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Typical Envelope and Duct Leakages in Newly Constructed MEC-Compliant Homes

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ABSTRACT

Newly constructed two-story colonial homes with full basements in Virginia and Maryland were tested to determine envelope and duct leakage, fan exhaust flows, and maximum basement depressurization. The homes met or exceeded the basic air sealing requirements found in the 1993-1995 Model Energy Code. Data from these homes provide baseline information for newly constructed homes and can be used to assess the impact of MEC prescriptive air sealing practices on such homes. A test method was also developed to determine basement leakage.

The homes had a mean envelope leakage of 4.6 air changes per hour at a 50 Pa pressure difference (ACH50). A basic air seal of caulk or glue at the double studs and plates, foundation sill sealer, and air barrier tape at window nailing flanges achieved air change rates ranging from 4.9 ACH50 to 7.0 ACH50. Homes with additional foaming or caulking of window rough openings and air barrier material placed at band joists resulted in leakage rates of 3.1 ACH50 to 4.0 ACH50. Total and unconditioned duct leakage at 25 Pa of pressure were 684 cfm and 173 cfm, respectively, for the average 2000 ft^2 home. Except for one fan with mechanical problems, bathroom fan flows for these houses ranged from 32 cfm to 58 cfm with an average flow rate of 42 cfm.

INTRODUCTION

Eleven houses with standard fiberglass batt wall insulation were tested to determine air infiltration, duct leakage, and maximum basement depressurization. These houses were tested as a control group of standard building practices as part of a larger survey (Pesce and Gilg 1998). Examining the results of these tests allows the evaluation of some of the current assumptions about building envelope infiltration. The 11 "standard practice" houses were provided by four different production builders participating in the study. The houses contributed by Builders 1, 3, and 4 were built in Virginia and complied with both the 1993 *Model Energy Code* (CABO 1995) and the 1992 CABO One and Two Family Dwelling Code. The houses contributed by Builder 2 were located in Maryland and were built in accordance with the 1993 BOCA Code.

The standard practice in all homes was R-13 fiberglass batts in 16 in. on-center stud wall cavities, as shown in Table 1. Attics were insulated with R-30 blown fiberglass insulation over the flat ceilings and R-30 batts over cathedral ceilings.

TABLE 1
Typical Insulation Practice

Component R-value	
Attic, flat	R-30 blown
Attic, scissors or vaulted	R-30 batt
Attic, knee walls	R-19 batt
Floors over garage	R-19 batt
Walls	R-13 batt
Basement	R-11 blanket

Builder 1 used unfaced wall batts with a polyethylene vapor retarder, while Builders 2, 3, and 4 used kraft-faced wall batts.

While insulating practices were fairly uniform among the different builders, there were some differences in their air-sealing practices. The air-sealing practices used by each builder are listed in Tables 2 and 3. All homes were constructed with three-ply kraft sheathing and vinyl siding on at least three sides.

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TABLE 2
Air-Sealing Treatment of Structural Members

Builder	Bottom Plate	Top Plate	Double Studs	Panel Joints and Corners	Band Joist	Foundation Sill Plate
1	Glue	No treatment	Glue	Glue and air barrier	Air barrier	Sill sealer
2	Glue	No treatment	Glue	Glue	Air barrier	Sill sealer
3	Caulk	Caulk	Caulk-	—	No treatment	Sill sealer
4	Caulk	Caulk	Caulk	—	No treatment	Sill sealer

TABLE 3
Air-Sealing Treatment of Penetrations

Builder	Wiring & Plumbing	Duct Penetrations	Rough Openings
1	Rock wool	Rock wool & sheet metal	Chinked, caulked, & taped
2	Foam	Foam & sheet metal	Foamed & taped
3	No treatment	Sheet metal	Chinked & taped
4	Rock wool	Rock wool & sheet metal	Chinked & taped

The individual houses are identified by a number, indicating the builder, and a letter, indicating the order in which the houses were tested. For example, house 1c was the third house by Builder 1 tested in the larger study. Only houses using standard practices are presented here, so there are gaps in the identification sequence.

