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CALCULATING INFILTRATION: AN EXAMINATION OF HANDBOOK MODELS

JOHN E. JANSSEN, P.E.
Member ASHRAE

A. NOEL PEARMAN, P.E.
Member ASHRAE

THOMAS J. HILL
Student Member ASHRAE

ABSTRACT

Better control of infiltration losses offers an opportunity for substantial energy savings. The ASHRAE Handbook: Fundamentals Volume presents two methods for estimating infiltration. The air change method is a gross estimate based on the number of windows and doors in each room. The crack method based on measurements of flow through the cracks around windows and doors accounts for crack size and the effect of weather.

Comparisons of tracer gas measurements with calculations by both the air change and crack methods are presented for test houses in California and Minnesota. Agreement is adequate for sizing equipment but not for assessing indoor pollution problems.

INTRODUCTION

Infiltration is one of the significant heat loss or gain mechanisms in residential buildings. It frequently accounts for around 20% of the load on heating or cooling systems. Infiltration also is the main means of control of indoor air quality in single family residences. Pollutants, including carbon dioxide and water vapor generated by people and their activities are diluted by infiltration. Pollutants such as organic vapors, formaldehyde, nitrogen oxides, carbon monoxide, radon, and a number of other gases come from the structure itself or processes going on in the home. Adequate infiltration or ventilation must be available to keep all pollutants diluted to acceptable concentrations.

Building practices prior to the oil embargo of 1973 generally resulted in houses with enough infiltration to minimize most indoor air quality problems. Now, however, serious efforts are being made to reduce infiltration to a point where control of the indoor pollution problem must be addressed. Thus, determination of the infiltration in residential structures is important from two points of view. Knowledge of the maximum infiltration is important for assessing energy conservation strategies and for sizing heating and cooling equipment. Knowledge of the minimum infiltration is important for assessing the magnitude of potential indoor pollution problems.

The ASHRAE Handbook, Fundamentals Volume, 1977 edition, Chapter 21[1] presents two methods for estimating infiltration. The first, rather gross, method is based on the number of air changes per hour to be expected in a room with a given number of windows or doors. The other method is based on the calculated leakage through cracks around windows and doors. The Handbook also provides guidance for estimating the effect of variations in wind pressure and indoor-outdoor temperature differences.

J. E. Janssen, Principal Engineering Fellow, Honeywell Inc., TSC, Minneapolis, MN.
A. N. Pearman, Senior Development Engineer, Honeywell Inc., TSC, Minneapolis, MN.
T. J. Hill, Associate Development Engineer, Honeywell Inc., TSC, Minneapolis, MN.

The objective of this study was to compare measured infiltration with values calculated by each of these methods. The comparison was made for four single family houses. One was at Mission Viejo, south of Los Angeles, one was in Walnut Creek, east of Oakland, CA and two were in the greater Minneapolis, MN area. The Mission Viejo house and one Minneapolis house were "super insulated" buildings. The other two represented standard construction in their respective areas.

CALCULATION METHODS

Air Change Method. Chapter 21 of the 1977 Fundamentals Volume, ASHRAE Handbook, presents the data shown in Table 1 for the nominal infiltration to be expected in residences.

The Handbook cautions that the air change method represented by the data in Table 1 is not accurate for industrial or commercial buildings due to the wide variation in the type and amount of fenestration used in larger buildings. The 1972 issue of the Fundamentals Volume[2] suggested further that some engineers use one-half the values recommended in Table 1 because air flows into the building through some of the openings and an equal amount of air flows out of other openings. Thus, it is suggested that the effective infiltration for a residence with weather-stripped windows or storm sash could be estimated to be 2/3 x 1/2 = 1/3 of the values presented in Table 1. The values used for whole house infiltration for this comparison, therefore, were 1/2 or 1/3 of the values in Table 1 depending on the presence of weather-stripping or storm sash. No extra allowance was given for windows or doors that have both weather-stripping and storm sash or storm doors.

