Contract Report

Radon Pressure Differential Project, Phase II: Infiltration

Final Technical Report: Draft

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The Department of Community Affairs
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By
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1. ABSTRACT

Testing has been done on 50 central Florida homes to assess and characterize house infiltration rates in new (age five years or less) Florida homes. These 50 were drawn randomly from a sample of 70 homes which had been previously tested to determine house airtightness, air distribution system leakage, and pressure differentials. The 50 homes had an average airtightness of 7.31 air changes per hour at 50 Pascals (ACH50). Significant leaks were found in the ductwork in a majority of homes tested, both on the supply and return sides of the air handler. When the air distribution system was sealed off, house ACH50 decreased to 6.53, indicating that 10.7% of the house leak area is in the duct system.

Infiltration rates with all mechanical air moving equipment turned off averaged 0.21 air changes per hour (ach). Infiltration varied from a low of 0.06 ach to 0.41 ach. Thirty-eight of 50 fell in the range of 0.10 to 0.25 ach. Infiltration was generally higher in the older homes (>3 years) and those with higher ACH50. When the air handler ran continuously, infiltration increased to 0.46 ach, indicating significant duct leakage. The return leak fraction, the proportion of air returning to the air handler which originates outside the house, averaged 8.9%.

Infiltration also increased when interior doors were closed. Since most Florida homes have central returns, closing interior doors increases pressures in the closed rooms and depressurizes the main body (e.g., living room, dining room, kitchen, etc.) of the house.

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Infiltration increased to 0.60 ach in these 50 homes with all the doors closed and the air handler operating. Exhaust fans create infiltration as well. With all exhaust fans and interior clothes dryers operating (moving an average 206 CFM) and with the air handler off, infiltration averaged 0.61 ach.

PFT (Perfluorocarbon Tracer) infiltration tests were done on 17 of these homes. Infiltration averaged 0.17 ach over 7-day test periods, from a low of 0.08 to 0.38 ach. The run time of the air conditioner was recorded. Based on the short-term infiltration tests with the air handler off, air handler on, and with interior doors closed, expected infiltration for these 7-day periods was calculated to be 0.27 ach. When adjustment is made for the fact that wind speeds were greater during the short-term tests than during the PFT tests, PFT's measure about 30% lower infiltration than expected from short-term tracer gas tests.

Assessment was made of infiltration prediction models. The most sophisticated model, the LBL model, predicted poorly. While on the average it predicted infiltration well, the scatter was great (r^2=0.359). When site-measured wind speed was used in place of weather bureau data, the coefficient of determination (r^2) improved to 0.450.

A very simple model, "divide by 20", predicted surprisingly well when "20" was changed to "40". This method takes the airtightness measure, ACH50, and divides by a fixed number, which for most of Florida is 20 to 23. Adjustment is also made for shielding, shape of the leak sites, and building height. It does not take into account specific weather conditions which might exist during a given period. This model predicts well when it is changed to "divide by 40". It predicts the magnitude of infiltration well and the prediction for individual houses is good (r^2=0.510).

2. INTRODUCTION

Radon intrusion rates into buildings are a function of radon source strength in the soil, the permeability of the soil, the cumulative size of penetrations in the house/soil interface, and the pressure differences across the house/soil interface. Radon activity levels in the home are a function of the entry rate and the rate of dilution, which is determined by the infiltration or ventilation rate of the building.

Radon entry is driven in part by pressure differential. Positive pressure in the space reduces or stops radon entry, and negative pressure increases radon entry. In "Radon Pressure Differential Project, Phase I, Final Technical Report", pressure differences were identified and characterized in 70 new homes as a function of the natural forces of wind and thermal buoyancy, duct leakage, closure of interior doors (which separate returns from spaces which receive supply air), and operation of exhaust equipment. The amount of pressure differential which occurs is a function of the run time of the air handler and the exhaust equipment.

Radon levels in the home are a function not only of radon entry rates, but also dilution rates as well. Higher infiltration (and ventilation) rates dilute radon levels, and lower infiltration (and ventilation) rates increase radon levels. In order to characterize the infiltration rates of Florida homes, infiltration tests were done on a subsample of these 70 homes. On 50 of the homes, short-term tracer gas tests were done (using SF6) to characterize the house infiltration rates with various mechanical systems operating or not operating. Of these 50, a subset of 17 were selected to do 7-day PFT (PerFluorocarbon Tracer) tests.

3. CONCLUSIONS

Natural infiltration rates in new Florida homes are low -- 0.21 ach. This rate is substantially below the ASHRAE recommended 0.35 ventilation rate. Consequently, natural infiltration may not be sufficient to ensure good air quality in new Florida homes.

Mechanical air moving equipment increases infiltration substantially. When air handlers are operating, infiltration increases to 0.46 ach because of duct leakage. Air distribution leakage on the return side was measured at 8.9%. Consequently, duct leakage strongly influences residential infiltration rates. If air handlers typically run 40% of the time during the cooling season, then overall infiltration is about 0.31 ach.

Closure of interior doors further increases infiltration. Pressure in the closed rooms increases infiltration to 0.61 ach. If doors are closed 15% of the time, then overall infiltration increases to about 0.32 ach.

PFT testing of 17 homes found that infiltration rates are lower than short-term infiltration tests would indicate. While predicted infiltration based on the short-term tests with air handler off, air handler on, and doors closed is 0.27 ach, PFT results indicate only 0.17 ach. Several variables may partially explain the difference. One unknown is how low natural infiltration is during Florida nights. Virtually all of our testing was done during the daytime hours of 10 AM to 6 PM, when wind speed and temperature differences are at their greatest. It may be that light nighttime winds and approximately zero temperature differential produce infiltration below 0.15 ach. If so, then predicted infiltration may drop to 0.25 ach, closer to the average 0.17 ach for the PFTs.

In any case, PFTs predicts that Florida homes have even lower infiltration rates, further indicating that mechanical ventilation may be required.

4. INFILTRATION TEST PROCEDURES

Short-term infiltration tests were done in the following manner. Four 80-minute tracer gas decay tests were performed in succession on each house. At the beginning of the first test, tracer gas (SF6) was injected into the return of the air distribution system with the air handler running continuously. An infrared specific vapor analyzer was used to measure the tracer gas (TG). The concentration was brought to about 35 to 45 parts per million (PPM). Mixing continued for a period of about 20 to 30 minutes.

Test 1 ran for 80 minutes with the air handler and all other air moving equipment in the house turned off. This test determines "natural" infiltration, that is infiltration caused by wind and thermal stack effects. Tracer gas concentrations were recorded at each 10 minute interval at four distributed locations throughout the house. Indoor and outdoor temperatures, and wind speed, were recorded for each 10 minute period.

Test 2 ran for 80 minutes with the air handler running continuously. During this test, the same data from test 1 was recorded at each 10 minute interval. In addition, TG concentrations were measured at the air distribution systems return(s), at one supply, and in the buffer zone(s) where return leaks (if any) were occurring. From these measurements, the return leak fraction could be calculated. This is the proportion of air returning to the air handler which originates outside the house envelope.

Test 3 ran for 80 minutes with the air handler turned off and all exhaust equipment in the house turned on. This included kitchen and bath exhaust fans and indoor dryers. The same data was recorded at each 10 minute interval.

Test 4 ran for 80 minutes with the air handler turned on, all exhaust equipment turned off, and all interior doors closed (in all previous tests interior doors were open continuously). TG sampling was done in each closed bedroom, at the central return, and at a sample point in the center of the main body of the house.

Infiltration rates for each test period were calculated, based on average concentrations at the four sample locations. The resulting nine data points for each test were plotted to assure that the concentration decay pattern was reasonable. In all cases decay was reasonable (no unexpected fluctuations) and dropped in steady steps. (This appears to be the result of the stability of the measuring instrument and the averaging of four measurements from around the house).

The infiltration rate was calculated by the following formula, taking the initial and final measured values as Ci (initial concentration) and Cf (final concentration).

$$ach = 60/n * \ln(Ci/Cf) \qquad \text{(Eq. 1)}$$

where n is the number of minutes of the test.

A best fit approximation (recommended in the ASTM E741-83 "Standard Test Method for Determining Air Leakage Rate by Tracer Dilution") to the TG data points was not used because the drop in concentration was consistently stable, and because using a best fit line approximation is based on the assumption that the infiltration rate is constant during the test period. This assumption is not valid because the driving forces for infiltration, especially wind, are not necessarily constant over the test period.

For example, if the wind is 2 MPH during the first 40 minutes of the test and 10 MPH during the second 40 minutes of the test, then the infiltration rate is likely to be very different during the two parts. A first-order best fit approximation would give a wrong answer to the infiltration rate during those 80 minutes. The true infiltration rate is related to the actual amount of tracer gas decay which occurs. To the extent that a best fit line deviates from this, the calculation is in error.

The return leak fraction (RLF) was calculated during test 2. By measuring the TG concentration at the return and supply, and noting the decrease of TG concentration from return to supply, a return leak fraction can be determined. RLF is calculated from the following equation (Cummings and Tooley, June 1989):

$$RLF = (A - B)/(A - C) \qquad \text{(Eq. 2)}$$

where A, B, and C are the TG concentrations at the return (in the room just before the grill), a supply, and the buffer zone from which the return leak air is drawn (e.g. attic, crawl space, garage), respectively.

In many cases, tracer gas concentrations in buffer zones are 30% or more of what is in the house. Obviously, the higher the concentration in the buffer zone, the less the return leak dilutes the house TG concentration. If the return leak is from the outdoors, the TG concentration in the air leaking into the return can be assumed to be zero.

In the case of test 4, with the interior doors closed, an infiltration rate was calculated for the closed rooms as a group and for the main body of the house. The overall infiltration rate of the house was determined by a floor-area weighted average of the closed room and main body infiltration rates. For each house we determined the fraction of the floor area which is in the closed rooms, and the fraction which is in the main body of the house, and used this in the calculation of the overall house infiltration rate.

5. PFT INFILTRATION TEST PROCEDURES

Long-term infiltration tests were done in a sample of 17 houses. The test procedures were as follows. Houses were selected from the sample of 50 homes on which short-term infiltration tests were done. We requested that the homeowners keep their houses closed and air conditioned during the 7-day test period. We also asked them to keep their thermostats at a constant temperature setting during the test period, in order to assure constant emission rates from the PFT emitters. These tests were performed during the months of August, September, and October in central Florida.

Two days before the testing began, four PFT emitters were placed at four distributed locations throughout the house. Typical placement was above door frames at a height of about 6'8", thus keeping them out of the way of children. This permitted tacking them into the sheetrock in places where the hole would not be noticed. The thermostat setting to be used during the 7-day test was begun at this time, so that the emission rate of the PFT emitters would stabilize. A run-time meter was installed on the air handler at this time.

Two days later the test was begun. Four receivers were located throughout the house, at least 8' from the emitters (in two houses we used only two receivers). The indoor temperature was recorded. The air handler run-time meter was recorded at the same time that the receivers were opened. An E-perm radon detector was placed in the house.

Seven days later the test was stopped. The PFT receivers were sealed and the stop time of the test was recorded. The E-perm radon monitor was retrieved and the stop time was recorded. The indoor temperature was recorded again. The run time meter was recorded, from which the hours of air handler operation could be determined. The PFT receivers were sent to the lab (National Association of Home Builders) for analysis.

Outdoor conditions of air temperature, air dewpoint, and windspeed were recorded at the Florida Solar Energy Center weather station, located within 25 miles of most of the homes. House shielding and terrain classifications were identified for each house, according to the LBL infiltration prediction model.

6. RESULTS AND ANALYSIS

6.1.1 Short-Term Tracer Gas Tests

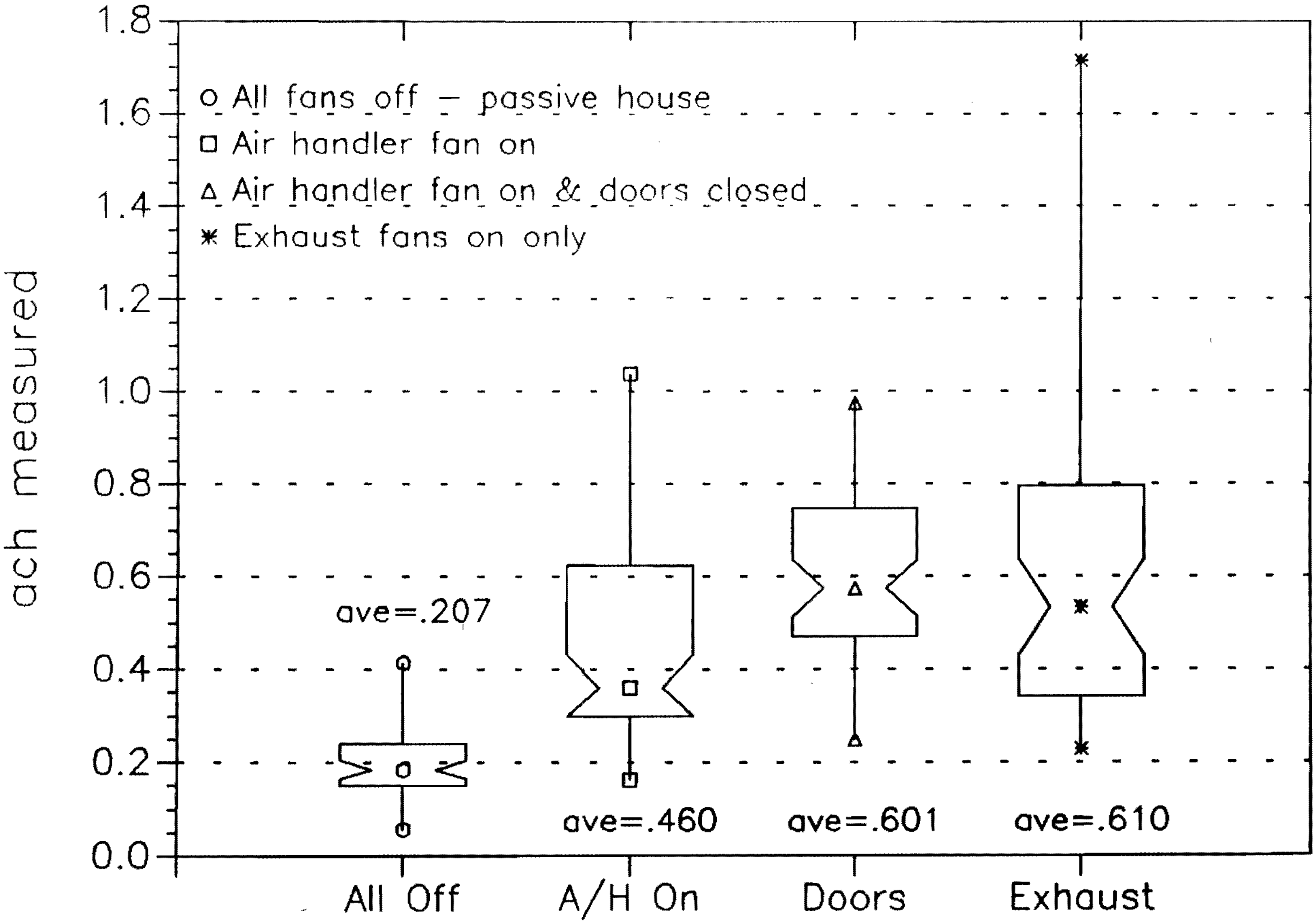
Fifty homes were selected randomly for short-term tracer gas testing from the larger sample of 70 homes. Volunteers were selected from the 70 houses without selection criteria, and all those who said yes were tested. We had difficulty getting the last five houses, either because people were not interested in participating or because we had difficulty coordinating with their busy schedules - the testing takes about 8 to 9 hours including setup and take down.

These 50 homes were very similar to the larger sample of 70 homes based on blower door test results. While the average house tightness for 70 homes was 7.23 ACH50, tightness was 7.31 ACH50 for the 50. The air distribution system was slightly tighter in the 50 homes. While 11.2% of the house ACH50 was in the duct system for the 70, 10.7% of the house ACH50 was in the duct system in the 50.

Tracer gas testing found that "natural infiltration" was low and mechanically induced infiltration was considerably higher in these homes. Figure 1 summarizes the infiltration rates of the 50 homes with various equipment turned on or off. Infiltration with the air handler off, or "natural infiltration", averaged 0.21 air changes per hour (achoff). Infiltration with the air handler on more than doubled to 0.46 ach (achon). Closing interior doors with the air handler running increased infiltration to 0.60 ach (achcl). Infiltration with the exhaust equipment running continuously averaged 0.61 ach (achexh).

