MEASUREMENT OF INFILTRATION IN A MOBILE HOME

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In order to properly calculate the expected heat gains and/or heat losses in mobile homes, the infiltration rate has to be known. The ASHRAE HANDBOOK OF FUNDAMENTALS (1) suggests an approximate method, referred to as the crack method which unfortunately does not apply too well to mobile homes.

Measurements of infiltration in a mobile home are now presented. The rate of decay method, with carbon monoxide as a tracer, was found to be dependable and economical. In the measurements, relatively high values of infiltration rates were noted. The different zones (i.e., main living area and sub-flooring) and different modes of conditioning (i.e., heating or air conditioning) were isolated attempting to identify the causes for high rates of infiltration. In addition, the essentially linear dependence of infiltration on temperature difference was confirmed while no dependable trends on the effects of wind were noted.

The reported measurements are limited by at least two conditions: (1) small pedestal-type fans were used in the living area of the mobile home to stimulate mixing and (2) the runs were all restricted to only one home which may or may not be representative of the product.

METHODS OF MEASUREMENT

The techniques used for the study of infiltration in buildings can be summarized to be primarily as follows (2):

1. Tracer Techniques

   a. The transfer index technique
   b. Equilibrium concentration method
   c. Rate of decay method

2. Model Techniques

   a. Full size replicas
   b. Scale Models
   c. Analogue models

Tracer Techniques

In the tracer technique, a tracer is released in the room in which the amount of infiltration is going to be determined. The tracer concentration is then measured over a convenient time interval, and from its change the infiltration is determined. Gases are usually used as a tracer, but particulates and aerosols have also been used.

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The Transfer Index Method. The transfer index method does not depend on assumptions about mixing. It yields a set of transfer indices between points showing the amount of air movement between them, from which it is possible to infer effective ventilation rates. The amount of information which may be produced about the detailed movement of air is large, but correspondingly, so is the effort involved.

The transfer index or the index of exposure to contamination is the integrated concentration of tracer found at one point following the liberation of unit quanitty of tracer at another (3).

If V = the volume of the room;

$\dot{V}$ = the rate of supply of ventilating air (infiltration)

q = the quantity of tracer liberated

q' = the rate of liberation of tracer

c = the concentration of tracer at the sampling point at time t

$\bar{c}$ = the mean equilibrium concentration of tracer at the sampling point when tracer is continuously liberated

T = the transfer index as defined above

Then the infiltration rate $I = \dot{V}/V$ (1)

and

$$T = \frac{1}{q}\int_0^{\infty} c\,dt = \frac{\bar{c}}{q'}, \qquad (2)$$

If mixing in the room is complete at all times then

$$c = c_o e^{-It} = (q/V)e^{-It}$$

and

$$T = \frac{1}{q}\int_0^{\infty} c\,dt = \frac{1}{V}\int_0^{\infty} e^{-It}\,dt = \frac{1}{VI} = \frac{1}{\dot{V}}$$

or, for continuous emission of the tracer

$$\dot{V}\bar{c} = q' \qquad (3)$$

and

$$T = \frac{\bar{c}}{q'} = \frac{1}{\dot{V}} = \frac{1}{VI} \qquad (4)$$

The index found is a function of position of the emittance point and the sampling point. The reciprocal of the transfer index has the dimensions of infiltration rate.

With equilibrium conditions, even without perfect mixing, the equilibrium concentration at a point divided by the rate of emission of tracer is the same as the transfer index from the point of emission to the point of measurement.

During an experiemnt, the concentration integral can be measured directly by an accumulative detector from a sample drawn continuously at a uniform rate throughout the test. When the concentration declines slowly, a long sampling time is required to reduce cut-off errors.

The advantage of the method is that it does not require complete mixing. On the other hand many measurement positions are needed to determine the infiltration in one room, and longtime determinations of concentrations are required.

Measurements of infiltration using the transfer index method are included in the listed references.

Equilibrium Concentration Method. The equilibrium concentration method consists of injecting a tracer gas continuously at a uniform rate; the concentration at any point in the room will approach an equilibrium valve if conditions are steady. With perfect mixing, this equilibrium would be the same at all points. The infiltration can be calculated knowing the rate of gas injection and the equilibrium concentration. If mixing is not perfect, the concentration is proportional to the transfer index from the point of emission to the measuring points.

The method is good because a single measurement is sufficient if perfect mixing occurs. However, a long time is usually needed before equilibrium is approached, which requires more tracer per test than other methods. Also, there are difficulties due to nonstatic conditions of weather and room concentration and problems ensuring a constant rate of gas emission.

Rate of Decay Method. Among the tracer techniques, the rate of decay method requires relatively little time and equipment and gives a single result which is an estimate of the rate of change of air in the enclosure, assuming perfect mixing. The air change rate of an enclosure is usually defined as the hourly rate at which the air enters (or leaves) the enclosure to the volume of the enclosure.

The conservation of species g (tracer) in the room can be stated as follows:

$$\frac{dm_g}{dt} = \frac{\partial}{\partial t} \int_{cv} \rho c \, d\forall + \int_{cs} \rho c \, \bar{V} . \, d\bar{A} \qquad (5)$$

where

m_g = mass of tracer gas

ρ = density of the air gas mixture

ρ_g = density of the tracer gas

c = $\frac{\rho_g}{\rho}$

V = velocity of the mixture crossing the boundaries

$\forall$ = volume of the enclosure

t = time

$\bar{A}$ = surface area of the enclosure

If there is not net production of tracer gas by chemical reaction, Eq 5 becomes

$$0 = \frac{\partial}{\partial t} \int_{cv} \rho c \, d\forall + \int_{cs} \rho c \, \bar{V} \cdot d\bar{A} \qquad (6)$$

The second right-hand term represents the net flow of tracer gas through the boundaries. This includes molar and molecular flow.

