VENTILATION, HUMIDITY, AND CONDENSATION IN MANUFACTURED HOUSES DURING WINTER

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ABSTRACT

Many manufactured homes have lower natural ventilation rates than those in site-built houses. This, combined with high occupancy levels, may lead to moisture problems, which can cause structural damage and health problems. The objectives of this study were to (1) obtain information on the moisture behavior of manufactured houses and moisture release from occupants and other sources and (2) evaluate the effect of mechanical ventilation. We measured the ventilation and indoor humidity in six manufactured houses during winter. The measurements indicate that ventilation in manufactured homes is often less than recommended. Using a mathematical model, the average moisture release and moisture storage rates were determined and the effect of mechanical ventilation with controls on humidity and comfort, condensation, and energy consumption during winter was analyzed. Results show that the average moisture release is similar to documented rates and that manufactured houses appear to store less moisture than site-built houses. However. moisture storage in manufactured houses is enough to reduce the potential for condensation during winter. To prevent significant condensation, natural ventilation is usually sufficient and mechanical ventilation is needed only in we of high occupancy and moisture loads or in an airtight house with negligible natural ventilation. ASHRAE's minimum ventilation requirements usually exceed the level needed to prevent condensation. and in cold winter climates. these minimum ventilation levels without humidification will cause the indoor air to be uncomfortably dry.

To improve ventilation, manufactured houses should be supplied with balanced mechanical ventilation with an automatic control and manual override. In the absence of a better inexpensive alternative, a humidistat control may be used during winter lo prevent condensation without excessive heat or comfort loss. However, a humidistat control does not ensure that ASHRAE minimum ventilation levels will be achieved.

INTRODUCTION

Manufactured houses often have low natural ventilation rates, often lower than those of average site-built houses (Hadley and Bailey 1990; Burch 1991). Without additional mechanical ventilation, many manufactured houses do not meet current national standards for minimum ventilation. *ANSI/ASHRAE Standard 62-1989, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 1989), prescribes 0.35 air changes per hour (ACH) for living areas but not less than 15 cfm (7.5 L/s) per person. These requirements have not yet been incorporated into the standards for manufactured houses (U.S. Department of Housing and Urban Development 1990). Current standards only require mechanical ventilation in houses without openable windows. However, homeowners do not want to open windows during winter because of drafts, energy loss, and security considerations. Therefore, natural ventilation may be insufficient to maintain indoor air quality. With efforts under way in some regions of the United States to encourage further reductions in air infiltration and energy consumption, the need for a critical assessment of ventilation in manufactured houses is even more pressing.

The combination of high occupancy load (i.e., large number of occupants per unit of floor area) and low ventilation rates may lead to condensation. other moisture problems, and even structural damage (CMHC 1983; Merrill and TenWolde 1989). In a recent study, Hadley el al. (1991) found moisture problems in 45% of the manufactured houses in their study sample and confirmed the importance of ventilation when the occupancy load is high. Additional mechanical ventilation may be needed to prevent frequent condensation on double-glazed windows and other moisture problems in manufactured houses (Burch 1991). Recently, it became evident that high humidity can also cause allergic and respiratory health problems for the occupants (Spengler et al. 1992).

It seems desirable to install mechanical ventilation in manufactured houses to prevent moisture problems and to ensure satisfactory air quality. Burch (1991) recommends that ventilation equipment with a minimum capacity of 55 cfm (26 Us) be installed but makes no recommendations for ventilation control. Increased ventilation causes an increase in heating costs and may produce uncomfortably dry air in cold winter climates. Homeowners will likely turn off the ventilation system if the indoor air becomes too

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dry. Some type of automatic ventilation control to minimize these effects seems desirable, but little is known about the effect of various ventilation controls on ventilation, condensation, and humidity levels in the house.

The first objective of this study was to obtain additional information on the moisture behavior of manufactured houses as well as additional data on moisture release from occupants and other sources. This was accomplished by measuring ventilation and humidity levels in six manufactured houses during winter and analyzing the results with a mathematical model for indoor humidity. This model is a modification of a model described earlier (TenWolde 1988). With it, average moisture release and moisture storage rates can be determined by matching model output with measured data.

The second objective was to expand on the results of Burch (1991) by evaluating the effect of mechanical ventilation on humidity and comfort, condensation. and energy consumption during winter. We assumed various ventilation control options and again used the modified model.

TABLE 1
Monitored House Characteristics and Occupancy

House number	Dimension ft (m)	Year of construction	Manu-facturer	Forced attic ventilation	Number of occupants
1	16x76 (4.9x23.2)	1988	A	Yes	1 or 2[a]
2	16x66 (4.9x20.1)	1982	A	No	1 or 2[a]
3	14x66 (4.3x20.1	1983	A	No	2
4	14x66 (4.3x20.1)	1982	A	No	1
5	14x66 (4.3x20.1)	N/A	B	No	2
6	16x66 (4.9x20.1)	1988	C	Yes	0

[a] Occupancy was reported as 1 during the week and 2 during the weekend.

TABLE 2
Measured Indoor Conditions

	Average conditions during measurement periods					
	December 1989		January 1990		February 1990	
	Temperature	RH	Temperature	RH	Temperature	RH
House number	°F (°C)	(%)	°F (°C)	(%)	°F (°C)	(%)
1	75.0 (23.9)	22.0	73.4 (23.0)	27.7	71.0 (23.9)	15.7
2	65.6 (18.7)	28.6	65.2 (18.4)	34.7	64.6 (18.1)	35.0
3	72.8 (22.7)	24.7	72.4 (22.4)	26.3	73.8 (23.2)	27.1
4	72.9 (22.7)	18.9	71.2 (21.8)	31.3	70.6 (21.4)	31.4
5	66.7 (19.3)	23.6	65.9 (18.8)	40.5	65.2 (18.4)	39.4
6	63.7 (17.6)	16.7	65.7 (18.7)	30.1	65.8 (18.8)	29.5

MEASUREMENTS

Houses

We measured indoor humidity and ventilation levels in six manufactured houses in Wisconsin. The houses were all located in one mobile home park near Cambridge, which is 14 miles (22 km) east of Madison. Five houses were occupied; the sixth house was unoccupied but sometimes humidified. The average rate of humidification was measured by tracking the amount of water used by the humidifier. The average rate during operation was 0.48 lb/h (0.22 kg/h).

The houses were made by three different home manufacturers. Table 1 lists house dimensions, house age, and number of occupants. The two newest houses had furnaces with fans that periodically ventilated the attics. Timers turned these fans off and on at four-hour intervals. No homeowners reported significant moisture problems, nor was there any evidence of problem during the measurement periods.

Procedures and Results

During a two-week period in December 1989 and January and February 1990, indoor relative humidity (RH) and temperature were recorded continuously with a hygrothermograph located in the living room. The data were reduced to hourly averages to facilitate analysis. **Table 2** lists some average temperature and relative humidity statistics.

Air infiltration was measured periodically in each house using a sulfur hexafluoride gas tracer decay technique. Generally, three air samples were collected three or more times at 1- to 1.5-hour intervals after the air was allowed to mix for one hour or more. The average of the three samples was used to calculate ventilation rates. Table 3 lists the results of the measurements and weather data from the Madison airport, which was approximately 20 miles (32 km) from the test site. For all houses except house 2, 50% or more of the measured ventilation rates were below the ASHRAE minimum ventilation standard of 0.35 ACH. The measurements were taken during the coldest three months when ventilation rates can be expected to be highest. Thus, we concluded that most of the time during winter these houses do not meet recommended ventilation levels.

