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BUILDING RESEARCH NOTE

MARK XI ENERGY RESEARCH PROJECT
AIR-TIGHTNESS AND AIR-INFILTRATION MEASUREMENTS

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The Division of Building Research of the National Research Council of Canada and the Housing and Urban Development Association of Canada are participating in a joint program to study energy conservation in four detached two-storey houses.[1] These houses are all of the same floor plan and size, and are located on adjacent lots (Fig. 1). One of the houses (H1) was built to a construction standard similar to other new houses in the same area; the other three (H2, H3, H4) were built with added insulation and a specially applied polyethylene vapour barrier to improve air tightness of the house envelope. All the houses are equipped with an electric furnace and a forced-air circulation system. In addition, one of the upgraded houses has a heat-pump unit and another has an air-to-air solar-heating system. A brief description of the houses is given in Table 1.

Tests were conducted to measure the air tightness of the four houses and the air-infiltration rates of the standard and heat-pump houses (H1 and H4). Because the building envelope of the standard and upgraded houses differs primarily in air-tightness value, a comparison of the simultaneously obtained infiltration data should show whether or not there is a correlation between infiltration and air tightness.

TEST METHODS

The air-leakage tests were conducted using the pressurization method. As shown in Fig. 2, a centrifugal fan with a capacity of 380 L/s was placed in the living room of the house. The discharge side of the fan was connected by a 10-cm diameter duct to an outside window where the window was replaced with a plywood panel. The flow rate of the fan was adjusted manually with a damper and was measured with a laminar flow element (MERIAM LFE ELEMENT; accuracy of 5 per cent of measured value). Pressure taps installed in the exterior walls at four levels enabled inside-to-outside pressure differences to be measured during the test using a diaphragm-type pressure transducer (static error band of 5 per cent full scale).

The air-leakage rates through windows and doors of the heat-pump house were also obtained by comparing the over-all air-leakage rates taken before and after the particular components were sealed with plastic sheets.

Air-infiltration rates were measured using the tracer-gas decay method,[2,3] with CO_2 as the tracer gas. This involves introducing a small amount of CO_2 into the house and measuring the decay of its concentration with time. The CO_2 was produced by placing pieces of dry ice on a hot plate in the living room; after a pre-determined amount of CO_2 was generated, the remaining dry ice was taken out of the house. After allowing sufficient time for the tracer gas to mix with the air inside the house, using the forced-air circulation system, the concentration of CO_2 was measured periodically. Plotting these data on semilog graph paper gives a straight line with a negative slope that equals the air-infiltration rate, assuming perfect mixing.[3] During the tests, a sample of air was drawn alternately from the return air duct of each test house using 0.63-cm polyethylene tubing, and was analyzed using an infrared gas analyzer (accuracy 1 per cent of full scale). An automatic system was used to take air samples and measure the CO_2 concentrations to avoid introducing additional CO_2 in the houses from the presence of research personnel. In addition, wind speed and direction were recorded. The cup anemometer was located approximately 18 m above ground and about 10 m to the rear of the houses (Fig. 1). Pressure differences across the exterior walls of the standard and heat-pump houses were also measured separately at four levels in cold weather and under calm conditions (wind speed below 1 m/s) to determine the neutral pressure level.

RESULTS AND DISCUSSION

The air-leakage rate in this paper is given in litres per second per unit area of building envelope. The area of building envelope is defined as the area of the exterior walls above grade plus that of the ceiling of the upper floor. Figure 3 shows the over-all air-leakage rates measured for the four houses in March 1979, approximately a year after they were constructed. It indicates that the standard house (H1) has greater air leakage than two of the upgraded ones (H2 and H4). The lower air-leakage rate for the upgraded houses indicates that the special care taken to seal around windows and doors, and the addition of the polyethylene vapour barrier effectively improved air tightness. Figure 3 also shows that the solar house (H3) is not nearly as airtight as the other upgraded houses. The solar collector and the ductwork of the air-to-air solar-heating system probably provide additional air leakage openings in the building envelope.

Air-leakage rate is usually expressed in terms of pressure differentials by the equation

$$Q = CA(\Delta P)^n \tag{1}$$

where

Q = air leakage rate, L/s

C = flow coefficient, $L/s \cdot m^2 (Pa)^n$

A = area of building envelope, m^2

ΔP = pressure difference across exterior wall, Pa

n = flow exponent

The flow exponent, n, is 0.71 for all of the houses and the corresponding flow coefficients are 0.110, 0.068, 0.102,and 0.075 for houses H1, H2, H3 and H4 respectively.

The over-all air-leakage rates of the four houses had also been measured in March 1978, shortly after they were constructed. As shown in Fig. 4, the air-leakage rates obtained in 1978 were lower than those obtained a year later. The difference is likely due to the increase in leakage openings caused by the drying and shrinkage of building materials. Figure 4 also shows the ranges of air tightness for 63 houses constructed in 1978 in the Ottawa area[4] and for 26 houses constructed between 1969 and 1977 in Sweden.[5] The results indicate that the Swedish houses, in general, are tighter than the Ottawa houses and that the four research houses are close to the upper range for the Swedish houses.

The air-leakage rates through windows and doors were measured in the heat-pump house. There was no detectable air leakage through the joints between the wall and the frames of windows or doors. The air-leakage rate through windows was quite low. As indicated in Fig. 5, the window leakage is about 50 per cent lower than the maximum air-leakage rate permitted in ASHRAE Standard 90-75 for windows.[6]

The tracer-gas method with CO_2 as the tracer gas was checked in the heat-pump house where a known air-change rate was induced using the equipment and method for conducting a fan-pressurization test. These results, given in Fig. 6, indicate that for an air-change rate of less than 0.5 air change per hour (the maximum air infiltration obtained in these houses under various outside conditions), the tracer-gas method gave a reading about 10 per cent lower than that induced by the fan. Poorer agreement (e.g., Pt. 1) was sometimes obtained under conditions of induced air-change rates above 0.5 air change per hour. Figure 7 shows the tracer-gas concentration versus time curve for Pt. 1. The air-infiltration rate determined from the curve was 0.57 air change per hour, which was about 24 per cent lower than the induced value (see Fig. 6). The measured data lie in almost a straight line (Fig. 7); a comparison with the results shown in Fig. 6 indicates that an assumed linear relationship does not necessarily give an accurate value of air-infiltration rate.

Air-infiltration measurements were conducted simultaneously in the standard and heat-pump houses (H1 and H4) between January and April 1979 to obtain data in cold weather. Additional measurements were conducted in the heat-pump house during July and August of the same year to investigate the effect of wind alone on air infiltration. Unfortunately, the same tests could not be repeated on the standard house because it was occupied during that period. The air-infiltration data for the two houses are shown in Figs. 8, 9, 10 and 11.

In Figs. 8 and 9, the air-infiltration rates are plotted against inside-outside temperature difference for three ranges of wind speed, i.e., below 3.5 m/s, above 5 m/s and that in between. For a wind speed lower than 3.5 m/s (below 8 mph), air infiltration increased with inside-outside temperature difference. The air-infiltration data measured under this condition were fitted to a power-law expression similar to Eq. 1. The reason for choosing this form instead of a linear expression is that it has been used extensively to define air-infiltration rates due to stack action in houses,[7] tall buildings,[8] and schools.[9] It also predicts zero infiltration in the absence of temperature difference. The infiltration equation for the two houses (H1 and H4) is

$$I = 0.187\ C\ (\Delta t)^{0.71} \qquad (2)$$

where I is the infiltration rate in air changes per hour, C is the flow coefficient as defined in Eq. 1 and Δt is the inside-outside temperature difference in degree Celsius.

