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REDUCTION OF THE EFFECTIVE LEAKAGE AREAS OF SINGLE-SECTION HUD-CODE MANUFACTURED HOMES DUE TO AIR INFILTRATION BARRIERS

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ABSTRACT

This paper addresses the effective leakage area (ELA) reduction in single-section HUD-code manufactured homes due to the application of an air infiltration barrier (AIB). The data used for the analysis were generated over a period of three seasons, through hourly measurements of air infiltration, temperature, and wind speed, at a site with two HUD-code homes, one sheathed with an AIB and the other one caulked (Wilhelm 1979). The effective leakage areas are calculated using a model (Sherman and Grimsrud 1980) that correlates the air infiltration rate in residences to (1) weather variables, (2) the effective leakage area of the house, and (3) coefficients that are determined by construction and terrain characteristics.

Two sets of ELA calculations are performed for both AIB and caulked homes. In the first one, the model has the site-built housing coefficients presented in the ASHRAE Handbook of Fundamentals *(ASHRAE 1989). In the second one, the construction coefficients in the model are modified to account for the particular construction characteristics of single-section HUD-code manufactured homes. The magnitude of the ELAs is discussed and recommendations are made for the value of the ELA reduction attributable to an AIB.*

INTRODUCTION

The most common procedure used to calculate air infiltration rates in houses is presented in the *ASHRAE Handbook of Fundamentals* (ASHRAE 1989). The *ASHRAE Handbook* assumes that the specific infiltration of a building is directly proportional to its effective leakage area (ELA). The effective leakage area is defined as the equivalent area of an orifice that allows the same airflow rate as the actual building, assuming it is exposed to the same pressure difference. The specific infiltration (i.e., ratio of infiltration to effective leakage area) is estimated according to a quadratic equation, which comprises two variables: the inside-outside temperature differential and the wind speed.

The *ASHRAE Handbook* makes available data for calculating the effective leakage area, and provides values for the coefficients assigned to the two weather variables. The data for ELAs and coefficients were derived for site-built houses, and for this reason neither is particularly appropriate for HUD-code manufactured homes.

The construction details of HUD-code-manufactured homes differ significantly from those of site-built houses. In site-built houses the ceiling gypsum board is interrupted by interior walls. The cavities of interior walls establish air circulation paths between the interior of the house and the attic. Air can move into the walls through improperly finished cabinets that are recessed in the walls, around interior door jambs, through electric receptacles, and through piping and wiring penetrations. Air can exit into the attic through cracks around the top plates of the walls. As a result, the ceilings of site-built houses are relatively leaky.

In contrast, the ceiling of a HUD-code manufactured

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home is typically composed of uninterrupted gypsum board or fiber board. The ceiling is attached to the bottom chord of the roof trusses *before* the entire roof (ceiling included) is installed on top of the walls. Consequently, the ceiling is continuous and the infiltration paths through and around interior walls are practically eliminated. The ceilings of HUD-code manufactured homes are relatively tight.

Site-built houses and single-section HUD-code manufactured homes also differ in the construction of the attic. Site-built houses have vented attics. The vents enhance the air infiltration through the ceiling. However, some of the multi-section homes and the great majority of single-section homes have non-vented attics.

Finally, while the typical site-built house has sheathing on the exterior walls, the typical HUD-code manufactured home is unsheathed. The potential for air infiltration paths through the walls is even greater for multi-section HUD-code manufactured homes, where the marriage walls offer much opportunity for air leakage.

Due to all these factors, it is to be expected that the distribution of leakage areas is different between the two types of dwellings, with the ceiling playing a greater role in site-built houses than in HUD-code manufactured homes.

In light of the distinct construction characteristics of HUD-code manufactured homes, the applicability of the ASHRAE data used for infiltration calculation needs to be examined. In particular, since manufactured home construction indicates that most of the leakage area is likely to be in walls, the effect of air infiltration barrier (AIB) sheathing needs to be evaluated. Currently, in site-built houses 50% of the leakage area is assumed to occur in walls (ASHRAE 1989).

The information presented below was developed to more accurately describe the effect of AIBs on air infiltration leakage rates in HUD-code manufactured homes.