TESTING METHODS AND MEASUREMENTS

Envelope Leakage

The depressurization blower door tests were performed in accordance with ASTM Standard E-779 (ASTM 1992) by setting up the blower door in the front door of the house. Readings were taken at approximately 5 Pa, 12.5 Pa, 25 Pa, 37.5 Pa, 50 Pa, 62.5 Pa, and 75 Pa, which minimized the effect that one bad data point would have on the analysis while still being few enough to measure quickly. Five readings were taken of flow and pressure at each pressure setting, and these five values were later used to calculate average readings for pressure and envelope leakage at each fan setting. Tests conducted under windy conditions were discarded and repeated the following day.

The envelope leakage is assumed to follow the standard leakage curve of $F = c\Delta P^n$ (ASTM Standard E-779), where F is the infiltration in cfm, ΔP is the pressure difference between the inside and outside of the house in Pa, and c and n are constants based on the geometry and leakiness of the building. The values of c and n for each house were determined by using a least squares fit of the measured data. By using the model found in *ASHRAE Fundamentals* (ASHRAE 1997) and the blower door data, the natural infiltration rate was calculated using TMY2s data (NREL 1995) to assign weather conditions on an hourly basis. From this, the average infiltration over the course of a year was calculated. The natural infiltration rates for Builders 1, 3, and 4 were calculated using the weather data for Sterling, Virginia. The rates for Builder 2 were calculated using the data set for Baltimore, Maryland.

The Basement Leakage Test

In addition to the standard infiltration measurement, measurements were made on some of the houses to evaluate the amount of air leakage occurring through the basement. If this leakage can be separated from the overall envelope leakage of the house, it may allow greater precision in leakage modeling and provide a possible refinement to the LBNL model. The test was performed by setting up a second blower in the interior basement door. This second blower door was the fan from a duct blaster set up in a blower door frame. When the house was pressurized, the basement fan was used to equalize the pressure between the upstairs and the basement. Since there would be no pressure difference between the basement and upstairs portion of the house, any leakage from the basement would presumably be going out of the building envelope. When the pressures were equalized, measurements were taken of the pressure difference between the house and outside air and of the fan flows in both the basement and front doors. This was done for pressure differences of about 12.5 Pa, 25 Pa, 50 Pa, and 75 Pa and the data were fitted to the standard leakage curve. This test was performed both with the ducts opened and after the ducts had been sealed with duct mask.

Duct Leakage

In addition to testing building infiltration, the leakage of the duct system was measured. This was done by separating the supply and return sides from each other at the air handler

TABLE 4
Duct Locations

Builder	First Floor		Second Floor	
	Material	Location	Material	Location
1	Metal	Conditioned	Metal	Conditioned
2	Metal	Conditioned	Metal/Flex	Attic
3	Metal	Conditioned	Metal/Flex	Attic
4	Metal	Conditioned	Metal/Flex	Attic

and testing each part separately in accordance with ASTM Standard E-1554 (ASTM 1994) and ASHRAE draft standard 152P (ASHRAE 1996). Pressure was measured in the supply and return plenums, and leakage readings were taken at duct pressurizations of approximately 12.5 Pa, 25 Pa, 50 Pa, and 75 Pa. These data points were then fitted to the standard leakage curve. Measurements were taken both of the total duct leakage and of the leakage of the ducts to unconditioned spaces.

Fan Flows

The amount of air drawn through the exhaust fans of the houses studied were measured using a flow hood. Three to five readings were taken of each fan, and these readings were averaged to produce fan flow data.

Basement Depressurization

At the end of each test sequence, each house was tested for the maximum basement depressurization. One tube from a digital pressure meter was placed in the basement while the other was run to the outside air. The pressure difference between the two states was measured with the air handler, exhaust fans, and various doors in different positions to determine which state created the greatest negative pressure in the basement relative to the outside.

