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#### Publisher's version / Version de l'éditeur:

*ASHRAE Transactions*, 85, 1, pp. 58-71, 1979

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**THE CALCULATION OF HOUSE INFILTRATION RATES**

by G. T. Tamura

Reprinted from  
ASHRAE Transactions  
Vol. 85, Part 1, 1979  
p. 58 - 71

DBR Paper No. 889  
Division of Building Research

Price \$1.25

OTTAWA

NR CC 18028

## SOMMAIRE

Les méthodes des fentes et du changement d'air de l'ASHRAE pour le calcul de la charge de chauffage due aux infiltrations sont probablement adéquates pour déterminer les dimensions d'un système de chauffage, mais elles ne le sont pas pour une analyse énergétique horaire d'un édifice. Comme la charge due aux infiltrations est un élément important de la charge globale de chauffage, il faut une méthode simple qui tienne compte de tous les facteurs importants du taux d'infiltration de l'air.

Entre 1960 et 1962, la DRB du CNRC a mesuré, les fuites d'air au moyen de la technique des traces de gaz, de deux maisons à un étage construites dans les années 50. Quelques années plus tard, en 1967-1968, les caractéristiques de fuite d'air des enceintes ont été mesurées au moyen de la technique de pressurisation. Les résultats de ces essais sur les deux habitations ont servi à mettre au point un procédé de calcul des taux d'infiltration de l'air similaire à celui récemment mis au point pour les édifices en hauteur. L'auteur a aussi identifié les besoins de recherche afin que la méthode de calcul puisse être appliquée à des habitations de conception, de construction et d'exposition au vent différentes.

Un modèle informatique d'habitation chauffée à l'huile (qui ne fait pas l'objet du présent exposé) a aussi été mis au point par la DRB du CNRC comme complément à cette étude.



# THE CALCULATION OF HOUSE INFILTRATION RATES

**G.T. TAMURA**  
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## INTRODUCTION

The ASHRAE crack and air change methods (1) for estimating infiltration heating load are probably adequate for sizing of heating systems, but are not suitable for carrying out hourly energy analysis of buildings. As the infiltration load is a significant component of the overall heating load, there is a need for a method that is easy to use, but takes into account all of the significant factors that determine the rates of air infiltration.

During 1960-1962, DBR/NRC conducted air leakage measurements on two single-story houses (2) built during the nineteen fifties using the tracer gas technique. It was followed several years later in 1967-1968 by the measurement of the air leakage characteristics of their enclosures using the house pressurization technique (3). The results of these tests on the two houses were used to develop a procedure for calculating infiltration rates similar to the one recently developed for high-rise buildings (4). Also, research needs were identified so that the calculation procedure can be applied to houses of different design, construction and wind exposure. //

A computer model (not the subject of this paper) for houses with oil furnaces was also developed by DBR/NRC which complement this study (5).

## TEST DATA ON THE TWO HOUSES

The description of the two houses, both 5-room bungalows located in the residential area of Ottawa, are given in Table 1 and Fig. 1 and 2 (the house numbers are the same as those in Ref 2 and 3 except for House No. 2 which is designated as House No. 3 in Ref 3). There are single-story houses adjacent to the two test houses except for the one side wall of House No. 1 which faces a wooded region.

## Tracer Gas Test

The infiltration rates were measured using the tracer gas technique with helium as the tracer gas. It was injected into the supply air duct of the warm air system and the decay in its concentration was measured in the return air duct with an NBS type of katharometer (6). The results of the tests are reproduced in Tables 2 and 3.

In addition to the tracer gas test, pressure differences across the outside walls were measured with pressure taps located in each wall of the test houses. They indicated that the pressure differences across the windward wall facing the backyard for both houses were about 50% of the velocity head of the on-site wind measured 7.6 m (25 ft) above ground. Also, the pressure differences across the exterior walls measured during calm periods in winter indicated that the neutral pressure levels were located 0.25 m (10 in.) above the ceiling of House No. 1 and 0.41 m (1 ft 4 in.) below the ceiling of House No. 2.

Measurements of CO<sub>2</sub> concentration in the flue gas with the furnace operating indicated that the flow rates up the chimney, including that of the diluent air through the barometric damper,

were about 0.40 air changes per hour for House No. 1 and about 0.38 air changes per hour for House No. 2.

### House Pressurization Test

The overall and the component air leakage characteristic of the enclosures of the two houses were measured using a 1.42 m<sup>3</sup>/s (3000 cfm) fan. The roof including the soffit, windows, doors, exhaust vents and chimney openings, were covered with plastic sheets and sealed with tape. A suction pressure of 75 Pa (0.30 inch of water) was maintained throughout the test by adjusting the flow control damper of the fan system. The increase in the flow rate after removal of each seal represented the leakage rate through that particular component. The results of the tests are given in part in Table 4.