Assuming that the gas concentration is uniform inside and outside the control volume (well mixed) and that the densities are constant and steady state conditions apply, Eq 6 becomes:

$$0 = \frac{\partial}{\partial t} (\rho c \forall) + \rho c \dot{\forall} - \rho' c' \dot{\forall}' \qquad (7)$$

where $\dot{\forall}$ volume rate at which the mixture is leaving the room

$\dot{\forall}'$ volume rate at which the mixture is entering the room

ρ' mixture density outside the room

c' gas concentration outside the room

When c' is zero Eq 7 becomes:

$$0 = \forall \frac{\partial}{\partial t} c + \rho c \dot{\forall}$$

or

$$\frac{\partial}{\partial t} c = - \frac{\dot{\forall}}{\forall} c \qquad (8)$$

When $c = c_o$ at $t = o$ the solution of Eq 8 is as follows:

$$c = c_o e^{-\dot{\forall} t/\forall}$$

$$\dot{\forall} t/\forall = \text{Ln} \ (c_o/c) \qquad (9)$$

Eq 9 shows that the number of air changes occurring during time t is equal to the natural logarithm of the ratio of the tracer-gas concentrations at the beginning and at the end of this time interval. The simplified Eq 9 has given good experimental results (4), but in order to use the equation the assumption have to be remembered. Well-mixed air is not always easy to get. This is sometimes done by fans placed within the building. Unfortunately the fans used to accomplish this requirement can affect the amount of infiltration. Diffusion through the walls is in most of the cases considered small, but Howard (5) showed differences in the rate of decay of gas concentration using hydrogen and and nitrous oxide. With impermeable walls the results were identical for the two gases. Moreover, the fact that infiltration exists with zero wind velocity and no temperature difference (between the inside and outside (6) could also be partially explained if diffusion was important. Other points to take in consideration are the absorption of gas by the walls, the chemical reaction of the tracer gas, condensation, solution, filtering, etc.

The main advantage of the rate of decay technique is that the method and the analysis of results are relatively simple and the period over which measurements have to be taken is not long (in the order of minutes).

Some of the difficulties, however, are the possibility of losses of tracer by condensation, settling or other means; the recirculation via cupboards and adjoining rooms; and the incomplete mixing in the absence of sufficient turbulence and/or thermally induced currents.

Model Techniques

Model techniques for determining the ventilation of a room or system of rooms are useful for the determination of basic relations between exterior-interior conditions and characteristics of the enclosure. The main problem with scale models is that some of the physical phenomena can be affected by the change of scale. Airflow and heat transfer can be affected by inevitable variation of the relative magnitudes of buoyancy, inertia and viscous forces, heat flow by radiation convection and conduction.

Wind-induced ventilation has been modeled in wind tunnels and valuable information has been obtained (7). No full scale comparison from the scale model predictions has been made.

Thermally induced ventilation is more complicated to achieve because different processes obey different scaling laws. According to Jakob, there are twelve dimensionless ratios which must be preserved.

Analogue models for mechanical ventilation via ducts have been electrically simulated. In the last years computerized analog models for predicting natural ventilation have been developed (7, 8, 9, 10 and 11).

Test Mobile Home. The mobile home used in this study is a 12 x 62 two-bedroom home (Fig. 1). It was obtained directly from a manufacturer without any special construction or assembly precautions. The air conditioner was a conventional external unit. The flexible duct work was installed as per instructions supplied to the home owner. The air return was through the sub-flooring cavity. Although spot checks were made for unusual gaps or holes, there was no thorough inspection (nor sealing) made.

The air volume of the mobile home was of approximately 5620 ft^3 ($159m^3$) living area and of 550 ft^3 ($15m^3$) in the sub-floor cavity. The windows were equipped with storm windows.

Test Procedure. The scheme employed for measurement of infiltration was the rate of decay method. CO was used as a tracer after injecting it at floor level on the west side of the mobile home, through the living room window. Three small fans were used within the home to mix the tracer (Fig. 2). The sampler used was a MSA Portable Co. indicator, Model D measuring ppm of CO with an accuracy of ± 1% F-S. and a reproducibility of ± 5% of reading.

Samples were extracted from six holes on the east wall. Three of these about 10 in. above floor level (through existing electrical outlets) and the three remaining holes near ceiling level and above the first set of holes (Fig. 2). The holes were sealed except for times during which the sampling tube was inserted through them.

In all runs the outside weather conditions and inside temperature were recorded. In some instances the furnace fan was on, whereas in others the air-conditioner blower was on. The various test results are documented in the following section.

Test results. March 7, 1974 (Run A). For this particular run, the temperature difference between inside and outside was less than 5F (3C) during the measurements T_i = 75F (24C)), and the wind speed was under 2 mph (3 km/hr). The gas was injected through the duct system at the outlet of the A.C. unit. Measurements were taken between noon and 3 P.M. on March 7. All six holes were used for sampling. Plugs were placed in them after each measurement. As indicated, three fans were used and relocated to mix the air within the room. Table 1 tabulates the results after an initial injection of CO.

TABLE 1

Time From First Injection (min)	Station	PPM
0^+ (shortly after)	1	500^+
3	2	500^+
6	3	455
10	4	390
15	5	310
20	6	245
25	1	205
27.5	4	190
30	2	170
32.75	5	160
35	3	135
37.5	6	130
40	1	115
42.5	4	105
45	2	95
47.5	5	90
50	3	80
52.5	6	70

An additional 0.150 lbm (68g) of CO was then injected, with the valve supplying the CO being closed 62.5 min after the beginning of the first run. The following resulted.

TABLE 2

Time After Second Injection (min)	Station	PPM	Time After Second Injection (min)	Station	PPM
0	2	425	27.5	3	220
0.5	2	450	30.5	1	170
1	2	470	32.5	4	185
1.5	2	465	34.5	2	205
5.5	1	360	36.6	5	210
7.5	2	335	38.6	3	205
9.5	3	310	40.5	6	205
11.5	1	290	43.5	1	165
13.5	2	260	45.5	4	170
15.5	3	245	45.5	Blower turned on	
15.5	Blower turned off		47.5	2	175
17.5	1	230	49.5	5	160
19.5	2	225	51.5	3	150
21.5	3	225	53.5	6	140
23.5	1	205	55.5	1	130
25.5	2	210	57.5	4	120

Table 2 (cont.)

