range.

5.0 AIR INFILTRATION DETAILS

5.1 Wind Direction

The CCTG data just discussed will now be reviewed for a case where adequate data points were available to allow discrimination between wind speed and direction over an extended range of wind speeds, as shown in Figure 5. Here the two sets of data points are for wind flowing from the direction of the neighboring experimental house vs. wind from all other directions. In the first data set, additional wind protection would be anticipated for the control house because of wind blockage by the experimental house and

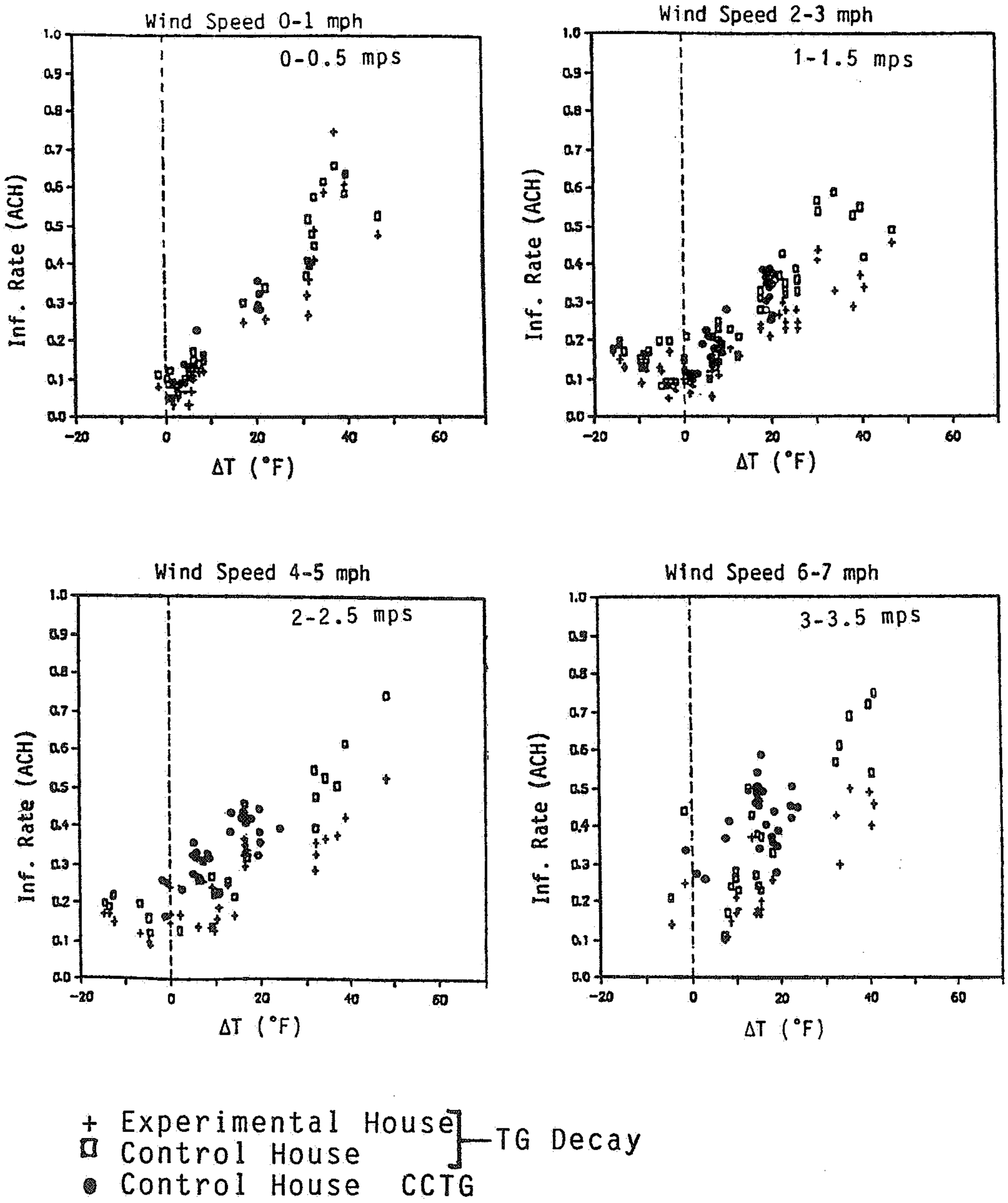

Figure 3. Binned wind speed data plotted to show the relationship of air infiltration rates to inside-outside temperature difference. Both tracer decay and constant concentration methods were used.