RESULTS AND DISCUSSION

Envelope Leakage

Following the procedure described above, the envelope leakage for the houses tested was calculated at 50 Pa and under natural conditions using both Class 4 and Class 5 wind coefficients. The results are presented in Table 5.

There is good agreement within the set of houses supplied by each builder. The only builder for which there was great variability was Builder 4, and this variability can be attributed to differences between the houses tested. Houses 4a and 4b were built with a high vaulted ceiling in the family room, while 4d and 4e both had an optional bedroom over the family room. House 4a was also built using a different floor plan than any of the other houses supplied by Builder 4.

The differences in infiltration between the builders can be explained by differences in air-sealing techniques. Builders 3 and 4 chinked their rough openings with fiberglass, while Builder 1 used caulk and Builder 2 used foam. Builders 1 and 2 also used air barrier material to cover cracks along the band joists, while Builders 3 and 4 used no such treatment. These factors may explain the lower infiltration rates found in the homes constructed by Builders 1 and 2.

The average natural infiltration for a standard practice house, giving equal weight to each builder, is 0.194 ACH. The individual averages of ACH$_{50}$ for each builder are presented in Figure 1. Results using both the Class 4 and Class 5 wind constant are presented in Table 5.

A typical assumption for the value of n in the infiltration equation ($F = c\Delta P^n$) is 0.65. This was confirmed by the measurements taken, in which n varied from 0.58 to 0.70. With the exception of the low extreme, all the values for n fell

TABLE 5
Air Change Rates of Houses Studied

House	CFM$_{50}$	Volume (ft^3)	Floor Area (ft^3)	ACH$_{50}$	Class 4 ACH$_{nat}$	Class 5 ACH$_{nat}$
1c	1403	22,779	1796	3.69	0.22	0.18
1d	1277	24,529	1917	3.12	0.16	0.13
2a	2775	43,873	3361	3.79	0.19	0.15
2b	3022	45,238	3537	4.01	0.20	0.16
2f	2905	45,546	3472	3.83	0.19	0.15
3a	2516	30,664	2219	4.92	0.30	0.25
3c	2731	30,348	2265	5.40	0.27	0.22
4a	3042	28,404	2062	6.42	0.33	0.27
4b	2821	24,245	2063	6.98	0.39	0.31
4d	2258	26,889	1990	5.04	0.24	0.20
4e	2135	25,341	1911	5.06	0.22	0.18

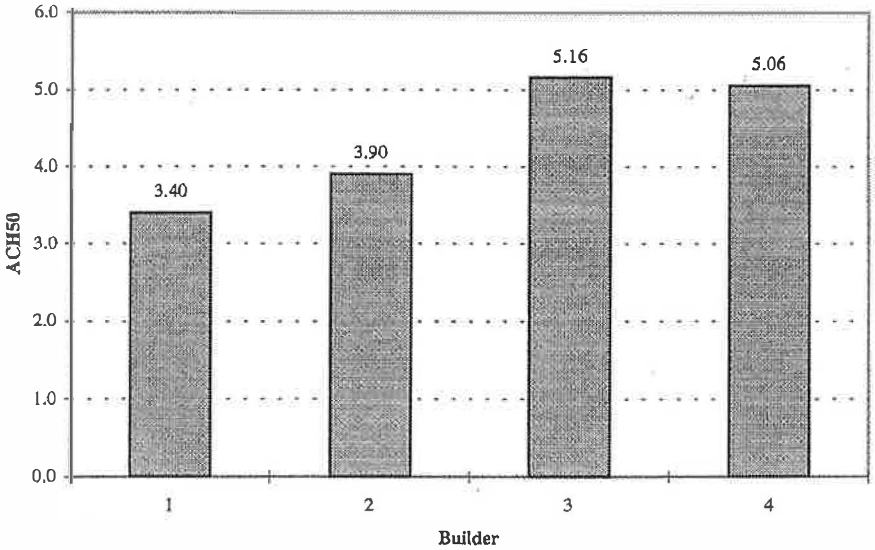

Figure 1 *Average air change rates.*

between 0.60 and 0.70. In order to calculate an average, overall value of n from the data collected, it is necessary to normalize the data to a common scale. To do this, each infiltration measurement was divided by the value of c for the specific house, yielding a normalized leakage of $F' = F/c$. Substituting this back into the leakage equation gives $F' = \Delta P^n$. Doing this for data points gathered from each builder and then finding the best value of n for each data set yields the results listed in Table 6.

