(RP-1019)

Field Studies of Ventilation Drying

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ABSTRACT

Many enclosure assemblies in many different climates have traditionally been ventilated with exterior air. The nature and magnitude of the benefits of providing a ventilated wall system have been debated, but little quantitative research has been conducted. This paper presents some of the results of a series of detailed ASHRAE-supported full-scale field test house studies that explored the role of ventilation and sheathing membranes in the drying of wood-framed walls. Several companion papers describe the technical background and the results of computer modeling and laboratory testing.

The studies involved five different 1.2 m wide and 2.4 m high wood-framed wall systems—three clad with brick and two with vinyl siding. Along with comprehensive boundary conditions (including driving rain), a total of over 20 sensors were used to monitor the moisture content, RH, and temperature within each wall system. Air velocity within the ventilation space of the brick veneer was also measured directly. A unique intra-wall wetting system was developed to uniformly and repeatedly wet the sheathing of the walls in a uniform manner. The walls were wetted three times at different times of the first year and their response-monitored. Changes were made to the size of the ventilation space in all walls, and a second year and three more wetting-drying cycles were imposed.

Results included: all walls allowed a very significant amount of drying, some of the walls exhibited no damage at all at the end of the experiment, drying rates varied significantly during different weather conditions, ventilation increased the drying potential of some walls, and the nature of the sheathing membrane influences the drying rate. It was also shown that solar-driven vapor diffusion acts to redistribute vapor from within the wall to the interior (where it did cause damage) and that ventilation reduces the magnitude of this flow. This reduction of inward drives due to ventilation had a larger effect for the absorptive brick cladding tested. The location of brick vents—both top and bottom—was clearly shown to be beneficial to drying. The vinyl siding profile tested allowed significant ventilation-induced drying, whether applied with or without furring.

INTRODUCTION

Moisture is one of the most important factors affecting building enclosure durability and performance, especially in cold climates. The design of moisture-tolerant enclosures should involve the simultaneous consideration and balancing of the potentials for wetting, storage, and drying. Design guidelines may stress the avoidance of wetting, but increased safe moisture storage capacity or drying potential can also improve the moisture tolerance of an assembly.

Drainage is usually regarded as the most important moisture removal mechanism, and internal drainage has recently received much attention for walls clad with EIFS, wood siding, stucco, etc. Drainage, however, does not necessarily remove sufficient moisture to ensure proper enclosure performance: other drying mechanisms must be provided. One drying mechanism that has not received the attention it is due is ventilation.

Many enclosure assemblies in many different climates have traditionally been ventilated with exterior air. North American building codes also contain requirements for the venting (and, hence, presumably ventilation) of roofs, walls, and crawlspaces.

An increasing proportion of wall systems incorporate a space behind the outer cladding (or screen). This space, which

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may be as small as one millimeter (1/25 in.), is used to drain rainwater that penetrates the cladding or penetrations (especially windows and doors). Such enclosure wall systems are termed *drained* or *drain screen* (Straube and Burnett 1999).

The term *rainscreen* is used in many different ways by different people. The term is often used to describe drained screened walls with several drainage planes (e.g., the back of the cladding and the exterior face of the sheathing membrane) and larger airspaces, often compartmentalized into air chambers. A ventilated and screened wall system employs an air gap behind the cladding and vents arranged in such a way as to encourage convective airflow driven by natural wind and buoyancy forces. This airflow can be used to facilitate drying of the wall system or to bypass the vapor resistance of the exterior cladding. The sheathing membrane applied over framing and/or sheathing acts as a capillary break and drainage plane. To allow outward drying from the stud space to the ventilation space, it is desirable for the vapor permeance of this membrane to be as high as possible.

Although the nature, mechanisms, and benefits of providing a ventilated wall system have long been debated, little quantitative research has been conducted. A research project (RP-1019) entitled, "Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls," was initiated and supervised by ASHRAE Technical Committee TC 4.4, Building Envelope Systems, to study the role of the sheathing membrane and ventilation in rainscreen wall systems.

This project included analytical work, laboratory testing, field drying studies, and advanced hygrothermal modeling. This paper presents some of the results and implications of the detailed full-scale field test house studies. Several companion papers (Burnett et al. 2004; Karagiozis 2004) describe the technical background and the results of computer modeling and laboratory testing.