The results were also correlated with results obtained with the air infiltration formula for a mobile home given by Goldschmidt and Wilhelm (1981):

$$I = 0.034 + 599\ (T_{a,i} - T_{a,o})/(T_{a,i} \bullet T_{a,o}) + 2.92\ w^2/T_{a,o} \qquad (1)$$

where

I = ventilation rate (1/h),
$T_{a,i}$ = indoor air temperature (K),
$T_{a,o}$ = outdoor air temperature (K), and
w = wind speed (m/s).

Figure 1 compares measured and calculated ventilation rates. The formula tended to significantly overpredict ventilation, but discrepancies should be expected from errors in measurement, differences in construction, differences in terrain, and discrepancies between local weather conditions and conditions recorded at the Madison airport. There was a poor correlation between ventilation rate, temperature, and wind speed; therefore, the constant measured average, as shown in Table 3, was used for our analysis.

TABLE 3
Results of Ventilation Measurements, December 1989 to February 1990

Date	Ventilation by house (ACH)[a] #1	#2	#3	#4	#5	#6	Outdoor temperature[b] °F	(°C)	Wind speed[c] mi/h	(m/s)
12/19	--	--	--	0.88[c]	0.96	--	3	(-16.1)	8.2	(3.7)
12/21	0.82	0.99	0.51	0.81	--	--	-13	(-23.0)	14.9	(6.7)
1/18	--	--	--	--	--	0.4	27	(-2.8)	11.4	(5.1)
1/23	0.54	--	0.22	--	0.14	0.18	33	(0.6)	11.3	(5.1)
1/24	0.27	--	0.16	0.45	--	0.23	36	(2.2)	11.9	(5.3)
1/26	0.44	--	0.27	0.33	0.33	0.4	23	(-5.0)	10.9	(4.9)
1/29	--	--	--	--	0.38	--	11	(-0.6)	11.2	(5.0)
1/30	0.30	--	0.13	0.25	0.38	0.34	29	(-1.7)	15.6	(7.0)
2/14	--	--	0.14	0.14	0.11	0.04	19	(-7.2)	15.3	(6.8)
2/16	0.16	0.43	0.43	0.27	--	0.86	25	(-3.9)	14.9	(6.7)
Average (ACH)	0.42	0.71	0.27	0.45	0.38	0.35				
Standard deviation	0.24	0.40	0.15	0.28	0.31	0.26				
ACH<0.35 (%)	50	0	71	57	50	57				

[a] ACH is air changes per hour.

[b] Average for the day, Madison airport.

[c] Based on two air samples.

HUMIDITY MODEL

The mathematical model calculates indoor relative humidity as a function of occupancy, ventilation, and moisture storage characteristics of the house (TenWolde 1988). The concept for the modified and the original models is based on the view that the model should he as simple as possible and require minimum input data.

To create the modified model, some modifications were made to the original. In the new model, moisture storage is related to an exponentially weighted hack average of indoor relative humidity rather than the arithmetic average used originally. This lets the model represent the actual sorption phenomenon better and allows one to report the results in terms of time constants. The effect of this change was checked by comparing results from the modified model with results from the original, using previously collected data in one of three occupied site-built houses described by TenWolde (1988). A best fit was found with a storage time constant of three days (compared to an arithmetic averaging period of one week) with all other parameters equal. Model prediction accuracy was virtually identical to that of the original. Because the storage averaging period was the same for all three houses. it was concluded that the moisture-storage time constant for the three site-built houses was on the order of three days. The modified model performs hourly calculations, rather than one calculation every three hours. and can accommodate a 24-hour cycle of hourly moisture release and indoor temperature input data. It optionally calculates relative humidity and the condensation/evaporation rate on a cold surface of choice, which may he an interior gluing surface or any other interior surface of the exterior building envelope.

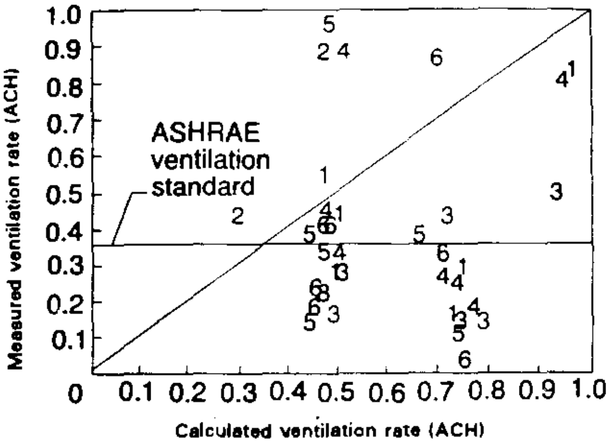

Figure 1 ***Measured ventilation rates and rates calculated with Equation 1 by house number (ACH = air changes per hour).***

Mathematical Basis

The model is based on a simple mass balance, including terms for moisture generation, sorption. ventilation, and condensation (optional):

$$Q_g - Q_a - Q_v - Q_c = 0 \qquad (2)$$

where

Q_a = moisture sorption rate. lb/h (kg/s);
Q_c = condensation rate on cold surface, lb/h (kg/s);
Q_g = moisture generation rate, lb/h (kg/s); and
Q_v = moisture loss through ventilation, lb/h (kg/s).

The moisture sorption rate is positive for adsorption (wetting) and negative for desorption (drying). Equation 2 ignores moisture loss by vapor diffusion through the exterior envelopes because it is generally small compared to ventilation losses.

Moisture Sorption The moisture sorption term represents the moisture storage capacity and is defined as

$$Q_a = k \bullet A(f_i - f_{i,t}) \qquad (3)$$

where

A = total floor area of the building, ft^2 (m^2);
k = sorption constant per unit of floor area, lb/h·ft^2 (kg/s·m^2);
f_i = indoor RH, %; and
$f_{i,t}$ = indoor RH, exponentially weighted time average, %.

The sorption constant, *k,* is related to the exposed area of hygroscopic materials available for storage and regulates the rate of moisture exchange. The term $f_{i,t}$, represents the hygric “memory” of the interior and is defined as

$$\phi_{i,\tau} = \sum_{n=N-4\tau}^{N-1} W(n)\,\phi_i(n) \Big/ \sum_{n=N-4\tau}^{N-1} W(n) \tag{4}$$

where

N = current hour;
t = moisture storage time constant of the interior. h; and
$W(n)$ = exponential weight factor.

The exponential weight factor, $W(n)$, in Equation 4 is defined as

$$W(n) = e^{-(N-n)/\tau}. \tag{5}$$

The weight factor assigns greater importance to the more recent indoor humidity history. It becomes very small for humidity conditions that are "older" than four time constants, and those contributions are therefore ignored. The values of the parameters k and t likely depend on the type of construction and furnishings (i.e., plaster or gypsum-hoard walls, exposed solid wood floors or carpeting, wood furniture, books, etc.).

Ventilation Net moisture loss from ventilation is the difference between the water vapor in the exhaust air and the water vapor in the air entering the building:

$$Q_v = h \cdot A \cdot I(p_{s,i} \cdot \phi_i/100 - p_{v,o})/C_1 \tag{6}$$

where

C_1 = C_2/ρ_a := 641.33 in. Hg·ft^3/lb (1.36 10^5 m^2/s^2);
C_2 = 48.1 in. Hg (1.63 10^5 Pa):
h = average room height, ft (m);
I = ventilation rate, 1/h (1/S);
$P_{s,i}$ = indoor saturation vapor pressure, in. Hg (Pa);
$P_{v,o}$ = outdoor vapor pressure. in. Hg (Pa); and
r_a = density of air. lb/ft^3 (kg/m^3).

