Air Pressures in Wood Frame Walls

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ABSTRACT

Wind pressures can play an important role in the wetting of exterior walls (driving rain). In response, the rain screen concept, including compartmentalization and air spaces, has been developed to provide pressure equalization and limit water entry into the wall. However, conventional construction such as wood lap siding has not been evaluated as to its ability to function as a rain screen. As part of a two-year project assessing the performance of hardboard lap siding, we measured air pressure differences across *the siding over* extended *periods of time in two single-story wood-frame buildings, specially* constructed *for this study in southern Florida. Three different wall constructions were included in the study. We found that the conventionally installed lap siding provided substantial air pressure equalization. Inward air pressure differences across the siding did not appear strong enough, or long enough in duration, to raise concern about significant waterpenetration through the siding overlaps, even during windy days.*

Air leakage has been recognized as an important mode of water vapor transport, and airtight construction is therefore recognized as an important ingredient of designing for high moisture tolerance. As part of the same study, we monitored air pressures across the siding, sheathing, and gypsumboard in two of the walls. We *found that wind-induced air pressures across the exterior walls were predominantly exfiltrative, even on the windward side of the building. Infiltrative pressures only occurred near windward comers of the building during short periods of time. We also found significant air leakage past the top plate into the wall cavity.*

This paper also presents a method for coordinating the design for airtightness (airflow retarders) with the design for control of vapor diffusion (vapor retarders). The calculations show that a vapor retarder of 1 perm ($57ng/Pa·s·m^2$) should be complemented with an air barrier system (ABS) with an ELA of 0.003 in.^{2}/ft^2 (2×10^{-5} m^2/m^2) or less. Specifying lower-perm vapor retarders (e.g., 0.1 perm, or 5.7 ng/Pa·s·m^2) would require specifying an extraordinary level of airtightness.

INTRODUCTION

Moisture entry and movement in walls are mainly governed by liquid water entry, air movement, and, to a lesser extent, water vapor diffusion. Historically, moisture control recommendations have focused on control of diffusion from the inside by vapor retarders and limiting water entry from the outside, but more recently air movement has become an important consideration.

The rain screen concept, well known from high-rise commercial building practice, has been proposed for residential wood-frame walls as a means to keep rainwater out of the wall. The rain screen design contains features to minimize water penetration due to raindrop momentum, capillarity, gravity, and air pressure difference. The ram screen wall is designed so that the air pressure difference across the exterior rain screen is nearly zero at all times (ASHRAE 1997). A ram screen generally includes an air space and an air barrier. It has generally been held that for wood siding to act as a rain screen, the siding needs to be installed on furring strips to create the pressure equalizing air space. As part of a study on hardboard siding, we had the opportunity to measure air pressures across conventionally installed lap siding without an air space to determine if the air space is needed for pressure equalization.

After rain penetration, air leakage is the second most important factor in moisture movement in walls. The *1997 ASHRAE Handbook—Fundamentals* states that, for purposes of moisture control, the building envelope should be airtight, regardless of climate. However, no level of required airtightness is given. Currently, codes in the U.S. often specify instal-

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lation of vapor retarders without requiring a minimum level of airtightness, although it is a well-known fact that vapor retarders can be rendered ineffective by air leakage. Does current building practice result in sufficient airtightness, or, if not, what level of air-tightness is needed to provide sufficient protection against moisture damage?

The measurements reported in this paper were made as part of a study on hardboard siding. The goal of the 34-month project was to determine if backpriming or factory finishing improves the durability and performance of hardboard siding when installed according to recommended practice. Eight-inch hardboard lap siding was installed on two test buildings in Delray Beach, Palm Beach County, in southern Florida. As part of that study, we measured air pressure differences across the siding. We also collected more detailed pressure information on two wall sections on one of the two buildings for a portion of the study. This paper reports only on the results of the pressure measurements and relates those results to the need for air-tightness for purposes of moisture control. The effects of backpriming and factory finishing will be reported elsewhere.

DESCRIPTION OF THE TEST BUILDINGS

Building Construction

The two buildings were single-story, wood-frame construction. They were 60 ft apart and there were no trees, bushes, or shrubs within 20 ft of the buildings. The building site was located in a commercial area, with a commercial building on the south side of the site and open terrain with scattered groups of trees on all other sides. One building was built with 12-in. overhangs, including the gable ends, but without gutters; the other building was built without overhangs, but with gutters (Figure 1). The buildings were identical in all other construction details. Dimensions of the buildings were 32 ft by 32 ft, with a slab-on-grade foundation. The buildings had balloon-framed gable ends with a 4/12 pitch roof with asphalt shingles. The rest of the roof was framed with standard roof trusses. One gable end faced NNE (35° from north). The attic of each building was vented with gable-end louvers, and the attic of the building with overhangs received additional venting from perforated aluminum soffits. Ceilings and exterior walls were insulated with fiberglass batt insulation (unfaced in the walls, faced in the ceiling, with the facing down). The buildings had interior electrical wiring, phone service, and air ducts for distribution of cooled air, with ceiling fans for additional air distribution. The air ducts were within the conditioned interior (i.e., not in the attic).

Wall Construction

The walls were wood-frame 2×4 construction. Three different wall constructions were used on each building:

1. No sheathing, #15 asphalted-felt building paper (OF).

2. Plywood sheathing (0.5 in. CDX), #15 asphalted-felt building paper (PF).

3. Plywood sheathing, woven polyolefin (PT).

Each wall section was 8 ft long. Adjacent wall sections were separated with a CCA-treated pine 2×6 sandwiched between the end studs of the wall sections, except at the comers. The outside face of the treated 2×6 separator protruded beyond the face of the siding. The separators
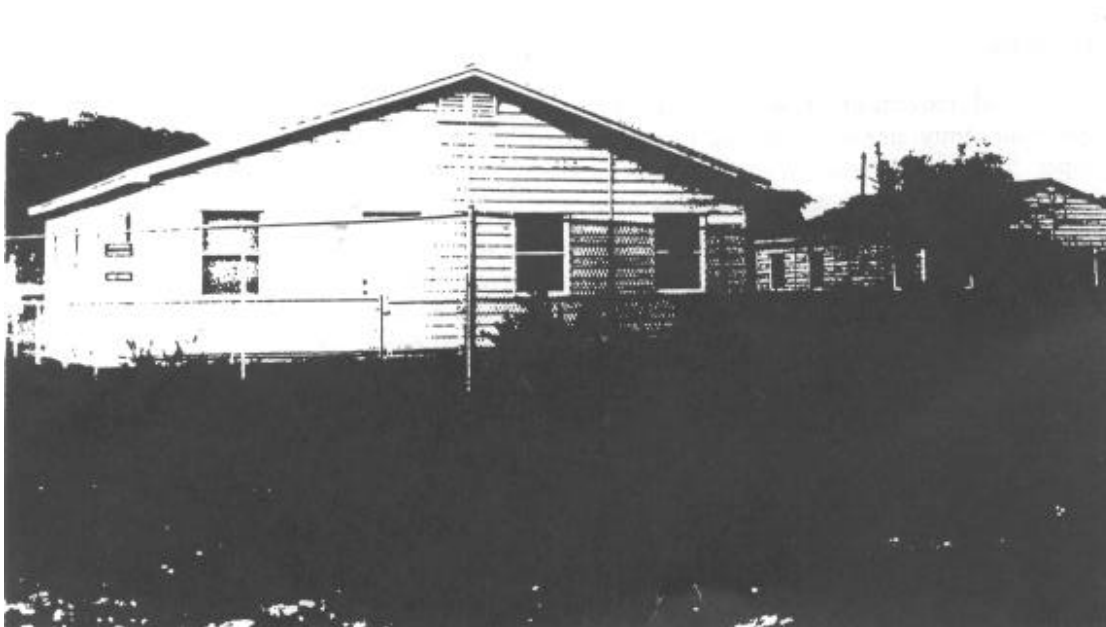

Figure 1   Test building with overhangs (foreground) and test building with gutters (background).
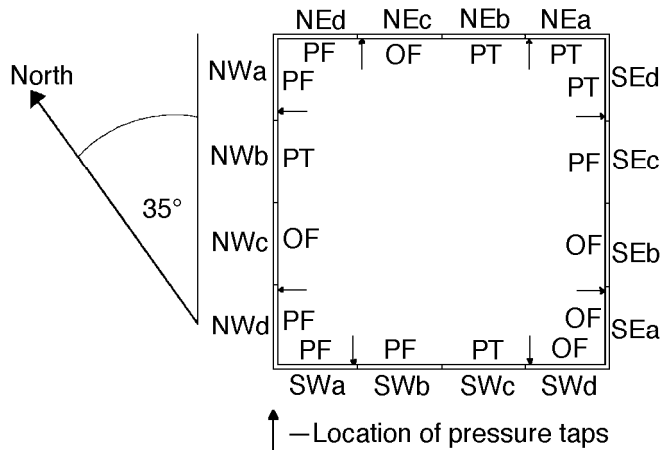
Figure 2 Plan view of test buildings with wall construction type, orientation, and location of pressure taps.

prevented air movement behind the siding between wall sections. Wall framing was installed so that the outside surface of siding was flush; on wall sections without plywood sheathing, this was achieved by moving the framing outward by 0.5 in. Wall construction on the gable ends was identical to that of the wall sections directly below.

Two doors and twelve windows were installed in each building. Figure 2 shows the orientation of both buildings, the designation given to each wall section, and the distribution of wall construction types around the building.

The walls were sided with 8-in. hardboard lap siding. All hardboard was produced at the same plant. The siding was installed by a professional contractor's crew following the manufacturer's installation recommendations. The minimum overlap between siding boards was 1 in. Half of the siding was pre-finished at the factory, the other half was painted after installation. Joints at windows, doors, and at the 2×6 separators were carefully caulked with urethane caulk.

Interior Conditions

Interior conditions were selected to simulate a typical south Florida home environment. The thermostats controlling the air conditioners in both buildings were set at 75°F (24°C). Measurements indicate that the building with gutters actually was maintained between 77°F and 82°F (25°C and 28°C) and the building with overhangs between 72°F and 79°F (22°C and 26°C). Because the buildings were unheated, indoor temperature was uncontrolled for short periods during winter. Indoor relative humidity was maintained at 50% with humidistat-controlled humidifiers. Water for the humidifiers was obtained from the air-conditioner's drip pans. Excess water from the drip pans was drained to the outside through sub-slab drains. Humidity occasionally floated above 50% during winter periods when the air conditioners did not run.

INSTRUMENTATION

To monitor the condition of the siding, which was the main focus of this study, we collected a large volume of hourly data, including moisture content of the siding in 82 locations on each building and temperature of the siding in 64 locations. The results of these measurements are not reported in this paper. All hourly data were collected and stored on a personal computer (one for each building) and transferred automatically to the laboratory in Madison by phone each day. The data acquisition system was installed and activated in February 1995. After some adjustments and corrections were made, data acquisition officially commenced on May 1, 1995, and ended on May 6, 1997.

Air pressure differences across the siding were monitored continuously at eight locations on each building. The pressure tubes were installed at mid-height of the wall section (i.e., approximately 4 ft [1.2 m] up from the ground), which minimized the inclusion of any stack effect in the pressure readings. Pressure at each location was measured with an individual differential pressure sensor, which had a range of ±200 Pa with a resolution of 0.1 Pa. The zero-pressure offset was recalibrated every hour. The location of the pressure taps is indicated in Figure 2. Pressure differences were recorded every five seconds, with pressure data collection suspended for roughly five minutes each hour for reading moisture pin, TOW, and thermocouple data (the computer in the guttered building also collected wind speed and direction data). The detailed pressure data were usually discarded every hour after an hourly average, maximum, minimum, and standard deviation were computed for each pressure tap. However, during several time periods, we instructed the computer by phone to store and transmit the detailed pressure data. On October 8, 1996, the pressure tap configuration in the building with overhangs was changed, as shown in Table 1. This change allowed us a more detailed look at the pressures inside the cavities and pressures across the entire wall of wall sections OSEd and OSWa. Many of these data were collected at 15-second intervals. The pressure taps in the building with gutters were left unchanged.

Hourly wind speed and direction data were collected starting the middle of September 1995. The orientation of the wind vane was verified at the time of installation by the position of the sun at local solar noon. Ten-minute average readings of wind speed and direction were collected hourly; instantaneous wind direction was also recorded hourly to verify the lo-minute average direction reading.