The Handbook also advises caution in the room volume to be used when applying the data from Table 1. Extra large rooms with relatively small window area (e.g., extra high ceilings) could be expected to have a lower volumetric exchange rate than small rooms with large window areas. The residences used in this study all had average size rooms with 2.44m (8 ft) ceilings. No allowances were made for room size.

CRACK METHOD

Wind Effect. The other common method for calculating infiltration is based on leakage through cracks around windows, window frames, doors, door frames, and diffusion through walls. Tables 2, 3, and 4 from the Fundamentals Volume, Chapter 21,[1] present leakage data in metric SI units.

The procedure was to calculate the total crack length for the perimeter of each window sash and use the appropriate leakage value from Table 2 or 4. The perimeter of each window and door frame was measured also and the leakage as specified in Table 2, item B3 was computed and added to the sash leakage. The frame leakage is due to the cracks between the window frame and the wall whereas sash leakage is through the cracks that allow for opening of the window sash.

Table 3 presents coefficients for leakage through the wall itself. The net wall area to be used is the total area minus the window and door areas in the wall. It should be noted that the Handbook Tables 2 and 3[1] values are given in cu ft per hour whereas Handbook Table 4[1] is given in cu ft per minute. The values have been converted to consistent units of litres per second for this paper.

Tables 2 and 3 also present the data as a function of pressure differential across the wall. The Table 4 data are presented for one pressure only, a 11.2m/s wind velocity (i.e., 25 mph or 75 Pa pressure) except for a few exceptions as noted. The comparisons presented here were all computed for 75 Pa pressure differential and then converted to lower pressure differentials. The pressure equivalent of velocity is given by:

$$P_v = B\, V_w^{\ 2} \tag{1}$$

B = Constant
= 0.6008 if P_v is Pascals and V_w is meters per second
= 0.000482 if P_v is in. of water and V_w is miles per hour

The flow through a crack is given by:

$$\dot{V} = C\,(P_w - P_i)^n \tag{2}$$

C = Flow coefficient from Tables 2, 3, or 4

Equation 2 can be written:

$$\dot{V}_2 = \dot{V}_1 \left[\frac{(P_w - P_i)_2}{(P_w - P_i)_1}\right]^n \tag{3}$$

The pressure difference, $P_w - P_i$, is the difference between the windward side and the inside of the building.

The flow coefficient, n, in Eq. 3 depends on the nature of the crack or opening. Flow through a sharp edge orifice would have an exponent n = 0.5. Flow through a porous plug would be characterized by n = 1.0. Experience has shown that n = 0.65 is a good compromise.

The Handbook goes on to explain that the pressure difference across the windward wall is:

$$P_w - P_i = \frac{P_w - P_L}{1 + (A_w/A_L)^{1/n}} \tag{4}$$

The value of n in equation 4 is the same as the flow exponent in Eq. 3.

For a square building with the wind quartering at 45° to a wall and a uniform distribution of cracks, two sides will face the wind and two will face away from the wind. Then $A_W/A_L = 1$ and $P_W - P_i) = 0.5\,(P_W - P_L)$. The same building with wind normal to one face will have 1 windward side and 3 leeward sides. For this case $A_W/A_L = 1/3$ and $(P_W - P_i) = 0.85\,(P_W - P_L)$.

The building with a quartering wind would experience infiltration leakage into the building on two sides and out of the building on two sides. Thus, only 1/2 the cracks length, if uniformly distributed, would allow infiltration. Exfiltration would occur through the other half of the cracks. In the case of wind normal to one wall, infiltration would occur through 1/4 of the cracks. Thus, both the effective wind pressure and the effective crack length are influenced by the wind direction and distribution of cracks.

Temperature Effect. The indoor-outdoor temperature difference also generates a pressure difference that induces infiltration. This is a major driving force in tall buildings. The temperature-induced chimney effect is a small effect in one- or two-story buildings, however. Chapter 21, 1977 Fundamentals Volume[1] gives, in SI units:

$$P_c = 0.0342\ Ph\,(1/T_o - 1/T_i) \tag{5}$$

The constant 0.0342 becomes 0.52 when P is in psi, h is in ft and T is in degrees Rankine. If the cracks and openings in the building envelope are uniformly distributed, h, the height of the neutral pressure level is one half the building height. This pressure due to chimney effect can be added to wind generated pressure to find the total pressure across the wall at the base of the windward side.