Background

It is well accepted that moisture is one of the primary causes of premature building enclosure deterioration. Excess moisture content combined with above-freezing temperatures for long enough will cause corrosion, rot, mold growth, and discoloration of many building materials. Saturated materials and freeze-thaw conditions can cause damage as well.

The four major sources of moisture that can damage a building enclosure are (Figure 1):

1. precipitation—especially driving rain—driven by gravity and capillarity,
2. water vapor in the air transported by diffusion and/or air movement through the wall (from either the interior or exterior),
3. built-in and stored moisture, and
4. liquid and bound groundwater, driven by capillarity and gravity.

It has become an axiom of modern enclosure design that wetting will occur at some time during the life of a building in at least some locations. Drainage is often the first and fastest means of removing water that penetrates. However, a significant amount of water deposited by condensation or rain penetration will remain in an enclosure, absorbed by the materials and adhered to surfaces.

Moisture is usually removed from an enclosure by (see the right side of Figure 1):

1. evaporation of liquid water transported by capillarity to the inside or outside surfaces;
2. evaporation and vapor transport by diffusion, air leakage, or both, either outward or inward;
3. drainage of unabsorbed liquid water, driven by gravity; and
4. ventilation (ventilation drying), a special case of #2.

The research project investigated drying of wood-framed walls that have had the sheathing wetted by rain penetration and/or exfiltration condensation. The drying mechanisms of cladding ventilation and diffusion through the sheathing membrane were the focus.

Previous Research

Detailed studies of wood-framed wall drying have been conducted in the past. For example, throughout the 1980s, a series of test huts were constructed in different Canadian climate zones to study the drying out of built-in construction moisture for wood-framed walls (McCuaig 1988; Forest and Walker 1990; Burnett and Reynolds 1991). These studies showed that significant drying was practical and possible. They also provided some evidence that ventilation could help drying, but the results were not conclusive, partly because all of the variables were not tightly controlled and partly because the wetting occurred only at the start of the study.

TenWolde and Carll (1992) also investigated wall ventilation in field experiments, but air leakage was allowed through the test specimens and, hence, dominated the results. They did find that in walls with no intentional air leakage, cavity ventilation promoted drying (TenWolde et al. 1995).

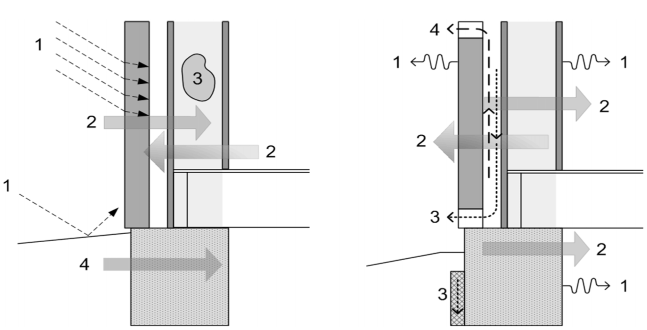

Figure 1 *Wetting (left) and drying (right) mechanisms for walls.*

A full-scale Canadian field study (Straube 1998; Straube and Burnett 1997) investigated the role of airspaces in ventilation drying and pressure moderation. This study demonstrated that ventilation could be useful as a means to control inward vapor drives behind brick veneers. It also presented and compared measurements of air moisture contents behind brick veneers and vinyl siding.

In a laboratory drying study (Lawton et al. 2002), several full-scale wall samples, 1.2 × 2.4 m, all with stucco cladding, were built and wetted by injecting 4 L of water over four days. The walls were exposed to approximately 10°C exterior conditions with no air movement and no simulated solar radiation (although no wind or solar radiation was imposed, the authors state that wind and solar effects would have no significant effect on drying). The major conclusions of this study were that:

- The drying process for all specimens was very slow and took months to achieve any significant effect.
- The rainscreen design (implied by the paper's authors to mean ventilation) does not enhance drying of water that penetrates into the stud cavity, nor is the drying rate affected by cladding design or by drainage cavity design (although the only cladding studied was stucco).
- Moisture movement within the specimens was very limited. From a practical perspective, where water initially accumulated is where it stayed.