AIR PRESSURES ACROSS LAP SIDING

Typical air pressure differences across the siding are shown in Figures 3 and 4. The data show the hourly average, maximum, and minimum pressure difference for two wall locations on the building with gutters for the period November 11 through December 8, 1995. Positive pressures indicate a higher pressure outside than behind the siding, which we call

TABLE 1
Changes in Pressure Tap Configuration of Building with Overhangs Made on October 8, 1998*

Channel	Pressure Difference	
	Prior to 10/8/96	After 10/8/96
# 1	Across siding of wall OSWd	Between cavity and outside, wall OSWa
# 2	Across siding of wall OSEa	Across entire wall OSEd
# 3	Across siding of wall OSEd	Unchanged
# 4	Across siding of wall ONEa	Between cavity and outside, wall OSEd
# 5	Across siding of wall ONEc	Unchanged
# 6	Across siding of wall ONWa	Unchanged
# 7	Across siding of wall ONWd	Across entire wall OSWa
# 8	Across siding of wall OSWa	Unchanged

* Wall OSWd means building with overhangs, southwest-facing wall, wall section d; etc.

infiltrative pressure, and negative (exfiltrative) pressures mean that the pressure behind the siding is greater than outside. Both buildings produced very similar air pressure data.

We picked a particularly windy day, November 14, 1995, to further investigate the pressures across the siding. The wind was predominantly from the west-northwest, and the average wind speed was 6.3 mph, with a maximum hourly reading (10-minute average) of 13 mph. Table 2 lists the daily average pressure difference, along with the maximum, minimum, and

standard deviation for that day. The numbers are based on a sampling rate of one measurement every five seconds.

The data show that average pressure differences across the siding are *small,* and in all but one direction, average pressures were negative, i.e., the average pressure behind the siding exceeded the average pressure on the exterior surface. Only the windward corner (ONWd) shows an average balance between infiltrative and exfiltrative pressures. We believe that the turbulent nature of the wind and constantly changing wind direction caused most of the walls to be under exfiltrative pressure for most of the time. The turbulent and transient nature of
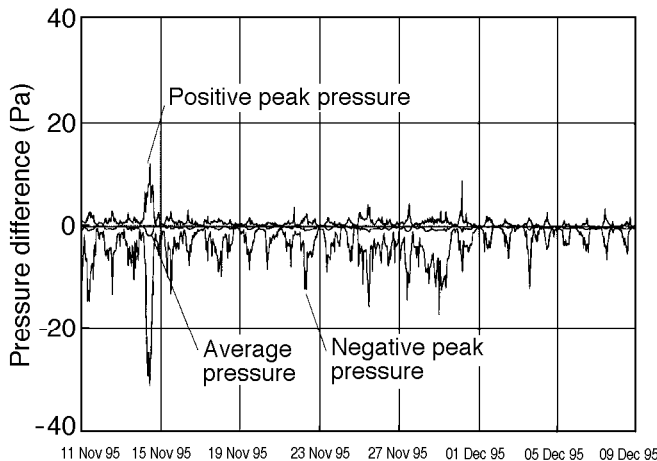

Figure 3 Hourly average, positive peak, and negative peak air pressure difference across the siding on wall section GSWa (southwest facing) of the building with gutters, November 11 to December 8, 1995. Positive values indicate that the exterior air pressure exceeds the pressure on the back of the siding. Peak values are hourly extreme values of data collected every five seconds.
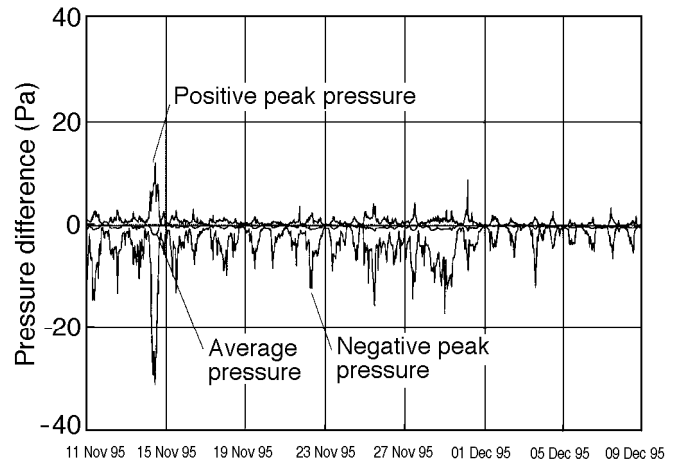

Figure 4 Hourly average, positive peak, and negative peak air pressure difference across the siding on wall section GNWd (northwest facing) of the building with gutters, November 11 to December 8, 1995. Positive values indicate that the exterior air pressure exceeds the pressure on the back of the siding. Peak values are hourly extreme values of data collected every five seconds.

TABLE 2
Daily Average, Peak Positive, Peak Negative, and Standard Deviation of Pressure Difference Measurements Across Siding of Building with Overhangs, November 14, 1995*

Location	Pressure Difference Across Siding (Pa)			
	Average	Peak Positive	Peak Negative	Stand. Dev.
Wall OSWa	−0.06	+0.3	−0.6	0.1
Wall OSWd	−1.09	+4.6	−44.8	1.9
Wall OSEa	−0.51	+2.0	−19.2	0.8
Wall OSEd	−0.47	+1.8	−19.5	0.8
Wall ONEa	−1.17	+7.6	−45.1	1.9
Wall ONEc	−2.79	+11.7	−49.0	4.0
Wall ONWa	−0.04	+13.5	−40.4	1.9
Wall ONWd	0.0	+0.3	−1.1	0.06

* Positive values indicate that the air pressure is infiltrative (from outside to inside). Wall OSWd means: building with overhangs, southwest-facing wall, wall section d, etc. Peak pressures and standard deviation are based readings made every five seconds.

the wind is further demonstrated by the high peak pressures on some of the wall sections. Infiltrative pressure peaks were offset by even larger exfiltrative pressure peaks. In fact, peak negative (exfiltrative) pressure exceeds peak positive (infiltrative) pressure on all sides, including the windward comer. Apparently, the time needed to equalize the pressure played a role. The positive pressure differences do not appear large enough, or last long enough, to provide a significant vehicle for water penetration through the siding. Finally, the type of wall construction (i.e., type of weather barrier or the presence of sheathing) did not appear to have a discernible effect on pressures across the siding.

It has been argued in recent years that in order to properly function as a rain screen, wood-based siding should be spaced out from the sheathing and ventilated to provide air pressure equalization. The pressure data in this report suggest that conventionally installed lap siding provides some air pressure equalization, although relatively large exfiltrative pressure peaks occasionally occur. These exfiltrative pressures do not cause concern for water penetration, and, therefore, an air space does not appear necessary for that purpose.[1] An air space may still be beneficial but primarily because it probably provides better drainage of water that may penetrate to the back of the siding (especially around windows and doors). An air space would reduce the chance of this water penetrating the weather barrier and wetting the sheathing.

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1. When we dismantled the building in May 1997, we removed and inspected most of the siding. There was indeed no evidence of water staining on the back of the siding or on the building paper other than some evidence of leakage that had occurred due to caulk failures around windows.

