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Indoor Ventilation Requirements for Manufactured Housing

Research Information Center
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U.S. Department of Commerce
National Institute of Standards and Technology
Building and Fire Research Laboratory
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Prepared for:
U.S. Department of Housing
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Division of Innovative Technology
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TABLE OF CONENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

In this study, a mathematical analysis is carried out to investigate the mechanical ventilation rates required in manufactured housing. The analysis reveals that the ventilation provided by natural infiltration is inadequate to comply with the ventilation requirements of ASHRAE Ventilation Standard 62-1889 and to prevent double-pane window condensation. The study recommends that both single-wide and double-wide mobile homes be equipped with mechanical ventilation equipment having a minimum installed capacity of 0.026 m^3/s (55 ft^3/min). It was found that considerably larger ventilation rates are needed to prevent condensation on single-pane windows. Therefore, it is recommended that double-pane windows be required in all heating climates.

Key Words: formaldehyde, HUD Manufactured Home Construction and Safety Standards, indoor ventilation, manufactured housing, mobile homes, ventilation, ventilation standards, and window condensation.

1. INTRODUCTION

1.1 Current Ventilation Requirements in HUD Standards

All manufactured homes constructed and sold in the United States must meet the requirements specified in the HUD Manufactured Home Construction and Safety Standards [1]. Henceforth in this report, these standards will be referred to as the HUD Standards. The HUD Standards require that habitable rooms of manufactured homes be provided with either operable window ventilation having an opening of 4% of the gross floor area or mechanical ventilation devices (i.e., fans) that may be used to ventilate the space at 2 air changes/h. Here the term "operable" denotes that windows may be opened and closed by the occupants. In bathrooms, either operable window opening of 0.14 m^2 (1.5 ft^2) or mechanical ventilation of 6 air changes/h must be provided.

During winter and summer climates, the occupants of mobile homes normally maintain windows in a closed position to prevent drafts, to conserve space heating and cooling energy, and to provide physical security of their homes. Mechanical ventilation fans, when provided, are sparingly operated because of noise generated by the equipment and because the occupants frequently don't know that ventilation equipment should be operated. Since windows are frequently closed and mechanical ventilation fans turned off, the primary source of ventilation is uncontrolled air infiltration through leaks and unintentional openings in the building envelope.

1.2 Air Infiltration Studies

A number of air infiltration studies have been recently conducted that document low infiltration rates in mobile homes. Goldschmidt and Wilhelm [2] measured natural infiltration rates in two mobile homes over a period of 16 months in Lafayette, Indiana. For these measurements, they developed a correlation for the rate of air infiltration expressed as a function of inside-to-outside temperature difference and wind speed. This correlation gives an infiltration rate of 0.25 air changes/h at an inside-to-outside temperature difference of 17°C (30°F) and a 3 m/s (7 mph) wind speed.

Other recent air infiltration studies support and corroborate the Goldschmidt and Wilhelm measurements. Teitsma and Peavy [3] reported air infiltration measurements for a mobile home located inside an environmental chamber at the National Institute of Standards and Technology (formerly the National Bureau of Standards). They determined a correlation that also gave 0.25 air changes per hour at an inside-to-outside temperature difference of 17°C (30°F). Hadley and Bailey [4] measured thirty-five current-practice mobile homes located in the Pacific Northwest using the perfluorocarbon-tracer technique during the 1989-1990 heating season. They reported a mean infiltration rate for this group of homes to be 0.28 air changes/h.

The infiltration rates cited in the above three studies are considerably smaller than typical values reported for new site-built homes (e.g., 0.4 air changes/h) (see Figure 6, Chapter 23, <u>ASHRAE Handbook of Fundamentals</u> [5]). Window condensation problems and inadequate indoor air quality (i.e., non compliance with the ASHRAE Ventilation Standard [6]) have been attributed to lower infiltration rates in mobile homes. These two problems are discussed below.

1.3 Window Condensation Problems

With regards to window condensation, Zieman and Waldman [7] in 1984 conducted a field survey of 49 mobile homes located in 5 different geographic locations of the United States. They found window condensation and associated moisture problems in 31% of the homes. Lee [8] surveyed sixty-five mobile home in Alberta, Canada, and found window condensation to be a major problem. Teitsma and Peavy [3] exposed a mobile home to winter climatic conditions inside an environmental chamber, and also found window condensation to be a serious problem.

The underlying cause of window condensation is the significant amount of moisture released by occupant activities. Lee [8] reports that a typical family of four generates 6.8 to 14 kg/day (15 to 31 lb/day) from perspiration, cooking, and bathing. The released moisture increases to 23 kg/day (51 lb/day) on wash days, during floor washing, or when drying clothes without an outside vent. Unless indoor moisture is diluted by way of ventilation with outdoor air (or dehumidification), then the indoor relative humidity rises and condensation occurs at the coldest interior room surface (i.e., interior surface of windows).

1.4 Non Compliance with ASHRAE Ventilation Standard 62-1989

With regards to indoor air quality, natural infiltration in mobile homes is often insufficient to comply with the ventilation requirements of ASHRAE Standard 62-1989 [6]. In Figure 1, natural infiltration rates predicted by the Goldschmidt and Wilhelm correlation [2] are compared to the outdoor ventilation

