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Measured Infiltration and Ventilation in Manufactured Homes

Super Good Cents

Residential Construction Demonstration Project

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Cycle II

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1. INTRODUCTION

Air infiltration is an important factor in heat loss and indoor air quality; in modern well-insulated homes, it may account for as much as half of the total heat loss. Due to the recent emphasis by home buyers and manufacturers on energy efficiency, tighter homes are being constructed. In the past, it was assumed that natural infiltration would provide adequate ventilation to maintain acceptable indoor air quality, but this is no longer the case in modern energy-efficient homes.

Previous studies in the Northwest have measured infiltration in site-built homes. These include the Northwest Residential Infiltration Survey, Cycles I and II (NORIS I and NORIS II) and the Residential Construction Demonstration Project (RCDP).

NORIS I was a probability sample intended to provide a baseline for homes completed between 1980 and 1987 [Palmiter & Brown, 1989a; Palmiter & Brown, 1989b]. NORIS II investigated homes in Snohomish County, Washington, built to April 1987 Super Good Cents (SGC) specifications [Palmiter et al, 1990a]. The RCDP site-built homes were constructed with the objective of demonstrating new construction techniques and product innovations; these homes were also required to meet April 1987 SGC specifications [Palmiter et al, 1990b].

The NORIS I telephone survey performed in 1987 showed that manufactured homes represented about 27% of post-1979, single-family homes within the Bonneville Power Administration (BPA) service area [Palmiter & Brown, 1989a]. Manufactured homes represented about 32% of new single-family electrically heated housing starts over the period from 1984 to 1989 [Harris, 1990]. Because all of the manufactured homes produced in the Northwest are constructed by eighteen manufacturers, these homes provide a unique opportunity for understanding and influencing energy conservation and ventilation practices in a large part of the housing market.

This report summarizes the results of infiltration measurements made on two groups of manufactured homes in the Bonneville Power Administration (BPA) service area: 131 energy-efficient homes constructed under RCDP, and a control group of 29 homes not participating in energy-efficiency programs.

The RCDP manufactured homes were built to Super Good Cents (SGC) Technical Specifications for Manufactured Homes [Bonneville Power Administration, 1987]. These specifications include building homes to certain insulation levels, implementing construction techniques and materials which reduce infiltration, and equipping homes with mechanical ventilation systems. Eight of the 18 manufacturers operating in the Northwest participated in constructing these homes.

The infiltration methodology for these homes is the same as that of the NORIS I, NORIS II and RCDP site-built studies. Two basic techniques were used to estimate infiltration: the perfluorocarbon tracer (PFT) method, and blower-door depressurization tests combined with the infiltration model developed at Lawrence Berkeley Laboratories (LBL). These techniques and their associated variables and corrections are discussed in detail in the NORIS I analysis report [Palmiter and Brown, 1989b].

The group of homes summarized in this report are also examined in a report entitled *Manufactured Homes Thermal Analysis and Cost-Effectiveness* [Baylon et al, 1990]. The earlier report evaluates these homes in terms of construction techniques, unit costs, thermal performance modeling and end-use monitoring.

2. METHODOLOGY

Site audits were performed on 139 RCDP homes and 35 control homes; ten of these had no blower door tests and four had no PFT results, and were eliminated from the analysis. This report summarizes the measurements on the remaining 131 RCDP homes and 29 control homes.

Originally, 149 home buyers were recruited through manufacturers to participate in the RCDP study. The incentive program included buyer, manufacturer and dealer rebates. Homeowners agreed to record readings from two electric meters to monitor water heat and space heat electric consumption and to complete questionnaires describing their use of the ventilation systems in their homes and their perceptions of indoor air quality and moisture problems. Occupants agreed to use no wood fuel for the duration of the monitoring period. Homeowners also agreed to field audits of their homes, which included a blower door test and a perfluorocarbon tracer (PFT) gas test.

During the random-dialing recruitment performed for the Northwest Residential Infiltration Survey, Ecotope identified 220 manufactured homes built between 1980 and 1986 [Palmiter & Brown, 1989a]. The control group includes 21 of these homes. The other eight control homes, of the same vintage as the RCDP homes but not built to SGC specifications, were recruited through the manufacturers.

Site visits, conducted under the direction of Battelle Pacific Northwest Laboratories, gathered information on the homes, including the ventilation systems. These visits were performed between November, 1989 and March, 1990. Testing protocol was similar to that of the NORIS survey [Ecotope, 1989] with additional modifications for measurement of furnace makeup flows [Battelle, 1989].

During the site visits, field contractors performed at least two blower door depressure tests. The first test was performed with the home "as-found." In this test the positions of the wall vents and ventilation dampers were left unchanged while the blower door test was conducted. The second test was performed with the SGC ventilation system sealed off if separate from the rest of the house ventilation (i.e., designated bath fans were not sealed, but separate whole house ventilation fans were). All window slot vents or other through-wall vents were sealed. In some cases one or both of the tests were done twice to test the repeatability of the results. In most cases, flow measurements of the ventilation systems were also taken with flow hoods.

Most furnaces in the RCDP manufactured homes had makeup air systems, which involve a duct extending from the furnace return air plenum to the roof of the home. A damper and/or a fan is installed in this duct to introduce fresh air into the furnace flow. When this system was present, the contractors measured the flow rate of the makeup air into the furnace using flow grids. We used the measured furnace electricity consumption over the period of the PFT test and the rating on the furnace to estimate a fractional run-time during the PFT test.

After the blower tests were completed, PFT sources were deployed for a test of approximately two weeks. The PFT concentrations were determined by Battelle Pacific Northwest Laboratories. Most homes were tested as a single zone. Larger homes often had more than one PFT source type, but the measured concentrations usually indicated that the home was a single zone, as might be expected for homes with forced air heating and central returns.

3. INFILTRATION BASICS

In this section, we discuss two techniques used to measure infiltration in residential buildings. The LBL infiltration model is based on pressurization testing to estimate the leakage area of a home; the PFT technique uses tracer gases to measure the air flow through a home. A more expansive discussion is of the two techniques is contained in the NORIS I report [Palmiter & Brown, 1989b].

Many factors influence the infiltration rate into a house: natural driving forces, which include inside-to-outside temperature differences and wind speeds, and mechanical systems such as forced air distribution systems, mechanical ventilation systems, or bath and kitchen exhaust fans. Occupants can also have significant effects by opening doors and windows and using fans and wood stoves. Unless otherwise noted, we use the term "infiltration" to mean the combined air flow due to all of these elements.

In this report, we use two measures of infiltration: air-changes per hour (ACH) and cubic feet per minute (cfm). Criteria based on cfm per occupant are used for commercial buildings; the underlying assumption is that the occupants are the primary source of pollutants (e.g., carbon dioxide). If the building itself produces the pollutants (e.g., formaldehyde, radon), as is often the case for residential structures, a criterion based on air changes is more appropriate.

3.1 LBL Model and PFT Measurements

The infiltration model developed at LBL has two components. The stack model predicts the temperature-driven infiltration and depends on house height, effective leakage area (ELA) of the home, and the temperature difference between inside and outside. The wind model predicts the wind-induced infiltration using the ELA, airport wind speed and local terrain and shielding factors.

The time-averaged PFT multizone measurement technique was developed at Brookhaven National Laboratory [Dietz et al, 1986]. PFT gas sources and samplers are deployed throughout the home and left for a period of about two weeks. The mass flow release rate of the sources is constant for a given temperature. After the test, the sampler contents are measured using a gas chromatograph; the analysis produces a volumetric air flow from inside to outside, or the infiltration rate.

The LBL model does not take into account any occupant or mechanical ventilation effects since it uses only envelope leakage to predict infiltration. The PFT test measures the actual air flow through the house, and includes occupant and mechanical ventilation effects which occur during the test. We would therefore expect the PFT measurements to be greater than the LBL predictions. However, in the NORIS I study, we found that the full LBL model actually overpredicted the PFT measurements.

In the LBL model, terrain and shielding classes are chosen to translate airport wind speeds to site windspeeds by categorizing the ground surface and shielding of the sites. Terrain and shielding classes range from 1 to 5, with class 1 being the most flat terrain or the least shielded building [Sherman and Grimsrud, 1980]. A sensitivity analysis of the LBL model indicates that the model is most affected by changes in terrain and shielding factors [Palmiter and Brown 1989b].

In this study, as seen in the NORIS I report, there is a strong correlation between contractors' choices of terrain with shielding, as well as a bias by contractor for the categories chosen. In the NORIS I, II and RCDP II studies, Max Sherman of LBL estimated new terrain and shielding classes for the homes based on photographs of the sites. Although the new estimates resulted in a reduction of the LBL wind effect, the full LBL model with the adjusted parameters still overpredicted by an amount correlated with the LBL wind prediction.

For the manufactured homes, the shielding and terrain classes were not adjusted, and the averages are each about one class less than in previous studies. Therefore, the predicted wind effect in this study is too large and is not comparable with that in the previous studies.

The LBL model predicts the actual infiltration rate of a home, while the PFT test measures the effective infiltration rate. The actual infiltration rate is the average of the hourly flows; the effective infiltration is the constant infiltration rate which would result in the average PFT concentration actually observed. The ratio between the effective and the actual infiltration rates is known as the ventilation efficiency.

In these studies, we used the LBL model to estimate the ventilation efficiency of each home. This was calculated as the ratio of the harmonic average of hourly infiltration rates to the arithmetic average. Because the PFT test measures effective infiltration, we corrected the raw PFT flows to actual flows using the estimated ventilation efficiency. This correction increases the PFT flows.

For the manufactured homes, the ventilation efficiency is about 0.90, resulting in a 10% increase in the raw PFT air-change rate. However, the ventilation efficiency depends on the magnitude of the wind effect, which is overpredicted in this study due to the unadjusted shielding and terrain factors; by comparison, the ventilation efficiency in NORIS I is 0.95, resulting in a 5% increase in the raw PFT flows. Thus, for these homes, the final PFT air-change rates are probably somewhat too large.

The actual air-change rate is the pertinent quantity for heat loss purposes, while the effective air-change rate should be used when addressing indoor air quality. For purposes of this report, we use the actual air-change rates; effective air-change rates are given in the Appendix.

In this study, as in the NORIS I, NORIS II, and RCDP II studies, all PFT volumetric flows were referenced to a pressure of one atmosphere (29.921 in. Hg) and a temperature of 68 F. The raw PFT values were also adjusted for density changes due to altitude of the sites. This adjusted value is called the effective PFT air changes per hour. For all the manufactured homes, this results in an average increase of only 2.0% because the majority are located near sea level.

3.2 Comparison of LBL and PFT Results

In previous studies, the LBL stack model showed better agreement with the PFT measurements than did the full LBL model, measured by correlations and by comparisons of means. Because of the difficulties with the wind portion of the LBL model, we chose to use the stack portion of the model as a reference for comparison in the earlier reports. Also note that because we have no adjusted terrain and shielding parameters for the homes in this study, the overprediction of the full LBL model is greater in this study than in previous ones.