If there is no condensation or it is ignored (Q_c = 0), Equations 2, 3, and 6 can be combined and written as

$$\phi_i = \frac{Q_g + k \cdot A \cdot \phi_{i,\tau} + h \cdot A \cdot I \cdot p_{v,o}/C_1}{k \cdot A + p_{s,i}[h \cdot A \cdot I/100C_1]}. \tag{7}$$

Condensation If the user wants to include surface condensation, the model checks to see if the temperature at the inside surface of the user-specified cold surface is below the dew point of the indoor air. The surface temperature is determined from

$$T_c = T_i - (U/h_i)(T_i - T_o) \tag{8}$$

where

T_c = surface temperature of cold surface, °F (°C);
T_i = indoor air temperature, °F (°C);
T_o = outdoor air temperature. °F (°C);
h_i = inside heat transfer coefficient, Btu/h·°F·ft^2 (W/m^2·K); and
U = total thermal conductance, Btu/h·°F·ft^2 (W/m^2·K).

The model assigns a value of 1.47 Btu/h·°F·ft^2 (8.35 W/m^2·K) to the inside heat transfer coefficient. The user may specify U, which includes heat transfer at both inside and outside surfaces. If the surface temperature is below the dew point of the indoor air, condensation takes place. If the surface temperature is above the dew point but the surface is still wet from previous condensation, evaporation occurs. The rate of wetting or drying is

$$Q_c = (S \cdot d/C_2)(\phi_i \cdot p_{s,i}/100 - p_{s,c}) \tag{9}$$

where

S = area of cold surface, ft^2 (m^2);
d = mass transfer coefficient, lb/h·ft^2 (kg/s·m^2); and
$P_{s,c}$ = saturation vapor pressure at cold surface, in. Hg (Pa).

The value of d is ste at 1.1 lb/h·ft^2 (0.0015 kg/s·m^2). The model considers only one condensing surface in the house.

by combining Equations 2, 3, 6, and 9, we arrive at the following formula for indoor relative humidity for the condensation/evaporation case:

$$\frac{\left[\begin{matrix} Q_g + k \cdot A \cdot \phi_{i,\tau} \\ + h \cdot A \cdot I \cdot p_{v,o}/C_1 + S \cdot d \cdot p_{s,c}/C_2 \end{matrix}\right]}{\left(\begin{matrix} k \cdot A + p_{s,i}[h \cdot A \cdot I/100C_1 \\ + S \cdot d/C_2] \end{matrix}\right)} \tag{10}$$

The model tracks the accumulation of condensate. Equation 10 is used as long as there is condensation or sondensate to be re-evaporated.

Ventilation and Mechanical Ventilation Control Options

The model currently offers several options for specifying ventilation:

- constant natural ventilation,
- variable natural ventilation as a function of temperatures and wind speed,
- continuous mechanical ventilation,
- mechanical ventilation with timer control, and
- mechanical ventilation with humidistat control.

The total ventilation is determined by adding the natural and mechanical ventilation quadratically:

$$I^2 = I_{nat}^2 + I_{fan}^2. \tag{11}$$

The program accepts a constant natural ventilation rate or calculates the natural ventilation rate with a generic form of Equation 1:

$$I_{nat} = a + b(T_{a,i} - T_{a,o})/(T_{a,i} \cdot T_{a,o}) + cw^2/T_{a,o}. \tag{12}$$

The user may specify parameters a, b, and c or use the default values in Equation 1.

The timer control in the model allows one on/off cycle per day. The humidistat control is assumed to have a deadband of 6% RH, i.e., the ventilation switches on at a setpoint of 3% RH above the RH setpoint and switches off at 3% RH below the setpoint. The program compares indoor relative humidity with the on/off criterion every six minutes, and the ventilation is turned (or remains) on or off accordingly.

MOISTURE GENERATION AND MOISTURE STORAGE ANALYSES

Measured and calculated relative humidity was compared using a trial-and-error method, varying the average moisture generation rate and sorption parameters. Then the combination of input parameters with the smallest difference between measured and calculated relative humidity was selected, based on the average of the difference and the sum of the squares of the difference. A large average difference primarily indicates an inappropriate choice of the average moisture generation rate, while the sum of the squares of the difference is sensitive to the choice of storage parameters as well. Final selection of parameters was also based on a visual inspection of graphs of the calculated and measured results. While seasonal average ventilation rates were used, surface condensation was not consided in the analysis. There were insufficient ventilation data for analyzing house 2. The results for the other houses are tabulated in Table 4.

TABLE 4
Moisture Release and Storage Characteristics of Manufactured Houses and Measured and Predicted RH Values

	House[a]				
Characteristic	#1	#3	#4	#5	#6
Average ventilation rate (ACH)	0.4	0.3	0.45	0.4	0.35
Floor area ($ft^2(m^2)$)	1216 (113)	924 (86)	924 (86)	924 (86)	1056 (98)
Number of occupants	1,2[b]	2	1	2	0
Moisture generation					
Unadjusted (lb/h(10^{-6}kg/s))	0.6 (76)	0.5 (63)	0.6 (75)	0.6 (75)	0.48[c] (60)
Per person (lb/h (10^{-6}kg/s)	0.46 (58)	0.25 (32)	0.6 (75)	0.3 (38)	-- (--)
Moisture storage parameters					
Time constant t (h)	24	9	9	9	9
Sorption rate k (10^{-3}lb.h · ft^2 (10^{-6}kg/s · m^2))	0.3 (0.41)	0.2 (0.27)	0.2 (0.27)	0.2 (0.27)	0.05 (0.068)
Measured-calculated RH (DRH)					
Average DRH (%)	0.23	-3.2	0.016	0.33	-4.1
Pavg(DRH^2) (%)	1.05	5.06	2.12	2.72	5.48
Square of correlation coefficient (R^2)	0.90	0.23	0.72	0.68	0.80

[a] Ventilation data for house #2 were insufficient for analysis.

[b] One occupant during the week, two during the weekend. Average occupancy is 1.3.

[c] Humidifier.

Moisture Generation

The unadjusted moisture release in the houses with one or two occupants varied between 0.5 and 0.6 lb/h (63 and 75 × 10^{-6} kg/s). The average generation rate was 0.58 lb/h (72 × 10^{-6} kg/s) with a standard deviation of 0.05 lb/h (6 × 10^{-6} kg/s). This translates into 14 lb/day (6.2 kg/day), which corresponds lo a range of 7 to 17 lb/day (3.3 to 8 kg/day) for site-built houses of similar size with single occupancy (TenWolde 1988). These values also fall within the range of moisture production rates reported by others.

The average moisture generation rate per person was 0.40 lb/h (51 × 10^{-6} kg/s) with a large standard deviation of 0.16 lb/h (20 × 10^{-6} kg/s). The moisture release data show no clear relationship with the number of occupants. Moisture generalion depends on other factors besides occupancy, such as moisture from cleaning and house plants (Hite and Bray 1948). More recently, large background contributions from the foundation and soil have been recognized as well.

Moisture Storage

The unoccupied house (#6) offered the opportunity to observe the moisture sorption behavior by turning the humidifier off and on. We measured the average water consumption of the humidifier and the average ventilation rate, leaving only storage parameters as unknowns. The house exhibited a relatively low capacity for moisture storage. **Figure 2** shows the match between measured relative. humidity and results from the model using a time constant of nine hours and a sorption rate of 0.05 lb/h · ft^2 (0.068 × 10^{-6} kg/s·m^2). The humidifier was removed at noon on February 23. The model's results closely followed

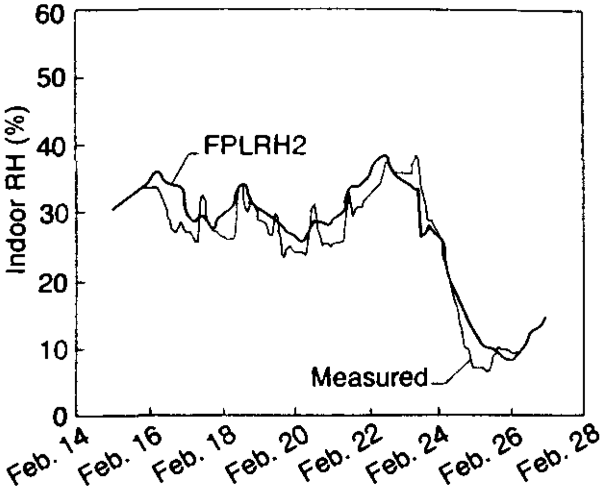

Figure 2 ***Measured indoor relative humidity in unoccupied manufactured house (#6) and results obtained with model.***

the measured decay in relative humidity. Results were similarly close during a humidifier shutoff in December.

