1832

AIC

85-30B.7

RELATION BETWEEN INDOOR AIR FORMALDEHYDE CONCENTRATIONS AND VENTILATION RATES FOR A GROUP OF SIXTEEN NEW HOUSES

D. A. FIGLEY

NATIONAL RESEARCH COUNCIL OF CANADA
OTTAWA, ONTARIO, CANADA

For Presentation at the 78th Annual Meeting of the
Air Pollution Control Association
Detroit, Michigan June 16-21, 1985

Introduction

One of the major problems in ventilation system design is the determination of the minimum outdoor air flow rate required to ensure acceptable air quality. To accurately assess the required amount of ventilation air, the system designer must be able to identify the type and strength of pollutant sources.

Formaldehyde gas is of particular concern in houses, since building materials, furnishings and occupant activities can be significant sources.

Two basic methods can be used for determining the net formaldehyde source strength in a house. The first method (analytical) would look at the contribution from the individual components and attempt to predict a cumulative effect. Ultimately, this is the ideal solution, since it allows the building designer to "tune" the system for optimal performance. Unfortunately, accurate data for material dynamics are rare and this approach is therefore restricted. The second method (experimental) is to construct buildings using various combinations of materials and measure the corresponding net source strength. While this approach is limited by the number of combinations possible, most housing can be characterized by a few basic types, which would define the range of typical construction.

One procedure for experimentally determining the net formaldehyde source strength relationship for a house involves operating the house at various ventilation rates and measuring the corresponding formaldehyde concentrations. Unfortunately, occupied houses pose special problems for this type of measurement. The time required to make formaldehyde dosimeter measurements, adjust ventilation rates and stabilize formaldehyde concentrations can cause disruptions in households which many homeowners will not accept. Further, variations in the formaldehyde release rate with temperature and humidity can confuse the analysis.

As an alternative, it may be possible to examine a group of similar houses and take a single measurement of the ventilation rate and formaldehyde level in each house. These data could then be analysed as if they were taken from one "average" house with variations in the ventilation rate. It is recognized that individual house variations will cause additional scatter in the data; however, this scatter will define the range of results that should be expected in field situations.

This study examines the experimental determination of the apparent net formaldehyde source strength in a group of sixteen nominally identical houses built by one contractor using similar construction details and materials. The houses were very well sealed compared with conventional houses. Pressure test results show a mean induced air leakage rate of 0.23 ach at 50 Pa, with a standard deviation of 0.09 ach. All of the houses had air-to-air heat exchangers, which were operated at various flow rates.

The seven-day average formaldehyde levels were measured and were correlated to ventilation rates (using simple steady-state models) to determine the apparent formaldehyde source strengths. The houses were divided into three groups:

1) unoccupied - houses completely finished but with no occupants or furnishings (4 houses);
2) occupied non-smoking - houses completely finished and occupied. No tobacco smoked in the houses (10 houses);
3) occupied smoking - houses completely finished and occupied. 10 - 25 cigarettes per day smoked in the houses (2 houses).

Description of the Houses

The houses were one- to two-year-old wood frame bungalows with full depth cast-in-place concrete basements. The main floor system consisted of wood floor joists covered with 15 mm exterior grade plywood subflooring topped with 9.5 mm particleboard underlay. The walls were double stud construction[1] with the 150 μm (6 mil) polyethylene film vapour barrier on the outside of the inner stud wall. Only glass fibre insulation was used in the walls and attics. All of the basements were insulated from the inside using wooden studs with glass fibre batts between the studs. The polyethylene film vapour barrier was continuous from the upper walls, over the header and downwards over the inside of the basement wall studs to the floor. The basement floors were bare concrete slabs.

Particleboard containing a urea formaldehyde resin was used in a number of locations in the houses:

1) 9.5 mm (3/8") underlay over the plywood subfloor,
2) shelving,
3) kitchen cupboards and vanities (most surfaces were vinyl-coated),
4) formica-topped kitchen counter,
5) various home furnishings.

Because it was difficult to quantify the amount of formaldehyde-bearing substances and the effect of coverings or sealants on the rate of formaldehyde release, only general observations were made. Except for personal furnishings, the amounts and distribution of formaldehyde sources (construction materials) appeared to be equal for all houses. All of the occupied (main) floor areas were covered with carpet or vinyl floor covering. For all of the houses, the main floor area ratio was approximately 70% carpet (including bedrooms) and 30% vinyl floor covering.