AIR AND MOISTURE FLOWS IN WALLS

Air Pressures in Walls OSWa and OSEd

The rearranging of pressure taps on the building with overhangs, as described in Table 1, allowed us a more detailed look at the pressure differences across wall sections OSEd and OSWa, specifically pressure differences across the sheathing/siding combination, across the entire wall, and across the siding. To demonstrate the pressure behavior of these walls, we focus on data collected on October 18, 1996, a day with "typical" wind speeds, and November 15, 1996, a very windy day.

Figures 5 and 6 show the hourly average pressure difference across the siding, between the outside and the cavity, and across the entire wall for walls OSWa and OSEd, respectively, on October 18, 1996. This day was of interest because of the rapidly changing wind direction in the early afternoon. The two figures also show the hourly wind speed and direction (10-minute averages). Wall section OSWa (Figure 5) was located on the west comer and faced southwest. The wall experienced exfiltrative (negative) pressures all day. even with south-southeast winds. Wall OSEd (Figure 6) was located on the east comer and faced southeast. It experienced infiltrative (positive) pressures with east to southeast winds, which abruptly changed to exfiltrative (negative) pressure when the wind shifted to the north. Average pressures across the siding were small (0.5 Pa or less) and relatively insensitive to wind speed. Hourly average pressures across the sheathing/weather barrier/siding combination were on the order of 0 Pa to 0.5 Pa in both walls most of the time but increased to almost 2 Pa in wall OSWa near midnight. Hourly average pressures across the gypsum board ($\Delta\rho_{cavity} - \Delta\rho_{wholewall}$) were on the order of 0.5 Pa most of the time but approached 1 Pa in OSEd during the middle of the day.
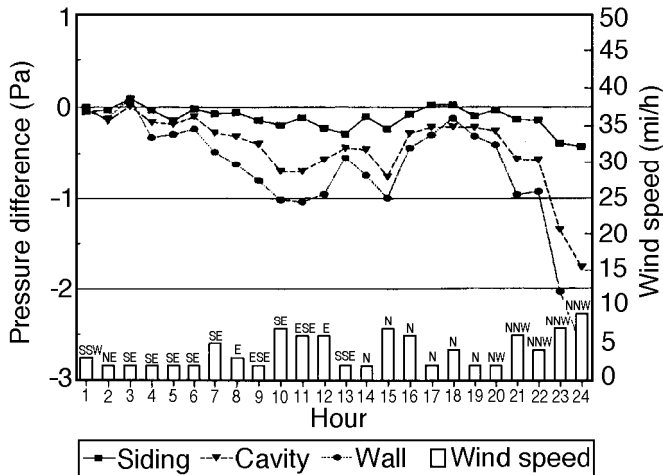
Figure 5 *Hourly average pressure difference across the siding, between the outside and the cavity and across the entire wall, for wall OSWa, with hourly wind speed (10-minute average) and direction on October 18, 1996. Positive values indicate that the air pressure is infiltrative.*
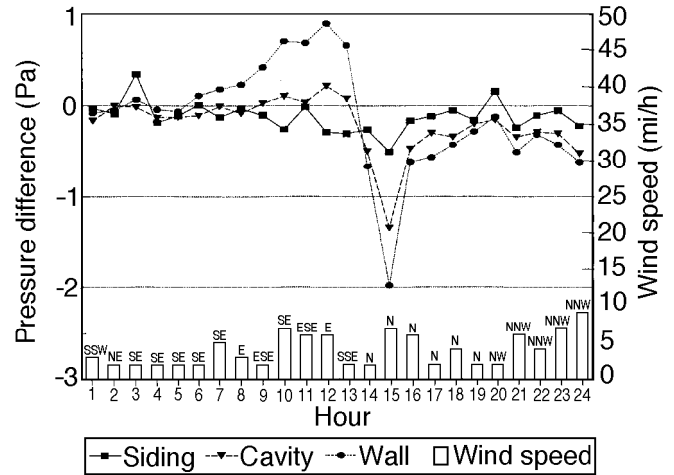

Figure 6 *Hourly average pressure difference across the siding, between the outside and the cavity and across the entire wall, for wall OSEd, with hourly wind speed (10-minute average) and direction on October 18, 1996. Positive values indicate that the air pressure is infiltrative.*

Figures 7 and 8 show instantaneous pressures, recorded every 15 seconds, between 8:45 a.m. and 9:00 a.m. on October 18, 1996. Winds were from the east to southeast at 2 to 3 miles per hour (10-minute average). Pressures across the siding on wall OSWa (Figure 7) remain well below 1 Pa, while exfiltrative pressures across the wall at times reach 3 Pa. Pressures on the windward wall OSEd (Figure 8) are of the same magnitude but fluctuate between infiltrative (positive) and exfihrative (negative). This demonstrates that even a windward-facing

wall can experience significant periods of exfiltrative airflows. The data also suggest that hourly average pressure data can be misleading when infiltrative and exfiltrative pressures cancel each other in the averaging process.

Figures 9 and 10 show the difference between pressure in the cavity and outside and inside pressure during the same period. The pressure between the cavity and inside was calculated by subtracting the pressure difference between the outside and the cavity from the pressure across the whole wall.
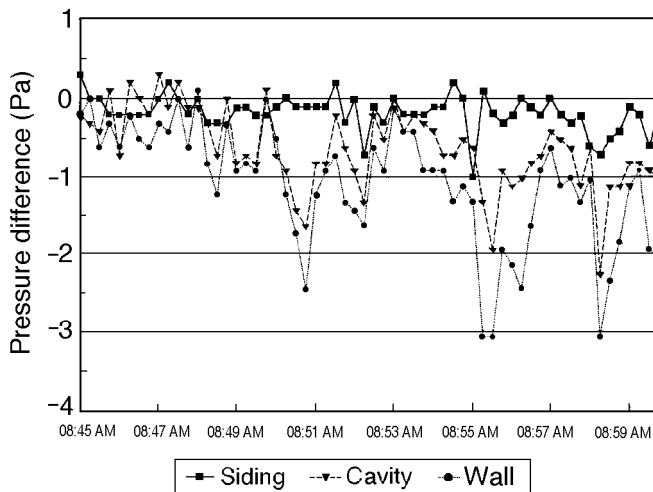