INFILTRATION MEASUREMENT

The tracer gas decay method was used to measure infiltration.[3] A dilute concentration of tracer gas, methane in this case, was introduced into the house. The rate of decay of concentration was then measured with a non-dispersive infrared instrument. The methane concentration was kept below 1,000 ppm. The lower flammability limit for methane in air is about 53,000 ppm (5.3%) so that the minimum safety factor was greater than 50.

The four houses measured in this study all had warm air heating systems. This made it convenient to use the heating system to distribute and sample the tracer gas. The experimental arrangement is shown in Fig. 1. Tracer gas was added to the return air at a constant flow rate for a measured time period. The tracer gas flow was stopped after the level in the house reached the 500 to 1,000 ppm range. The decay time was measured from the time the tracer gas charging period stopped.

The decay in the tracer concentration is given by

$$C_T = C_{To} e^{-t/\tau} \tag{6}$$

or

$$\tau = \frac{t_2 - t_1}{\ln \frac{C_{T1}}{C_{T2}}} \tag{7}$$

In one time interval equal to the time constant, τ, the volume of air infiltrated will be equal to the volume of the house.

$$V_h = \tau \dot{V}_i \tag{8}$$

or

$$\dot{V}_i = \frac{V_h}{\tau} \tag{9}$$

The volume of the house, V_h, can be measured from its geometry, or it can be measured by measuring the amount of tracer gas added and observing the concentration it produces. Since the tracer is added over a period of time and some is lost through exfiltration while charging the house, allowance must be made for this loss.

The amount of tracer added is:

$$\dot{V}_T t \tag{10}$$

and the amount lost is

$$\dot{V}_i \int_0^t C_T dt \tag{11}$$

Thus, the tracer left in the house at the end of the charging period is,

$$V_h C_{To} = \dot{V}_T t - V_i \int_o^t C_T dt \qquad (12)$$

or

$$C_{To} = \frac{\dot{V}_T t}{V_h} \quad \frac{V_i}{V_h} \int_o^t C_T dt \qquad (13)$$

The integral term in Eq. 13 is the loss of tracer during the charging period. It has been shown[3] that this equation can be integrated to yield:

$$V_h = \frac{\dot{V}_T}{C_{To}} \tau(1-e^{-t/\tau}) \qquad (14)$$

The infiltration rate is then

$$\dot{V}_i = \frac{V_h}{\tau} = \frac{\dot{V}_T}{C_{To}} (1-e^{-t/\tau}) \qquad (15)$$

The procedure was to feed the tracer gas into the return duct as shown in Fig. 1, at a rate such that 15 to 20 min. would be required to reach the desired concentration. This allowed the concentration in the house to build up slowly and fairly uniformly throughout the house. The assumption of uniform tracer concentration made in Eq. 11 was then reasonably achieved.

The decay data were plotted on a semi-log plot as shown in Fig. 2.

Sometimes the data near the start of the decay period depart from the straight line relationship shown in Fig. 2. This indicates mixing was not complete. However, the straight line that was subsequently produced was extrapolated back to the start of the decay period to determine the beginning tracer concentration, C_{To}, for use in Eq. 14 and 15. Comparison of the volume of the house computed from Eq. 14 and the volume computed from geometrical measurements provided a check on the uniformity of tracer gas distribution.

CALCULATION PROCEDURE

Estimating infiltration by the air change method is relatively straightforward. The data presented in Table 1 were used for this purpose. The volumetric leakage into and out of each room was based on the number of openings, number of exposures and the room volume. The flow was reduced by one third in each case to allow for weather-stripping and storm windows. The total flow as added and then divided by the total building volume to obtain the gross leakage presented in Table 5. The 1972 issue of the Fundamentals Volume[2] suggested that the infiltration be further reduced to one half the above calculated value to account for infiltration in some cracks and exfiltration out of other cracks.