TABLE 6
Average Values of *n*

Builder	n
1	0.624
2	0.673
3	0.640
4	0.657

Applying this process to all 62 points gathered yields $n_{tot} = 0.654$. Giving each builder equal weight by averaging the four curves instead of the 62 individual data points results in $n_{avg} = 0.649$. These curves, along with the two extremes, are represented graphically in Figure 2.

It has been suggested (Palmiter and Bond 1994) that readings at pressure differences less than 10 Pa would be inaccurate and not conform to the curve suggested by the readings at higher pressures. They hypothesized that the value of n would be increased from ~0.65 to ~0.70, distorting the shape of the leakage curve. The data presented here show that the reading at ~5 Pa was generally in good agreement with the rest of the data for any given house. It should be noted that care must be taken with this particular measurement, as wind conditions can skew low pressure readings. In this study, houses were tested with little or no wind present.

As demonstrated by Figure 2, the value of n in the leakage equation ($F = c\Delta P^n$) can vary from 0.60 to 0.70. If a single measurement is taken at 50 Pa and n is assumed to equal 0.65, the estimated leakage at 4 Pa can range, respectively, from 12% less to 13% greater than the nominal leakage.

Studies comparing the blower door infiltration model to actual measured infiltration using tracer gas indicate 30% to 60% overprediction of the LBNL model (Palmiter and Bond 1994), which may mean that pressurized house leakage follows a simple power law, as discussed above, but natural infiltration may not.

Basement Leakage

The basement leakage test was performed for houses 1a and 4b. Since both the overall house leakage and the leakage from the basement were measured during this test, the fraction of house leakage escaping through the basement can be calculated. The results of this test are presented in Table 7. Three other houses using nonstandard insulating practices (cellulose and blown-in blankets) were also tested in this manner to evaluate the technique. Those results are presented in Table 8 for comparative purposes. The columns labeled "Fraction" show the fraction of total envelope leakage occurring through the basement.

When the ducts are sealed, theoretically no air from the above-grade portion of the house is entering the ducts, so all of the duct leakage to unconditioned spaces will have to come from the basement. If most or all of the unconditioned duct leakage with the ducts unsealed comes from the above-grade portion of the house, the difference between the basement leakage with the ducts sealed and the ducts unsealed should be roughly equal to the unconditioned duct leakage. The difference between the basement leakage test with the ducts sealed and the basement leakage test with the ducts unsealed was

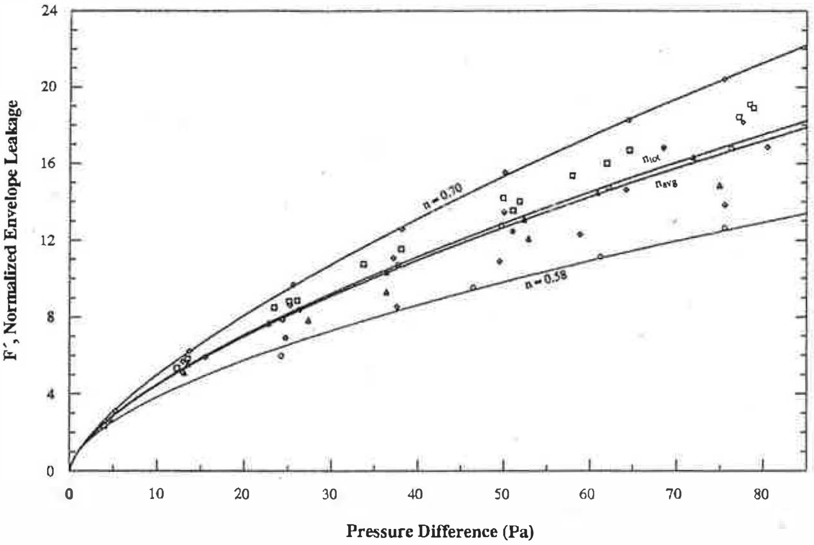

Figure 2 *F′ vs. pressure difference.*

called the "basement leakage difference," or BLD, and is shown in Table 9.