Figure 7 *Instantaneous pressure difference (IS-second sampling rate) across the siding, between the outside and the cavity and across the entire wall, for wall OSWa between 8:45 a.m. and 9:00 a.m. on October 18, 1996. Winds were from the southeast. Positive values indicate that the air pressure is infiltrative.*
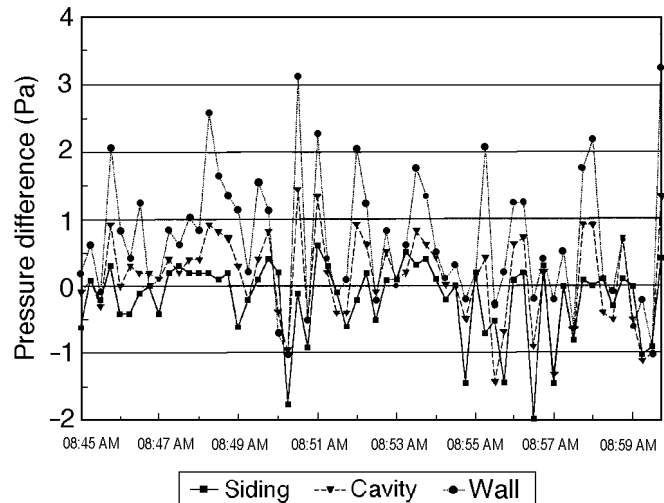

Figure 8 *Instantaneous pressure difference (15-second sampling rate) across the siding, between the outside and the cavity, and across the entire wall for wall OSEd between 8:45 a.m. and 9:00 a.m. on October 18, 1996. Winds were from the southeast. Positive values indicate that the air pressure is infiltrative.*
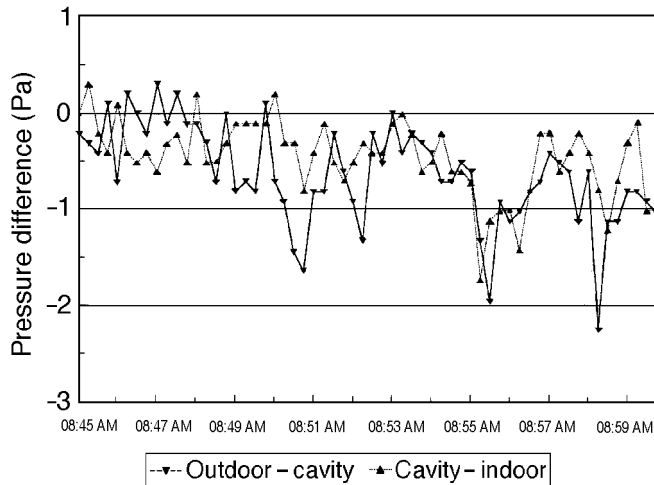
Figure 9 *Instantaneous pressure difference (15-second sampling rate) between the cavity of wall OSWa and the outside and inside air, respectively, between 8:45 a.m. and 9:00 am. on October 18, 1996. Winds were from the southeast. Positive values indicate that the air pressure is infiltrative.*
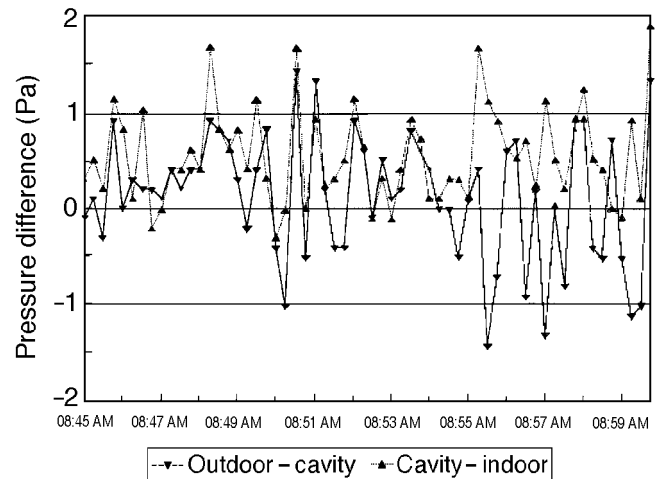

Figure 10 *Instantaneous pressure difference (15-second sampling rate) between the cavity of wall OSEd and the outside and inside air; respectively, between 8:45 a.m. and 9:00 a.m. on October 18, 1996. Winds were from the southeast. Positive values indicate that the air pressure is infiltrative.*

It appears that in both walls pressure drops across the sheathing and siding were often of similar magnitude as pressure drops across the gypsum board, even though the sheathing with the weather barrier had been expected to resist most of the pressure. The large gap at the top plate that was revealed during inspection of wall section OSEd explains these results for that wall, but in wall OSWa air apparently also bypassed the exterior sheathing and barrier to a considerable degree.

Windward wall OSEd also shows periods when the cavity appears simultaneously pressurized compared to inside and outside. We first observed and reported a similar phenomenon in walls with vents to the outside in a test building in Madison (TenWolde et al. 1995); the current data indicate the same effect can take place in conventional wood-frame walls. We found that later on October 18, with slightly more southerly winds, the cavity of wall OSWa also was pressurized for short periods of time, while the cavity of wall OSEd continued to be pressurized at times as well. This pressurization most likely was due to air infiltrating through the top of the wall.

Figures 11 and 12 present similar 15-second pressure data for walls OSWa and OSEd between 10:45 p.m. and 11:00 p.m. on November 15. During this period, winds were strong from the east to northeast with wind speeds of around 18 miles per hour (lo-minute average). Pressure across the siding was still relatively modest, usually less than 2 Pa, with some spikes of 10 Pa to 15 Pa. Some pressure spikes of 15 Pa to 20 Pa occurred across the gypsum board, especially in wall OSWa. Figure 13 shows pressures averaged over the same 15-minute period for both walls. Wall OSWa saw an average exfiltrative pressure of about 6 Pa and the sheathing/weather barrier/siding combination a pressure of almost 4 Pa.