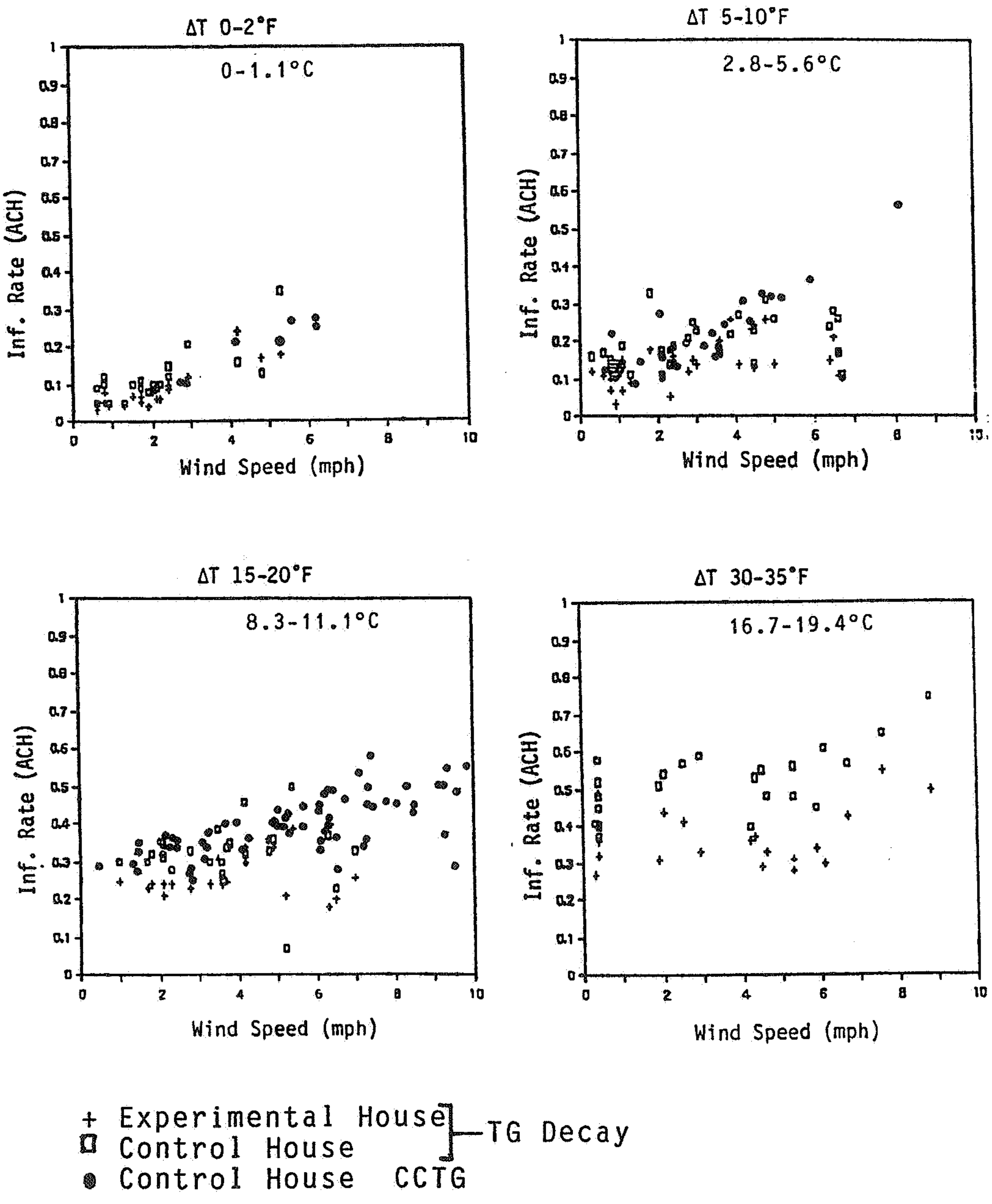

Figure 4. Binned differential temperature data plotted to show the relationship of air infiltration rates to wind-speed. Both tracer decay and constant concentration methods were used.

because the wind is impinging on the garage side of the control house (i.e., protecting the basement zone). Clearly the data indicate there is a wind directional effect; the average air infiltration drops in the control house for winds from that shielded direction, and the coefficient of determination (R^2) for the wind data from other directions is improved (R^2 increased to 0.8 from 0.66).