Electric baseboard heaters (convective) were used for space heating. No wood heaters or fireplaces were installed in the houses.

The mechanical air exchange and air distribution for each house was controlled by an air-to-air heat exchanger (ATAHE). Exhaust air from the house was collected from the kitchen and bathroom areas on the main floor and the supply air was ducted into the basement near an electric baseboard heater (Figure 1). Registers were installed through the floor in each room to allow passive air movement from the basement to the main floor. The exhaust and intake fans were interlocked, fixed-speed units with ON-OFF control from a humidistat on the main floor.

Testing Procedure

Elapsed time meters were connected to the ATAHE fan power supply and the mechanically-induced air flow was calculated by multiplying the running time by the air flow rate. In cases where the supply and exhaust air flows through the ATAHE were not balanced, the larger was used as the heat exchanger flow rate.

The airtightness of the houses was measured using the fan depressurization technique.[2] Shaw's method was used to estimate the average air infiltration from the fan test data.[3] Local weather station data were used to calculate the average wind speed and outdoor temperature.

The total air exchange was calculated as the sum of the mechanical ventilation rate plus one-half of the infiltration rate. Since the infiltration rates are very small (< 0.05 ach), the error associated with this approximation is negligible.

Dupont C-60 formaldehyde dosimeters were used to measure the seven-day average formaldehyde concentration in the houses. Two active dosimeters were placed upstairs, one in the living room and one in a bedroom. An unexposed dosimeter was left in the bedroom as a control. The measurements were taken between January 5 and 12, 1984. During this period the average outdoor temperature was -18°C.

An aspirating psychrometer was used to estimate the temperature and relative humidity at each dosimeter location. Since the control settings for the temperature and humidity were not adjusted during the testing, only a single primary measurement was taken to establish the actual control points.

The unoccupied houses were normally maintained at a set-back temperature to conserve energy. The first set of formaldehyde readings were taken with the house "as is" (Test 1). After the first set of dosimeters were removed, the house temperatures were increased to normal occupied room temperature and five days later, a second set of dosimeters were installed (Test 2).

Results

Basic house data, test conditions and results are summarized in Table I.

The flow coefficient and the flow exponent derived from the fan depressurization test were used to estimate the natural infiltration, (V_I) using Shaw's expression:[3]

$$V_I = 0.32C\Delta T^n/V \quad \text{(wind speed, < 3.5 m/s)} \tag{1}$$

where

V_I = natural air change rate (ach)
C = flow coefficient (L/s Pa^n)

ΔT = indoor-outdoor temperature difference (K)
n = flow exponent
V = house volume (m^3).

The values for V_I are listed in Table I.

The average mechanical ventilation rates (V_M) were calculated based on steady-state flow velocities measured by a heated probe anemometer traverse. The total air flow was divided by the total elapsed time to get an average air change rate:

$$V_M = 3.6\ V_a T_e/(T_t V) \tag{2}$$

where

V_M = time averaged air flow rate (ach)
V_a = heat exchanger flow rate (L/s)
T_e = heat exchanger fan running time (h)
T_t = total time of test period (h).

The total ventilation rate, V_T, (ach) was calculated as:

$$V_T = V_M + 0.5V_I \tag{3}$$

A generalized mass balance model for a one-compartment system (Figure 2) could be writtten as:

$$V\ dC_i/dt = kVV_T(C_o-C_i) + S - E \tag{4}$$

where

C_i = average pollutant concentration in the house ($\mu g/m^3$)
t = time (h)
k = mixing factor (k=1 perfect mixing)
C_o = concentration of pollutant in the ventilation supply air ($\mu g/m^3$)
S = source term ($\mu g/h$)
E = sink term ($\mu g/h$).

S represents the summation of all of the formaldehyde sources in the compartment. For building materials, S is a complex function of the material age and type, temperature, humidity and indoor formaldehyde concentration.[4,5] A variety of inputs from smoking, cleaning and other occupancy-related activities, can be difficult (usually impossible) to model mathematically.

Since formaldehyde is a reactive chemical, its removal (E) depends upon many factors including the materials in the space, temperature, humidity and occupancy patterns. Traynor[6] has indirectly measured the reactivity for one set of conditions, but accurate data for most situations are not available.

In a field study of this type, it is very difficult to describe the parameters governing S and E accurately enough to make valid estimations. An alternate approach is to assume that for a given group of houses, a net pollutant source rate ($\hat{N}$) can be identified, which represents the net cumulative effect of all of the internal sources and sinks.