THEORY

In the model (Sherman and Grimsrud 1980), the infiltration is split into two distinct regimes: the wind regime, when the dynamic wind pressure dominates the infiltration, and the stack regime, when the indoor-outdoor temperature difference dominates the infiltration. In both instances, the infiltration is considered to be directly proportional to the effective leakage area of the building. A reduction in the effective leakage area of a building results in a reduction of the air infiltration rate into the building.

Infiltration in the wind regime is expressed as follows:

$$Q_{wind} = f_w^* A_o v' \quad (1)$$

where

Q = infiltration (m^3/s)
A_o = total leakage area of the structure (m^2)
v' = weather tower wind speed (m/s)
f_w^* = reduced wind parameter (dimensionless). It is expressed by:

$$f_w^* = C'(1-R)^{1/3} \{\alpha(H/10)^{\gamma}/[\alpha'/10)^{\gamma'}]\} \quad (2)$$

where

C' = generalized shielding coefficient
R = vertical leakage fraction (that is, the fraction of leakage area in floor and ceiling vs. the entire leakage area)
$\alpha, \alpha', \gamma, \gamma'$ = terrain parameters (Sherman and Grimsrud 1980; ECCS 1978)
H = height of the structure (m)
H' = height of the wind measurement tower (m)

Infiltration in the stack regime is given by the following expression:

$$Q_{stack} = f_s^* A_o (\Delta T)^{1/2} \quad (3)$$

where

Q = infiltration (m^3/s)
ΔT = indoor-outdoor temperature difference (K)
f_s^* = reduced stack parameter [$m/(sK^{1/2})$]. It is expressed by:

$$f_s^* = (1/3)(1 + R/2)[1 - X^2/(2 - R)^2]^{3/2} (gH/T)^{1/2} \quad (4)$$

where

X = ceiling-floor leakage area differential divided by the total leakage area of the house (m^2)
g = acceleration of gravity (9.8 m/s^2)
T = average indoor temperature (K)

In the model (Sherman and Grimsrud 1980) it is assumed that stack-induced and wind-induced infiltration add in quadrature, so the combined infiltration rate, Q, is given by the following expression:

$$Q = (Q^2_{stack} + Q^2_{wind})^{1/2} \quad (5)$$

By substituting the expressions of Q_{stack} and Q_{wind} in the above equation, the total infiltration can be expressed as follows:

$$Q = A_o (f_s^{*2} \Delta T + f_w^{*2} v'^2)^{1/2} \quad (6)$$

EXPERIMENT CONDITIONS

Two HUD-code manufactured homes were tested to measure infiltration with and without continuous AIB (Goldschmidt et al. 1980; Wilhelm 1979). Both homes were located at an airport site, west of the city of Lafayette, IN. The site was grassy flatland. Several single-story buildings were located 100 to 150 m east of these HUD-code homes.

Description of the HUD-Code Manufactured Homes

Both homes were single-section, 20.13 m long by 4.27 m wide, with 2.29 m ceilings. Therefore, each home had an envelope area of 283.66 m^2 and a volume of 196.83 m^3. The homes were insulated with R-14 fiberglass batts in the ceiling, R-11 in the walls, and a combination of R-11 and R-7 in the floor. (R-values are in inch-pound units.) Each home contained 17 windows equipped with storm sashes and 2 doors (the front door was a storm door). One HUD-code home was sheathed with a rigid, continuous AIB (3.2 mm extruded polystyrene stapled onto the wood studs); the other one was caulked.

Measurement of Air Infiltration Rates

The air infiltration rates in both homes were measured using the decay tracer gas technique (Wilhelm 1979).

The wind speed was measured with an anemometer mounted on a tower located on the AIB home. The anemometer was located 5 m above the ground. The temperatures were measured with copper-constantan thermocouples.

ANALYSES OF THE INFILTRATION TEST DATA

Overall, 708 infiltration points were analyzed. These data points were obtained for winter, spring, and summer months, and represent simultaneous measurements at both homes. The fall data were not used because the AIB sheathing was removed from the HUD-code home.