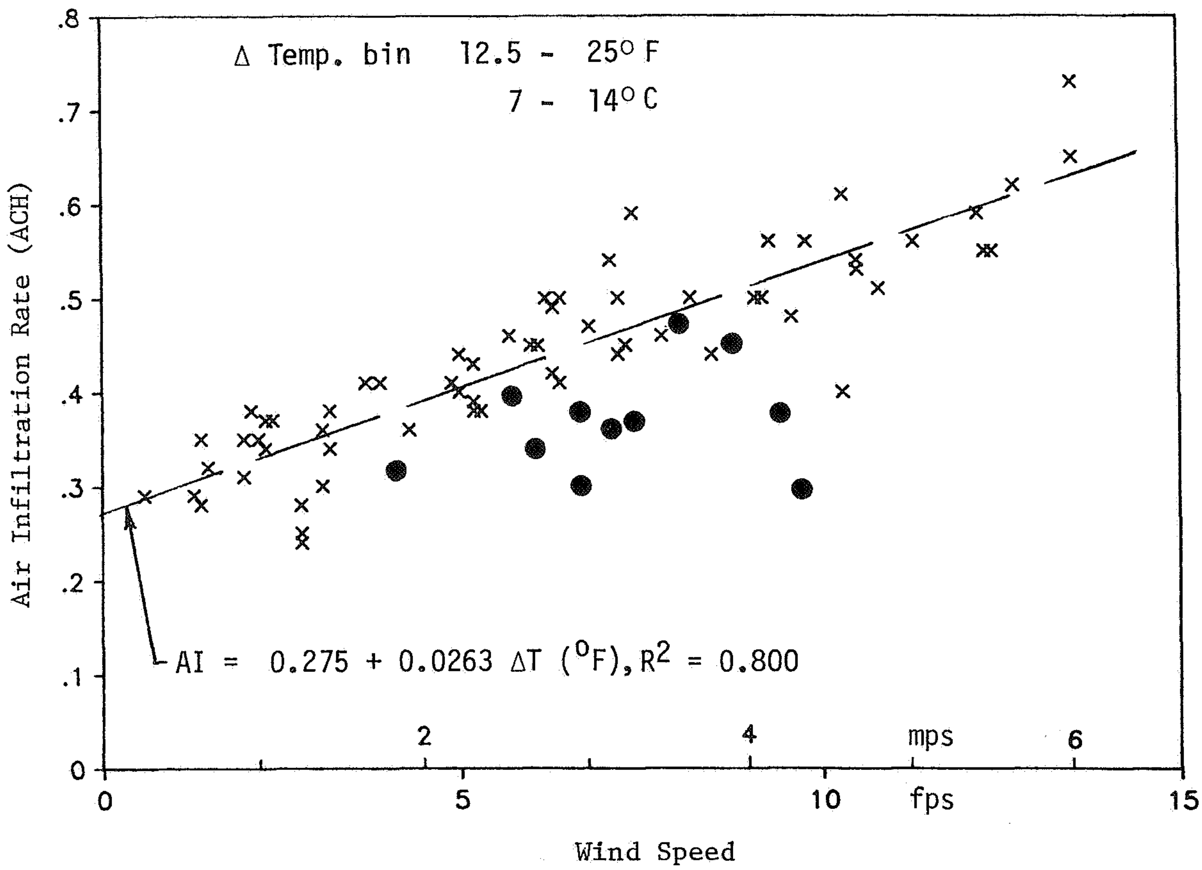

Figure 5. Binned temperature data showing the relationship of wind speed and air infiltration rate for wind direction. ● Wind from "protected" direction; x All other wind directions.