The Fraunhofer-Institut für Bauphysik has conducted field monitoring of ventilation flow and drying effectiveness for different types of panel cladding during several projects. One project measured the ventilation velocity and air exchange rate behind asbestos cement shingles and wood siding with various types of cavities and venting arrangements (Popp et al. 1980). The cladding was installed over initially wet, aerated concrete blockwork, and the moisture content (and, hence, drying rate) of these blocks was monitored over a period of two years. It was clear the drying rate was much faster when the cladding was ventilated, although even venting (small openings through the cladding without a clear airflow space behind) improved the drying rate (Figure 2).

A complementary project involved the field measurement of ventilation behind large format cladding panels on a three-story building (Mayer and Kuenzel 1983). Similar results were found. Most of the conclusions from these two reports can be found in Kuenzel and Mayer (1983).

Another series of Canadian laboratory climate chamber studies, dubbed the Envelope Drying Rate Analysis (EDRA) program, were recently completed (Hazleden and Morris 2002). The 1.2 m wide by 2.4 m high test panels were wetted by partial submersion in water prior to being assembled into complete walls. Two phases of tests were completed. In Phase 1, steady outdoor conditions at 5°C and 70% relative humidity were simulated with no wind or sun. In Phase 2, the panels were exposed to simulated daily radiation peaking at 120 W/m^2 (equivalent to diffuse radiation on the north side of a high latitude building) and a simulated wind pressure difference of 1 to 5 Pa between the top and bottom of the assemblies. The sample walls included both stucco and vinyl siding, vented and ventilated designs, polymer and paper-based sheet sheathing membranes, and OSB and plywood sheathing.

Some important findings included:

- Panels with ventilation spaces dried faster than comparable panels without such spaces.
- Panels with wider ventilation spaces dried faster than panels with narrow ventilation spaces.
- Panels with top and bottom vented (i.e., ventilated) spaces dried faster than comparable panels with bottom-only vented spaces.
- Solar radiation had little or no effect on panels without ventilation spaces (all panels included a low permeance interior vapor barrier), but increased ventilated wall panel drying rates.

Hansen et al. (2002) performed a field study investigating the effects of ventilating cavities in timber-framed wall assemblies. After initial hygrothermal modeling work, they stated "the simulations indicated that a ventilated cavity behind the cladding might increase the moisture content behind the wind barrier." They conducted a field experiment with 12 different walls with various types of cladding and wind barriers and ventilated/nonventilated spaces and space/no space combinations. The walls were not wetted in any way. They found that all walls remained below critical wood moisture content levels (below 20% MC), and seasonal variations were observed. It was concluded that ventilation had no significant effect on timber-framed wall systems. The authors stated:

> the behavior of wood frame walls with non-ventilated cavities, in terms of the moisture content behind the wind barrier, was not found to be inferior to the behavior of wood frame walls with a ventilated cavity.

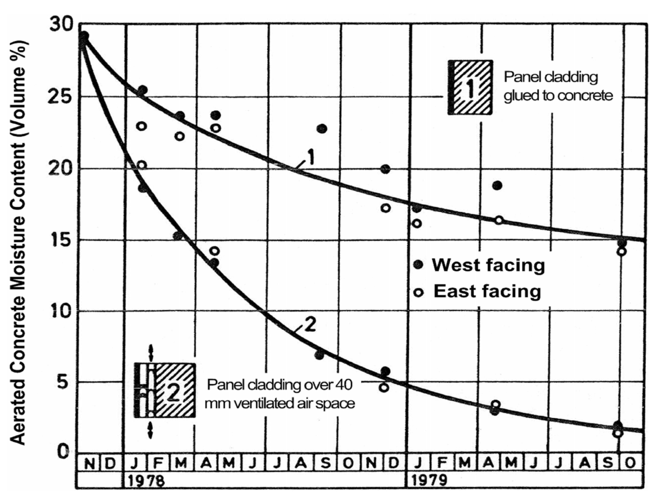

Figure 2 *Ventilation drying observed in full-scale field research (Popp et al. 1980).*

The study could not—and was not intended to—answer the question, "Does ventilation encourage drying of accidental wetting?"

Hence, the review of previous and contemporary work shows that there is no consensus about the benefits of ventilating the cladding of wood-framed wall systems. Field studies in cool and mixed humid climates have generally found benefits to drying, and that wetting was not induced by ventilation. Climate chamber studies have provided less convincing results, although more detailed studies do tend to show enhanced drying due to ventilation.