Figures 8 and 9 also show that when the wind speed is higher than 3.5 m/s the infiltration rate exceeds the values that would apply for the same Δt with low wind speeds. But the scatter of the data makes it difficult to separate the wind effects from the temperature effects. The air-infiltration data obtained in warm-weather conditions are plotted versus wind speed in Fig. 10. Although the results indicate that air infiltration increases with wind speeds for both houses, the scatter in the data suggests that wind direction may be important. These results were therefore replotted in Fig. 11 against wind speeds for different wind directions, which revealed a dependency of air infiltration on wind speed and direction.

The monthly averaged heat losses due to infiltration were calculated for the two houses (H1 and H4) using measured infiltration rates and the monthly mean air temperatures of the 1978-1979 heating season (Fig. 12). The results were then compared with the measured total purchased energy for the same period of time.[10,11] As shown in Fig. 12, air infiltration accounted for approximately 20 per cent of the total energy consumption for both the standard and heat-pump houses. (The percentage would be about 30 per cent for the heat-pump house if its air tightness were the same as that of the standard house.)

A direct comparison of the simultaneously measured air-infiltration rates of the two houses (H1 and H4) is shown in Fig. 13 for two ranges of wind speed. The results indicate that the ratio of infiltration rates is the same as the ratio of the flow coefficients when the wind speed is lower that 3.5 m/s. A similar trend is apparent for high wind conditions but the scatter in the data, due to the dependence on wind direction, is too large to permit a definite conclusion.

An attempt was then made to correlate air infiltration (tracer-gas method) with air leakage (fan-pressurization method) for the three wind-speed ranges using the data from the two research houses (H1 and H4) and data from two other single-storey houses.[12] As shown in Fig. 14, for a wind speed lower than 3.5 m/s, $I/\Delta t^n$ increases with the flow coefficient, where n is the flow exponent as defined in Eq. 1. For higher wind speeds, infiltration appears to be proportional to the flow coefficient as well but the scatter in the data is too wide and the data base too small to lead to a definite conclusion. The two single-storey houses (No. 1 and No. 2) have chimneys whereas H1 and H4 do not. Because a chimney provides an opening above the roof, it raises the neutral-pressure level of the house. The neutral-pressure level, therefore, is at about the same height for each house (approximately 2.7 m above ground for houses H1, H4 and No. 1, and 2 m for house No. 2). Consequently, the pressure differentials caused by stack action, which act on the four houses,are about the same under the same ambient air temperatures, and their air-infiltration rates may be compared with each other directly. If the two single-storey houses did not have chimneys, it is likely that their air-infiltration rates would be lower than that shown in Fig. 14.

CONCLUSION

Air-leakage rates were measured in the four energy-conservation research houses using the fan-pressurization method. It was found that air leakage of the standard house was about 10 per cent higher than that of the solar house and about 50 per cent higher than that of the other two upgraded houses. The high air leakage of the solar house probably can be attributed to the air leakage through the ductwork and the solar collector of the air-to-air solar-heating system. There was no detectable air leakage through joints around windows and doors. The air leakage through windows of the heat-pump house, which were tested as installed, is about 50 per cent lower than the maximum value permitted by ASHRAE 90-75 for new building design.

Air-infiltration rates were measured simultaneously in the standard and heat-pump houses using the tracer-gas method with CO_2 as the tracer gas. It was found that for a wind speed lower than 3.5 m/s, the air-infiltration rate can be expressed in terms of inside-outside temperature difference by an equation similar to the air-flow equation with the same exponent. The ratio of the infiltration rates of the two houses is approximately equal to the ratio of the flow coefficients, which indicates that there is a correlation between infiltration and air leakage as measured by fan-pressurization tests. The results for the two single-storey houses (No. 1 and No. 2) also appear to support this conclusion. The significance of inside-outside temperature is reduced as wind speed increases.

Air infiltration, on an average, accounted for about 20 per cent of the total energy purchased for the standard and heat-pump houses in the 1978-1979 heating season.

ACKNOWLEDGEMENT

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TABLE 1

DESCRIPTION OF TEST HOUSES

HOUSE	H1	H2	H3	H4
Type	single detached 2 storey, 3 bedroom with attached garage	same as H1	same as H1	same as H1
Floor area, m^2	118	118	118	118
Ceiling area, m^2	63.7	63.7	63.7	63.7
Volume (including basement), m^3	386	386	386	386
Outside envelope, m^2	227.7	227.7	227.7	227.7
Outside wall area, m^2	164	164	164	164
Window area, m^2	15.5	15.5	15.5	15.5
Outside door area, m^2	4.2	4.2	4.2	4.2
Length of sash crack for window, m	42.85	67.59	67.59	67.59
Outside wall	brick on front wall up to 1 storey high aluminum siding on remaining wall	same as H1	same as H1	same as H1
Inside wall	plaster board	same as H1	same as H1	same as H1
Window	double glazed, wood-frame sliding and double-hung	triple glazed, wood-frame casement, awning	triple glazed, wood-frame casement, awning	triple glazed, wood-frame casement, awning
Construction	standard wood-frame construction	same as H4	same as H4	upgraded wood-frame construction with additional insulation and a 4-mil polyethylene vapour harrier throughout
Heating system	forced-air with electric furnace, no chimney	forced-air with electric furnace, no chimney	forced-air with air-to-air solar-heating system, electric furnace, no chimney	forced-air with heat pump, electric furnace no chimney