This assumption leads to a reduction of Equation (4), where the steady-state pollutant concentration (assuming well mixed air within the space) would be related to the air flow rate, the outside pollutant concentration and the net pollutant emmission rate, by the expression:

$$C_i = C_o + \dot{N}/V_T V \tag{5}$$

where

$\dot{N}$ = net pollutant emmission rate (μg/h).

For houses, the occupied floor area may be a better indicator of formaldehyde source strength than the volume. Multi-storey houses usually have a higher amount of particleboard area per unit volume than single storey houses, since more of the floor area is wood frame construction. Typically, occupied floors have a similar distribution of construction materials, floor coverings and furnishings, which are assumed to be the major building-related formaldehyde sources. For the single storey houses in this test, the basement walls were insulated and the vapour barrier was installed, but no additional construction or finishing was done.

If the relationship between source strength and main floor area is assumed to be linear (i.e. pollutant sources are distributed based on occupied floor area), an alternate expression can be developed:

$$C_i = C_o + 3600\ (\dot{N}_a A/V_T V) \tag{6}$$

where

$\dot{N}_a$ = net pollutant source strength per unit floor area (μg/s·m^2)
A = house floor area (m^2).

In this form, indoor formaldehyde concentration and ventilation rate data from similarly constructed and occupied houses of different sizes can be used to estimate the formaldehyde source strength and outdoor formaldehyde concentration. The air flow parameter (V_T) is used since many ventilation system designers refer to air change rates. An expression of the form of Equation (6) was fitted through the data for each house group.

Since the value V/3600A in Equation (6) is a constant for the houses, variations in C_i are caused by changes in the air change rate. The average formaldehyde concentration is plotted against $V_T V/3600A$ and V_T for the groups of houses in Figure 3.

For the four unoccupied houses (A,B,C,D) with low indoor temperatures (Test 1) a least squares curve fit of the form of Equation (6) yields:

$$C_i = 11 + 0.0088\ (3600A/V_T V) \tag{7}$$

with an index of determination of 0.62. The net formaldehyde source strength for the houses alone was 0.0088 μg/s·m^2. This rate was calculated with a group mean indoor temperature of 13°C.

Since temperature is known to have a strong effect on some chemical reaction rates, the unoccupied house temperatures (A,C and D) were increased (Test 2) to the same range as the occupied houses. The temperature in house B could not be adjusted for this test.

For a group average indoor temperature of 21°C, the data gave an increased net source strength according to the expression:

$$C_i = 11 + 0.029\ (3600A/V_TV) \tag{8}$$

with an index of determination of 0.94. These data are also shown on Figure 3. Since the range of air flow rates for Test 2 was restricted, the curve was forced through the value of the outdoor formaldehyde concentration calculated by Test 1.

Analysis of the data for the nine occupied houses with no smoking (F to N) and an average indoor temperature of 21°C, gives:

$$C_i = 26 + 0.036\ (3600A/V_TV) \tag{9}$$

The index of determination is 0.68. The cumulative net formaldehyde source strength of the building and the occupants was 0.036 $\mu g/s \cdot m^2$. The data from house E was not used in the curve fitting since the formaldehyde levels were significantly lower than for the group as a whole.

Houses P and Q were occupied by smokers and were considered separately.

The average relative humidity versus $V_TV/3600A$ and V_T for the houses is shown in Figure 4. A moisture source strength analysis similar to that done on the formaldehyde data yielded a weak correlation between humidity and ventilation rates for the unoccupied houses (index of determination = 0.28) and a very weak correlation for the occupied houses (index of determination = 0.19). For this analysis, houses with smokers and those without smokers were lumped together as occupied houses.

Discussion

At present, Canada does not have an air quality standard which outlines the maximum permissible pollutant concentrations in residences. ASHRAE[7] suggests a maximum formaldehyde level of 120 $\mu g/m^3$ (0.1 ppm) and although this level is the subject of some debate, it can be used as a baseline for comparison.

Of the nine occupied houses examined in this study, seven had formaldehyde levels below 120 $\mu g/m^3$. The two houses (I,N) that had marginally higher formaldehyde levels also had heat exchangers that were operating only one-third of the time.