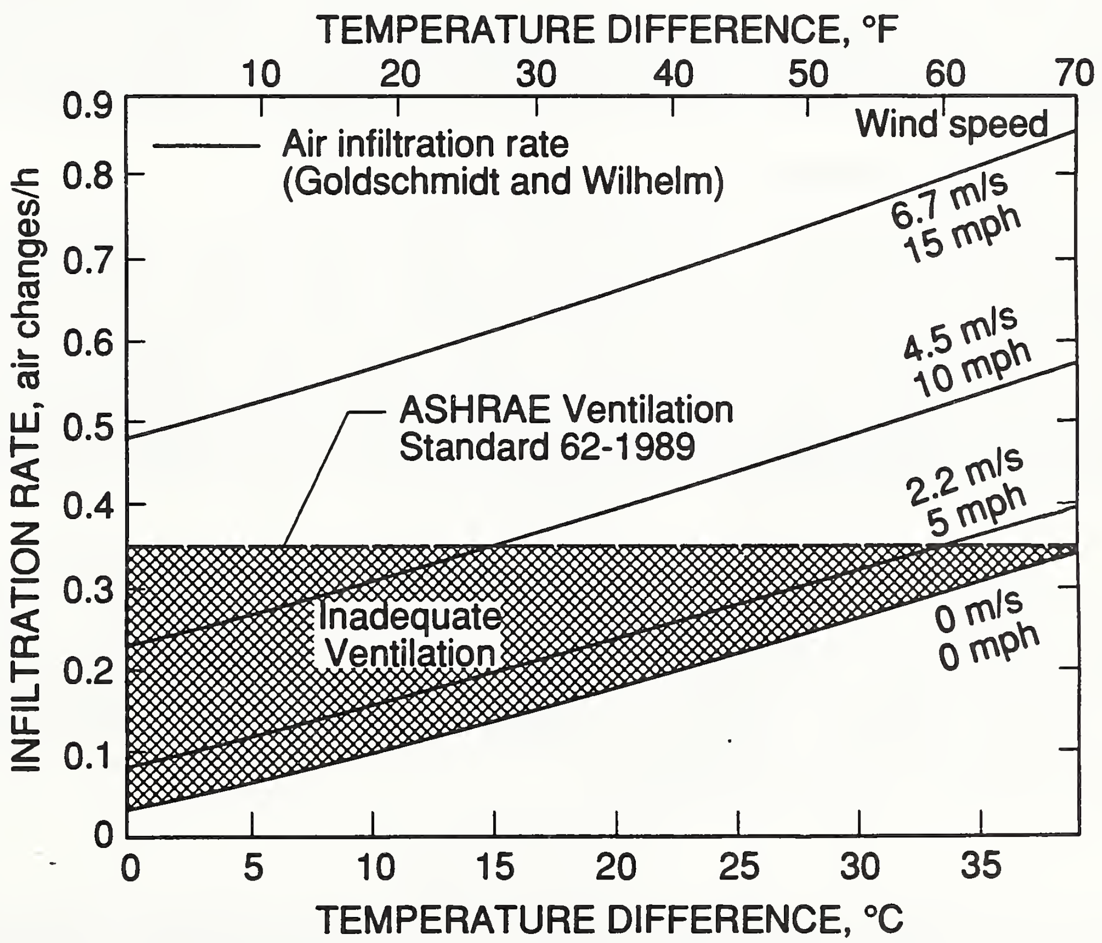


Fig. 1. Comparison of natural infiltration rates for a single-wide mobile home to the ASHRAE Ventilation Standard 62-1989.

requirements (i.e., 0.35 air changes/h) specified in the ASHRAE Standard. It should be pointed out that the ASHRAE Standard also requires compliance with another path (i.e., 0.0071 m^3/s (15 ft^3/min) per person). For a single-wide home with a typical occupancy of 2 persons, a requirement of 0.0071 m^3/s (15 ft^3/min) per person converts into approximately 0.30 air changes/h.

The cross hatched region in Figure 1 labeled "inadequate ventilation" indicates the outdoor climatic conditions that produce natural infiltration rates which are less than the ventilation requirements of the ASHRAE Standard. Note that inadequate ventilation occurs during mild weather conditions (i.e., small inside-to-outside temperature differences and low wind speeds). When a mobile home operates with inadequate ventilation, it does not mean that the mobile home categorically has an indoor air quality problem. Rather, it means that the infiltration rate is below a recommended ventilation rate based on indoor air quality concerns. The existence of an actual indoor air quality problem depends on the strength of pollutant sources.

1.5 Scope of Report

In this report, an analysis is carried out to investigate the required mechanical ventilation rates that will simultaneously prevent window condensation and provide compliance with the ASHRAE Ventilation Standard 62-1989. Mechanical ventilation rates that prevent window condensation will obviously prevent surface condensation in less conductive components of the building envelope (i.e., at framing). However, these mechanical ventilation rates may not prevent hidden condensation such as in attic spaces which will be addressed in a subsequent report.

2. THEORY FOR PREDICTING REQUIRED MECHANICAL VENTILATION RATES

2.1 Providing Compliance with the ASHRAE Ventilation Standard

The required mechanical ventilation rate (Q_m)[1] that provides compliance with the ASHRAE Ventilation Standard 62-1989 was calculated by the relation:

$$Q_m = \sqrt{Q_t^2 - Q_{inf}^2} \qquad (1)$$

This equation comes from Chapter 23 of The ASHRAE Handbook of Fundamentals [5]. Note that the total ventilation rate (Q_t) and the ventilation rate provided by natural infiltration (Q_{inf}) subtract in quadrature, as opposed to linearly. This is because mechanical ventilation alters the neutral pressure plane in a

[1] All symbols are defined in the Nomenclature.

building, and thereby changes the ventilation rate provided by natural infiltration.

In evaluating the above equation, the ASHRAE Ventilation Standard requirement (I_t) of 0.35 air changes/h was used in the analysis. The total ventilation rate (Q_t) was predicted by the relation:

$$Q_t = \frac{VI_t}{60} \tag{2}$$

A total ventilation rate is predicted to be 0.0155 m^3/s (32.8 ft^3/min) for single-wide homes and 0.0269 m^3/s (56.9 ft^3/min) for double-wide homes.

The ventilation rate provided by natural infiltration (Q_{inf}) was determined by the Goldschmidt and Wilhelm infiltration correlation [2]:

$$I_{inf} = 0.034 + 599\frac{T_{a,i} - T_{a,o}}{T_{a,i}T_{a,o}} + 2.92\frac{w^2}{T_{a,o}}$$

$$\text{and} \tag{3}$$

$$Q_{inf} = \frac{V{\cdot}I_{inf}}{60}$$

Note that the ventilation rate provided by natural infiltration is a strong function of the inside-to-outside temperature difference ($T_{a,i} - T_{a,o}$) and the wind speed (w).

2.2 Preventing Window Condensation

The required mechanical ventilation rate to prevent condensation on windows was calculated by the same procedure outlined above, except that the total ventilation rate (Q_t) was determined by the relation:

$$Q_t = \frac{W}{\rho V(\omega_i - \omega_o)} \tag{4}$$

This equation is based on a moisture balance of a mobile home in which the moisture (W) released by occupant related activities is set equal to the rate removed by air exchange with outdoor air.

The indoor humidity ratio (ω_i) was calculated using psychometric relations and corresponded to a dew-point temperature equivalent to an interior glass surface temperature (T_g) predicted by the steady-state relation:

$$T_s = T_i - \frac{U}{h_i}(T_i - T_o) \tag{5}$$

2.3. Assessing Additional Energy Expenditure

When a mobile home is mechanically ventilated, additional energy is expended to heat the supplemental outdoor air and to operate the ventilation equipment.

The supplemental ventilation rate (ΔQ) is determined by taking the difference between the total ventilation rate (Q_t) of a mechanically ventilated mobile home and the natural infiltration rate (Q_{inf}) for the same home without mechanical ventilation.

The hourly occurrences of outdoor temperature may be collected into temperature bins. The additional energy expenditure (E_h) for each temperature bin may be predicted by the relation:

$$\begin{aligned} E_h = {} & \rho \cdot \Delta Q \cdot C_p \cdot (T_i - T_o) \cdot NH / 3.6 \times 10^{-6} \\ & + \frac{Q_m}{Q_{cap}} E_f \cdot NH \end{aligned} \tag{6}$$

where the constant 3.6×10^{-6} converts from J into kWh. In the analysis, the ventilation capacity of the fan (Q_{cap}) was taken to be 0.024 m^3/s (50 ft^3/min) and its power consumption (E_f) was 0.040 kWh.

3. PARAMETERS USED IN ANALYSIS

A continuous moisture generation rate of 1.3×10^{-4} kg/s (1 lb/h) for occupant activities (cooking, bathing, etc.) was used in the analysis of both single-wide and double-wide mobile homes. This rate is consistent with 11 kg/day (25 lb/day) for a typical family of four reported by Anderson [9] and 6.8-14 kg/day (15-31 lb/day) for a typical family of four reported by Lee [8].

The thermal transmittance was taken to be 6.30 $W/m^2 \cdot K$ (1.11 $Btu/h \cdot ft^2 \cdot °F$) for single-pane windows and 3.2 $W/m^2 \cdot K$ (0.57 $Btu/h \cdot ft^2 \cdot °F$) for double-pane windows [5]. The outdoor weather data used in the analysis was taken from Weather Year for Energy Analysis (WYEC) [10].