Chapter 21 of the Handbook, 1977 Fundamentals, does not present a detailed calculation procedure for the crack method. The recent Cooling and Heating Load Calculation Manual, ASHRAE GRP158[4] is more helpful. The following was used for this comparison.

1. The crack length for each window sash including the crack between the overlapping sash in double windows was computed. The perimeter around doors was computed also.

2. The perimeter of each window and door frame was computed.

3. The wall areas minus window and door areas and attic floor areas were calculated.

4. Appropriate leakage coefficients were then selected from Tables 2, 3, or 4.

Initial leakage calculations were then made for a pressure difference of 75 Pa (0.30 in. H_2O) since the data used from Table 4 were for this pressure.

5. A wind normal to the west side of the MED II, Minnetonka and New Brighton houses was assumed. Wind normal to the north side of the Walnut Creek house was assumed since the west side of that house had no windows. The area of the windward and leeward sides of each house was then computed.

6. Eq. 4 was then used to adjust the wind velocity pressure to an effective outdoor minus indoor pressure difference.

7. Eq. 3 was then used to compute the effective infiltration from the leakage computed in Step 4. Calculations were made at wind velocities of 11.2m/s (25 mph), 6.7m/s (15 mph), and 2.2m/s (5 mph).

RESULTS AND DISCUSSION

The results of the tracer measurements and calculations are compared in Table 5. The MED II house used a furnace with a sealed combustion system, i.e., it drew combustion air from outside. Also, the duct work was all in the conditioned space. Thus, this heating system had no effect on the infiltration rate. The Walnut Creek house also had a furnace in a sealed closet; combution air was drawn from outside. The duct work, however, was located in the crawl space and attic. It was found that leakage from the joints in this duct work was a substantial leakage path. This leakage was estimated by measuring the amount of tracer added, the concentration it produced and then computing the house volume from Eq. 13. The difference between this and the geometrical measured volume was then used to estimate the tracer leakage from the ducts during the charging period. The value of 0.13 AC/hr with the furnace off was the difference between the actual measured value and the estimated duct leakage. The Walnut Creek house was the only one with ducts located in unconditioned space.

Leakage from ducts passing through unconditioned space has been found to be a major infiltration path.[3] There is no provision for estimating this leakage in the Handbook. An infiltration flow equal to 5% of the duct flow for ducts passing through unconditioned space, however, would not be unreasonable. This includes ducts in basements that are indirectly connected to the main part of the house. Split level houses, for example, are sometimes built with the only access to the basement through the garage.

The Minnetonka and New Brighton houses both had furnaces located in the basement. In both cases the basement was connected with the rest of the house through interior stairways. Since the furnace drew its combustion air from the conditioned space, infiltration increased slightly when the burner was on as shown for the Minnetonka house. Both Minnesota houses were nearly identical in size. The New Brighton house was more heavily insulated, however. It had 6mm (2 in.) polystyerene sheeting in addition to 8.9mm (3.5 in.) fiber glass in the walls and R37 vs R20 attic insulation.

The adjusted air change method calculations agreed reasonably well with measurements. The agreement is probably adequate for sizing heating equipment since infiltration accounts for only 20-25% of the total load at the design point and some reserve capacity is desirable. The air change method does appear to have a size effect. The two California houses had about one-third of the volume of the Minnesota houses. The air change method appears to overestimate infiltration in a small house unless the ducts are in the unconditioned space. The air change method makes no allowance for wind nor exhaust losses such as the furnace vent.

The cracked method calculations were made for three different wind velocities. In all cases the wind was assumed to be normal to one wall. This gave the highest infiltration. At 11.2m/s (25 mph) the calculated values were greater than the measured values. The wind velocities during the measurements were around 10 mph. The crack method calculations at 6.7 m/s (15 mph) were in reasonably good agreement except for the MED II house where the wind velocities were lower. The crack method values at 2.2m/s (5 mph) are in fair agreement with the expected infiltration in the MED II house at this velocity. The duct leakage in the Walnut Creek house makes comparisons with calculations uncertain.