Time After Second Injection (min)	Station	PPM
59.5	2	110
61.5	3	100
63.5	6	95

The results of Table are shown in Fig. 3. The slope implies on infiltration rate of 2.4 changes per hour and shows a surprisingly consistent trend.

It must be underscored that the measurements were taken while the blower was on. The leaks between the sub-flooring and the outside are hence included.

Fig. 4 presents data of Table 2. The concentration history as the blower is on, then turned off for 30 min and finally on again is now noted. The data when the blower is off is indeed scattered; this is due to lack of mixing of the tracer. However, the decrease in concentration during the time the blower is off should correspond to the infiltration in the home, excluding the leaks from the air conditioner and the return air through the sub-floor cavity and to the exterior of the mobile home. The return air circulates through a sub-floor cavity below the floor boards and above the insulation. The insulation is supported by a hard board sheet material. The space between the insulation and the floor, supported by the floor joists, is of about 5 in. (12.7 cm). Fig. 4 suggests that the infiltration when the blower is on is of 2.3 changes per hour (in agreement with Fig. 3), whereas with the blower off it reduces to about 0.6 changes per hours. This latter amount agrees with what would be expected for a home without outside wind.

Test Results: November 30, 1974 (Run B). The run was in essence a repeat of the March 7 test, except that the outside and inside temperatures were both 33F (0.5C), and the wind ranged from 10 to 20 mph (15 to 30 km/hr) from the ESE. The results (again with the A.C. fan on) are presented in Fig. 5. They are essentially in agreement with the previous results.

Test Results: November 30, 1974 (Runs C,D,E). Runs, C, D and E were conducted limiting the sampling through only one sampling hole (#2 for C and D and #5 for E). The temperature difference was essentially zero with an outside temperature between 40 and 41F (4 and 5C). For all three cases wind velocity was under 1 mph (1.6 km/hr) and except for the last 10 min of run C, the air-conditioner blower was left on. The results are plotted in Fig. 6, 7 and 8. The value of $\frac{\dot{V}}{V}$ (= I) when the blower was off (Run C) more or less agrees with that obtained during Run A. It must be noted that in Run A, samples were taken at all sampling holes, whereas the data of Run C was limited to #2. As a matter of fact, the slope of Run C does not lie to far from the spread in Run A, obviously due to incomplete mixing.

Test Results: December 17, 1974 (Run F). All supply and return air ducts connecting the sub-flooring and the living area were purposely sealed off. With part of the supply duct work removed, the air was forced to curculate solely within the sub-flooring. With the air-conditioner blower on all the time and with sampling done at the supply duct, the data of Fig. 9 were obtained. The initial infiltration rate was of 12.3 changes per hour. The ultimate decrease is attributed to CO having leaked and accumulated in the living area.

Test Results: December 14, 1974 (Run G). Run G was essentially the same as Run F except that CO was first introduced (at a high concentration) in the living area. The data, plotted in Fig. 10, shows a decreasing infiltration rate (for the sub-flooring only), indicating that a considerable part of the CO-rich air in the living area returns into the sub-flooring. The conclusions of Runs F and G are somewhat tenuous; they simply indicate the existence of considerable leaks between the sub-flooring and the living area of the mobile home.

Test Results: April 1975 (Runs H-O). This set of runs was taken in order to determine the temperature dependence of the infiltration rate. As before, three mixing fans were used to mix the tracer gas. However, in order to simulate winter-time conditions, the air conditioner was blocked off and the furnace operated instead. Obviously, at the time of injection of CO, the gas supply to the furnace was completely shut off. During the runs the outside temperature ranged from 37 to 32F (2 and 0C) while the wind speed was always less than 5 mph (8 km/hr). The results are tabulated on Table 3. As an example, Run K, is plotted on Fig. 11.

TABLE 3

Run	ΔT	U	A/C Blower	Furnace Blower	I(ch/hour)
A	<5°F	<2mph	On	Off	2.3
A	<5°F	<2mph	Off	Off	0.57-0.84
B	0	10-20mph	On	Off	2.54
C	0	<1mph	On	Off	2.68
C	0	<1mph	Off	Off	0.83-1.3
D	0	<1mph	On	Off	2.69
E	0	<1mph	On	Off	2.65
F			On	Off*	12.3
G			On	Off**	3.6 to 1.9
H	58-57	~2mph	Off	On	1.66
I	52-50	~1mph	Off	On	1.69
J	44-43	~0	Off	On	1.64
K	39-37	~0	Off	On	1.45
L	25-22	~0	Off	On	1.27
M	20-18	~0	Off	On	0.83
N	0	~0	Off	On	1.18
O	0	~0	Off	On	1.39

Note: X F = (X - 32)1.8°C

1mph = 1.6 km/hr

* Subflooring only (no CO injected in living area).

** Subflooring only (and CO injected in living area).

CONCLUSIONS

The infiltration rates in the mobile home depend primarily on whether or not the blowers for air conditioning or heating are turned on.

Without either of the blowers in operation, the infiltration rate is in the order of 0.8 (for negligible wind and no temperature difference between the inside and outside).

