ANALYSIS OF INFILTRATION BY TRACER GAS TECHNIQUE, PRESSURIZATION TESTS, AND INFRARED SCANS

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ABSTRACT:

The natural ventilation experienced by three unoccupied houses was measured over a one year period by a tracer gas technique. An energy audit was also performed using a fan to pressurize and depressurize the house along with an infrared scanner to detect the leakage paths. The houses were of a standard design and identical except for insulation levels. All houses were built by the same contractor at the same time. The tracer gas measurements were converted to a format similar to the pressurization results by using a previously developed model. The two methods placed the houses in the same relative ranking in terms of leakiness but the pressurization technique indicated much smaller differences than did the tracer gas technique.

INTRODUCTION

In late 1977, three test houses were built at the Owens-Corning Fiberglas Technical Center in Granville, Ohio to examine the effect of different insulation strategies on the total heating and cooling load. Several precautions were taken to eliminate as many of the extraneous variations between houses as possible. The three ranch houses were built to the same NAHB floor plan shown in Figure 1. They were built by the same contractor at approximately the same time. All three houses face in the same direction and are located next to each other, as seen in Figure 2. The houses were located on laboratory grounds and access during the tests was restricted to authorized personnel, including maintenance people. To reduce the influence of equipment behavior, the houses were heated with a forced-air, electrical resistance heating system and cooled by a central brine forced-air system. The houses were spaced 46 m apart to minimize the disturbance of the air flow patterns on one house caused by a house upwind. This distance was determined by calculations that indicated spacing should be at least ten times the house height. All three houses were given a 4 mil, polyethylene vapor barrier but were not humidified. The windows were double glazed with storm windows. An internal mass of furnishings was simulated by approximately 3200 kg of concrete blocks distributed throughout the conditioned space. Supply air ducts in the houses were 0.7 $K\,m^2/W$ (R-4) insulated duct board with taped joints to minimize conduction losses and air leakage. Heating and cooling was controlled by laboratory calibrated thermostats set at 20 C during the heating season and 26 C during the cooling season. Natural air infiltration was measured in all three houses using tracer gas devices[1].

The primary differences between the houses were the insulation levels and the associated HVAC size requirements. Insulation levels were designed to represent

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the past, present, and future in home insulation. House C had no insulation, representing typical past construction. House B contained 3.3 K m^2/W (R-19) insulation in the ceiling and 1.9 K m^2/W (R-11) in the walls and floor, HUD minimum standards for the area. House A was built using the Arkansas concept with 6.7 K m^2/W (R-38) ceilings and 3.3 K m^2/W (R-19) walls and floors. As a result of the different insulation levels in the houses, HVAC sizing was varied to maintain approximately a 20 percent oversizing factor. This kept the dynamic behavior of each house approximately the same. Table 1 lists the differences between houses.

All possible efforts were made to maintain strict uniformity among the houses except for insulation levels and associated equipment sizing. Despite these precautions, the air infiltration experienced by each house was expected to introduce some variability in the heating and cooling loads. As the amount of air infiltration cannot be accurately specified using typical construction techniques, an effort was made to measure the infiltration in each house and to then understand whatever difference might be found between houses. Towards this end, various measurements were made to determine the leakage characteristics of each house. Extensive measurements of the natural infiltration for each house were made using automated gas tracer devices. Data from these measurements were used to develop regression models, which in turn were used to calculate infiltration loads. Pressurization and depressurization measurements were also made to determine the leakage characteristics of each house. Finally, infrared scans were made during the pressure tests to trace the leakage paths into and out of the house. The pressurization of the houses and the infrared scans were conducted as part of a program to develop new retrofit techniques. This effort included the auditing of a large number of houses in the local community. From it, a comparison between the three test houses and the general population of houses in terms of air leakage was possible.

TEST PROCEDURES

Pressure Tests

The depressurization and pressurization infiltration measurements were taken using equipment and procedures developed at Princeton University[2]. A calibrated blower door device, shown in Figure 3, was used to provide a pressure differential between the inside and outside of the house. This pressure differential was controlled by the speed of the fan motor. By taking angular velocity of the fan at various pressure differentials and converting the angular velocity to volumetric flow rate, a curve of air flow rate versus pressure differential was generated.

The air infiltration routes were detected with an infrared scanner. A Hughes Probeye Infrared Scanner was used in this project. When scanning inside, the house was depressurized causing cold air to be drawn in from the outside along the infiltration paths. This cold air path was readily detectable by the infrared scanner. When scanning in the attic, the house was pressurized to enhance the flow of warm air into the attic.

Natural Infiltration Measurement

In early April of 1978, automated air infiltration units developed at Princeton University[1] were installed in the basement of each house. These units use sulfur hexafluoride as the tracer gas. The gas was injected periodically into the houses in discreet amounts and immediately upstream of the blower. Samples were taken in the return air system upstream of the cooling coils. The raw data were recorded automatically on cassette tapes and reduced to air change rate and hourly averages. Samples were taken once every 15 minutes. The air handling system was operated continuously throughout the testing period to ensure adequate mixing of the tracer gas. Weather data were collected on-site at the control house (see Figure 3) at five-minute intervals and converted to hourly averages.