The sizes of the homes used in the analysis are given in Table 1:

Table 1

Sizes of Mobile Homes in m (ft)

Dimension	Single Wide Inside	Single Wide Outside	Double Wide Inside	Double Wide Outside
Length, m (ft)	19.9 (65.3)	20.1 (66)	16.9 (55.3)	17.1 (56)
Width, m (ft)	4.1 (13.3)	4.3 (14)	8.3 (27.3)	8.5 (28)
Height, m (ft)	2.3 (7.5)	-	2.3 (7.5)	-

Closets, cabinets, and interior furnishing were assumed to reduce the inside volume available for ventilation by 14%.

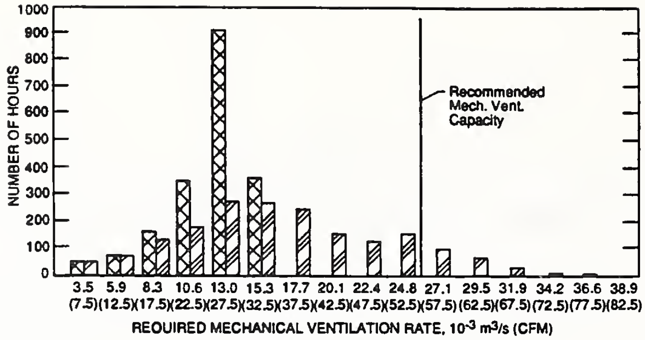
4. REQUIRED WINTER MECHANICAL VENTILATION RATES

A one-year analysis using hourly WYEC weather data [10] was carried out for five cities representing five different climatic regions of the United States. The five cities included: Lake Charles, LA; Atlanta, GA; Boston, MA; Madison, WI; and Portland; OR. For each hour having an outdoor temperature less than 16°C (60°F), the required mechanical ventilation rate was calculated by Equation (1). When compliance with the ASHRAE Ventilation Standard was used as a criteria, then the total ventilation rate was taken to be 0.35 volume changes/h. When prevention of condensation at the interior window surface was used as a criteria, then the total ventilation rate was based on the theory presented in Section 2.2. For both cases, the ventilation rate provided by natural infiltration was predicted by the infiltration correlation given in Equation (3).

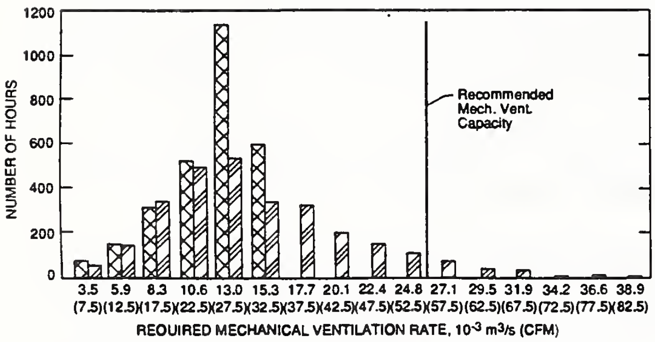
4.1 Single-Wide Mobile Homes

Homes with Double-Pane Windows. The required mechanical ventilation rates for single-wide mobile homes are summarized in the five plots given in Figure 2. A separate plot is given for each city. In each plot, a pair of frequency distribution plots, called histograms, are presented that give the number of hours that the required mechanical ventilation rate occurs in 0.0024 m^3/s (5.0 ft^3/min) bins. The first histogram, denoted by cross-hatching , pertains to ventilation rates that prevent condensation on double-pane windows. The second histogram, denoted by cross-hatching , pertains to mechanical ventilation rates that comply with the ASHRAE Ventilation Standard.

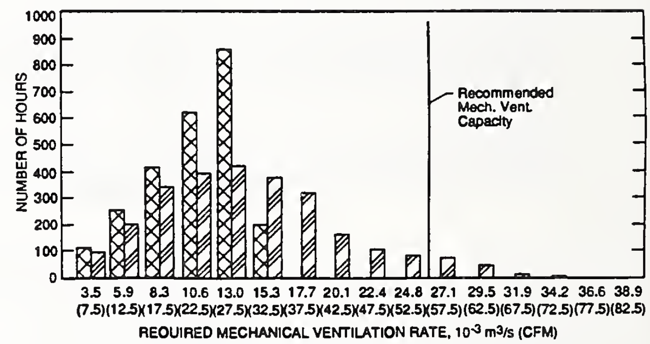
From the five plots given in Figure 2, it can be seen that the required mechanical ventilation rate is less that 0.026 m^3/s (55 ft^3/min), except for a small number of hours. This result indicates that the capacity of installed ventilation equipment should be at



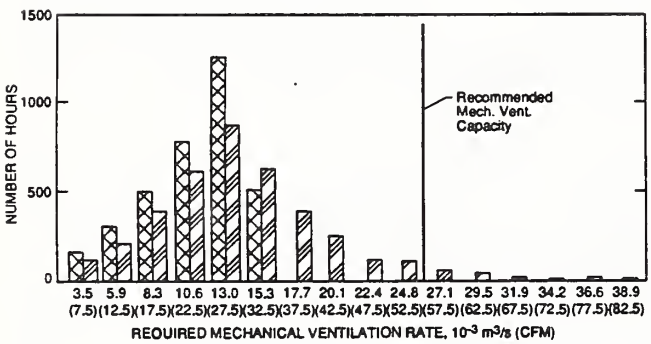
a. Lake Charles, Louisiana



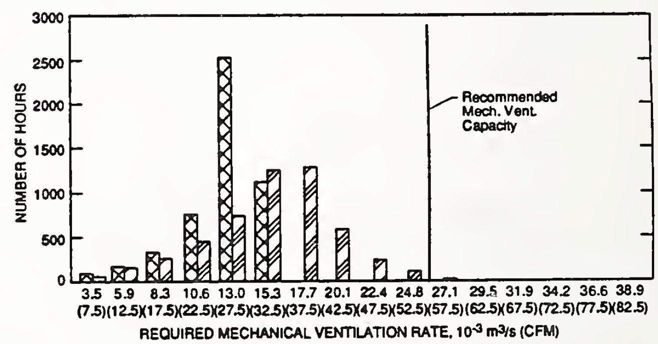
b. Atlanta, Georgia



c. Boston, Massachusetts



d. Madison, Wisconsin



e. Portland, Oregon

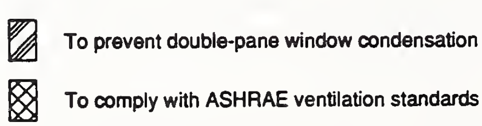


Fig. 2. Required mechanical ventilation rates for single-wide mobile homes.

least 0.026 m^3/s (55 ft^3/min) in order to be capable of complying with both of the ventilation criteria.

An interesting finding is that the required mechanical ventilation that prevents double-pane window condensation in single-wide mobile homes tends to be larger than that required to comply with the ASHRAE Ventilation Standard. This finding can be seen by examining Figure 2 where mechanical ventilation rates that prevent window condensation are seen to be distributed higher compared to those that comply with the ASHRAE Ventilation Standard. This finding can also be seen from a plot of the required mechanical ventilation rates versus outdoor temperature (see Figure 3). In this plot, the outdoor humidity and wind speed was taken to be 80% and 2.2 m/s (5 mph), respectively. In Figure 3, it is seen that the required mechanical ventilation rate that prevents window condensation is higher than that to comply with the ASHRAE Ventilation Standard.