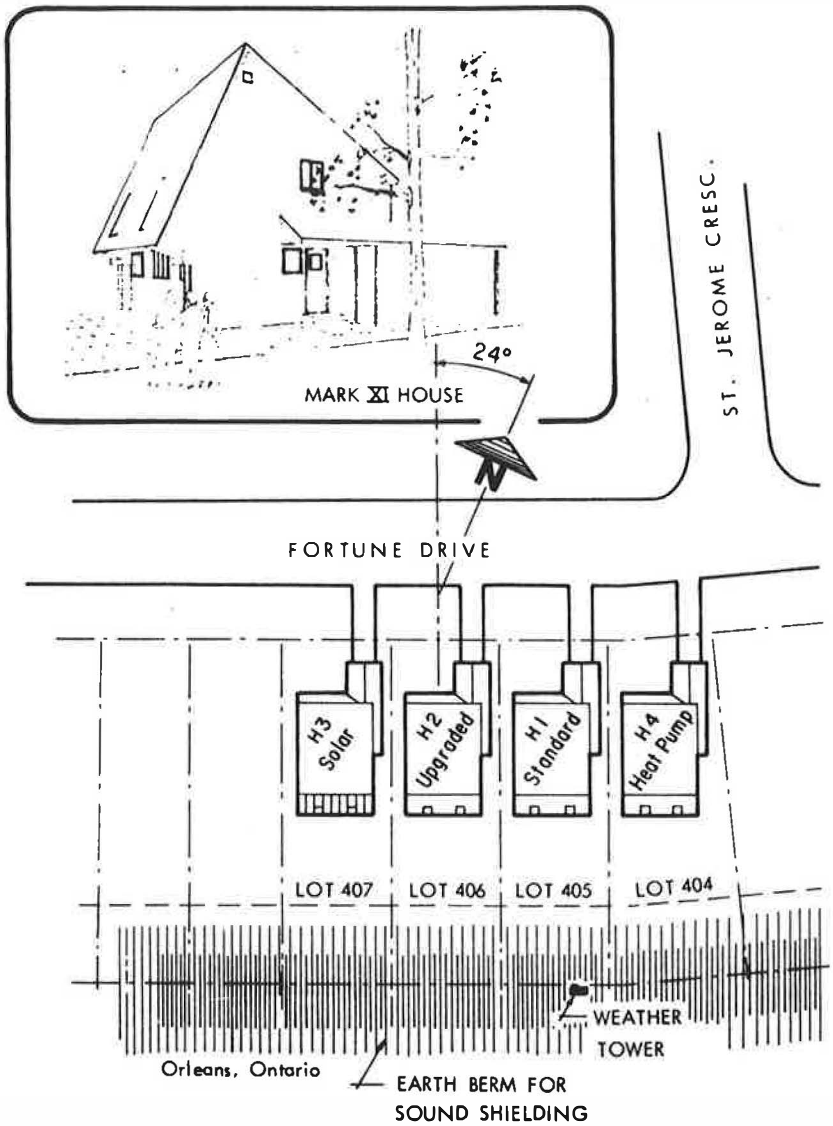

FIGURE 1

SITE PLAN - MARK XI PROJECT

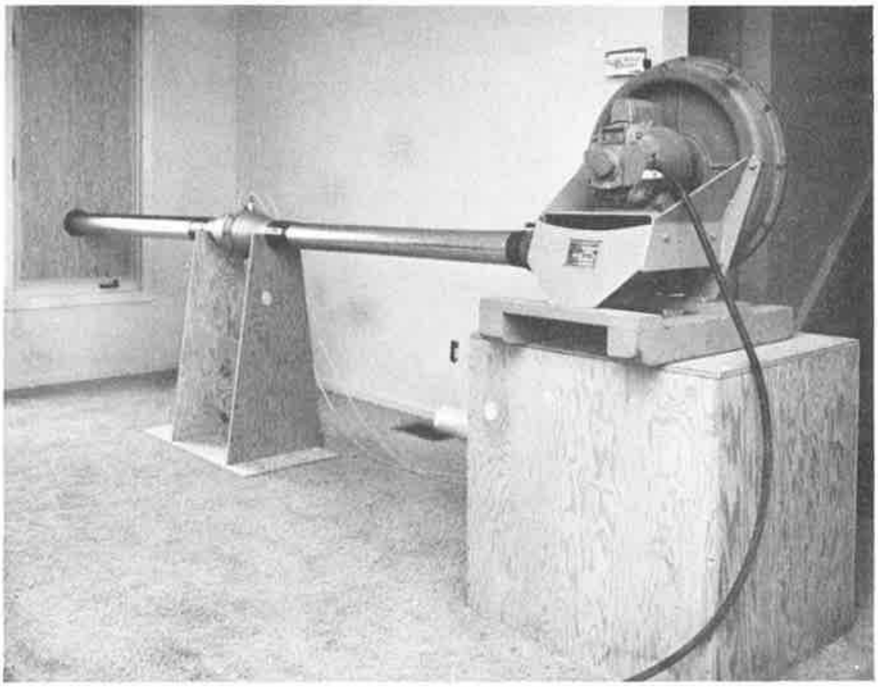

FIGURE 2   Equipment for fan-pressurization test

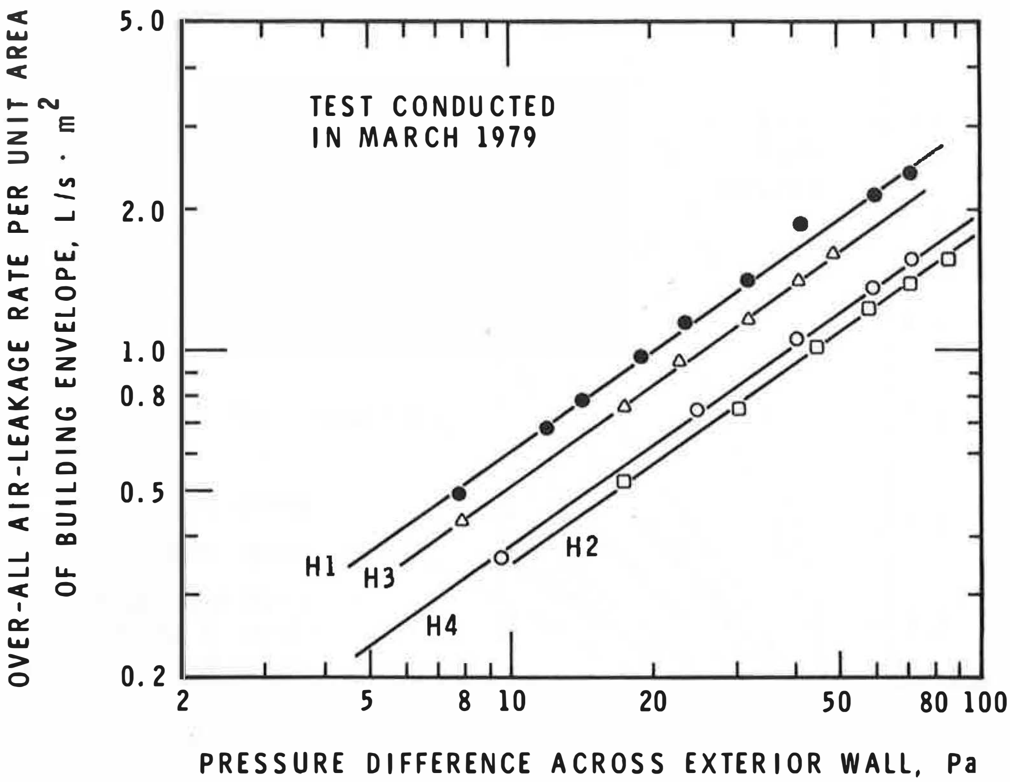

FIGURE 3