Initially, all three units were operated continuously to provide a continuous record of the infiltration experienced by each house. However, over the course of the year-long data collection period, interruptions occurred because of severe weather and equipment malfunctions. For 1978 and 8 months in 1979, 2249 hours of data were collected for House A, 1985 hours for House B, and 1637 hours for House C.

RESULTS

Pressure Tests

Blower door testing indicated that the houses were very tight in comparison to ten one-story ranch houses surveyed in the Columbus area. Additionally, the differences between the test houses were much smaller than those between the survey houses. The air change rates versus pressure differential for the three houses are shown in Figure 4. The air change rates at 50 Pa (0.2 inches H_2O) were 8.1 for A, 7.4 for House B, and 8.7 for House C. The air change rates under pressurization and depressurization were essentially the same. Readability in the air flow rate readings ranged from about ± 15 percent at very low pressure differences (10 Pa) to about ± 5 percent at high pressure differences (50 Pa). These results can be compared to the current Swedish Standard of 3.0 air changes/hr at 50 Pa. The other one-story ranch houses surveyed had air change rates at 50 Pa ranging from 12 to 20. Thus, the range of air change rates in the test houses was small in comparison to local housing and the test houses were relatively tight compared to local housing.

In addition to this test, a series of pressurization tests using equipment with smaller capacity were conducted to measure the effect of the ducts on house infiltration. Figure 5 shows the pressure versus air change relationship in the houses with the registers and supply ducts sealed to isolate the air distribution system from the conditioned portion of the house. In this plot, Houses A and B are essentially equal and House C is somewhat more porous. A possible reason for this is that House C, being uninsulated, had no insulation stuffed into the cracks around doors and windows. Insulating these cracks appears to make a noticeable difference. Figure 6 shows the change caused by unsealing the vents but leaving the blower off. As expected, the ducts add somewhat to the overall porosity of the house. Figure 7 shows the effect of blower operation on the tightness of the house. The pressurization of the supply ducts tends to make the house appear tighter under these test conditions. Actually, the blower operation probably increases the air exchanged between the house and the basement. The magnitude of this increase depends on the leakage area of the ducts and the blower capacity (as it influences duct pressure). The magnitude of the influence that furnace blower capacity can have on duct pressure and, hence, duct leakage is shown in Figure 8. House C, because of a larger heating and cooling load, has a blower with a measured capacity 2 1/2 times that of houses A and B (see Table 1). The magnitude of the duct pressure in House C can be significantly higher than that in A or B. With the same leakage area, this would exaggerate the air loss to the basement, attic, and crawl space. The effect of the duct leakage on the actual heating and cooling load is not easy to predict. The air is being exchanged, not with the outside, but with a space whose temperature is probably different than that of either conditioned space or the outside. The duct leakage influences both pressure tests and natural infiltration measurements.

An additional effect of a larger furnace blower is the possibility of slightly over pressurizing the house. This pressurization would increase the amount of air exchanged with the outside. It would also tend to make the house look tighter than it really is during pressurization tests by acting as a separate air source. The same pressure difference across the envelope requires less air flow. For comparison purposes, a bar chart of air change rate at 20 Pa for the three houses, showing the influence of the ducts and furnace blower, is given in Figure 9.

The infiltration paths detected by the infrared scanner were essentially in the same location in all three houses and varied only in degree. The interior walls of all three houses acted as air paths between the basement and attic. In each case, the kitchen walls were worst. These walls were connected to the kitchen cabinet soffits, which were open to the attic. Other interior walls varied in severity with holes for electrical wiring or similar breaks in the top or bottom plates contributing additional infiltration in the particular cavity in which the break was located. However, the primary path for infiltration in the interior walls was the small crack between the drywall and the top or bottom plate. Additional infiltration paths were located around plumbing stacks. Minor infiltration was detected around wall electrical outlets. The results of the infrared scan showed that even in relatively tight houses, standard construction and insulation techniques can result in infiltration and heat loss through interior walls. When the wall is a connecting path between the outside via the basement or crawl space, bandjoist, bottom plate, and the attic, the warm wall tends to pump the air into the attic by a chimney effect, carrying some heat with it.

Natural Infiltration

The natural infiltration measurements were made from the summer of 1978 to July of 1979, using tracer gas devices. Due to various problems encountered in data collection, the infiltration record was not continuous. For this reason, a format for displaying and comparing data was needed. Statistical regressions were made relating infiltration to weather parameters, in this case, dry bulb temperature and wind speed. The form of the regression was the one developed by Reeves, McBride, and Sepsy[3]. This technique relates infiltration to the pressure across the building envelope:

$$I = \beta_o^* \sqrt{P} \tag{1}$$

where

I is infiltration, air change/hr

β_o is a statistical regression proportionally constant

P is the weather-induced pressure drop across the building envelope, Pa

The pressure is estimated using the sum of the theoretical wind and stack pressure[3]. This technique has the advantage of providing a simple comparison between houses by using the regression coefficients. The magnitude of β_o is an indication of the house response to weather conditions; a large value of β_o indicates that the house is relatively porous to the weather-induced pressure difference across the building envelope. This technique assumes that infiltration will be zero when the weather-induced pressure difference is zero. A variation in this technique was suggested by evidence from pressure tests that leaks in the ducts, coupled with continuous blower operation, caused a measured infiltration independent of weather. This variation includes a constant component of infiltration of the form

$$I = \beta_1 \sqrt{P} + \alpha \tag{2}$$

where

I is infiltration, air change/hr

β_1 is a regression coefficient indicating sensitivity to weather

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*The regression coefficient and crack length parameter of the original model have been combined here.