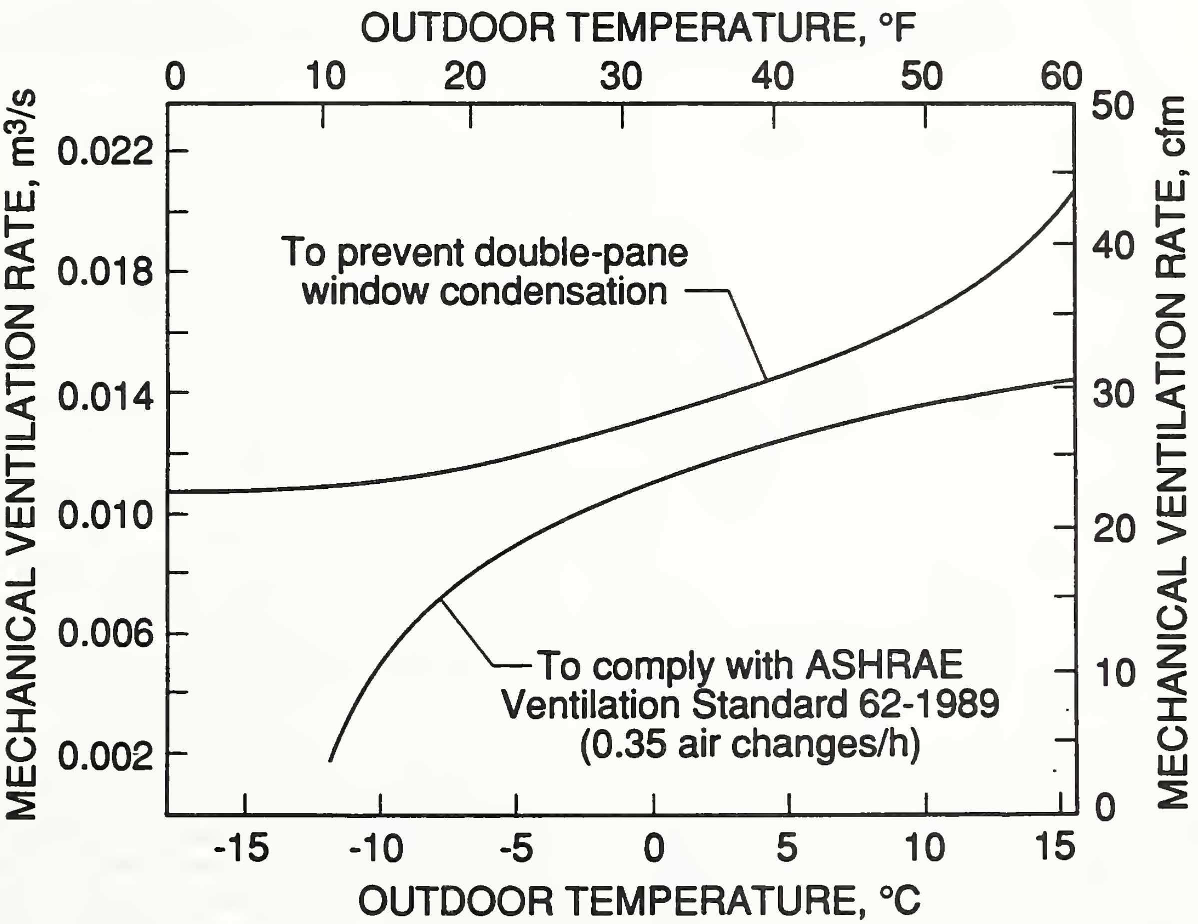


Fig. 3. Plot of required mechanical ventilation rates for single-wide mobile homes versus outdoor temperature.

The above finding means that, if a single-wide mobile home is ventilated to prevent window condensation, compliance with the ASHRAE Ventilation Standard is automatically attained. One method of providing a variable ventilation rate is to control the ventilation equipment with a humidistat. The occupant adjusts the set point of the humidistat to control window condensation.

Additional Space Heating Energy Expenditures. When a single-wide mobile home is mechanically ventilated at a variable rate to prevent double-pane window condensation, additional energy expenditures are required to heat the outdoor ventilation air and to operate the ventilation equipment. An analysis of the additional energy expenditures was carried out for five cities for which the required ventilation rates were predicted. The results are summarized in Table 2.

Table 2

Additional Energy Expenditures for Single-Wide Mobile Homes (When Ventilating to Prevent Double-Pane Window Condensation)

Location	Geographic Region	Energy Penalty kWh	$/year[1]
Lake Charles, LA	Gulf coast	401	30
Atlanta, GA	Southern	638	48
Boston, MA	New England	967	73
Madison, WI	Northern	1012	77
Portland, OR	Pacific Northwest	1046	79

[1] Note: Based upon an electricity cost of 7.6 cents/kWh.

Note that the largest additional energy expenditure is 1046 kWh which converts into an electrical cost of only $79 per year.

Homes with Single-Pane Windows. Mobile homes constructed in the United States must have an overall heat transmission coefficient less than maximum transmission coefficients specified in the HUD Standards. To comply with the specified maximum transmission coefficients, manufactures use double-pane windows in outdoor winter design temperature Zones 2 and 3 (see Figure 4). Compliance can be achieved with single-pane windows in the southern part of the United States (Zone 1).

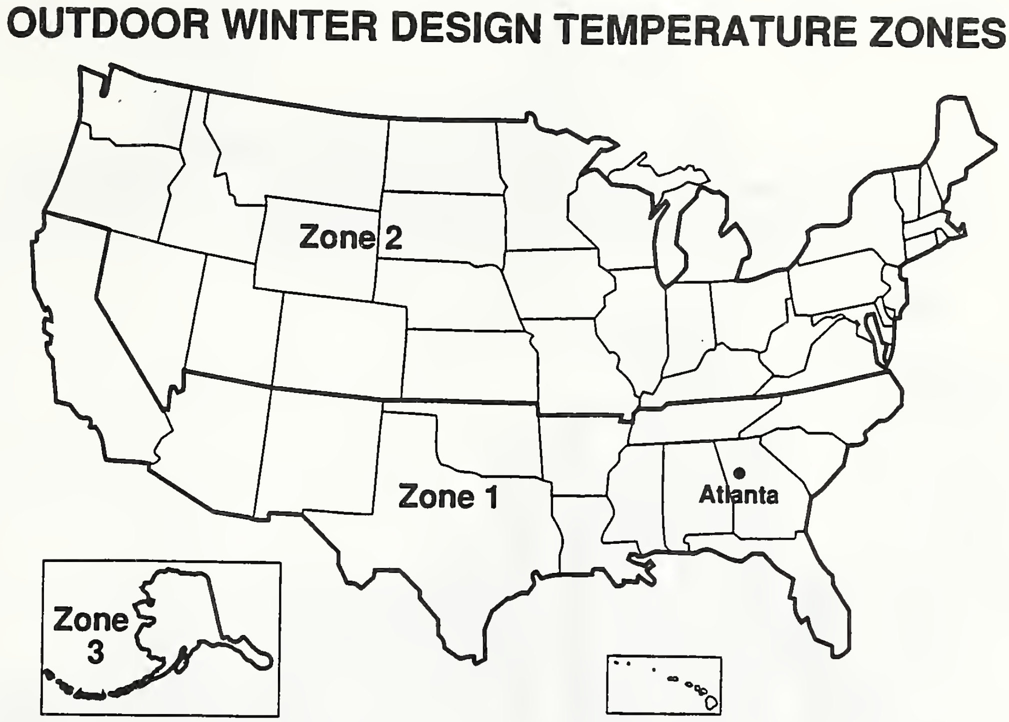


Fig. 4. Outdoor winter design temperature zones.

