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VENTILATION AND MOISTURE IN NEW ENERGY-EFFICIENT MANUFACTURED HOMES

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INTRODUCTION

Manufactured housing accounts for approximately 35% of new housing starts in the Pacific Northwest region of the United States. This segment of the housing market represents approximately 40 average megawatts(1) of potential end-use efficiency resource.[1] Many of the energy conservation measures implemented at the factory or during setup involve tightening of the shell, thereby reducing whole house infiltration. While these goal of these measures will reduce heating and cooling energy consumption, this energy savings is not without its negative side effects. Along with the reduced infiltration is the potential for increased levels of indoor air contaminates (including moisture) and a general lowering of the quality of the indoor air.

In order to establish a database of infiltration and ventilation characteristics in current practice manufactured housing, a multiyear field testing program was undertaken by the Bonneville Power Administration[2,3] begining in the mid-1980s. This program was later expanded to include 20 homes that had been upgraded to meet the regional Model Conservation Standards (MCS) for energy efficiency.[4] The results from these initial studies (Table I) indicates that significant improvement in shell tightness are possible. In fact, these new manufactured homes were also tighter than site-built homes constructed during the same time period that were tested as part of the Northwest Residential Infiltration Survey (NORIS).[5]

During the 1989-1990 heating season, Pacific Northwest Laboratory (PNL)(2) for the Office of Energy Resources, Bonneville Power Administration (Bonneville), measured the ventilation characteristics in 139 newly constructed energy-efficient manufactured homes and a sample of 35 current practice manufactured homes not built to the energy efficient standards. The new energy-efficient homes were built to the MCS. This phase of the program was part of Bonneville's Residential Construction Demonstration Program (RCDP). A standard blower door test was used to estimate shell leakiness, and a passive perfluorocarbon tracer (PFT) technique was used to estimate overall air exchange rates. In addition, one-time measurements of the designated whole-house exhaust system flow rate was taken. An occupant and structure survey was conducted at the time of the testing to obtain information on house characteristics, daily occupant activities and ventilation system operation. The homes were located in Oregon, Washington, Idaho, and western Montana.

This paper will summarize the infiltration/ventilation characteristics in this sample of new and energy-efficient manufactured homes built and situated in the Pacific Northwest. The reported incidence of moisture and/or condensation as observed by the occupants will also be detailed. These results should be indicative of conditions in new energy-efficient manufactured housing.

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(1) An average megawatt is 8760 megawatt-hours of energy

(2) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC-06-76-RLO 1830.

VENTILATION STANDARDS

The Super Good Cents (SGC) energy-efficiency technical specifications for manufactured homes[6] require that a mechanical ventilation system be installed that is capable of providing ventilation air to the whole house. The system may be either of two types. The first option is a whole-house system integrated with a spot ventilation system (normally a bath fan) capable of operating at a nominal ventilation rate of 50 cubic feet per minute (cfm). The second option is a separate whole-house system sized to provide the exhaust ventilation at a rate of 10-cfm per bedroom and combined living area. The whole-house system is to be controlled with a mechanical timer to operate automatically all year and to allow manual operation if desired. The automatic timer is to be based on time-of-day.

Makeup air for the whole-house system is to be provided through fresh-air ports installed in an exterior wall in each bedroom and the living area. They are to be sized to provide fresh air at a rate of 10 cfm per designated area.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) has established minimum ventilation rates to achieve acceptable indoor air quality, assuming that no unusual pollutant sources are in the building. The first ASHRAE ventilation standard was published in 1973; it was modified in 1981 and again in 1989. The revised standard (ASHRAE Standard 62-1981) specified minimum outside air exchange rates of 10 cfm per room, excluding bathrooms and kitchens. In 1989, ASHRAE revised the ventilation standard in response to studies showing that current ventilation rates were not sufficient to prevent pollutants from reaching unacceptable levels. The new standard (ASHRAE Standard 62-1989) specifies a minimum whole-house air exchange rate of 0.35 air change per hour (ACH) or an outside air flow rate of at least 15-cfm per occupant, whichever is greater[7].

The current U.S. Department of Housing and Urban Development (HUD) standard does not stipulate a minimum ventilation rate, but the new proposed HUD standard recommends a minimum rate of 0.35 ACH, and an outside air flow rate of at least 25 cfm.

SAMPLE AND PROTOCOL

Eight different manufacturers built the homes that participated in the RCDP program. Additional information regarding the study, sample, and protocol not included in the next two sections can be found in this study's final report.[8]

Sample Characteristics

The 139 newly constructed energy-efficient homes (RCDP) were built and set up for occupancy between March 1988 and October 1989. The set of current practice homes built to the HUD code consisted of ten new homes (hereafter referred to as CP-1) built during the same time period and by the same manufacturers as the RCDP homes, and a nonrandom sample of 25 "volunteer" homes (CP-2). The homes tested were located in Washington, Oregon, Idaho and western Montana. Approximately 78% of the homes were in Washington.