Spot checks were made of how wind direction (matching wind speed and temperature difference) can affect individual zone air exchange rates. For example, a 4.5 mps wind impinging on zone (5) raised the 0.14 AI rate to 0.33 ACH. At the same time the AI rate in zone (2) on the leeward side of the house dropped from 0.22 to 0.05 ACH. This is given as a typical example of what air infiltration changes can take place as a result of wind direction and that such changes should be of concern when considering whether or not individual room ventilation rates are being met. This point of ventilation adequacy was discussed with regard to ventilation standards in Reference 8 using the seasonal variations in air infiltration that have been documented in this research.

5.2 AI Rates in the Upper and Lower Floors of the Control House

Using the original SF_6 decay data to establish typical upper and lower floor air infiltration rates, it is evident in Figure 6 that noticeable differences are present, under the weather conditions specified, for the air circulation fan operated periodically and continuously.

Using those same specified weather conditions, but for a much narrower range of values, hourly data from the CCTG measurements have been used to form a similar average air exchange rate schematic for the upper and lower floors of the control house. Although the house average rates are similar to the original data, there are changes in the distribution. Upper level air exchange rates are reduced from 0.36 to 0.12 ACH for the periodic fan case, and correspondingly, the basement AI rates are found to be greater than the previous measurements.

In the case of the fan on continuously, the CCTG system was found to be capable of measuring difference in zonal air exchange rates although clearly these differences were substantially reduced from the fan being used periodically. Both the SF_6 decay and the constant concentration measurements point out that under continuous fan operation the upper floor and lower floor air exchange rates are no longer markedly different. These results point out that mechanical air movement, even without mechanical ventilation per se can help reduce weather dependence of the local ventilation rates.

Method Time Period	Control House	Environmental Conditions: Outdoor Temperature	Environmental Conditions: Wind Speed	Control House Constant-Concentration
	0.47 ± 0.23 ACH	WHOLE HOUSE AVERAGE		0.42 ± 0.02 ACH
SF_6 Decay May 6-12[a]	0.36 ±0.13	49.5°F ±10.4	4.6 mph ±3.5	0.12±0.02
CCTG Mar 30-Apr 2[a]	0.66 ±0.41	49.6°F ±0.6	4.7mph ±0.5	0.90±0.02
	0.30 ± 0.12 ACH			0.42 ± 0.02 ACH
SF_6 Decay May 13-19[b]	0.30 ±0.12	59.9°F ±11.2	4.1 mph ±2.0	0.21±0.03
CCTG Mar 29[b]	0.30 ±0.11	63.9°F ±1.8	4.2 mph ±0.3	0.46±0.04

[a]Circulation fan operated periodically.

[b]Circulation fan operated constantly.

Figure 6. Average upstairs and downstairs air infiltration rates determined by the tracer gas decay and constant concentration methods. Units are in ACH.

Perhaps the most dramatic illustration of the variations in air infiltration rates of the upper versus lower floor, and individual zones is found by plotting the air exchange over days of testing as shown in Figure 7. Variation between upper floor zones is of the order of 1 to 1 ranging to 5 to 1, between the lower and upper floors is as great as 10 to 1. Air exchange rates below 0.1 ACH are repeatedly shown to take place in many of the upper floor zones over the test period illustrated. This is best seen when the bedroom zones are plotted separately in Figure 8.

The variations observed between the measured air infiltration rates using the two tracer gas measurement methods is a result of eliminating the influence of tracer gas concentrations in adjacent zones. Such influences are particularly noticeable between the two floor levels causing a marked decrease in upper floor infiltration readings with the CCTG system.