α is the blower/duct component of infiltration, air change/hr.

Results from applying the two forms of the equation are shown in Tables 2 and 3. To illustrate the differences between houses due to changing seasons and aging, the data are divided into three periods--data taken in the summer of 1978, that taken in the winter of 1978-79, and that taken in the summer of 1979. Tables 2 and 3 show that the addition of the constant component of infiltration accomplishes two things. First, the RMS error decreases significantly. Second, the regression coefficient, β_1, remains relatively constant in Houses A and C during the summers of 1978 and 1979, which is not true for the regression coefficient, β_o. Table 3 also indicates that the houses were more sensitive to the weather in the winter than in the summer, as shown by the increased β_1 values. A possible reason for this is the thermal contraction of the building components caused by the cold weather. Also, in houses A and C, for which the comparison of two sets of summer data are possible, it appears that aging does not significantly affect the sensitivity of the infiltration to the weather. This result is seen from the relatively constant β_1 values for the two summer data sets.

A summary of the weather and infiltration for each data set is shown in Table 4. The range of temperatures present in each data set is quite typical for this area of the United States. The range of wind speeds is relatively low. This is reflected in the relatively small range of infiltration rates experienced by each house. The reason for the lower than average wind speeds can be attributed to the sheltered location of the houses. The houses are located in a shallow valley and are sheltered on two sides by trees. This can be seen in Figure 2. Figure 10 shows a typical day with predicted and measured infiltration for house A.

The values of β_1 for these data sets are approximations based on statistical fits. There is some variability associated with the calculated value of β_1. The trends found in the data presented here require further verification through natural infiltration measurements and pressurization tests made during winter and summer weather conditions.

CONCLUSIONS

During the course of the study, information concerning test procedures and house behavior was developed. Investigations of the effect the air handling system has on the test methods indicate that the ducts and furnace blower capacity significantly influence the porosity of a house as measured by the pressure test method. The magnitude of this effect in terms of heating and cooling load is not easily quantified. Leakage paths through semi-conditioned areas such as the basement, crawl space, and attic will change the actual loads.

Using the pressurization test as well as natural infiltration measurements, a variation of the model formulated by Reeves et al. was suggested to account for the infiltration caused by the air handling system. The additional term is a constant in the test houses because of the continuous blower operation. For situations where the blower operates only on demand for heating or cooling, the coefficient α would depend on blower operation time. In this situation, α may be correlated with the weather conditions.

The natural infiltration measurements indicated that infiltration rates may have a seasonal dependence. During the winter, β_1 was consistently larger than during the summer. Additionally, the relatively constant values of β_1 calculated for the two summer data sets of houses A and C indicates that aging does not affect the sensitivity of house infiltration to the weather. These conclusions are preliminary. Only two years of data are available and additional data in the form of pressurization testing and natural infiltration measurements are needed to substantiate them.

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NOMENCLATURE

I - infiltration rate, air change/hr.

P - weather induced pressure, $P = 136 \cdot P_{atm} \cdot h \cdot (\frac{1}{T_o} - \frac{1}{T_i}) + \frac{249.6}{T_o} \cdot WS^2$

T_o - outside dry bulb temperature (C)

T_i - inside dry bulb temperature (C)

WS - wind speed (m/s)

h - height of the neutral space in the house (1.2m)

β_o - regression coefficient based on Equation 1

β_1 - regression coefficient based on Equation 2

α - the intercept defined in Equation 2 which represents the component of infiltration caused by furnace blower and ducts.

TABLE 1 DIFFERENCES IN TEST HOUSES

ITEM	HOUSE A	HOUSE B	HOUSE C
INSULATION			
CEILING	6.7 K m^2/W	3.3 K m^2/W	0
WALLS	3.3 K m^2/W	1.9 K m^2/W	0
FLOORS	3.3 K m^2/W	1.9 K m^2/W	0
FURNACE BLOWER CAPACITY	.378 $\frac{m^3}{s}$	.378 $\frac{m^3}{s}$	.944 $\frac{m^3}{s}$
SUPPLY DUCT SIZES (DIAMETER)	.15 m	.15 m	.18 m
HEATING/AIR CONDITIONING	8.3 k W HEATING 5 k W COOLING	8.3 k W HEATING 7.3 k W COOLING	24.8 k W HEATING 15.4 k W COOLING
STUD SIZE	3.8 cm x 14 cm (1 1/2 in x 5 1/2 in)	3.8 cm x 8.9 cm (1 1/2 in x 3 1/2 in)	3.8 cm x 8.9 cm (1 1/2 in x 3 1/2 in)