(The box plot format requires some explanation. The three stars represent the high, median, and low value for a given bin of data. The box contains two quartiles.

Figure 1. Measured Infiltration Rates in 50 Central Florida Homes With Air Handler (AH) Off, AH On, Interior Doors Closed and AH On, and Exhaust Equipment Only Operating.



Therefore, the top of the box separates the third and fourth quartiles, while the bottom of the box separates the first and second quartiles.)

Natural infiltration in these 50 homes is similar to that found in other studies of central Florida homes. A sample of 9 homes averaged 0.22 ach (Cummings, 1988). A sample of 12 homes averaged 0.26 ach (Cummings and Tooley, 1989). A sample of 5 homes averaged 0.14 ach (Cummings and Tooley, 1989). A sample of 155 mixed-age homes averaged 0.29 ach, or about 40% higher than this study's sample of 50 (Cummings and Tooley, October 1990). Blower door tests were done on 90 of these 155 homes. ACH50 was 12.2, or 67% leakier than the sample of 50 in this study.

One of the driving forces of natural infiltration is wind speed. Figure 2 shows that there is a general, though poorly defined, trend toward higher infiltration at higher wind speed. The least-squares best fit r^2 is 0.258, indicating that 26% of the variation in infiltration is explained by wind velocity. For each MPH increase in wind, natural infiltration increases about 0.025 ach.

House airtightness is a more powerful predictor of natural infiltration. Figure 3 shows that house airtightness accounts for nearly 50% of the variation in infiltration (r^2=.492). For each one ACH increase in ACH50, natural infiltration increases about 0.02 ach. Figure 4 plots the best fit lines for achoff vs ACH50 for three groups of homes based on wind speed during the test (group 1 < 2 MPH, group 2 = 2 to 4 MPH, group 3 > 4 MPH at site). The figure illustrates that both house tightness and wind speed impact infiltration.

Natural infiltration increases with age, as a general trend (Figure 5). Houses built in the past two years average about 0.18 ach, while those three years old or older average 0.24 ach. The pattern of increasing infiltration with increasing age can be explained by the fact that ACH50 shows the same general pattern of increase with age. Those built in the past two years average 6.3 ACH50, while those four or five years old average 8.6 ACH50 (Figure 6).

Figure 2. Measured "Natural" Infiltration (all fans off) Versus Wind Velocity Measured by 7' Tower on Site.

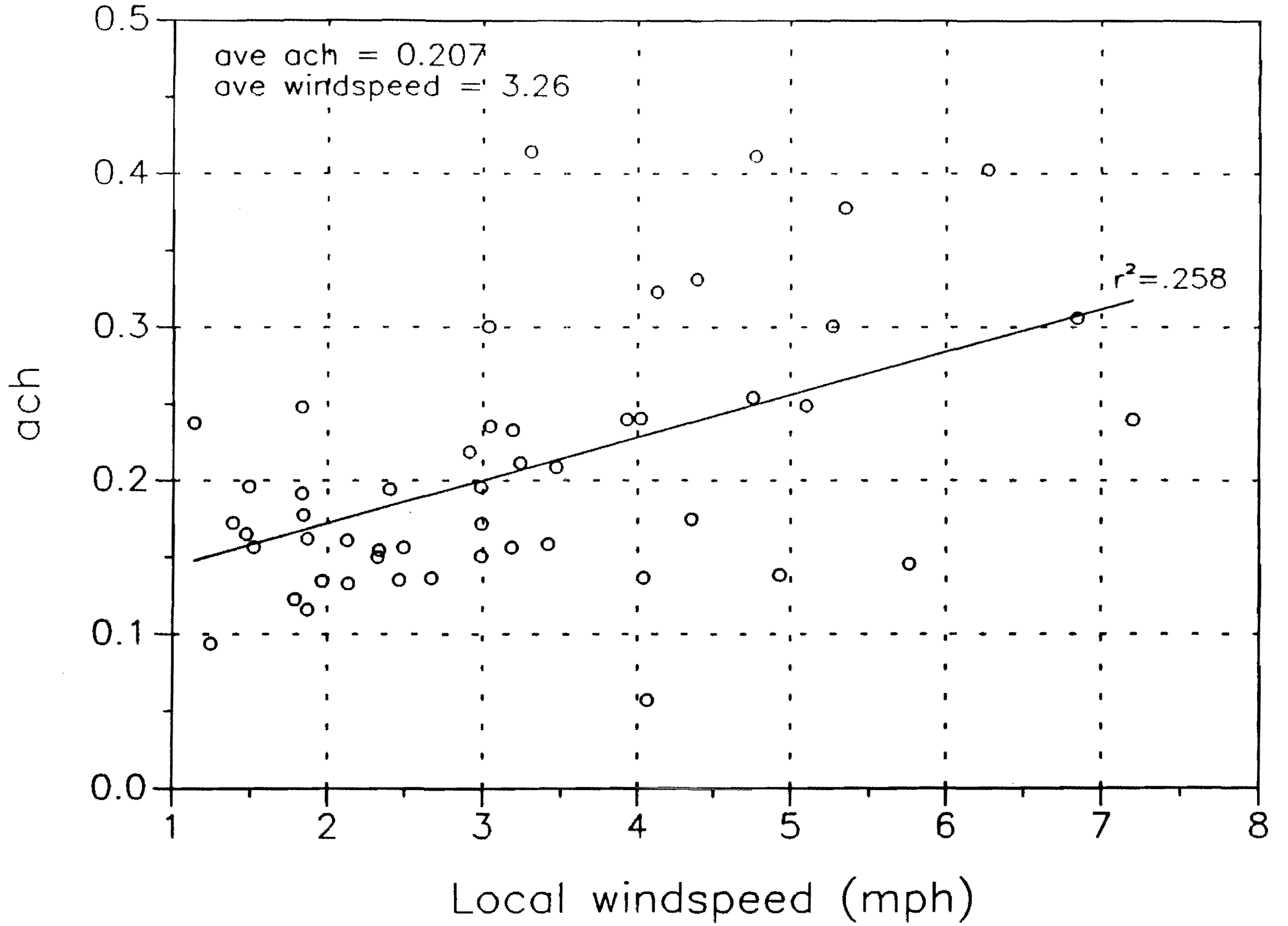


Figure 3. Measured "Natural" Infiltration (all fans off) Versus House Airtightness for 50 Homes.

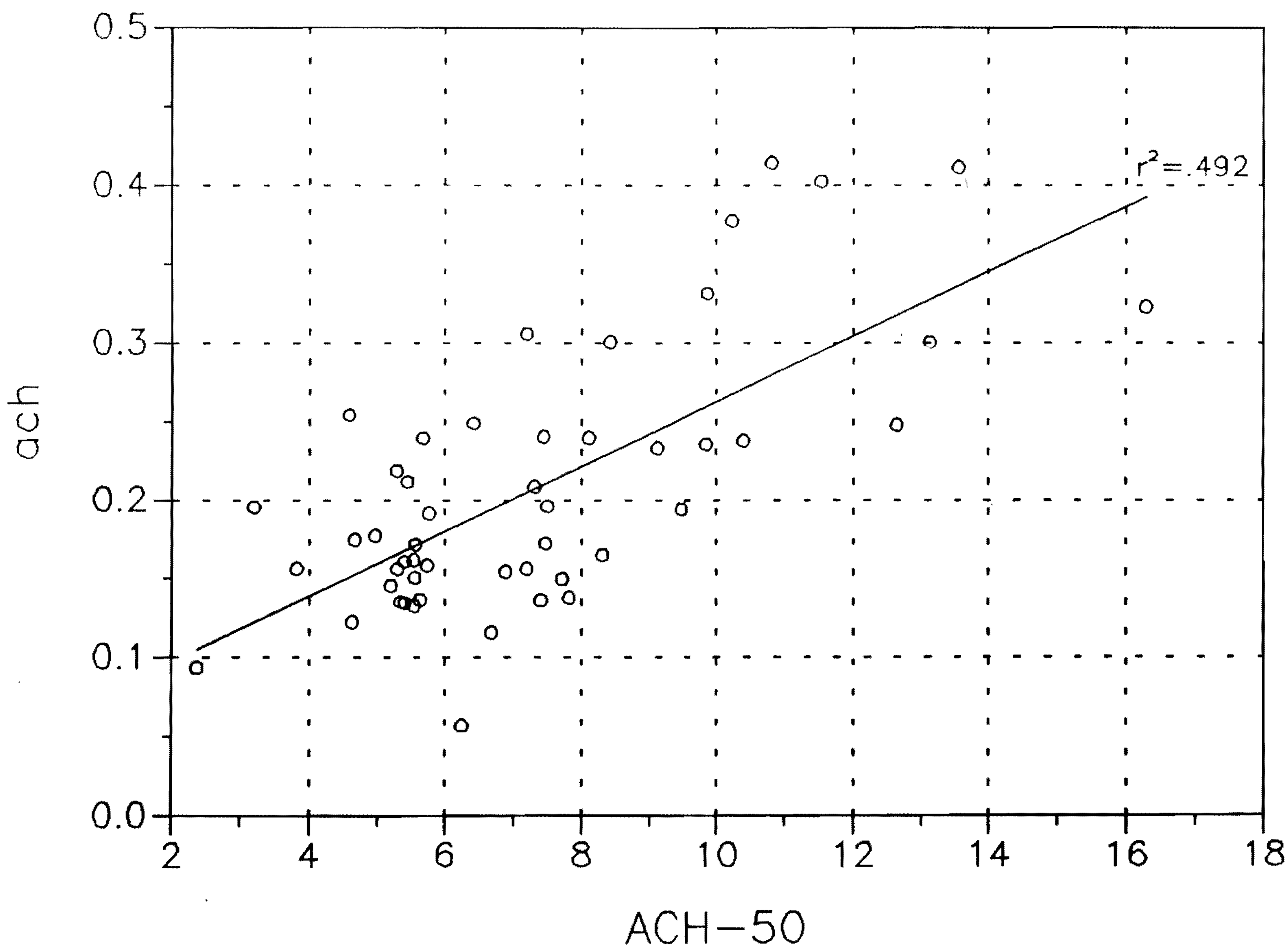


Figure 4. Least-squares Best Fit Lines For Measured "Natural Infiltration" (all fans off) Versus House Airtightness For Wind Speed < 2 MPH, 2-4 MPH, and > 4 MPH.

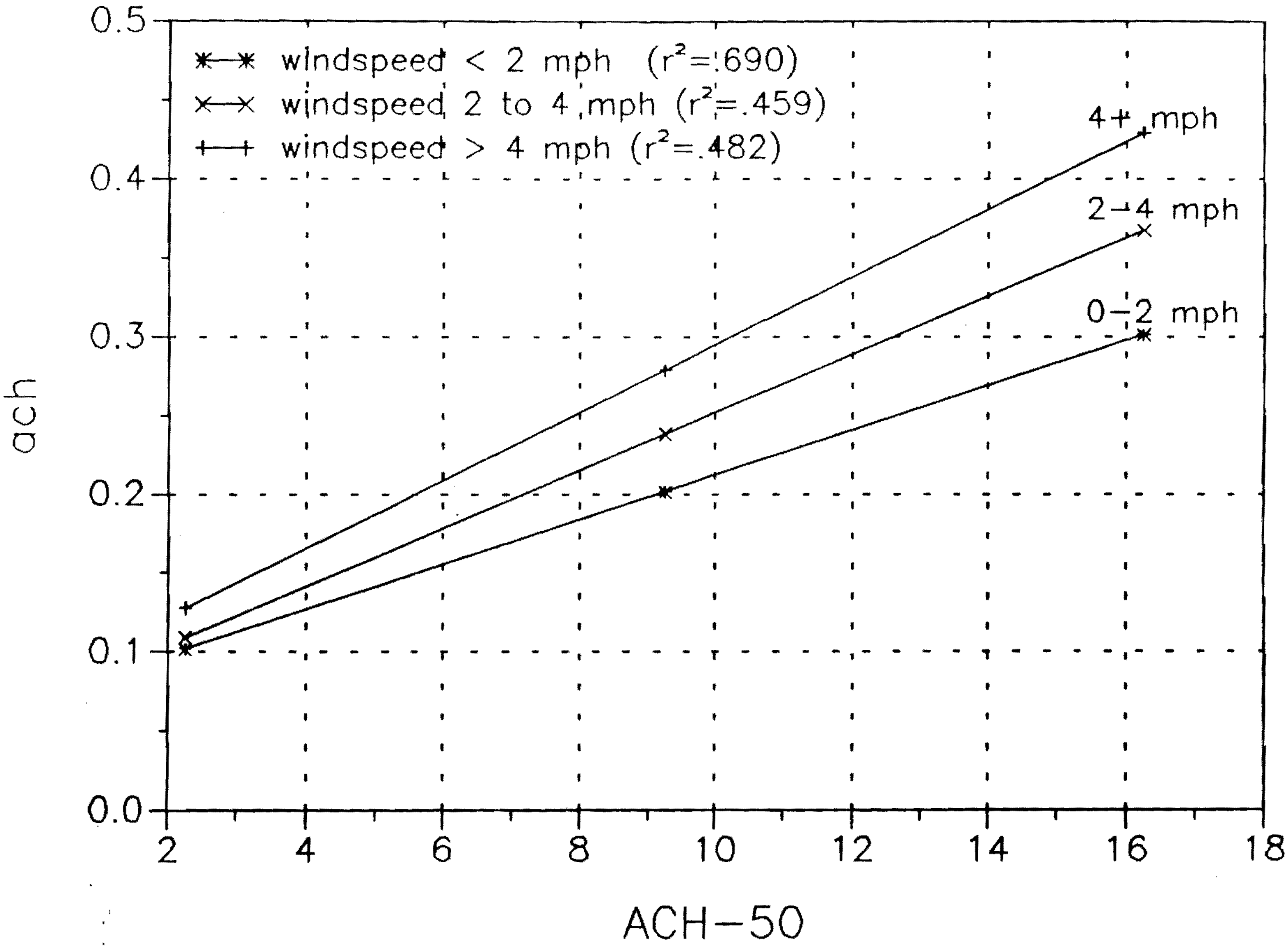


Figure 5. House "Natural" Infiltration As A Function Of House Age For 50 Homes.