The occupied houses appeared to store more moisture than did the unoccupied house. as evidenced by a sorption rate for occupied houses that was four to six times higher than that of the unoccupied house. However, the apparent time constant was the same for houses 3, 4, and 5 (nine hours). Only house 1 exhibited a larger time constant (24 hours). The difference between the occupied and unoccupied house was probably due to differences in interior furnishings and other moisture-adsorbing materials; house 6 was a show model with very little furniture and no books, magazines, clothing, or other such items.

In general, the model's results for houses 1, 4, and 5 closely matched measured indoor relative humidity. Figure 3 illustrates this with some of the measured and calculated relative humidity for house 4. Indoor relative humidity in house 3 followed a less predictable pattern. which was most likely caused by unknown variations in the number of occupants and occupant activities (Figure 4). Figure 4 shows that even for this house, the model predicted relative humidity accurately part of the time.

The results indicate that there was less long-term moisture storage in manufactured houses than in site-built houses; a 9-hour to 24-hour time constant corresponds with 72 hours (3 days) for several site-built houses. However. the sorption constant for the occupied manufactured houses varied between 0.2 and 0.3 × 10^{-3} lb/h·ft^2 (0.27 and 0.41 × 10^{-6} kg/s·m^2) compared to 0.033 × 10^{-3} lb/h·ft^2 (0.045 × 10^{-6} kg/s·m^2) for site-built houses. Apparently, moisture in manufactured houses moves more rapidly in and out of storage than in site-built houses. These results mean that relative humidity conditions in manufactured houses are likely to change more rapidly with changes in weather and occupancy and that moisture storage can suppress the effect of short-term events such as showers and cooking.

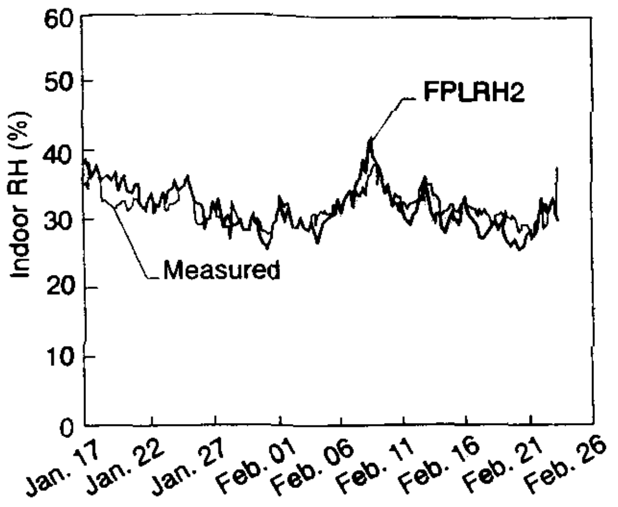

Figure 3 ***Measured indoor relative humidity in occupied manufactured house (#4) and results obtained with model.***

VENTILATION AND HUMIDITY ANALYSES

The model was used to determine the likely effect of various ventilation strategies on indoor humidity. condensation potential on double-glazed windows, comfort and health, and energy consumption during winter. The analysis was done for a single-wide house, with some additional analysis for a double-wide house. The analysis covers two locations—Madison, Wisconsin, a cold winter climate, and Portland, Oregon, a Pacific Northwest climate—and covers the period from October 1 through March 31, using ASHRAE weather year for energy calculations (WYEC) weather data. Four ventilation options were evaluated: natural ventilation as a function of temperatures and wind speed (no mechanical ventilation). continuous mechanical ventilation, mechanical ventilation on timer (one on/off setting per day), and mechanical ventilation on humidistat. Occupancy, airtightness, mechanical ventilation capacity, humidistat setting, moisture storage parameters, and thermostat settings were varied.

House Characteristics

The single-wide and double-wide houses in this analysis were identical to the houses evaluated by Burch (1991). The dimensions and other pertinent construction features are described in **Table 5.** We assumed that closets, cabinets, and interior furnishings reduced the inside volume available for ventilation by 14% (Burch 1991). The assumed glazing area is approximately 8% of the floor area, which is the required minimum glazing area (U.S. Department of Housing and Urban Development 1990).

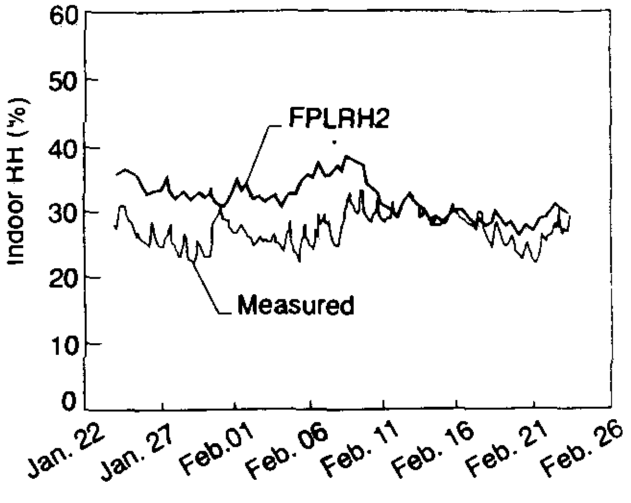

Figure 4 ***Measured indoor relative humidity in occupied manufactured house (#3) and results obtained with model.***

TABLE 5
Description of House Used for Analysis

Characteristic	Measurements Single-wide	 Double-wide
Outside length 1ft (m))	66 (20.1)	56 (17.1)
Inside length (ft (m))	65.3 (19.9)	55.3 (16.9)
Outside width (ft (m))	24 (1.31	28 (8.5)
Inside width (ft (m))	13.3 (4.1)	27.3 (8.3)
Ventilated floor area (ft^2 (m^2))	746.9 (69.4)	1,509.7 (140.3)
Height (ft (m))	7.5 (2.3)	7.5 (2.3)
Window area (ft^2 (m^2))	60 (5.6)	121 (11)
Window thermal transmittance ($Btu/h \cdot °F \cdot ft^2$ ($W/m^2 \cdot K$))	0.51 (2.9)	0.51 (2.9)

TABLE 6
Moisture Release Used in Analysis

Time (h)	Moisture release for two adults/ two children (lb/h (10^{-6}kg/s))	Characteristic for two adults/ two children	Moisture release for two adults (lb/h (10^{-6}kg/s))	Characteristic for two adults
1	0.8 (101)	All resting	042 (53)	Both resting
2	0.8 (101)		042 (53)	
3	0.8 (101)		0.42 (53)	
4	0.8 (101)		042 (53)	
5	0.8 (101)		0.12 (53)	
6	0.8 (101)		0.42 (53)	
1	2.1 (290)	3 showers	1.82 (229)	2 showers
8	1.1 (139)	1 adult, 1 shower	0.42 (53)	1 adult
9	1 (126)	Dish washing, etc.	0.62 (78)	Dish washing, etc.
10	1 (126)		0.62 (18)	
11	0.6 (76)		042 (53)	
12	0.6 (76)		0.42 (53)	
13	0.6 (76)		0.42 (53)	
14	0.2 (25)	No occupants	0.02 (3)	No occupants
15	0.2 (25)		0.02 (3)	
16	0.6 (16)	1 adult	0.42 (53)	1 adult
17	0.8 (101)	Children home	0.42 (53)	
18	4.1 (517)	Cooking, all home	2.52 (318)	Cooking, 2 adults
19	1.4 (176)	Dish washing	1.22 (154)	Dish washing
20	1.2 (151)		0.61 (18)	
21	1.1 (139)		0.62 (78)	
22	0.8 (101)	All resting	042 (18)	Both resting
23	0.8 (101)		0.42 (53)	
24	0.8 (101)		0.42 (53)	

Indoor Conditions

The indoor temperature was a constant 70°F (21.1°C), except for a few runs with a thermostat setback to 65°F (18.3°C) from 10 p.m. to 7 a.m.