Early work on the Lafayette data (Goldschmidt et al. 1980; Wilhelm 1979) used regression techniques which correlated air infiltration rates with weather variables, but did not explicitly recognize the site characteristics and the ELAs of the homes. These correlations represented a step forward, and are probably quite accurate in predicting the air infiltration change due to an AIB in a climate similar to Lafayette, IN, and at a site similar to the one where the tests were conducted. The correlations are not applicable in locations with substantially different climate conditions and for terrains which are not flat and sparsely built.

The Lafayette data are again analyzed in this paper because the large amount of information available from the tests is unique with regard to the effect of AIBs on HUD-code manufactured homes.

First, the applicability of the model (Sherman and Grimsrud 1980) to HUD-code single-section manufactured homes is verified. This model was developed from a theoretical basis, but was applied to date only to site-built houses. Next, the ELA reduction due to the AIB is calculated for use with the model (Sherman and Grimsrud 1980).

Applicability of the Model

As discussed in the theory section, the model (Sherman and Grimsrud 1980) assumes that the total air infiltration rate is dependent on wind speed and indoor-outdoor temperature difference, according to Equation 6. This equation can be transformed as follows:

$$Q^2 = a\,\Delta T + bv'^2 \qquad (7)$$

where

$a = A^2{}_o f_S^{*2}$

$b = A^2{}_o f_W^{*2}$

Equation 7 states that the square of the infiltration rate is a linear function of the square of wind speed and of the indoor-outdoor temperature difference. The coefficients a and b were derived by using a multilinear regression routine which was part of the STATPAK library (STATPAK 1986).

The best-fit correlation for the caulked home is:

$$Q_C{}^2 = a_C\,\Delta T_C + b_C\,v'^2 \qquad (8)$$

with a_c = 1.810 10^{-6} (m³/s)² K⁻¹
b_c = 76.700 10^{-6} (m³/s)² (m/s)⁻²
and r_c = (correlation coefficient) = 0.869

Figure 1 shows the scattergram of Q_C measured against Q_C predicted, using Equation 8 defined above. The regression has a standard error of $1.5\cdot10^{-3}$ m³/s and a confidence level of almost 100%.

It should be noted again that all correlations presented in this paper are based on 708 observations. Because of this large number of observations, there is almost 100% confidence for all correlations in this paper that the r_C correlation coefficients were not obtained by accident. Further, the F-test values are always very large, giving almost 100% confidence that the data do correlate.

The best-fit correlation for the AIB home is:

$$Q_A{}^2 = a_A\,\Delta T_A + b_A\,v'^2 \qquad (9)$$

with a_A = 5.970 10^{-6} (m³/s)² K⁻¹
b_A = 19.800 10^{-6} (m³/s)² (m/s)⁻²
and r_A = (correlation coefficient) = 0.889

Figure 2 shows the scattergram of Q_A measured vs. Q_A predicted, using Equation 9. The regression has a standard error of $0.4\cdot10^{-3}$ m³/s, and a confidence level of almost 100%.

These correlations verify that the general quadratic form of the model (Sherman and Grimsrud 1980) is applicable to single-section HUD-code-manufactured houses.

Leakage Area Calculations

Leakage areas were not available for the HUD-code homes tested in Lafayette, IN. However, estimation of these leakage areas can be made by using the model.

Estimation of ELAs Using the Site-Built Data from the *ASHRAE Handbook* The most widely used method for estimating air infiltration rates is presented in the *ASHRAE Fundamentals* (ASHRAE 1989). This method simplifies the form of the model (Equation 6) by precalculating f_w^* (Equation 2) and f_s^* (Equation 4).