OVER-ALL AIR-LEAKAGE RATE FOR THE FOUR ENERGY-CONSERVATION RESEARCH HOUSES

BR 5991-2

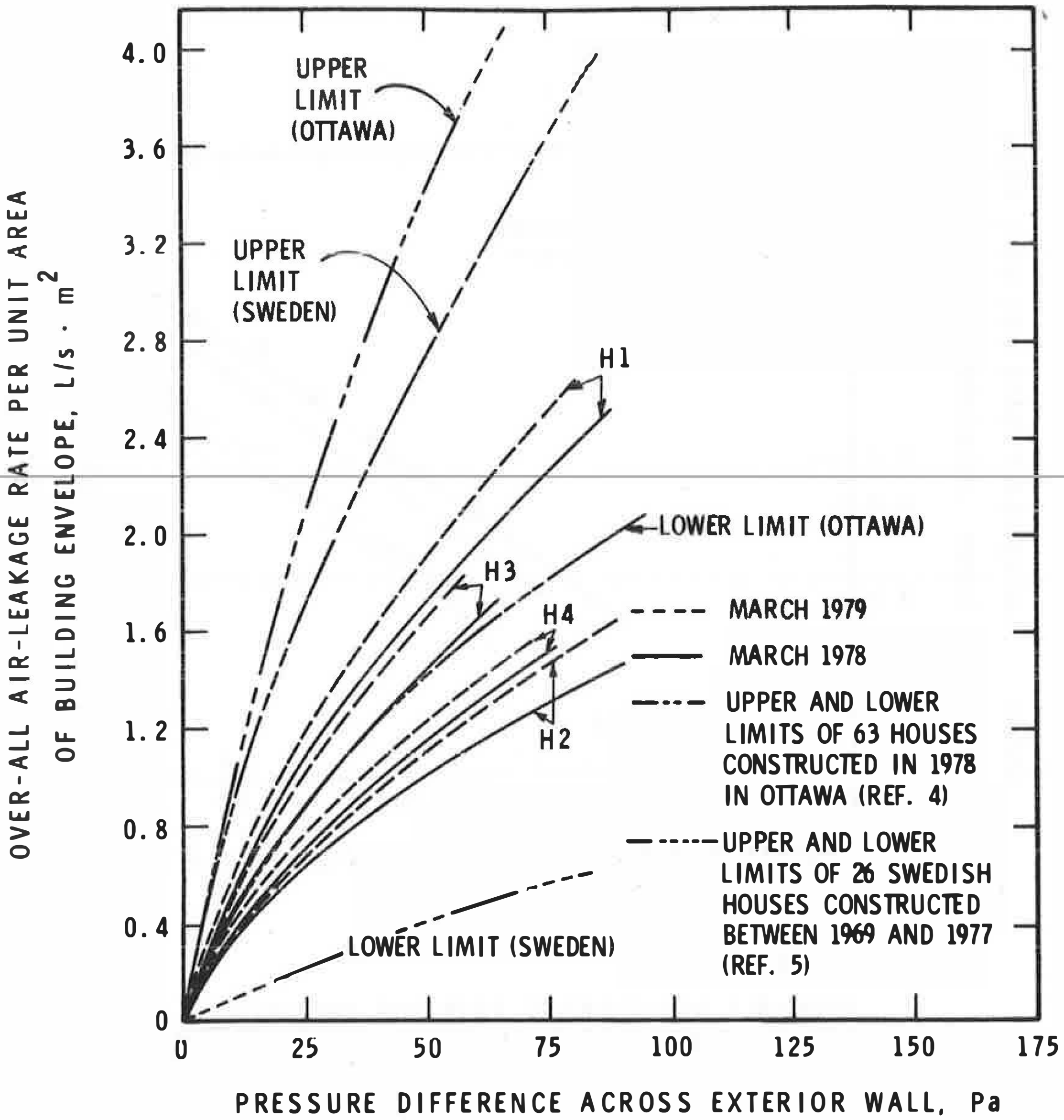

FIGURE 4

COMPARISON OF AIR-LEAKAGE RATE OF THE FOUR HOUSES AND OTHERS

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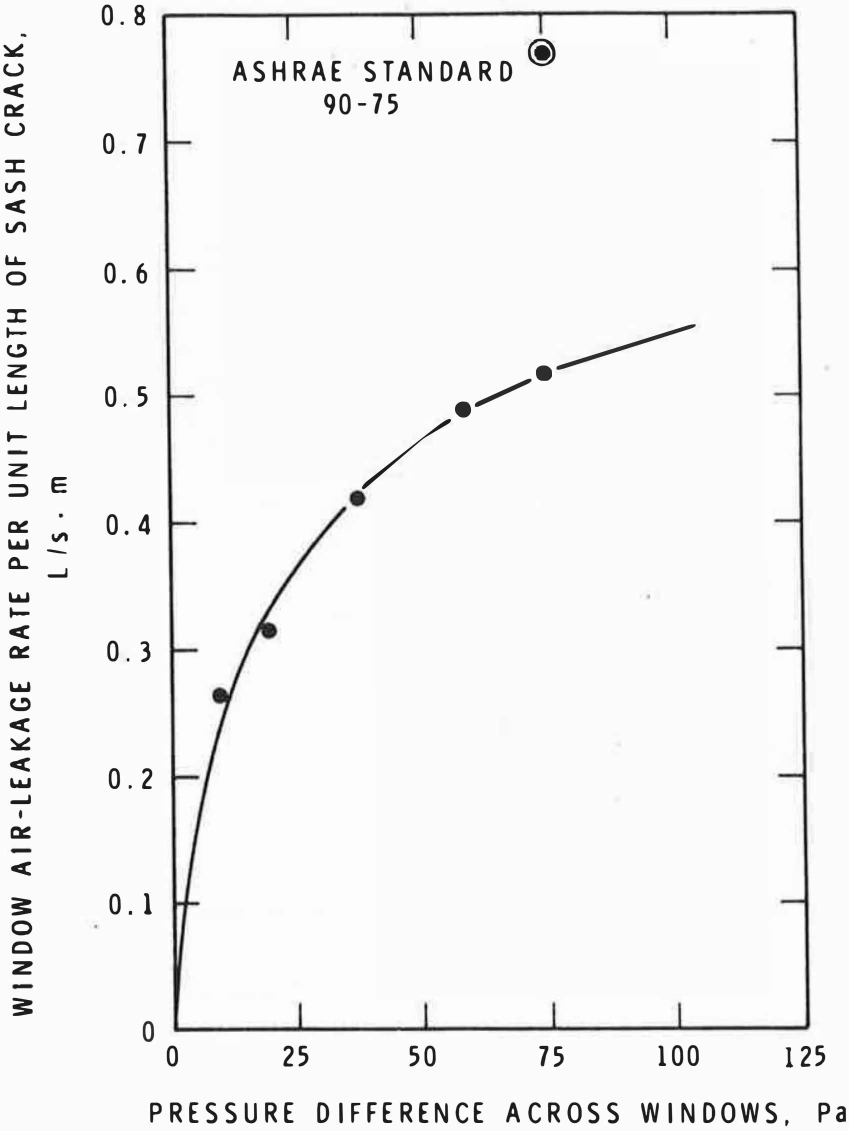

