AIR EXCHANGE RATES IN NEW ENERGY-EFFICIENT MANUFACTURED HOUSING

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ABSTRACT

During the 1989-1990 heating season, Pacific Northwest Laboratory, for the Bonneville Power Administration, measured the ventilation characteristics of 139 newly constructed energy-efficient manufactured homes and a control sample of 35 newer manufactured homes. A standard door fan pressurization technique was used to estimate shell leakiness, and a passive perfluorocarbon tracer technique was used to estimate overall air exchange rates. A measurement of the designated whole-house exhaust system flow rate was taken as well as an occupant and structure survey.

The energy-efficient manufactured homes have very low air exchange rates, significantly lower than either existing manufactured homes or site-built homes. The standard deviation of the effective leakage area for this sample of homes is small (25% to 30% of the mean), indicating that the leakiness of manufactured housing stock can be confidently characterized by the mean value. There is some indication of increased ventilation due to the energy-efficient whole-house ventilation specification, but not directly related to the operation of the whole-house system. The mechanical systems as installed and operated do not provide the intended ventilation; consequently indoor air quality could possibly be adversely impacted and moisture/condensation in the living space is a potential problem.

INTRODUCTION

During the 1989-1990 heating season, Pacific Northwest Laboratory (PNL),[1] for the Office of Energy Resources, Bonneville Power Administration, measured the ventilation characteristics in 139 newly constructed energy-efficient manufactured homes and a sample of 35 relatively new, or current practice, manufactured homes. This program was part of Bonneville's Residential Construction Demonstration Program (RCDP), and the new energy-efficient homes were built to the Model Conservation Standards (MCS). The standard door fan pressurization technique 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 and furnace fan ventilation flow rate were 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 tested were located in Oregon, Washington, Idaho, and western Montana.

The purpose of this paper is to describe the performance of the whole-house ventilation system and to present results of the air leakage and air exchange measurements.

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FIELD MEASUREMENT PROTOCOLS

A PNL infiltration field measurement protocol manual (1) 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, walkthrough 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 purpose of the walkthrough audit/house measurement task was to document the actual installed ventilation systems and controls and their current state of operation. Information was gathered about window,

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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: to confirm the performance of the installed ventilation systems; to determine if they were operating correctly; and 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 if they were working properly, and the fresh-air 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 2 to 4 weeks later for analysis.

MANUFACTURED HOME 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 U.S. Department of Housing and Urban Development (HUD) code consisted of 10 new homes (CP-1) built during the same time period and by the same manufacturers as the energy-efficient homes, and a nonrandom sample of 25 "volunteer" homes (CP-2).

The homes tested were located in Washington, Oregon, Idaho and western Montana. The distribution of homes by class and state is shown in Table 1.

Approximately 94% of the sample were single-level, double-wide homes. Two homes were double-wide with a basement, two homes 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

Table 1 Distribution of Homes by Class and State

	Washington	Oregon	Idaho	Montana	Total
CP-1	10	0	0	0	139
RCDP	106	26	5	2	10
CP-2	20	3	2	0	25
Total	136	29	7	2	174

basements had either vented (92%) or unvented (8%) crawl spaces.

Home areas ranged from 1020 to 2600 ft^2. CP-1 homes ranged from 1222 to 1859 ft^2, RCDP homes from 1020 to 2600 ft^2, and CP-2 homes from 1027 to 1964 ft^2.

VENTILATION SYSTEM PERFORMANCE

Two types of fresh-air ventilation systems were found in the RCDP manufactured homes. The first was a whole-house exhaust ventilation system, a unique requirement for the new RCDP homes specification package. The second was a fresh-air intake system connected to the central furnace. The current practice homes had only the furnace system. As part of the testing conducted in each home, a one-time measurement of the flow rates of the whole-house exhaust ventilation system and the furnace system was made.

Designated whole-house exhaust system

The whole-house exhaust systems have two basic components--the exhaust fan and the make-up air inlet ports. The whole-house systems installed in the RCDP homes included either a designated bath fan or a separate system installed in the hallway.