In the *ASHRAE Handbook*, the specific infiltration (ratio of infiltration rate to effective leakage area) is estimated as follows:

$$Q / A_O = (A\,\Delta T + B\,v'^2)^{1/2} \qquad (10)$$

where

Q / A_O = specific infiltration [m³/(h cm²)]
A = stack coefficient, f_s^*, [(m³/h)² cm⁻⁴ K⁻¹]
ΔT = average indoor-outdoor temperature difference (K)
B = wind coefficient, f_w^*, [(m³/h)² cm⁻⁴ (m/s)⁻²]
v' = average wind speed measured at a local weather station (m/s)

The coefficients A and B in Equation 10 are selected from tables based on building height and shielding class. These coefficients are predetermined according to the model (Sherman and Grimsrud 1980), which was summarized in a previous section of this paper, with the following assumptions:

R = 0.5 X = 0.0
H = 2.5 m H' = 10 m
Terrain Class: III

Some of the above assumptions (R and H) do not conform with the actual construction characteristics of HUD-code homes. Therefore, the effective leakage areas calculated using the coefficients of the *ASHRAE Hand-*

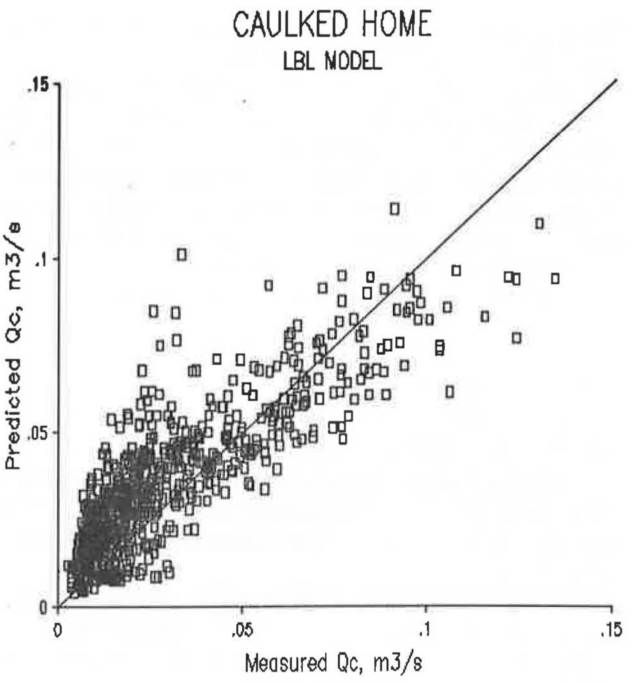

Figure 1 *Scattergram of the measured caulked home air infiltration rate, Q_C, against the predicted Q_C using Equation 8*

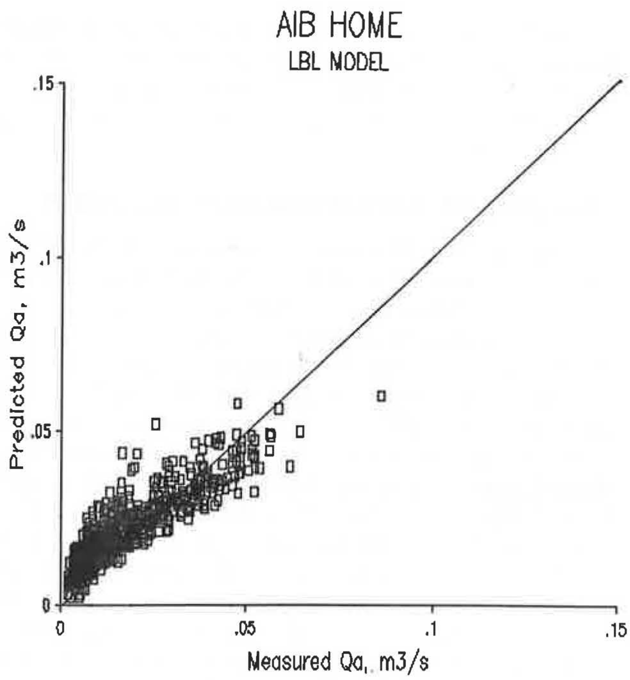

Figure 2 *Scattergram of the measured AIB home air infiltration rate, Q_A, against the predicted Q_A using Equation 9*