Occupancy and Moisture Generation

To be able to draw a comparison with results from a previous analysis by Burch (1991). some runs were made with a constant 1 lb/h (126 × 10^{-6} kg/s) moisture generation rate. The rest of the runs were done with two 24-hour cycles of hourly moisture release input data—one for two adults and two children to simulate high moisture loads and one for two adults to represent a more moderate load (Table 6). The rates were adapted from published data for various occupant activities (Hite and Bray 1948). The daily rate for two adults and two children was 24 lb/day (10.9 kg/day). allowing a comparison with the results for the constant release rate. The daily release rate for two adults was 14.4 lb/day (6.53 kg/day), which is about the same as the measured average in the four occupied manufactured houses. The main difference between the two cycles, besides the number of occupants, is in background moisture release: 0.2 lb/h (25 × 10^{-6} kg/s) for the two adults/two children cycle and 0.02 lb/h (3 × 10^{-6} kg/s) for the other cycle.

Moisture Storage

The most prevalent measured combmation of t = 9h and k = 0.2 × 10^{-3} lb/h·ft^2 (0.27 × 10^{-6} kg/s·m^2) was used in most runs. Some results were obtained with no moisture storage and some with high moisture storage: t = 24 hours and k = 0.3 × 10^{-3} lb/h·ft^2 (0.41 × 10^{-6} kg/s·m^2), which match the measured parameters for house 1.

Ventilation

The natural ventilation rate as specified by Equation 1 (Goldschmidt and Wilhelm 1981) was used for most runs (“standard” airtightness). Burch (1991) used the same formula and parameter values in his analysis. For Madison, this results in average natural ventilation rates of 0.44 to 0.47 ACH during the three coldest winter months, using monthly average temperatures and wind conditions. The measured average ventilation in five of the six manufactured houses was between 0.27 and 0.45 ACH (Table 3).

To evaluate airtight construction, several runs were done with much lower values for the parameters a. b, and *c* in Equation 12: *a* = 0, *b* = 200, and *c* = 1 (compared to 0.034, 599, and 2.9). This indicated natural ventilation rates of 0.14 to 0.15 ACH for Madison and 0.11 to 0.12 ACH for Portland during winter. These low natural ventilation rates can he achieved with careful airtight construction, but most of the currently existing manufactured houses probably fall between these two levels of airtightness. All runs for Portland were done with airtight construction.

The capacity of the mechanical ventilation system was 55 cfm (26 L/s). This capacity was found to be insufficient in the airtight house, and a capacity of 80 cfm (38 L/s) was used. It was assumed that the systems delivered their full rated flows. Hadley and Bailey (1990), as well as others, found that ventilation systems often performed well below their rated capacities for a variety of reasons. To ensure the above ventilation rates, the rated capacities of the systems should probably he at least 80 cfm (38 L/s) and 100 cfm (47 L/s). respectively.

The timer-controlled ventilation ran 50% of the time. turning on at 6 p.m. and off at 6 a.m. The humidistat settings were 35% and 40% RH in Madison and 50% and 40% RH in Portland.

Evaluation Criteria

Current standards for ventilation and health and comfort provide criteria by which to evaluate the results. In addition. we calculated the portion of the space heating attributable to ventilation to provide a measure of the effect of various evaluation strategies on energy consumption.

ANSI/ASHRAE Standard 62-1989. Ventilation for Acceptable Indoor Air Quality, lists the following requirements for living areas in residential buildings. There should be 0.35 ACH but not less than 15 cfm (7.5 L/s) per person. The standard states that occupant loading shall be based on the number of bedrooms as follows: first bedroom, two persons: each additional bedroom. one person. Where higher occupant loadings are known, they shall be used. The standard also lists requirements for kitchen and bathroom exhaust fans but provides an exemption when openable windows are present. On the basis of this standard, the ventilation results were evaluated using both the 0.35-ACH criterion and the 15 cfm (7.5 L/s) per person criterion. The first criterion is important for removal of background pollutants such as formaldehyde, while the second criterion is occupancy sensitive and aimed at dilution of pollutants from occupants and their activities.

ANSI/ASHRAE Standard 55-1981, Thermal Environmental Conditions for Human Occupancy (ASHRAE 1981), provides guidance for comfort criteria for indoor relative humidity. The standard indicates that at 70°F (21.1 °C) the. relative humidity should be between 28% and 78%. Thus, at nod indoor temperatures the air is experienced as too dry if the relative humidity is less than 28%. Relative humidities of more than 78% are likely to encourage mold and mildew growth, which may lead to respiratory and other health problems, odors, and discoloration of surfaces. The standard also mentions an ideal relative humidity between 30% and 60% to minimize growth of allergenic or pathogenic organisms, but this range is too restrictive for residential conditions. The results showed that the criterion for condensation on double-glazed windows was more stringent than the high-humidity criterion of 78% RH; therefore, only the condensation criterion was used.

Finally, the space-heating requirements caused by ventilation were calculated from the hourly ventilation rate and indoor-outdoor temperature differences. Power consumption by the ventilation system was not included.

Results for Madison, Wisconsin

To evaluate the adequacy of a ventilation strategy, results were expressed in terms of the percentage of time a given criterion was met or not met during the six-month evaluation period. Only energy consumption data are expressed in their original energy units.

Effect of Moisture Storage on Window Condemnation To gauge the importance of moisture storage on window condensation, we ran the following parameters:

House:	single-wide
Moisture release:	1 lb/h (126×10^{-6} kg/s)
Indoor temperature:	70°F (21.1°C)
Airtightness:	Standard
Mechanical ventilation capacity:	55 cfm (26 L/s)
Mechanical ventilation controls:	off, continuous, timer
Moisture storage:	none, standard, high

The case without moisture storage coincided with parameters used by Burch (1991). The results are shown in Figure 5 and confirm the need for mechanical ventilation to prevent condensation (Burch 1991). However, they also clearly show that even the moderate amount of moisture storage in a manufactured house considerably reduced the incidence of window condensation. Even with the moderate standard storage parameters, window condensation without mechanical ventilation decreased from 100% to 81% of the time and with the high storage parameters to 69% of the time. The results for mechanical ventilation with timer control showed this reduction even more dramatically; without storage, the windows were wet 49% of the time. but with storage, they were wet only 9% of the time. High storage reduced condensation to 8%. This means that because of moisture storage, the mechanical ventilation required to limit window condensation is probably less than that recommended by Burch (1991).