FIGURE 5

WINDOW AIR-LEAKAGE RATE OF THE UPGRADED HEAT-PUMP HOUSE

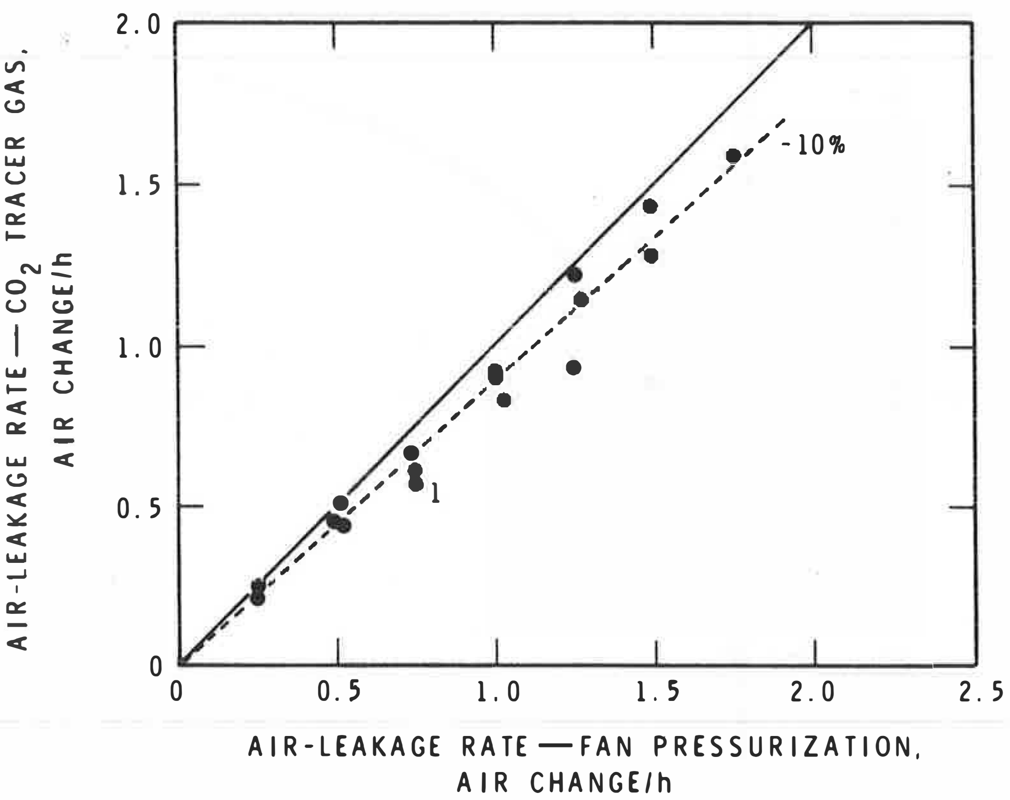

FIGURE 6

VALIDATION OF TRACER-GAS METHOD

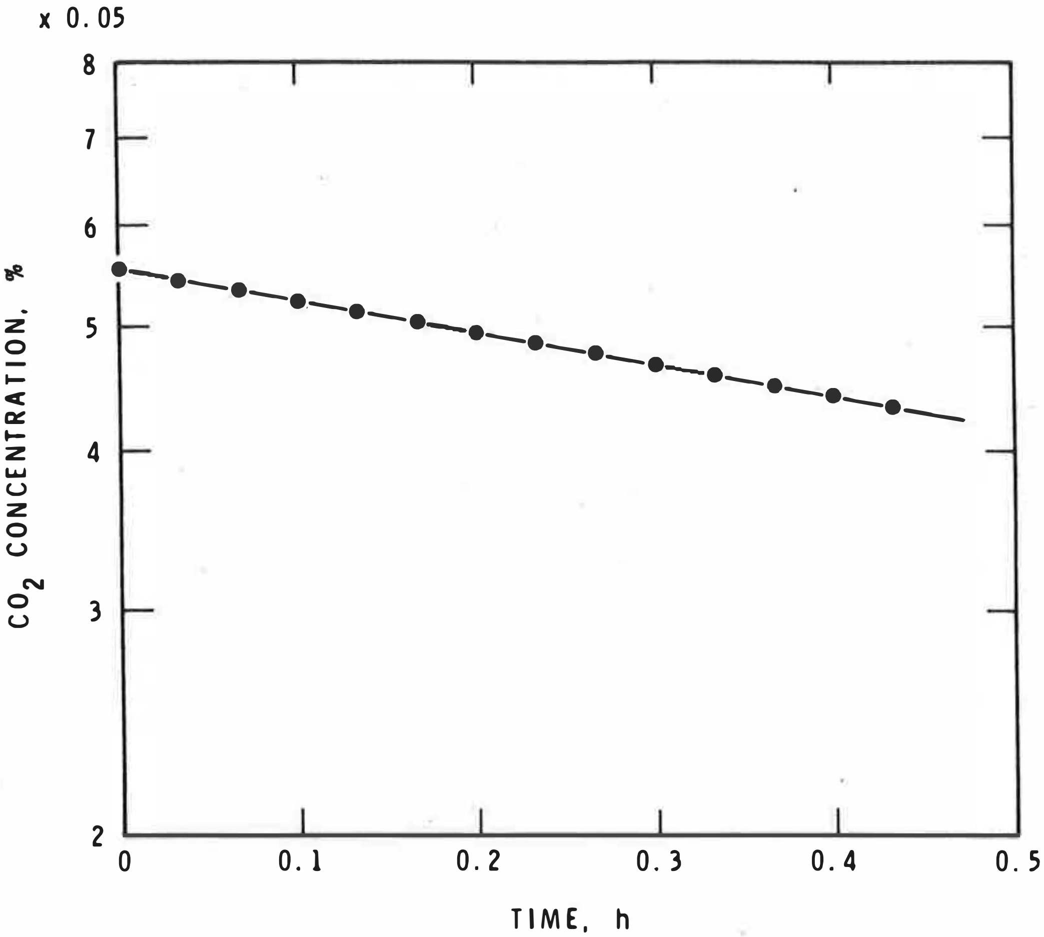

FIGURE 7

SAMPLE PLOT OF CO_2 CONCENTRATION VS TIME FOR HEAT-PUMP HOUSE