A one-year analysis was carried out to investigate the required mechanical ventilation rates to prevent condensation on single-pane windows for a mobile home located in Atlanta, GA. The results are given in Figure 5. They indicate that the required mechanical ventilation rates are considerably larger than either those required to prevent condensation on double-pane windows or those required to comply with the ASHRAE Ventilation Standard. Sometimes mechanical ventilation rates as high as 0.0472-0.0708 m^3/s (100-150 ft^3/min) are needed to prevent single-pane window condensation.

The above analysis indicates that window condensation can be more reasonably controlled by requiring double-pane windows in all heating climates, as opposed to using mechanical ventilation to prevent condensation on single-pane windows.

4.2 Double-Wide Mobile Homes

An analysis similar to that given in Section 4.1 was carried out for double-wide mobile homes with double-pane windows. The results are given in Figure 6. As in the case for the single-wide homes, the required mechanical ventilation rate is less than 0.026 m^3/s (55 ft^3/min), except for a small number of hours. This result indicates that the installed capacity of ventilation equipment should be at least 0.026 m^3/s (55 ft^3/min) in order to be capable of complying with both of the ventilation criteria.

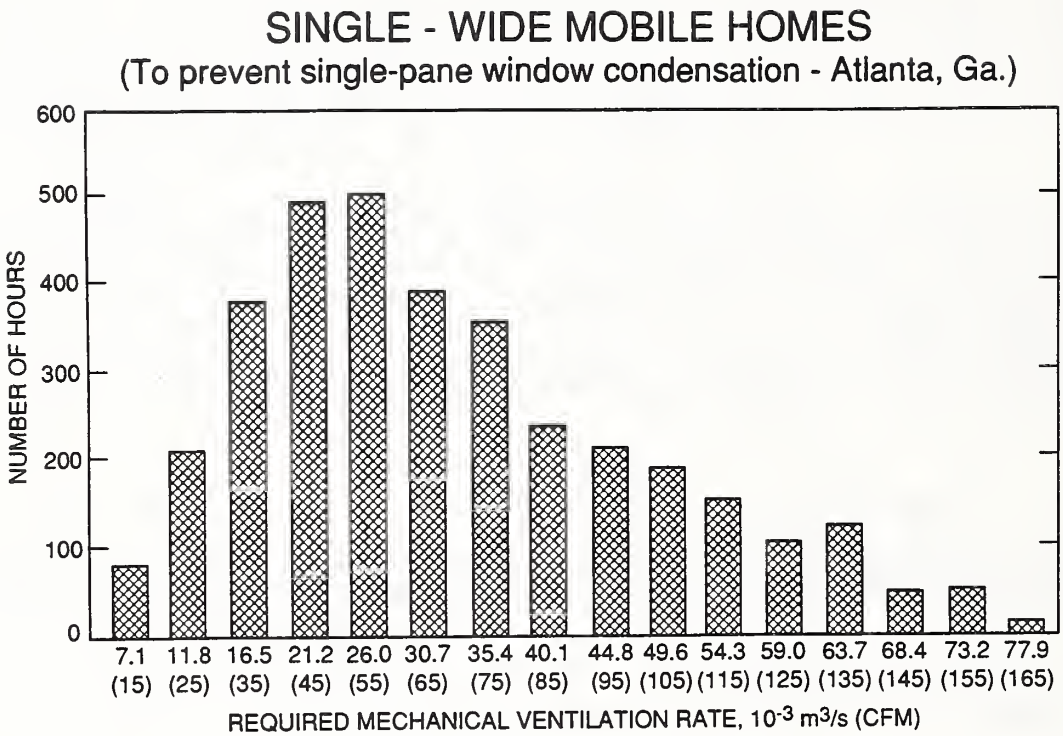


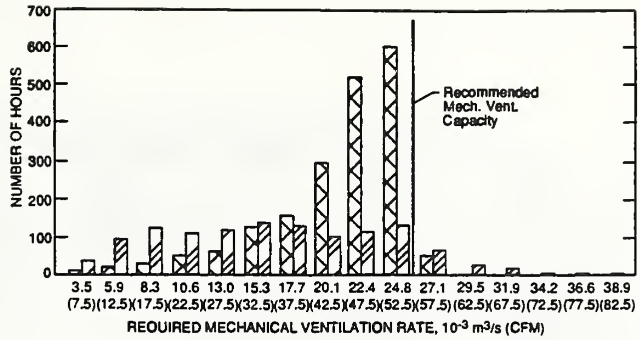
Fig. 5. Required mechanical ventilation rates to prevent single-pane window condensation in Atlanta, GA.

The required mechanical ventilation rates that prevent window condensation in double-wide mobile homes tended to be distributed lower compared to those required to comply with the ASHRAE Ventilation Standard. The opposite was observed for the single-wide mobile home analysis. This finding can be seen from the frequency distribution plots given in Figure 6 and the plot of required ventilation rates versus outdoor temperature given in Figure 7. An explanation is given below.

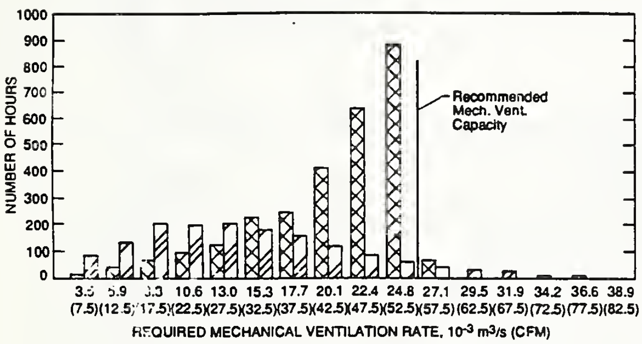
A double-wide mobile home has considerably larger inside volume compared to single-wide home. From Equation (2), it is seen that for a total infiltration rate (I_t) equal to 0.35 volume changes/h, a larger total ventilation rate (Q_t) is required in double-wide compared with single-wide mobile homes.