The relationship between the PFT results and the LBL model, for the four studies discussed in this report, is shown in Figure 1. The PFT results display a much closer relationship with the LBL stack model than with the full model. A more detailed analysis of this comparison is given in the NORIS and RCDP reports [Palmiter & Brown 1989b, Palmiter et al 1990a, Palmiter et al 1990b].

3.3 Ventilation Systems

Super Good Cents standards require the installation of a ventilation system. The NORIS I homes and the manufactured control homes were not built to these standards and had no ventilation systems (although some of the control homes had furnace makeup air systems, as discussed in Section 7.2). In the NORIS II study, homes without forced-air systems had exhaust-fan ventilation systems, and homes with forced-air systems usually had makeup air systems to the furnace. Ventilation systems in the RCDP site-built homes included air-to-air heat exchangers and exhaust-air heat pump as well as exhaust-fan ventilation systems. The RCDP manufactured homes all had exhaust-fan ventilation systems controlled by 24-hour timers. In addition, 90% of the RCDP and 52% of the control homes had makeup air systems to the furnace.

The amount of air flow added by a ventilation system is considerably smaller than the amount of air flow through that ventilation system. This is particularly true of exhaust-only systems. A detailed discussion of this effect is contained in the RCDP report [Palmiter et al, 1990b] and in a detailed case study on four homes [Palmiter & Bond, 1990].

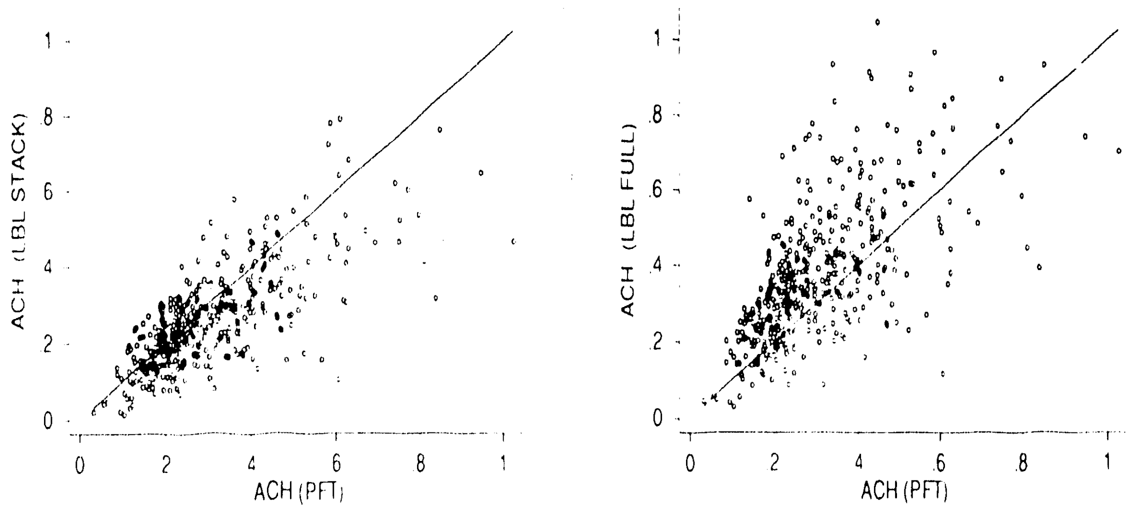

Figure 1. LBL predictions versus PFT measurements in four infiltration studies.
The line indicates equality. Homes with air-to-air heat exchangers or exhaust-air heat pumps are not included.

If there is leakage in the portions of the air handler ducts outside a home, any unbalanced leakage will induce the same amount of infiltration as would a fan of the same size. This is true regardless of whether the supply or return leakage is larger. In a set of detailed case studies, we measured added infiltration of 8 to 43% of the natural infiltration [Palmiter & Bond, 1990]. Thus, the presence or absence of forced-air systems is an important factor in infiltration.

For both groups of manufactured homes, the PFT measurements were generally larger than the LBL stack predictions. As in the report on RCDP site-built homes, we attribute the difference between the PFT and LBL stack predictions to the combined effects of the ventilation systems, the impact of furnace leakage and makeup air systems, and occupant and wind effects. We will refer to this combined effect as "mechanical ventilation."

4. EFFECTS OF RCDP PROGRAM ON MANUFACTURED HOMES

Table 1 summarizes results for the RCDP and control groups of manufactured homes. More detailed summaries and comparisons are given in the Appendix. Both samples show factors of around five from the lowest to highest values of the infiltration parameters.

The first line of the table gives the number of homes in each study; the number of occupants is about the same for the two groups. The second block of the table shows basic physical characteristics of the homes. The manufactured homes compare well with the control group; on average, RCDP homes were about 5% larger than the control homes, but the difference was not statistically significant.

Other physical characteristics of the homes, such as the contractor-selected terrain and shielding, were also comparable. However, more of the control homes had wood stoves or fireplaces. This may affect the comparison of home tightness because these devices tend to increase the leakage area of a home.

Table 1. Comparison of manufactured RCDP and control homes.

	Units	RCDP	Control	Ratio
Number of homes		131	29	--
Number of occupants		3.06	3.03	1.01
Stack height	ft	8.14	8.02	1.02
Area	ft^2	1472	1402	1.05
Volume	ft^3	11884	11280	1.05
Effective leakage area	in^2	68	92	.75
Specific leakage area		3.27	4.56	.72
Air changes at 50 Pa	1/h	6.10	8.75	.70
Inside temperature	F	68.7	68.0	--
Temperature diff	F	28.4	27.1	1.05
TMY temperature diff	F	28.5	27.4	1.04
Airport wind speed	mph	8.61	8.64	1.00
Air changes (PFT)	1/h	.267	.334	.80
Air changes (LBL Stack)	1/h	.224	.305	.74
Air changes (LBL Full)	1/h	.377	.500	.76
Air flow (PFT)	cfm	52.7	62.9	.84
Air flow (LBL Stack)	cfm	44.1	57.3	.77
Air flow (LBL Full)	cfm	73.8	95.6	.78
TMY air changes (PFT)	1/h	.268	.336	.80
TMY air changes (Stack)	1/h	.225	.309	.73
TMY air changes (LBL)	1/h	.380	.518	.73

Three measures of tightness determined from the blower-door test are given in the third block of Table 1. The first is the effective leakage area (ELA) at 4 Pascals, as defined by Sherman et al [1982]; the specific leakage area (SLA) is 10,000 times the ELA divided by the floor area; and air changes at 50 Pascals is a common measure of tightness used in many building standards.

The ELA depends strongly on the size of the home; the SLA and air changes at 50 Pascals are normalized for size. Each of these measures shows that the RCDP homes are 25 to 28% tighter than the control homes. These differences are highly statistically significant.

We assigned each home to the nearest National Weather Service (NWS) station, from which we obtained hourly outdoor temperatures and windspeeds. Weather conditions during the PFT test are summarized in the fourth block of the table. These conditions are comparable for the two groups.

Air change rates and air flows from the PFT test, the LBL stack model, and the LBL full model are given in the fifth block of the table. The PFT-measured air changes are about 20% lower for the efficient houses; the LBL stack and full air changes are about 25% lower. When air flows are measured in cfm, the efficient homes have 16% less infiltration as measured by the PFT test and 23% less infiltration as predicted by the LBL model.

The last block of the table gives PFT and LBL results based on TMY data for the heating season. Weather conditions for a TMY heating season closely approximated those during the PFT tests in this study, so the TMY air-change rates are close to the measured infiltration rates.

The decrease in infiltration is approximately proportional to the decrease in ELA and SLA. This agrees with the results from earlier studies, which indicate that tightness is the primary determinant of infiltration. As homes become tighter, we expect total infiltration to decrease linearly with the leakage area, all other things being constant. It is this decrease which mechanical ventilation systems are supposed to counteract.

According to the difference between the PFT results and the LBL stack prediction, the added ventilation in the efficient homes is somewhat greater than in the control homes; the values are 0.043 ACH for the efficient homes and 0.029 ACH for the control homes. It should be noted that these values include infiltration induced by occupant and wind effects and the impact of furnace leakage and makeup air systems as well as the exhaust-fan ventilation system. Also, the apparent additional ventilation is small relative to the magnitude of noise in the data. Estimates for the infiltration produced by the ventilation systems alone are given in Section 7.1.

5. OCCUPANT SURVEY

Occupants of both control and RCDP manufactured homes were asked to complete a survey which covered a variety of items. Many of the questions referred to ventilation systems and their operation, or to subjects which might affect or reflect ventilation effectiveness, such as occupant scheduling, and perceptions of condensation and/or mildew problems. We limit our discussion here to 122 SGC homes and 28 control homes that responded to the surveys and had PFT and blower door results.

Eighty-three percent of the SGC occupants responded that they ran their ventilation systems automatically. Of those, 74% said their systems ran an average of 1 to 4 hours a day. Thirty-two percent of occupants complained about noise from the systems, but only 5 occupants said the noise caused them not to use the systems. Similarly, only 3 occupants reported that uncomfortable drafts caused by the ventilation systems caused them to turn the systems off. Two occupants said both draftiness and noise caused them to not use the fans. About 22% of occupants said they did not understand their ventilation systems, but 85% said they knew when to operate the systems. Table 2 shows when occupants said they operated their whole-house ventilation systems.

Condensation and/or mildew problems were reported in 53% of the SGC homes. Occupants with mildew problems in their bathrooms ran their fans at least when the bathrooms were occupied, as well as for whole house ventilation. However, of the 59 occupants who reported condensation problems, only 9 indicated that they used their ventilation systems specifically during the times when moisture was a problem. On the other hand, the number of hours that occupants ran their systems did not correlate with problems having to do with condensation and/or mold and mildew. Only 10 occupants noted specifically that condensation increased with the ventilation system turned off. Tables 3 and 4 show where occupants reported moisture problems.

Table 2. Times of use for whole-house ventilation systems (SGC).

When home is stuffy		When condensation is present		When someone is home		Automatically		Other times	
No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
20	16%	9	7%	7	6%	101	83%	16	13%

Table 3. Moisture problems reported in RCDP SGC homes (122).

	Bathrooms		Kitchen		Dining Rm		Living Rm		Bedrm		Other	
Problem	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
Mold/mildew:	13	11%	5	4%	7	6%	5	4%	NA	--	9	7%
Condensation	38	31%	29	24%	19	16%	22	18%	25	20%	14	11%

Table 4. Moisture problems reported in control homes (28).

	Bathrooms		Kitchen		Dining Rm		Living Rm		Bedrm		Other	
Problem	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.	No.	Pct.
Mold/mildew:	5	18%	2	7%	2	7%	4	14%	NA	--	5	13%
Condensation	10	36%	9	32%	6	21%	9	32%	10	36%	7	25%

The cells of the two tables are similar except perhaps for increased problems reported in living room spaces of control homes. Overall, 71% of the control homes reported moisture problems of some sort, compared to 53% of the SGC homes. Both groups of homes exhibit slightly lower PFT air change rates for homes with moisture problems, but the ratio of the means between homes with and without moisture problems for both groups is only 3-5%, an insignificant difference.