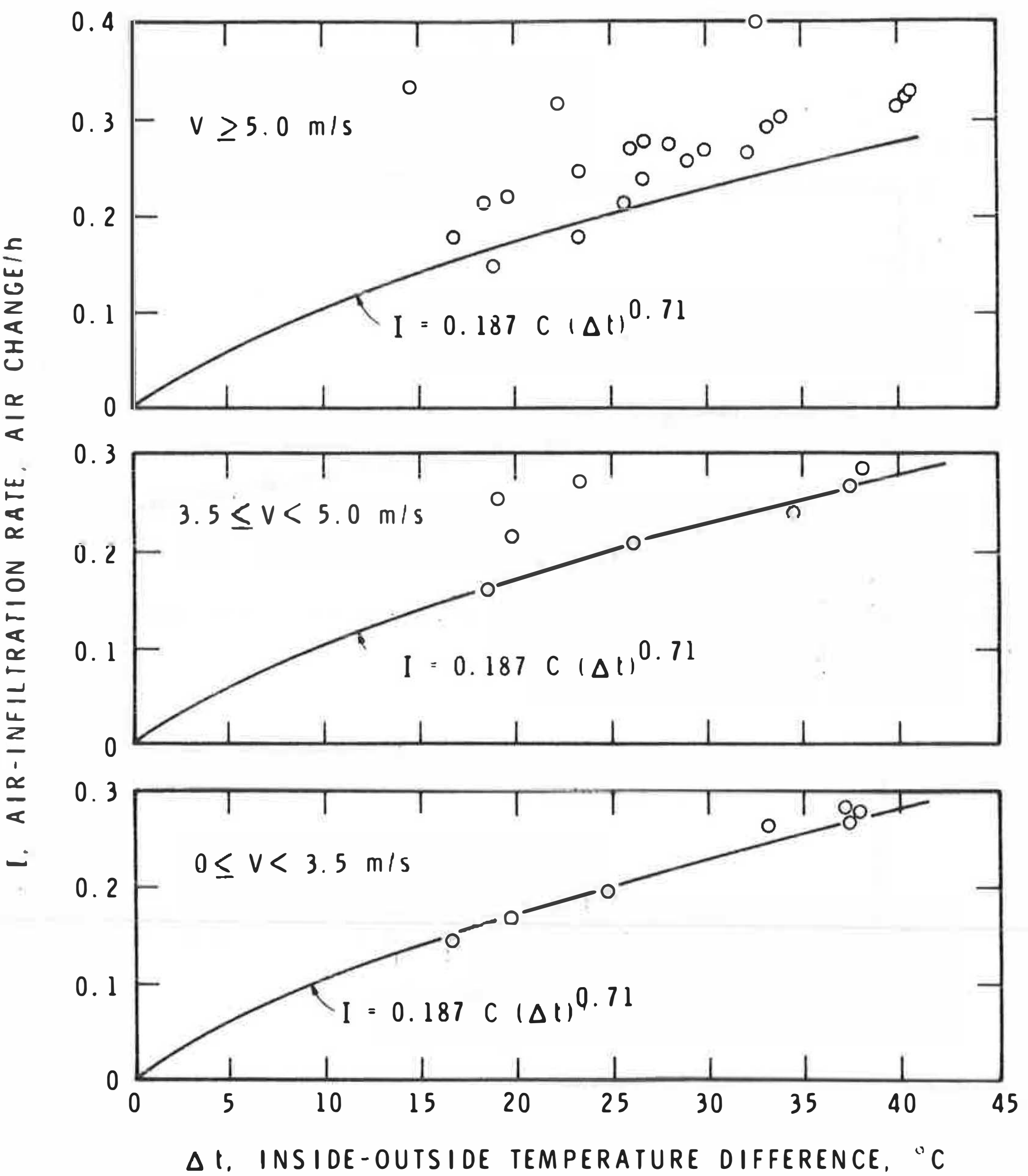

FIGURE 8

AIR-INFILTRATION RATE VS INSIDE-OUTSIDE TEMPERATURE DIFFERENCE FOR HOUSE H1

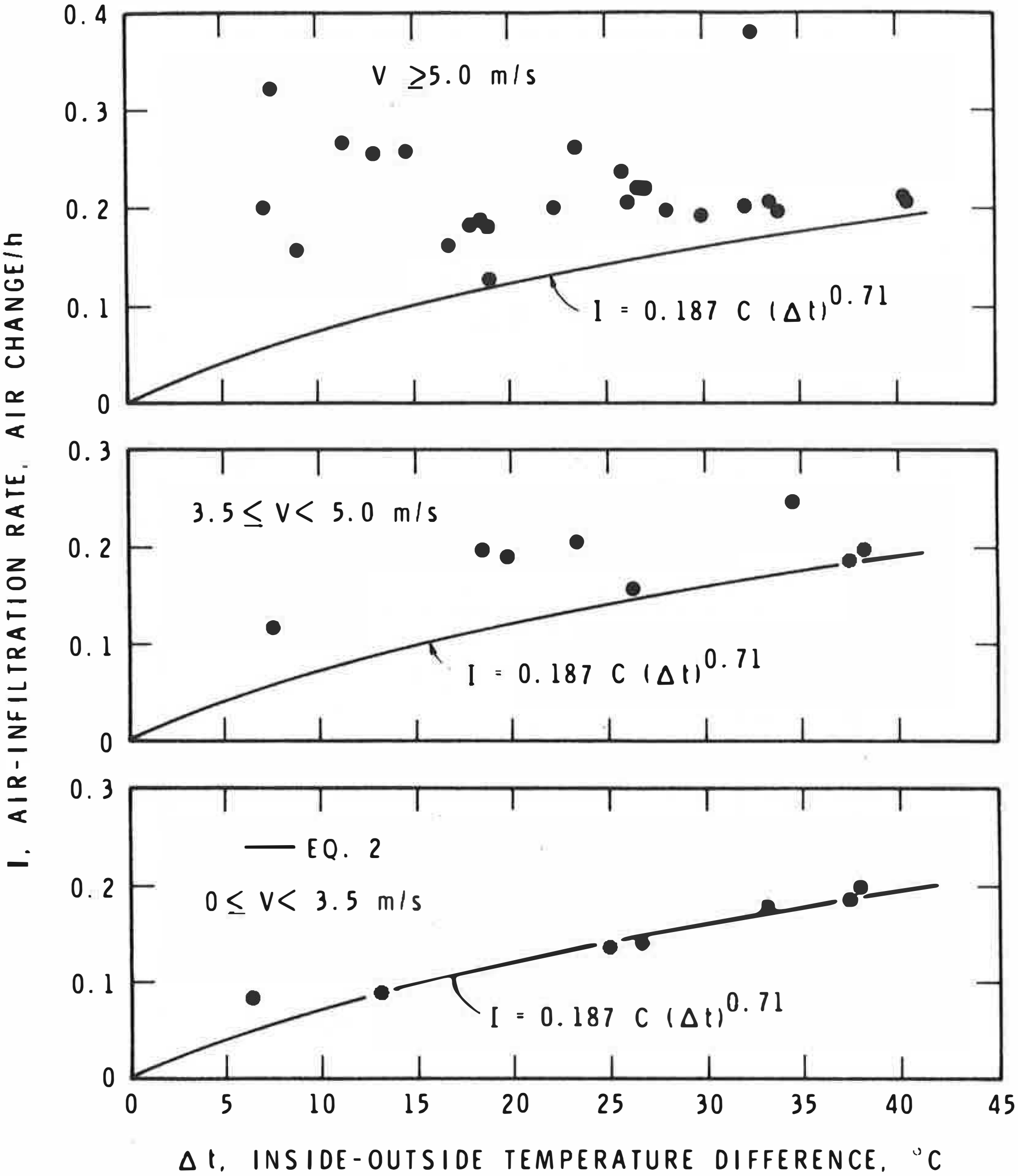

FIGURE 9

AIR-INFILTRATION RATE VS INSIDE-OUTSIDE TEMPERATURE DIFFERENCE FOR HOUSE H4

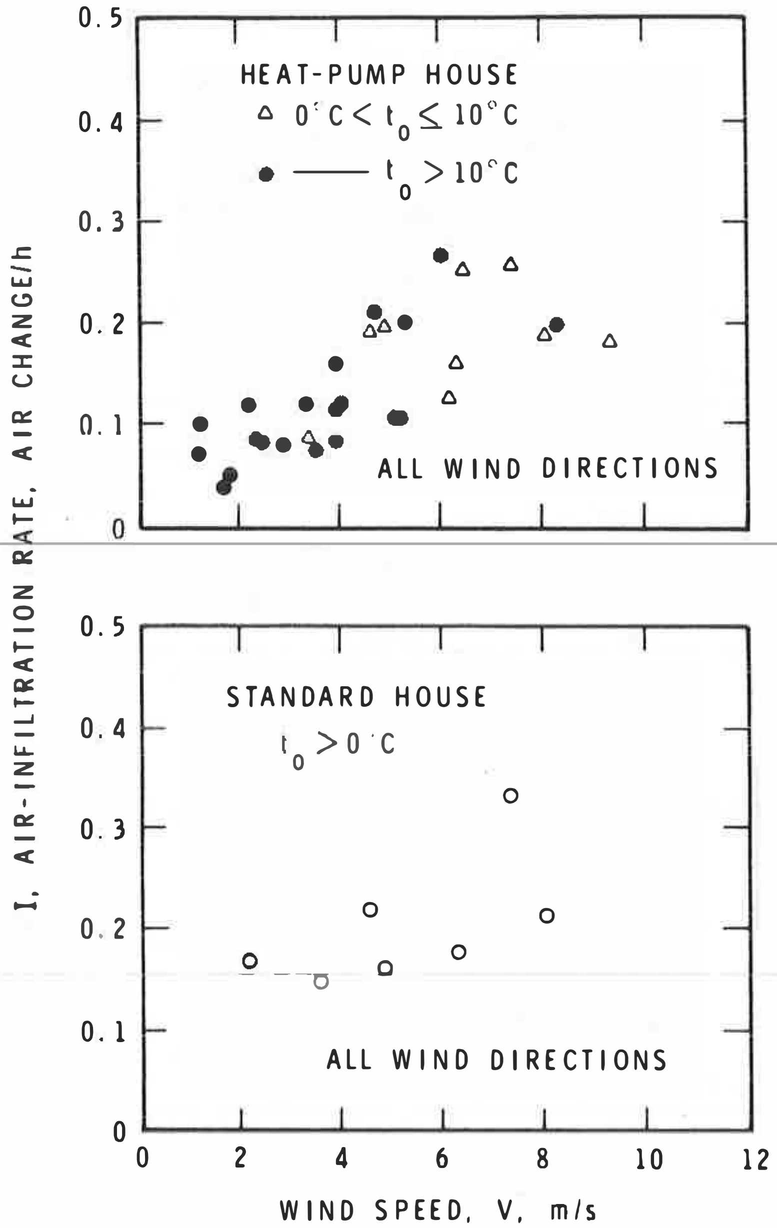