EXPERIMENTAL PROGRAM

An experimental program was developed to answer some of the questions about ventilation and sheathing membranes in ventilated screened wall systems. The drying experiments were designed to study the influence of three primary variables on the drying of wood-framed walls under natural field exposure conditions: the sheathing membrane, the cladding type, and the nature of the ventilation. Accidental wetting, defined as water that penetrated past the sheathing membrane (drainage plane) due to leaks at penetrations (such as windows, decks, doors, etc.) or cold weather air leakage condensation, was acknowledged as important if any practical value was to be gained. It was also important to repeat the drying experiment in different weather conditions to understand their effect. The study was to investigate the performance empirically, increase our understanding of the underlying physics, and to provide data for benchmarking subsequent advanced hygrothermal modeling work by others.

The drying of moisture from a framed study bay containing low-density vapor-permeable insulation is controlled by the

- driving potentials between the wetted layer and the exterior or interior and
- properties of the interior layers, sheathing, sheathing membrane, air cavity, and cladding.

In this study, inward drying was prohibited by the installation of a low-permeance interior vapor barrier. The remaining wall properties that influence the drying are summarized as an equivalent resistor network in Figure 3.

Note that the wet layer could be anywhere inside the enclosure—here it has been placed immediately contacting the back of the exterior sheathing to reflect the conditions of the experiment.

Hence, for any undrained water inside of the exterior sheathing membrane (whether from cold weather exfiltration condensation or rain leakage) to be transported to the exterior, it must pass through four steps, each of which can be the rate-limiting step that defines the drying rate:

- *Sheathing.* In the case of fiberboard, all transport properties are high; in the case of gypsum, diffusion is very high; and in the case of OSB, all are low, with liquid transport especially slow.
- *Sheathing membrane.* In most hydrophobic polymeric membranes, vapor diffusion transports moisture. In cellulose-based membranes, liquid, vapor, and surface diffusion can all play a significant role.
- *Surface transfer.* Although a relatively high permeance layer, in the case where the other steps have low resistance, the resistance of this layer can become important. Its permeance increases with air velocity and flow type (turbulent or laminar).
- *Cladding.* Vapor can move through the cladding by convection and/or diffusion, depending on the cladding type. Ventilation flow dramatically changes this resistance, which can be very approximately considered as an equivalent vapor permeance (Straube and Burnett 1995; TenWolde and Carll 1992).

The experimental plan intentionally chose to reduce the impact of the sheathing properties on the drying by using highly vapor-permeable fiberboard sheathing.

Of course, the exterior weather conditions and the temperature inside the assembly define the driving potentials for drying. In this study, both very cold (–20°C) and hot (+30°C) weather conditions were studied, which are representative of large parts of North America.

Experimental Approach

Although the authors have considerable experience monitoring walls in the field—both in special test huts and in actual buildings—most field studies have not included drying of accidental wetting. Therefore, for this study, we developed and employed a new setup to simulating accidental water entry events.

The general goal of the wetting apparatus design was the delivery of a defined quantity of water to a known location at a chosen time. Experiments by us and others have shown that simply injecting water through a tube will result in water draining to the base plate through some unknown and nonrepeatable path, followed by nonrepeatable wetting of the base of the wall. Field experience has shown that rainwater penetration often results in plumes of sheathing rot below the penetration site and not necessarily (or even usually) damage only

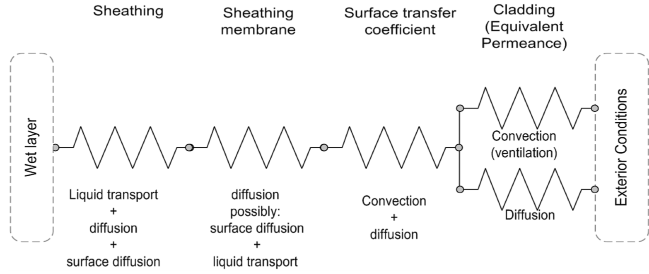

Figure 3 *Drying steps for wood-framed wall with moisture inside of sheathing membrane.*