Table 5. Moisture problems and air change rates for SGC and control homes.

	SGC Homes			Control Homes		
Moisture Problems?	No.	Pct.	ACH (PFT)	No.	Pct.	ACH (PFT)
No	57	47%	0.271	8	29%	0.352
Yes	65	53%	0.263	20	71%	0.334
Total	122	100%		28	100%	

In comment spaces provided, 9 of the 27 occupants with mold or mildew explained that most of it occurred on windows and/or window frames. If we assume this to be the case for the rest of the homes, we can tabulate the occurrence of mold and mildew with window types, as shown in Table 6.

Table 6. Window types and occurrence of mold and mildew.

	Is mildew a problem?				
	No		Yes		
Window type	No.	Pct.	No.	Pct.	Total
Vinyl	54	78.26	15	21.74	69
Aluminum w/ Storm	11	68.75	5	31.25	16
Aluminum w/ TB	17	80.95	4	19.05	21
Aluminum	13	81.25	3	18.75	16
Total	95	77.87	27	22.13	122

Except for aluminum frames with storm windows, the percentages are not verv different, and the aluminum with storm windows have a lower U-value than the straight aluminum frames, which in turn have the best occupant record for lack of mold and mildew.

Even though many occupants reported moisture problems of some kind, 96% of the SGC occupants and 75% of the control home occupants considered their homes to be well-ventilated. This may reflect what occupants deem to be problems. The question of condensation occurring in homes is not phrased as a negative question, and occupants may view condensation on walls and/or windows as normal during showering or cooking.

There is little correlation between occupant responses in the survey and the actual infiltration and ventilation rates measured with the PFTs. Infiltration tends to increase with the total number of occupants. It is difficult to see an increase in infiltration with the reported number of hours the ventilation systems ran, partially because the majority of occupants (70%) responded that ventilation run times were all between one and four hours a day.

Occupants tended to leave their systems operating automatically, and did not vary the settings on the systems. About two thirds of the SGC occupants said they received a booklet on indoor air quality. The remainder either never received them or were unsure if they had one or not. Of those who received them, 70% said they understood the information presented, and 23% said they understood some but not all of the information. When asked about indoor air quality, 80% of the control and SGC occupants answered that they either mildly or strongly agreed that it was of concern to them. While this may be true in an abstract sense, it is not clear that many occupants have a clear grasp on how to go about ensuring indoor air quality, or the factors that may affect it.

The lack of correlation between ventilation system run-times or settings, envelope tightness, and occupants' perceptions of air quality and moisture problems indicates that the problems observed are driven by the occupants' habits rather than by the ventilation systems. Given that the average flow rate of the designated bath fans for the SGC homes is only 32 cfm, and that the fans are run for whole-house ventilation less than 2 hours a day, this is not surprising. Moisture-related problems might be solved either from operating the systems for a much longer period of time each day, or by utilizing a more efficient system.

6. MANUFACTURED AND SITE-BUILT HOMES

6.1 Comparison of Four Studies

In this section, we compare results from the RCDP manufactured homes and control group with those from the NORIS I, NORIS II, and RCDP site-built homes. The NORIS I homes represent current practice from 1980 to 1987; the NORIS II homes were constructed to April 1987 SGC specifications in Snohomish County; and the RCDP site-built homes incorporated energy-efficient techniques and were built to April 1987 SGC standards.

Table 7 summarizes results from these studies; more detailed summaries and comparisons are given in the Appendix. Both samples of manufactured homes show smaller amounts of scatter than do the earlier samples; the range of tightness varies by a factor of four rather than a factor of ten. This is to be expected, as the manufacturing process is very standardized. However, the amount of scatter that does exist indicates that there is still room for improvement.

Table 7. Comparison of four studies.

		Site-Built			Manufactured	
	Units	NORIS I	NORIS II	RCDP II	RCDP	Control
Number of homes		134	49	129	131	29
Number of occupants		3.35	3.04	2.94	3.06	3.03
Homes with forced air	%	52.2	30.6	40.3	100	100
Stack height	ft	11.71	12.15	10.89	8.14	8.02
Area	ft^2	1844	1977	1897	1472	1402
Volume	ft^3	15500	16450	15933	11884	11280
Effective leakage area	in^2	125	104	70	68	92
Specific leakage area		4.78	3.74	2.79	3.27	4.56
Air changes at 50 Pa	1/h	9.28	7.18	5.55	6.10	8.75
ACH50/20	1/h	.464	.359	.278	.305	.438
Inside temperature	F	67.2	66.3	67.4	68.7	68.0
Temperature diff	F	23.9	21.3	21.0	28.4	27.1
TMY temperature diff	F	26.6	23.6	28.2	28.5	27.4
Airport wind speed	mph	8.89	9.88	8.83	8.61	8.64
Air changes (PFT)	1/h	.384	.267	.276	.267	.334
Air changes (Stack)	1/h	.341	.262	.176	.224	.305
Air changes (LBL)	1/h	.427	.354	.264	.377	.500
Air flow (PFT)	cfm	99.8	73.5	69.9	52.7	62.9
Air flow (Stack)	cfm	88.6	71.4	43.9	44.1	57.3
Air flow (LBL)	cfm	10.6	97.7	66.4	73.8	95.6
TMY air changes (PFT)	1/h	.401	.285	.325	.268	.336
TMY air changes (Stack)	1/h	.357	.277	.206	.225	.309
TMY air changes (LBL)	1/h	.446	.371	.279	.380	.518

The first line of the table gives the number of homes in each study. The number of occupants in the NORIS I study is greater than that in the other studies, probably reflecting the fact that the average age of the homes is greater. All of the manufactured homes have forced-air heating systems, compared with 31 to 52% of the site-built homes.

Basic physical characteristics of the homes are given in the second block of each table. As expected, manufactured homes are smaller than site-built homes. The lower average stack height for manufactured homes reflects the fact that they are rarely over one story.

The third block of Table 7 gives three measures of tightness from the blower-door test. In this case, the SLA and air changes at 50 Pa (ACH50) give better comparisons, because they are normalized for size and the manufactured homes are much smaller than the site-built homes. The ACH50 divided by 20 is a commonly used "rule of thumb" for estimating the infiltration rate of a home. The comparison of this estimate with the actual infiltration values will be discussed in Section 6.3. All four measures show that the manufactured homes are tighter than the NORIS I and II homes, but less tight than RCDP site-built homes. The control homes, measured by the SLA, fall between NORIS I and NORIS II homes in tightness.

NWS weather data during the PFT test are summarized in the fourth block of the table, along with Typical Meteorological Year (TMY) data for the heating season (November-April). The indoor-outdoor temperature differences compare well with the TMY heating season averages, with the notable exception of the RCDP study, where there is a 34% difference. The airport wind speeds in all of the studies are fairly similar.

Table 8 summarizes the temperature differences for the homes in the four studies. Those in the current study were about 30% greater than those in previous studies because the manufactured homes were measured under colder conditions. Infiltration in Northwest homes is primarily stack-dominated, so an increase of 30% in temperature difference produces an increase in infiltration of about 14%. For purposes of comparing infiltration under the same weather conditions for a heating season, infiltration values using TMY weather data are more appropriate.

Table 8. Comparison of NWS and TMY weather for four studies.

		Temperature Difference (Inside-Outside, F)		
Study	**# of homes**	**NWS**	**TMY**	**Ratio**
NORIS I	134	23.95	26.61	0.900
NORIS II	49	21.27	23.46	0.907
RCDP site-built	132	21.01	28.46	0.738
RCDP manufactured	131	28.43	28.46	0.999
Control manufactured	29	27.10	27.36	0.990

Air change rates and air flows from the PFT test, the LBL stack model, and the LBL full model are given in the fifth and sixth blocks of Table 7. Comparisons of air flows in cfm should be interpreted with care, because the manufactured homes are about 20% smaller than the site-built homes. The same air flow produces a much larger air change rate in a smaller home.

The last block of the table gives air-change results extrapolated to TMY weather data for the heating season. The line labeled "PFT" is the measured PFT value adjusted by the ratio of the LBL stack model predictions for TMY heating-season weather versus PFT-period weather. The values in this block represent our best estimate of heating-season air-change rates. These values provide better comparisons between studies, particularly in the case of the RCDP homes which were measured under much warmer conditions.

Air change rates in the three earlier studies show a decreasing trend with newer homes. The manufactured homes continue this trend for PFT air changes and for all of the air flow measurements in cfm. The PFT-measured infiltration in the RCDP manufactured homes, adjusted for heating-season weather, is 0.268 ACH. This is a 33% decrease from the average in NORIS I and an 18% decrease from the average for the RCDP site-built homes. The infiltration in these homes was also 20% less than in the control homes, which had an average ACH of 0.336.

Box plots of four measures of tightness and ventilation are given in Figure 2. The upper two graphs show tightness as measured by the SLA and the ACH at 50 Pa. As the figure shows, homes in NORIS I and the manufactured homes control group--the two groups with no energy-efficient measures--are the least tight. The RCDP site-built homes are the tightest, while the NORIS II and the RCDP manufactured homes fall in between.

Heating-season infiltration, measured by the adjusted PFT test and predicted by the LBL stack model, is shown in the lower graphs. For the LBL stack predictions, infiltration tracks building leakage, so the RCDP site-built homes have the least infiltration and the NORIS I and manufactured control homes have the most. The relationship of the PFT measurements between studies is about the same as that of home tightness and LBL stack, except that the RCDP site-built homes show the presence of effective ventilation systems and hence no longer have the lowest infiltration values.

The difference between the PFT measurements and stack predictions, for PFT-period weather data, gives an estimate of 0.043 ACH or 8.6 cfm for mechanical ventilation effects in the RCDP manufactured homes. This value represents an average over the entire testing period; if a ventilation system runs infrequently, it will produce a very small net effect.

The NORIS I homes, which had no ventilation systems, show about the same amount of additional ventilation as the RCDP manufactured homes; we attributed this to occupant effects such as opening windows and doors, operating fans, and burning wood. In the NORIS II homes, there is no additional ventilation, although these homes did have ventilation systems. We concluded that the ventilation systems in these homes were ineffective because of low run-times. The RCDP site-built homes, primarily those with heat-recovery ventilation systems, did show the effects of mechanical ventilation.