### STACK ACTION

The equation for calculating infiltration rate is as follows (4):

$$Q_s = C_w S \left[ 0.0342 \gamma p \left( \frac{\Delta T}{T_i T_o} \right) \right]^n \frac{(\beta H)^{n+1}}{n+1} \quad (1)$$

where

$Q_s$  = total infiltration rate caused by stack action, m<sup>3</sup>/s (cfm)

$C_w$  = exterior wall flow coefficient, m<sup>3</sup>/s·m<sup>2</sup>·Pa<sup>n</sup> (ft<sup>3</sup>/min·ft<sup>2</sup>·(in. of water)<sup>n</sup>)

$S$  = perimeter of the building, m (ft)

$\gamma$  = ratio of actual to theoretical pressure difference (thermal draft coefficient)

$p$  = atmospheric pressure, Pa (lb/in.<sup>2</sup>)

$T_o$  = absolute temperature outside K (R)

$T_i$  = absolute temperature inside K (R)

$\Delta T$  = inside-outside temperature difference,  $T_i - T_o$ , K (R)

$n$  = flow exponent

$\beta$  = ratio of height of neutral pressure level above ground to building height

Note: When British units are used, constant 0.0342 in Eq 1 is replaced by 0.52.

This equation was rearranged and the following assumptions were made:

$\gamma = 1$  (assumption that the interior of the house is essentially open)

$p = 100$  KPa (14.7 psia at sea level)

$n = 0.65$

$T_i = 294$  K (530 R)

$$Q_s = 3 C_w A_w \beta^{1.65} H^{0.65} \left( \frac{\Delta T}{T_o} \right)^{0.65} \quad (2)$$

where

$A_w$  = total exterior wall area, m<sup>2</sup> (ft<sup>2</sup>)

Note: When British units are used, constant 3.0 in Eq 2 is replaced by 0.0385.

and in air changes/hr.

$$Q'_S = 10,800 \frac{C_w A_w^\beta}{V} H^{0.65} \left( \frac{\Delta T}{T_o} \right)^{0.65} \quad (3)$$

$Q'_S$  = infiltration caused by stack action, air change/hr

$V$  = house volume,  $m^3$  ( $ft^3$ )

Note: When British units are used, constant 10,800 in Eq 3 is replaced by 2.31.

The values of  $C_w$  for both houses were calculated by using the air leakage data given in Table 4 and the following flow equation:

$$Q = C_w A_w (\Delta P)^n \quad (4)$$

where

$Q$  = leakage flow through the exterior walls including windows and doors,  $m^3/s$  (cfm)

$\Delta P$  = pressure difference across the exterior walls, Pa (in. of water)

The calculated value of  $C_w$  for House No. 1 was  $1.1 \times 10^{-4} m^3/s \cdot m^2 \cdot Pa^{0.65}$  ( $0.77 ft^3/min \cdot ft^2 \cdot (in. \text{ of water})^{0.65}$ ) and for House No. 2 was  $4.6 \times 10^{-4}$  (3.2). The leakage flow through the windows and doors was 58% of the total wall leakage for House No. 1 and 23% for House No. 2.

The value of  $H$ , the height from grade to the first floor ceiling level, was 3.0 m (10 ft) for both houses. The value of  $\beta$ , the ratio of height of the neutral pressure level above ground to the building height,  $H$ , determined from measurements of pressure differences across the outside walls during calm periods was 1.08 for House No. 1 and 0.87 for House No. 2. The relatively high location of the neutral pressure levels are probably due to the chimney which is high level opening and the leakage openings in the ceiling construction.

The infiltration rates for House No. 1 calculated for various outside temperatures using Eq 4 are plotted on Fig. 3 together with the measured values for calm periods from Table 2. It shows that the calculated values agree reasonably well with the measured values. The calculated values for House No. 2 given in Fig. 4 indicate that the infiltration rates were much greater for this house than for House No. 1 due mainly to the greater value of  $C_w$ . The few available measured values from Table 3 are also plotted on Fig. 4 which tend to validate Eq 3.

#### WIND ACTION

The equation for wind infiltration rate was developed from Eq 4 which was modified to fit the measured leakage values for both houses obtained during the summer with little or no stack action. The examination of the measured values plotted on Fig. 5 and 6 indicated that the wind infiltration rates varied as a function of wind velocity and appeared to be insensitive to wind direction. Trial fitting of measured values to Eq 4 indicated that the infiltration rate is influenced by the area of the exposed wall facing the street (front wall) or the back wall. The side walls were shielded from wind by adjacent houses. The effective windward wall area ( $A_w$  of Eq 4) was taken as one-third of the total wall area weighted to the dimension of the exposed wall as follows:

$$\frac{A_w}{3} \begin{pmatrix} a \\ - \\ b \end{pmatrix}$$

where

$a$  = length of wall facing front or back

$b$  = length of side wall

The pressure difference across the windward wall,  $\Delta P$ , was taken as some fraction of the velocity pressure of the on-site wind which was related to that at the weather station as follows:

$$\Delta P = F P_v$$

$$P_v = 0.60 (E V_s)^2$$

$$\Delta P = 0.60 F (E V_s)^2$$

where

$F$  = constant, pressure difference coefficient

$P_v$  = velocity head of on-site wind, Pa (in. of water)

$V_s$  = wind velocity at weather station, m/s (mph)

$E$  = constant, ratio of on-site to weather station wind speed (the values of  $E$  were 0.65 for House No. 1 and 0.56 for House No. 2 based on measurements over a wide range of wind condition<sup>2</sup>).