The crack method also appears to underestimate infiltration in larger houses as seen by the comparisons for the Minnesota houses. A value of only 0.1 AC/h at 2.2m/s (5 mph) appears lower than could be expected in practice. It seems likely that losses through partition walls to the attic, and losses through leaky fireplace dampers, vent fans, etc. should be included in crack method calculations.

The temperature effect was investigated for the Minnetonka house. Eq. 5 was used to estimate the pressure gradient due to stack effect. The distance from the neutral plane was assumed to be 3m (10 ft, probably greater than the actual distance) and the temperature difference was assumed to be 28°C (50 F) which also was slightly greater than the actual temperature difference. This gave an indoor/outdoor pressure difference due to stack effect of only 0.4 Pa (0.0015 in. H_2O). This would raise the infiltration from 0.10 AC/h to 0.12 AC/h at 2.2m/s (5 mph) wind velocity. It appears that the temperature induced stack effect can be safely ignored for one- or two-story residential buildings.

CONCLUSIONS

This comparison considers only the models presented in the 1977 edition of the ASHRAE Handbook, Fundamentals volume. These models were developed at a time when fuel was cheap and only gross approximations were of interest. When applied to houses of normal construction, it is surprising that the models are as accurate as they seem to be. No allowance is made for leakage via partition walls, under sole plates or out furnace and fireplace vents. The models are inadequate, however, when special efforts are made to achieve low infiltration. Current research on new more complete models should be included in the Handbook.

The air change method, although very superficial, appears to estimate infiltration, for normal construction, with sufficient accuracy for sizing heating and cooling equipment.

The air exchange rates presented in Table 1 should be reduced by one-third as suggested for use with weather-stripped windows and doors or storm windows. It is also advisable to assume that infiltration occurs through half the cracks in residential buildings and exfiltration occurs through the other half. Thus, the ventilation rate due to infiltration should be reduced to one-half the value calculated from Table 1 data. A typical residence with weather-stripped windows has an infiltration rate of 2/3 x 1/2 = 1/3 the gross values presented in Table 1. The air change method provides no guidance for estimating the minimum infiltration, e.g., the minimum air available for diluting indoor air contaminants. The method provides only minimal guidance for reducing infiltration.

The crack method provides more insight as to the effect of wind and temperature on building infiltration. More specific directions are needed in the ASHRAE Handbook[1] for the application of the crack method. The Load Calculation Manual[4] also could benefit from more specific application guidance. There appears to be a size effect in both calculation methods. They tend to overestimate infiltration in small homes and underestimate infiltration in large homes. Infiltration paths such as duct leakage which are not considered can be a major source of error in calculations.

The crack method gives reasonable estimates for sizing equipment and consideration can be given to local wind conditions. Temperature effects can be ignored when estimating infiltration at the design point.

The crack method calculations appear to underestimate infiltration at low wind velocity. The crack method would predict zero infiltration at zero wind velocity and zero indoor-outdoor temperature difference. Better models are needed for calculating infiltration at low wind velocity and low indoor-outdoor temperature difference when indoor pollution may become troublesome.

Unconsidered leakage paths such as leakage into partition walls and thence into the attic, leakage through electrical fixtures, leakage into the furnace vent, and leakage through other exhaust dampers need to be considered. These unconsidered leaks reduce the pollution problem. Efforts to reduce these leaks will increase the need for better modeling methods. The indoor air pollution problem requires more precise knowledge of building air leakage under low wind and low thermal load conditions.

NOMENCLATURE

A = Area
C = Concentration
h = Height to Neutral Pressure Level
n = Flow Exponent
P = Pressure
T = Absolute Temperature
t = Time
V = Velocity or Volume
$\dot{V}$ = Volumetric Flow
τ = Time Constant

Subscripts

c = Chimney
h = House
i = Inside or Initial
L = Leeward
o = Outside
T = Tracer
v = Velocity
w = Wind or Windward

Table 3 Infiltration Through Walls
Leakage in Litres Per Second Per Metre of Crack

Type of Wall		Pressure Difference Pascals				
		12	25	50	75	100
Brick Wall[a]						
8.5 in.	Plain	0.13	0.23	0.41	0.62	0.72
	Plastered[b]	0.001	0.001	0.004	0.005	0.007
13 in.	Plain	0.13	0.21	0.36	0.52	0.62
	Plastered[b]	0.003	0.001	0.001	0.002	0.003
	Plastered[c]	0.0008	0.006	0.012	0.017	0.022
Frame Wall						
	Lath and Plaster[d]	0.002	0.004	0.006	0.007	0.008

[a] Constructed of porous brick and lime mortar - workmanship poor.