to the base plate region. Framed wall systems are complex three-dimensional assemblies. Another goal of the apparatus was to provide uniform wetting over the entire surface of the sheathing to simplify computer model verification and our understanding of the physics. Exfiltration condensation is also likely to result in somewhat uniform wetting along the back of the sheathing in cold weather with eventual saturation of the sheathing. Although different from rain penetration (which occurs for shorter periods of time at a higher intensity and focused location), we believe the uniform wetting chosen still represents similar physics with simplified geometry. Finally, it was also desirable to provide a large enough moisture load (a spike in moisture content readings) to generate measured data that provides better resolution for the validation of computational models under a greater range of conditions. It is difficult to calculate the magnitude of an "accidental leak" since this quantity is a result of the highly variable coincidence of wind speed, wind direction, and storm duration that act on a leak to cause penetration. Hence, we wanted relatively large wetting events of a magnitude that might be within the very wide range of possible wetting. The conclusions of the experiment would not be expected to change for different wetting volumes. Wetting with the same intensity over small areas would result in either the same (if no redistribution) or less severe conditions (if redistribution occurred).

The intra-wall wetting system was developed to meet these goals. It comprises an array of very small (1/8 in. or 3 mm outside diameter) flexible tubes, feeding 15 sheets of thin, highly absorptive but vapor-permeable sheets covering the entire inside-facing surface of the sheathing. Between 1350 and 1800 g of water were injected in three steps over 24 hours to simulate a wetting event—this is equivalent to about 500 to 600 g/m^2. Upon completion of the experiment, the walls were partially disassembled. Although some mold growth was observed, the wetting systems were still in good condition and appeared to be functional.

An exterior sheathing of a 12 mm thick layer of untreated low-density (420 kg/m^3) high-permeance (about 1600 ng/Pa·s·m^2 or 28 US perms) fiberboard was chosen instead of the more common OSB or plywood for two reasons. First, the fiberboard worked together with the wetting apparatus to absorb and store the imposed wetting event. Secondly, the high-permeance layer ensured that the sheathing was not the rate limiting drying step, i.e., the experimental variables of sheathing membrane, ventilation, or cladding would dominate the moisture flow.

The five full-scale 1.22 m wide and 2.44 m high panel test specimens consisted of brick veneer or vinyl siding over wood-framed wall assemblies because these are the most common residential wall systems in North America. Either spun bonded polyolefin (SBPO) or #15 asphalt impregnated felt paper (AIF) was applied over the sheathing. The walls were tested with two different configurations: in the first, vinyl was directly applied and a 50 mm clear gap was provided behind the brick. In the second, the vinyl was installed over 20 mm strapping, and the air gap behind the brick veneer was reduced to 20 mm (see Figure 4).

All of the brick veneer walls included two weep holes and two upper vents (each 10 × 80 mm open head joints). In vented brick veneer wall arrangements, the top vents were sealed with silicone sealant. The top vents were left open in the ventilated walls to encourage through flow of air. All other characteristics of the wall assemblies were similar.

A total of 15 temperature, 6 relative humidity, and 5 wood moisture content (using electrical resistance readings) sensors were installed in each test specimen. Typical instrumentation details and wood moisture-resistance correlations can be found in Straube et al. (2002).

The instrumented panels were installed in a natural exposure and test facility facing east in August 2001. The east orientation was chosen as it faces the direction of the most driving rain (hence, this load was the worst) and lies in the middle of likely solar radiation exposure (hence, representing a typical solar load). The interior conditions were maintained at about 21°C. Exterior conditions (temperature, humidity,