For all the houses with a walk-out basement, the BLD was about 60% of the unconditioned duct leakage, while the BLD was about 45% of unconditioned duct leakage for houses without a walk-out basement. When the envelope leakage test was conducted, it was run with the interior basement door both opened and closed in an attempt to isolate the basement. It was thought that the difference between the envelope leakage with the basement open and with the basement closed (BOC) might make up the difference between the unconditioned leakage and the difference between the two basement leakage tests, but it does not.

TABLE 7
Basement Leakage at 50 Pa for Standard Houses (cfm)

		Ducts Unsealed		Ducts Sealed	
House	**CFM_{50}**	**Leakage**	**Fraction**	**Leakage**	**Fraction**
1a[1]	**2311**	**816**	**0.353**	**983**	
4b[1]	**2821**	**1315**	**0.466**	**1514**	**0.537**

TABLE 8
Basement Leakage at 50 Pa for Some Other Houses (cfm) *

		Ducts Unsealed		Ducts Sealed	
House	**CFM_{50}**	**Leakage**	**Fraction**	**Leakage**	**Fraction**
1b	1503	475	0.316	553	0.368
4f[1]	2756	1129	0.410	1346	0.488
4g	2691	1043	0.388	1223	0.454

TABLE 9
Comparisons to Basement Leakage Test (cfm)

House	BLD	Uncond. Leakage	BOC
1a	167	—	178
1b	78	171	35
4b	199	331	192
4f	217	371	135
4g	180	389	101

One possible explanation is that the basement leakage test was performed with the air handler closed. This would reduce the ability of the equipment to pressurize the ducts, leading to duct losses smaller than those generated in the unconditioned leakage test. Another possibility is that a significant portion of the unconditioned duct leakage occurs through the basement even when the ducts are unsealed. Further testing is necessary to resolve this issue.

Duct Leakage

Applying the same curve-fitting techniques to the duct leakage data as the data from the blower door generates a leakage curve that can be used to calculate the duct leakage at 25 Pa, shown in Table 10.

In addition to the leakage test, the pressurization of the ducts under normal operation was measured. Pressures were measured at the supply and return plenums and were taken relative to the house pressure. These measurements are presented in Table 11. The houses provided by Builder 2 had two air-handling systems, so the values to the left of the slash

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[1] This house had a walk-out basement.

TABLE 10
Duct Leakage at 25 Pa (cfm)

	Supply Ducts		Return Ducts	
House	Total	Uncond.	Total	Uncond.
1c	297	34	98	24
1d	399	69	87	41
2a	504	134	208	104
2b	606	13	215	104
3a	516	165	93	42
3c	483	166	191	92
4a	663	133	667	43
4b	645	149	156	92
4e	456	160	126	54

TABLE 11
Normal Duct Pressures (Pa)

House	Supply	Return
1c	22	–42
1d	13	–31
2a	35/67	–69/–30
2b	13/43	–55/–30
3a	34	–93
3c	27	–91
4a	48	–43
4b	44	–61
4e	32	–44

are the pressures found in the system serving the first floor, while the values to the right are for the second floor air handler.

Fan Flows

The flow of air through the exhaust fans of each house was measured. For Builders 1, 3, and 4, the exhaust fans consisted of three bathroom fans. Builder 2 included a kitchen fan vented to the outside in addition to the usual three bathroom fans. The results are shown in Table 12, while the results from homes using nonstandard insulating practices are presented for comparison in Table 13.