TABLE 2 $I = \beta_o \sqrt{P}$

RESULTS OF REEVES, MCBRIDE, AND SEPSY MODEL

HOUSE	HOUSE A	HOUSE B	HOUSE C
SUMMER 1978 HRS. OF DATA β_o rms error	 162 HRS 0.201 0.175 AIR CHANGES/HR	NOT AVAILABLE	 178 HRS 0.166 0.079 AIR CHANGES/HR
WINTER 1978 - 1979 HRS. OF DATA β_o rms error	NOT AVAILABLE	 197 HRS 0.096 0.0572 AIR CHANGES/HR	 87 HRS 0.176 0.106 AIR CHANGES/HR
SUMMER 1979 HRS. OF DATA β_o rms error	 746 HRS 0.113 0.064 AIR CHANGES/HR	 661 HRS 0.125 0.084 AIR CHANGES/HR	 490 HRS 0.131 0.101 AIR CHANGES/HR

TABLE 3 $I = \beta_1 \sqrt{P} + \alpha$

RESULTS OF MODIFIED REEVES, MCBRIDE, AND SEPSY MODEL

HOUSE	HOUSE A	HOUSE B	HOUSE C
SUMMER 1978 HRS. OF DATA β_1 α rms error	 162 HRS 0.037 0.282 AIR CHANGES/HR 0.062 AIR CHANGES/HR	NOT AVAILABLE	 178 HRS 0.055 0.195 AIR CHANGES/HR 0.052 AIR CHANGES/HR
WINTER 1978 - 1979 HRS. OF DATA β_1 α rms error	NOT AVAILABLE	 197 HRS 0.041 0.195 AIR CHANGES/HR 0.035 AIR CHANGES/HR	 87 HRS 0.094 0.263 AIR CHANGES/HR 0.095 AIR CHANGES/HR
SUMMER 1979 HRS. OF DATA β_1 α rms error	 746 HRS 0.038 0.129 AIR CHANGES/HR 0.039 AIR CHANGES/HR	 661 HRS 0.035 0.151 AIR CHANGES/HR 0.060 AIR CHANGES/HR	 490 HRS 0.045 0.157 AIR CHANGES/HR 0.081 AIR CHANGES/HR

TABLE 4

WEATHER AND INFILTRATION STATISTICS

HOUSE	HOUSE A	HOUSE B	HOUSE C
Summer 1978			
Hours of data	162	N/A	178
To, max, min, ave (C)	38.6, 17.9, 24.8		28.5, 10.3, 19.6
WS, max, min, ave (m/s)	5.0, .2, .8		4.5, 0.0, 1.1
I, max, min, ave (hr^{-1})	.60, .10, .32		.50, .18, .28
Winter 1978-1979			
Hours of data		197	87
To, max, min, ave (C)	N/A	-.1, -21.5, -7.1	1.3, -15.6, -6.7
WS, max, min, ave (m/s)		5.8, .1, 2.2	4.6, .1, 1.5
I, max, min, ave (hr^{-1})		.52, .24, .33	1.04, .37, .55
Summer 1979			
Hours of data	746	661	490
To, max, min, ave (C)	29.8, 6.3, 20.5	29.4, 6.3, 20.3	29.8, 6.3, 19.0
WS, max, min, ave (m/s)	3.7, 0, 1.2	3.7, 0, 1.2	4.6, .1, 1.3
I, max, min, ave (hr^{-1})	.69, .11, .19	.66, .02, .20	.49, .02, .23