*Note:* When British units are used, constant 0.60 is replaced by 0.00048.

Then substituting the above in Eq 4 gives

$$Q_w = 0.24 a/b A_w C_w F^{0.65} (E V_s)^{1.3} \quad (5)$$

*Note:* When British units are used, constant 0.24 in Eq 5 is replaced by 0.0023.

also Eq 5 expressed in air changes/hr is

$$Q_w' = 850 a/b \frac{A_w C_w}{V} F^{0.65} (E V_s)^{1.3} \quad (6)$$

*Note:* When British units are used, constant 850 in Eq 6 is replaced by 0.14.

The infiltration rates caused by wind were calculated for both houses and plotted together with measured values on Fig. 5 and 6 against the on-site wind velocity. The value of  $F$  assumed was 0.50 based on the exterior wall pressure measurements on both houses. The calculated values were lower than the measured values by 0.05 air changes per hour at low wind speed. The difference between the two values decreased with higher wind speeds.

#### COMBINED WIND AND STACK ACTION

The equation for calculating infiltration rate caused by the combined forces taken from Ref 4 is:

$$\frac{Q_{ws}}{Q_{1rg}} = 1 + 0.24 \left( \frac{Q_{sml}}{Q_{1rg}} \right)^{3.3} \quad (7)$$

where

$Q_{ws}$  = infiltration rate caused by the combined wind and stack action

$Q_{1rg}$  = larger value of  $Q_w$  and  $Q_s$

$Q_{\text{sm1}}$  = smaller value of  $Q_w$  and  $Q_s$

This equation was derived empirically using air leakage data obtained from the computer model building subjected to various combinations of wind and stack action. It shows that  $Q_{ws}$  is about equal to the infiltration rate caused by the larger of the two motive forces. When  $Q_w$  equals  $Q_s$ ,  $Q_{ws}$  is 24% greater than either  $Q_w$  or  $Q_s$ . The two ratios in Eq 7 are plotted on Fig. 7. The infiltration rate caused by the furnace operation also can be included by first determining  $Q_{ws}$  and comparing it with  $Q_f$  (furnace operation) in Eq 7.

The above calculation procedure was applied to the test conditions given in Tables 2 and 3. In calculating the infiltration rates during the second winter test of House No. 2, a reduced value of  $C_w$  was used to account for the increase in air tightness obtained by sealing all window cracks with tape. The calculated and the measured infiltration rates are compared in Tables 5 and 6. The average difference between the two values was 0.04 and 0.07 air changes per hour for House No. 1 and No. 2 respectively.

## DISCUSSION

The proposed procedure for calculating infiltration rate gave values which agreed reasonably well with the measured values. The accuracy of the measured values, which depends on the uniform mixing of tracer gas and room air, and instrument error in measuring the tracer gas concentration, however, was not determined. Also, the net inside volume which accounted for interior construction and furnishings was roughly estimated to convert calculated infiltration rate in air flow rate ( $\text{m}^3/\text{s}$ ) into air changes per hour. Hunt and Burch (7) reported that the air change rates measured by  $\text{SF}_6$  dilution and forced ventilation rates obtained with a fan were in essential agreement for three measurements of air change rates. More tests of this type are required to validate and to improve the tracer gas technique.

The infiltration rates calculated using Eq 3 for stack action were in good agreement with the measured values for both houses. One of the house characteristics required is the height of the neutral pressure level which depends on the vertical distribution of leakage openings in the house enclosure. If the houses tested had no chimney (electrically heated) which represents a high level opening, the height of the neutral pressure level would have been closer to mid-height and, hence, the infiltration rates probably would have been less. The height of the neutral pressure level for various types of houses is required. It can be determined by obtaining the vertical profile of the exterior wall pressure difference during calm periods in winter with the furnace not operating.

The other house characteristic required in Eq 3 and also in Eq 6 is the exterior wall leakage values. These can be obtained for different construction and type of houses from fan pressurization tests such as the one described in Ref 3. Tests on six houses, including 1- and 2-story houses, indicated that the outside walls contributed 35 to 90% of the overall leakage with the remainder through the ceiling construction; hence, the component as well as the overall leakage should be measured.

Eq 6 for calculating wind infiltration rate underestimated the measured values, particularly at low wind speeds (Fig. 5 and 6). There appears to be a residual measured infiltration rate of about 0.05 air changes/hr at zero wind speed. This is also evident in Fig. 3 and 4 for the stack infiltration rates at zero temperature difference. Hunt and Burch and other investigators have also noted this phenomenon, which may be attributed to the tracer gas technique but is not as yet satisfactorily explained.