5. REQUIRED SUMMER MECHANICAL VENTILATION RATES

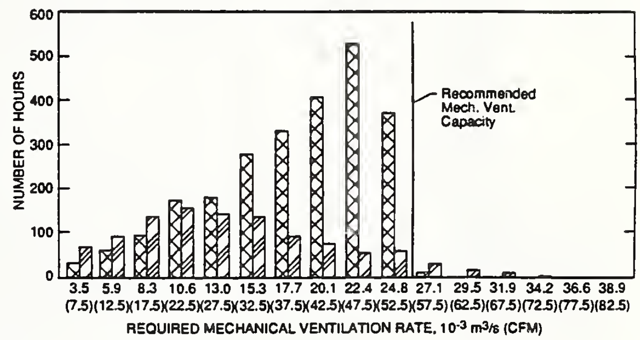
During the summer season, when mobile homes are air conditioned, window condensation is not a problem. However, mobile homes are generally operated with their windows closed and insufficient ventilation is provided by natural infiltration to comply with the ASHRAE Ventilation Standard 62-1989. An analysis was carried out



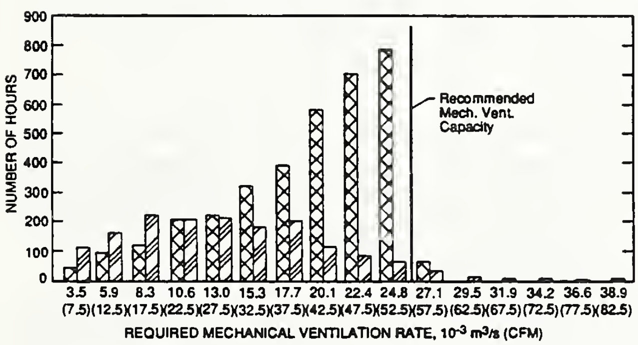
a. Lake Charles, Louisiana



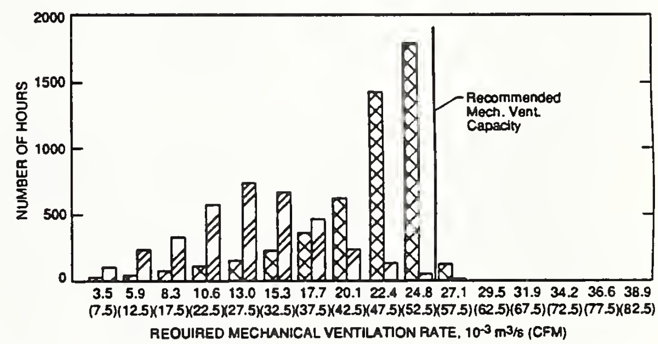
b. Atlanta, Georgia



c. Boston, Massachusetts



d. Madison, Wisconsin



e. Portland, Oregon

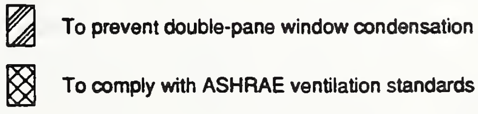


Fig. 6. Required mechanical ventilation rates for double-wide mobile homes.

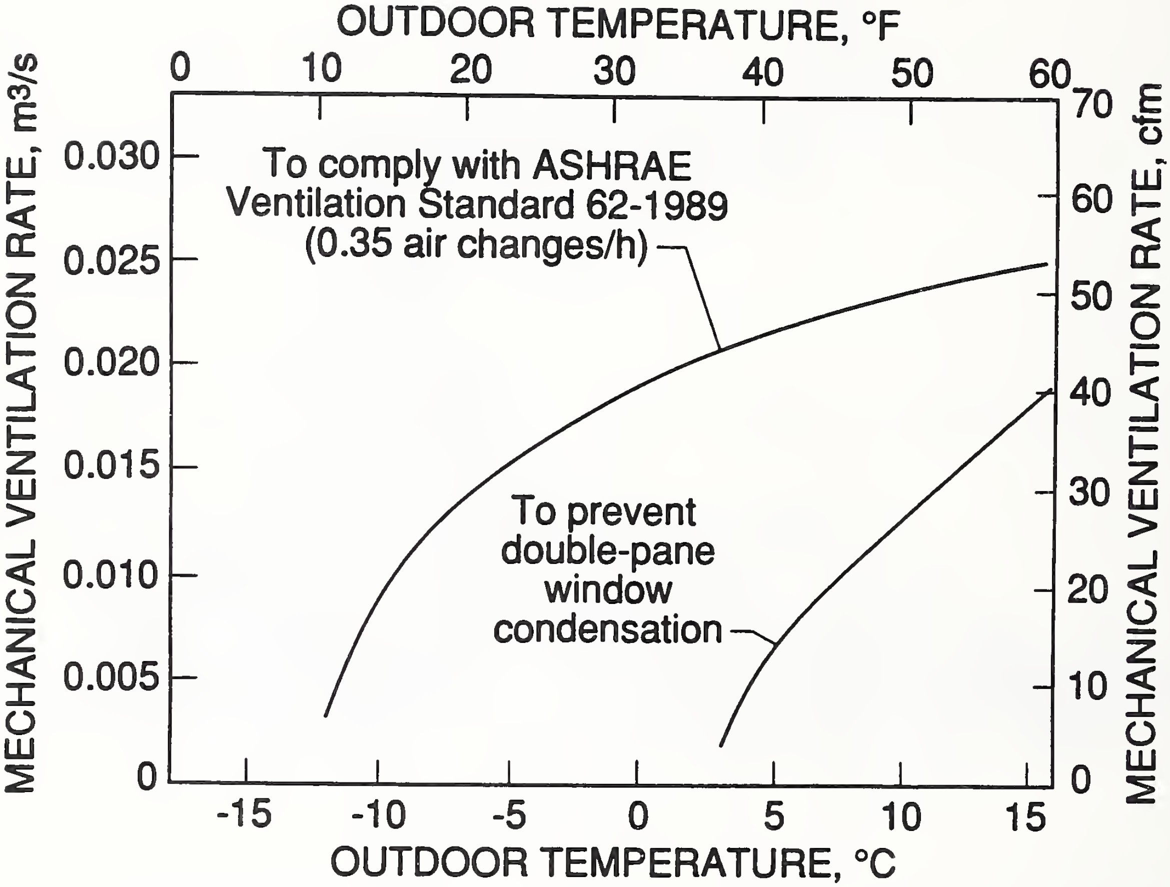


Fig. 7. Plot of required mechanical ventilation rates for double-wide mobile homes versus outdoor temperature.

using Equation (1) to investigate the summer mechanical ventilation rates that are needed to comply with the ASHRAE Standard ventilation requirement of 0.35 volume changes/h. For this analysis, the natural infiltration rate was taken to be one-half the typical winter value for a mobile home, or 0.125 volume changes/h.

From Equation (2), the total ventilation rate to provide compliance with the ASHRAE Ventilation Standard was found to be 0.0155 m^3/s (32.8 ft^3/min) for a single-wide home and 0.0269 m^3/s (56.9 ft^3/min) for a double-wide home. From Equation (3), the ventilation rate provided by infiltration was predicted to be 0.00552 m^3/s (11.7 ft^3/min) for a single-wide home and 0.00958 m^3/s (20.3 ft^3/min) for a double-wide home. Then from Equation (1), the required mechanical ventilation rate was found to be 0.0144 m^3/s (30.6 ft^3/min) for a single-wide home and 0.0251 m^3/s (53.2 ft^3/min) for a double-wide home. Mechanical ventilation equipment with an installed capacity of 0.026 m^3/s (55 ft^3/min), which was recommended for winter, would also be adequate for the summer season.

6. PRACTICAL CONSIDERATIONS

When ventilation equipment is installed in a mobile home, it is important that approximately an equivalent amount of ventilation opening be provided for intake air. Otherwise, the ventilation equipment will create a negative pressure inside the mobile home which will tend to reduce the rated output capacity of the ventilation equipment.

Another important consideration is the design of a quiet ventilation system which will encourage use by the home occupants. This can be accomplished by the installing ventilation equipment in the attic space with indoor air drawn through a flexible duct and exhausted through either a roof or gable vent.