The interrelationship between temperature, humidity and the formaldehyde release rate from building materials is complex and not well understood at the present time. Andersen[8] has developed an empirical relationship to predict formaldehyde source strengths for a limited range of temperature and humidity but this expression has been shown to predict excessively high values when compared to other studies.[5] Kuhn and Wanner[9] have shown that increasing the temperature or relative humidity will increase the steady-state formaldehyde concentration (hence the source strength) for a given air flow rate. Their results show that increasing the indoor air temperature from 20°C to 23°C will increase the steady-state formaldehyde concentration by approximately 15%. They also showed that increasing the indoor RH from 40% to 50% caused an increase in the steady-state formaldehyde concentration of approximately 35%. Kuhn and Wanner's results indicate that a ±25% scatter in the source strength data is to be expected, based on the variation in temperature and humidity within the house groups, and this is consistent with the observed results.

The increase in the indoor temperature of the unoccupied houses resulted in a corresponding lowering of the relative humidity, but little change in the absolute humidity of the air. Andersen's equation suggests that absolute humidity (not relative humidity) affects formaldehyde source strength, so the change in net source strength from Test 1 to Test 2 should be primarily related to temperature. Interpolation from Kuhn and Wanner's data for average temperatures of 13°C and 21°C suggests an increase in net source strength of approximately 3.7 times. The apparent net source strengths for the unoccupied houses increased from 0.0088 $\mu g/s \cdot m^2$ to 0.029 $\mu g/s \cdot m^2$, or 3.3 times.

A considerable amount of discussion has been raised regarding the use of building materials containing formaldehyde. Comparison of the data in Figure 2 shows that the apparent source strength for the occupied houses (0.036 $\mu g/s \cdot m^2$) is approximately 20% higher than for the unoccupied houses (0.029 $\mu g/s \cdot m^2$) at the same average indoor air temperature. This suggests that occupancy has some effect on indoor formaldehyde levels but that the building may be the major contributor.

The two houses with smokers showed elevated formaldehyde levels when compared with the non-smoking households, but not enough data were obtained to establish a relationship.

The predicted value of the supply air (outdoor air) concentration (C_o) is lower for the unoccupied houses than for the occupied houses. This discrepancy could be related to the location of the houses, since all of the unoccupied houses were located in a small, isolated town (C_o = 11 $\mu g/m^3$), while seven of the nine occupied houses were located in a large city (C_o = 26 $\mu g/m^3$). The formaldehyde dosimeters used for the study were not suitable for exposure in freezing conditions, so no field measurements of the ambient levels could be taken to substantiate the calculated values. These levels are consistent with the values in the UFFI manual,[10] which suggests ambient air formaldehyde concentrations of 24 $\mu g/m^3$ for houses in urban areas with high traffic and local industry and 12 $\mu g/m^3$ for houses in suburban areas with light traffic.

For the unoccupied houses, the average bedroom formaldehyde concentration was 10% higher than the living room levels for the set-back temperatures and 19% higher at normal room temperatures. For the occupied houses without smokers, the average bedroom level was 14% higher than the living room. Since the air-to-air heat exchanger systems did not have ducting to the bedrooms, lower air flow rates and higher pollutant levels would be expected in these areas. The high formaldehyde level in the bedroom of house G may be due to the very recent (within two months) acquisition of a complete bedroom suite constructed with veneer-faced particleboard.

Since temperature, transient storage, and occupancy effects influence moisture generation, a good correlation between humidity and air flow should not exist for occupied houses. The weak correlation of the data for the unoccupied houses indicates a non-uniform source strength.

In general, humidity does not appear to be a good indicator or basis of control for air quality control systems. Since many air-to-air heat exchanger systems use a humidistat as an ON/OFF or HIGH/LOW controller, it is important to establish an independent method of ensuring an adequate ventilation rate. In the case of single speed units, the flow rate should be set and no control provided; for multiple speed fans, the low speed setting should provide the necessary continuous flow and the humidistat can control the high speed operation.

For any of the houses in this study, the natural ventilation rate was inadequate for indoor air quality control. As Figure 3 indicates, a minimum air change rate of approximately 0.3 ach would be required to maintain the indoor formaldehyde concentration below 120 $\mu g/m^3$.

Conclusions

Although these houses represent a small sample, the type and quantity of construction materials are typical of many wood frame houses built in recent years. From these data, a number of generalizations can be drawn:

- The high levels of airtightness of these houses have reduced the infiltration to less than 5% of the air exchange rate required to maintain the indoor formaldehyde concentration below 120 $\mu g/m^3$. Continuously operated mechanical ventilation systems are necessary to provide adequate air exchange rates.

- In houses without air distribution systems, the air exchange system must circulate air through the entire house to prevent localized areas from having low ventilation and high pollutant concentrations.