The majority of the homes (94%) were double-wide, single-level homes. Two homes were double-wide with a basement; two were single-wide, single-level; and six were triple-wide, single-level. One of the existing code homes had a stick-built addition. Those homes without basements had either vented (92%) or unvented (8%) crawl spaces. The size of the homes ranged from 1020 to 2600 ft^2.

Field Measurement Protocols

A manual of field measurement protocols[9,10] was used as a training aid and standard reference manual for the field technicians. A hands-on training session for each of the technicians took place in October 1989 at one of the sample homes. Each technician was trained in the specific procedures outlined in the training manual. Specific data sheets were used in the field to record information.

Once in the field, the technicians completed six tasks at each home--a homeowner survey, characteristics audit, ventilation system audit, heating system audit, blower door test, and a PFT test. A brief summary of each follows:

- The homeowner survey was taken to determine the occupant's knowledge/perception of how the home and its ventilation systems operated. The survey also requested information such as number of occupants, number of rooms, and number of hours of ventilation system use.

- The characteristics audit task was to document the actual installed ventilation systems and controls and their current state of operation. Information was gathered about window, wall, door, and ceiling characteristics and orientations. For the current practice homes, additional information was taken on wall thickness and window and door characteristics.

- The ventilation system audit and flow measurement task was completed for three reasons: 1) to confirm the performance of the installed ventilation systems; 2) to determine if they were operating correctly; and 3) to measure the flow rate of the whole-house exhaust system. The whole-house system consisted of two components--the exhaust and makeup air sub-systems. For the exhaust component, the system type was identified, and the location of the designated whole-house fan was noted. All controls, switches, and timers were tested to see whether they were working properly. The flow rate was measured using a flow hood. All vent locations were noted. All other exhaust fans in the homes were identified.

- The heating system audit was completed to identify the primary and any secondary heating systems installed in the home. Thermostat settings, locations, and operating schedules were noted, as were the locations of heating system and ducts (heated/unheated spaces).

- The blower door test was completed with calibrated doors and gauges. Depressurized tests for two conditions were completed--as-found, and sealed vents and fans. Indoor and outdoor temperatures, relative humidity, and wind direction information were taken before and after the tests. Each home exterior was photographed from multiple compass orientations.

- The PFT test was set up as a one-zone configuration (single-level home), unless the home was set up over a basement, in which a two-zone configuration was used. Temperatures at each PFT source location were recorded. Sample tubes were deployed by the field technicians and returned to PNL by the occupants two to four weeks later for analysis.

TEST RESULTS

The manufactured homes were tested between early November 1989 and early April 1990. Each was tested for air leakage using standard blower door techniques. All tests were conducted in the depressurization mode. Results of blower door tests are reported as the estimated effective leakage area (ELA) and the estimated air change rate at 50 Pascal (Pa) pressure differential (ACH-50). The ELA is calculated at a reference pressure differential of 4 Pa and is a measure of the total of all leakage areas around doors, windows, vents, and other openings in the building shell. The ACH-50 is a relative indicator of the leakiness of the envelope. For making comparisons between homes of different sizes, the ACH-50 is a more meaningful calculation than the ELA because it has been normalized by building volume. All blower door results in this report are calculated at standard conditions of one atmosphere pressure and 25°C.

The PFT test was conducted over a two- to four-week period following the site visit. The PFT technique measures the overall average air exchange rate in the home in its lived-in, as-operated configuration. The measured air exchange rates are a combination of natural infiltration and mechanical ventilation during the period of PFT testing. The PFT air exchange rates are also calculated at standard conditions of 1 atmosphere and 25°C.

Air Leakage

Blower door tests were completed on 163 of the 174 homes in the sample. The results of the ELA and ACH-50 calculations for each category of home tested are summarized in Table II. As shown, the RCDP homes appear to be slightly tighter than the CP-1 homes and significantly tighter than the CP-2 home set.

Air Exchange Rates

The PFT testing was conducted in 169 of the 174 homes. The measurement period in each home was designed to last for two weeks, but ran to as much as six weeks in a few homes because of difficulties in recovery of the sample tubes.

The mean air exchange rates and standard deviations for the RCDP, CP-1, and CP-2 homes were 0.23±.07 ACH, 0.31±.17 ACH, and 0.29±.10 ACH, respectively. Although the RCDP homes tended to have lower infiltration rates than the other two groups of homes, the difference in mean air exchange rate is not statistically significant. This is partly because of the relatively small sample sizes of the two current practice groups. In the RCDP homes, 128 of the 139 homes were less than the minimum ventilation rate of 0.35 ACH recommended by ASHRAE in Standard 62-1989.