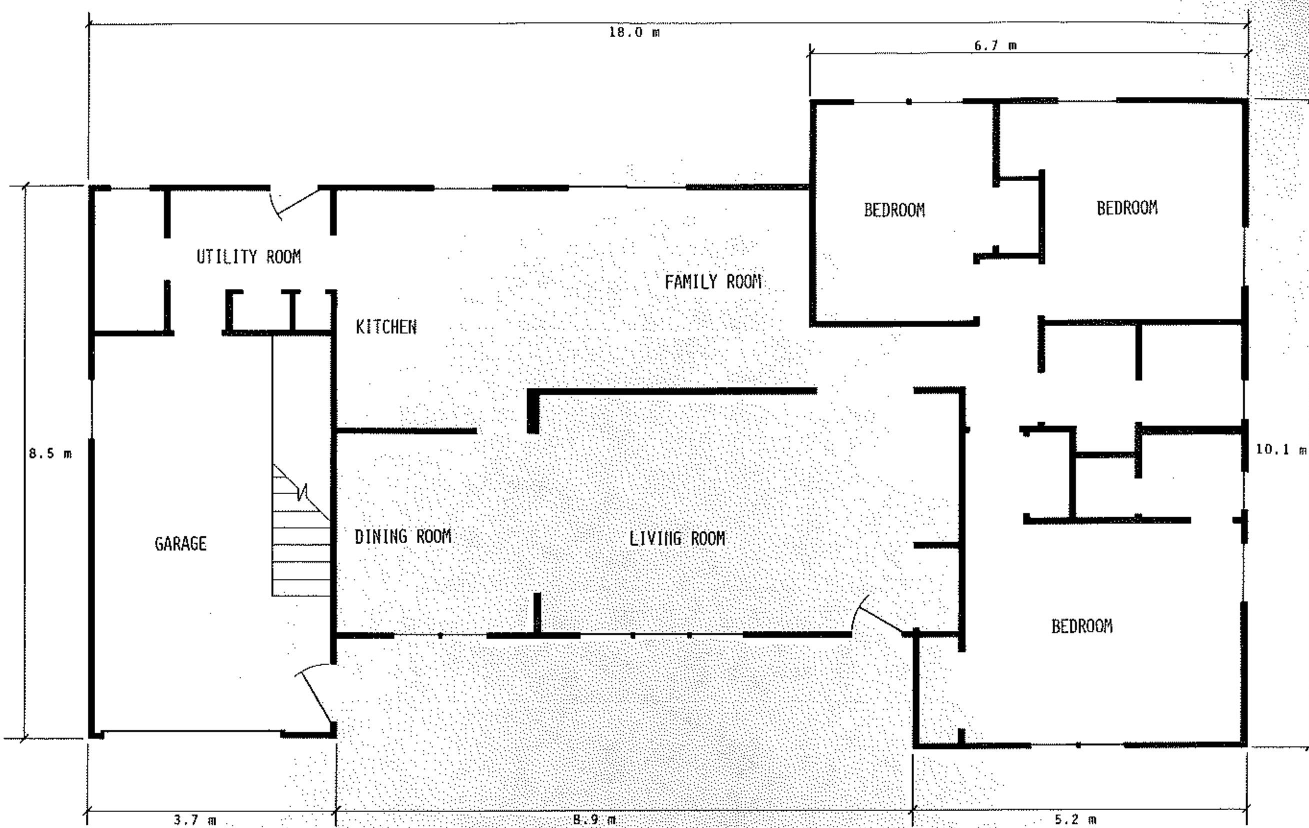
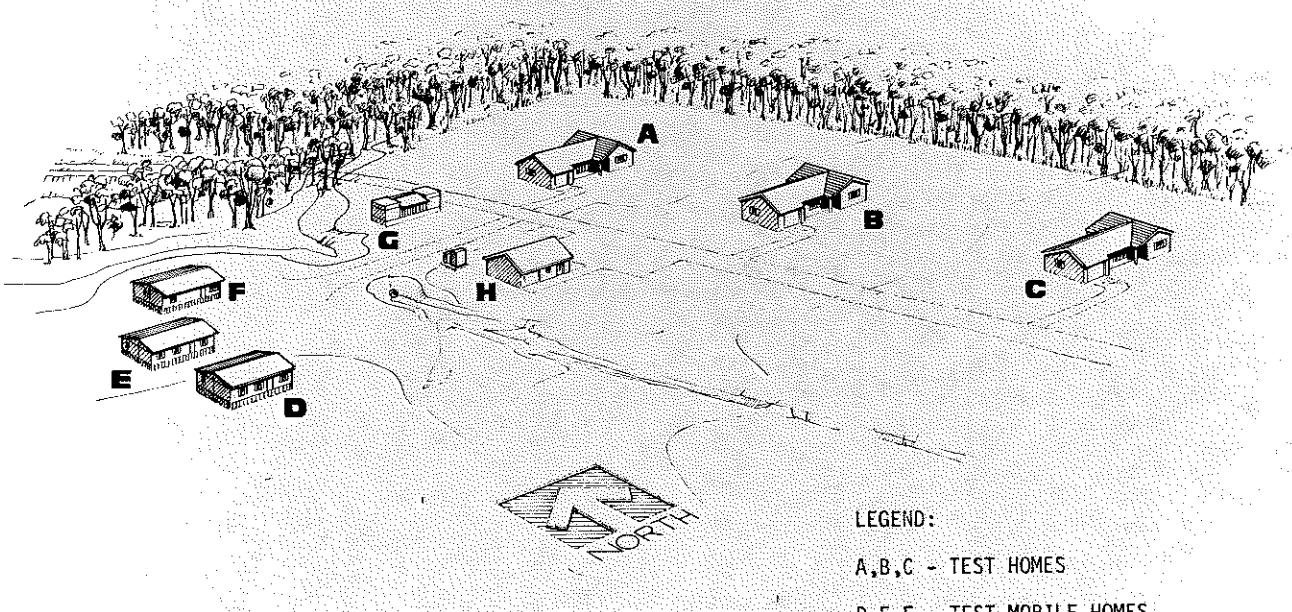


FIGURE 1 TEST HOMES FLOOR PLAN



LEGEND:

A,B,C - TEST HOMES

D,E,F - TEST MOBILE HOMES

G - MOISTURE RESEARCH FACILITY

H - CONTROL CENTER

FIGURE 2 LOCATION OF TEST HOMES

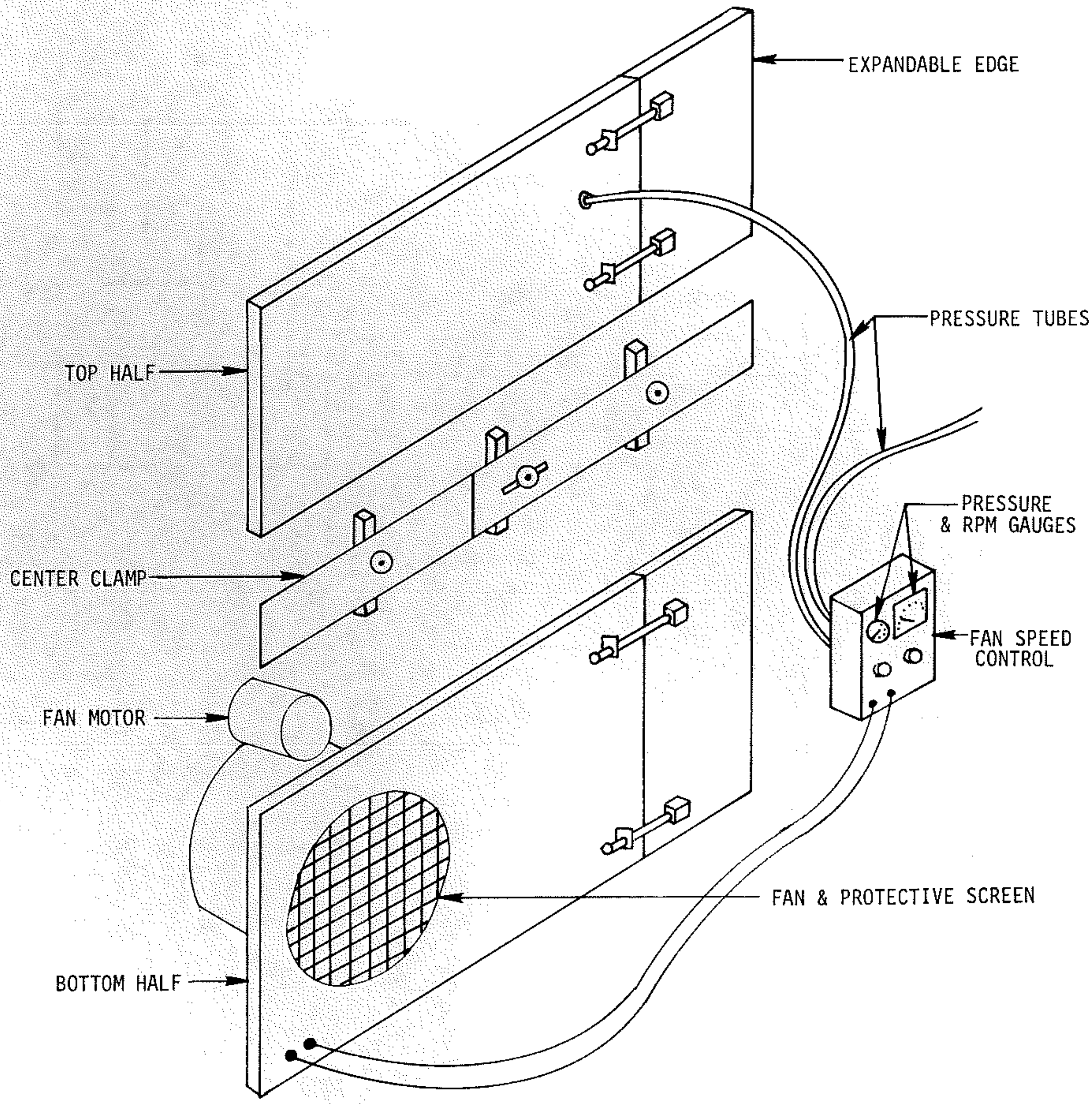


FIGURE 3 BLOWER DOOR AND CONTROL PANEL

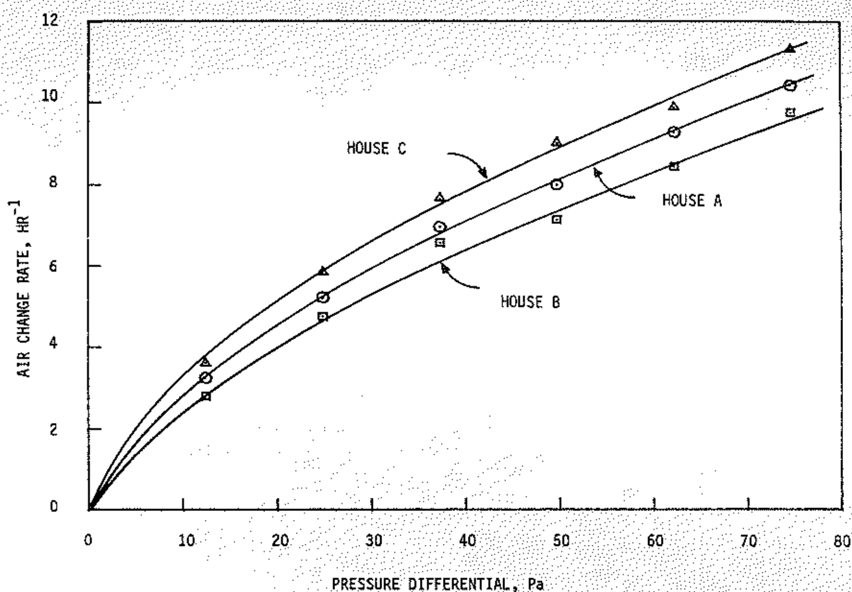