Make-up air is brought into the home via through-the-wall ports located in the bedrooms and living area. The total number of ports ranged from three to nine, with four being the most prevalent. One type of wall port used in these homes is self-regulating and cannot be closed except by intentional sealing by the homeowner. The second type of wall port is equipped with a closing mechanism. Most all of the ports were found in the open position at the time of testing, although some were sealed. Because the ports are occupant-controlled, this observation may give some indication of occupant behavior or reaction to the ventilation system. Either the occupants did not know how to close the vents, (and they had been open from installation), or they wanted more fresh air circulation in the home, or the vents could not be closed. There were no indications from the field technicians of inability to open/close the through-wall vents.

The whole-house systems are to be sized according to the number of bedroom and combined living areas. For example, the whole-house system for a four-bedroom home with a single combined living area must draw a nominal flow rate of 50 cfm (10 cfm/bedroom + 10 cfm/other combined living areas) to be in compliance with the RCDP home ventilation specifications.

Figure 1 is a cumulative frequency distribution plot of the fraction of homes at different measured flow rates. One home did not appear to have a whole-house system installed. Of the remaining 138 RCDP homes, 125 (91%) had a vent system flow rate of 50 cfm or less; 10 of these homes had no measurable flow rate. The average flow rates for the whole-house ventilation systems, based on a one-time measurement, were 31.9 cfm for the integrated bath system and 28.1 cfm for the separate system.

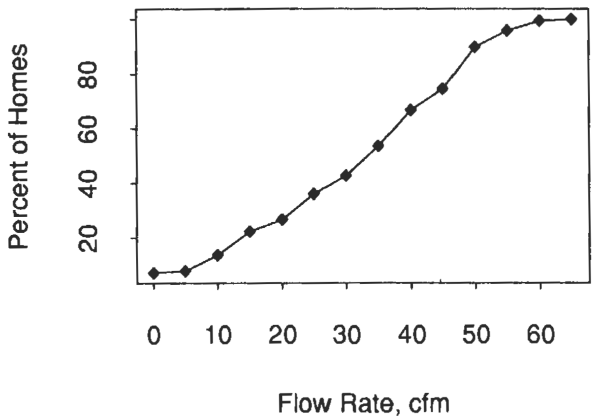

Figure 1 Cumulative Frequency Distribution of Whole-House Vent System Flow Rate

Based on this information, these ventilation systems as installed and operated are not performing as specified. Why are these not providing adequate ventilation? Comments from field technicians included a discussion about the design of a designated bath fan. With this design, there is a duct/screen flush with the ceiling with a standard cover attached by stand-offs approximately 0.5 to 1 in. high. The air must flow around the cover and then up the duct to be exhausted. In one home, by simply removing the cover, the measured ventilation flow rate increased by 25% to 30%.

Furnace fresh-air systems

One of the ventilation system options in the HUD code to improve indoor air quality is a system that draws fresh air directly from the outside into the furnace compartment whenever the furnace is running. This system was designed as a 3- to 4- in. flexible duct with a gravity or motorized damper that was run to the outside of the home, terminating under the eave or on the roof. Flow rates for this system are to be at least 25 cfm with the furnace fan in normal operation.

A one-time flow measurement of the fresh-air flow rate was made while the furnace was operating. Forty-four homes (25%), mostly from the CP-2 homes, recorded no flow rate when the furnace was operating. A furnace fresh-air system was not installed in 32 of the homes--18 from the CP-2 homes and 14 from the RCDP homes.

Figure 2 is a standard boxplot of furnace fresh-air flow rate by class of home tested. It includes only those homes with a flow reading greater than zero. The most obvious finding in this plot is that the CP-1 and CP-2 homes have a significantly higher flow rate than the RCDP homes. Nearly 83% of the CP-1 homes that had furnace systems installed had a flow rate greater than 25 cfm. The average flow rates were 35 cfm, 46 cfm, and 48 cfm for the RCDP, CP-1, and CP-2 homes, respectively.