[b] Two coats prepared gypsum plaster on brick.

[c] Furring, lath, and two coats prepared gypsum plaster on brick.

[d] Wall Construction: bevel sliding painted or cedar shingles, sheathing, building paper, wood lath, and three coats gypsum plaster.

Table 4 Window and Door Specification
Leakage in 1/s•m Crack Unless Noted Otherwise

Specification/Material	Type of Class	Air Leakage**
ANSI A134. 1 Aluminum	A-B1 (Awning)	1.16
	A-A2 (Awning)	0.77
	C-B1, C-A2, C-A3 (Casement)	0.77
	DH-B1 (Hung)	1.16
	DH-A2, DH-A3, DH-A4 (Hung)	0.77
	HS-B1, HS-B2, HS-A2 (Sliding)	1.16
	HS-A3 (Sliding)	0.77
	J-B1 (Jalousie)	7.62 1/s•m^2
	JA-B1 (Jai-Awning)	1.16
	P-B1, P-A2 (Projected)	0.77
	P-A2.50 (Projected)	0.58
	P-A3 (Projected)	0.77***
	TH-A2 (Inswinging)	0.58
	TH-A3 (Inswinging)	0.77***
	VP-A2 (Pivoted)	0.58
	VP-A3 (Pivoted)	0.77***
	VS-B1 (Vert. Sliding)	1.16
ANSI A134. 2 Aluminum	SGD-B1 (Sliding Glass Door)	5.08 1/s•m^2
	SGD-B2, SGD-A2, (Sliding Glass Door)	2.54 1/s•m^2
	SGD-A3 (Sliding Glass Door)	2.54 1/s•m2***
ANSI A200. 1 Wood	All Types Windows	
	Class A	0.77
	Class B	0.77
ANSI A200. 2 Wood	All Types Sliding Glass Doors	2.54 1/s•m^2
Fed. MHC & SS* 280. 403	Windows (All Types) Sliding Glass Doors	2.54 1 s•m^2
Fed. MHC & SS* 280. 405	Vertical Entrance	5.08 1/s•m^2

* Federal Mobile Home Construction and Safety Standard

** At 75 Pa (0. 30 in. water) pressure or 11. 2 m/s (25 mph) wind velocity.

*** At 300 Pa (1. 30 in. water) pressure or 22. 3 m/s (50 mph) wind velocity.

REFERENCES

1. ASHRAE Handbook, Fundamentals Volume, 1977, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

2. ASHRAE Handbook, Fundamentals Volume, 1972, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

3. Janssen, J. E., Glatzel, J. J., Torborgh, R. H., and Bonne, U., "Infiltration In Residential Structures," Heat Transfer In Energy Conservation, ASME Symp. Bulletin, 1977.

4. Rudoy, W. and Cuba, J. F., "Cooling and Heating Load Calculation Manual," ASHRAE GRP 158.

Table 1 Air Changes Occurring Under Average Conditions in Residences, Exclusive of Air Provided for Ventilation*

Kind of Room	Number of Air Changes per Hour
Room with no windows or exterior doors.	0.5
Rooms with windows or exterior doors on one side.	1
Rooms with windows or exterior doors on two sides.	1.5
Rooms with windows or exterior doors on three sides.	2
Entrance halls	2

*For rooms with weather-stripped windows or with storm sash, use two-thirds these values.