Because the wind data issued by the meteorological station are the only ones readily available for hourly energy analysis of buildings, more information on the relationship between the wind speed measured at weather stations and residential areas is required (factor E of Eq 6). Also, more information on the exterior wall pressure differences caused by wind are required (factor F for windward wall of Eq 6). The wind infiltration equation devised to fit the measured infiltration values of the two houses does not take into account the wind direction. This shortcoming may be important for a completely exposed house or for a townhouse. Because of the dynamic nature of wind superimposed by the turbulence caused by nearby structures and trees, the mechanism of wind infiltration in houses is complex and is the most difficult to account for in the overall infiltration rate (8).

The flow rates through the chimney,  $Q_f$ , given in Tables 5 and 6 are those measured with the furnace in constant operation. As the furnace operation was not controlled, it often changed cycles during the tracer gas tests as indicated in Tables 2 and 3 and, hence, the actual flow rates were probably less than those indicated in Tables 5 and 6. More information on the measured values of gas flow in chimneys serving various heating appliances is required.



Eq 7 for calculating infiltration rates due to combined forces gave values which were in good agreement with the measured values. If the infiltration rates due to individual forces were added, the calculated values would have been far in excess of the measured values. If the average wind speed measured at a weather station is taken as 4.5 m/s (10 mph) and the value of E is 0.6, then the inside-to-outside temperature difference of 13°C (23°F) for House No. 1 and 5°C (9°F) for House No. 2 would give the same infiltration rate as that caused by wind; stack action would govern the infiltration rate for greater temperature differences.

The tracer gas tests were conducted with all exterior doors and windows closed. The occupant use of the house likely will affect the infiltration load over a heating season. Some information in this area is reported by Harrje et al (9).

## CONCLUSION

The proposed procedure involves determining separately the infiltration rates caused by stack action (Eq 3), wind action (Eq 6), and furnace operation, and then determining the resultant infiltration rate under the combined condition (Eq 7). It gave good agreement with the measured values for two single-story detached houses located in a residential district. The average differences between the calculated and the measured values were 0.04 and 0.07 air changes per hour for House No. 1 and No. 2 respectively. Further checks against measured values of more houses are required.

For general application of the proposed method, test data for various types of house design and construction, wind exposure and heating system required are:

1. neutral pressure level under calm condition and furnace off;
2. exterior wall leakage characteristic;
3. ratio of local to meteorological wind speed;
4. pressure differences across the exterior walls for different wind exposure; and
5. gas flow rate through chimneys serving various heating appliances.

The proposed method does not take into account the infiltration rate caused by occupant use of windows, doors and various household appliances. More information is required in this area to assess its contribution to the infiltration load over a heating season.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

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TABLE 1  
DESCRIPTION OF TEST HOUSES

	House No. 1	House No. 2
type	bungalow, 5-room with full basement	bungalow, 5-room with full basement
floor area <sup>1</sup>	77 m <sup>2</sup> (830 ft <sup>2</sup> )	100 m <sup>2</sup> (1070 ft <sup>2</sup> )
volume <sup>2</sup>	337 m <sup>3</sup> (11,900 ft <sup>3</sup> )	433 m <sup>3</sup> (15,300 ft <sup>3</sup> )
outside wall area <sup>3</sup>	108 m <sup>2</sup> (1,170 ft <sup>2</sup> )	126 m <sup>2</sup> (1,360 ft <sup>2</sup> )
construction	insulated wood-frame	insulated wood-frame
outside walls	brick veneer on four walls	brick veneer and wood siding on front wall, stucco finish on remaining walls
inside finish	plaster	plaster
windows	double horizontal sliding sashless-wood frame	wood double-hung vertical sliding with storm sash
heating system	forced warm air with gun type oil burner	forced warm air with gun type oil burner

*Note:*

1. Floor area based on inside dimension. (Basement not included).
2. Net volume, including basement and allowing 10% for furnishing and partitions.
3. Outside wall area above grade based on inside dimension.

TABLE 2

## RESULTS OF INFILTRATION TESTS FOR HOUSE NO. 1

Test No.	Temperature Difference C	Average Wind Velocity m/s	Wind Direction	Furnace Cycle	Infiltration Rate, Air Change/hr
Winter Test					
1	41.7	0.2	W	off-on	.36
2	35.5	3.8	NE	off-on	.41
3	29.4	1.4	S	off	.22
4	21.1	1.7	SW	on	.23
5	17.8	3.4	SW	off	.24
6	23.3	3.7	N	on-off	.25
7	25.0	4.3	NE	off	.25
8	19.4	3.2	SW	on-off	.16 <sup>1</sup>
Summer Test					
9	1.7	1.3	N	off	.07
10	-2.5	1.9	E	off	.10
11	-1.1	2.7	NW	off	.16
12	-1.1	0.4	E	off	.07
13	-3.3	3.2	SW	off	.17
14	1.1	1.5	W	off	.09
15	3.3	3.6	N	off	.17
16	-1.1	1.2	W	off	.08
17	-1.7	1.6	SW	off	.11
18	3.3	3.2	E	off	.14
19	1.7	0.4	S	off	.06
20	1.7	2.6	E	off	.13
Winter-Spring Test					
21	19.1	5.4	NE	off	.28
22	19.7	2.7	E	off	.22
23	18.9	0.4	E	off	.18
24	16.6	2.7	NE	off	.18
25	18.6	4.0	E	off	.23
26	16.1	2.8	SW	off	.20
27	16.6	4.9	W	off	.25
28	16.1	3.4	W	off	.18
29	18.6	1.2	E	off	.15
30	16.1	0.0	-	off	.12
31	10.5	0.9	-	off	.12
32	8.9	1.2	E	off	.13