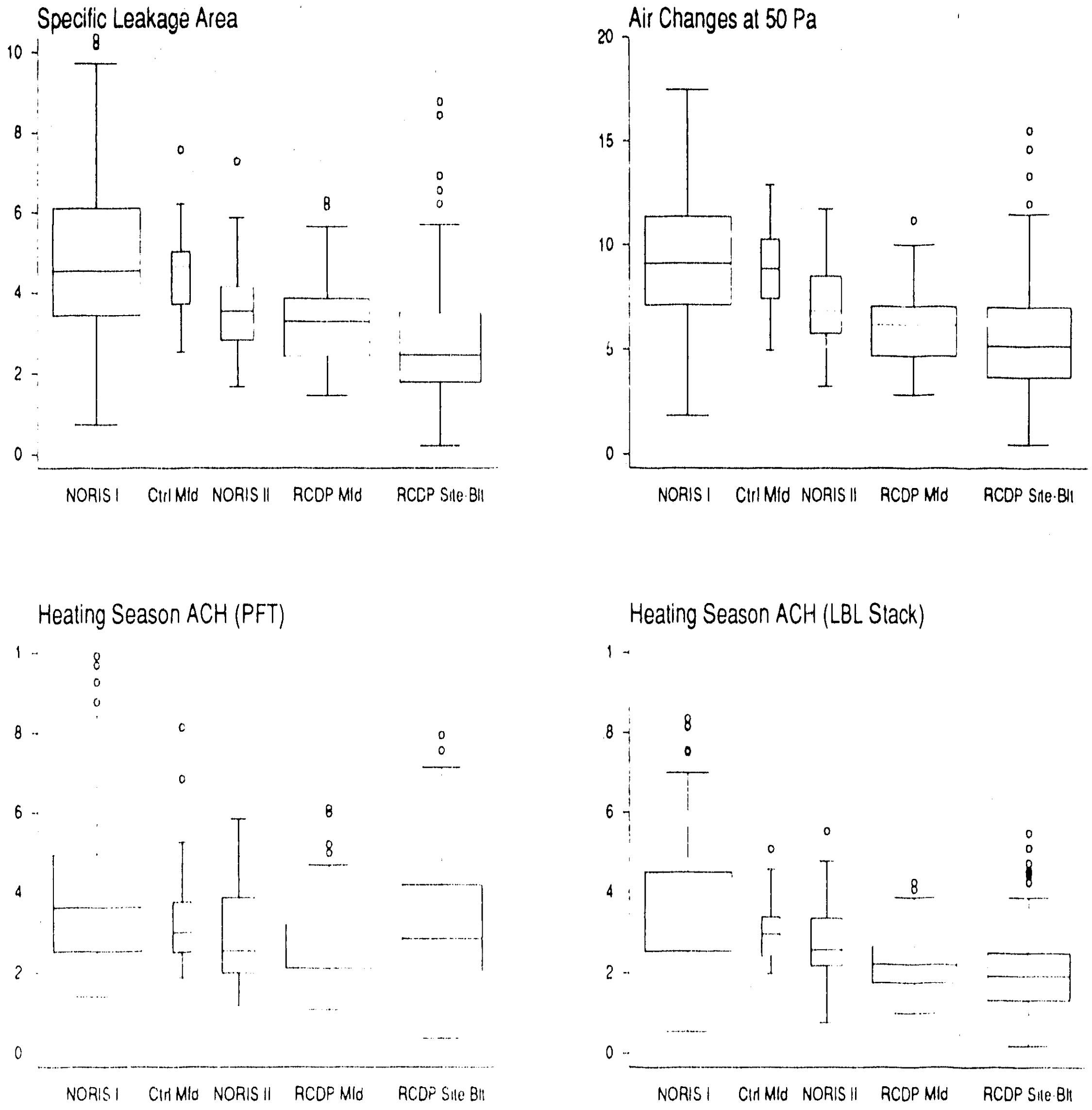

Figure 2. Box plots of tightness and infiltration by study.
The width of each box is proportional to the square root of the number of homes in the study. The line in the middle of each box marks the median (the value below which half of the sample falls). The height of the box can be taken as a measure of the scatter within a study.

The mechanical ventilation in the RCDP manufactured homes is much smaller than that in the RCDP site-built homes, and about the same as that measured in the NORIS I homes, which had no ventilation systems. The added infiltration may be caused by occupant effects alone, as it was in NORIS I. Unfortunately, the occupant survey data does show any correlation between occupant use of fans and added infiltration.

The earlier RCDP study included homes with seven different kinds of ventilation systems, including air-to-air heat exchangers and exhaust-air heat pumps. In the RCDP study, we found that the latter two system types added significant amounts of infiltration, while infiltration added by other ventilation system types was relatively small. All the manufactured homes had either designated bath fan or whole-house ventilator systems; in RCDP site-built homes, these systems induced about 0.05 ACH or 14 cfm. These values are very similar to the mechanical ventilation measured in the manufactured homes.

The air flow measurements in cfm show an even greater difference between the RCDP site-built and manufactured homes. The manufactured homes average only 9 cfm of additional ventilation; the RCDP homes average 26 cfm. Although the 9-cfm flow translates to a larger air-change value in a smaller manufactured home than it would in a larger site-built home, ventilation systems are usually sized in cfm and the actual flow may be a more appropriate measure for determining the effectiveness of the system.

6.2 Homes with Forced-Air Heating Systems

In previous studies, we found that forced-air distribution is an important factor in infiltration. Because all of the manufactured homes have these systems, it is desirable to compare them with only those homes in other studies which also have such systems. However, site-built and manufactured homes may not have comparable duct leakage; also, site-built homes with forced air tend to be large homes, so the comparison may not be applicable.

Comparisons of the homes with forced air are given in Table 9. For NORIS I, NORIS II, and RCDP site-built homes, homes with forced air systems tend to be leakier and to have higher air-change rates than homes without such systems. Thus, the manufactured homes appear relatively tighter in these comparisons.

As measured by the specific leakage area and air changes at 50 Pa, the RCDP manufactured homes are tighter than forced-air site-built homes. The average PFT air changes are lower than those in the site-built homes. As before, the manufactured control homes fall between NORIS I and NORIS II in terms of tightness.

Table 9. Comparison of homes with forced-air heating in four studies.

		Site-Built			Manufactured	
	Units	**NORIS I**	**NORIS II**	**RCDP**	**RCDP**	**Control**
Number of homes		70	15	52	131	29
Number of occupants		3.21	3.13	2.96	3.06	3.03
Stack height	ft	12.11	12.93	10.70	8.14	8.02
Area	ft^2	1978	2408	1918	1472	1402
Volume	ft^3	16829	20864	16314	11884	11280
Effective leakage area	in^2	158	127	88	68	92
Specific leakage area		5.65	3.80	3.40	3.27	4.56
Air changes at 50 Pa	1/h	10.46	6.92	6.70	6.10	8.75
ACH50/20	1/h	.523	.346	.335	.305	.438
Inside temperature	F	67.8	66.0	68.9	68.7	68.0
Temperature difference	F	23.8	21.1	20.6	28.4	27.1
TMY temperature diff	F	25.9	23.1	28.8	28.5	27.4
Airport wind speed	mph	8.90	9.98	7.57	8.61	8.64
Air changes (PFT)	1/h	.448	.297	.316	.267	.334
Air changes (Stack)	1/h	.404	.267	.211	.224	.305
Air changes (LBL)	1/h	.492	.355	.311	.377	.500
Air flow (PFT)	cfm	126.3	100.3	82.2	52.7	53
Air flow (Stack)	cfm	113.4	91.6	54.1	44.1	44
Air flow (LBL)	cfm	137.6	122.5	80.9	73.8	74
TMY air changes (PFT)	1/h	.465	.314	.375	.268	.336
TMY air changes (Stack)	1/h	.421	.279	.248	.309	.225
TMY air changes (LBL)	1/h	.513	.367	.331	.518	.380

6.3 Envelope Tightness

A rule of thumb often used to predict the infiltration of a home is to divide the ACH50 by 20. However, this estimate is primitive; the relation between tightness and infiltration is not linear. For example, if two homes have the same volume and leakage area, but one has a height 30% lower than the other, the shorter home will have a stack infiltration rate that is 16% lower. Because the average stack height of the manufactured homes in this study is about 29% lower than that of the site-built homes in previous studies, we would not expect a predictor based on tightness alone to yield the same results for manufactured and site-built homes.

An optimal home is tightly constructed and well ventilated. Ideally, a manufacturer would perform a tightness evaluation on each new home to ensure adequate sealing, and a predictable and effective method of ventilation would be installed in the home to provide the necessary additional ventilation.

Generally, a measurement such as ACH50 is not recommended to predict infiltration because it does not account for many of the other factors involved. If it is used, it should be taken as a predictor of the natural infiltration which depends on tightness, not the PFT measurement which depends both on tightness and ventilation.

For the RCDP manufactured homes, a comparison of the means indicates that the relationship is better described by dividing the ACH50 by 27. In the other studies, the divisors range from 26 to 28. In no case was the divisor as low as 20. It is important to realize that the relationship established for a set of homes may not hold for homes with other characteristics.

The Super Good Cents Standards used for these homes specify a minimum tightness of 7.0 ACH at 50 Pa [Bonneville Power Administration, 1987]. This standard is intended to correspond to a natural infiltration rate of 0.35 ACH, required to meet minimum ventilation rates prescribed by ASHRAE Standard 62-1989. According to the results of these studies, a given ACH50 will result in a lower natural infiltration rate than previously thought. For example, the ACH50 for NORIS I homes averages 9.28, yet 50% of these homes failed the ASHRAE standard.

7. PERFORMANCE OF VENTILATION SYSTEMS

7.1 Exhaust-Fan Ventilation Systems

The ventilation systems in the RCDP manufactured homes consisted of an exhaust fan controlled by a 24-hour timer. The discussion of ventilation systems will be limited to these homes, as the control homes did not have ventilation systems. Two RCDP homes which did not have exhaust system measurements are also excluded. The same model of exhaust fan, rated at 50 cfm at 25 Pa, was used in all of the homes.

We can estimate the ventilation provided by the exhaust-fan systems using a simple fan model [Palmiter and Bond, 1990]. The infiltration added by an exhaust-only ventilation system is half of the flow through the fan under typical winter conditions. Three predictions are given in Table 10. In each case, the first line gives the flow through the fan, the second line the ventilation that would be added, and the third the total infiltration that would be achieved.

The first line of Table 10 gives the flow produced by the measured flows and run-times. Run-times averaged 2.5 h/day, with a median of 2.0 h/day. These run-times are similar to those for exhaust-fan systems in the RCDP site-built homes. It should be noted that occupants normally operate bath fans about 1.5 hours per day; the average run-time of 2.5 h/day is a fairly small increase over normal use.

The fan flows average 31.6 cfm, 37% below the rating of the fan. The delivered flow varies noticeably among manufacturers; this will be discussed in Section 9. The systems as found induce an average of 1.68 cfm or 0.009 ACH in additional infiltration. The exhaust fans would have induced more ventilation if they had run continuously; these estimates are given in the second line of the table. The last line shows the consequences of the fans operating continuously at rated capacity (50 cfm).

The comparison shows the effects of low run-times and achieved capacities on infiltration. If the fans had run continuously at rated capacity, infiltration rates would have been 31% higher. The impact on levels of compliance with ventilation standards will be discussed in Section 8. It is clear that fans of this capacity must be operated 24 h/day in order to have a significant impact on total infiltration rates.

Table 10. Effects of exhaust-fan ventilation systems in RCDP manufactured homes (n=129).