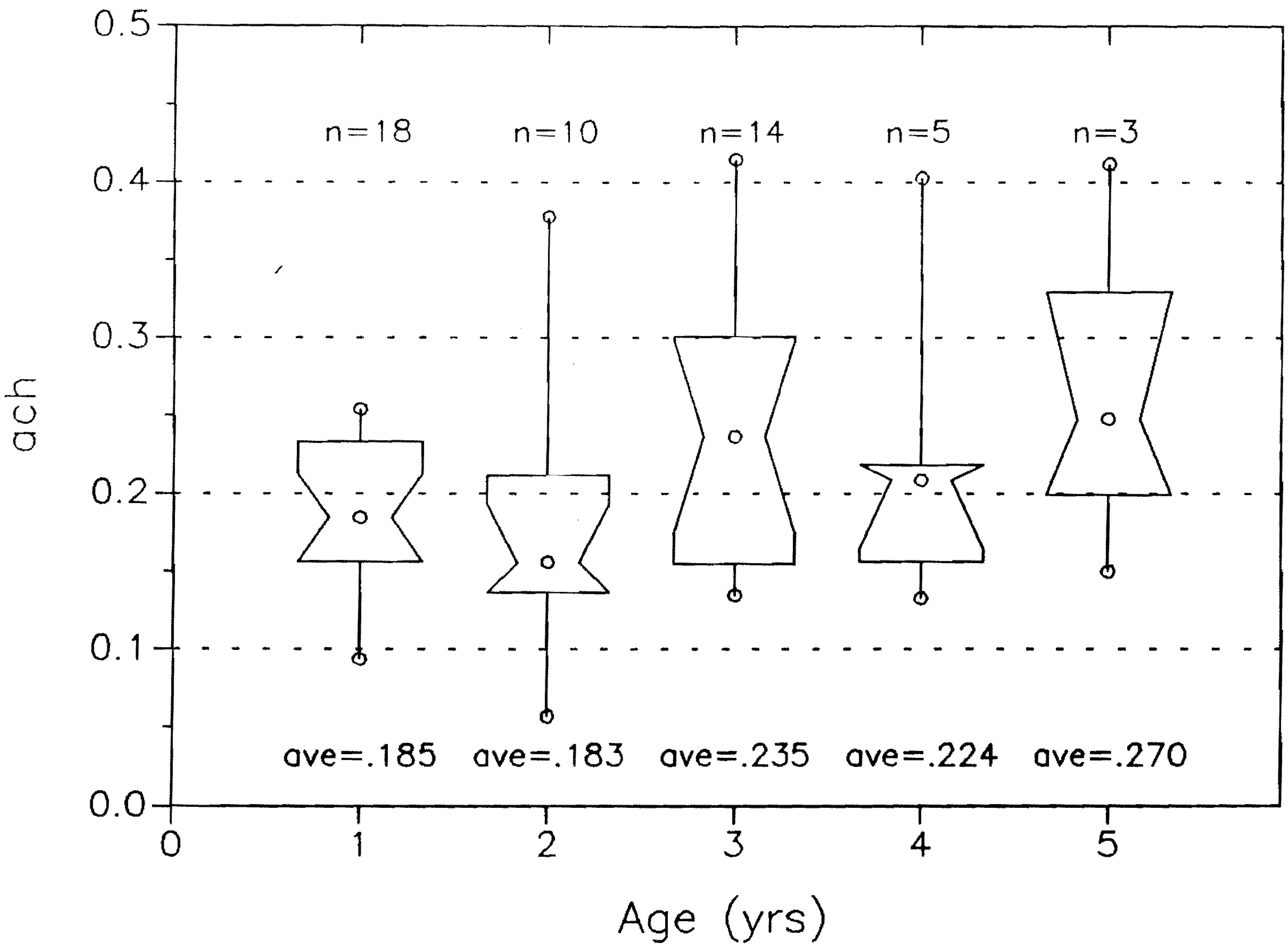
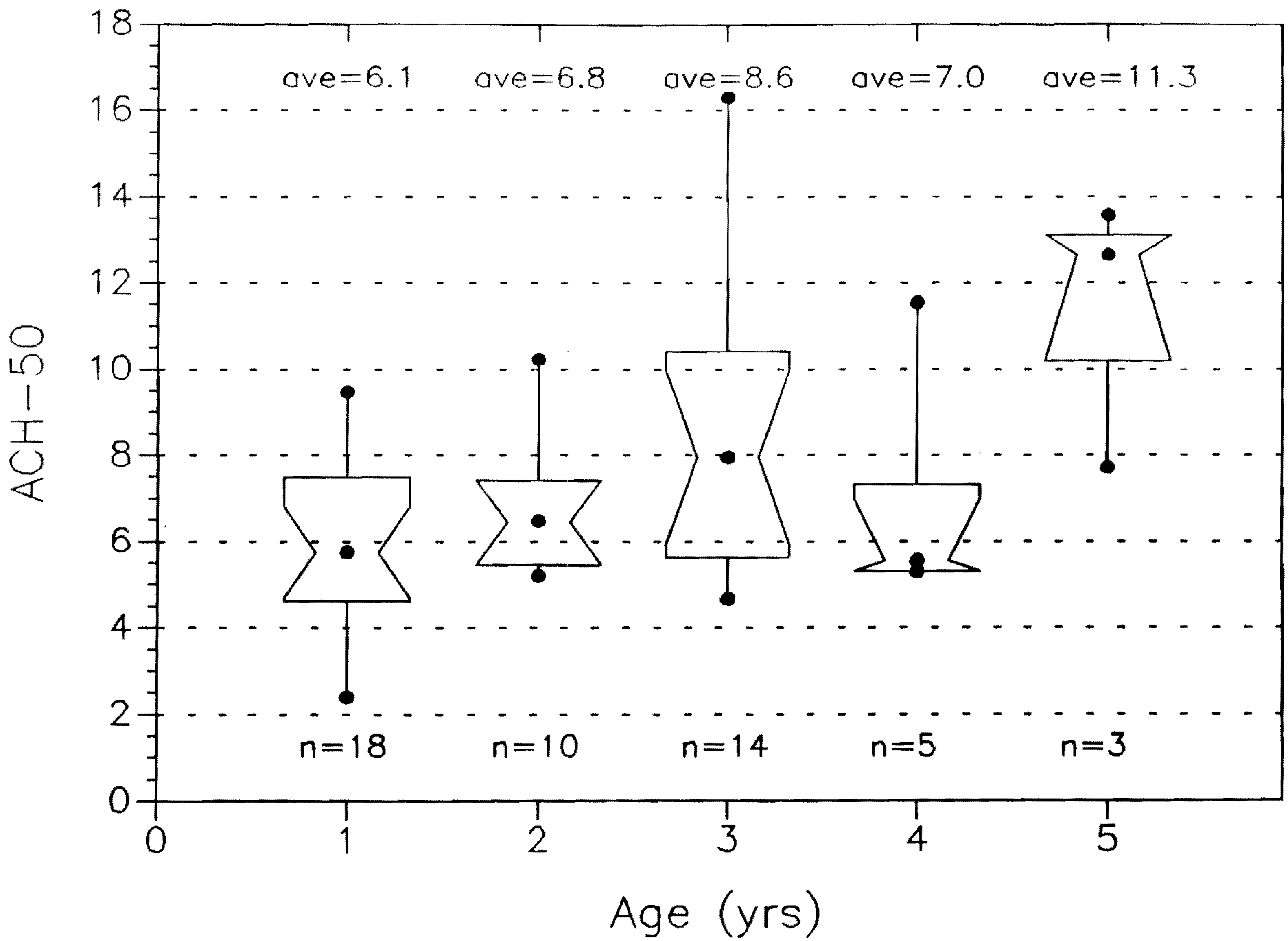


Figure 6. House Airtightness Versus Age For 50 Homes.



Infiltration can be defined as the uncontrolled flow of air through unintentional openings in the house envelope. It is driven by pressure differentials created by wind, temperature difference, and appliances. Infiltration is often unreliable in providing ventilation air to homes because the driving forces are variable and intermittent. Natural infiltration (wind and temperature driven) is insufficient to meet the ventilation recommendations of ASHRAE 62-1989. This standard recommends that 0.35 ach be achieved in a residence, or 15 CFM ventilation air per person, whichever is greater, in order to maintain good indoor air quality. Per person ventilation is based upon number of bedrooms. Two persons are considered to occupy the first bedroom and one in each additional. Therefore, a four bedroom house would require 5 times 15 CFM = 75 CFM. This would be equal to about 0.37 ach in a 1500 square foot house with 8 foot ceilings.

Florida homes do not achieve this level of 0.35 ach infiltration under most weather conditions. During our tests the average was 0.21 ach. Only four exceeded 0.35 ach during our short-term test, and these four were at wind speeds averaging 5.0 MPH (at the site), considerably above the average 3.4 MPH measured for all the houses.

It should also be considered that wind speeds are considerably greater during daytime hours (when our tests were performed) compared to nighttime. Wind data from the Florida Solar Energy Center weather station indicates that summer winds average 8.0 MPH during the hours of 10 AM to 6 PM, when most of our testing was done, versus only 6.1 MPH during the remaining hours of the day. In addition, temperature differentials between indoors and outdoors during nighttime hours is near zero, while it is about 10F during the daytime hours in which we do our testing. Consequently, for both of these reasons, overall annual natural infiltration in new Florida homes is most likely to be considerably lower than the 0.21 ach which we measured.

Air leakage from central heating and cooling air distribution systems accounts for a large proportion of Florida's infiltration. When the air handler is operating, infiltration averages 0.46 ach, or about 125% greater than natural infiltration. Figure 7 shows that wind is not a good predictor of infiltration when the air handler is operating. However, as can be seen in Figure 8, return leak fraction (RLF) is a good predictor of infiltration when the air

Figure 7. Measured Infiltration With the Air Handler Running Continuously Versus Wind Speed In 49 Homes.

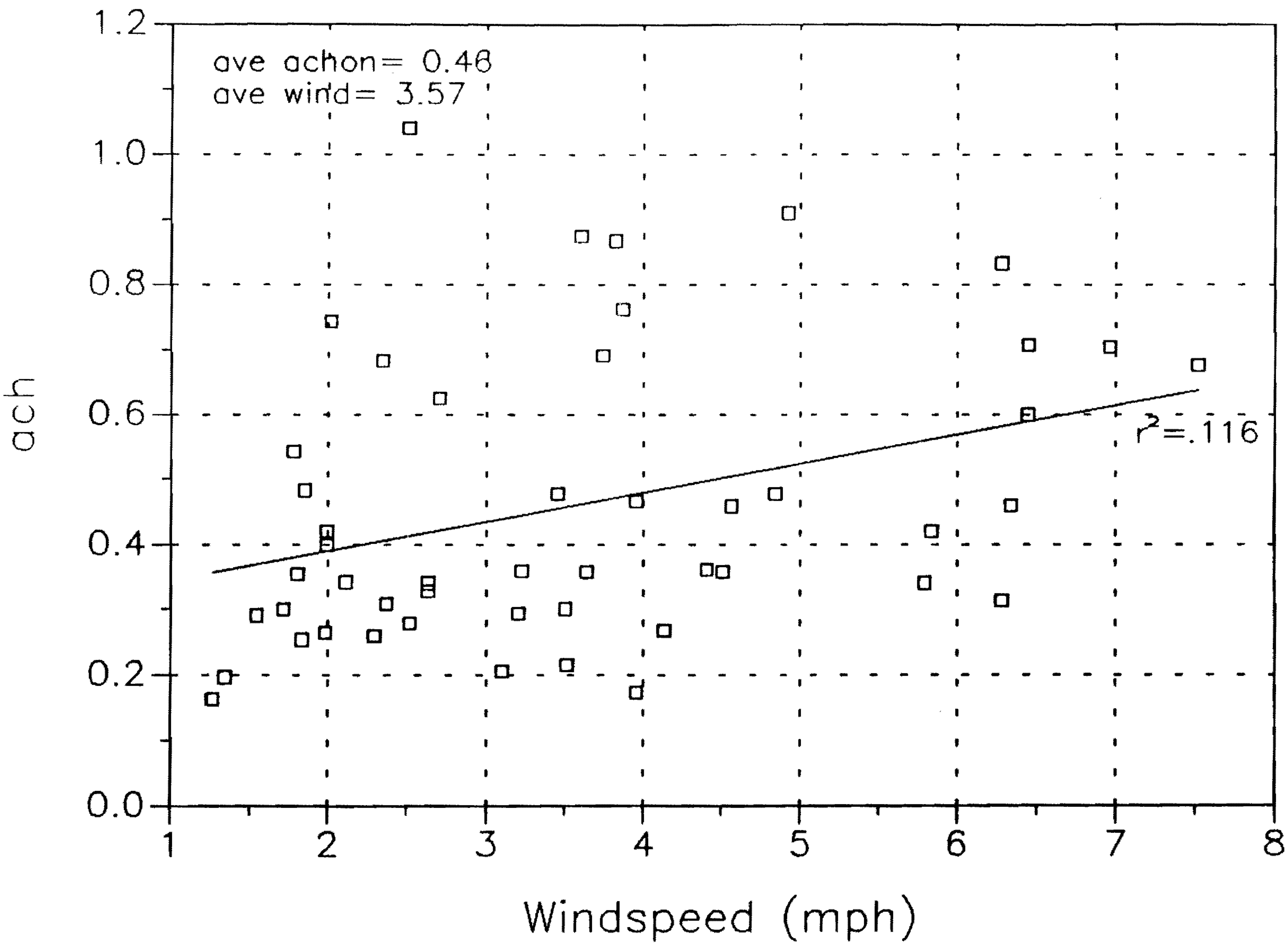
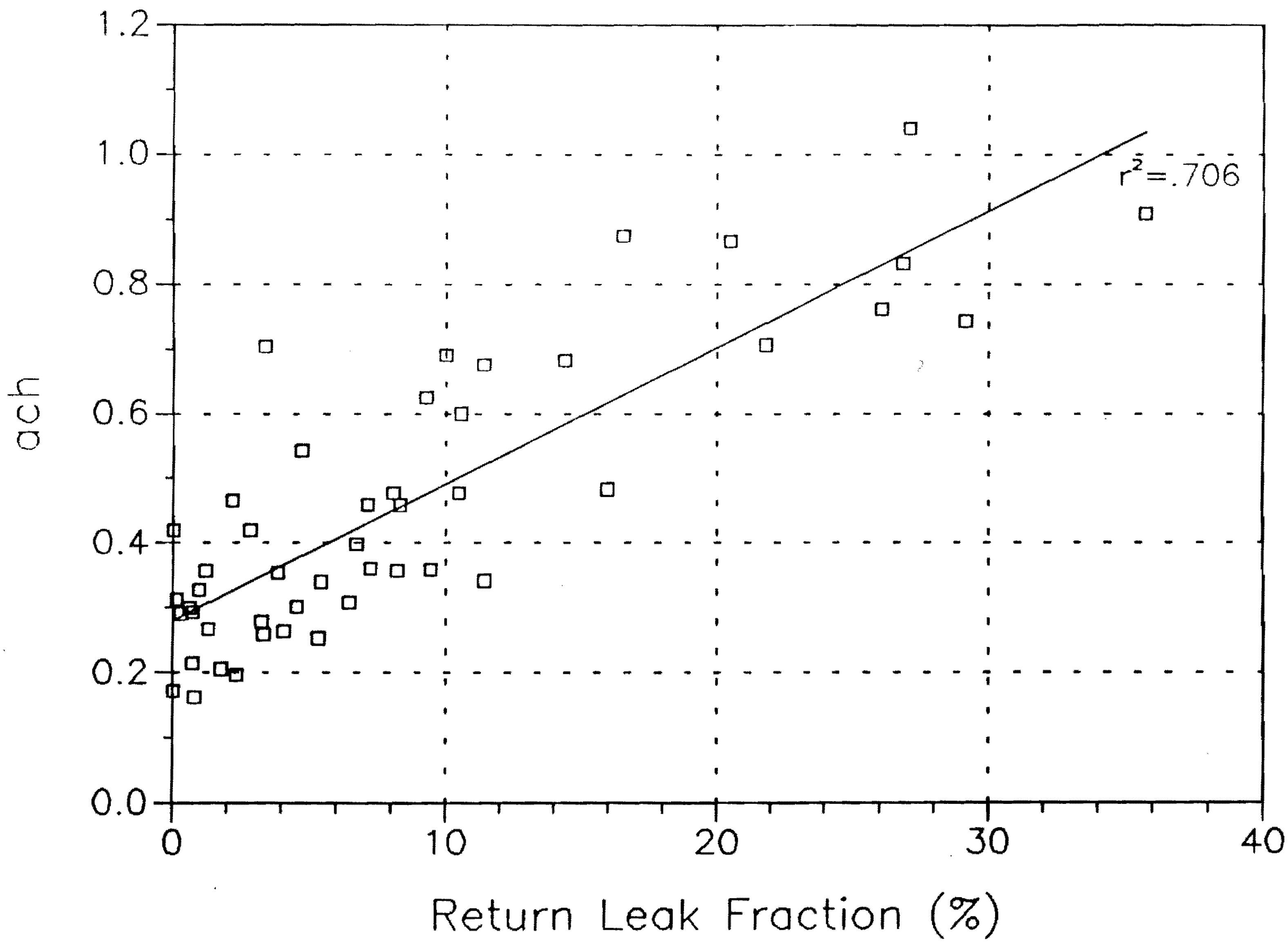


Figure 8. Measured Infiltration With the Air Handler Running Continuously Versus Return Leak Fraction Of Air Distribution System.



handler on (r^2 = 0.706). This indicates that the air handler is the dominant driving force for achon. The reason RLF is a fairly good predictor of achon is that return leaks tend to be dominant in Florida homes based on our visual inspections and upon other research (Cummings, Tooley, and Moyer, October 1990). If supply leaks were dominant in a significant number of these homes, then there would be much greater scatter in the data of Figure 8.

If the air handler operation time is known, then an estimate of overall infiltration can be made. Based on research done on central Florida homes, average air handler run time during the cooling season is about 9 hours per day, or 37% operation time (Cummings, Tooley, Moyer, and Dunsmore, August 1990). If this holds for these 50 homes, then overall infiltration during the cooling season would be about 0.30 ach. If the assumption were made that natural infiltration averages about 0.17 ach instead of the measured 0.21 ach [based on the fact that wind speed during our achoff tests was 7.5 MPH (FSEC station), while the average summer wind speed was 6.8 MPH (FSEC station)], then overall cooling season infiltration would be 0.28 ach. Therefore, even including infiltration from duct leaks, infiltration is lower than ASHRAE 62 ventilation standard. Elimination of duct leaks from new Florida homes would even further reduce infiltration below the ASHRAE standard.