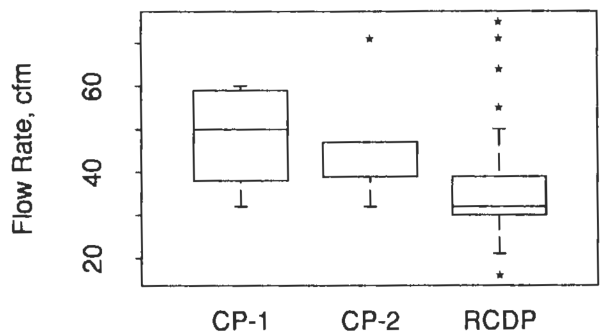

Figure 2 Furnace Fresh-Air System Flow Rates

Field technician notes included observation that the end of the furnace flex duct was not always flush with the intended connection--often there was a gap where air flow would escape. In many homes, the furnace flex ductwork was pinched off during installation when sharp bends were made--as many as two near-90 degree bends were made in some of the ducts examined. With a bend this sharp, the duct essentially collapses and restricts air flow.

Five categories of dampers were identified with the furnace fresh air systems--gravity, humidity, motorized, other, and unidentifiable. In 47 homes, it was not obvious to the field technicians that a damper was installed. In addition, the technicians found that 35% of the dampers actually installed were not operating. Over half the installed dampers were gravity type, and nearly 90% of those were installed in the energy-efficient homes. Nonoperable damper information by damper type is summarized in Table 2.

Table 2 Nonoperable Dampers by Damper Type

Damper Type	Number Failing (%)
Gravity	11 (16)
Humidity	1 (100)
Motorized	9 (75)
Other	19 (44)

In some of the homes, the field technicians observed that the dampers were effectively jammed in the closed position by the flex duct when the system was installed at the factory. It is likely that these systems have probably not functioned correctly since they were built.

LEAKAGE AND VENTILATION TEST RESULTS

The manufactured homes were tested between early November 1989 and early April 1990 using a field protocol (1) based on the Northwest Residential Infiltration Survey (NORIS) protocol (2). The blower door test was completed at the time of the initial site visit. The PFT test was conducted over a 2- to 4-week period following the site visit.

Air leakage

Each of the homes was tested for air leakage using the standard blower door technique. All tests were conducted in the depressurization mode. Results of blower door tests are generally reported as the estimated effective leakage area (ELA) and the estimated air exchange rate at 50 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. 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 because it has been normalized by interior volume. All blower door results presented are at standard conditions of 1 atmosphere pressure and 25°C.

Two blower door tests were completed on 164 of the 174 homes in the sample. The first test was conducted with the home in the as-found condition. For this test, all fireplace and wood stove dampers, glass doors, and any other flue openings were closed, and all exhaust fans and forced-air heating systems were turned off. For the second vents-sealed test, in addition to the above, all fresh-air intakes, exhaust and dryer vents, and the fresh-air intake to the central forced air furnace were to be sealed closed.

The ELAs for the as-found tests and the vents-sealed tests are compared graphically in Figure 3. The overall sample mean and standard deviation of the ELAs for the two tests are 72.8 ± 24.1 in^2 and 67.0 ± 24.0 in^2, respectively. The difference between the two tests ranged from -47.5 in^2 to 61.7 in^2. Surprisingly, for 29 homes, the ELAs for the vents-sealed tests were less than the as-found ELAs (negative values). Ten homes showed no difference in ELAs, while the differences in ELAs for the remaining 155 homes were positive. Although the ELAs were not expected to increased when the vents were sealed, they did so enough times that this finding cannot be dismissed as a random event. The cause is related to something physically happening in the home.