	Average Run-time (h/day)	Fan flow		Ventilation (ACH)	
		cfm	ACH	Added	Total
As found	2.5	31.6	0.165	0.009	0.268
Running continuously	24.0	31.6	0.165	0.082	0.341
Running continuously at rated flow	24.0	50.0	0.262	0.131	0.390

From an engineering viewpoint, the optimum home is nearly airtight and has a mechanical ventilation system. In the RCDP manufactured homes, natural infiltration is still dominant. To make an exhaust-type system function predictably, the house must be tight enough that the flow through the fan is greater than twice the natural infiltration rate.

As long as there is a significant component of natural infiltration, problems with control and predictability will result in either energy waste or inadequate ventilation. It must be emphasized that if a home is tight enough for the proper operation of a mechanical ventilation system (less than 3 ACH at 50 Pa), the *continuous* operation of that system is *mandatory* to attain the ASHRAE Standard 62 *minimum* recommended ventilation rate of 0.35 ACH.

For pollutants such as formaldehyde, which is emitted by the building fabric itself, there is no advantage to intermittent ventilation. For instance, in a home with a constant formaldehyde emission rate, in the absence of natural infiltration, the average integrated exposure for an occupant who is home 12 hours per day will be exactly the same for a 50-cfm fan running 24 hours/day as for a 100-cfm fan running 12 hours/day.

If there is only 50 cfm of ventilation during the 12-hour occupancy period, the occupant exposure will be double what it would be if the 50-cfm fan ran 24 hours/day. As noted previously, operation for only one or two hours per day produces almost no additional ventilation in terms of occupant pollutant exposure.

7.2 Furnace Ventilation Systems

Makeup air systems in manufactured homes incorporate a duct extending to the roof of the home which provides fresh air to the furnace return air plenum. These systems effectively create a return leak to the furnace, which will cause the home to be slightly pressurized if no other effects are involved. Although these systems introduce outdoor air into a home, they are not considered ventilation systems for the purposes of the Bonneville Super Good Cents program.

These systems were present in 118, or 90%, of the RCDP manufactured homes and 15, or 52%, of the control homes. We found three different makes of makeup air systems in the homes in this study: Blend-Air, POS, and Ventilaire. Each type of system has a damper in the makeup duct; the Blend-Air system differs from the other two in that it also has a fan in the duct. Table 11 gives a breakdown of the numbers and percentages of homes with each type of system.

Table 12 summarizes the effects of makeup air systems in the 51 RCDP manufactured homes for which we have both intake flow measurements and furnace run-times. In 34 RCDP homes, the measured flow through the makeup duct was reported as zero. It is likely that the inaccessibility of the duct in some systems resulted in these zero readings, so the value of zero is spurious; we have eliminated these homes from the summary. The average makeup flow in the remainder of the systems is 33.8 cfm; the systems with makeup fans measured 13 cfm higher on average than those without fans. The mean furnace run-time is 3.5 h/day.

We can estimate the infiltration effects of the makeup systems using the simple fan model previously discussed; these estimates are shown in the second block of the table in both cfm and ACH. The estimates assume that there are no leaks in the supply ducts and that the positive pressure induced is not offset by other effects such as exhaust fans.

Table 11. Furnace ventilation systems in manufactured homes.

	RCDP		Control	
Furnace ventilation	Number	%	Number	%
None	13	10	14	48
Blend-Air	14	11	2	7
POS	78	59	11	38
Ventilaire	26	20	2	7

We expect that furnaces would have run more often in the control homes because of the higher air-change (and heat loss) rates. Therefore, the average ventilation provided by makeup systems would have been somewhat larger in the control homes.

Table 12. Effects of furnace ventilation systems in RCDP manufactured homes.

	Units	Mean	Median
Run-time	h/day	3.46	3.17
Delivered flow	cfm	33.8	32.0
Delivered air changes	1/h	.175	.158
Added air flow	cfm	2.39	2.19
Added air changes	1/h	.012	.010

8. COMPARISON WITH VENTILATION STANDARDS

8.1 ASHRAE Standard 62

There are a growing number of standards relating to ventilation, indoor air quality, and air leakage. We evaluated the manufactured homes in terms of ASHRAE Standard 62 [1989] for minimum ventilation, and compared the failure rates of these homes with those in other studies. Standard 62 requires a minimum whole-house ventilation rate of 0.35 ACH, but not less than 15 cfm per person.

Table 13 gives the percentage of homes failing to comply with ASHRAE Standard 62-1989. The values are based on the PFT-based air changes and cfm. For the earlier studies, this percentage is given separately for ducted and non-ducted heating systems as well as for the sample as a whole. In each case, failure rates are higher for homes without forced-air systems. All of the manufactured homes had forced-air systems, so this study is most comparable with the forced-air groups in other studies.

Since one can argue that the ASHRAE value of 0.35 ACH is somewhat arbitrary, percentages of homes which would fail the standard if this value were reduced are also shown in Table 13. It should also be noted that most national standards for residential ventilation require higher rates (typically 0.5 ACH).

The failure rate for manufactured homes is higher than that for any of the earlier studies, especially when compared with the forced-air homes in each study. Eighty-five percent of the energy-efficient manufactured homes fail ASHRAE Standard 62-1989. The control homes have lower failure rates than the efficient homes, but the rates are still higher than those of forced-air homes in the previous studies.

The second block of the table shows the percentage of homes which fail the guideline of 15 cfm per occupant. This criterion is much less restrictive than the air-change requirement. Again, failure rates of manufactured homes are higher than those in other studies.

Table 13. Percentage of homes failing minimum ventilation standards.

	NORIS I			NORIS II			RCDP Site-Built			Manufactured	
	FA	NoFA	Total	FA	NoFA	Total	FA	NoFA	Total	RCDP	Ctrl
< 0.35 ACH *	37	64	50	60	85	78	62	78	71	85	72
< 0.30 ACH	21	56	38	60	71	67	48	75	64	73	55
< 0.25 ACH	11	41	25	47	65	59	38	61	52	53	31
< 15 cfm/occ	6	36	20	13	29	24	12	32	24	33	28
< 20 cfm/occ	21	52	36	27	38	35	29	47	40	60	55

* ASHRAE Standard 62-1989

As discussed in Section 7.1, the ventilation systems in the RCDP manufactured homes would have achieved higher air-change rates if they had run continuously and if the fans had delivered rated capacity. The effects of these changes on compliance are shown in Table 14. If the systems had operated 24 hours per day, 59% of these homes would have failed ASHRAE Standard 62-1989; if the fans had delivered the rated capacity of 50 cfm continuously, only 36% would have failed.

It should also be noted that in the absence of natural infiltration, the exhaust fans alone will not deliver 0.35 ACH. For these homes, the fans would have to be rated at an average of 69.3 cfm to meet this standard.

The proportion of homes failing to meet Standard 62 is cause for concern. Even if the required ventilation were only 0.25 ACH, 53% of the RCDP manufactured homes would fail the requirement, although these homes all had ventilation systems and forced-air heating. On the average, these homes are fairly tight, but needed infiltration rates have not been achieved by their ventilation systems. The problem of operating the systems long enough to produce adequate ventilation has not been addressed.

8.2 Super Good Cents Ventilation Standards

The construction of the RCDP manufactured homes was governed by the Super Good Cents Technical Standards for Manufactured Homes [BPA, 1987]. The ventilation standards require exhaust fans, provisions for intake air, and a system controller.

Of the RCDP homes, 121 had designated bath fan exhaust systems and eight had whole-house ventilation systems. These differ only in the location of the exhaust fan; in the designated bath-fan system, the exhaust fan is located in a bathroom and is controlled by a timer or dehumidistat in addition to the spot controls in the bathroom. In the whole-house ventilation system, the fan is located in a hallway or utility room.

In these homes, intake air was provided by through-wall intake vents. The number of intake vents was generally sufficient to meet the specifications.

Table 14. Effects of exhaust-fan ventilation systems on compliance in RCDP manufactured homes (n=129).

	Average Run-time (h/day)	Fan flow (cfm)	Total Ventilation (ACH)	Std. 62 Failure Rate
As found	2.5	31.6	0.268	85%
Running continuously	24.0	31.6	0.341	59%
Running continuously at rated flow	24.0	50.0	0.390	36%

For exhaust flows, the SGC specifications require a whole-house ventilation capability of 10 cfm for each bedroom plus an additional 10 cfm for the combined living area. They also require spot ventilation capabilities of 50 cfm for each bathroom and 100 cfm for the kitchen. The spot and whole-house requirements may be met with the same fan; that is, a bathroom fan with a flow of 50 cfm fulfills both the ventilation requirement for the bathroom and for the whole house if it is controlled with a timer or dehumidistat.

Results of comparison between measured fan flows and Super Good Cents specifications are given in Table 15. Measured flows are available for 129 homes; 63% of these do not meet the whole-house ventilation requirements. If all the fans had functioned at rated capacity, only two homes would have failed the whole-house requirements; these homes had been constructed as three-bedroom homes but were installed over daylight basements so that they became five-bedroom homes.

Because the flow measured was that through the designated ventilation system, the measurements cannot be used to infer spot ventilation capabilities for eight of the homes. However, 85% of the 121 homes with designated bath-fan systems fail the requirements for bathroom spot ventilation.

Table 15. Comparison of measured fan flows with SGC specifications.

	Sample Size	Percent Failure
Whole-house ventilation (as found)	129	63%
Whole-house ventilation (as rated)	129	2%
SGC spot ventilation capability	121	85%

9. MANUFACTURER EFFECTS

The RCDP manufactured homes in this study were built by eight manufacturers in the Northwest. Tightness and ventilation are subject to systematic variation due to differences in builder practice; an analysis of variance shows that 75% of the tightness, as measured by air changes at 50 Pa, can be explained by the differences among manufacturers. We examine this variation in this section.

We assigned a number to each builder for purposes of this analysis. These numbers are the same as those used in the cost-effectiveness report [Baylon et al, 1991]. Two manufacturers, #1 and #4, had less than five homes in this study and are combined into a single category labeled "Other". Table 16 gives the means of the most important infiltration parameters and the infiltration in both air changes and cfm. The variation among builders is also illustrated in Figure 3.

The first block of the table gives two measures of home tightness: specific leakage area and air changes at 50 Pa (ACH50). The ACH50 is also shown in the upper left graph in Figure 3. By both measures, builder #2 has the tightest homes and also the smallest amount of scatter. The homes of builders #5 and #8 are the least tight. In each group, the standard deviation is about 20% of the mean, with manufacturer #6 having a much greater amount of scatter.

It is interesting to examine the differences in the measured ventilation system effectiveness between manufacturers. Because the same model of fan was used for each system, we can assume that any variation in fan flow rates was caused by differences in installation. Average fan flow rates for each builder are given in the second block of the table and graphed in the upper right graph in Figure 3.

Table 16. Mean values of infiltration characteristics by manufacturer.