Additional infiltration is created by closing interior doors when the air handler is operating. Infiltration increased 30% in this sample of 50 homes from 0.46 achon to 0.60 achcl when the doors are closed. The reason for the increase in infiltration is increased pressure differentials. Closing doors increases pressure in the closed rooms, and depressurizes the main portion of the house. The reason for this is that returns are located in the central portion of the house. Closing interior doors restricts the return air flow from these rooms. The average pressure differential across the closed doors was 8.2 Pa, with a maximum pressure differential across a door of 45 Pa. The greatest main body depressurization (relative to outdoors) was -14.8 Pa.

Figure 9 shows that windspeed is a poor predictor (r^2=0.073) of infiltration with the air handler on and the doors closed. Figure 10 shows that RLF is a better, though still poor,

Figure 9. Measured Infiltration With the Air Handler On and Interior Doors Closed Versus Wind Speed at the Site.

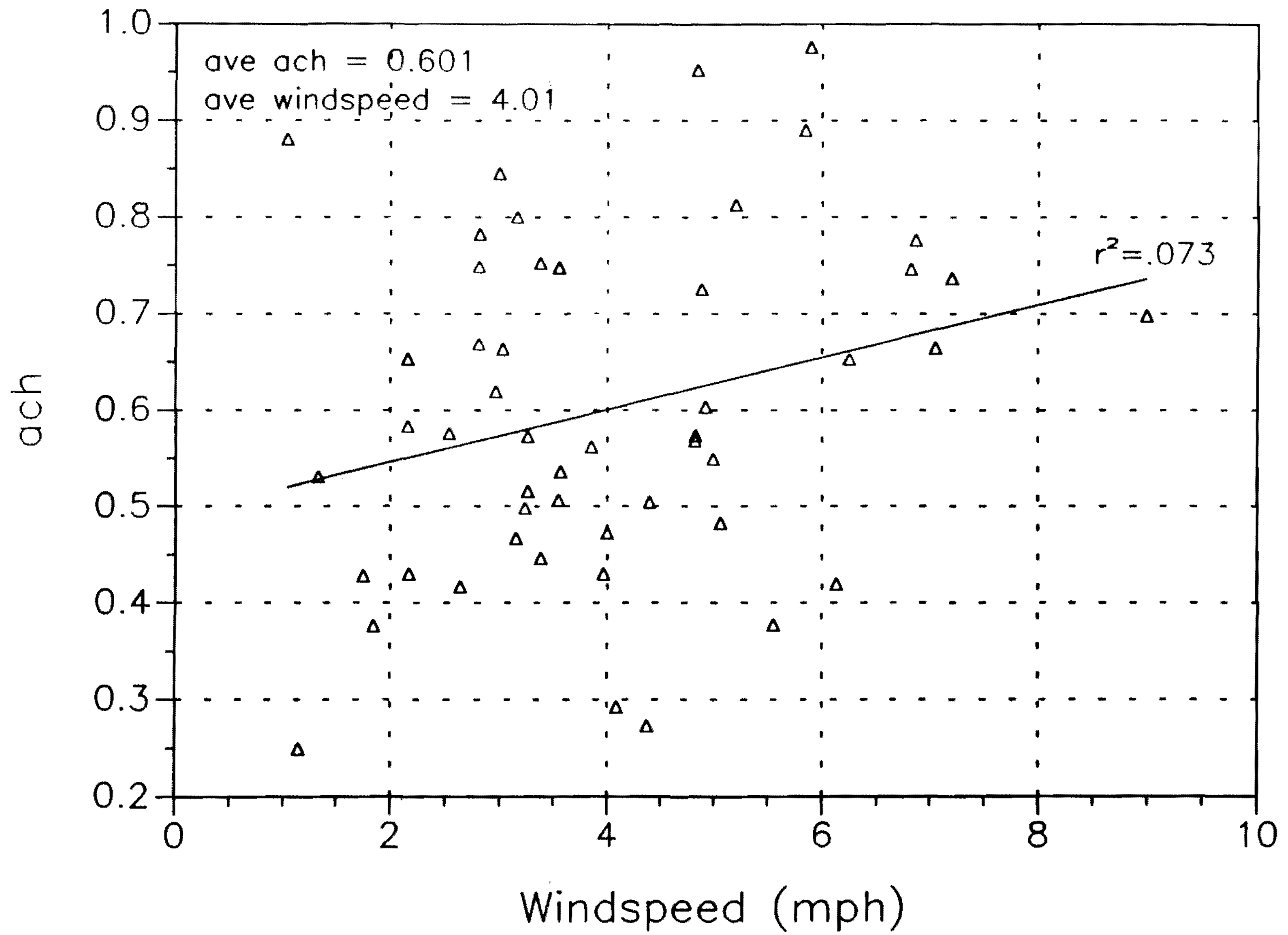
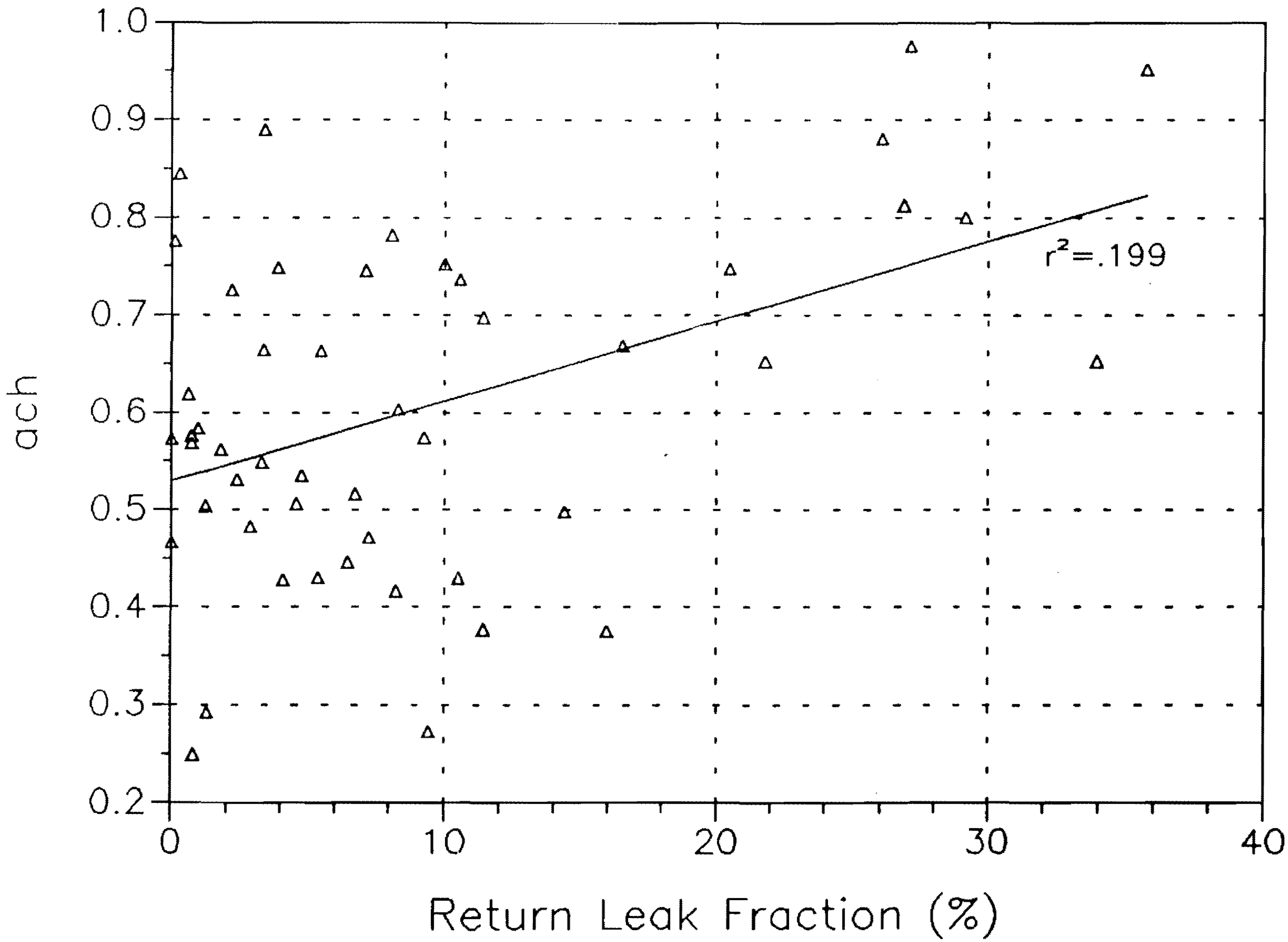


Figure 10. Measured Infiltration With the Air Handler On and Interior Doors Closed Versus Air Distribution System Return Leak Fraction.



predictor (r^2=0.199). It might be expected that pressure differential across closed doors would be a good predictor. The coefficient of determination, however, is actually quite poor (Figure 11 - r^2=0.102). An important reason is that duct leakage dominates infiltration in many of these homes. In order to remove some of the influence of duct leaks upon achcl, Figure 12 plots achcl vs differential pressure across the doors for those with RLF less than 5%. The relation between differential pressure and infiltration is now much clearer, and the coefficient of determination is much higher (r^2=.334).

Exhaust fans, dryers, and other equipment which exhaust house air increase the infiltration rate. In some cases infiltration is large. Six homes exceed 1.0 ach when all the exhausts are operating continuously. Figure 13 shows higher infiltration rates in homes with higher exhaust equipment CFM.

The infiltration which exhaust fans actually create in homes is a function of the operation time of the equipment. This varies from home to home depending upon the number of pieces of exhaust equipment, the number of persons in the family, and the family lifestyle.

6.1.2 PFT Infiltration Tests

In order to assess longer-term infiltration rates in Florida homes, PFT tests were done on 17 homes from the sample of 50 homes. Table 1 summarizes the PFT tests, the blower door airtightness tests, the short-term tracer gas tests, air handler run time, estimated door closure fraction (occupants' estimate), and weather conditions during the tests for these 17 homes. The average PFT test length was 7.5 days. They were done during the months of August, September, and October, 1990. Average wind speed and outdoor temperature for the PFT test periods were obtained from the FSEC weather station.

Average PFT-measured infiltration was 0.17 ach. It varied from a low of 0.08 ach to 0.38 ach. In general, tighter homes (as expressed by ACH50) have lower week-long infiltration. Figure 14 shows that ACH50 predicts 54% of the variation of week-long infiltration (r^2=0.541). There are a number of variables which can account for the fact that house tightness does not explain a larger proportion of the variation in infiltration:

Figure 11. Measured Infiltration With the Air Handler On and Interior Doors Closed Versus Pressure Differential Across the Closed Doors.

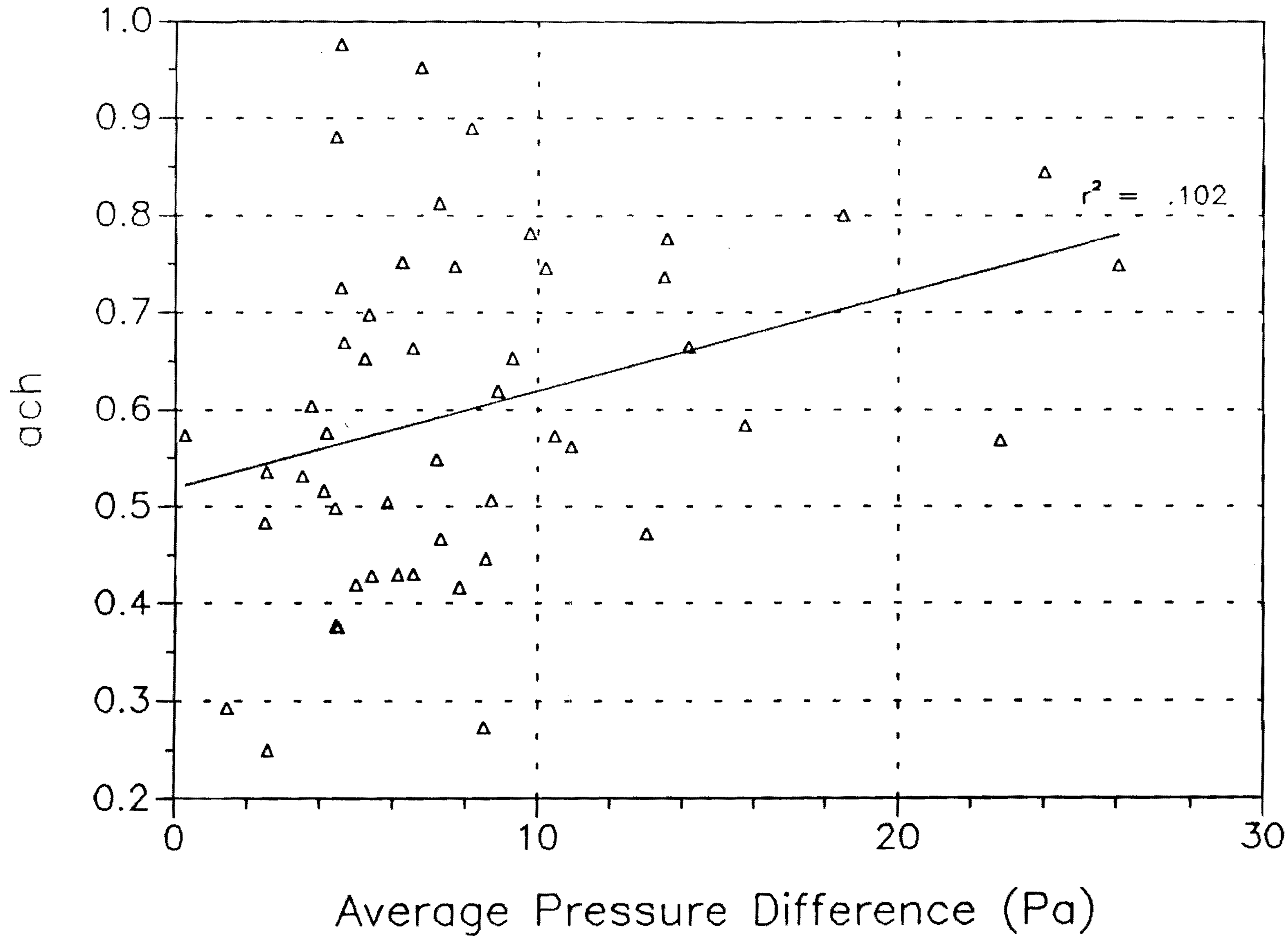


Figure 12. Measured Infiltration With the Air Handler On and Interior Doors Closed Versus Pressure Differential Across Closed Doors For Homes Where Return Leak Fraction < 5%.