- Humidity is not an acceptable mechanism of control for the ventilation system, since the moisture source strengths are variable.

- The design air flow rate should be chosen based on several factors, including occupancy and building type. The selection of building components that do not emit formaldehyde (reducing the source strength) can reduce the amount of ventilation required to control this pollutant. Since other indoor air pollutants may also be present, reduction of formaldehyde sources is not, in itself, a justification for reducing supply air quantities.

- Although temperature, humidity and concentration are extremely important factors in formaldehyde release and decay rates, a range of normal conditions exists. Within this range, similar houses can be grouped and an average net source strength calculated. Despite the wide range of field data, this method can give the mechanical system designer a useful basis for system selection and an appreciation of the variability of individual buildings.

An extensive study involving a larger number of houses with a variety of construction styles and types of formaldehyde-emitting sources would be necessary to define the range of conditions occurring in modern building stock.

Analysis is currently underway to utilize available source emissions and decay rates to re-examine this data set using a more general model.

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.

References

1. Alberta Energy and Natural Resources, Energy Efficient Housing--A Prairie Approach, Energy Conservation Branch, Edmonton (1982).

2. H.W. Orr and D.A. Figley, An Exhaust Fan Apparatus for Assessing the Air Leakage Characteristics of Houses, BR Note 156, Division of Building Research, National Research Council of Canada, Ottawa (1980).

3. C.Y. Shaw, "A correlation between air infiltration and air tightness for houses in a developed residential area" ASHRAE Transactions, **87**, Pt. 2, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta (1981).

4. T.G. Matthews, A.R. Hawthorne, C.R. Daffron, T.J. Reed and M.D. Corey, "Formaldehyde release from pressed-wood products", Proceedings 17th International Washington State University Particleboard/Composite Materials Symposium, Pullman, (1983).

5. R.A. Wadden and P.A. Scheff, Indoor Air Pollution - Characterization, Prediction and Control, John Wiley & Sons, New York (1983) pp. 64-67.

6. G.W. Traynor, D.W. Anthon and C.D. Hollowell, "Technique for determining pollutant emissions from a gas fired range", Atmospheric Environment, **16**, (12) 2979 (1982).

7. ASHRAE, Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE 62-1981, Atlanta (1981).

8. I. Andersen and M.L. Lundqvist, "Indoor air pollution due to chipboard used as a construction material", Atmospheric Environment **9**, 1121 (1975).

9. M. Kuhn and H.U. Wanner, "Verunreiningung der raumluft durch materialien", Sozial-und Präventivmedizin **27**, 260, Zurich (1982).

10. UFFI Program Contractor Training Manual, Consumer and Corporate Affairs Canada, UFFI Centre, Hull, Quebec (February 1983).

TABLE I. House Data and Test Results

House	Inside temp(°C)	RH (%)	Volume (m^3)	Main floor area(m^2)	V_I (ach)	V_M (ach)	V_T (ach)	LR HCOH ($\mu g/m^3$)	BR HCOH ($\mu g/m^3$)	Av. HCOH ($\mu g/m^3$)	Cig. smoked/ day	$V_T V/3600A$ $(m/s)\times10^3$
Unoccupied - Test #1												
A	14	46	475	98	0.01	0.13	0.14	43	40	42	0	0.19
B	14	57	475	98	0.01	0.15	0.16	70	71	70	0	0.22
C	11	45	475	98	0.01	0.68	0.69	15	20	17	0	0.93
D	13	45	475	98	0.01	0.44	0.45	23	28	26	0	0.61
Unoccupied - Test #2												
A	22	29	475	98	0.01	0.50	0.51	42	55	49	0	0.69
C	20	34	475	98	0.01	0.54	0.55	47	70	58	0	0.74
D	21	31	475	98	0.01	0.42	0.43	61	59	60	0	0.58
Occupied Non-smoking												
E	20	34	475	98	0.01	0.17	0.18	75	81	78	0	0.24
F	21	48	576	118	0.02	0.28	0.29	91	109	100	0	0.39
G	21	33	475	98	0.01	0.34	0.35	77	141	109	0	0.47
H	23	46	427	88	0.01	0.32	0.33	85	85	85	0	0.44
I	19	45	475	98	0.02	0.27	0.28	126	140	133	0	0.38
J	23	42	475	98	0.01	0.51	0.52	81	91	86	0	0.70
K	22	42	475	98	0.03	0.50	0.52	66	87	77	0	0.70
L	20	52	475	98	0.02	0.35	0.36	82	93	88	0	0.48
M	21	46	475	98	0.02	0.52	0.53	63	92	78	0	0.71
N	22	48	536	110	0.04	0.24	0.26	137	146	142	0	0.35
Occupied Smoking												
P	17	55	475	98	0.01	0.76	0.77	69	82	76	10	1.04
Q	20	46	475	98	0.02	0.52	0.53	109	97	103	25	0.71