	Units	2	3	5	6	7	8	OTHER
Number of homes		34	13	23	9	10	38	4
Specific leakage area		2.26	2.84	3.75	3.96	3.10	3.82	4.57
Air changes at 50 Pa		4.25	5.01	7.01	7.43	6.07	7.01	8.37
Measured fan air changes	1/h	.203	.241	.165	.184	.221	.077	.247
Measured fan flow	cfm	38.3	47.8	31.2	29.4	50.1	14.7	43.3
Air changes (PFT)	1/h	.222	.240	.289	.311	.268	.284	.349
Air changes (LBL stack)	1/h	.155	.211	.259	.246	.217	.259	.322
Air flow (PFT)	cfm	43.1	47.5	56.3	50.9	61.6	57.9	63.4
Air flow (LBL stack)	cfm	29.5	41.3	50.4	39.3	52.3	52.3	60.3

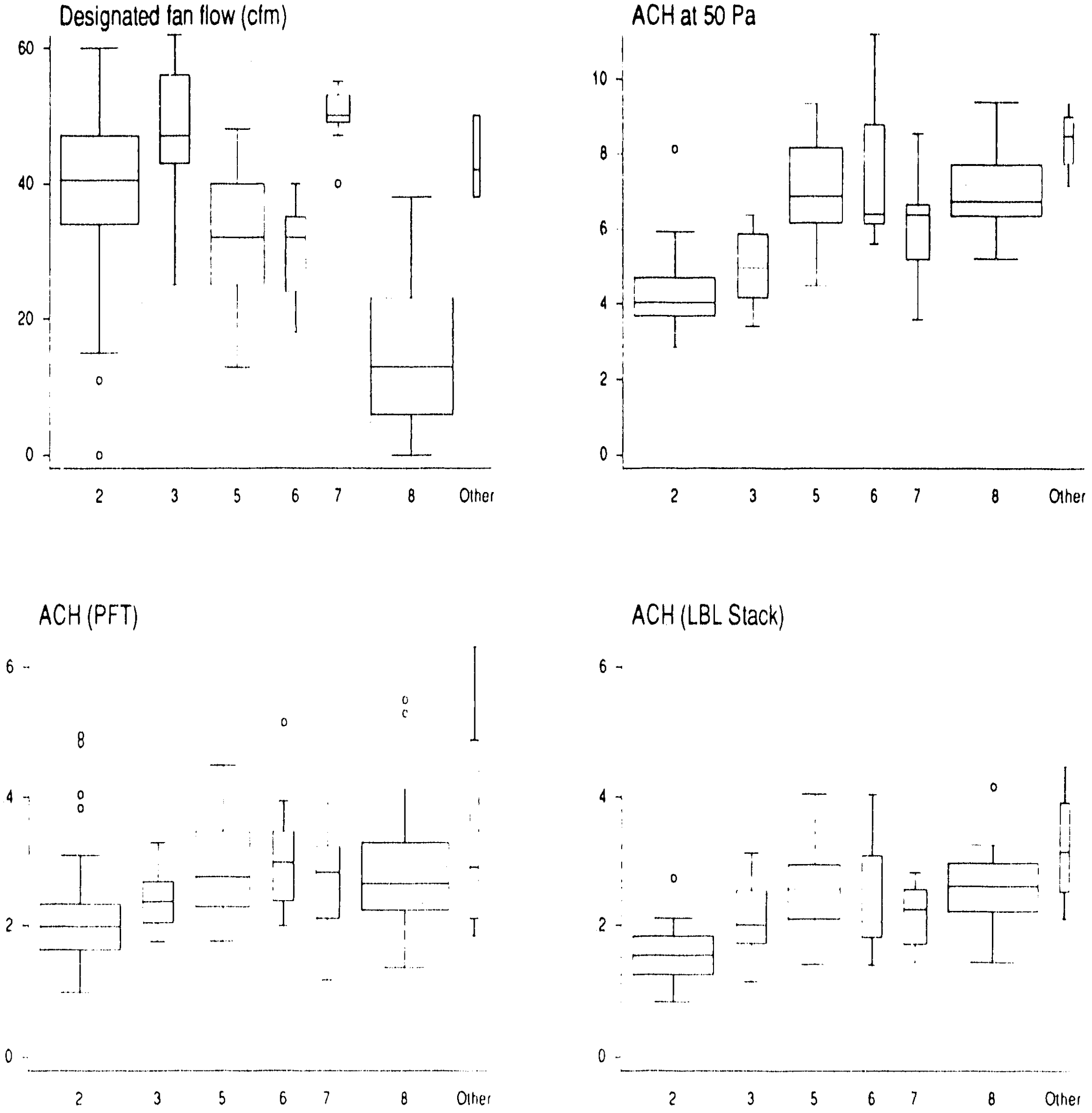

Figure 3. Box plots of fan flow, tightness and infiltration by manufacturer.
The upper graphs show measured exhaust fan flow and the air changes at 50 Pa. The lower graphs depict infiltration in air changes.

The lowest fan flows are found in the homes of builder #8; these rates averaged 14.7 cfm, or 29% of the rated capacity. Field inspections of this builder's homes revealed that the exhaust duct from the fan usually follows a long path to a soffit vent on the wall and that the end of the duct may be partially blocked by insulation or by the wall itself. Builder #3 has the highest fan flows; these average 47.8 cfm or 96% of the rated capacity. In these homes, the exhaust duct led from the fan directly to the roof above. These systems minimized hydraulic resistance, so the fans were able to deliver more flow.

The third and fourth blocks of the table give mean values of the infiltration in air changes and cfm, as measured by the PFT test and predicted by the stack portion of the LBL model. The PFT and stack-model air changes are also shown in the lower graphs in Figure 3. Both measures are correlated with the tightness, but the degree of scatter within each group is greater for the PFT measurements than for either the tightness measures or the LBL stack predictions.

Compliance with ventilation standards, as discussed in Section 7.2, also varies widely among manufacturers. Failure rates for each manufacturer are listed in Table 17 and depicted graphically in Figure 4.

Table 17. Percentage of specification failure by manufacturer.

		2	**3**	**5**	**6**	**7**	**8**	OTHER
Number of homes		34	13	23	9	10	38	4
Fail ASHRAE Std. 62	%	38	100	83	78	80	75	82
Fail SGC ventilation	%	41	8	83	78	20	100	33
Fail spot ventilation	%	85	54	100	100	33	100	67

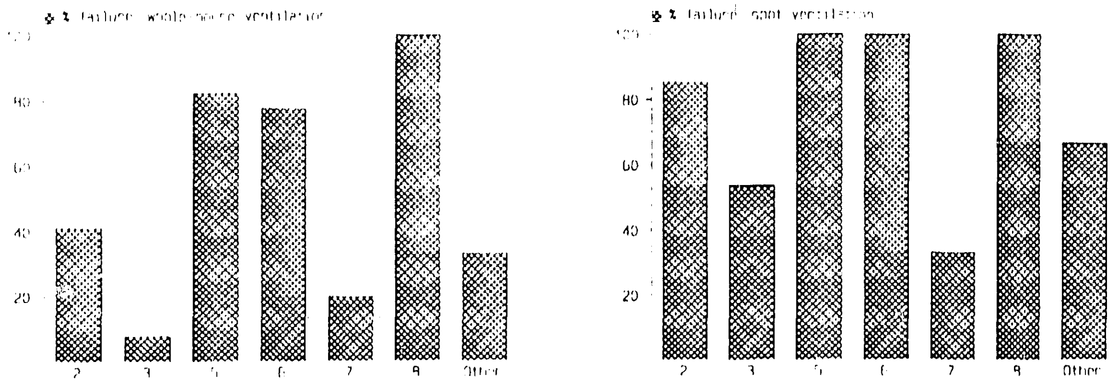

Figure 4. Percentage of homes failing Super Good Cents standards for whole-house and spot ventilation, by manufacturer.

10. FINDINGS AND CONCLUSIONS

This report summarizes the results of ventilation and infiltration measurements on a total of 160 manufactured homes in the Pacific Northwest. These homes include 131 energy-efficient homes built under the Residential Construction Demonstration Project (RCDP) to Super Good Cents (SGC) standards, and 29 control homes which did not participate in energy-efficiency programs. We also compare the manufactured homes with three earlier studies, the Northwest Residential Infiltration Survey Cycles I and II (NORIS I and NORIS II), and RCDP site-built homes.

All of the manufactured homes had forced-air heating systems. The RCDP manufactured homes all had exhaust-fan ventilation systems; none of the control homes had exhaust ventilation systems. Furnace makeup air systems were present in 90% of the RCDP homes and 52% of the control homes.

The standard deviations of the infiltration and tightness parameters are large, about 30% of the mean, compared with 40 to 50% in the NORIS I baseline study. Although the variation has decreased relative to the NORIS I study, it is still much too great for efficient and predictable operation of mechanical ventilation systems.

The RCDP manufactured homes were fairly tight. The average air-change rate at 50 Pa (ACH50), measured by blower door pressure tests, was 6.1 ACH. By this measure, these homes are 30% tighter than the control homes and 34% tighter than NORIS I homes; they were 10% less tight than RCDP site-built homes. The measured infiltration rate was 0.27 ACH, about 20% less than that in the control homes and 30% less than in NORIS I.

The tightness of the home, as indicated by the ACH50 or specific leakage area, is the single most important variable for predicting natural infiltration, both within studies and between studies. The decrease in the ACH50 from the control homes to the RCDP manufactured homes is 30%; the decrease in the measured infiltration is 20%; thus indicating that the added infiltration due to the mechanical ventilation systems is relatively small.

The LBL stack model has been found to predict natural infiltration well. Using this prediction, we estimate that the added infiltration due to wind, exhaust-fan ventilation systems, furnace makeup ventilation systems, duct leakage, and occupant use of other fans and opening of doors and windows combined is about 0.04 ACH for the RCDP manufactured homes and 0.03 for the control homes. The infiltration added by the SGC-required exhaust-fan systems must be considerably less than the value of 0.04 ACH.

The same make and model of fan, rated at 50 cfm, was used for all of the exhaust ventilation systems in the RCDP manufactured homes. The measured flow rates through the exhaust fans averaged 32 cfm or 0.165 ACH, 37% below rated capacity. The measured flow rate through the furnace makeup ventilation system averaged 34 cfm or 0.18 ACH.

The run-time of the exhaust-fan systems had a mean of 2.5 h/day and a median of 2.0 h/day; During the PFT tests, the run-time of the furnace averaged 3.5 h/day, with a median of 3.2 h/day.

Using a recently developed model for combining natural infiltration and ventilation due to fans in conjunction with the measured run-times of the fans and the measured flow rates, we estimated the infiltration added by the ventilation systems. The bath fan exhaust systems contributed about 0.009 ACH; the furnace ventilation systems added about 0.012 ACH.

The measured infiltration rates in the manufactured homes are low relative to ASHRAE Standard 62-89, which requires a *minimum* ventilation rate of 0.35 ACH. Eighty-five percent of the RCDP and 72% of the control manufactured homes fail this standard. Even if the necessary air-change rate were reduced to 0.25 ACH, 53% of the RCDP homes and 31% of the control homes would fail. This level of failure is a major cause for concern.