This means that the gypsum board sustained an average pressure of about 2 Pa. The siding pressure difference was slightly over 1 Pa. The average pressure across wall OSEd, which was on the windward comer of the building, was in the inward direction but was only about 2 Pa, primarily because there were many pressure reversals during the 15-minute period. Pressure across the gypsum board was on the order of 2 Pa in the inward direction.
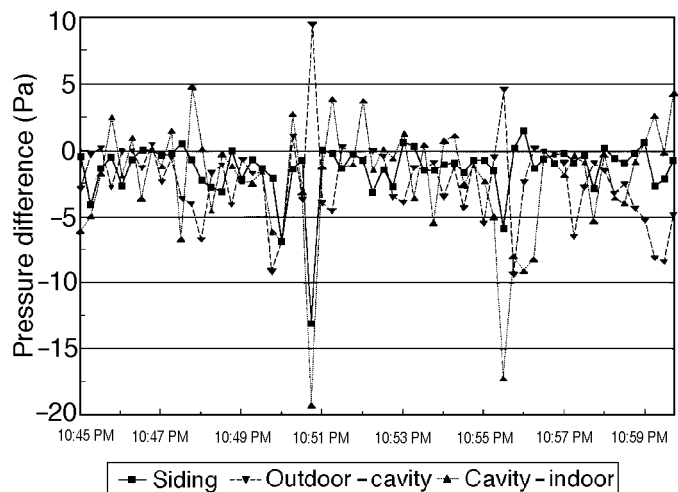

Figure 11 *Instantaneous pressure difference (15-second sampling rate) across the siding, between the outside and the cavity, and across the entire wall for wall OSWa between 10:45 p.m. and 11:00 p.m. on November 15, 1996. Winds were from the east to northeast. Positive values indicate that the air pressure is infiltrative.*

Figure 12 *Instantaneous pressure difference (15-second sampling rate) across the siding, between the outside and the cavity, and across the entire wall for wall OSEd between 10:45 p.m. and 11:00 p.m. on November 15, 1996. Winds were from the east to northeast. Positive values indicate that the air pressure is infiltrative.*
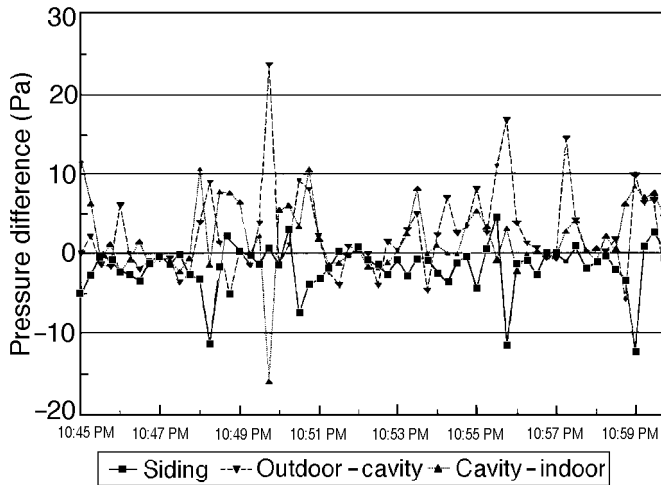
Several observations can be made from the data presented above.

1. There was reasonably good pressure equalization across the lap siding.

2. Pressures across the gypsum board were greater than expected, probably because of air leakage through the top of the wall.

3. Most of the walls experienced exfiltrative wind pressures most of the time; only walls on the windward corner experienced extensive periods of inward pressure, but even then, many pressure reversals occurred. This is different from data obtained from wind tunnel experiments, where wind direction and speed do not vary. Such data, including the data presented in chapter 15 of *ASHRAE Fundamentals* (ASHRAE 1997), tend to show more extensive regions of infiltrative wind pressure on a low-rise building.

4. Windward walls sometimes experience short periods of pressurization of the cavity, with pressures that are higher than outside and inside pressures. This most likely occurs due to air infiltrating through the top of the wall.

The data, as well as the inspection of the walls, indicate that exterior air barriers have limited value if the top plate is not carefully sealed.

MOISTURE FLOWS

It has long been recognized that water vapor flow with air leakage can be more important than vapor flow through diffusion. It has often been stated that vapor retarders can only be effective if effective air barriers are in place. However, how effective does an air barrier need to be to limit overall vapor
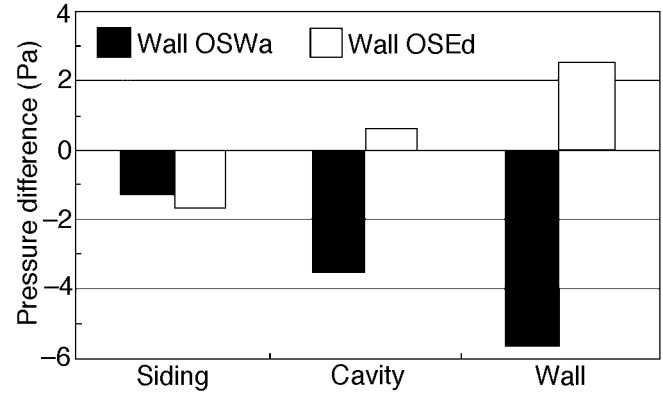

Figure 13 *Fifteen-minute average pressure difference across the siding, between the outside and the cavity, and across the entire wall for walls OSWa and OSEd between 10:45 p.m. and 11:00 p.m. on November 15, 1996. Winds were from the east to northeast. Positive values indicate that the air pressure is infiltrative.*

transfer? Obviously, when a vapor retarder is present or specified, the vapor transfer by air leakage needs to be limited to the amount that is transferred by diffusion through the vapor retarder, or less.

When considering the potential for moisture damage due to air leakage, average conditions are of greater interest than extreme conditions of short duration. Wood-frame walls usually have enough internal moisture storage capacity to "ride out" the effects of events of short duration. However, it is the sustained leakage that occurs throughout the season that can eventually overwhelm the wall's storage capacity.

Our measurements indicated that average wind pressures across walls of residential single-story buildings are on the order of 0 Pa to 1 Pa and tend to be exfiltrative (inside pressure is higher than outside pressure). This does not include the effect of stack pressure (pressure tubes were installed at mid-height of the wall) or pressures generated by air distribution systems. Thus, an approximate range of 0.5 Pa to 1 Pa may be viewed as a reasonable estimate of minimum expected sustained pressure difference across a wall. While air exfiltration tends to dry walls in cooling climates, it can have the opposite effect in heating climates. In heating climates, local building codes often require vapor retarders of 1 perm or less. Can sustained air pressures of 0.5 Pa to 1 Pa negate the effectiveness of such a vapor retarder?

In the following section, we use simple equations to compare moisture flow by diffusion and air leakage and to correlate vapor retarder requirements with those for air barriers.

Moisture Flow by Air Leakage

ASHRAE Fundamentals (ASHRAE 1997) states that water vapor movement by air leakage can be represented by

$$w = \rho\, W v \tag{1}$$

where

w = water vapor flux, lb/h·ft² (kg/s·m²);

ρ = density of air, lb/ft³ (kg/m³);

W = humidity ratio;

v = airflow velocity, ft/h (m/s).