Table 2 Infiltration Through Double-Hung Wood Windows
Litres Per Second Per Metre of Crack

Type of Window	Pressure Difference Pascals 25	50	75	100	125
A. Wood Double-Hung Window (Locked)					
1. Nonweather-stripped loose fit[a]	2.0	3.1	3.9	5.0	5.8
2. Nonweather-stripped, average fit,[b] or weather-stripped, loose fit	0.70	1.1	1.5	1.8	2.1
3. Weather-stripped, average fit	0.36	0.59	0.77	0.93	1.1
B. Frame-Wall Leakage[c] (Leakage is that passing between the frame of a wood double-hung window and the wall)					
1. Around frame in masonry wall, not caulked	0.43	0.67	0.88	1.1	1.2
2. Around frame in masonry wall, caulked	0.08	0.13	0.15	0.18	0.21
3. Around frame in wood frame wall	0.34	0.54	0.75	0.90	1.1

[a] A 2.4mm crack and clearance represent a poorly fitted window, much poorer than average.

[b] The fit of the average double-hung wood window was determined as 1.6 mm crack and 1.2mm clearance by measurements on approximately 600 windows under heating season conditions.

[c] The values given for frame leakage are per metre of sash perimeter, as determined for double-hung wood windows. Some of the frame leakage in masonry walls originates in the brick wall itself, and cannot be prevented by caulking. For the additional reason that caulking is not done perfectly and deteriorates with time, it is considered advisable to choose the masonry frame leakage values for caulked frames as the average determined by the caulked and non-caulked tests.

Table 5 Infiltration Comparison

House	Wind m/s	Furnace Condition	Measured Inf. AC/h	Calculated Infiltration				
				Air Change		Crack		
				Gross AC/h	Adjusted AC/h	11.2m/s AC/h	6.7m/s AC/h	2.2m/s AC/h
MED II So. Calif.	2-4	Sealed	0.3	1.21	0.60	1.59	0.82	0.20
Walnut Creek Calif.	4	On	0.75	1.09	0.55	1.58	0.82	0.20
Walnut Creek Calif.		Off	0.13					
Minnetonka MN.	4	On	0.49	0.80	0.40	0.84	0.43	0.10
Minnetonka MN.	4	Off	0.46					
New Brighton MN.	4-6	On	0.50	.77	0.39	0.94	0.49	0.12

House Volumes: MED II, 245m^3; Walnut Creek, 230m^3; Minnetonka 690m^3; New Brighton 690m^3