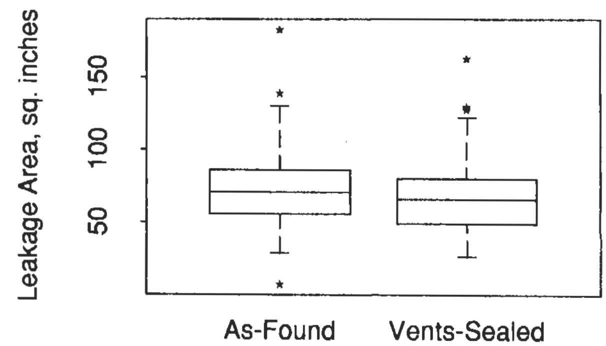

Figure 3 Effective Leakage Area

The results of the ELA and ACH-50 calculations for the vents-sealed test for each category of homes tested are summarized in Table 3 and shown graphically in the boxplot in Figure 4. The RCDP homes appear to be slightly tighter than the CP-1 homes, and significantly tighter than the CP-2 home sample.

Table 3 Manufactured Homes Air Leakage Test Results

	ELA (in^2)		ACH-50	
	Mean	St. Dev	Mean	St. Dev
RCDP	94	29	6.0	1.6
CP-2	130	41	9.0	1.5
CP-1	118	27	7.3	1.6

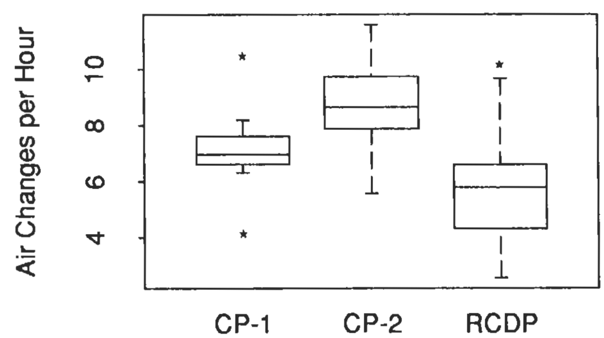

Figure 4 Air Change Rate at 50 Pa Pressure

There is also a significant difference in the air leakage rates in the homes built by the different manufacturers. Figure 5 is a standard boxplot of the ACH-50 for the set of homes by each manufacturer. The manufacturers are identified by code number only. Manufacturer 0 is the current practice group (several unrecorded manufacturers). From these data, it is obvious that the homes built by two manufacturers (4 and 5), which represent 28% of the sample, are tighter than all of the others. The air leakage rate in the

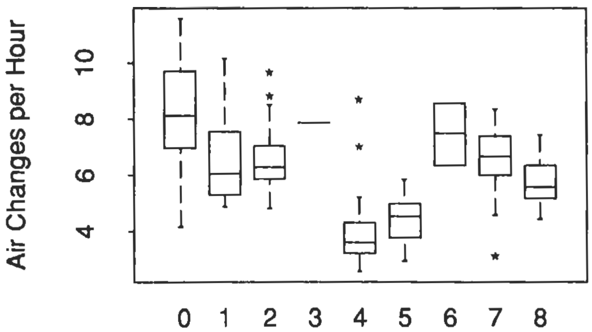

Figure 5 Air Change Rates at 50 Pa Pressure for Each Home Manufacturer

homes built by the other six manufacturers were comparable to the current practice group of homes.

Air exchange rates

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 testing was conducted in 169 of the 174 homes. The measurement period in each home was designed to last for 2 weeks, but ran to as much as 6 weeks in a few homes because of difficulties in sample tube recovery.

The PFT testing results are summarized in Table 4 and shown graphically in Figure 6. The mean air exchange rates for the RCDP, CP-1, and CP-2 homes are 0.23 ACH, 0.30 ACH, and 0.27 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. The within-group variances (indicated by the standard deviation) for the RCDP homes are much smaller than for the CP-1 and CP-2 homes, indicating that the manufacturers participating in this program were able to build homes with a high degree of consistency.