<sup>1</sup>barometric damper sealed

TABLE 3

## RESULTS OF INFILTRATION TESTS FOR HOUSE NO. 2

Test No.	Temperature Difference C	Average Wind Velocity m/s	Wind Direction	Furnace Cycle	Infiltration Rate, Air Change/hr
Winter-Spring Test					
1	25.5	1.3	NE	-	.37
2	25.0	4.6	NE	on-off	.63
3	14.4	1.2	SW	off	.42
4	26.6	3.2	NW	on-off	.49
5	33.3	4.6	NW	on-off-on	.55
6	22.8	1.1	NW	off	.39
7	16.6	2.6	NE	off	.50
8	17.8	1.9	NE	off-on-off	.40
9	13.9	0.0	-	off	.24 <sup>1</sup>
10	18.3	2.7	SW	off	.39
11	21.6	4.1	NW	off	.45
12	10.0	2.5	NE	off	.59 <sup>2</sup>
13	3.3	1.9	SW	off	.25
Summer Test					
14	0	3.6	NW	off	.23
15	-1.7	3.4	SW	off	.20
16	-1.1	1.9	S	off	.12
17	1.1	2.3	W	off	.14
18	1.1	0.7	N	off	.11
19	0	0.2	-	off	.06
20	-1.7	2.5	S	off	.21 <sup>1</sup>
Winter Test - Windows Sealed					
21	25.5	4.2	SW	on-off-on	.49
22	39.4	1.1	NW	off-on-off	.39
23	39.4	2.8	NE	on-off-on	.57
24	21.1	4.6	SW	off-on-off	.42
25	25.5	4.6	SW	on-off-on	.45
26	32.7	4.7	SW	off-on-off	.46
27	26.6	2.2	S	off-on-off	.45
28	20.5	0.2	-	off-on-off	.33
29	36.6	5.1	W	off-on-off	.46
30	32.7	0.5	-	off-on-off	.45

<sup>1</sup>barometric damper sealed<sup>2</sup>fireplace damper open

TABLE 4

TOTAL AND COMPONENT WALL LEAKAGE RATES  
values in  $\text{m}^3/\text{s}$  at 75 Pa (cfm at 0.30 inch of water)

	House No. 1	House No. 2
Wall construction	0.080 (170)	0.736 (1,560)
Windows and doors	0.113 (240)	0.217 (460)
Ceiling	0.354 (750)	0.184 (390)
	0.547 (1,160)	1.137 (2,410)

*Note:*

1. Leakage values exclude those of fireplace, smoke pipe and exhaust vents.
2. Windows and doors with storm units.

TABLE 5

COMPARISON BETWEEN CALCULATED AND MEASURED  
AIR INFILTRATION RATES FOR HOUSE NO. 1

Test No.	$Q_s$	$Q_w$	$Q_f$	Calculated	$Q_c$ Measured	Difference
Winter Test						
1	0.27	0.00	0.40	0.42	0.36	0.06
2	0.24	0.15	0.40	0.41	0.41	0.00
3	0.21	0.04	-	0.21	0.22	-0.01
4	0.17	0.05	0.40	0.40	0.23	0.17
5	0.15	0.16	-	0.19	0.24	-0.05
6	0.19	0.14	0.40	0.40	0.25	0.15
7	0.16	0.17	-	0.20	0.25	-0.05
8	barometric damper sealed					
Summer Test						
9	0.02	0.04	-	0.04	0.07	-0.03
10	0.03	0.06	-	0.06	0.10	-0.04
11	0.01	0.10	-	0.10	0.16	-0.06
12	0.01	0.01	-	0.01	0.07	-0.06
13	0.04	0.12	-	0.12	0.17	-0.05
14	0.01	0.05	-	0.05	0.09	-0.04
15	0.04	0.14	-	0.14	0.17	-0.03
16	0.01	0.04	-	0.04	0.08	-0.04
17	0.02	0.05	-	0.05	0.11	-0.06
18	0.04	0.12	-	0.12	0.14	-0.02
19	0.02	0.06	-	0.06	0.06	0.00
20	0.02	0.09	-	0.07	0.13	-0.06
Winter-Spring Test						
21	0.16	0.23	-	0.25	0.28	-0.03
22	0.16	0.09	-	0.16	0.22	-0.06
23	0.15	0.01	-	0.15	0.18	-0.03
24	0.14	0.09	-	0.15	0.18	-0.03
25	0.15	0.16	-	0.19	0.23	-0.04
26	0.14	0.10	-	0.15	0.20	-0.05
27	0.15	0.21	-	0.23	0.25	-0.02
28	0.14	0.13	-	0.17	0.18	-0.01
29	0.15	0.03	-	0.15	0.15	0.00
30	0.14	0.00	-	0.14	0.12	0.02
31	0.10	0.02	-	0.10	0.12	-0.02
32	0.09	0.03	-	0.09	0.13	-0.04