7. CAVEATS AND CAUTIONS

The above recommended mechanical ventilation rates may not be adequate to control formaldehyde levels in mobile homes. This is because a reduction in formaldehyde concentration achieved by ventilation is accompanied by an increase in the formaldehyde emission rate from urea-formaldehyde-bonded products, which tends to offset the dilution effect of ventilation. An analysis of formaldehyde emissions in mobile homes is carried out in the Appendix.

8. RECOMMENDATIONS

Based on the analysis presented in this report, it is recommended that both single-wide and double-wide mobile homes be equipped with mechanical ventilation equipment having a minimum installed capacity of 0.026 m^3/s (55 ft^3/min). When this mechanical ventilation equipment is opeated, it will combine with the natural infiltration rate of a mobile home to produce a total ventilation rate that will both prevent double-pane window condensation and provide compliance with the ASHRAE Ventilation Standard (i.e., 0.35 volume changes/h). Furthermore, since it was found that very large ventilation rates are needed to prevent condensation on single-pane windows, it is recommended that double-pane windows be required in all heating climates.

9. ACKNOWLEDGMENTS

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11. NOMENCLATURE

Symbol	Units	Description
A		constant
a,b		coefficients in formaldehyde emission model
B	K^{-1}	constant
c	K	constant
C	ppb	formaldehyde concentration
C_b	ppb	constant
C_p	J/kg·K	specific heat of air
E	$\%^{-1}$	constant
E_f	kWh	power consumption of ventilation equipment
E_h	kWh	additional energy expenditure
g	$mg/m^3 \cdot ppb$	conversion factor from ppb to $mg/m^3 = 1.228 \times 10^{-3}$
h_i	$W/m^2 \cdot K$	inside surface heat transfer coefficient
I	h^{-1}	air infiltration rate
l	m^2/m^3	loading
NH	h	number of hours
Q	m^3/s	ventilation rate
ser	$mg/m^2 \cdot h$	formaldehyde surface emission rate
T	°C	temperature
T_a	K	absolute temperature
U	$W/m^2 \cdot K$	window thermal transmittance
V	m^3	inside house volume
w	m/s	outdoor wind speed
W	kg/s	moisture generation rate
ΔQ	m^3/s	supplemental ventilation rate
ϕ	%	relative humidity
ρ	kg/m^3	density of air
ω	kg_w/kg_d	humidity ratio

Subscript	Description
cap	rated capacity of ventilation equipment
i	material index or indoor air
inf	infiltration
m	mechanical ventilation
o	outdoor air
r	reference condition of 23°C, 50% rh, and C=100 ppb
s	surface property
t	combined effect due to infiltration and mechanical ventilation
w	wet

APPENDIX

CONTROLLING FORMALDEHYDE EMISSIONS IN MOBILE HOMES

1. INTRODUCTION

Indoor formaldehyde concentrations are generally higher in mobile homes than in site-built homes because urea-formaldehyde (UF) products are used to a considerably greater extent. Products contributing to this problem are UF-bonded particle board used in the floor decking and the UF-bonded hardwood plywood used in the wall paneling. Other factors contributing to higher formaldehyde levels are the lower infiltration rates and the smaller inside volumes found in mobile homes.

Formaldehyde concentrations measured in mobile homes during five surveys conducted from 1983 to 1985 are compared in Figure A-1 [11]. In each of the five surveys, the investigators measured formaldehyde concentrations in a large group of homes and correlated the results as a function of the age of home. The mean represents the arithmetic average of the homes in a particular age group. It should be pointed out that some homes in an age group had formaldehyde concentrations higher than the mean.

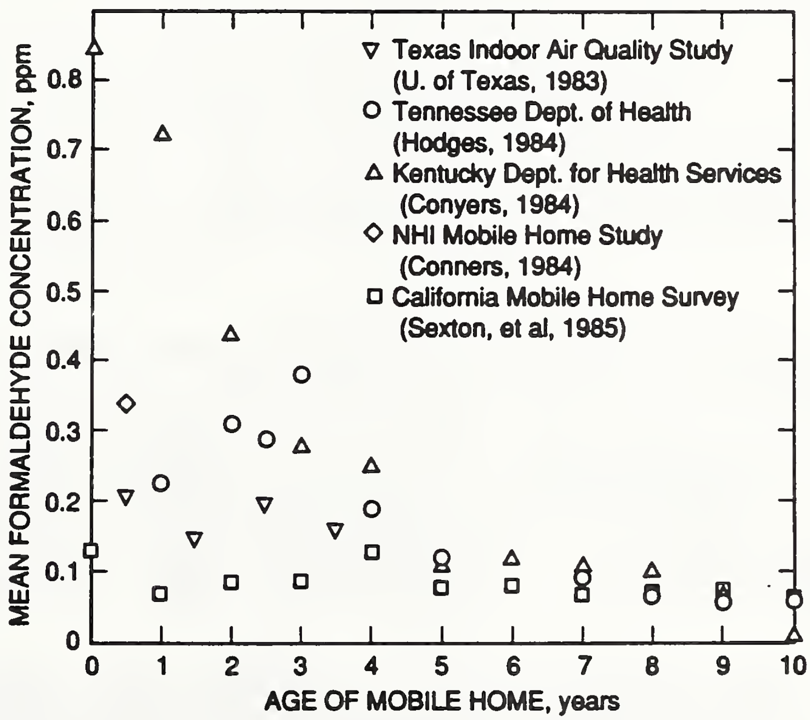

Fig. A-1. Surveys of formaldehyde concentration in mobile homes.

From Figure A-1, mobile homes having an age less than 5 years, had formaldehyde concentrations considerably in excess of 0.1 ppm. A formaldehyde concentration of 0.1 ppm is regarded as a level of concern (see Table C-4, ASHRAE Ventilation Standard 62-1989 [6]). Moreover several European countries recommend and/or promulgate a maximum formaldehyde concentration of 0.1 ppm in their indoor air quality standards. It should be pointed out that formaldehyde emission rates in UF-bonded products have decreased since 1985.

2. FORMALDEHYDE EMISSION MODEL

The formaldehyde emission rate from an i-th type material surface of a mobile home may be determined from Fick's diffusion law:

$$\frac{ser_i}{ser_r} = a_i - b_i C \tag{A-1}$$

All symbols are defined in the Nomenclature.

The Oak Ridge National Laboratory [12] empirically determined the coefficients a_i and b_i to be as follows:

$$b_i = \frac{[1 + B(T - 296.15)]\,[1+E(\phi - 50)]}{C_b - 100} \tag{A-2}$$

and

$$a_i = b_i C_b \left(\frac{\phi}{50}\right)^A \exp[-c(T^{-1} - 296.15^{-1})] \tag{A-3}$$

The constants A, B, c, E, and C_b are given in Table A1.

Table A1

Empirical Constants for Formaldehyde Emission Model

Pressed-Wood Product	c K	A	C_b ppb	B K^{-1}	E $\%^{-1}$
Particle Board	9,400	0.37	360	0.025	0.016
Hardwood Plywood	6,500	0.66	410	0.053	0.029

When formaldehyde emitting surfaces are present inside an enclosure, then the NIST indoor air quality model described in Reference [13] relates the surface emission rates to the concentration in the enclosure:

$$\Sigma l_i ser_i = CgI \qquad \text{(A-4)}$$

In analyzing the formaldehyde concentration (C) present in a mobile home, the following steps were followed:

1) From the chamber test, the surface emission rate (ser_i) for each press-wood product was predicted using Equation (A-4).