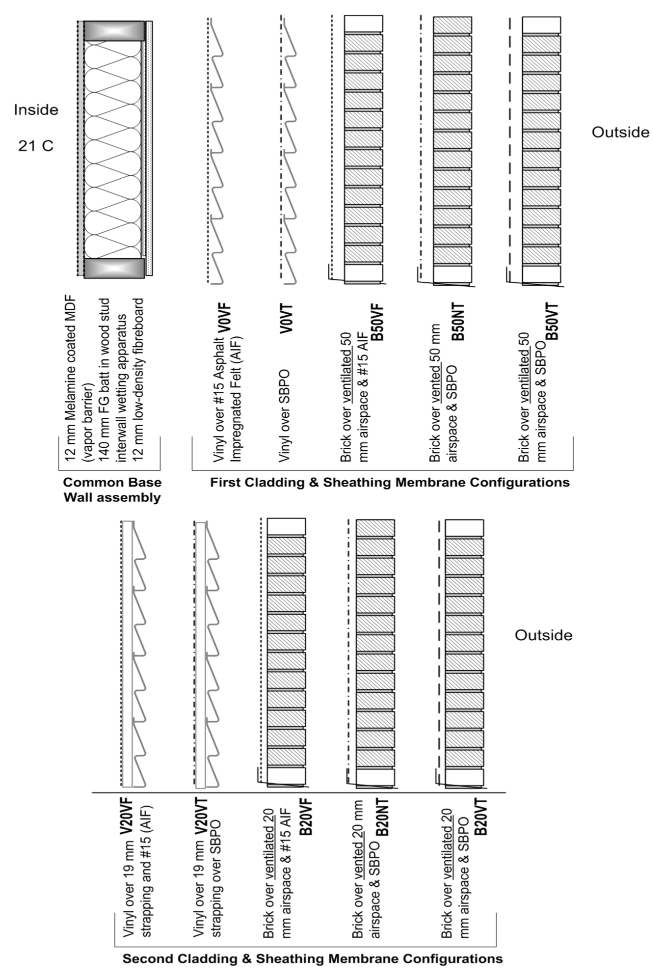

Figure 4 *Wall specimens.*

horizontal global radiation, wind speed, and wind direction) were monitored at a nearby weather station, and driving rain and total incident solar radiation were measured between test panels on the east face of the test hut. A total of about 150 sensors were measured every five minutes, and the hourly average was saved to disk by an automated data acquisition system.

After construction, the walls were left for five months to acclimatize. The wall systems were subsequently uniformly wetted a total of nine times over a range of weather conditions. Hygrothermal conditions were monitored during drying periods. The first experiment began on February 11, 2002, with subsequent wettings on May 9 and July 26. The ventilation spaces were modified for the second wall configuration and wetted on September 4, 2002, with wettings on January 2, 2003, and May 22. A third configuration, not reported on here, began May 22, and ended January 9, 2004.

RESULTS

First Configuration

The weather conditions during the first test configuration are shown in Figure 5. The conditions during the first drying experiment were cold, cool, and wet during the second springtime experiment, and warm during the third wetting.

The results of the moisture content of the studs and the sheathing for each of the five test specimens over the three wetting events (eight months) are shown in Figure 6. A moisture content drop of 10% was chosen somewhat arbitrarily to indicate significant drying. It is worth noting that this is about three-fourths of the imposed moisture load. The full plots are shown to demonstrate that the choice of 5% or 15% would not have significantly changed the interpretation of the data. The approximate average rate and duration of drying are shown on each plot in bold lines and summarized in Table 1. The right axis plots the number of hours of condensation conditions per day at the interior vapor barrier. Condensation conditions were defined as any hour in which the batt space dew-point temperature (calculated from measured RH and temperature) exceeded the measured temperature at the inside of the interior finish layer. Small clear acrylic windows installed in each panel allowed us to visually confirm the presence of condensation on this layer. Moisture will remain stored at this layer for some time after condensation occurs. Hence, the time of wetness at this layer may be slightly underestimated by the condensation condition measurements.

High moisture content conditions were recorded in some walls at the inner stud MC (10 mm from the interior face of the interior finish in the middle of the stud). The percentage of days for each wall for each of three MC categories are summarized. Moisture contents below 20% are generally considered safe (although some mold growth could be expected at room temperatures), whereas moisture levels of over 25% are approaching the level at which decay may occur.

It can be seen that the bulk of the fiberboard drying occurred over a short period following the wetting.

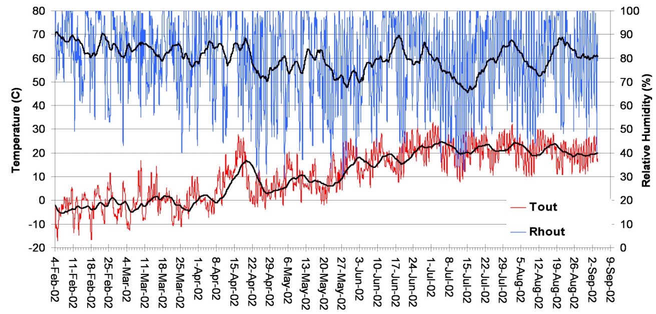

Figure 5 *Weather conditions during first configuration tests.*

It is clear the fiberboard sheathing in the vinyl siding clad walls (V0VT and V0VF) dried significantly faster than the brick veneer clad walls (B50VT, B50VF, and B50NT) during cold and cool outdoor conditions. For the brick veneer clad walls with SBPO, the ventilated wall (B50VT) dried faster than the nonventilated wall (B50NT).