Note:

1. Values in air changes/hr
2.  $Q_s$  = calculated values caused by stack action alone
3.  $Q_w$  = calculated values caused by wind action alone
4.  $Q_f$  = measured values caused by furnace operation
5.  $Q_c$  = values caused by combined forces

TABLE 6  
COMPARISON BETWEEN CALCULATED AND MEASURED  
AIR INFILTRATION RATES FOR HOUSE NO. 2

Test No.	$Q_s$	$Q_w$	$Q_f$	Calculated	$Q_c$ Measured	Difference
Winter-Spring Test						
1	0.51	0.06	-	0.51	0.37	0.14
2	0.50	0.31	0.38	0.57	0.63	-0.06
3	0.34	0.05	-	0.34	0.42	-0.08
4	0.52	0.19	0.38	0.57	0.49	0.08
5	0.61	0.31	0.38	0.65	0.55	0.10
6	0.47	0.05	-	0.47	0.39	0.08
7	0.37	0.15	-	0.38	0.50	-0.12
8	0.39	0.10	0.38	0.47	0.40	0.07
9	barometric damper sealed					
10	0.40	0.15	-	0.40	0.39	0.01
11	0.45	0.16	-	0.45	0.45	0.00
12	fireplace damper open					
13	0.12	0.06	-	0.13	0.25	-0.12
Summer Test						
14	0	0.23	-	0.23	0.23	0.00
15	0.06	0.22	-	0.22	0.20	0.02
16	0.02	0.10	-	0.10	0.12	-0.02
17	0.02	0.13	-	0.13	0.14	-0.01
18	0.02	0.03	-	0.03	0.11	-0.08
19	0	0.01	-	0.01	0.06	-0.05
20	barometric damper sealed					
Winter Test - Windows Sealed						
21	0.41	0.23	0.38	0.50	0.49	0.01
22	0.56	0.04	0.38	0.60	0.39	0.21
23	0.56	0.14	0.38	0.60	0.57	0.03
24	0.36	0.25	0.38	0.47	0.42	0.05
25	0.41	0.25	0.38	0.50	0.45	0.05
26	0.49	0.25	0.38	0.55	0.46	0.09
27	0.42	0.10	0.38	0.49	0.45	0.04
28	0.36	0.10	0.38	0.43	0.33	0.10
29	0.53	0.30	0.38	0.59	0.46	0.13
30	0.48	0.02	0.38	0.53	0.45	0.08

Note:

1. Values in air changes/hr
2.  $Q_s$  = calculated values caused by stack action alone
3.  $Q_w$  = calculated values caused by wind action alone
4.  $Q_f$  = measured values caused by furnace operation
5.  $Q_c$  = values caused by combined forces