Table 4 Manufactured Home Air Exchange Rate Test Results

	PFT-ACH Mean	PFT-ACH St. Dev
RCDP	0.23	0.07
CP-2	0.27	0.10
CP-1	0.30	0.17

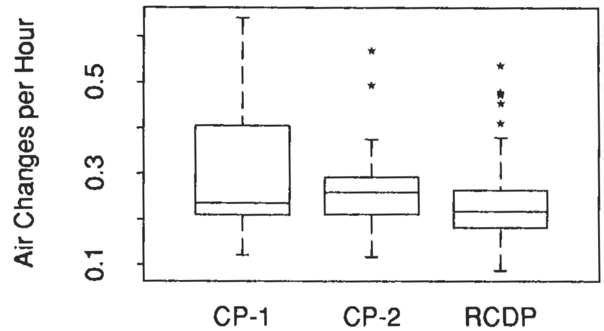

Figure 6 Air Change Rates for Each Class of Homes

In the RCDP homes, 128 of the 139 homes failed to meet the minimum ventilation rate of 0.35 ACH recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) in Standard 62-1989. The current HUD code does not stipulate a minimum ventilation rate, but the new proposed HUD code recommends a minimum rate of 0.35 ACH.

There is some indication of increased ventilation in the RCDP homes relative to the current practice homes that is at least partly attributable to the energy-efficient ventilation package. The RCDP homes are designed to be structurally tighter, and the results of the blower door tests indicate that they are being built that way. The results of the PFT testing show no corresponding difference in overall air exchange rates between the groups of homes. This finding could be reflecting the increased ventilation in the energy-efficient homes from routine operation of the whole-house ventilation system in some of the homes; passive ventilation through the fresh-air ports in the walls, particularly during windy periods; or windows opened by the occupants to eliminate perceived "stuffiness." A more thorough review of the operation of the ventilation system and the indication of home ventilation noted in the occupant activities records is required to fully understand this phenomenon. Whatever the cause, however, the whole-house ventilation system still performs well below ASHRAE recommended rates.

Table 5 compares the results of this study with other, similar studies conducted in the Northwest region. The results from this study indicate that the RCDP homes are tighter than conventional HUD current practice homes located in the Northwest. These new manufactured homes are also tighter than current practice and energy-efficient site-built homes constructed during the same time period.

CONCLUSIONS

Four important findings are indicated from the results of these air exchange rate measurements:

Table 5. Comparison of Recent Air Exchange Rate Measurements in the Northwest Region

	Sample Size	Average Floor Area (ft^2)	ELA (in^2)	ACH-50 (air changes per hour)	PFT-ACH
MHDP Study					
RCDP	139	1496	94±29	6.0±1.6	0.23±.07
CP-2	25	1407	130±41	9.0±1.5	0.27±.10
CP-1	10	1506	118±27	7.3±1.6	0.30±.17
Tulalip Study[1]	20	893 to 1222	67 to 99	5.1	--
NW Baseline[2]	93	~1360	157	8.4	--
NORIS-[3]	134	1844	125±71	9.3±3.5	0.38±.18
NORIS-[4]	49	1977	106±46	7.2±1.2	0.27±.10

[1]HUD code, upgraded to meet regional Model Conservation Standards (MCS) for energy efficiency (5)
[2]Recent HUD-code homes (6)
[3]Site-built current practice homes (3)
[4]Site-built homes certified under the April 1987 Super Good Cents specifications.

- The RCDP manufactured homes have very low air exchange rates, significantly lower than those of either existing manufactured homes or site-built homes.
- The standard deviation of the ELAs for this sample of homes is small (25% to 30% of the mean), indicating that the leakiness of manufactured housing stock can be confidently characterized by the mean value.
- There is some indication of increased ventilation due to the energy-efficient whole-house ventilation specification. However, the increase is not directly related to the operation of the whole-house system, but more to passive ventilation.
- The mechanical ventilation systems as installed and operated do not provide the intended ventilation. Indoor air quality could be adversely impacted, and moisture/condensation in the living space could become a problem.

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