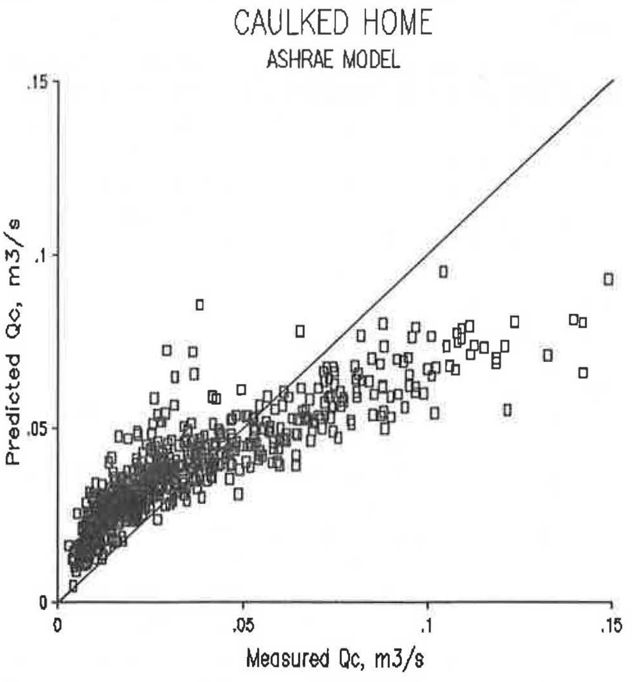

Figure 3 *Scattergram of the measured caulked home air infiltration rate, Q_C, against the predicted Q_A using the ASHRAE model for site-built homes*

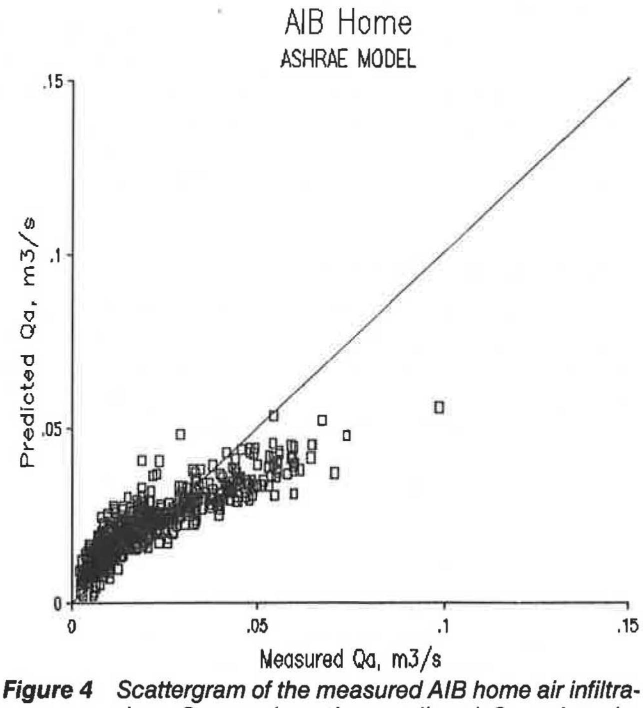

Figure 4 *Scattergram of the measured AIB home air infiltration, Q_A, against the predicted Q_A using the ASHRAE model for site-built homes*

book are expected to be roughly estimated.

Based on the *ASHRAE Handbook A* and *B* coefficients, for a one-story home with shielding class II (ASHRAE 1989, p. 23.18), the ELAs that give the best fit of the test data to Equation 10 are respectively, for the caulked and the AIB home, as follows:

$$A_{o,C} = 464 \text{ cm}^2$$
$$A_{o,A} = 261 \text{ cm}^2$$

For the caulked home, the standard error is 3.5 cm^2. The specific ELA obtained with this calculation for the caulked home is 1.64 cm^2/m^2. Figure 3 presents the scattergram of Q_C measured against Q_C calculated, using Equation 10 with $A_o = A_{o,C}$. The standard error of the regression is $16.4 \cdot 10^{-3}$m^3/s, and the confidence level is almost 100%.

For the AIB home, the standard error is 7.3 cm^2. The specific ELA obtained with this calculation for the AIB home is 0.92 cm^2/m^2. The specific ELA reduction attributable to the AIB is 0.72 cm^2/m^2 of envelope area.