TenWolde and Carll (1992) introduced the concept of representing the moisture flow by air leakage as an equivalent parallel vapor diffusion resistance Z_e.

$$Z_e = S/Q\rho c \tag{2}$$

where

Z_e = equivalent vapor diffusion resistance, perms⁻¹ (Pa·s·m²/kg, or m/s);

Q = airflow, ft³/h (m³/s);

S = surface area, ft² (m²);

c = W/p_v = 145 grain/lb·in. Hg (6.14 Pa⁻¹);

p_v = vapor pressure, in. Hg (Pa).

In order to calculate the equivalent vapor permeance ($1/Z_e$), the airflow Q must be known. This requires data on air pressure differences and data on equivalent leakage area (ELA) or on leakage rates at a specific reference pressure.

Equivalent Leakage Area

Equivalent leakage area is calculated from the following formula (ASHRAE 1997):

$$A_L = C_L Q_r \frac{\sqrt{\rho/2\Delta p_r}}{C_D} \tag{3}$$

where

A_L = equivalent leakage area, in² (m²);

Q_r = predicted airflow rate at reference pressure difference, cfm (m³/s);

Δp_r = reference pressure difference, in. of water (Pa);

C_L = unit conversion factor = 0.186 (C_L = 1 in SI);

C_D = discharge coefficient.

The most commonly used reference pressure in the U.S. is 0.016 in. of water (4 Pa) with $C_D = 1$ and in Canada, 10 Pa with $C_D = 0.611$.

A commonly used equation for airflow is the power law equation:

$$Q = c_1 \Delta p^n \tag{4}$$

with exponent n between 0.5 and 1. Assuming the constant c_1 and exponent n remain the same over a wide range of airflows, airflow Q (in ft³/h or m³/s) at any given pressure differential Δp can be related to airflow Q_r (in cfm or m³/s) at a reference pressure Δp_r with

$$Q = C_Q\left(\frac{\Delta p}{\Delta p_r}\right)^n Q_r \tag{5}$$

where C_Q is a conversion factor from cfm to ft³/h ($C_Q = 60$ in IP, $C_Q = 1$ in SI). With Equations 3 and 5, flow at any given pressure difference can be calculated from published ELA values:

$$Q = C_Q\left(\frac{\Delta p}{\Delta p_r}\right)^n \frac{A_L C_D}{C_L}\sqrt{\frac{2\Delta p_r}{\rho}} \tag{6}$$

Finally, Equation 6 can be used with Equation 2 to give the equivalent vapor permeance (in perms or s/m) for vapor transport by air leakage:

$$\frac{1}{Z_e} = C_z C_D\left(\frac{\Delta p}{\Delta p_r}\right)^n \frac{A_L}{S}\sqrt{2\rho\Delta p_r} \tag{7}$$

where
$C_Z = cC_Q/C_L = 46.8 \times 10^3$ (6.14 in SI).

Leakage Rate at Specific Reference Pressure

Instead of ELA, airtightness data are often presented in the form of leakage rate Q_r at a specified reference pressure, e.g., at 75 Pa. For leakage rates presented in that form, Equation 2 and Equation 5 can be used to derive the equivalent vapor permeance:

$$\frac{1}{Z_e} = C_Q \rho c \frac{Q_r}{S}\left(\frac{\Delta p}{\Delta p_r}\right)^n \tag{8}$$

Correlation Between Vapor Retarder and Air Barrier Requirements

Equations 7 and 8 can be used to correlate specific design choices for vapor retarders with matching needs for airtightness. Historically, air barriers have been installed for reasons of energy conservation, but it has become clear in recent years that airtightness requirements for moisture control can be far more stringent. In general, a vapor retarder can only be effective if the equivalent vapor permeance due to airflow is less than the vapor permeance of the vapor retarder. If the equivalent perm value is larger, airflow dominates, and the vapor retarder is no longer effective. In the next section, we will use equality of the two perm values as the criterion for minimum airtightness.

Table 3 provides calculated equivalent permeance values for various levels of airtightness for several pressure differences. The values were calculated using airflow exponent values of 1 for air barrier systems and airtight materials (ELA less than 0.03 in.²/ft²). For less airtight systems or materials, we used exponents of 0.7 to 0.9 (see notes below Table 3).

The airtightness levels in Table 3 represent a wide variety of systems or materials, starting with values representing air barrier systems as classified by the Institute of Research in Construction (IRC) at the National Research Council Canada

TABLE 3
Equivalent Perm Values For Various Levels of Airtightness for Several Pressure Differences*

Airtightness per Unit of Surface Area		Note	Equivalent Permeance, perms (ng/Pa·s·m²)			
ELA, at 4 Pa, in./ft² (m²/m²)	Leakage Rate at 75 Pa, cfm/ft² (L/s·m²)		at 0.5 Pa	at 1 Pa	at 4 Pa	at 10 Pa
0.0001 (6.9×10⁻⁷)	0.0066 (0.034)	1	0.029 (1.7)	0.057 (3.3)	0.23 (13)	0.57 (33)
0.00015 (1×10⁻⁶)	0.0098 (0.05)	2	0.043 (2.5)	0.086 (4.9)	0.34 (20)	0.86 (49)
0.0003 (2.1×10⁻⁶)	0.02 (0.1)	3	0.086 (4.9)	0.17 (10)	0.68 (39)	1.7 (98)
0.00045 (3.1×10⁻⁶)	0.03 (0.15)	4	0.13 (7.5)	0.26 (15)	1.0 (57)	2.6 (149)
0.0008 (5.6×10⁻⁶)	0.053 (0.27)	5	0.23 (13)	0.46 (26)	1.8 (103)	4.6 (264)
0.003 (2.1×10⁻⁵)	0.15 (0.75)	6	1.1 (63)	1.8 (103)	6.9 (396)	16 (919)
0.005 (3.5×10⁻⁵)	0.20 (1.0)	7	1.8 (103)	3.3 (190)	12 (689)	26 (1490)
0.01 (6.9×10⁻⁵)	0.27 (1.4)	8	5.4 (310)	8.7 (500)	23 (1320)	44 (2530)

* Notes:
1. Type 3 air barrier system, according to Institute for Research in Construction (IRC) classification; flow exponent $n = 1$; discharge coefficient $C_D = 1$.
2. Maximum leakage rate for Type 3 air barrier system (IRC); flow exponent $n = 1$; discharge coefficient $C_D = 1$.
3. Maximum leakage rate for Type 2 air barrier system (IRC); flow exponent $n = 1$; discharge coefficient $C_D = 1$.
4. Maximum leakage rate for Type 1 air barrier system (IRC); flow exponent $n = 1$; discharge coefficient $C_D = 1$.
5. Minimum ELA for continuous air infiltration barrier, ASHRAE (1997); flow exponent $n = 1$; discharge coefficient $C_D = 1$.
6. Maximum ELA for continuous air infiltration barrier, ASHRAE (1997); flow exponent $n = 0.9$; discharge coefficient $C_D = 1$.
7. Example: best estimate for ELA of rigid sheathing, ASHRAE (1997); flow exponent $n = 0.9$; discharge coefficient $C_D = 1$.
8. Flow exponent $n = 0.7$; discharge coefficient $C_D = 1$

(NRC 1989) (see notes 1 through 4 below Table 3). This is followed by values representing the airtightness range for air infiltration barriers as published in *ASHRAE Fundamentals* (ASHRAE 1997), as explained in notes 5 and 6 below Table 3.