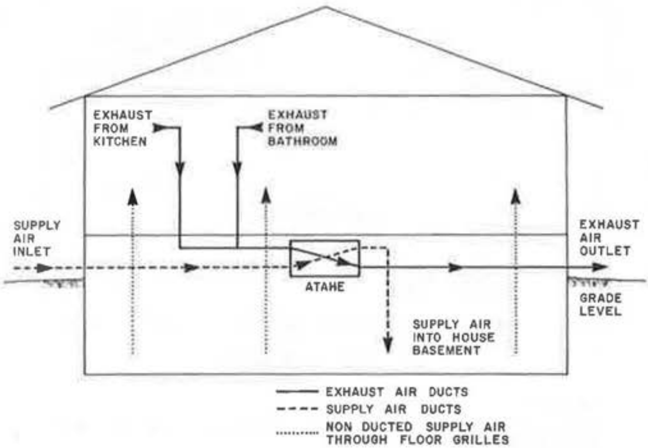

FIGURE 1
HOUSE VENTILATION SCHEMATIC

BR 6631-1

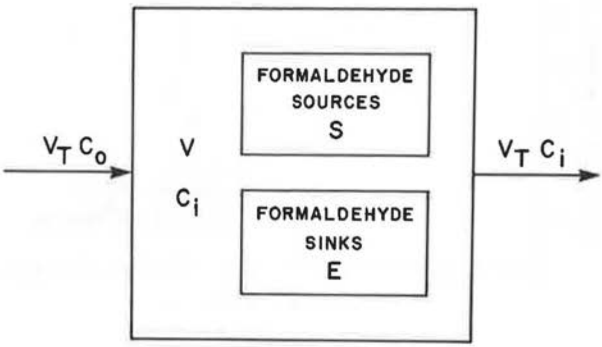

FIGURE 2
ONE-COMPARTMENT MASS BALANCE MODEL FOR INDOOR FORMALDEHYDE CONCENTRATION

BR 6631-2

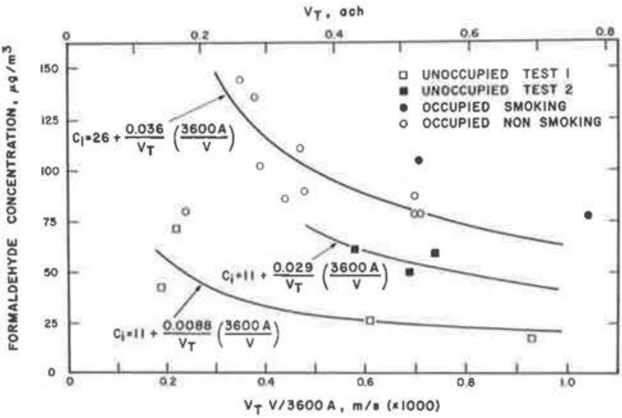

FIGURE 3

INDOOR FORMALDEHYDE CONCENTRATION VS AIR FLOW FOR FOUR TEST CASES

BR 6631-3

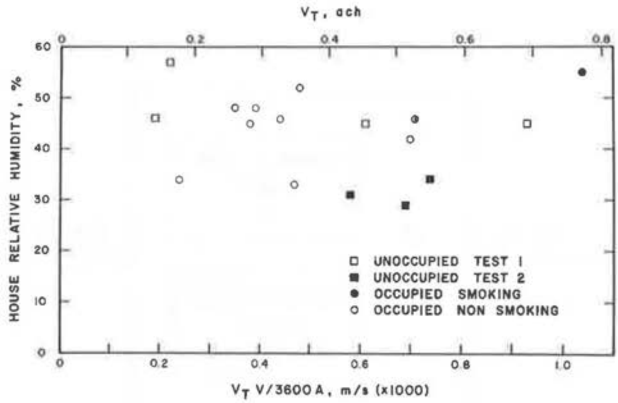

FIGURE 4

INDOOR RELATIVE HUMIDITY VS AIR FLOW FOR FOUR TEST CASES

BR 6631-4