Figure 4 shows the scattergram of Q_A measured against Q_A calculated, using Equation 10 with $A_o = A_{o,A}$. The standard error of the regression is $7.9 \cdot 10^{-3}$m³/s, and the confidence level is almost 100%.

Using the same equation with the same coefficients for both site-built and HUD-code homes has the advantage of simplicity. However, approximations are introduced by these simplifications. The 0.72 cm²/m² ELA differential due to the AIB is expected to yield reasonably accurate results with Equation 10 and with the *ASHRAE Handbook* coefficients in locations which are cold and windy, comparable to Lafayette, IN. More approximation is to be expected for milder weather conditions.

Estimation of Effective Leakage Areas Using Data Specific to HUD-Code Homes Better predictions of the ELA reduction, for use in *all* climates, can be obtained by assigning values specific to HUD-code homes for the variables in the model's (Sherman and Grimsrud 1980) equation.

To this end the following assumptions are made:

$H = 2.29$ m	according to HUD-code homes tested
$H' = 5.00$ m	according to height of anemometer
$C' = 0.285$	shielding class II according to description of terrain where tests were undertaken
$\alpha = 1 \quad \gamma = 0.15$	terrain class II according to site description
$\alpha' = 1 \quad \gamma' = 0.15$	wind measurements were accomplished on site
$X = 0$	assume floor leakage area is equal to ceiling leakage area, as per Chapter 23 of *ASHRAE Handbook of Fundamentals* (ASHRAE 1989)
$T_C = 296.3$ K	average indoor temperature calculated over winter, spring, and summer for caulked home
$T_C = 296.2$ K	average indoor temperature calculated over winter, spring, and summer for the home with AIB

Estimate of the ELA as a Function of the Vertical Leakage Fraction HUD-code homes sheathed with an AIB tend to have a higher vertical leakage fraction, R, than caulked homes. This is because by sheathing the wall, the small leakage areas in the ceiling and roof become relatively important. However, in this paper it is assumed that both caulked and AIB HUD-code manufactured homes have the same vertical leakage fraction value, R. This assumption is made in the interest of simplicity, to allow the development of only one correlation capable of estimating the infiltration rate for both types of homes. In order to establish this correlation, the procedure of the *ASHRAE Handbook* is employed (Equation 10).

Using the model expressed by Equation 6, the coefficients A and B can be determined as follows:

$$A = f_s^{*2} = (1/9)\,(1+R/2)^2\{1-[X/(2-R)]^2\}^3\,(gh/T) \quad (11)$$

and

$$B = f_w^{*2} = C'^2\,(1-R)^{2/3}\{\alpha(H/10)^{\gamma}/[\alpha'(H'/10)^{\gamma'}]\}^2 \quad (12)$$

Note that in Equations 11 and 12, the same value of R is used to determine both coefficients A and B. Using the assumptions made in the previous section (assuming T = 296.25 K, which is the average of 296.3 K and 296.2 K), the variation of the coefficients A and B as a function of R can be expressed as:

$$A = 8.417 \cdot 10^{-3}\,(1+R/2)^2$$

and

$$B = 64.261 \cdot 10^{-3}\,(1-R)^{2/3}$$

For a given value of R, a best curve fit of the test data to Equation 10 allows determination of the effective leakage area, A_o. Table 1 summarizes the results of the regression analysis for three values of R (R = 0.0; R = 0.25, and R = 0.50).

TABLE 1
Calculated Effective Leakage Areas of the Two HUD-Code Manufactured Homes

Vertical Leakage Area Fraction, R	Caulked Home ELA (cm²)	Standard Error (cm²)	AIB Home ELA (cm²)	Standard Error (cm²)
R = 0.00	334	4.7	185	2.3
R = 0.25	359	5.1	199	2.5
R = 0.50	393	5.7	219	2.7

Table 2 presents the specific ELAs for these homes, where specific ELA = ELA/(total envelope area).