A number of conclusions about the "companion" airtightness required to preserve the full effectiveness of a vapor retarder can be drawn from the results in Table 3.

- A vapor retarder of 1 perm should be complemented with an air barrier system (ABS) with an ELA of 0.003 in.²/ft² (2×10^{-5} m²/m²) or less. This corresponds with the airtightness provided by an air infiltration barrier.
- If sustained average pressures of 4 Pa or higher are expected, a vapor retarder of 1 perm should be complemented with an air barrier system (ABS) with an ELA of 0.00045 in.²/ft² (3.1×10^{-6} m²/m²) or less. This corresponds with the minimum requirements for a Type 1 ABS (IRC classification). With sustained average pressures of 10 Pa or higher, a 1-perm vapor retarder should be complemented with a Type 3 ABS.
- Vapor retarders with a perm rating of 0.1 perms can only be fully effective when sustained average air pressures remain below 0.5 Pa and an ABS is installed with an ELA of 0.0003 in.²/ft² (2.1×10^{-6} m²/m²) or less. This corresponds with a Type 2 ABS. If average pressures are on the order of 1 Pa, a Type 3 ABS is desired.

As previously stated, a reasonable design value for sustained average pressure across low-rise residential walls is on the order of 0.5 Pa to 1 Pa, not including the effects of stack effect and air distribution systems. That means that requiring vapor retarders with perm ratings substantially below 1 perm also requires an extraordinary level of airtightness. Recent testing of various ABS configurations in wood-frame walls (CMHC 1991) showed that air barrier systems provided air leakage rates between about 0.024 and 0.07 cfm/ft² (0.12-0.35 L/s·m²) at 75 Pa. Table 3 shows that the level of airtightness is sufficient to provide a permeance equivalent of less than 1 perm, i.e., a 1-perm vapor retarder would be effective in a wall with such an ABS.

The data in Table 3 conversely suggest that without a carefully applied ABS, a 1-perm vapor retarder is rendered ineffective. The CMHC tests showed that wood-frame walls without an ABS leaked between 0.22 and 0.24 cfm/ft² (1.1-1.2 L/s·m²). Table 3 shows that with that level of air leakage, a 1-perm vapor retarder is not effective. Because the weather barriers in our test houses were not extended over the top plate, they did not provide sufficient airtightness, and even a 1 perm vapor retarder, had it been installed, would have had little effect on moisture movement into, or out of, the wall.

It has often been reported that the introduction of polyethylene vapor retarders significantly lowered the incidence of condensation in walls in cold climates. The information in Table 3 suggests that this success probably had more to do with the fact the polyethylene provided improved air tightness than with its very low permeance. In fact, the effectiveness of the polyethylene vapor retarder almost certainly depended on its function as an air barrier, a function it was not intended to perform.

The results in this study suggest that the traditional definition of the vapor retarder as a material with a permeance of 1 perm or less turns out to be quite practical because the corre-

sponding required airtightness levels can be practically and economically achieved.

DISCUSSION

The values offered in Table 3 are only approximate and should be viewed in terms of their order of magnitude. It could also be argued that using the criterion that the vapor retarder is compromised when the airflow carries the same amount of water vapor as diffuses through the vapor retarder is not stringent enough and that the convective vapor flow should be kept an order of magnitude below the diffusion flow. However, this would. in our opinion, lead to unrealistically stringent requirements for airtightness.

Finally, the airtightness corresponding with the effectiveness of vapor retarders can also be used to determine whether diffusion analysis methods, such as the MOIST computer model (Burch and Chi 1997). can be used or whether airflow is likely to dominate the movement and accumulation of moisture.

CONCLUSIONS

*   In a conventional installation of lap siding, there was substantial air pressure equalization across the siding. Pressure behind the siding usually slightly exceeded outside pressure, and peak negative (exfiltrative) pressure differences across the siding generally exceeded peak positive (infiltrative) pressure differences on all sides, including the windward comer. Even during windy days, positive air pressure differences did not appear strong enough, or long enough in duration. to raise concern about significant wind-driven water penetration through the siding overlaps.

*   There was evidence of air leakage past the top plate into the wall cavity. This air bypassed the weather barrier and created larger than expected air pressures across the gypsum board. This air leakage led to periods when the cavity was pressurized with respect to both the inside and outside.

*   Wind-induced air pressures across the exterior walls were predominantly exfiltrative, even on the windward side of the building. Infiltrative pressures only occurred near windward comers of the building during short periods of time. This differs from data obtained in wind tunnel experiments, which tend to show that more extensive portions of the windward wall areas are subject to infiltrative wind pressure.

*   A vapor retarder of 1 perm should be complemented with an air barrier system (ABS) with an ELA of 0.003 in.^{2}/ft^2 (2×10^{-5} m^2/m^2) or less.

*   In standard wood-frame construction without a continuous air barrier system. air leakage past the top plate can

render any vapor retarder ineffective.

*   The traditional definition of the vapor retarder as a material with a permeance of 1 perm or less turns out to be a practical one because the corresponding required airtightness levels can be practically and economically achieved. Specifying lower-perm vapor retarders (e.g., 0.1 perm) requires specifying an extraordinary level of airtightness.

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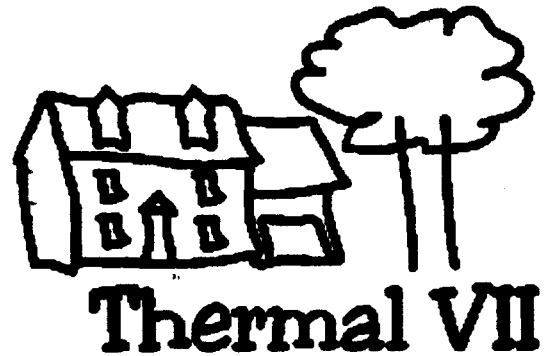
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