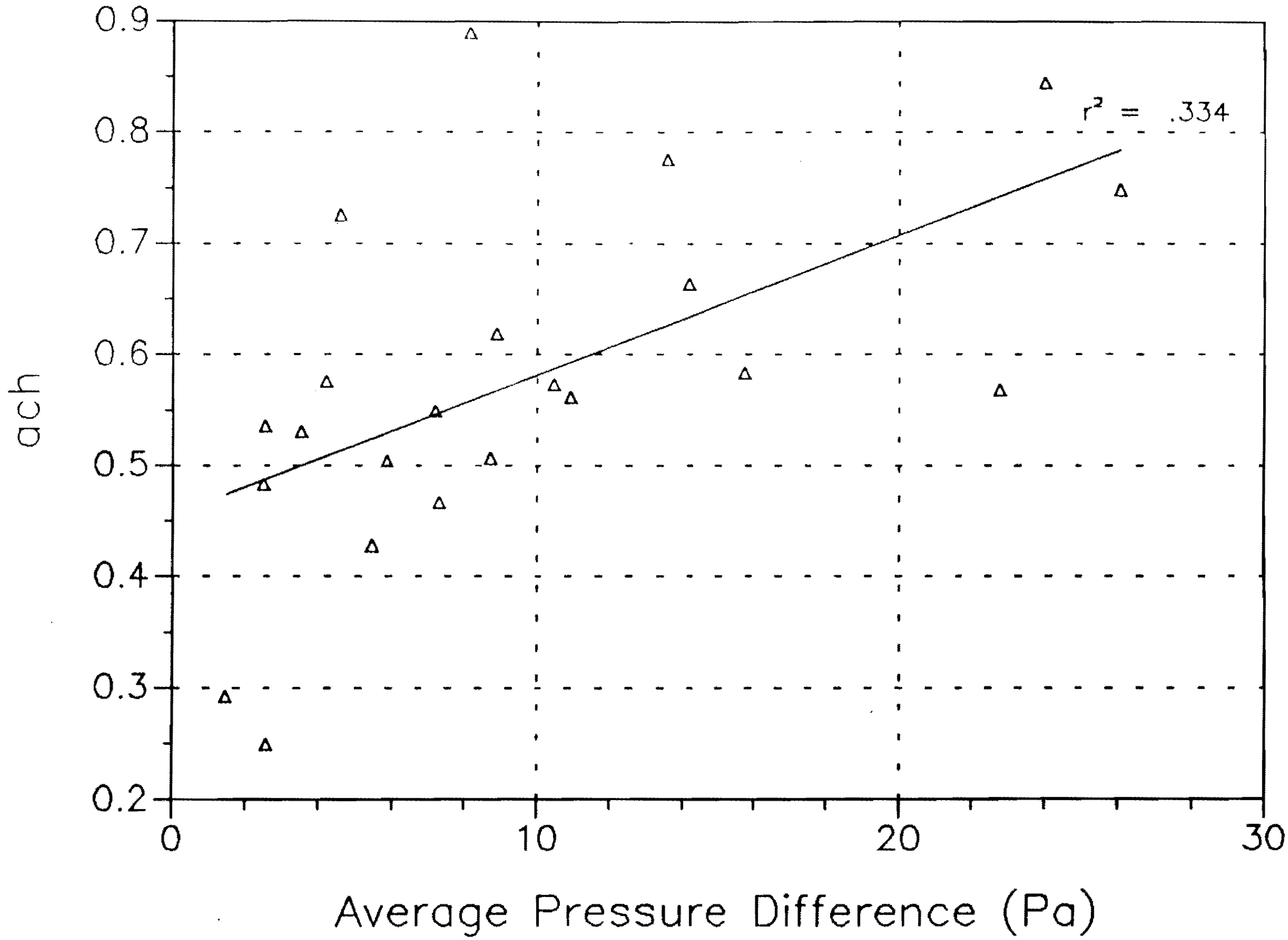


Figure 13. Measured Infiltration With All Exhaust Equipment Operating Versus the Measured Exhaust Equipment Air Flow.

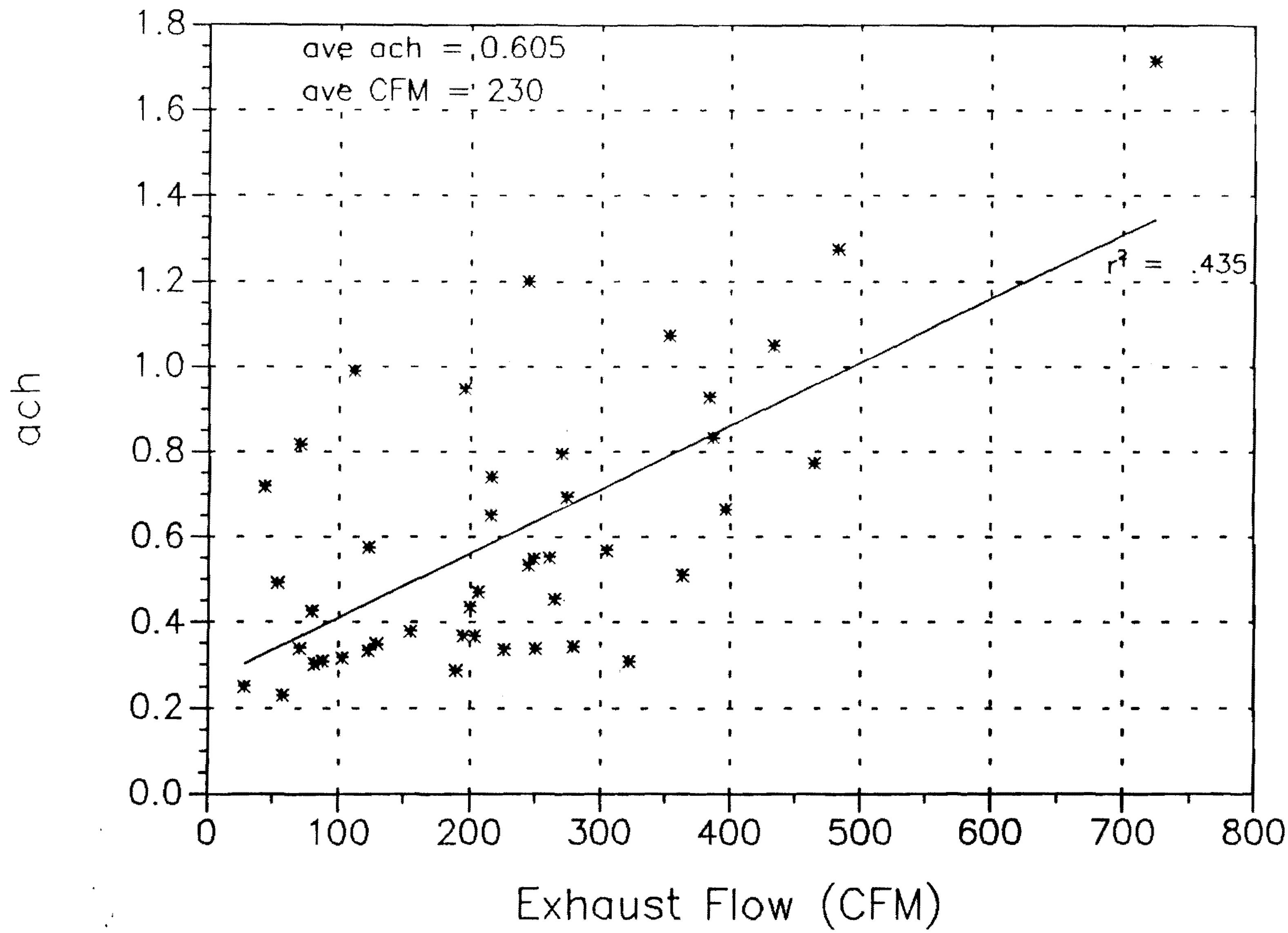


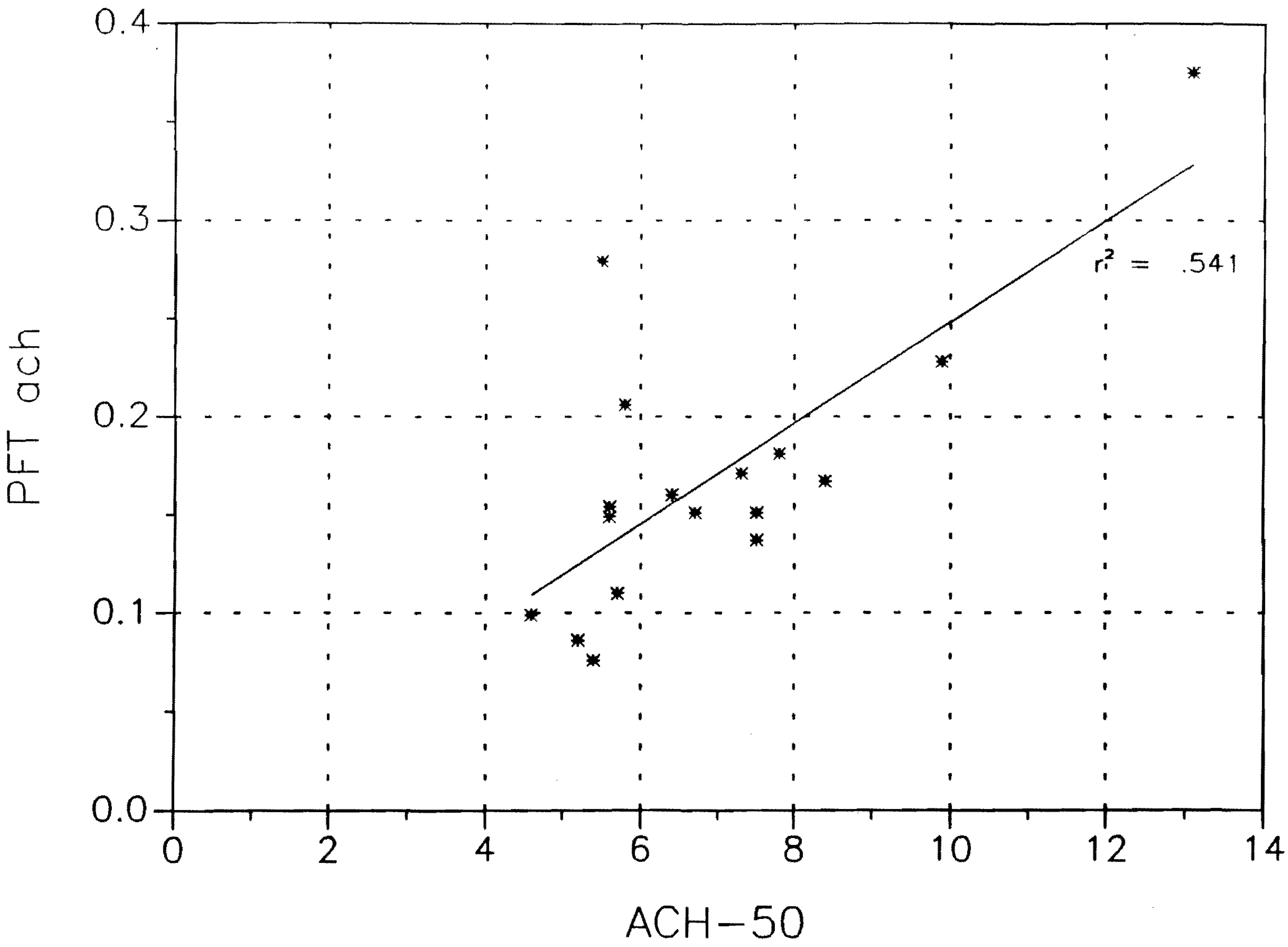
TABLE 1

PFT and Tracer Gas Infiltration Tests Compared. PFT Tests Were About 7 Days in Length. Short Term Tests Were Used to Predict What Infiltration Would be Expected During the PFT Test Periods.

PFT Testing								Short Term SF_6 Testing								
NAME	Test Length (Days)	Wind MPH	Outdoor Temp. °F	Indoor Temp. °F	AH Run Time Fraction (RTF)	PFT ach	ACH50	80 min. achoff	Wind at Site achoff (MPH)	FSEC Wind (MPH)	achoff at 3.4 MPH	80 min. achon	80 min. achclosed	Door Closed Fraction	Calculated ach*
Kettles	6.94	NA	NA	79.9	.358	.160	6.400	.249	5.100	13.1	.210	.360	.472	0.000	.264
Kalaghchy	10.90	7.6	82.1	74.0	.357	.167	8.400	.301	5.270	11.4	.240	.419	.483	.021	.304
Bell	6.02	5.9	81.2	75.0	.350	.279	5.500	.162	1.870	5.8	.210	.354	.748	.419	.318
Reninger	6.00	6.5	81.8	76.0	.350	.151	7.500	.172	1.380	5.4	.220	.291	.845	.113	.267
Carr	6.00	6.2	81.2	80.0	.300	.099	4.600	.254	4.760	9.1	.210	.313	.776	0.000	.241
Wasserman	7.88	6.9	81.3	80.9	.153	.154	5.600	.151	3.000	10.4	.160	.340	.653	0.000	.188
Nichols	6.83	7.7	81.3	78.0	.405	.137	7.500	.196	1.490	6.9	.280	.196	.531	0.000	.246
O'Hara	12.96	7.4	80.1	79.0	.203	.206	5.800	.192	1.830	6.2	.250	.420	.573	.458	.299
Dowdy	7.00	8.0	80.7	80.6	.118	.181	7.800	.138	4.930	9.0	.120	.867	.748	.385	.203
Cook	8.13	7.6	79.8	80.3	.211	.171	7.300	.209	3.470	7.3	.210	.458	.603	.392	.274
Darrick	7.00	7.8	79.7	77.8	.393	.375	13.100	.300	3.040	5.7	.310	.466	.726	.330	.405
Linden	7.85	7.3	79.4	80.3	.274	.086	5.200	.145	5.760	9.0	.110	.706	.653	0.000	.273
Dawkins	5.73	7.2	79.6	79.8	.255	.228	9.900	.331	4.390	8.6	.290	.690	.752	0.000	.392
Schooley	8.88	7.4	78.4	78.8	.248	.149	5.600	.137	4.040	8.9	.120	.477	.430	0.000	.209
Clark	9.90	8.5	76.4	83.5	.179	.151	6.700	.116	1.870	4.1	.150	.253	.431	.175	.174
Roberts	6.85	8.9	75.4	80.7	.245	.110	5.700	.240	7.200	16.3	.150	.675	.698	.096	.279
Burleigh	3.00	7.4	76.8	75.4	.175	.076	5.400	.212	3.240	7.6	.220	.215	.576	.040	.222
Average	7.52	7.4	79.7	78.8	.269	.169	6.941	.206	3.685	8.52	.204	.441	.629	.143	.268

* Calculated ach = achoff x (1-RTF) + achon x (1-DCF) x RTF + achcl x DCF x RTF

Figure 14. PFT Measured Infiltration Versus House Airtightness (ACH 50).

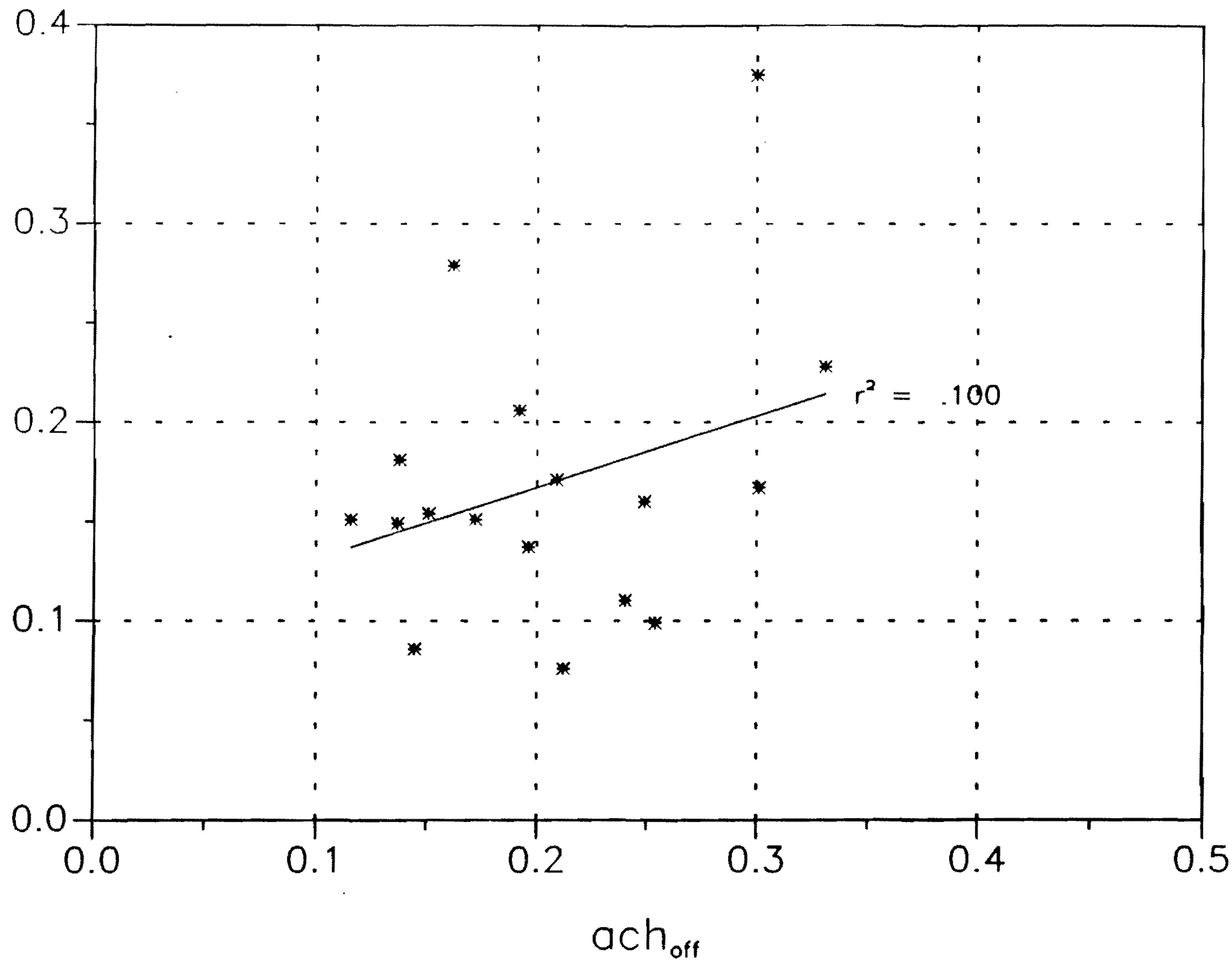


1. Wind speed varied from one PFT test to another. If the wind speed were the same during all the PFT tests, then the correlation would improve.
2. The homes had different levels of shielding from the wind.
3. Temperature difference between indoors and outdoors varied from one PFT test to another.
4. Temperature difference between the house and attic varied for different houses, depending upon the roof surface color, shingle type, outdoor temperature, and the amount of solar radiation during the PFT test.
5. The location of the leaks in the house envelope varied from house to house. Infiltration varies depending upon how evenly the leaks are distributed around the house envelope and upon the distribution of the leaks high and low in the structure.
6. The amount of door opening and closing varied during the PFT test periods, depending upon occupancy and lifestyle
7. The amount of duct leakage and air handler operation time varied from one house to another.
8. The amount of infiltration caused by closure of interior doors, and the fraction of the time that the doors were closed, varied from one house to another.
9. The amount of infiltration caused by exhaust equipment (exhaust fans, interior dryers, central vacuum systems, etc.) varied from house to house depending upon the use time and size of the exhaust air flow.