When the furnace blower is on, the infiltration rate increases to values between 1.2 and 1.7 air changes per hour. This is attributed to leakages in the sub-flooring adding to the infiltration in the living area. The net infiltration has a dependence on the temperature difference between the indoors and outdoors. This dependence, noted in Fig. 12, indicates that the infiltration rate, (with the furnace blower on) varies with temperature differences by a relationship given (within 30% accuracy) as:

$$I \doteq 1.1 + 0.011\ \Delta T\ (\pm 30);\ \Delta T \text{ in F}$$

$$(I \doteq 1.1 + 0.0198\ \Delta T;\ \Delta T \text{ in C})$$

These results are to be compared with measurements by Hunt and Busch [12] where they found

$$I = 0.117 + 0.0108\ \Delta T$$

$$(I = 0.117 + 0.0194\ \Delta T;\ \Delta T \text{ in C})$$

for a four-bedroom townhouse. The now measured values, although one order of magnitude larger, do in effect show a surprisingly similar value for the change in infiltration rate with temperature difference. The similarity of these may be purely coincidental. The coefficient of thermal expansion for air at 65F (18OC) is of about $0.0018°R^{-1}$ $(0.0034°K^{-1})$, and does not seem to relate to the above noted slopes of $0.011°R^{-1}$ $(0.0198°K^{-1})$.

The net infiltration rate is highest when the air-conditioner blower is on. (Although the air conditioner is not designed tc provide make-up air there obviously are leaks in the ductwork and joints.) Essentially the same value (2.3 to 2.7 changes per hour) was noted for runs in which the wind velocity was substantial 10 to 20 mph (15 to 30 km/hr) and tests when the wind was negligible.

There has to be some effect, however, inasmuch as the wind velocity will affect the pressure drop across the cracks causing the infiltration. As a matter of fact, measurements of Tamura et al.(13) referred to in Ref. 14, suggested an increase of I at a rate of 0.017 to 0.020 per mph increase (up to 8 mph). It must be noted, however, that in that case the infiltration rates were in the order of 0.2 to 0.6, much lower than the values now noted.

The infiltration rate for the sub-flooring and air conditioner isolated from the living area was measured as 12.3 changes/hour. This was for the particular case when the living area had no tracer gas in it.) The sub-flooring has a volume of approximately 550 ft^3 ($15m^3$), whereas the living area's volume is of about 5620 ft^3 ($159m^3$). An infiltration rate of 12.3 for the sub-flooring and 0.8 for the living area would only account for a net infiltration rate of 1.8, somewhat lower than the measured 2.3 to 2.7.

It is quite obvious that for this particular mobile home infiltration rates much higher than those for stick-built homes are noted. Furthermore these values do in effect depend on whether or not the air is forced to circulate through the air ducts and whether or not the air is forced to circulate through the air ducts and whether or not the air conditioner is in operation.

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ACKNOWLEDGEMENTS

The initial phases of this work were conducted under the sponsorship of Lear Siegler, Inc. Later phases were partially sponsored by NBS through a DOC contract No. 5-35808. The authors also acknowledge the assistance of Mr. Jim Powell in some of the data taking, and the valuable help of Cesar Sanchez in various aspects of the work.

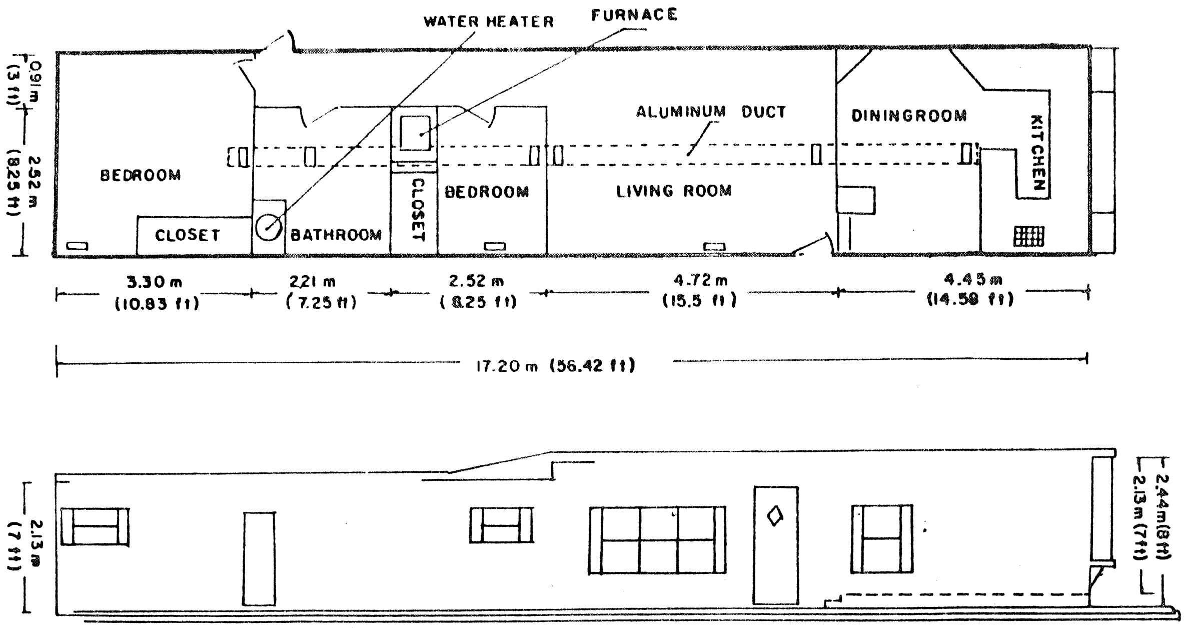
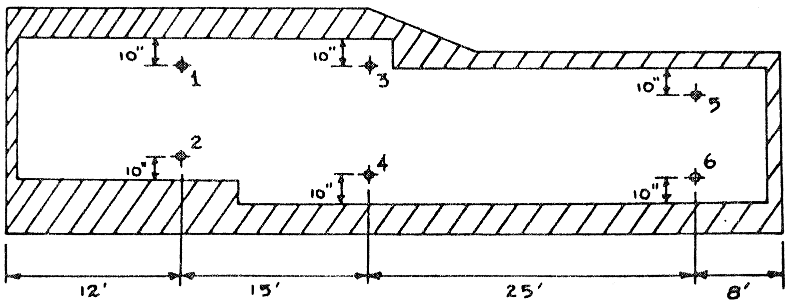


Fig. 1 Mobile home floor plan

Situation of the Holes (1/2")