TABLE 2
Calculated Specific Leakage Areas of the Two HUD-Code Manufactured Homes

Vertical Leakage Area Fraction, R	Caulked Home Specific ELA (cm²/m²)	AIB Home Specific ELA (cm²/m²)	Absolute Reduction in Specific ELA (cm²/m²)	Percentage Reduction in Specific ELA (%)
R = 0.00	1.18	0.65	0.53	44.9
R = 0.25	1.27	0.70	0.57	44.9
R = 0.50	1.39	0.77	0.62	44.6

As shown in the Introduction, the vertical leakage fraction (R) representative of HUD-code manufactured homes is smaller than the one representative of site-built homes; for site-built homes R = 0.5, as per the *ASHRAE Handbook* (ASHRAE 1989). However, the value of R for HUD-code homes must be higher than 0, since even with continuous ceilings and floors there will be at least some air leakage through horizontal surfaces. As a result, $0.0 < R < 0.5$. By analyzing Table 2, it can be noted that the reduction in specific ELA corresponding to R = 0.25 (0.57 cm²/m²) is very close to the arithmetic average of the reductions in the three specific ELAs (0.573 cm²/m²). Therefore, it is reasonable to assume that R = 0.25 when quantifying the effect of an AIB for single-section HUD-code homes.

Figures 5 and 6 present the scattergrams of the measured infiltration rate against the predicted infiltration rate with R = 0.25 for the caulked and the AIB homes, respectively. The standard errors of these regressions are, respectively, $15.4 \cdot 10^{-3}$ m³/s and $7.5 \cdot 10^{-3}$ m³/s. The

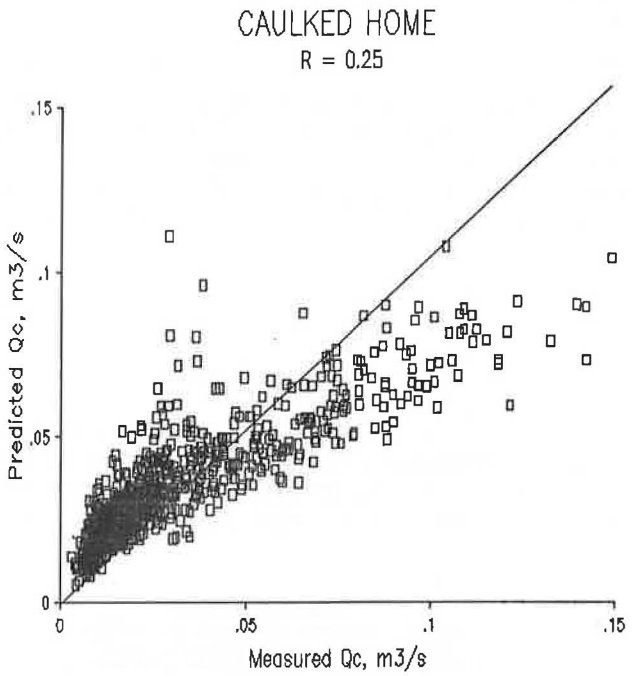

Figure 5 *Scattergram of the measured caulked home air infiltration rate, Q_C, against the predicted Q_C using the model with R = 0.25*

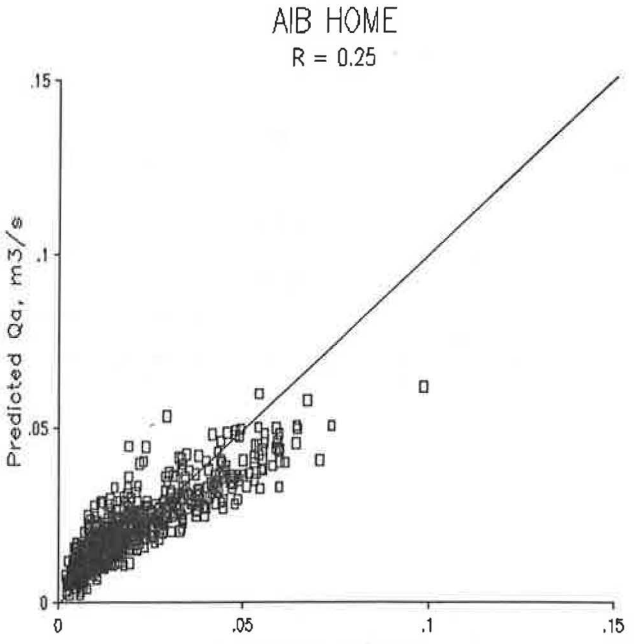

Figure 6 *Scattergram of the measured AIB home air infiltration, Q_A, against the predicted Q_A using the model with R = 0.25*

confidence level is almost 100%.