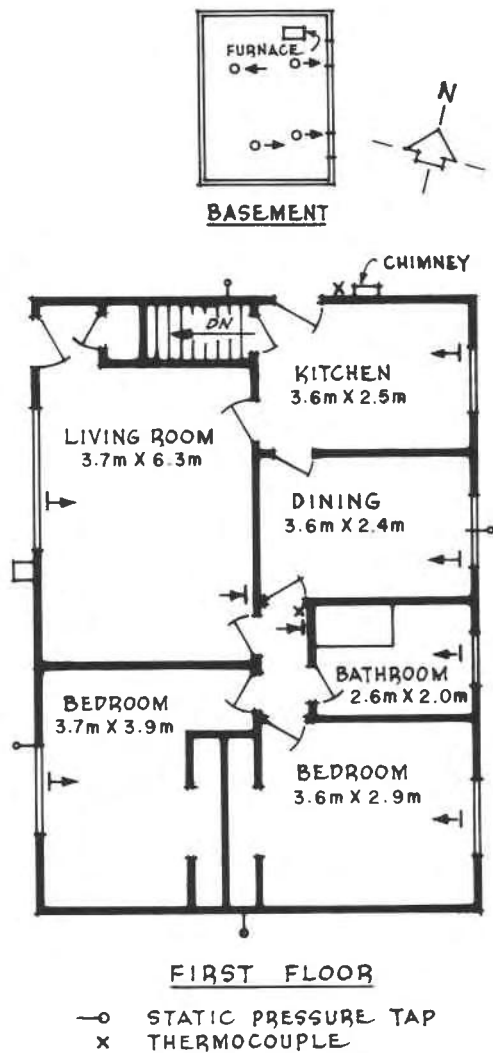


Fig. 1 House No. 1

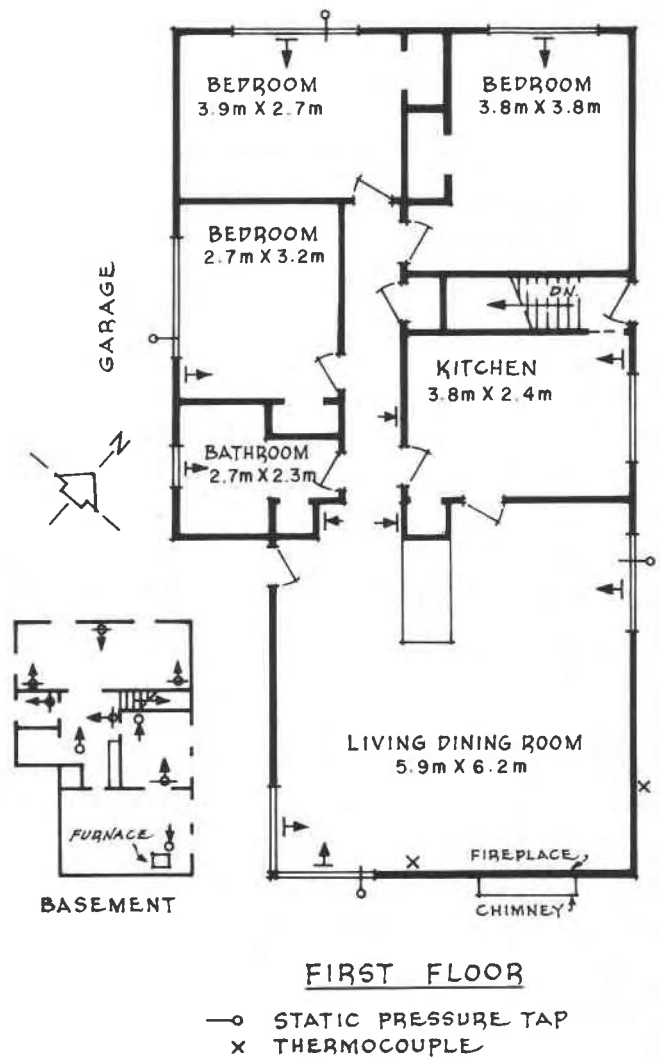


Fig. 2 House No. 2



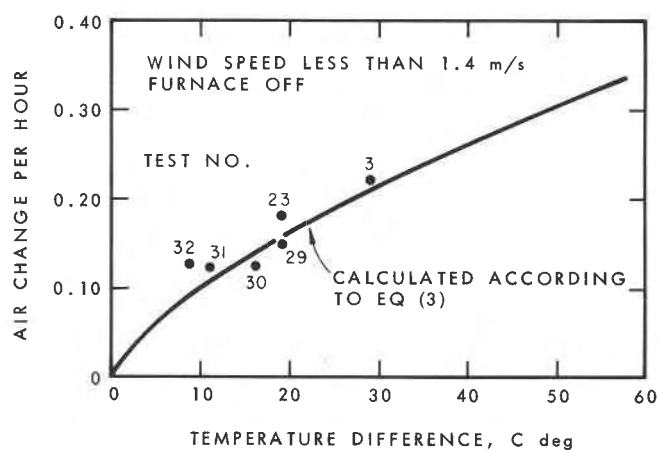


Fig. 3 Infiltration rates caused by stack action for House No. 1

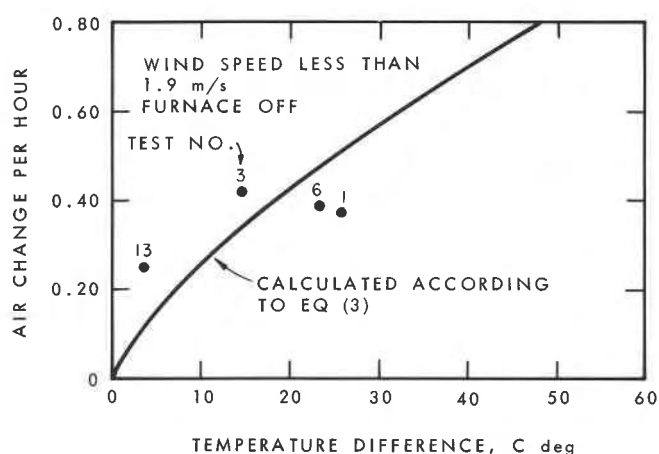


Fig. 4 Infiltration rates caused by stack action for House No. 2

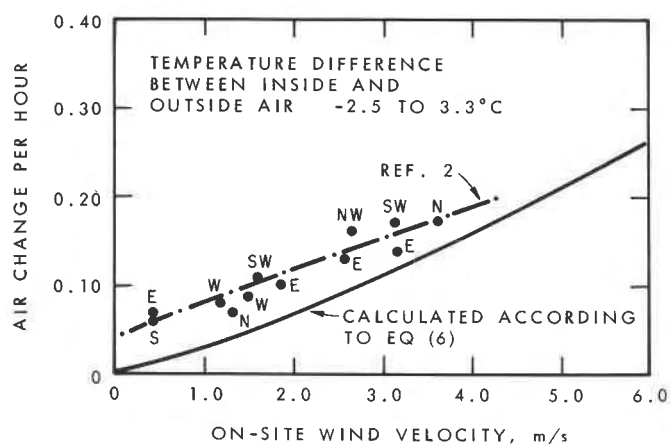