Air Distribution

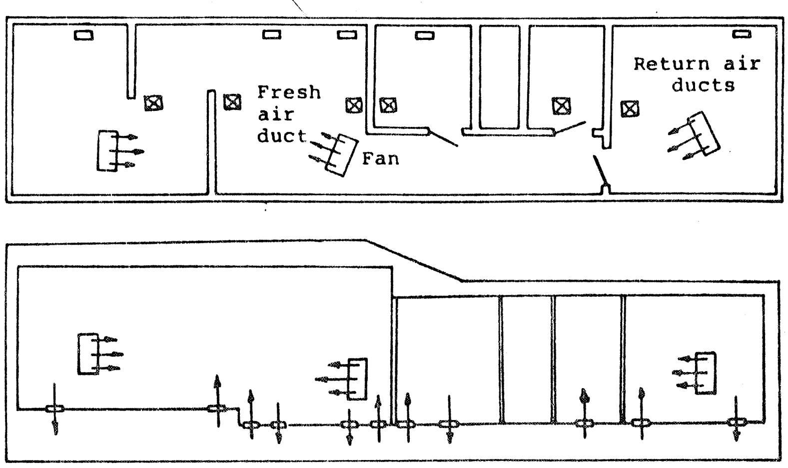


Fig. 2 Location of sampling holes

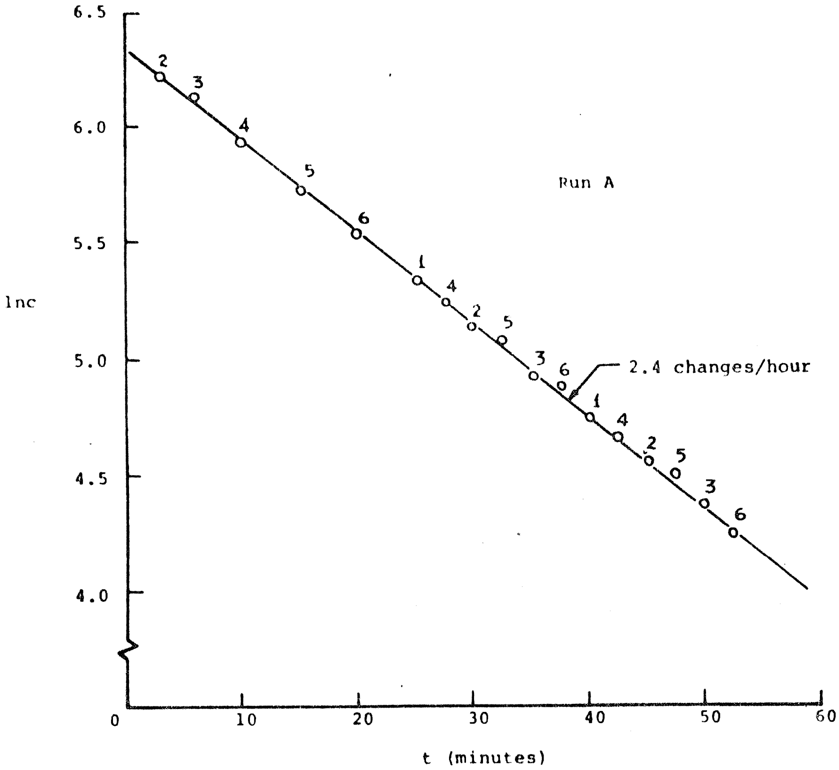


Fig. 3 lnc vs t (Table 1)

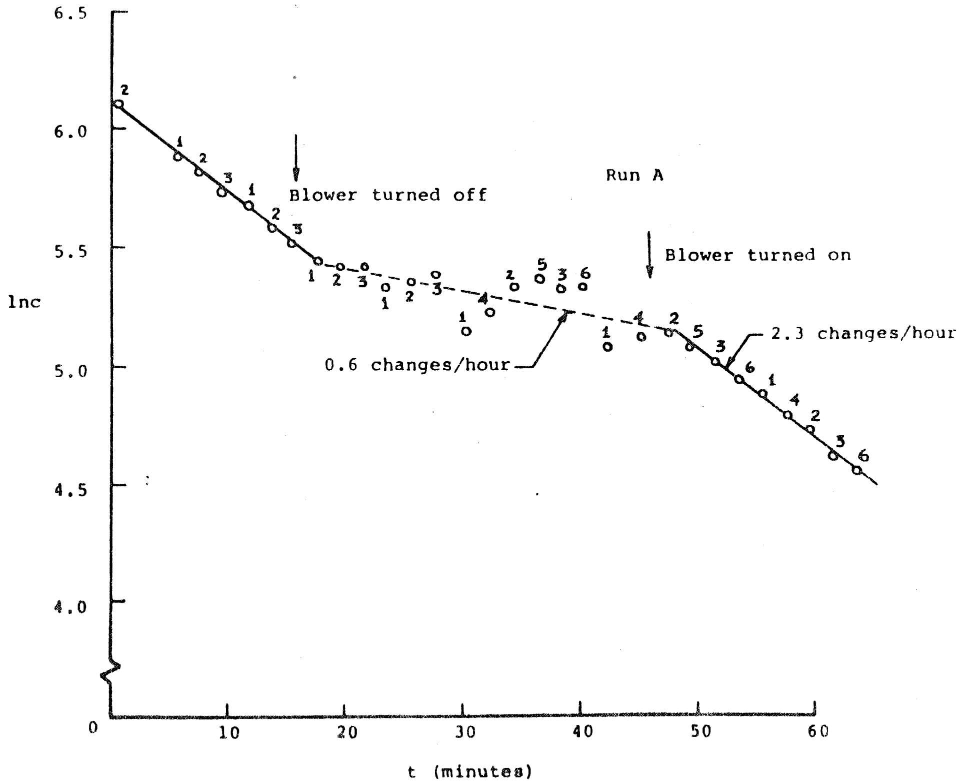


Fig. 4 lnc vs t (Table 2)