FIGURE 10

AIR-INFILTRATION RATE VS WIND SPEED

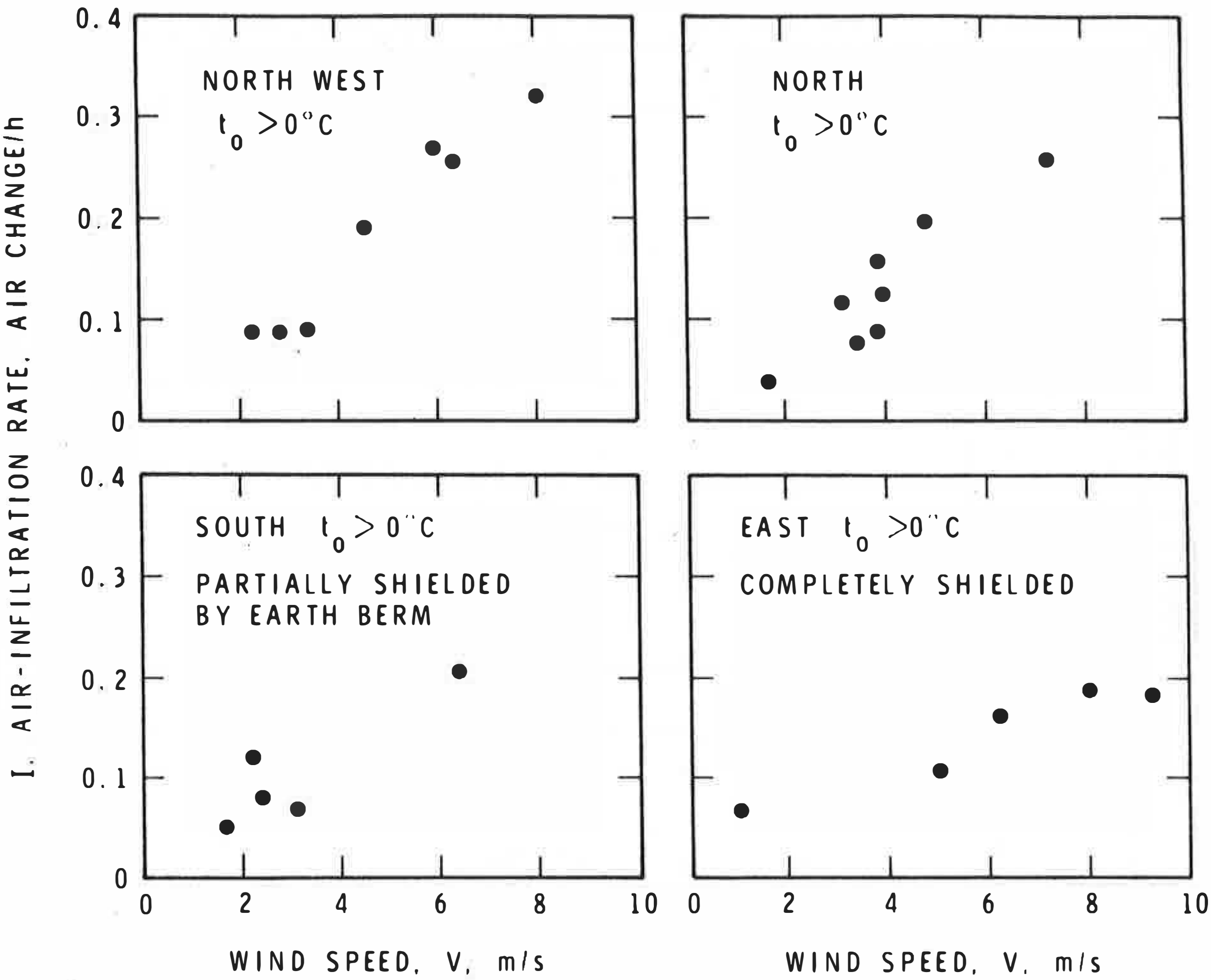

FIGURE 11

AIR-INFILTRATION RATE AT VARIOUS WIND SPEEDS AND WIND DIRECTIONS FOR HEAT-PUMP HOUSE

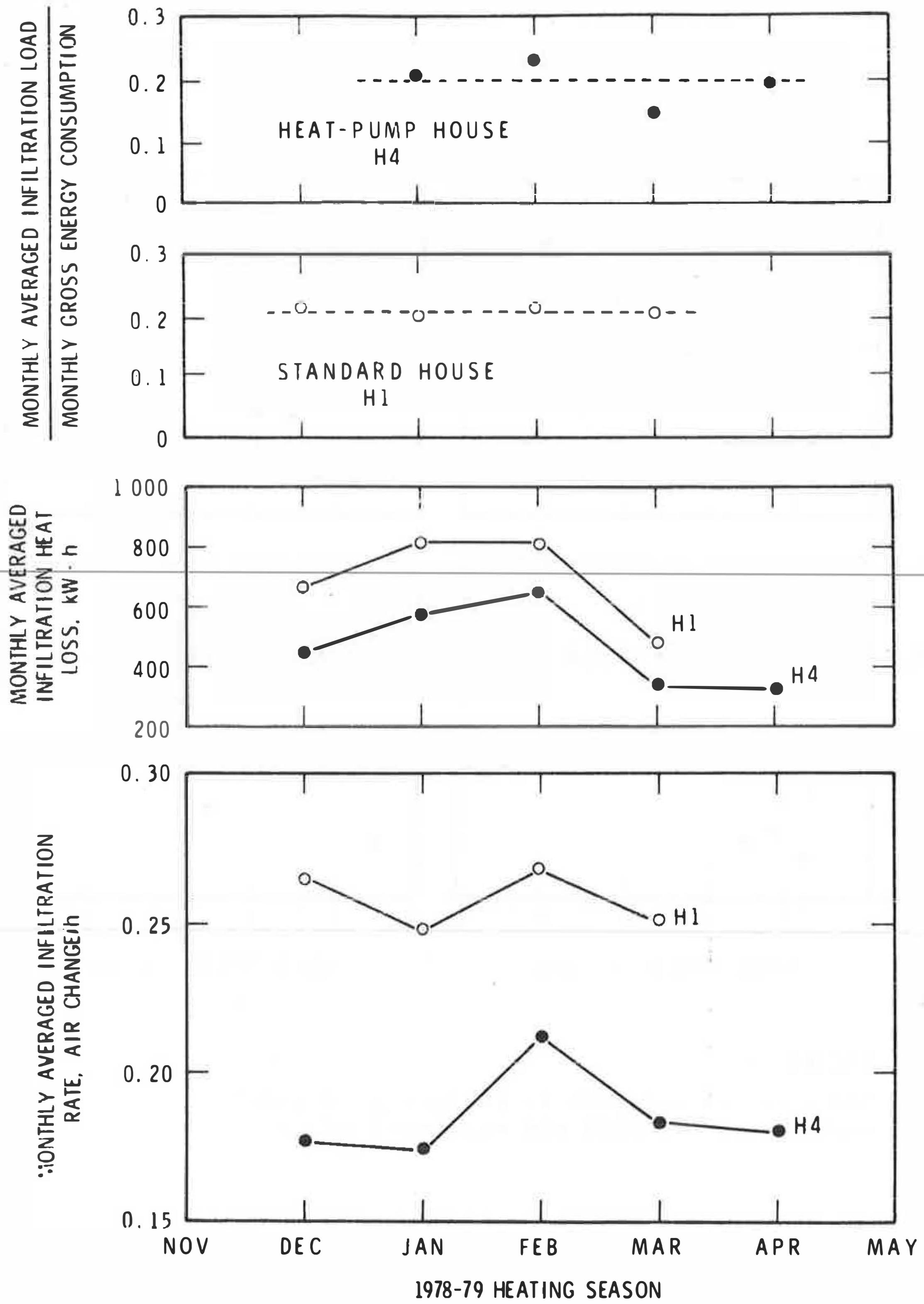

FIGURE 12

MONTHLY AVERAGED INFILTRATION LOAD AND