When it is considered how many variables can impact infiltration besides house airtightness, it is surprising that the correlation between PFT infiltration and ACH50 is as good as it is. If additional variables (wind and temperature) were brought into the analysis, then the prediction could be improved. It is interesting to note that dividing ACH50 by 40 predicts week-long PFT infiltration remarkably well.

Infiltration rates from the short-term infiltration tests can be compared to the PFT tests. Figure 15 is a plot of PFT versus achoff. The coefficient of determination is poor (r^2=0.100). The fit can be improved by modifying achoff to normalize it to an average

Figure 15. PFT Measured Infiltration Versus Tracer Gas Infiltration With the Air Handler Off.



(site) wind speed of 3.3 MPH; r^2=0.282 (Figure 16). Achoff was normalized by following a line parallel to the best fit line from the test wind speed to 3.3 MPH.

The fit can be further improved by taking into account the run time of the air handler. A formula can be used to predict the infiltration rate over an extended period, based on the short-term test results of achoff and achon.

$$\text{achcalc} = \text{achoff} * (1 - \text{RTF}) + \text{achon} * \text{RTF}$$

where achoff is the infiltration rate during the short-term test with all air moving equipment turned off, achon is the infiltration rate during the short-term test with the air handler operating continuously, and RTF is the measured run time fraction of the air handler during the PFT test. Figure 17 shows that the coefficient of determination is improved by including air handler run time; r^2=0.316.

Additional improvement is achieved by also taking into account the estimated interior door closure time. (The door closure time is an estimate by the occupants of their typical pattern of door closure.) The formula is modified as follows:

$$\text{achcalc} = \text{achoff} * (1 - \text{RTF}) + \text{achon} * (1 - \text{DCF}) * \text{RTF} + \text{achcl} * \text{DCF} * \text{RTF}$$

where achcl is the infiltration rate during the short-term test with the air handler operating continuously and interior doors closed and DCF is the door closed fraction based on occupant estimate. This calculated ach is located in the right-most column of Table 1. Figure 18 shows that the best fit line now has a coefficient of determination of r^2=0.468.

While there is significant correlation between achcalc and the PFT test results, the average PFT ach is 36% lower than achcalc, 0.17 ach versus 0.27 ach. How can this great a difference exist?

Figure 16. PFT Measured Infiltration Versus Tracer Gas Infiltration With the Air Handler Off; Achoff Normalized to Normal Wind Speed (3.4 MPH at Site).

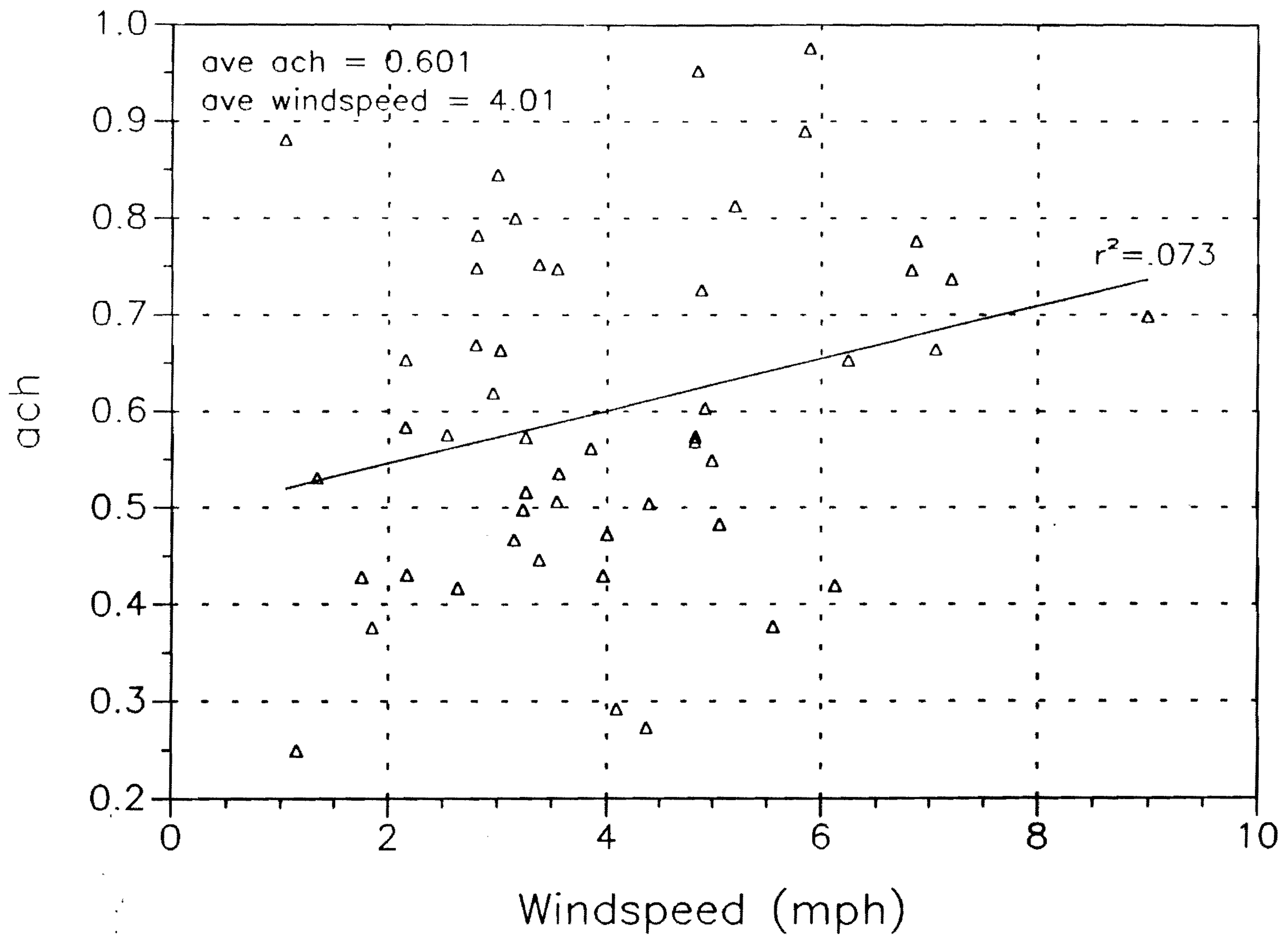


Figure 17. PFT Measured Infiltration Versus Calculated Infiltration Based On Tracer Gas Measured Achoff (wind normalized) and Achon (achcalc = achoff,n x (1-RTF) plus achon x RTF).

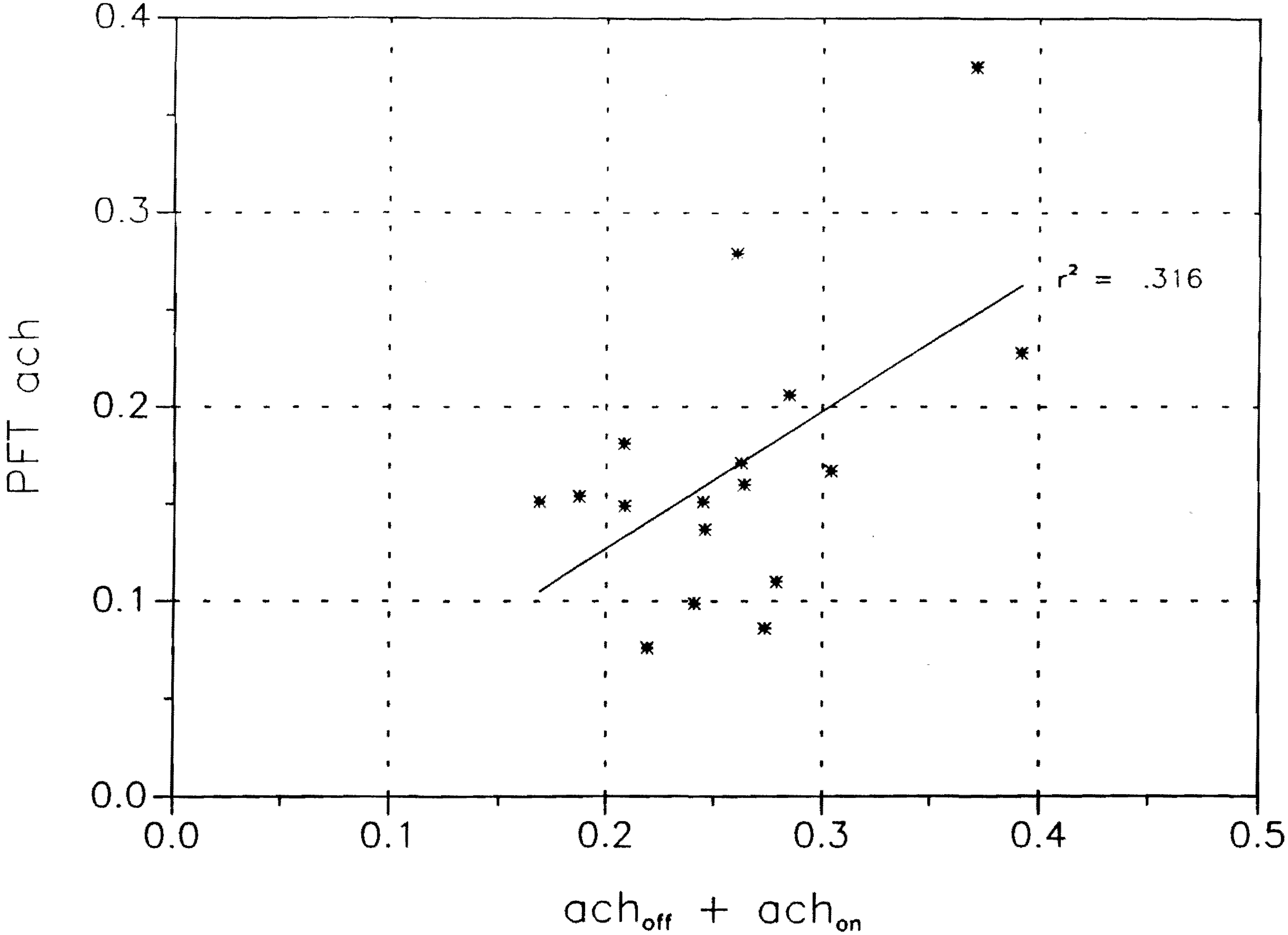
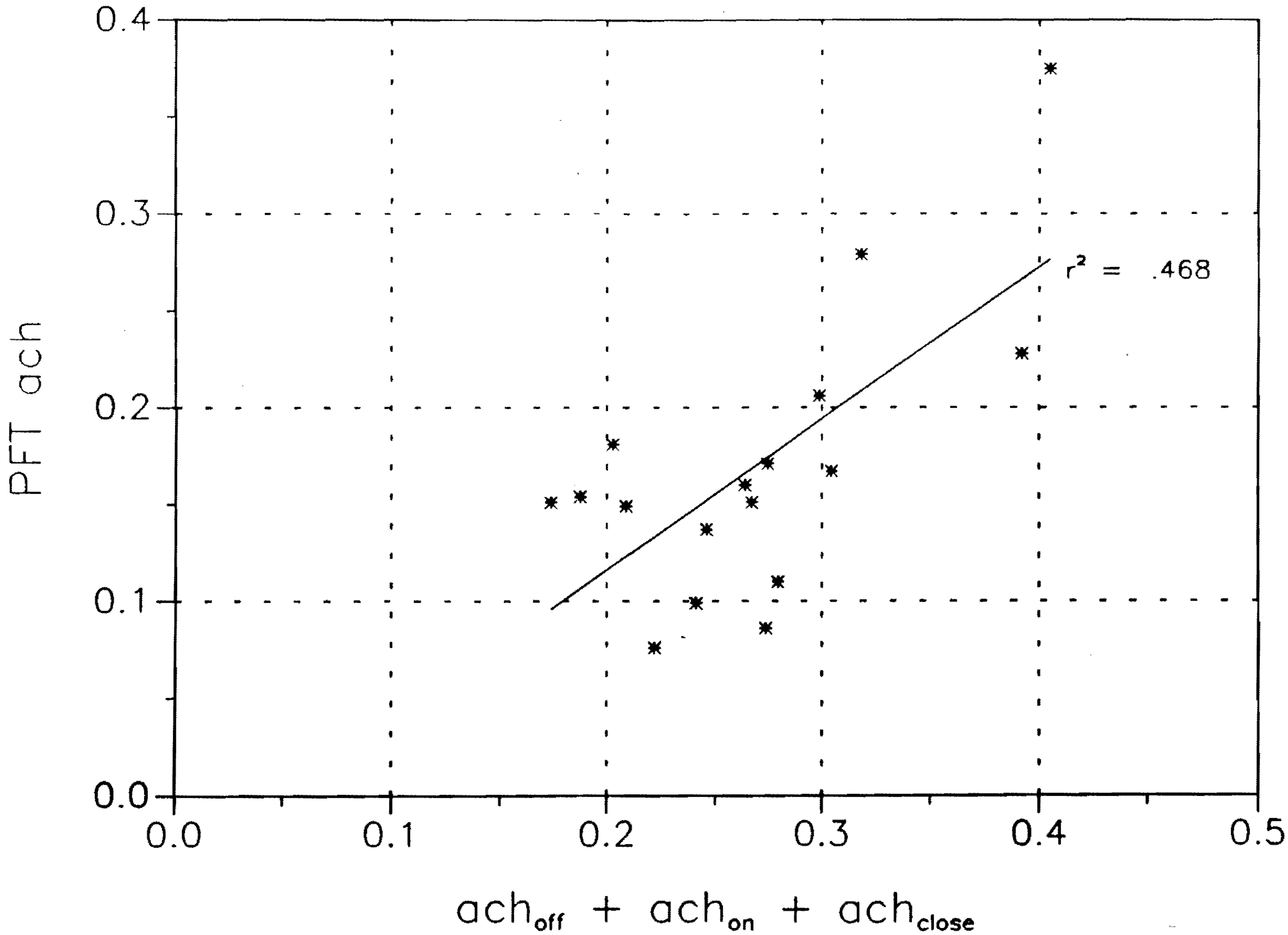


Figure 18. PFT Measured Infiltration Versus Calculated Infiltration Based On Tracer Gas Measured Achoff (wind normalized), Achon, and Achcl (with door closed). (achcalc=achoff, n x (1-RTF) + ach x (1-DCF) x RTF + achcl x DCF x RTF.)



A closer analysis of the short-term test results may account for some of the difference. Achoff may overpredict average natural infiltration because wind speeds during those short-term tests averaged 8.5 MPH (FSEC station) compared to 7.4 MPH (FSEC station) during the PFT tests. Information about nighttime natural infiltration rates during Florida summer nights is not available, but logically they are significantly lower than during the day. This conclusion is based upon the fact that nighttime wind speeds are lower and temperature difference between indoors and outdoors is near zero. If it is estimated that nighttime achoff is 0.13 ach, based on near zero wind velocity at the house (estimate from Figure 2) and near zero delta-temperature, then achoff for the day will be about 0.17 ach.

Achon (infiltration rate with the air handler on) is also affected by wind velocity. Wind velocity during achon tests was higher than the achoff and PFT tests. In cases where duct leaks were large, achon was largely determined by the air handler and little by the wind. In those homes where duct leakage was small, wind would affect achon significantly. Therefore, achon may overestimate infiltration when the air handler is on.