Occupancy The following parameter values were used:

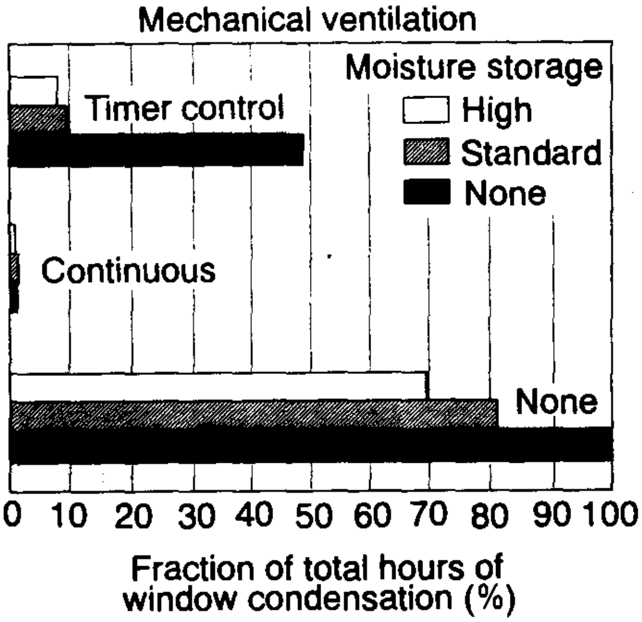

Figure 5 ***Effect of moisture storage on window condensation, Madison, Wisconsin (parameters same as those mentioned in text).***

House: single-wide
occupancy: two adults, two adults/two children
Indoor temperature: 70°F (21.1°C)
Airtightness: standard
Mechanical ventilation
capacity: 55 cfm (26 Lis)
Mechanical ventilation
controls: off, continuous, timer, humidistat (40% and 35% RH setpoints)
Moisture storage: standard

Table 7 shows that window condensation was not a significant problem with only two adults, but with two adults and two children, window condensation occurred more than 40% of the time, indicating a need for mechanical ventilation. For two adults and two children, continuous ventilation almost completely prevented condensation but caused the air to be too dry almost 30% of the time. The timer and humidistat controls also reduced condensation to insignificant levels with fewer dry air problems. Without mechanical ventilation, air exchange was less than 0.35 ACH 43% of the time (independent of occupancy), and the per-person requirements were met 74% of the time with only two adults present. indicating a need for some additional ventilation. In the case of two adults and two children, per-person requirements were met only 46% of the time without mechanical ventilation. The continuous mechanical ventilation improved this to 85% but caused significant problems with dry air. Neither the timer nor the humidistat controls satisfied all ventilation criteria at all times, but they provided a compromise with improved ventilation and reduced problems with dry air while preventing condensation.

TABLE 7
Effect of Occupancy and House Size on Humidity and Condensation for Houses in Madison, Wisconsin[a]

Occupancy, house size, and ventilation control	Fraction of total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15 cfm (7.5 L/s) per person	Too dry
Two adults				
Single-wide house				
Off	12.4	42.6	26.3	19.1
Continuous	0	0	0	42.0
Timer (on 6 p.m. - 6 a.m.)	1.0	18.8	5.2	33.4
Humidistat, 35% RH	0.1	10.8	4.6	23.1
Humidistat, 40% RH	0.2	18.4	9.1	20.3
Two adults/two children				
Single-wide house				
Off	41.2	42.6	53.5	9.0
Continuous	1.0	0	14.9	29.4
Timer (on 6 p.m. - 6 a.m.)	4.4	18.8	23.7	18.5
Humidistat, 35% RH	1.5	5.0	28.2	12.8
Humidistat, 40% RH	2.2	10.1	34.3	11.2
Double-wide house				
Off	2.2	42.6	24.7	39.1
Continuous	0.2	9.6	1.0	46.0
Timer (on 6 p.m. - 6 a.m.)	0.5	24.3	5.0	42.3
Humidistat, 35% RH	0.2	24.2	7.8	40.9
Humidistat, 40% RH	0.2	31.9	12.7	39.6

[a] Indoor temperature: 70°F (21.1°C)
Airtightness: standard
Mechanical ventilation capacity: 55 cfm (26 L/s)
Moisture storage: standard

How Size The following parameter values were used:

House: single-wide. double-wide
occupancy: two adults/two children
Indoor temperature: 70°F (21.1°C)
Airtightness: standard
Mechanical ventilation
capacity: 55 cfm (26 Lis)
Mechanical ventilation
controls: off, continuous, timer, humidistat (40% and 35% RH setpoints)
Moisture storage: standard

Table 7 shows that, in contrast to the single-wide house, no Significant condensation problems were indicated in the double-wide house with two adults and two children. Per-person ventilation was adequate at least 75% of the time, even without mechanical ventilation, but the 0.35-ACH criterion was met only 57% of the time. Therefore, some mechanical ventilation was desirable, either timer- or humidistat-controlled. Dry air was a problem in the double-wide house, but the problem was not aggravated much by additional ventilation, Humidification should be considered in this case.

Thermostat Setback The following parameter values were used:

House: single-wide
occupancy: two adults/two children
Indoor temperature: 70°F (21.1°C), setback cycle
Airtightness: standard
Mechanical ventilation
capacity: 55 cfm (26 L/s)
Mechanical ventilation
controls: off, continuous, timer, humidistat (40% and 35% RH setpoints)
Moisture storage: standard

The thermostat setback to 65°F (18.3°C) had little effect on any of the factors evaluated (Table 8). The setback cycle increased condensation from 41% to 51% of the time, but all ventilation strategies adequately solved this problem. Ventilation and dryness were not much affected.

Airtightness The following parameter values were used:

House: single-wide
occupancy: two adults, two adults/two children
Indoor temperature: 70°F (21.1°C)
Airtightness: airtight
Mechanical ventilation
capacity: 55 cfm (26 L/s), 80 cfm (38 L/s)

TABLE 8
Effect of Thermostat Setback on Humidity and Condensation for Houses in Madison, Wisconsin[a]

Thermostat setting and mechanical ventilation control	Fraction of total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15 cfm (7.5 L/s) per person	Too dry
Indoor temperature 70°F (21.2°C)				
Off	41.1	42.6	53.5	9.0
Continuous	1.0	0	14.9	29.4
Timer (on 6 p.m. - 6 a.m.)	4.4	18.8	23.7	18.5
Humidistat, 35% RH	1.5	5.0	28.2	12.8
Humidistat, 40% RH	2.2	10.1	34.3	11.2
Setback cycle				
Off	50.8	44.4	54.0	5.8
Continuous	1.8	0	16.9	23.6
Timer (on 6 p.m. - 6 a.m.)	7.8	19.0	25.8	13.9
Humidistat, 35% RH	2.3	3.6	26.8	9.8
Humidistat, 40% RH	3.1	8.1	32.6	8.2

[a] House: single-wide
Occupancy: two adults/two children
Setback cycle: 70°F (21.2°C) 7 a.m. - 10 p.m.: 65°F (18.3°C)
10 p.m. - 7 a..m.
Airtightness: standard
Mechanical ventilation capacity: 55 cfm (26 L/s)
Moisture storage: standard

TABLE 9
Effect of Occupancy on Humidity and Condensation in Airtight House in Madison, Wisconsin.

Occupancy and mechanical ventilation control	Fraction of total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15 cfm (7.5 L/s) per person	Too dry
Two adults				
Off	98.8	96.8	77.4	0
Continuous	0.1	0	0	31.0
Timer (on 6 p.m. - 6 a.m.)	8.0	48.3	29.4	3.7
Humidistat, 35% RH	3.3	20.8	12.7	0.1
Humidistat, 40% RH	10.2	34.0	21.7	0
Two adults/two children				
Off	99.1	96.8	81.1	0
Continuous	22.3	0	53.3	13.4
Timer (on 6 p.m. - 6 a.m.)	45.9	48.3	76.8	0
Humidistat, 35% RH	6.6	9.8	57.0	0
Humidistat, 50% RH	15.6	19.0	60.0	0

[a] House: single-wide
Indoor temperature: 70°F (21.1°C)
Airtightness: airtight
Mechanical ventilation capacity: 55 cfm (26 L/s)
Moisture storage: standard

TABLE 10
Effect of Capacity of Mechanical Ventilation System on Humidity and Condensation in Airtight House in Madison, Wisconsin[a]