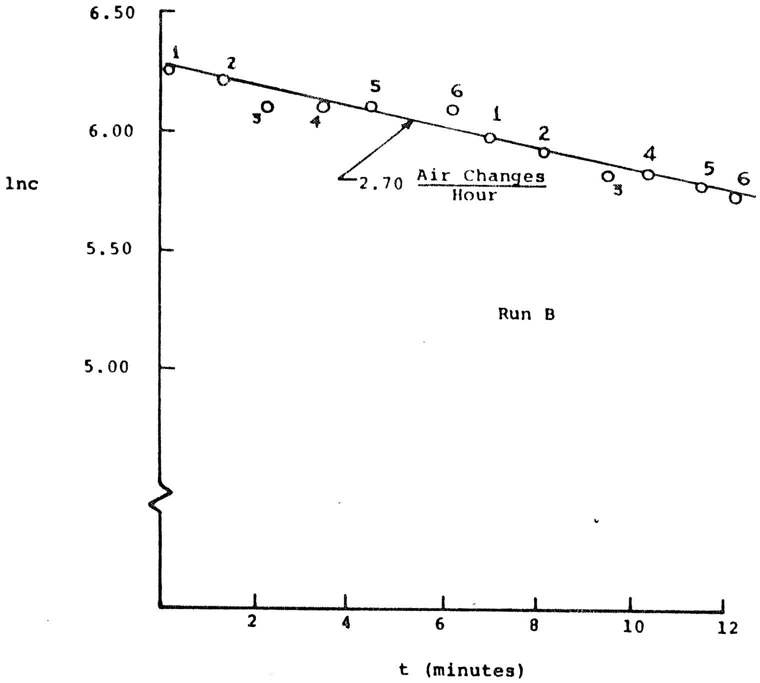


Fig. 5 lnc vs t

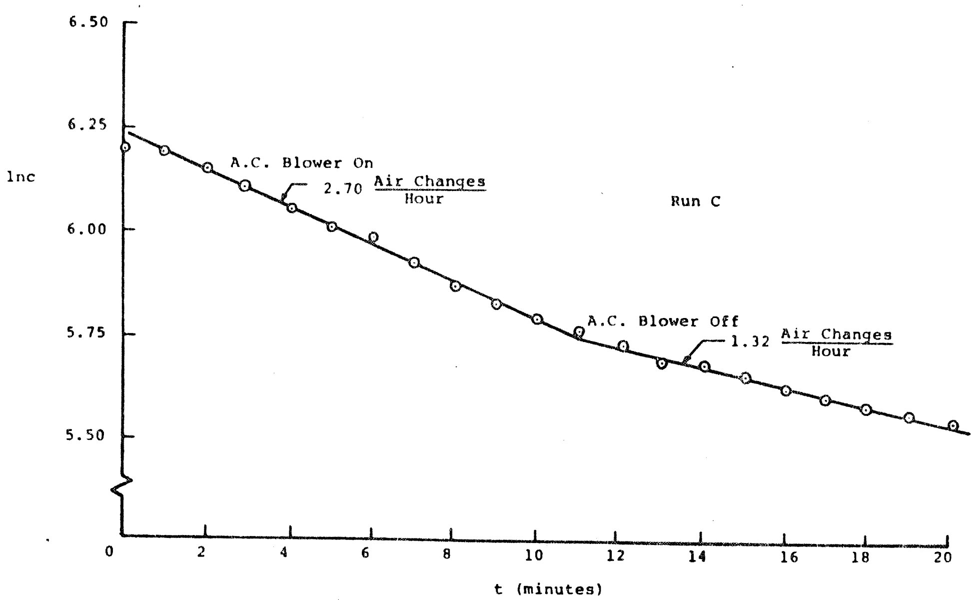


Fig. 6 lnc vs t

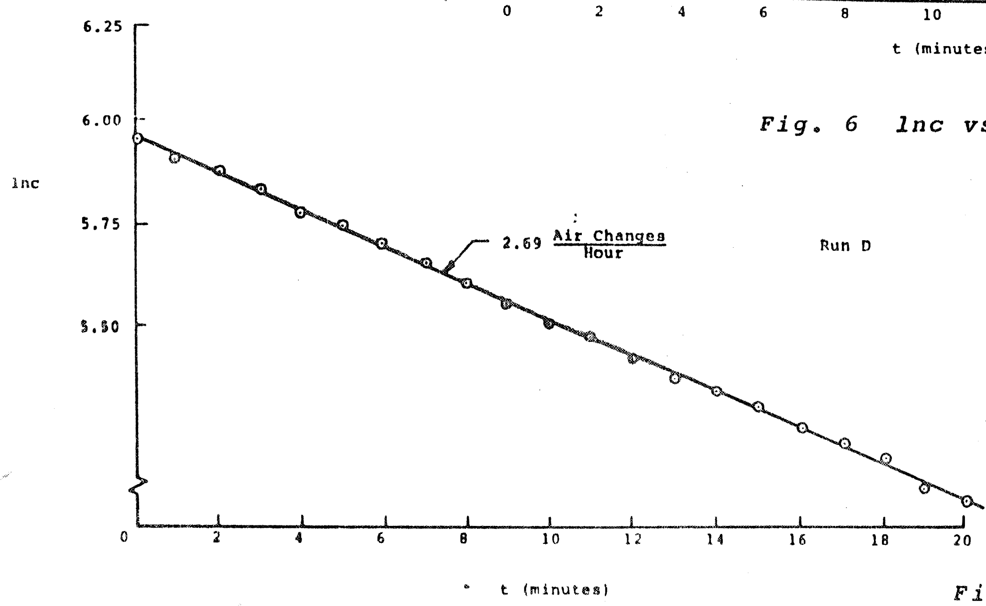


Fig. 7 lnc vs t

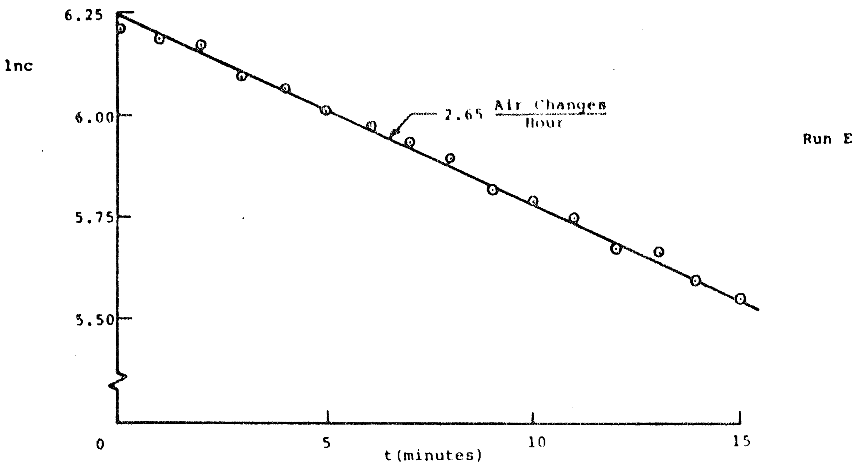


Fig. 8 lnc vs t

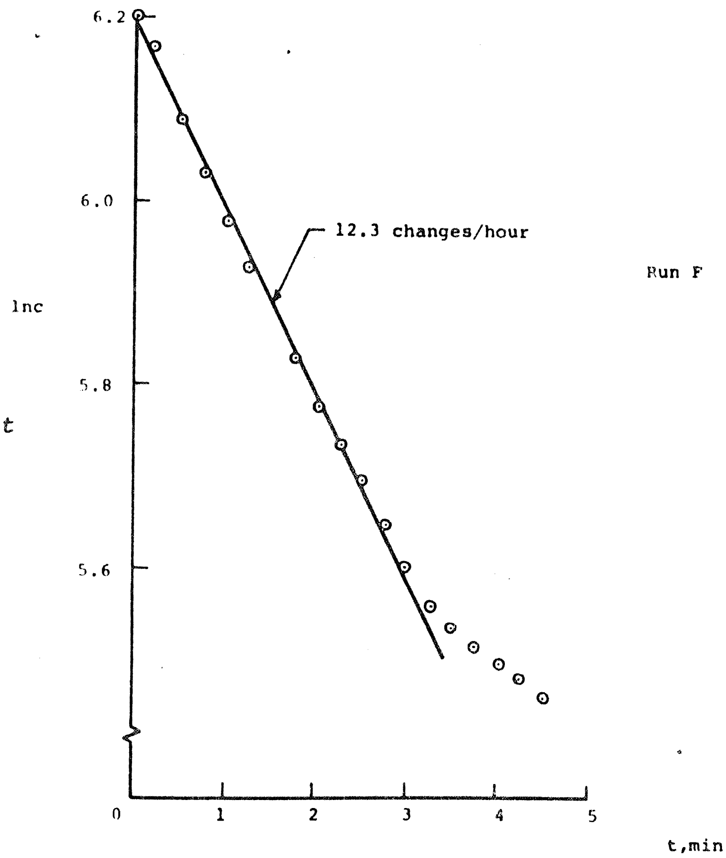


Fig. 9 lnc vs t

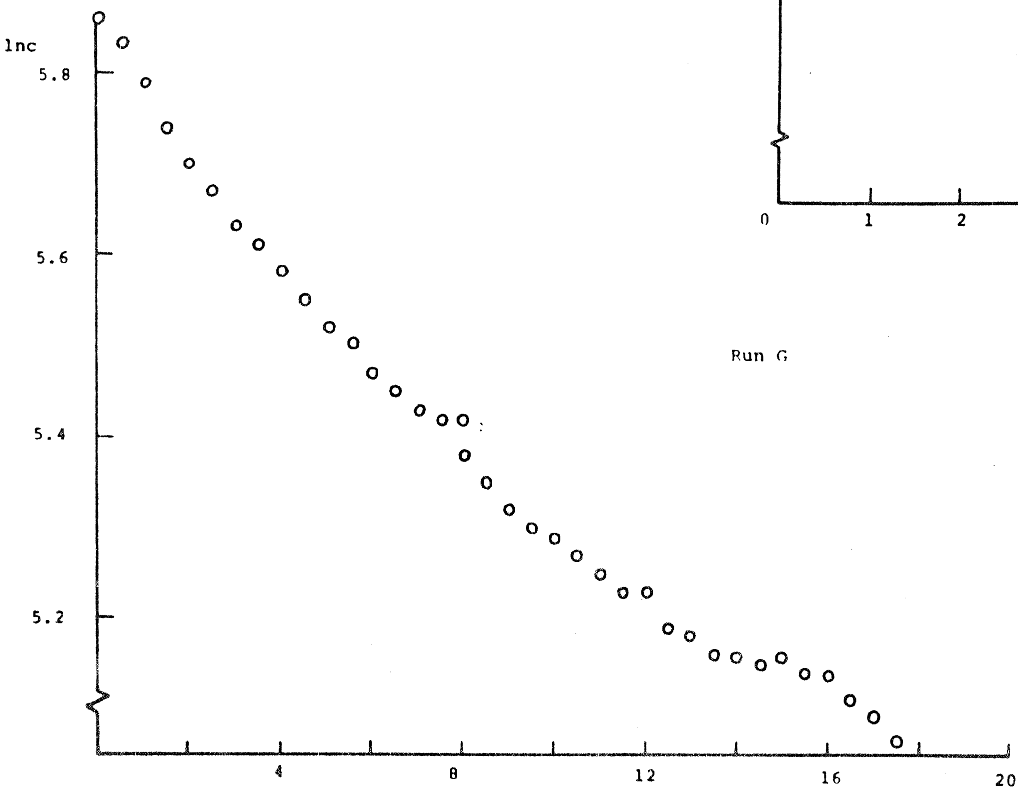


Fig. 10 lnc vs t

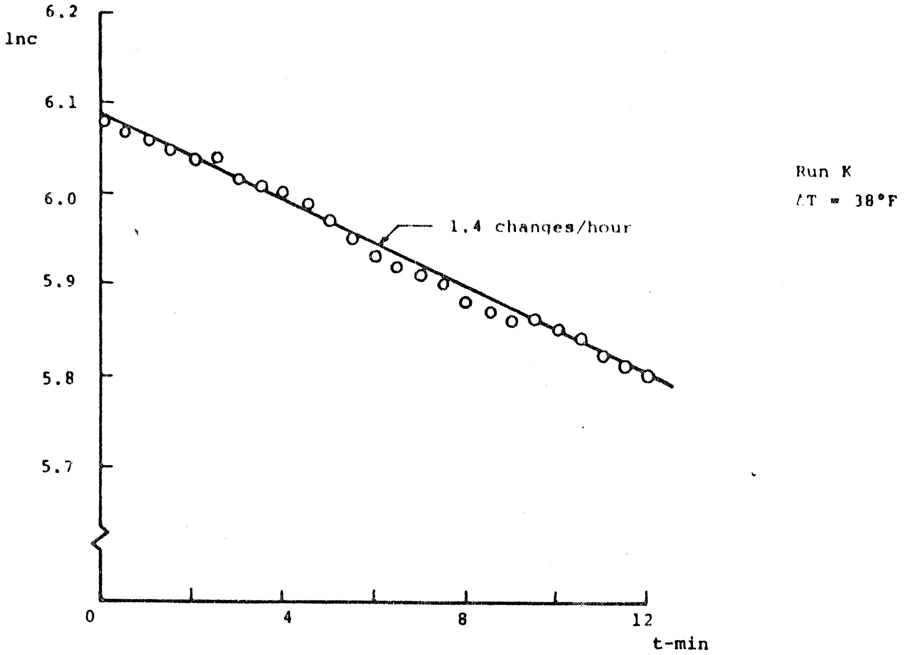


Fig. 11 lnc vs t

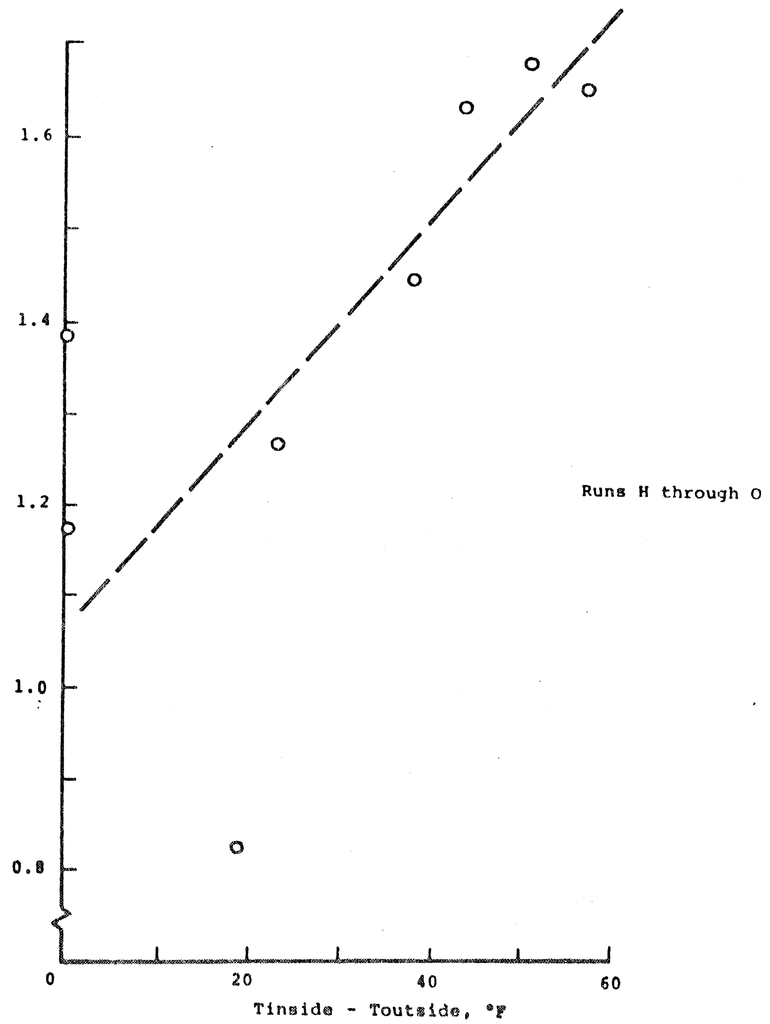


Fig. 12 Infiltration vs temperature difference

DISCUSSION

PAUL W. CURINGTON (Texas Power & Light Co., Dallas, TX): How few air changes per hour should one seek in a mobile home? Will the answer also hold true for conventional residences?

PAUL STRICKER (Ontario Hydro, Toronto, Ont.): What is the desirable rate of infiltration required in a mobile home?

VICTOR GOLDSCHMIDT: Certainly less than 2 changes per hour. I don't have the final value recommended in the current NFPA 501B/ANSI A119.1. However, an earlier draft calls for infiltration heat losses in the order of 0.7BTU/hr x ft of perimeter x ΔT. In our case this would correspond to something less than 1.2 air changes per hour. I expect that the corresponding values of infiltration in conventional residences would be lower.

JAMES E. PIPER (Piper Hydro Inc., Anaheim, CA): Do you plan to do similar work on other structures in the future?

GOLDSCHMIDT: We have no immediate plans to do so.

T.E. WERKEMA (Dow Chemical Co., Midland, MI): What is your observation on the efficacy of CO measuring techinques?

GOLDSCHMIDT: We were extremely pleased with CO as a tracer for infiltration measurements. It has three points to its favor: it's practically neutrally buoyant in air, the background concentration is negligible, and the sampling instrumentation is economical. Its toxicity, however, is a strong disadvantage and has now led us to use SF_6 as a tracer.