The formula may also overpredict the impact of achon upon achcalc. The reason is that the air handler operation occurs mostly during the afternoon and early evening hours of a summer day, which is the same time of day when wind is at a maximum and therefore natural infiltration is at its maximum. The formula assumes that achon occurs equally throughout the day, thus overestimating achcalc.

For these reasons, the calculated infiltration would be lower, and thus closer to the PFT tests. If achoff is taken to be 0.17 ach (instead of 0.21), then achcalc reduces from 0.27 to 0.25 ach. If achon is taken to be 0.41 (instead of 0.44), then achcalc reduces to 0.24 ach. Even with these adjustments, PFT still predicts about 30% lower. The authors are unaware of additional explanation for the PFT tests predicting lower.

6.1.3 Infiltration Prediction Models

Measuring infiltration rates in homes by means of tracer gas testing is difficult, expensive, and time consuming. Equipment cost begins at $5000. When tests are done for an hour or two, the infiltration rate is known only for that specific period, for that specific set of wind, temperature, and mechanical system conditions. In order to accurately characterize a house's natural infiltration rate, a number of tests must be done over a range of wind and temperature conditions. Infiltration with the air handler on, and with doors closed and the air handler on, must also be measured. From this, an estimate of annual infiltration rate may be made which hopefully would be within ±10% of the true infiltration.

Another option for determining house infiltration rates is PFT testing. PFT testing allows characterization of actual house infiltration over a period of weeks or months. It requires a minimum of work and specialized training. Since the tests would ideally be done over several seasons in order to characterize annual infiltration, the cost would be on the order of $500 or more.

As an alternative to tracer gas infiltration testing, predictive models have been developed to predict natural infiltration based on a blower door test and weather data (the models are described in Appendix A). The blower door test provides a measure of the house envelope airtightness and can be done at a nominal cost of $50 or less. This tightness is often expressed in ACH50 (air changes per hour when the house is depressurized to 50 Pa) and ELA (equivalent leak area, which is an amalgamation of all of the house's leaks into a fictitious hole of specified dimensions). How well do these models work?

A model has been developed by Lawrence Berkeley Laboratories. This model characterizes the house according to ELA, height inside the conditioned space, and the fraction of the leak area located in the floor, ceiling, and walls. The driving forces for infiltration are wind and temperature difference. Wind speed can be obtained from a central weather station and modified to represent local conditions.

Modification to the weather station wind data is done by means of terrain and shielding classifications. Each house is assigned a terrain and shielding class on a scale from 1 to 5. Class 1 is the most exposed and open. The terrain calculation reduces the wind speed of the airport weather station to what is occurring locally in the neighborhood. The shielding calculation further reduces the wind speed to represent what actually strikes the house.

Infiltration is calculated separately for thermal stack effect and wind effect. Stack effect is based on the building height, the absolute temperature difference from indoors to outdoors, the house ELA, the fraction of the house ELA located in the floor and ceiling (we have used R=0.67), and the fraction of the floor+ceiling total ELA which is in the ceiling (we have used X=1.0). (A more detailed description of the LBL model is contained in Appendix A in this report.)

In order to assess the predictive ability of the LBL model, predicted infiltration versus measured infiltration has been plotted (Figure 19) for the 50 homes using house characteristics, shielding and terrain classifications, and weather data specific to each test period. Wind speed data is from the regional weather station (FSEC or the Orlando airport) for the infiltration test period, and is modified according to terrain and shielding. On average, the model predicts very nearly the same as what is measured. But prediction is poor, on a house to house basis, with r^2 of only 0.359.

When the site measured wind speed is used, r^2 improves to 0.450, but the model underpredicts (Figure 20). Because the wind speed measurement on site is affected by terrain and shielding, we have set shielding classification to 1 (based on personal communication from Max Sherman). Even so, predicted infiltration is lower (about 80% of measured) because the site-measured wind speed is lower than the terrain-corrected weather bureau wind speed.

Another infiltration prediction model is "divide by 20" (Sherman, 1987). In this method, natural infiltration is determined by dividing ACH50 by 20. This divisor is modified for various climate zones of the U.S.. For example, central Florida is "divide by 20 to 23."

Figure 19. LBL Model Predicted Infiltration Using Weather Bureau Wind Data Versus Tracer Gas Measured Infiltration With the Air Handler Off.

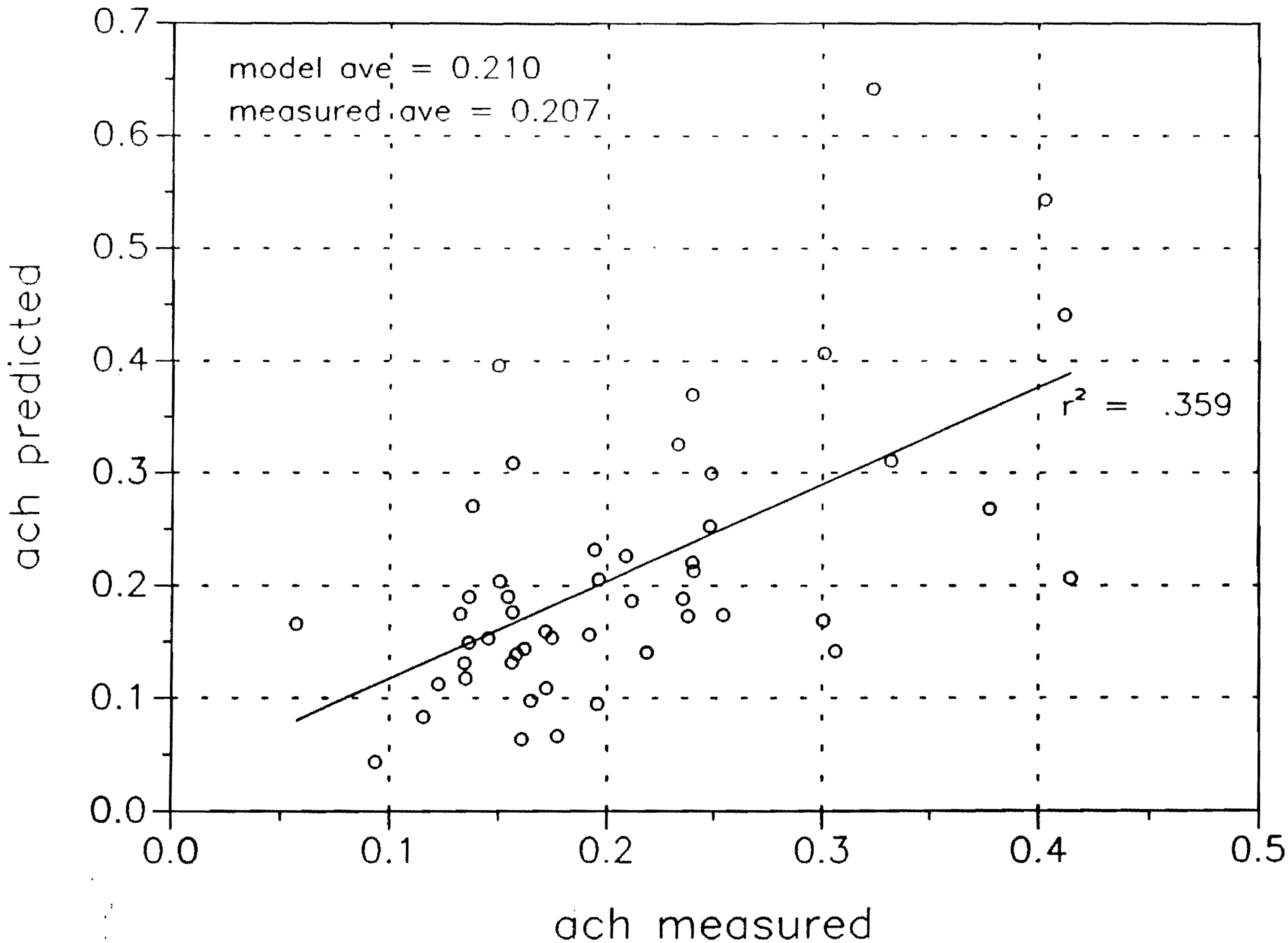
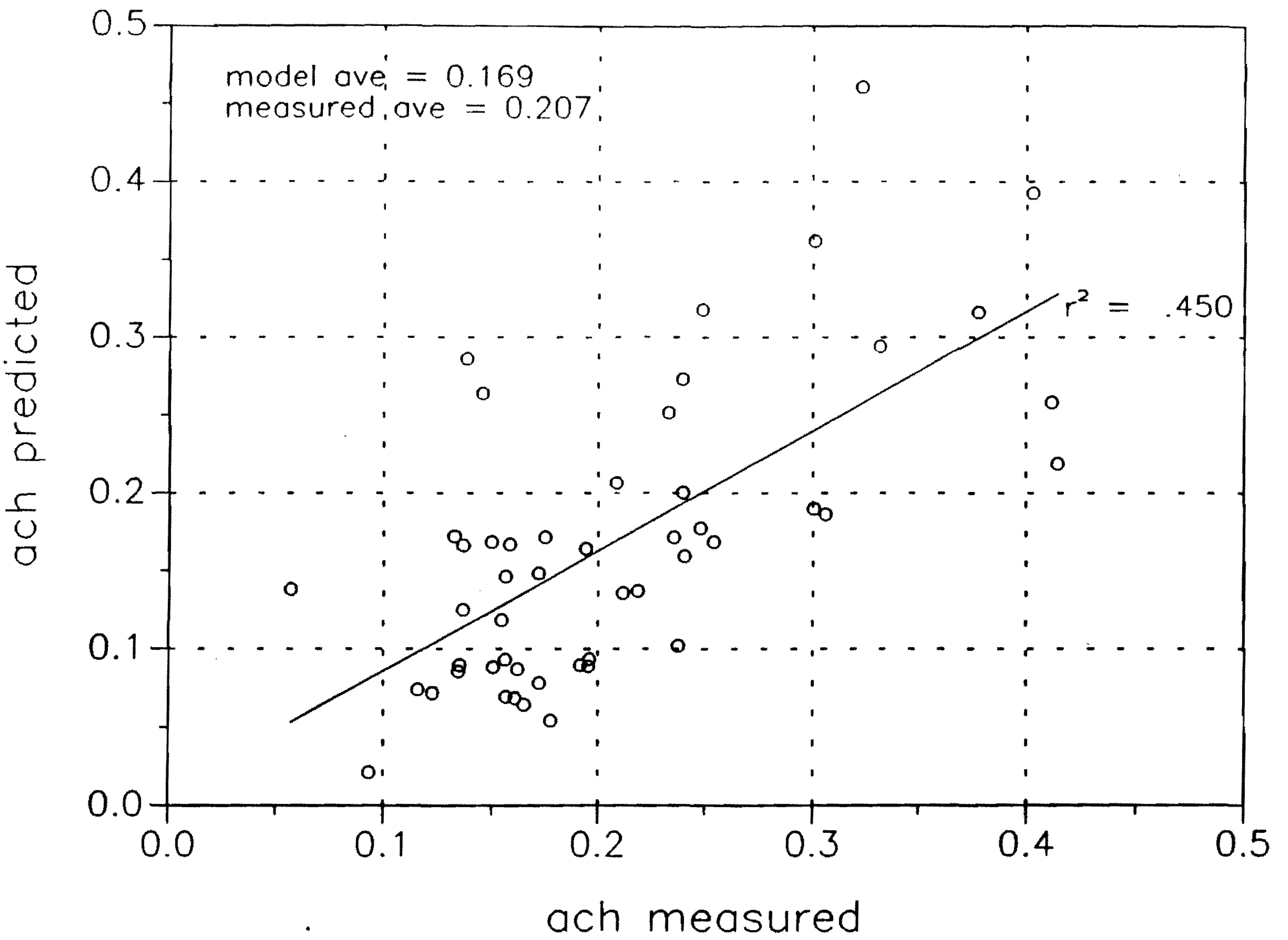


Figure 20. LBL Model Predicted Infiltration Using Site Measured Wind Data Versus Tracer Gas Measured Infiltration With the Air Handler Off.



Correction factors are also included for building height, wind shielding, and shape of leaks (see more detailed summary in Appendix A). In Florida, "divide by 21.5" and correcting for building height, shielding, and hole shape overpredicts natural infiltration by a factor of two. "Divide by 40" predicts very well in aggregate and fairly well for individual homes with r^2=0.51 (Figure 21). It is surprising that this simple model predicts infiltration twice as well as the complex model, especially when it is considered that divide by 40 does not take into account the wind and temperature conditions occurring during the test.

Another model, called "normalized leak approximation", has been developed and is contained in ASHRAE 119-1988. This model takes into account building airtightness (ELA), building height, floor area, wind speed, and temperature difference from indoors to outdoors. Figure 22 plots predicted infiltration versus measured infiltration. The NLA model overpredicts infiltration by about 2 to 1, and the coefficient of determination is low; r^2 = 0.205.

Figure 23 summarizes the four infiltration prediction models. The ASHRAE 119 "normalized leak approximation" model is very poor. It overpredicts by a factor of two and has a very low coefficient of determination. The LBL model is somewhat better. On the average it predicts the average infiltration of the 50 homes well, but the scatter is great, with r^2=0.359. The simpler model, "divide by 40", provides rather good prediction in aggregate, and for individual houses as well (r^2=0.510).

ACKNOWLEDGEMENTS

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Figure 21. "Divide by 40" Infiltration Prediction Model Versus Tracer Gas Measured Infiltration With the Air Handler Off.

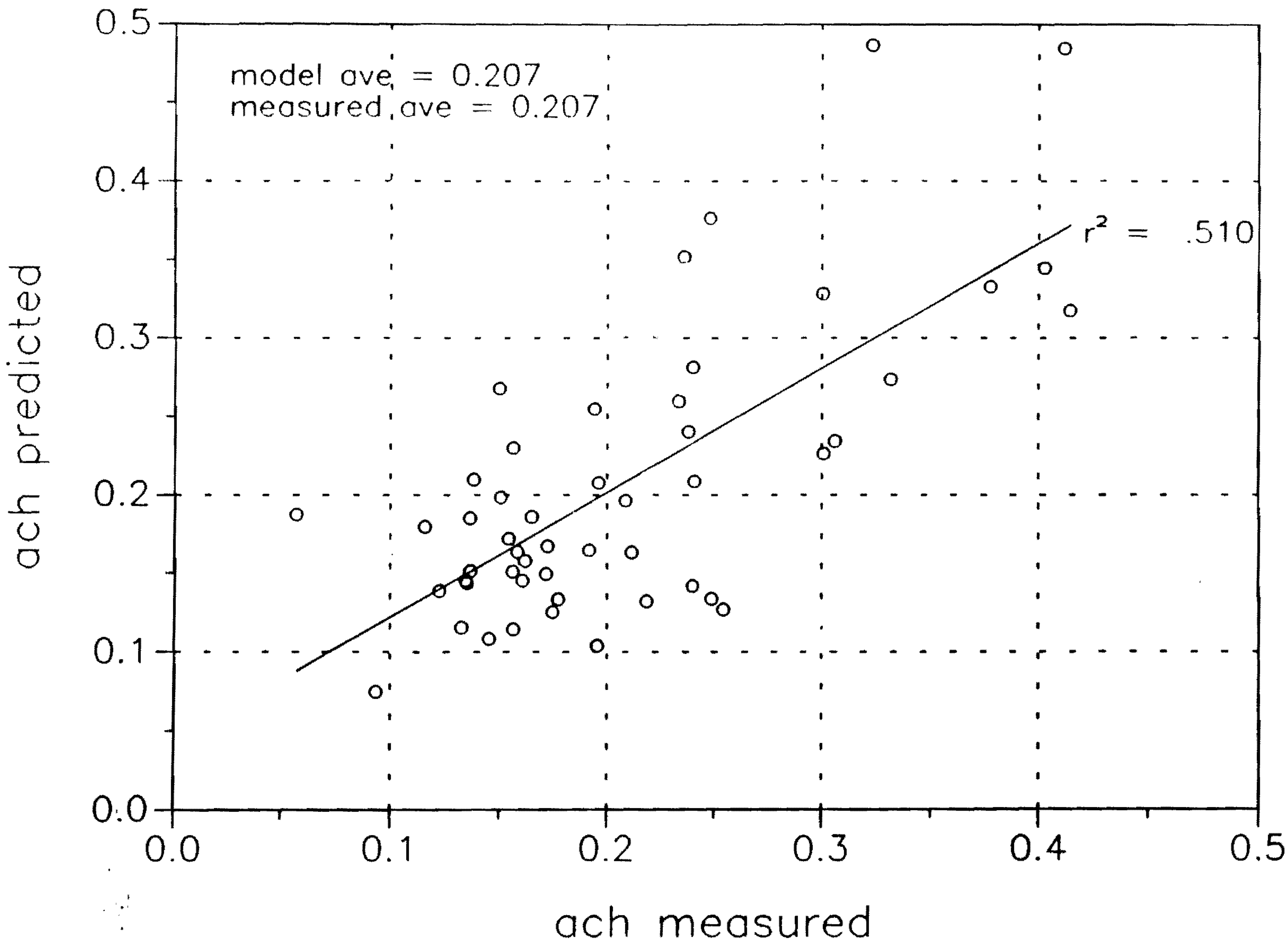


Figure 22. "Normalized Leak Approximation" Prediction Model Versus Tracer Gas Measured Infiltration With the Air Handler Off.