MOISTURE

Collection of information on moisture and/or the occurrence of condensation in the home was secondary to the primary objectives of the study. A one-time measurement of relative humidity was made in a limited number of the homes at time of the occupant survey. The occupant was also asked whether he/she were aware of any odor and/or moisture problems in the home. The field technician also independently reported the presence of odors and or indications of moisture and/or condensation.

Relative Humidity

Relative humidity was measured in the dining area of 90 of the homes at the time of the occupant survey, before conducting the blower door test. The average humidity was 54% but ranged between 17% and 80%. This one-time humidity measurement did not show any significant relationship to any of the other indicators of ventilation or long-term indicators of moisture problems.

Moisture/Condensation

Moisture problems in homes are most readily apparent as either condensation on windows or mold growth. During the homeowner survey, the occupant was asked whether he/she was aware of any odor or moisture problems in the home. During the field technicians walkthrough of the home, the technician also noted any odors or indication of moisture problems (either current or past). Unless there were moisture problems occuring at the time of the home survey, there was no way to verify the owners response to this question. In seven of the homes, the technician indicated moisture problems not reported by the occupant. These two independent determinations of moisture in the home were combined into a single indicator of the occurrence of moisture problems. Moisture problems were found in 45% of the homes.

Table III and Table IV show the relationship between the presence of moisture problems and two measures of ventilation--the effective leakage area (ELA) and PFT air exchange rates (ACH). The ELA is an measure of the leakiness of the building envelope and provides an indication of the potential for natural infiltration in the home--the larger the ELA the greater the natural infiltration. Table III clearly indicates that, as one would expect, moisture problems are more prevalent in the tighter homes (ELA < 60 in^2), but not exclusively.

Table IV is the same as Table III, except the second variable is the PFT measured air exchange rate. This is a measure of the overall air change rate for the home in its lived-in, as-operated configuration. It differs from the natural infiltration derived from the blower door test in that it also includes occupancy effects (door and window openings, spot exhaust fan operation, whole-house ventilation system operation, etc.). As with the ELA, moisture problems are more common in tighter homes with the lower air change rates, but there is not a clear distinction between the homes based solely on the air exchange rate.

The relationship between daily exhaust fan use (excluding the automatic whole-house system) and moisture are shown in Table V. Average daily exhaust fan use was estimated by the occupant and includes all fan usage except the automatic whole-house ventilation system. In this context, extended fan use is assumed to be a proxy for moisture generation (cooking, bathing, etc.). Average daily fan use is slightly greater in those homes that experience moisture problems than those homes without moisture, but again the distinction between the two is not great. For example, 33% of the homes with moisture problems used their exhaust fans more than 2 hours per day, compared to 26% for those without moisture problems.

From these results, one thing becomes apparent: tight building envelopes and low air exchange rates are necessary, but not sufficient conditions for moisture problems to occur. Rotated Factor Analysis (FA)[(3)] was applied to a subset of the data collected from each home in an attempt to identify the parameters closely associated with moisture problems. The parameters (or components) selected for the FA were the incidence of moisture, effective leakage area of the building envelope (ELA), PFT derived air exchange rates, exhaust fan use, number of adults (per 100 ft^2) and number of children (per 100 ft^2). Only those factors with eigenvalues greater than 1 were selected for rotation. The characteristics of the resultant three factors are shown in Table VI. In each factor, the individual component loading (CL) is indicative of the relative importance of that component toward explaining the total variance--i.e., the greater the loading, the greater the dependence. Component loadings with an absolute value less than 0.2 indicates insignificant dependence. Loadings greater than an absolute value of 0.9 indicate a strong dependence. Between 0.9 and 0.2, the dependence is proportionately weaker. Components that exhibit similar loadings are also highly correlated. In the first factor (F-1), the air exchange rate (CL=0.833) and ELA (CL=0.871) dominate and are of nearly equal importance. There is only an marginally significant negative dependence with the occurrence of moisture (CL= -0.216).

(3) Refer to texts by Harmon[12] or Cattell[13] for more details.

Intuitively, this is correct considering the known direct relationship between the ELA and total air exchange rates. The inverse relationship of ventilation to the incidence of moisture is also consistent with our earlier discussions, indicating a decrease in moisture problems in homes with higher ventilation rates.

Both the second and third factors (F-2 and F-3) are dominated by those components that characterize occupant activity. The second factor indicates a strong inter-dependence of fan use (CL=0.685) and the number of children in the home (CL=0.830). There is also a marginally significant connection to the incidence moisture in the home (CL=0.239).

The third factor indicates a strong positive relationship between the number of adults in the home (CL=0.811) and the incidence of moisture problems (CL=0.702). The number of adults is a proxy for occupant activity such as cooking and bathing, which contribute to the overall increase in moisture in the home.