Figure 4 Depressurization Test Results

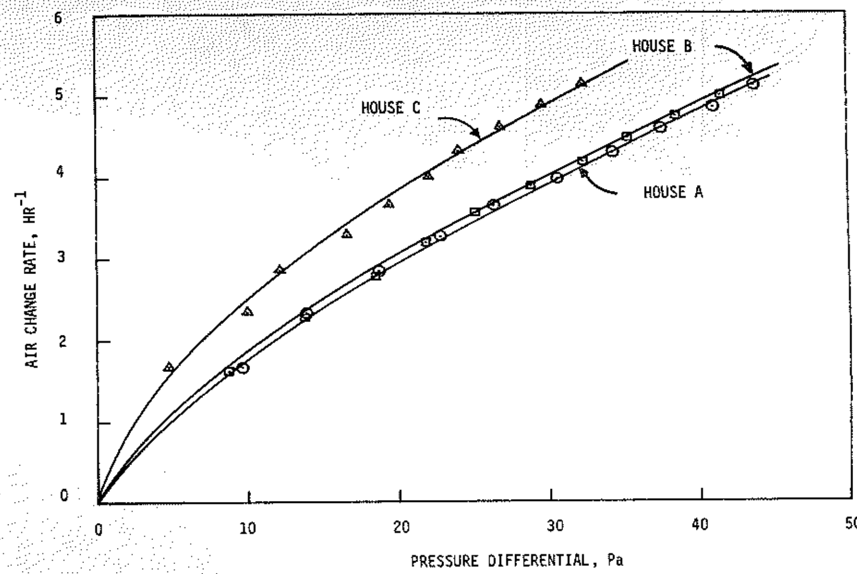


Figure 5 Pressurization Test Results
Ducts Isolated From Conditioned Space

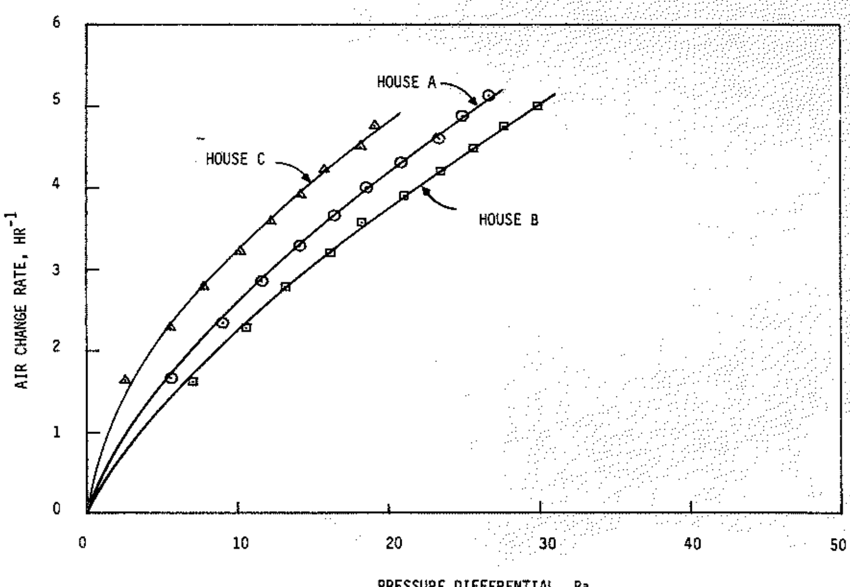


Figure 6 Pressurization Test Results
Blower Off-Ducts Exposed To Conditioned Space