The fiberboard dried most quickly during the hot, dry summer period. In fact, the drying occurred so quickly during hot, dry weather that ventilation had no noticeable effect relative to the fast drying rates. The thermal buoyancy forces (one of the forces driving ventilation) were not much different during hot, dry conditions than during sunny weather in the winter. Although the fiberboard sheathing dried quickly during the summer (and, to a lesser extent, during the spring), the RH and MC measurements show that it did not dry only to the outside. The stud moisture contents and the hours of condensation on the vapor barrier increased dramatically after a wetting. Based on the hourly plots of temperature and relative humidity, these phenomena were caused by solar-driven moisture. Condensation on the interior view windows was also observed and confirmed that the measured conditions correlated with actual condensation. This moisture redistribution was especially noticeable in the vented (nonventilated) brick veneer wall and the walls with the #15 asphalt impregnated felt sheathing membranes. The nonventilated brick veneer showed significant wetting during the late spring/early summer, and the studs never dried before the third wetting. Table 1 also shows the significant percentage of time the inner stud MC remained about 25%. Table 2 and Figure 7 show that the batt space of the nonventilated brick wall spent a significant proportion of the time above 90% RH.

The fact that the B50VT wall experienced no dangerous stud moisture contents and dried faster than both the B50NT and B50VF walls shows the combined benefit of both ventilation and the SBPO sheathing membrane.

Second Configuration

The weather conditions for the second wall configuration experiments are shown in Figure 8. This set of experiments experienced colder weather on average than the first.