CONCLUSIONS

A number of important conclusions can be drawn from this study.

- The manufactured homes tested during this particular study were found to have very low air exchange rates, even lower than site-built homes constructed during the same approximate time period.

- There is strong evidence that the ventilation systems in these homes, as installed and operated, do not provide the level of fresh-air specified by the various ventilation standards. Under these conditions, it is possible that indoor air quality could be adversely impacted.

- The incidence of moisture/condensation in these homes was significant. More than 45% of the manufactured homes exhibited some form of moisture problem.

- Tight envelope construction and/or low air exchange rates were necessary but not sufficient conditions for moisture problems. The cause of the problem is more directly related to the number of adults living in the home and their activities

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TABLE I Comparison of Recent Air Exchange Rate Measurements in the Northwest Homes.[3,4,5,11]

	Sample Size	Average Floor Area (ft^2)	Effective Leakage Area (in^2)	ACH-50	PFT-ACH
Tulalip Study[(1)]	20	893 to 1222	67 to 99	5.1	--
NW Baseline[(2)]	93	~1360	157	8.4	--
NORIS-1[(3)]	134	1844	125±71	9.3±3.5	0.38±.18
NORIS-2[(4)]	49	1977	106±46	7.2±1.2	0.27±.10

(1) HUD Code homes, upgraded to meet regional MCS for energy efficiency
(2) Recent HUD Code homes
(3) Site-built current practice homes
(4) Site-built homes certified under the April 1987 Super Good Cents Program

TABLE II Blower Door Derived Air Leakage Measurements for the Vents Sealed Test

Home Category	ELA, in.^{2} Mean	ELA, in.^{2} SD[(a)]	ACH-50 Mean	ACH-50 SD
RCDP	62	21	5.6	1.6
CP-2	91	28	8.8	1.5
CP-1	83	17	7.1	1.6

(a) Standard deviation.

Table III Cross-tabulation of moisture and effective leakage area (ELA). For each data point, the upper number is the number of occurrences and the lower number is the percent of the column total. Slight differences in the totals are a result of rounding errors.

ELA	Moisture No	Moisture Yes	Total
20-40	2 3.1%	6 13.3%	8 7.3%
41-60	13 20.0%	14 31.1%	27 24.5%
61-80	20 30.8%	10 22.2%	30 27.3%
81-100	22 33.8%	12 26.7%	34 30.9%
101-120	6 9.2%	2 4.4%	8 7.3%
121-140	2 1.8%	0 0.0%	2 1.8%
140+	0 0.0%	1 1.8%	1 1.8%
Total	65 100.0%	45 100.0%	110 100.0%

TABLE IV Cross-tabulation of moisture and PFT air exchange rate (ACH). For each data point, the upper number is the number of occurrences and the lower number is the percent of the column total. Slight differences in the totals are a result of rounding errors.

	Moisture		
PFT ACH	No	Yes	Total
0.11-.20	19 29.2%	15 33.3%	43 30.9%
0.21-0.30	37 56.9%	23 51.1%	60 54.9%
0.31-0.40	6 9.2%	2 4.4%	8 4.5%
0.41-0.50	3 4.6%	2 4.4%	5 4.5%
0.51-0.60	0 0.0%	2 4.4%	2 1.8%
0.61-0.70	0 0.0%	1 2.2%	1 0.9%
Total	65 100.0%	45 100.0%	110 100.0%

TABLE V Cross-tabulation of moisture by estimate exhaust fan use. For each entry, the upper number is the number of observations for that entry and the number is the percent of the sample total for that entry. Slight differences in the totals are a result of rounding errors.

	Moisture		
Hours	No	Yes	Total
0	2 3.1%	0 0.0%	2 1.8
0-1	28 43.1%	17 37.8%	45 40.9%
1-2	18 27.7%	13 28.9%	31 28.2%
2-3	6 9.2%	6 13.3%	12 10.9%
3-4	5 7.7%	6 13.3%	11 10.0%
4-5	2 3.1%	2 4.4%	4 3.6%
5-6	3 4.6%	1 2.2%	4 3.6%
6-7	1 1.5%	0 0.0%	1 0.9%
Total	65 100.0%	45 100.0%	110 100.0%

TABLE VI Component loaddings and eigenvalues for the first 3 rotated factors.

	Component Loading		
Componet	CL-1	CL-2	CL-3
ACH	0.833	0.136	0.131
Fan use	0.095	0.685	0.088
Moisture	-0.216	0.239	0.702
ELA	0.871	0.086	-0.126
Adults	0.194	-0.104	0.811
Children	0.092	0.830	-0.008
Eigenvalue	1.72	1.26	1.02
% variance explained	28.7	21.1	17.7