For the RCDP homes, if the exhaust fans were operated 24 h/day, the failure rate would be 59%; if the fans ran continuously and delivered the rated capacity of 50 cfm, the failure rate would be 36%, which can be compared with the 50% failure rate in the NORIS I baseline study. It is clear that fans of this capacity must be operated 24 h/day in order to have a significant impact on total infiltration rates. It should also be noted that, in the absence of stack and wind infiltration effects, a 50-cfm fan will not provide 0.35 ACH. Meeting Standard 62 under these conditions would require 70-cfm fans for these homes.

As calculated using measured exhaust fan flows, 63% of the homes failed to meet Super Good Cents requirements for whole-house ventilation rates. Of the 121 homes with measured bath-fan flows, 85% lacked sufficient spot ventilation capacity as defined by SGC specifications.

There were significant differences in tightness and the concomitant measured infiltration rates among the six most predominant manufacturers. The homes of two manufacturers averaged between 4 and 5 air changes at 50 Pa, while the others generally exceeded 7.

There were also significant differences in exhaust-fan flow rates among manufacturers. In particular, fan flow rates in the homes built by the manufacturer responsible for the greatest number of RCDP manufactured homes (29%) averaged only 15 cfm; the other manufacturers all averaged above 30 cfm. One manufacturer averaged 50 cfm, the rated capacity. Failure to achieve the rated capacity is due to improper installation and duct terminations, and can be remedied by proper specifications.

From an engineering viewpoint, the optimum home is nearly airtight and has a mechanical ventilation system. Although the RCDP manufactured homes are tighter than the control homes, some are not tight enough, and natural infiltration is dominant. To make an exhaust-type system function predictably, the house must be tight enough so that the flow through the fan is greater than twice the natural infiltration rate. In the same way, ventilation produced by a balanced neutral-pressure system will be most predictable when the house is so airtight that the natural infiltration is close to zero.

As long as there is a significant component of natural infiltration, problems with control and predictability will result in either energy waste or inadequate ventilation. It must be emphasized that if a home is tight enough for the proper operation of a mechanical ventilation system (less than 3 ACH at 50 Pa), the *continuous* operation of that system is *mandatory* to attain the ASHRAE Standard 62 *minimum* recommended ventilation rate of 0.35 ACH.

These findings emphasize the need for further research into the causes of variation in infiltration rates and the need to devise reliable methods of achieving desired levels of tightness and ventilation. This work is all the more urgent as regions and utilities are currently implementing various infiltration and ventilation construction standards.

Without a clear understanding of these problems and the subsequent development of training programs for builders and inspectors (emphasizing diagnostic use of blower doors to ascertain tightness and *tested* methods of ventilation system design), these new standards will remain empty specifications with unpredictable consequences.

11. ACKNOWLEDGEMENTS

The measurement protocols and analysis methodology used in this study are an improvement and continuation of those developed in the NORIS I, NORIS II and RCDP projects. These projects constitute an ongoing effort spanning a time period of over three years and involving field work in a four-state area.

As with any project of this nature, the work could not have reached a successful conclusion without the cooperative efforts of many people. This work was performed for the Bonneville Power Administration, under the direction of Steve Onisko as Project Manager.

The field work and PFT analyses were supervised by Don Hadley of Battelle Pacific Northwest Laboratory. Four field contractors performed the field work; the homeowners allowed us to spend over half a day measuring their homes and retrieved and returned the PFT sampling materials. Mike Lubliner of the Washington State Energy Office and Tom Hewes of the Oregon Department of Energy worked with the manufacturers to produce the homes and were responsible for field checks.

Additional insights into infiltration and ventilation in manufactured homes were gained in a project sponsored by the Electric Power Research Institute. Max Sherman of Lawrence Berkeley Laboratory made valuable contributions to the development of the fan model.

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APPENDIX - DETAILED RESULTS

The infiltration results are summarized in Tables A1 through A4. The tables are arranged to facilitate several comparisons of interest. Table A1 compares the RCDP manufactured homes with the control group. It provides answers to the question, "For manufactured homes, how do RCDP and control homes compare?"

In Table A2, results from RCDP site-built and manufactured homes are summarized. This table addresses the differences between site-built and manufactured homes which participated in the RCDP program.

Table A3 compares the RCDP manufactured homes with NORIS I homes. It addresses the question, "How do RCDP manufactured homes compare with a statistical sample of all-electric homes completed between January 1, 1980 and November 1, 1987?" Table A4 compares the results from the control group of homes with those from NORIS I. It addresses the differences between site-built and manufactured homes which did not participate in energy-efficient programs.

The infiltration measures presented in the tables include several leakage parameters as determined from blower-door depressurization tests, the PFT tracer test results, and infiltration predictions from the LBL infiltration model. The LBL model results are given both for the full model and for the stack (temperature-driven) portion. They are given for the PFT measurement period based on concurrent hourly Sea-Tac National Weather Service data, as well as for a typical heating season based on November through April hourly Typical Meteorological Year (TMY) data. The LBL model data were also used to project the PFT results to the TMY data.

The infiltration results are given as both air-changes per hour (ACH) and as total flow rate in cubic feet per minute (cfm). In addition to the infiltration results, the tables include characteristics of the homes and pertinent occupant data. They also tabulate the percentage of homes which fail ASHRAE Standard 62 (1989) for minimum ventilation rates and the percentage of homes which fail a criteria of 15 cfm per occupant.

The calculation of the infiltration variables and discussions of their interpretation and interrelations are discussed at length in the NORIS I report. However, in order to facilitate understanding of the tables, they are prefaced by a brief key. Some of these issues are expanded upon in the following discussions.

In each table the comparisons are summarized by the ratio of two mean values. We performed a statistical test (generally a two sample t-test) for each pair of means. The results of the statistical tests are indicated by a symbol next to the ratio. The symbols denote three standard categories of p-values or statistical significance levels. These are interpreted as follows. The symbol § denotes a p-value less than or equal to 0.001, which means that if repeated pairs of samples of the same size were drawn, then less than 1 in 1000 of these pairs of samples would exhibit a difference in the means as large as that observed in our one sample, if in fact the two population means were equal. Thus small p-values indicate high levels of statistical significance and large p-values indicate low levels of statistical significance. It should be noted that large true differences may fail to be statistically significant simply because the sample sizes are too small relative to the standard deviation.

All calculations are based on hourly National Weather Service (NWS) data at airport weather stations chosen for their proximity to each home, unless labeled otherwise. Typical Meteorological Year (TMY) data are based on a heating season of October through April.

Area Volume	Calculated from the interior dimensions of the home
Bathrooms	Rooms containing a bath, shower or toilet
Bedrooms	Rooms used by occupants or guests for sleeping
Rooms not kitchen/bath	Total of all rooms which are not kitchens or bathrooms
Stack height	The average height of a column of warm indoor air which displaces cold outdoor air
Shielding class Terrain class	LBL model parameters used to generate reductions in airport wind speed, estimated from photographs of the home
Number of occupants	All occupants, including children of any age
Number of exhaust fans	All exhaust fans, including fans used in the ventilation system
Number of wood stoves Number of fireplaces	Number of devices using indoor or outdoor air
Inside temperature	An average of the temperatures in each PFT zone. Recorded temperatures are used in the NORIS I and NORIS II studies when available; otherwise, temperatures measured at the site visit are used
Outside temperature	Average outside temperature over the period of the PFT test
Temperature difference	Difference between average interior temperature and average outside temperature
Wind speed	Average wind speed over the period of the PFT test
TMY outside temperature	Average outside temperature over a typical season
TMY temperature difference	Difference between average interior temperature and average outside temperature for a typical heating season
TMY wind speed	Average wind speed over a typical heating season
Effective leakage area (ELA)	LBL effective leakage area calculated from the blower door depressure test on the house as found
Specific leakage area (SLA)	10,000 times the ELA divided by the floor area

Normalized leakage area (NLA)	1000 times the ELA divided by the floor area and multiplied by a height correction factor (height over 8.2 feet raised to the 0.3 power), as discussed in ASHRAE Standard 119 (1989)
Air changes at 50 Pa	Predicted from the blower door depressure test on the house as found
Cfm/occupant (PFT)	PFT air flow divided by the actual number of occupants
Less than 15 cfm/occupant	Homes for which the PFT air flow is less than 15 cfm per occupant
Fail Standard 62 (.35 ACH)	Homes for which the PFT air change rate is less than .35 per hour
Effective ACH (PFT)	PFT flow rates which would have occurred at 20°C and the atmospheric pressure at the elevation of the site
Effective ACH (LBL)	Effective ventilation predicted by the LBL model (see NORIS I report for a full discussion of effective ventilation)
Air changes (PFT)	PFT flow rates at 20°C and atmospheric pressure at the site, divided by the ratio of LBL effective ACH to LBL ACH.
Air changes (Stack)	Air changes predicted by the stack portion of the LBL model
Air changes (LBL)	Air changes predicted by the combined stack and wind portions of the LBL model
TMY air changes (PFT) TMY air changes (Stack) TMY air changes (LBL)	Air changes as above, predicted for a typical meteorological year
Air flow (PFT)	Infiltration air flow predicted by the PFT test, adjusted for temperature, pressure, and efficiency
Air flow (Stack)	Infiltration air flow predicted by the stack portion of the LBL model
Air flow (LBL)	Infiltration air flow predicted by the combined stack and wind portions of the LBL model
Air changes (Wind)	Air changes predicted by the wind portion of the LBL model

Table A1. Comparison of RCDP and control manufactured homes.