Using R = 0.25, the equations for determining the effect of AIBs on single-section HUD-code manufactured homes are:

For Shielding Class I (no obstructions or local shielding, C' = 0.324):

$$Q / A_o = (0.01065 \, \Delta T + 0.06856 \, v'^2)^{1/2} \quad (13)$$

For Shielding Class II (light local shielding with few obstructions, C' = 0.285):

$$Q / A_o = (0.01065 \, \Delta T + 0.05305 \, v'^2)^{1/2} \quad (14)$$

For Shielding Class III (moderate local shielding, some obstructions within two house heights, C' = 0.240):

$$Q / A_o = (0.01065 \, \Delta T + 0.03762 \, v'^2)^{1/2} \quad (15)$$

For Shielding Class IV (heavy shielding, obstructions around most of perimeter, C' = 0.185):

$$Q / A_o = (0.01065 \, \Delta T + 0.02235 \, v'^2)^{1/2} \quad (16)$$

For Shielding Class V (very heavy shielding, large obstructions around the surrounding perimeter within two house heights, C' = 0.102):

$$Q / A_o = (0.01065 \, \Delta T + 0.00680 \, v'^2)^{1/2} \quad (17)$$

The reduction in the air infiltration rate, Q, attributable to the AIB can be calculated by assuming that A_o = 0.57 cm²/m² in Equations 13 through 17.

DISCUSSION OF VALUES FOR EFFECTIVE LEAKAGE AREAS

To the authors' knowledge, no other systematic study was attempted to evaluate the effective leakage areas of HUD-code single-section manufactured homes. However, a recent study by Ek et al. (1989) examines ELAs of almost 100 unsheathed HUD-code *double-section* manufactured houses. In this type of manufactured home the average specific effective leakage area was 2.7 cm²/m². As shown in Table 2, if coefficients are specifically derived for the caulked HUD-code single-section manufactured home, the specific ELA varies between 1.18 cm²/m² and 1.39 cm²/m², depending on whether R = 0.0 or 0.50. If the coefficients of the *ASHRAE Handbook* are used, the specific ELA for the caulked home is 1.64 cm²/m²; however, the ASHRAE coefficients are applicable to site-built houses, not to HUD-code homes.

All three values for specific ELAs in single-section caulked homes are lower than the double-section specific ELA, as expected, since double-section homes have an additional infiltration path at the marriage walls. Actually, because these single-section figures are only 44% to 60% of the double-section value, it is likely that the specific ELAs for single-section homes are conservative. This comparison supports the results of the ELA calculations in this paper.

CONCLUSIONS AND RECOMMENDATIONS

The air infiltration rate in two HUD-code single-section manufactured homes, one caulked and one with an AIB, was found to vary quadratically with the temperature difference and the square of wind velocity, according to a model (Sherman and Grimsrud 1980). A correlation of the form presented in the *ASHRAE Handbook of Fundamentals* (ASHRAE 1989, Chapter 23) was developed for HUD-code single-section manufactured homes, relating specific infiltration to weather conditions.

Further analyses of the effective leakage areas for both single-section manufactured homes showed that the application of continuous AIB board:

(a) reduces the ELA by 0.57 cm² for each m² of envelope area (in this case, 160 cm²). This value is for use with Equations 13 through 17, which were developed specifically for HUD-code single-section manufactured homes;

(b) can be assumed to reduce the ELA by 0.72 cm^2 for each m^2 of envelope area, if the ASHRAE site-built Equation 10 and the ASHRAE site-built coefficients (ASHRAE 1989) are used. These assumptions will yield best results in cold, windy locations; and

(c) can be assumed to reduce the ELA by 43% regardless of which of the equations presented in this paper is used. (The range is 43% to 45%.)

It is recommended that the values in paragraph (a) above be used for the development of new HUD standards.

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