Ventilation system capacity and mechanical ventilation control	Fraction of total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15 cfm (7.5 L/s) per person	Too dry
55 cfm (26 L/s)				
Continuous	2.4	0	53.3	13.4
Timer (on 6 p.m. - 6 a.m.)	45.9	48.3	76.8	0
Humidistat, 35% RH	6.6	9.8	57.0	0
80 cfm (38 L/s)				
Continuous	0	0	0	34.7
Timer (on 6 p.m. - 6 a.m.)	11.0	48.3	31.2	4.0
Humidistat, 35% RH	4.7	23.2	16.1	0

[a] House: single-wide
Occupancy: two adults/two children
Indoor temperture: 70°F (21.1°C)
Airtightness: airtight
Moisture storage: standard

Mechanical ventilation controls: off, continuous, timer, humidistat (40% and 35% RH setpoints)
Moisture storage: standard

Table 9 shows that condensation was a serious problem in the airtight house, even with only two occupants. Mechanical ventilation generally solved the condensation problem, but even running the mechanical ventilation continuously did not satisfy the per-person ventilation requirements for two adults and two children. Dryness was not a significant problem in the airtight house. Table 10 shows the effect of increasing the capacity of the mechanical ventilation system to 80 cfm (38 L/s) with two adults and two children. A larger ventilation system that ran continuously satisfied all ventilation criteria. The humidistat set at 35% RH delivered significantly better ventilation than the timer, posed fewer problems with dryness, and appeared to be a viable alternative to continuous mechanical ventilation.

Increase in Space-Heating Requirements Caused by Mechanical Ventilation Table 11 lists the increase in space-heating requirements caused by the mechanical ventilation system during the period from October 1 through March 31. The power requirements for the ventilation equipment were not included. These values are based on the assumption that natural and mechanical ventilation add quadratically (Equation 11). With that assumption, the increase in heat loss from mechanical ventilation is larger in airtight houses than in nonairtight houses. The ventilation standard generally was best satisfied with continuous mechanical ventilation, but the energy penalties were not always insignificant when compared to other heat losses. For instance, beat loss from natural ventilation in the single-wide standard house was about 8.6 × 10^6 Btu (2,500 kWh) over the six-month period. Continuous 55-cfm (26-L/s) mechanical ventilation increased this by more than 60% to 14 × 10^6 Btu (4.100 kWh). The effect on the airtight house was more dramatic; beat loss from ventilation increased by more than 470%. from 2.7 × 10^6 Btu (800 kWh) to 15.6 × 10^6 Btu (4,600 kWh), with continuous 80-cfm (38-L/s) mechanical ventilation.

Condensation control can be achieved with much less penalty. Humidistat control in the standard single-wide house resulted in increases of about 1.4 to 3.3 × 10^6 Btu (400 to 1,000 kWh), depending on occupancy, compared with about 5.4 × 10^6 Btu (1,600 kWh) for continuous mechanical ventilation. In the airtight house, the increase with a humidistat vaned from 4.6 to 8.8 × 10^6 Btu (1,300 to 2,600 kWh), depending on occupancy and the mechanical ventilation system. This compares with 8.3 to 12.9 × 10^6 Btu (2,400 to 3,800 kWh) for continuous mechanical ventilation.

TABLE 11
Increase in Space-Heating Requirements Caused by Mechanical Ventilation, Madison, Wisconsin, October 1 to March 31[a]

House size, occupancy, and mechanical systam capacity	Increase in space heating arranged by ventilation control (106 Btu (kWH))			
	Continuous	Timer	Humidistat 40% RH	Humidistat 35%RH
Double-wide, two adults/two children, 55 cfm	3.4 (1,000)	1.9 (560)	0.7 (200)	1.3 (380)
Single-wide, two adults/two children, 55 cfm	5.4 (1,600)	2.9 (850)	2.4 (700)	3.3 (970)
Single-wide, airtight				
Two adults/two children				
55 cfm (26 L/s)	8.3 (2,400)	4.3 (1,300)	6.1 (1,300)	7.1 (2,100)
80 cfm (38 L/s)	12/9 (3,800)	6.8 (2,300)	8.0 (2,300)	8.8 (2,600)
Two adults				
55 cfm (26 L/s)	8.3 (2,400)	4.3 (1,300)	4.6 (1,300)	5.8 (1,700)
80 cfm (38 L/s)	12.9 (3,800)	6.8 (2,000)	NA	6.8 (2,000)

[a] Power requirements for mechanical ventilation are not included.

Results for Portland, Oregon

In Portland, only the airtight, single-wide house was evaluated and the humidistat settings were 50% and 40%. All other parameters were the same.

Occupancy and Mechanical Ventilation System Size The following parameter values were used:

House: single-wide
occupancy: two adults, two adults/two children
Indoor temperature: 70°F (21.1°C)
Airtightness: airtight
Mechanical ventilation capacity: 55 cfm (26 L/s), 80 cfm (38 L/s)
Mechanical ventilation controls: off, continuous, timer, humidistat (50% and 40% RH setpoints)
Moisture storage: standard

Table 12 shows the results for the two types of occupancy. Very serious condensation was indicated, even with only two occupants. With two adults and two children, even mechanical ventilation on a timer, running 50% of the time, did not adequately solve the condensation problem. Either the mechanical ventilation needed to run continuously or run on a humidistat control, but even then personal ventilation requirements were met less than half the time. As with the houses in Madison. Wisconsin, effective control of condensation was accomplished with less ventilation than was required to satisfy ventilation standards.

As with the airtight house in Madison. Wisconsin, a larger mechanical ventilation system is preferable (Table 13). The increased ventilation adequately satisfied ventilation requirements. even with the humidistat control. As was the case in Madison, the humidistat performed better than the timer in the airtight house. The results also indicate that dry air was not a serious problem in Portland during winter.

TABLE 12
Effect of Occupancy on Humidity and condensation in Airtight House in Portland, Oregon[a]

Occupancy and mechanical ventilation control	Fraction total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15cfm (7.5 L/s) per person	Too dry
Two adults				
Off	98.4	96.5	81.7	0
Continuous	0.5	0	0	3.2
Timer (on 6 p.m. - 6 a.m.)	15.2	48.0	32.7	0
Humidistat, 40% RH	0.5	5.9	3.9	0
Humidistat, 50% RH	1.1	20.4	14.1	0
Two adult/two Children				
Off	99.0	90.5	84.7	0
Continuous	2.8	0	54.3	0.6
Timer (on 6 p.m. - 6 a.m.)	67.8	48.0	81.4	0
Humidistat, 40% RH	2.8	2.6	55.5	0
Humidistat, 50% RH	1.6	10.0	58.5	0

[a] Housesingle-wide
Indoor temperature: 70°F (21.1°C)
Airtightness: airtight
Mechanical ventilation capacity: 55 cfm (26 L/s)
Moisture storage: standard

TABLE 13
Effect of Capacity of Mechanical Ventilation System on Humidity and Condenration in Airtight House in Portland, Oregon[a]

Ventilation system capacity and mechanical ventilation control	Fraction of total time (%)			
	Condensation	Less than 0.35 ACH	Less than 15 cfm (7.5 L/s) per person	Too dry
55 cfm (26 L/s)				
Continuous	2.8	0	54.3	0.6
Timer (on 6 p.m. - 6 a.m.)	67.8	48.0	81.4	0
Humidistat, 40% RH	2.8	2.6	55.5	0
Humidistat, 50% RH	4.6	10.0	58.5	0
80 cfm (38 L/s)				
Continuous	0.3	0	0	4.8
Timer (on 6 p.m. - 6 a.m.)	18.6	48.0	34.9	0.7
Humidistat, 40% RH	0.3	6.7	5.3	0
Humidisat, 50% RH	1.4	22.4	17.7	0

[a] House: single-wide
Occupancy: two adults/two children
Indoor temperature: 70°F (21.1°C)
Airtightness: airtight
Moisture storage: standard

Increase in Space–Heating Requirements Caused by Mechanical Ventilation Table 14 lists the increase in space-heating requirements caused by mechanical ventilation (ignoring electric power requirements for the mechanical ventilation system). Without mechanical ventilation. heat loss from natural ventilation was only about 1.3 × 10^6 Btu (380 kWh). To prevent condensation. mechanical ventilation with energy penalties between 2.8 and 4.6 × 10^6 Btu (800 and 1,400 kWh) sufficed. To adequately meet ventilation requirements for two adults and two children, a minimum energy penalty of about 5.8 × 10^6 Btu (1,700 kWh) was indicated.