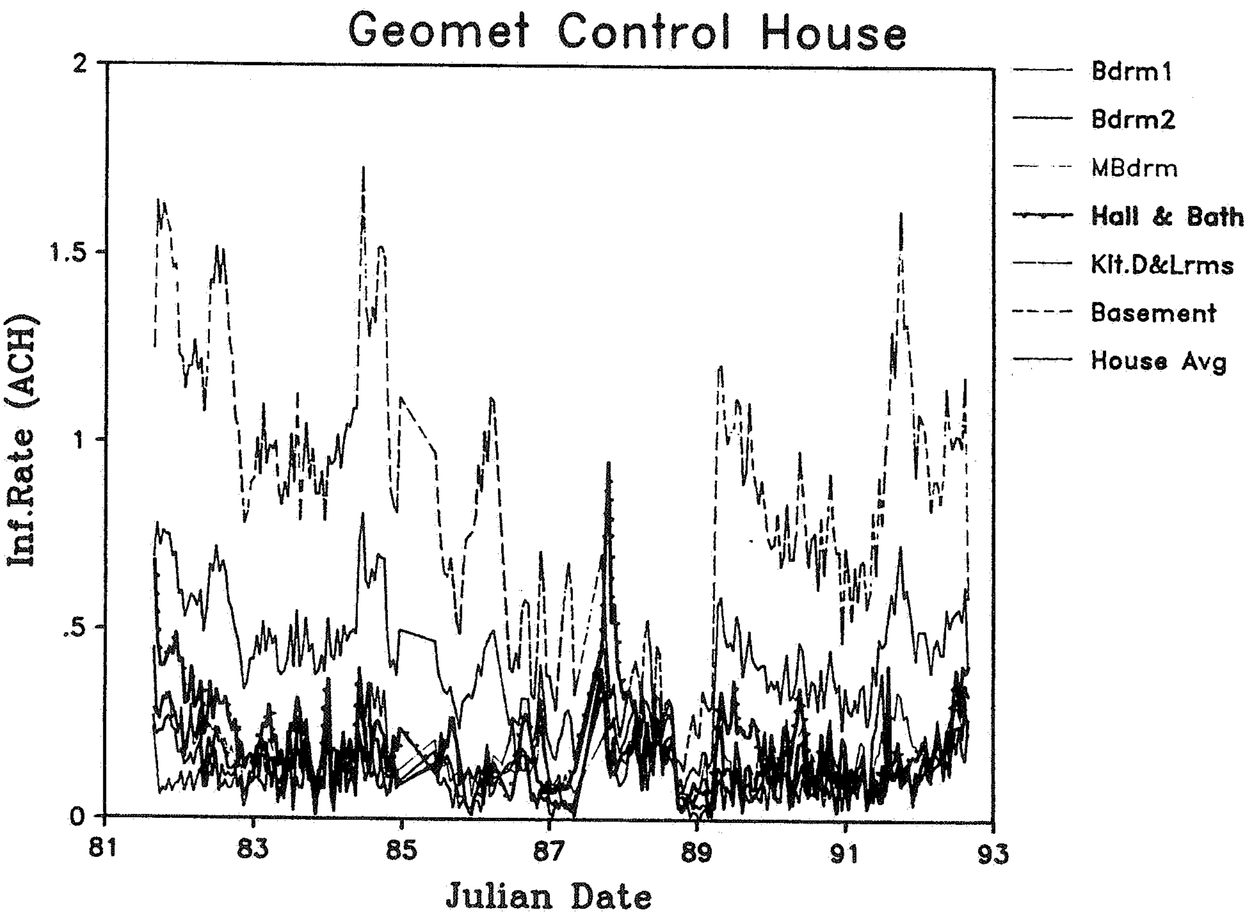

Figure 7. Detailed time history of 6 zones in the control house measured with the CCTG system at 10 minute intervals and hourly summary.