Variable	Units	RCDP (n=131)		Control (n=29)		Ratio	
		Mean	SD	Mean	SD		
Area	ft^2	1472	263	1402	249	1.05	
Volume	ft^3	11884	2305	11280	2202	1.05	
Bathrooms		2.02	.17	2.00	.00	1.01	
Bedrooms		2.93	.56	2.86	.52	1.02	
Rooms not kitchen/bath		6.52	.91	6.34	.81	1.03	
Stack height	ft	8.14	.81	8.02	.27	1.02	
Shielding class		2.91	.98	3.07	.96	.95	
Terrain class		2.63	.85	2.76	.87	.95	
Number of occupants		3.06	1.63	3.03	1.32	1.01	
Number of exhaust fans		3.99	.46	4.14	.69	.96	
Number of wood stoves		.03	.17	.24	.44	.13	§
Number of fireplaces		.00	.00	.07	.26	.00	†
Inside temperature	F	68.7	3.8	68.0	4.2	--	
Outside temperature	F	40.3	6.0	40.9	6.1	--	
Temperature difference	F	28.4	7.4	27.1	8.3	1.05	
Windspeed	mph	8.6	2.5	8.6	3.1	1.00	
TMY outside temperature	F	40.3	3.5	40.7	3.4	--	
TMY temperature diff.	F	28.5	5.0	27.4	5.4	1.04	
TMY windspeed	mph	8.5	1.3	9.1	1.5	.94	*
Eff. leakage area (ELA)	in^2	68	20	92	27	.75	§
Specific leakage area		3.28	.99	4.56	1.07	.72	§
Norm. leakage area		.327	.099	.454	.109	.72	§
Air changes at 50 Pa	1/h	6.10	1.73	8.75	1.89	.70	§
Cfm/occupant		20.3	10.2	25.1	16.4	.81	*
Less than 15 cfm/occ	%	32.8	47.1	27.6	45.5	1.19	
Fail Std 62 (0.35 ACH)	%	84.7	36.1	72.4	45.5	1.17	
Effective ACH (PFT)	1/h	.242	.084	.303	.128	.80	†
Effective ACH (LBL)	1/h	.341	.136	.455	.159	.75	§
Air changes (PFT)	1/h	.267	.094	.334	.151	.80	†
Air changes (Stack)	1/h	.225	.072	.305	.086	.74	§
Air changes (LBL)	1/h	.379	.160	.500	.181	.76	§
TMY air changes (PFT)	1/h	.268	.092	.336	.143	.80	§
TMY air changes (Stack)	1/h	.225	.067	.309	.082	.73	§
TMY air changes (LBL)	1/h	.380	.149	.518	.165	.73	§
Air flow (PFT)	cfm	53	21	63	30	.84	*
Air flow (Stack)	cfm	44	16	57	21	.77	§
Air flow (LBL)	cfm	74	33	96	45	.78	†
Air changes (Wind)	1/h	.273	.153	.356	.189	.77	*

* $.01 < p \le .05$ † $.001 < p \le .01$ § $p \le .001$ ‡

Table A2. Comparison of RCDP site-built and manufactured homes.

		RCDP Manufactured (n=131)		RCDP Site-Built (n=129)			
Variable	**Units**	**Mean**	**SD**	**Mean**	**SD**	**Ratio**	
Area	ft^2	1472	263	1897	620	.78	§
Volume	ft^3	11884	2305	15933	5503	.75	§
Bathrooms		2.02	.17	2.18	.69	.93	†
Bedrooms		2.93	.56	3.02	.77	.97	
Rooms not kitchen/bath		6.52	.91	6.62	1.72	.98	†
Stack height	ft	8.14	.81	10.89	2.91	.75	§
Shielding class		2.91	.98	3.22	1.01	.90	*
Terrain class		2.63	.85	3.40	.94	.77	§
Number of occupants		3.06	1.63	2.94	1.32	1.04	
Number of exhaust fans		3.99	.46	4.18	1.37	.96	
Number of wood stoves		.03	.17	.16	.37	.19	§
Number of fireplaces		.00	.00	.39	.51	.00	§
Inside temperature	F	68.7	3.8	67.4	3.2	1.02	†
Outside temperature	F	40.3	6.0	46.4	5.4	.87	*
Temperature difference	F	28.4	7.4	21.0	5.5	1.35	§
Windspeed	mph	8.6	2.5	8.8	2.3	.97	§
TMY outside temperature	F	40.3	3.5	39.0	4.6	1.03	
TMY temperature diff.	F	28.5	5.0	28.5	4.7	1.00	
TMY windspeed	mph	8.5	1.3	8.2	2.2	1.04	
Eff. leakage area (ELA)	in^2	68	20	70	34	.97	
Specific leakage area		3.28	.99	2.79	1.53	1.18	†
Norm. leakage area		.327	.099	.299	.157	1.10	
Air changes at 50 Pa	1/h	6.10	1.73	5.55	2.86	1.10	
Cfm/occupant		20.3	10.2	30.1	26.5	.67	§
Less than 15 cfm/occ	%	32.8	47.1	24.0	42.9	1.37	
Fail Std 62 (0.35 ACH)	%	84.7	36.1	71.3	45.4	1.19	†
Effective ACH (PFT)	1/h	.242	.084	.253	.136	.96	
Effective ACH (LBL)	1/h	.341	.136	.242	.132	1.41	§
Air changes (PFT)	1/h	.267	.094	.276	.146	.97	
Air changes (Stack)	1/h	.225	.072	.176	.089	1.28	§
Air changes (LBL)	1/h	.379	.160	.264	.148	1.44	§
TMY air changes (PFT)	1/h	.268	.092	.325	.172	.82	†
TMY air changes (Stack)	1/h	.225	.067	.206	.104	1.09	
TMY air changes (LBL)	1/h	.380	.149	.279	.155	1.36	§
Air flow (PFT)	cfm	53	21	70	38	.75	§
Air flow (Stack)	cfm	44	16	44	22	1.01	
Air flow (LBL)	cfm	74	33	66	37	1.12	
Air changes (Wind)	1/h	.273	.153	.173	.126	1.58	§

* $.01 < p \le .05$ † $.001 < p \le .01$ § $p \le .001$ ‡

Table A3. Comparison of RCDP manufactured and NORIS I homes.

		RCDP Manufactured (n=131)		NORIS I (n=134)			
Variable	Units	Mean	SD	Mean	SD	Ratio	
Area	ft^2	1472	263	1844	598	.80	§
Volume	ft^3	11884	2305	15500	5620	.77	§
Bathrooms		2.02	.17	2.31	.72	.87	§
Bedrooms		2.93	.56	3.19	.84	.92	†
Rooms not kitchen/bath		6.52	.91	6.93	1.74	.94	*
Stack height	ft	8.14	.81	11.71	3.46	.70	§
Shielding class		2.91	.98	3.42	.99	.85	§
Terrain class		2.63	.85	4.13	1.12	.64	§
Number of occupants		3.06	1.63	3.35	1.37	.91	
Number of exhaust fans		3.99	.46	3.52	1.51	1.13	§
Number of wood stoves		.03	.17	.71	.64	.04	§
Number of fireplaces		.00	.00	.55	.72	.00	§
Inside temperature	F	68.7	3.8	67.2	3.8	1.02	†
Outside temperature	F	40.3	6.0	43.2	4.3	.93	§
Temperature difference	F	28.4	7.4	24.0	5.5	1.19	§
Windspeed	mph	8.6	2.5	8.9	1.8	.97	
TMY outside temperature	F	40.3	3.5	40.6	4.2	.99	
TMY temperature diff.	F	28.5	5.0	26.6	5.5	1.07	†
TMY windspeed	mph	8.5	1.3	9.1	1.5	.93	§
Eff. leakage area (ELA)	in^2	68	20	125	71	.55	§
Specific leakage area		3.28	.99	4.78	2.17	.69	§
Norm. leakage area		.327	.099	.527	.245	.62	§
Air changes at 50 Pa	1/h	6.10	1.73	9.28	3.47	.66	§
Cfm/occupant		20.3	10.2	34.4	25.9	.59	§
Less than 15 cfm/occ	%	32.8	47.1	20.1	40.2	1.63	*
Fail Std 62 (0.35 ACH)	%	84.7	36.1	50.0	50.2	1.69	§
Effective ACH (PFT)	1/h	.242	.084	.368	.178	.66	§
Effective ACH (LBL)	1/h	.341	.136	.408	.179	.84	§
Air changes (PFT)	1/h	.267	.094	.384	.183	.70	§
Air changes (Stack)	1/h	.225	.072	.341	.156	.66	§
Air changes (LBL)	1/h	.379	.160	.427	.186	.89	
TMY air changes (PFT)	1/h	.268	.092	.402	.184	.67	§
TMY air changes (Stack)	1/h	.225	.067	.357	.161	.63	§
TMY air changes (LBL)	1/h	.380	.149	.446	.202	.85	†
Air flow (PFT)	cfm	53	21	100	64	.53	§
Air flow (Stack)	cfm	44	16	89	55	.50	§
Air flow (LBL)	cfm	74	33	111	65	.67	§
Air changes (Wind)	1/h	.273	.153	.215	.131	1.27	§

* $.01 < p \le .05$ † $.001 < p \le .01$ § $p \le .001$ ‡

Table A4. Comparison of manufactured control homes and NORIS I homes.

		Control (n=29)		NORIS I (n=134)			
Variable	Units	Mean	SD	Mean	SD	Ratio	
Area	ft^2	1402	249	1844	598	.76	§
Volume	ft^3	11280	2202	15500	5620	.73	§
Bathrooms		2.00	.00	2.31	.72	.86	*
Bedrooms		2.86	.52	3.19	.84	.90	*
Rooms not kitchen/bath		6.34	.81	6.93	1.74	.91	†
Stack height	ft	8.02	.27	11.71	3.46	.69	§
Shielding class		3.07	.96	3.42	.99	.90	
Terrain class		2.76	.87	4.13	1.12	.67	§
Number of occupants		3.03	1.32	3.35	1.37	.91	
Number of exhaust fans		4.14	.69	3.52	1.51	1.17	*
Number of wood stoves		.24	.44	.71	.64	.34	§
Number of fireplaces		.07	.26	.55	.72	.12	§
Inside temperature	F	68.0	4.2	67.2	3.8	1.01	
Outside temperature	F	40.9	6.1	43.2	4.3	.95	*
Temperature difference	F	27.1	8.3	24.0	5.5	1.13	*
Windspeed	mph	8.6	3.1	8.9	1.8	.97	
TMY outside temperature	F	40.7	3.4	40.6	4.2	1.00	
TMY temperature diff.	F	27.4	5.4	26.6	5.4	1.03	
TMY windspeed	mph	9.1	1.5	9.1	1.5	1.00	
Eff. leakage area (ELA)	in^2	92	27	125	71	.73	*
Specific leakage area		4.56	1.07	4.78	2.17	.95	
Norm. leakage area		.454	.109	.527	.245	.86	
Air changes at 50 Pa	1/h	8.75	1.89	9.28	3.47	.94	
Cfm/occupant		25.1	16.4	34.4	25.9	.73	
Less than 15 cfm/occ	%	27.6	45.5	20.1	40.2	1.38	
Fail Std 62 (0.35 ACH)	%	72.4	45.5	50.0	50.2	1.45	*
Effective ACH (PFT)	1/h	.303	.128	.368	.178	.82	
Effective ACH (LBL)	1/h	.455	.159	.408	.179	1.12	
Air changes (PFT)	1/h	.334	.151	.384	.183	.87	
Air changes (Stack)	1/h	.305	.086	.341	.156	.89	
Air changes (LBL)	1/h	.500	.181	.427	.186	1.17	
TMY air changes (PFT)	1/h	.336	.143	.402	.184	.84	
TMY air changes (Stack)	1/h	.309	.082	.357	.161	.87	
TMY air changes (LBL)	1/h	.518	.165	.446	.202	1.16	
Air flow (PFT)	cfm	63	30	100	64	.63	†
Air flow (Stack)	cfm	57	21	89	55	.65	†
Air flow (LBL)	cfm	96	45	111	65	.86	
Air changes (Wind)	1/h	.356	.189	.215	.131	1.66	§

* $.01 < p \leq .05$ † $.001 < p \leq .01$ § $p \leq .001$ ‡

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