2) The reference surface emission rate (ser_r) for each product was evaluated from Equation (A-1).

3) And finally, the concentration (C) due to combined emissions of all the press-wood products with typical loadings in a mobile home was predicted by simultaneously solving Equations (A-1) and (A-4).

3. RECOMMENDED MODIFICATIONS TO FORMALDEHYDE CHAMBER TEST

3.1 Description of Current Formaldehyde Chamber Test

The HUD Standards state that all plywood and particle board materials bonded with a resin system or coated with a surface finish containing formaldehyde shall undergo the formaldehyde chamber test. In this test, an equivalent loading (m^2/m^3) of a material is tested in the chamber as would be found in a mobile home. The loadings for plywood and particle board are specified to be 0.95 m^2/m^3 (0.29 ft^2/ft^3) and 0.43 m^2/m^3 (0.13 ft^2/ft^3), respectively. During the test, the chamber is ventilated at 0.5 air changes/h and the chamber air temperature is held at 25±1°C (77±2°F) and 50% rh. After the formaldehyde concentration reaches an equilibrium, the measured concentration must be less than 0.2 ppm for plywood and 0.3 ppm for particle board materials.

3.2 Consequence of Current Formaldehyde Chamber Test

In this section, the formaldehyde emission model is used to analyze the formaldehyde concentration in a mobile home. The home is typically loaded with both particle board and hardwood plywood that marginally meets the current formaldehyde chamber test (i.e., 0.3 ppm for the particle board and 0.2 ppm for the hardwood plywood). In the analysis, a wide range of ventilation rates are considered. The indoor temperature and relative humidity were 21°C (70°F) and 50%, respectively.

The resulting formaldehyde concentrations are plotted as a function of the indoor ventilation rate in Figure A-2. Note that at a typical ventilation rate for natural infiltration (i.e., 0.25 air changes/h), the formaldehyde concentration is 0.25 ppm. This result is consistent with the formaldehyde concentrations reported by the surveys summarized in Figure A-1. It can be seen that as the ventilation rate is increased, the formaldehyde concentration

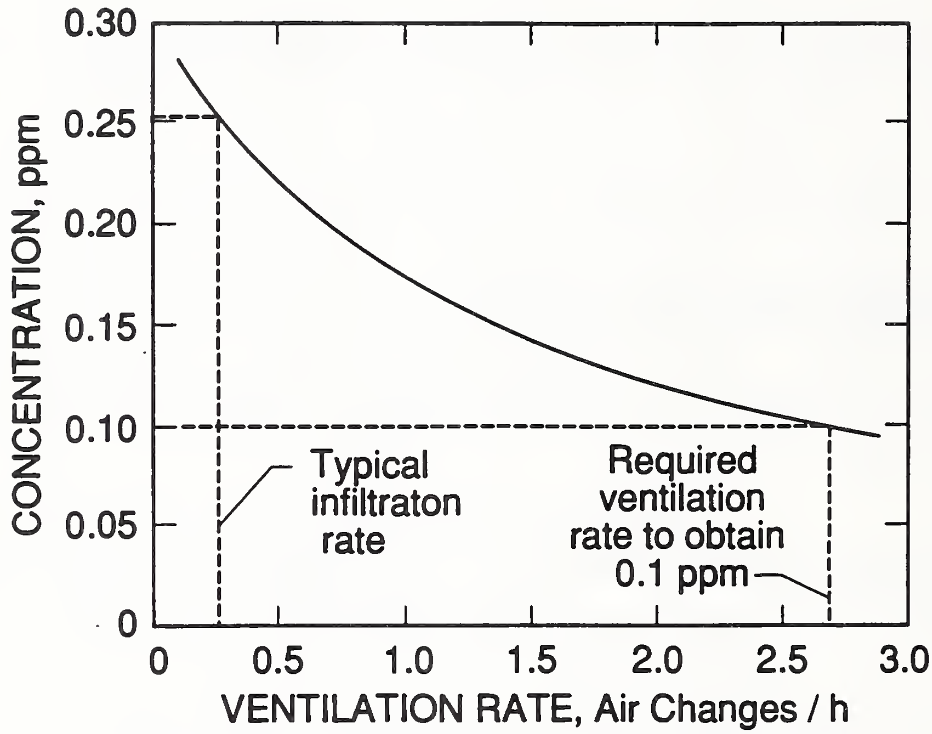

Fig. A-2. Mobile home formaldehyde concentration versus ventilation rate when UF bonded products are used in a single-wide home that marginally meets the current requirements of the HUD Standard.

is reduced. However, to lower the formaldehyde concentration to 0.1 ppm requires a ventilation rate of 2.7 air changes/h which significantly exceeds the requirements of the ASHRAE Ventilation Standard (i.e., 0.35 air changes/h). Ventilation has a weak effect because the emission rate increases as the concentration is decreased.

3.3. Revised Formaldehyde Chamber Test

To maintain indoor formaldehyde concentrations below 0.1 ppm, it is more appropriate to modify the formaldehyde chamber test and reduce the emission rates for the UF-bonded products, as opposed to requiring an unreasonably high ventilation rate. It is recommended that the maximum permitted formaldehyde concentration in the chamber test be revised to 0.1 ppm for all UF-bonded products. Furthermore, it recommended that this revised chamber test be conducted at a ventilation rate of 0.25 air changes/h which is consistent with the natural infiltration rate for a mobile home. The chamber test is currently carried out at a ventilation rate of 0.5 air changes/h.

The formaldehyde emission model was used to investigate the formaldehyde concentration in a mobile home containing both UF-bonded particle board and hardwood plywood that meet the revised formaldehyde chamber test. For the analysis, the temperature and relative humidity in the mobile home was 21°C (70°F) and 50%, respectively and the temperature of the chamber test was 25°C (77°F). When the ventilation rate corresponds to a typical natural infiltration rate of 0.25 air changes/h, the formaldehyde concentration was predicted to be 0.104 ppm. When the ventilation was increased to meet the ASHRAE Ventilation Standard (i.e., 0.35 air changes/h), the formaldehyde concentration decreased to 0.082 ppm.

4. RECOMMENDATIONS

It is recommended that the formaldehyde chamber test, specified in the HUD Standards, be modified in the following ways: 1) The chamber test should be carried out at a ventilation rate consistent with a natural ventilation rate that is typical of mobile homes (0.25 air changes per hour), and 2) The maximum formaldehyde concentration for all materials tested in the chamber should be set at 0.1 ppm.

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

In this study, a mathematical analysis is carried out to investigate the mechanical ventilation rates required in manufactured housing. The analysis reveals that the ventilation provided by natural infiltration is inadequate to comply with the ventilation requirements of ASHRAE Ventilation Standard 62-1889 and to prevent double-pane window condensation. The study recommends that both single-wide and double-wide mobile homes be equipped with mechanical ventilation equipment having a minimum installed capacity of 0.026 m^3/s (55 ft^3/min). It was found that considerably larger ventilation rates are needed to prevent condensation on single-pane windows. Therefore, it is recommended that double-pane windows be required in all heating climates.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

formaldehyde, HUD Manufactured Construction and Safety Standard, indoor ventilation, manufactured housing, mobile homes, ventilation, ventilation standards, window condensation.

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