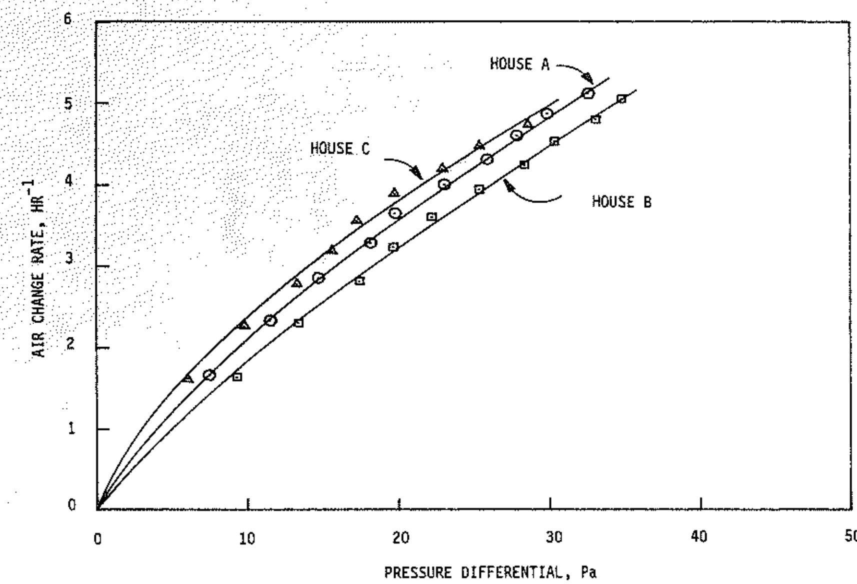


Figure 7 Pressurization Test Results
Blower On

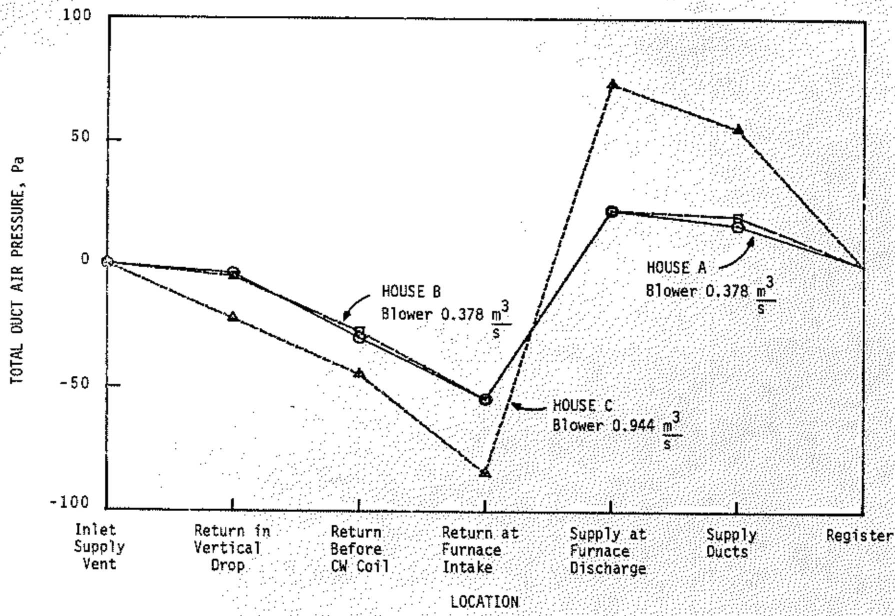


FIGURE 8 TOTAL PRESSURE OF SEVERAL LOCATIONS IN VENTILATION SYSTEM

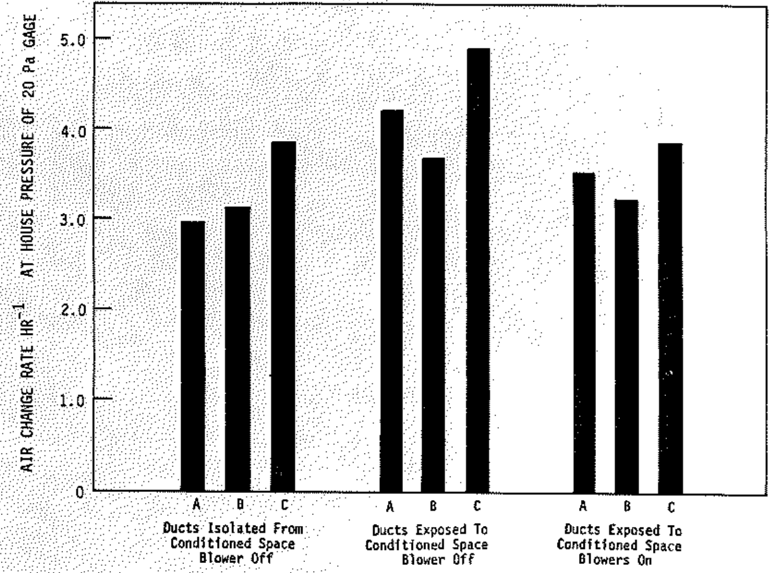


FIGURE 9 SUMMARY OF PRESSURIZATION TEST RESULTS

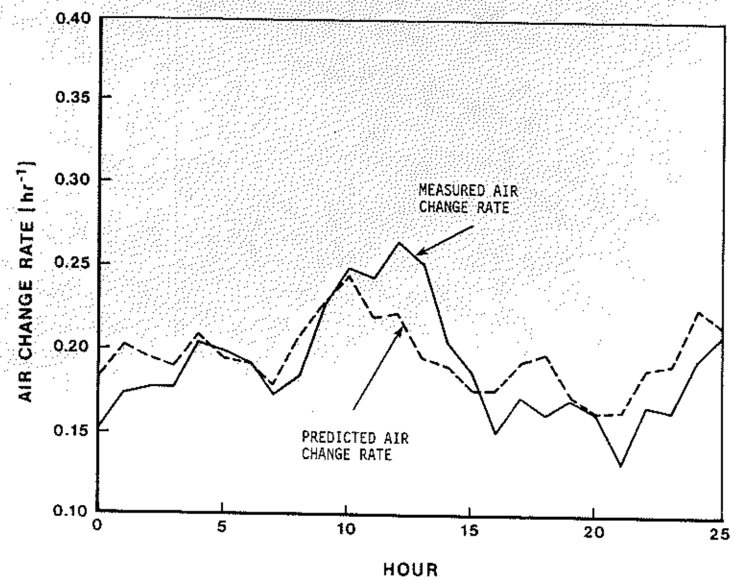


FIGURE 10 COMPARISON OF PREDICTED VS. MEASURED INFILTRATION

HOUSE A