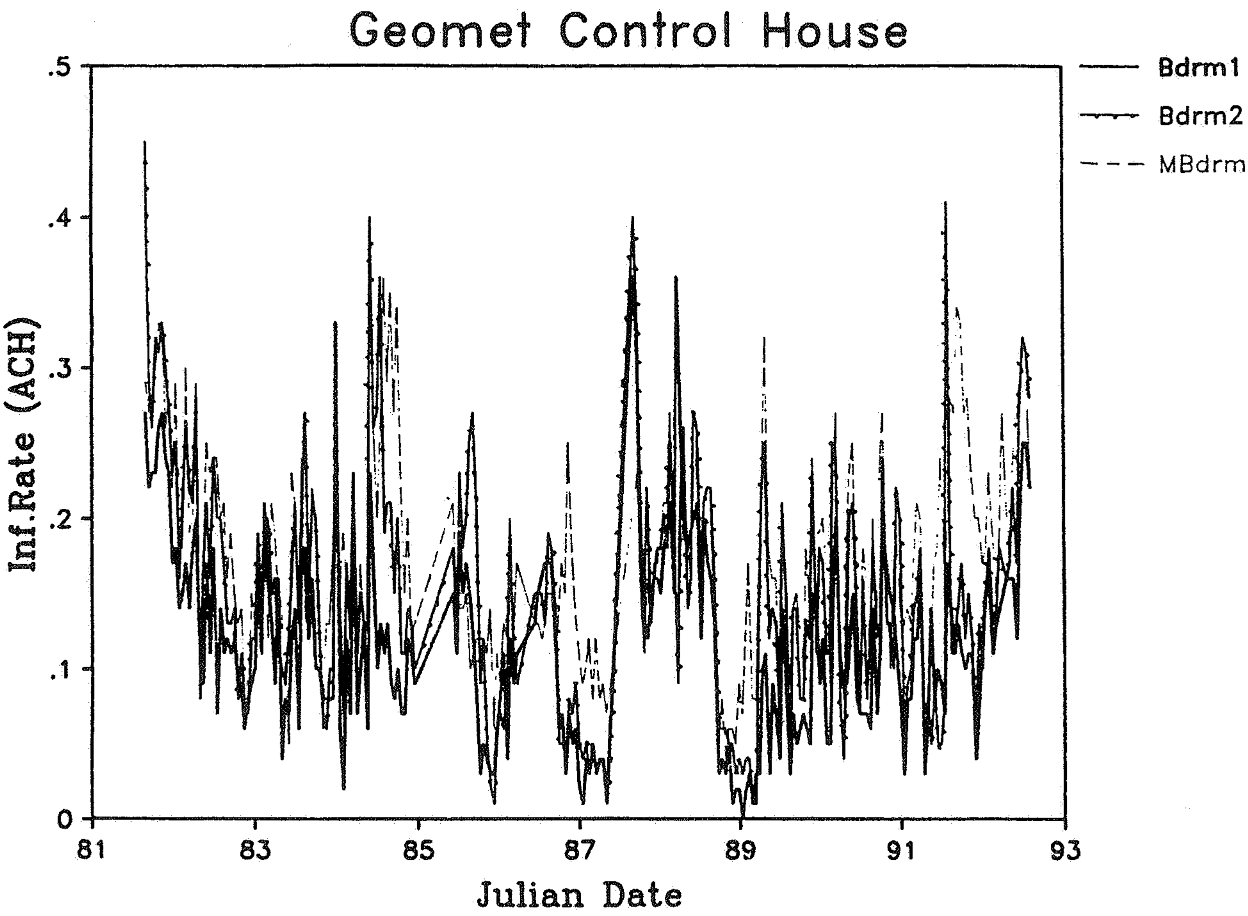

Figure 8. Air infiltration rates in the bedroom zones determined by the CCTG method.

5.3 Open Versus Closed Doors

As can be seen from Figure 2, door closure for zone isolation in these houses can only be achieved for the case of the three bedroom zones. Since the two floors are connected with an open staircase one cannot alter upper and lower floor communication. The doors were closed and data analysis was made over three hours before and after the closure, and again when the doors were opened. No significant changes in air exchange rates with the outside were observed, although exchange between zones would be expected to be reduced. Weather variations were taken into account in the comparisons.

6.0 CONCLUSIONS

The validity of the extensive documentation of air infiltration over the seasons in the GEOMET test houses using tracer gas decay was confirmed in the control house using the constant concentration method involving six individual zones of air infiltration measurement. Operation of the CCTG system was entirely successful and yielded additional air infiltration information on: individual zone variations, upstairs downstairs variations, and wind effects. These added ventilation rate details provide further data on the influences of weather and house system functions and thus prove useful in analyzing the impact on indoor air quality and energy.

7.0 ACKNOWLEDGMENTS

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