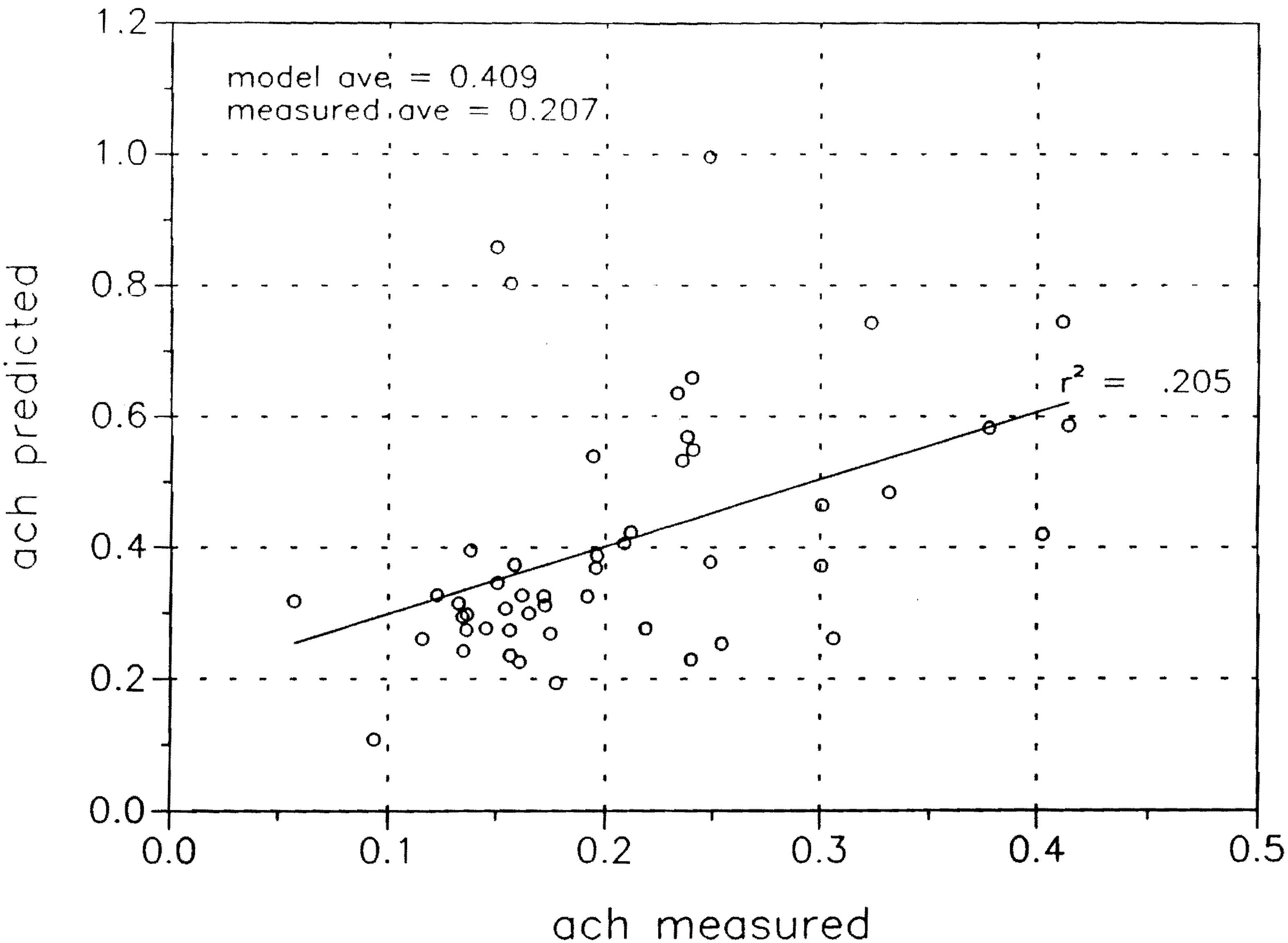
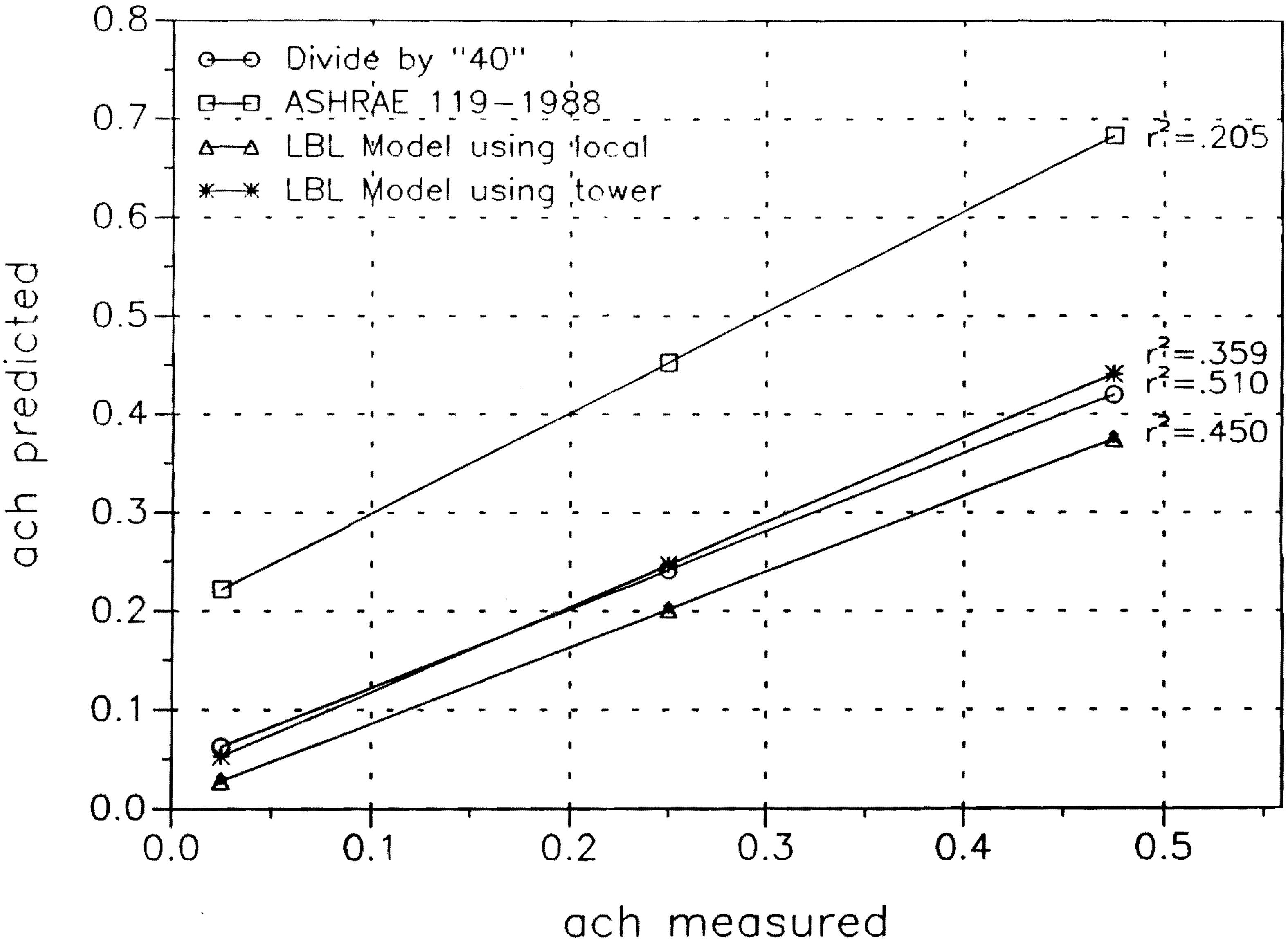


Figure 23. Best Fit Line for Four Infiltration Prediction Models Versus Tracer Gas Measured Infiltration With the Air Handler Off.



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INFILTRATION MODELS

AIRTIGHTNESS DIVIDED BY 20......

In the later part of the 1970's, a simple relationship was noticed between the airtightness of a building (ACH_{50}) and its measured infiltration rate. The model in its most basic form says that natural infiltration is ACH_{50} divided by 20. This relationship, though somewhat crude by scientific standards seemed to give a fairly good approximation.

This formula takes into account some of the variables that influence the infiltration rates of buildings. It is commonly believed that the two largest driving forces of infiltration (at least in cold climates) are stack and wind effects. Stack effect is attributed to the air movement due to the temperature difference between inside and outside and the height of the building. If both the temperature difference and the height of the building are large, then the induced infiltration caused by stack effect will be large as well. Wind effect is the infiltration due to the force of wind. Climatic conditions (how windy an area is) and shielding (how protected from the wind) are the two major components of the model. The size and location of the holes in the building are important as well. From these three ingredients (stack, wind, and hole description), a simple relationship has been derived; "divide ACH_{50} by 20". Correction factors have been developed for height, shielding, leak type, and climate.

Height Correction Factor

Number of stories	1.0	1.5	2.0	3.0
Correction "H"	1.0	0.9	0.8	0.7

Wind Shielding Factor

Shielding Type	Hidden	Normal	Exposed
Correction "S"	1.2	1.0	0.9

Leakiness Factor

Hole Type	Tight	Normal	Loose
Correction "L"	1.4	1.0	0.7

Climate Factor "C"

This factor is based upon geographical location, but values range from 14 to 26. The average value of 20 is commonly used.

Once the appropriate values have been chosen and the airtightness test performed, an infiltration approximation can be calculated according to the following equation.

$$ach_{predicted}=\frac{ACH_{50}}{C\times H\times S\times L} \tag{1}$$

The problem with the model, at least when used in comparison with tracer gas testing in Central Florida, was that it over predicted the infiltration rates by a factor of 2 very consistently. Therefore, we have changed the climate factor to "40". Dividing ACH_{50} by "40" appears to give a good approximation to the infiltration rates that have been observed.
(Source:Energy Auditor & Retrofitter; Jul/Aug 1986; pp16-19)

Lawrence Berkeley Laboratory (LBL) Model.......

The LBL Model was first presented in 1979 by M. Sherman and D. Grimsrud in the ASHRAE Transactions. This model provides a means of predicting natural (wind and temperature) infiltration rates based upon specific known parameters that effect the infiltration rates of buildings. Since wind and stack effects are considered to be the two main driving forces of infiltration rates (assuming a passive house - that is no mechanical devices causing an airflow),

$$Q_{weather}=\sqrt{Q_{wind}^2+Q_{stack}^2} \tag{2}$$

then a mathematical expression for the airflow (Q) through a building may be considered. The stack effect (Q_{stack}) is caused by a temperature difference which produces a pressure gradient between the floor and ceiling of the building. The variables include temperature difference, leak area, height of ceiling, and ceiling/floor fractions.

$$Q_{stack}=L_o\times f_s\times\sqrt{g\times H_s\times\left|\frac{\Delta T}{T}\right|} \tag{3}$$

where:

- L_o = Total leak area of the envelope (m^2)
- f_s = Stack factor
- g = Acceleration of gravity (9.8 m/sec^2)
- H_s = Stack height of building (high-low leak) (m)
- ΔT = Inside to outside temperature difference (°K)
- T = Absolute (inside) temperature (°K)

and:

$$f_s=\frac{1+\frac{R}{2}}{3}\times(1-\frac{X^2}{(2-R)^2})^{3/2} \quad (4)$$

where:

R = Fraction of total house leak area located in the floor and ceiling

X = Proportion of total floor and ceiling leak area which is located in the ceiling

The wind effect (Q_{wind}) is a function of the building's leakage area and the distribution of that leak across the envelope. Also, it is a function of the localized wind velocity and the shielding of the building' surfaces.

$$Q_{wind}=L_o\times v_1\times C\times(1-R)^{1/3} \quad (5)$$

where:

v_1 = Localized wind speed

C = Shielding coefficient (1 of 5 classes) as follows...

0.324	Class I	no local shielding
0.285	Class II	light shielding, few obstructions
0.240	Class III	moderate shielding, some obstructions
0.185	Class IV	heavy shielding, many obstructions
0.102	Class V	very heavy shielding, large obstructions

One of the very attractive traits of this model is its ability to approximate the local wind speed from weather station windspeed (such as an airport tower or other official weather data collection facility). This is accomplished by using a conversion formula....

$$v_1=v\times\frac{\alpha_w\times(\frac{H_w}{10})^{\gamma_w}}{\alpha_t\times(\frac{H_t}{10})^{\gamma_t}} \quad (6)$$

where:

v = measured wind speed

α_w = terrain coefficient at site

γ_w = terrain exponent at site

α_t = terrain coefficient at tower

γ_t = terrain exponent at tower

H_w = Height of ceiling above grade at site

H_t = Height of tower

The terrain coefficients and exponents are also described according to a class designation of 1 to 5 ranging from an open expanse to very protected as follows:

Class	Alpha	Beta	Description
I	0.10	1.30	ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	flat terrain with some isolated obstructions
III	0.20	0.85	rural area with low buildings, trees or other scattered obstructions
IV	0.25	0.67	urban, industrial or forest area
V	0.35	0.47	center of large city or other heavy built-up area

When v_1 is calculated, then Q_{wind} is calculated. With calculated values for Q_{stack} and Q_{wind}, $Q_{weather}$ can now be computed. It is in units of cubic meters per second. To convert to air changes per hour, multiply by 3600 sec per hour and divide by the volume of the house.

Normalized Leak Approximation

ASHRAE 119-1988 was designed to establish performance requirements for air leakage of residential buildings to reduce the air infiltration loads and to provide a means of standardizing the airtightness of those buildings. This Standard provides a means to classify buildings in one of ten different airtightness classes. The Standard then, through the use of a U.S. map with infiltration degree-days superimposed upon it, provides a method by which acceptable building tightness may be determined. The procedure uses a normalization process to determine the various classes. The procedure is as follows:

$$L_n=1000\times\frac{L}{A}\times\left(\frac{H}{H_o}\right)^{0.3} \tag{7}$$

where:

- L_n = Normalized Leakage
- H_o = Height of a single story (8 ft)
- H = Height of the building (ft)
- L = Leakage area of the building (ft^2)
- A = Floor area of the building (ft^2)

The Appendix B of the Standard provides the model to determine an approximate infiltration rate of that building using the normalized leakage area and a specific infiltration based on infiltration degree-days. With this model it is possible to assume that the infiltration rate is approximately equal to the normalized leakage area.

$$ach_{predicted} \approx L_{normalized} \quad (8)$$

However, when weather data is available, it is then possible to construct a specific infiltration averaged over a time period. The infiltration rate can then be approximated as follows.

$$ach_{predicted} \approx \frac{s}{s_o} \times L_{normalized} \quad (9)$$

where:

s = Specific infiltration (ft/min)
s_o = Typical specific infiltration (140 ft/min)

These value of specific infiltration is calculated according to the following expression.

$$s = \sqrt{f_w^2 \times v^2 + f_s^2 \times |T_{in} - T|} \quad (10)$$

where:

f_w = 0.132
v = hourly wind speed measured at 20ft (ft/min)
f_s = 17.6 (ft/min-$^oF^{1/2}$)
T_{in} = typical interior temperature ^oF
T = outside temperature ^oF

For the Central Florida area the specific infiltration (s) is given in the standard as 126 ft/min. Therefore the expression becomes as follows:

$$ach_{predicted} \approx \frac{126}{140} \times L_{normalized} \quad (11)$$

or

$$ach_{predicted} \approx 0.9 \times L_{normalized} \quad (12)$$