Fig. 5 Infiltration rates caused by wind for House No. 1

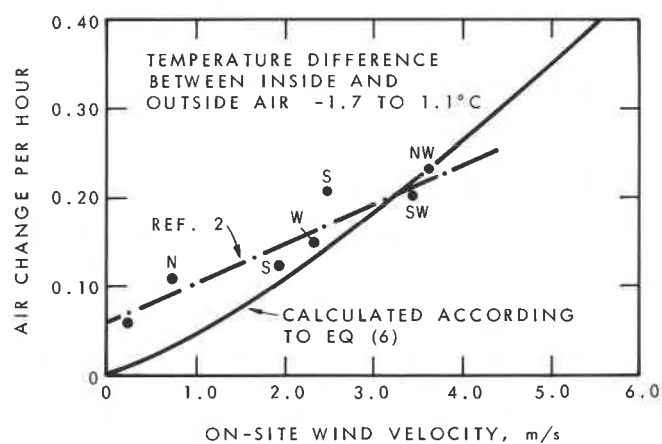


Fig. 6 Infiltration rates caused by wind for House No. 2

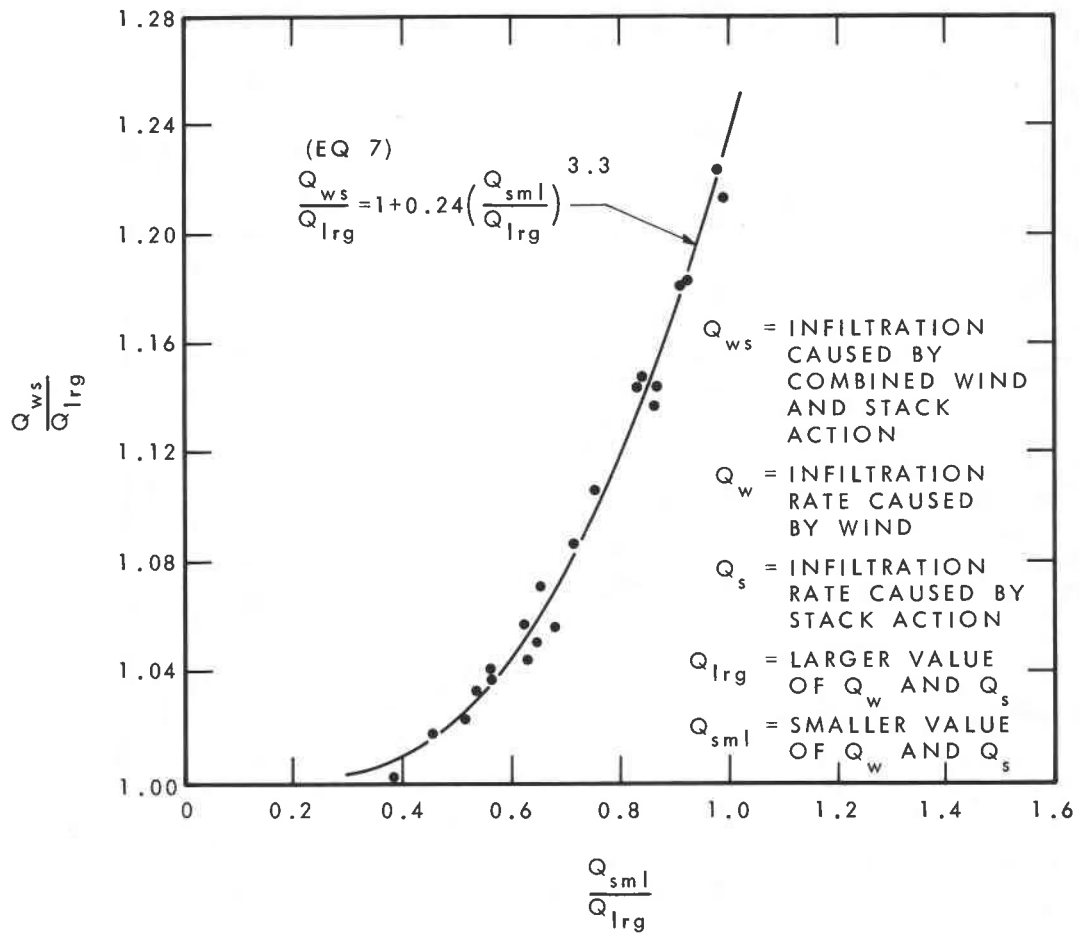


Fig. 7 Factors for determining infiltration rates caused by combined wind and stack action

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