DISCUSSION

The analysis covers only the period from October through March and does not address humidity and ventilation issues during the summer months. It also does not deal

TABLE 14
Increase in Space Heating Caused by Mechanical Ventilation. Portland. Oregon. October 1 to March 31[a]

House size, occupancy, and mechanical system capacity	Increase in space heating by arranged by ventilation control (x10^6 Btu (kWH))			
	Continuous	Timer	Humidistat 50% RH	Humidistat 40% RH
Single-wide,airtight				
Two adults/two children				
55 cfm (26 L/s)	5.4 (1,600)	2.8 (820)	4.7(1,400)	5.2 (1.500)
80 cfm (38 L/s)	8.4(2,500)	4.3(1,300)	5.8 (1,700)	7.4(2,200)
Two adults				
55 cfm (26 L/s)	5.4 (1,600)	2.8 (820)	3.9(1,100)	4.9(1,400)
80 cfm (38 L/s)	8.4 (2,500)	4.3(1,300)	4.6 (1,300)	6.9 (2,000)

[a] Power requirements for mechanical ventilation are not included.

with ventilation and humidity issues in southern climates. Air conditioning greatly affects indoor humidity conditions. and a humidistat may not provide appropriate control for ventilation during the summer.

The assumption that natural and mechanical ventilation add quadratically is quite controversial. If the ventilation system significantly changes the pressure in the house, the natural Ventilation pattern is completely changed and natural ventilation may become negligible. In that use. more mechanical ventilation is needed to obtain the some results. If the system is perfectly balanced and does not affect the indoor pressure, the natural and mechanical ventilation rates could simply be added to obtain the total ventilation rate. This means that less mechanical ventilation is needed. Reality is likely somewhere between these two extremes. Of course, this issue is less important in airtight houses.

The results show that meeting *ANSI/ASHRAE 62-1989* criteria requires mechanical ventilation in many manufactured houses, but the additional ventilation leads to additional heat loss. This additional heat loss is especially painful in energy-efficient, airtight houses. To question or discuss the validity of the standards is not within the scope of this paper, but insufficient ventilation may led to unacceptable indoor air quality and damage from excessive moisture. Concerns about health and durability should outweigh energy considerations.

Building as airtight as economically possible remains desirable because it provides better control and performance of the mechanical ventilation system. Entrance and flow of fresh air into the house can only be controlled in an airtight house. Airtight construction also provides the opportunity to install a heat recovery ventilator (also known as an air-to-air heat exchanger) to recover part of the ventilation heat loss and provide fresh air at a more comfortable temperature.

Problem with dry air in cold winter climates may be solved with additional humidification, which should probably be controlled with a humidistat to prevent excessive condensation during cold weather. An alternative to humidification is installing an enthalpy recovery ventilator (ERV). Because an ERV not only recovers part of the energy from the exhaust air but also returns some of the water vapor, it may solve or alleviate the problem with dry air. However, they are still relatively expensive and their effectiveness in providing ventilation and preventing condensation needs further evaluation.

Because of variations in ventilation needs, equipment performance. and the cost of overventilation, providing ventilation control that is sensitive to occupancy is desirable. The results of the analysis show that a humidistat control is far from perfect in providing ventilation but that it generally resulted in better ventilation than- timer control. It also prevented condensation on the windows with the least cost in energy. Other inexpensive controls that are more directly sensitive to occupant loads should be developed and evaluated. Controls that are carbon dioxide sensitive may offer a better alternative but are currently still expensive. In the interim. a humidistat provides a viable, inexpensive compromise during winter However, the ventilation should be sufficient at all times to remove non-occupant-related pollutants (e.g., formaldehyde). This may be accomplished by low-level, continuous mechanical ventilation.

CONCLUSIONS

Many manufactured houses require mechanical ventilation to supplement natural ventilation during winter to meet *ANSI/ASHRAE 62-1989* minimum criteria. In case of high occupancy, high moisture loads, or an airtight house. mechanical ventilation is also needed to prevent condensation on the windows.

Moisture storage in manufactured houses significantly reduces the potential for condensation during winter. Ventilation required to prevent condensation on double-glazed windows during winter is less than the minimum ASHRAE requirements.

Humidistatsontrolled ventilation generally provides better condensation control than does a timer-controlled system. Neither control guarantees that ASHRAE minimum ventilation levels are achieved at all times.

In cold winter climates, meeting all ventilation requirements without causing the indoor air to be too dry during winter is impossible unless the air is humidified or an enthalpy recovery ventilator is used.

Additional space-heating requirements caused by mechanical ventilation are significant when compared with other modes of heat loss, especially in an airtight, energy-efficient house. Energy penalties could be greatly reduced by using a heat recovery ventilator.

A moderate thermostat setback during the night does not significantly increase the potential for condensation.

RECOMMENDATIONS

The author recommends that manufactured houses be supplied with mechanical ventilation equipment with a minimum capacity of 55 cfm (26 L/s). In very airtight houses, the capacity should be larger. An automatic control that reacts to variable occupant ventilation needs should be provided with a manual override. Inexpensive controls and control strategies with good occupant sensitivity need to be developed to provide adequate ventilation at all times with a minimum loss of heat and comfort. Perhaps a carbon-dioxide-sensitive control can be used for this purpose. In the absence of a satisfactory inexpensive alternative. the author suggests that, during winter, the equipment be controlled with a humidistat to provide condensation control with minimum heat and comfort loss.

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NOMENCLATURE

r_a = density of air, lb/ft^3 (kg/m^3)
t = moisture storage time constant, h
f_i = indoor RH, %
f_{it} = indoor RH, exponentially weighted time average, %
f_0 = outdoor RH, %
A = total floor area of the building, ft^2 (m^2)
C_1 = C_2/r_a = 641.33 in. Hg·ft^3/lb (1.36 × 10^5 m^2/s^2)
C_2 = 48.1 in. Hg (1.63 × 10^5 Pa)
d = mass transfer coefficient, lb/h·ft^2 (kg/s·m^2)
h = average room height, ft (m)
h_i = inside heat transfer coefficient, Btu/h·°F·ft^2 (W/m^2·K)
I = ventilation rate, 1/s (1/h)
k = moisture sorption parameter, lb/h·ft^2 (kg/s·m^2)
$P_{s,c}$ = saturation vapor pressure at cold surface, in. Hg (Pa)
$P_{s,i}$ = indoor saturation vapor pressure, in. Hg (Pa)
$P_{v,0}$ = outdoor vapor pressure, in. Hg (Pa)
Q_a = moisture sorption rate, lb/h (kg/s)
Q_c = condensation rate on cold surface, lb/h (kg/s)
Q_g = moisture generation rate, lb/h (kg/s)
Q_v = moisture loss through ventilation. lb/h (kg/s)
S = area of cold surface, ft^2 (m^2)
$T_{a,i}$ = absolute indoor air temperature, K
$T_{a,0}$ = absolute outdoor air temperature, K
T_c = temperature of cold surface. °F (°C)
T_i = indoor air temperature, °F (°C)
T_0 = outdoor air temperature, °F (°C)
U = total thermal conductance. Btu/h·°F·ft^2 (W/m^2·K)
w = wind speed, mph (m/s)

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