TABLE 12
Fan Flows for Standard Houses (cfm)

House	Downstairs	Upstairs	Master	Kitchen
3a	**32**	**36**	**44**	—
4e	**34**	**37**	**38**	—

TABLE 13
Fan Flows for Other Houses (cfm)

House	Downstairs	Upstairs	Master	Kitchen
1b	—	44	45	—
45	38	45	48	—
2c	53	43/51[*]	51	—
2d	48	—	58	234
2f	52	—	46	204
3e	36	43	47	—
4c	45	33	24[†]	—
4f	43	43	44	—
4g	31	31	32	—

[*] This house had two upstairs bathrooms besides the master bath.

[†] This fan was poorly installed and could be heard grinding against the casing.

Each bathroom fan was rated at 50 cfm, but 19 of the 31 bathroom fans tested had flow rates more than 10% below this rate. Likely explanations for this are convoluted or overly long duct runs connected to the fans or too low a pressure head generated by the fan for the duct lengths required in new construction.

Basement Depressurization

Using the basement depressurization testing technique, the measurements listed in Table 14 were taken of the basement depressurization.

In all cases except house 4d, maximum basement depressurization occurred when the air handler was turned on, the exhaust fans were running, the interior basement door was open, and all other doors in the house were closed. The only difference between the maximum depressurization state of house 4d and the others was that maximum basement depressurization occurred when the air handler was turned off. The large depressurization experienced by house 2f was probably

TABLE 14
Maximum Basement Depressurizations

House	Pressure (Pa)
2f	4.9
3a	3.2
4b	1.7
4a	1.7
4d	0.6
4e	3.2

due in part to the presence of a powerful downdraft exhaust fan in the kitchen. The other builders in the study did not install this feature in their houses. The measurement can be used to assess the danger of combustion appliance backdrafting under the most extreme operating conditions. The average depressurization for the houses tested was 2.5 Pa, well below problem levels.

CONCLUSIONS

Envelope Leakage

- The differences in infiltration between the builders can most likely be explained by differences in air-sealing techniques. Chinking rough openings with fiberglass and caulking the plates provided an ACH_{50} of 5.0 to 5.2, while using foam or caulk on the rough openings, gluing the plates, and adding an air barrier at the joists further reduced this to about 3.9 ACH_{50} or lower.
- The houses tested for this study were all constructed to meet or exceed the air-sealing practices specified in the 1993-1995 *Model Energy Code* (section 502.3 in both editions [CABO 1995]). The data suggest that homes constructed using these practices will have air change rates lower than 0.5 ACH, the base level assumed for calculation in MEC.
- The value of n from the leakage equation $F = c\Delta P^n$ typically falls between 0.60 and 0.70 with an average value of 0.65. This confirms that default values for n accurately represent new two-story homes with basements.

Basement Leakage

- The basement leakage tests indicate that slightly less than half the infiltration of the house is occurring through the basement. Further measurements are required to confirm the applicability or accuracy of the leakage estimate.

Duct Leakage

- Averaging the data from the 11 homes tested, it was found that 74% of the total duct leakage and 66% of duct leakage to unconditioned spaces at 25 Pa occurred on the supply side. Since 66% of the duct leakage to unconditioned spaces comes from the supply ducts, the majority of the air lost in this way will be coming directly from the furnace.
- On average, the duct leakage to unconditioned spaces is about 28% of the total duct leakage at 25 Pa of pressurization.
- The duct leakage to unconditioned spaces at 50 Pa ranged from 7% to 16% of the total envelope leakage, with an average of 12%. With the exception of the two extremes, this percentage fell between 11% and 13% for all houses.
- The duct leakage data show that the largest amount leakage in the type of home tested occurred on the su ply side. At 25 Pa the total duct leakage for a 2000 home ranged from 395 cfm to 1330 cfm, with an avera of 684 cfm. The unconditioned duct leakage ranged fr 58 cfm to 258 cfm with an average value of 173 cfm.