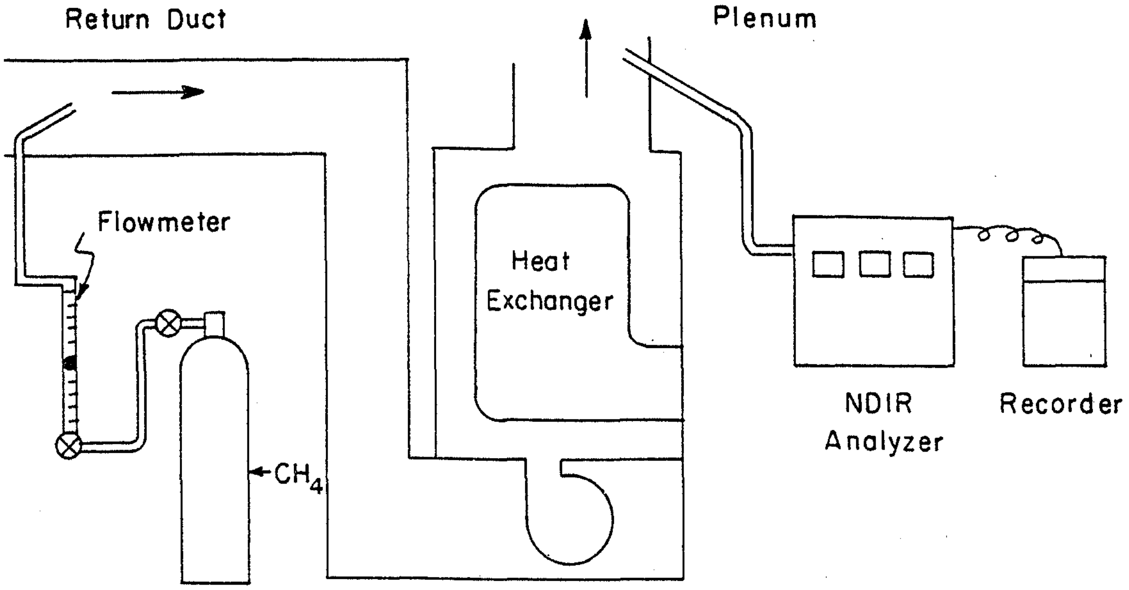

Fig. 1 Infiltration measurement setup

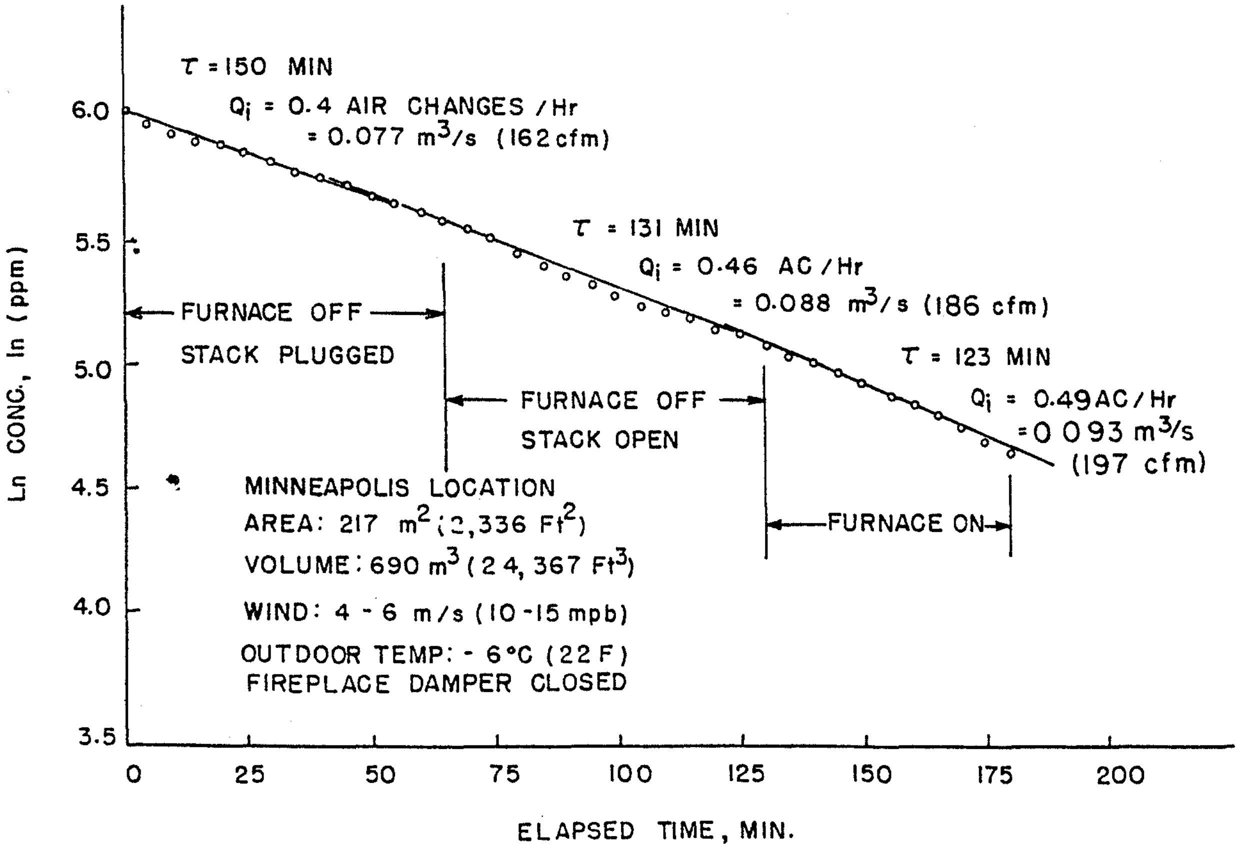

Fig. 2 Decay of tracer with time