ITS CONTRIBUTION TO TOTAL ENERGY CONSUMPTION

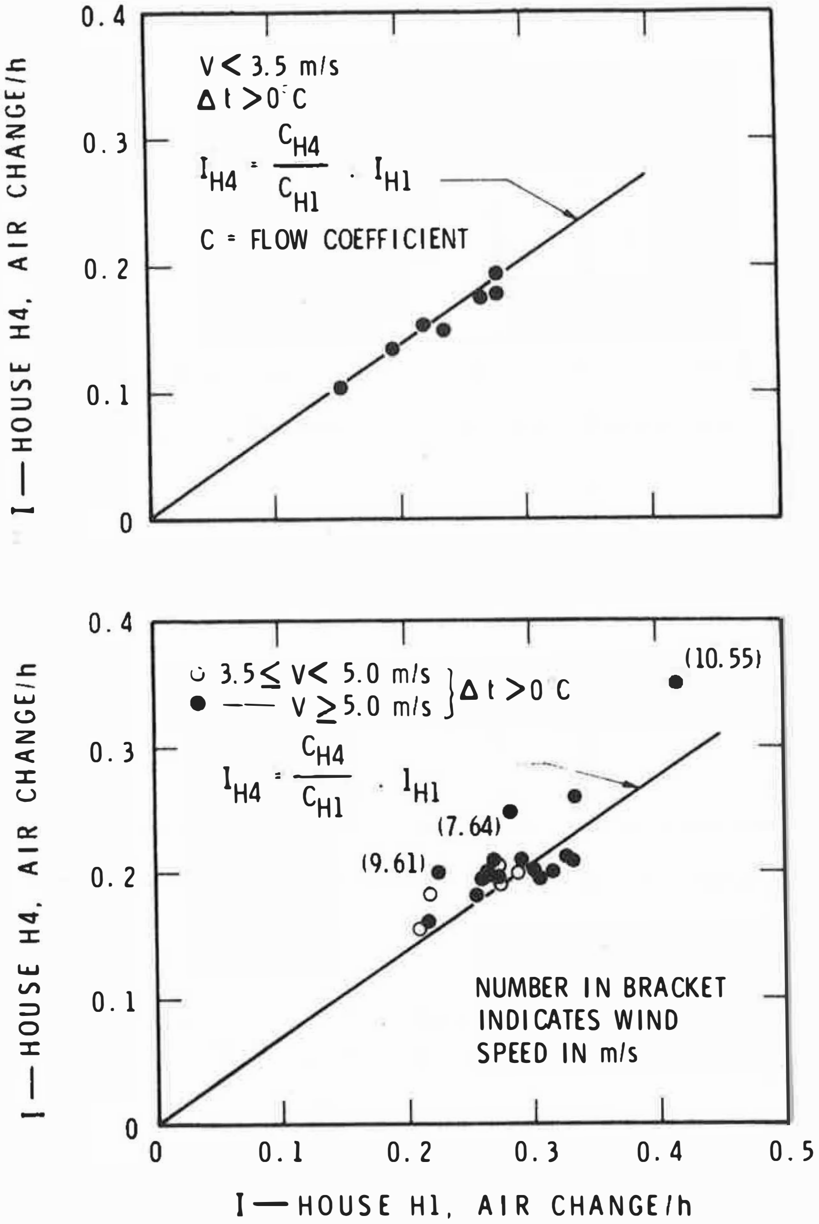

FIGURE 13

COMPARISON OF SIMULTANEOUSLY MEASURED INFILTRATION RATES OF H1 AND H4

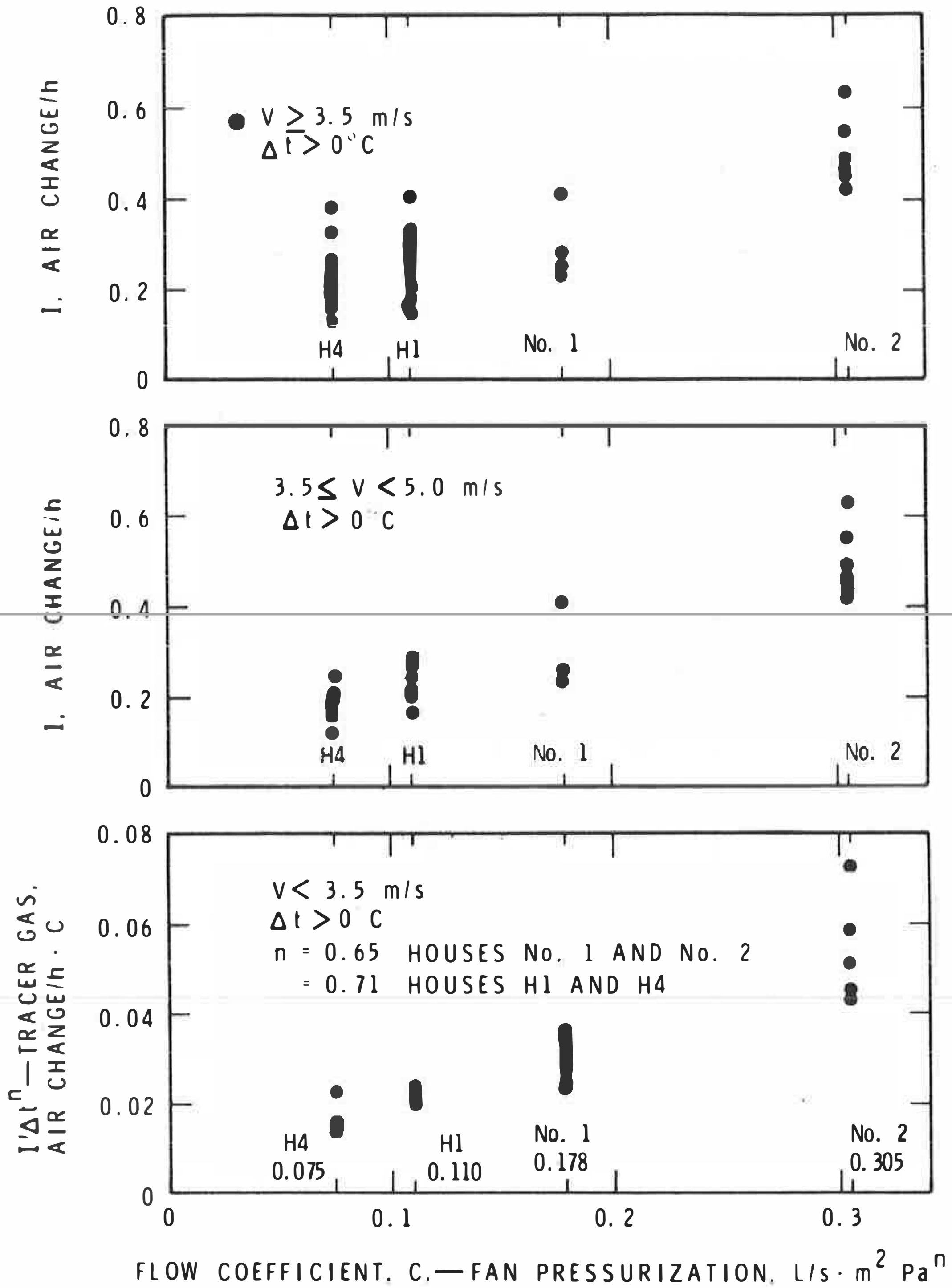

FIGURE 14

PROPOSED CORRELATION BETWEEN INFILTRATION AND AIR-LEAKAGE