Fan Flows

- Bathroom exhaust fans installed in the houses test have airflow rates ranging from 30 cfm to 60 cfm. Th suggests that in many cases duct runs or duct sizes a too long or too small, respectively, to meet the manufa turer's stated flow or that the fan head is too small meet the duct resistances typically found in new home

Back Drafting

- The worst-case depressurization for the houses teste ranged from 0.6 Pa to 4.9 Pa below outdoor air pressur with an average value of 2.5 Pa. A literature review (G 1995) indicates that a typical house depressurizatio limit (HDL) ranges from 5 Pa to 7 Pa below outdoor a pressure.

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APPENDIX

Relevant Literature

Lawrence Berkeley National Laboratories compiled a national database (Sherman and Dickerhoff 1994) containing data from 12,000 new and existing homes built between 1850 and 1993. Air changes at 50 Pa ranged from 0.47 ACH_{50} to 83.6 ACH_{50}. The average air change of the houses in this database is 29.7 ACH_{50} and the average construction date is 1965. Because such a wide range of construction dates was sampled, the LBNL database reflects the current state of all U.S. housing rather than newly constructed homes. Some recent studies that provide baseline data for air infiltration in newly constructed homes are summarized in Table A-1.

TABLE A1
Recent Infiltration Studies

Study	State	Number of Houses	Foundation	Average ACH_{nat}	Average ACH_{50}
Nelson et al. 1993	Minnesota	8	Basement	0.27	4.18
Kemper Management Services & Southern Electric International. 1994	Iowa	59	1-story, basement	0.34	4.73
		68	2-story, basement	0.40	4.87
		8	Split level	0.62	8.68
Synertec 1994	New York	14	Basement	—	6.52
		1	Crawl space	—	6.90
		2	Slab	—	4.55
Florida Solar Energy Center 1995	Florida	20	1-story, slab	0.16	6.04
		6	2-story, slab	0.23	7.19
NAHB Research Center 1996	Kansas	6	Basement	—	5.48
		1	Slab	—	6.20
	Maryland	7	Basement	—	4.43
	Virginia	4	Crawl space	—	6.90
Sun Power 1996	Colorado	10	Basement/Crawl	0.30	—
Sun Power 1997	Colorado	24	Basement/Crawl	0.35	—

- Eight homes in the Minneapolis-St. Paul metropolitan area were selected at random for the study conducted by Nelson et al. (1993). All of the homes tested had conditioned basements.
- All the homes surveyed for the 1994 Kemper Management Services and Southern Electric International had caulking and weather stripping.
- The study by Synertec (1994) evaluated the air leakage of 50 newer homes, 17 of which were less than two years old.
- The Florida Solar Energy Center reassessed the airtightness of 76 Florida homes (Cummings and Moyer 1995), separating out the youngest 26 for comparison. These younger houses were about two to three years old.
- The NAHB Research Center completed a study for the Gas Research Institute in 1996 (Pesce and Lyons) that contained air infiltration data for 18 newly constructed single-family homes. These houses had air change rates at 50 Pa ranging from 2.80 ACH_{50} to 7.40 ACH_{50}, with an average value of 5.42 ACH_{50}.
- The 1996 study conducted by Sun Power was performed for the Governor's Office of Energy Conservation in Colorado. The natural infiltration rate was calculated for 10 of the 23 new homes studied. Sun Power obtained additional data on 25 other new homes in 1997, one of which was removed from the study as an obvious outlier. All builders in both studies undertook some basic air sealing, usually utility penetrations to the attic and crawl spaces.

Palmiter and Bond (1991, 1994), in a two-part study funded by the Electric Power Research Institute (EPRI), found that the Lawrence Berkeley National Laboratory (LBNL) infiltration model predicts natural infiltration rates that are 28% higher than actually occurs. This was more pronounced for wind-driven infiltration, which was overpredicted by 61%, than it was for infiltration driven by the thermal stack effect, which was overpredicted by 26%. One of the suggestions made by Palmiter and Bond (1994) to correct this overprediction was to use wind shielding constants one class higher than suggested by the LBNL model. For example, use urban shielding (Class 5) for suburban homes (Class 4).

Data from Table A-1, the Palmiter results, and the data presented by this study suggest that the natural infiltration in newly constructed homes may be lower than is generally believed.