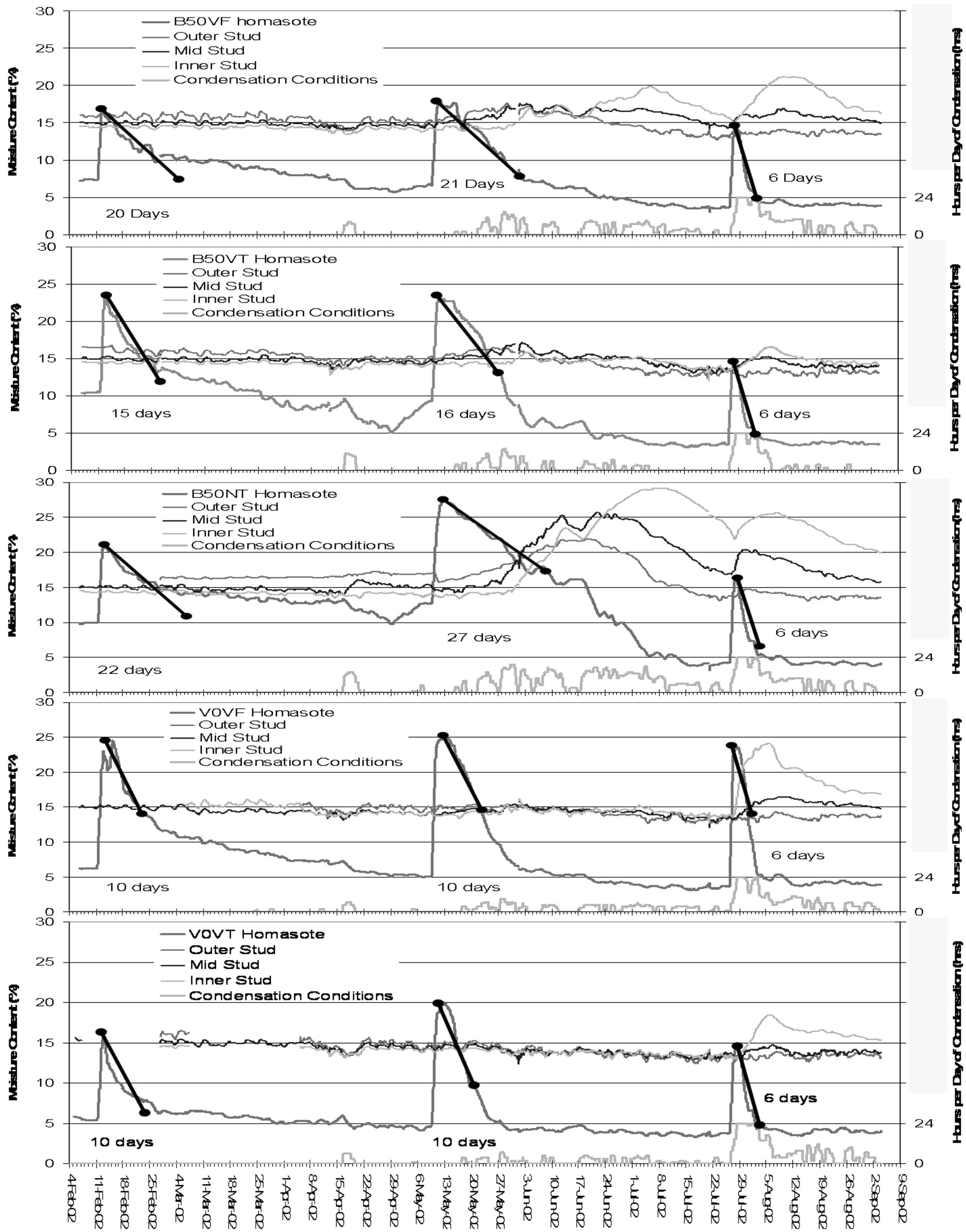

Figure 6 *First setup moisture content measurements.*

Table 1. First Wall Configuration—Drying Times and Hours of Wetness

Wall	Time for 10% moisture content drop in fiberboard			Inner stud MC (% of 205 days)		
	1st Experiment Late Cool Winter	2nd Experiment Cool Spring	3rd Experiment Hot Summer	<=20%	20%-25%	> 25%
B50VF	20 days	21 days	6 days	93.6	6.4	0
B50NT	22 days	27 days	6 days	53.6	27.8	18.6
B50VT	15 days	16 days	6 days	100	0	0
V0VF	10 days	10 days	6 days	91.7	8.3	0
V0VT	6 days	9 days	6 days	100	0	0

Table 2. First Wall Configuration—Condensation Condition Occurrence

Experiment	B50VF		B50VT		B50NT		V0VF		V0VT	
	(hrs)	(%)	(hrs)	(%)	(hrs)	(%)	(hrs)	(%)	(hrs)	(%)
First	21	1%	30	1%	52	2%	24	1%	16	1%
Second	569	22%	351	13%	897	34%	481	18%	412	16%
Third	29	13%	4	2%	24	11%	34	16%	31	14%

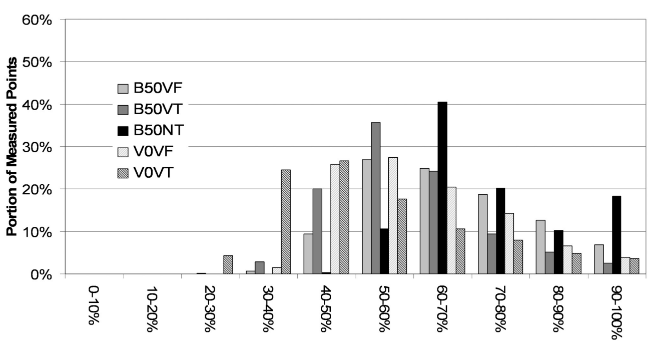

Figure 7 *Batt space relative humidity conditions (first wall configuration).*

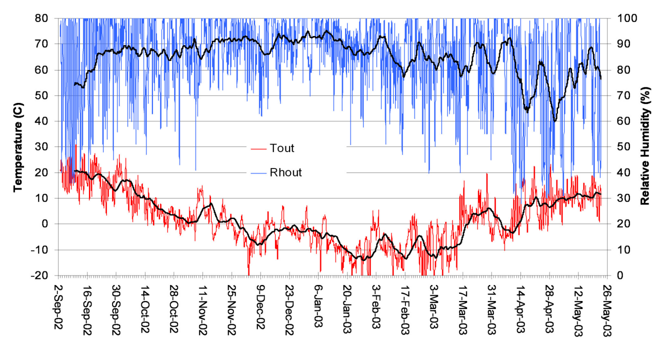

Figure 8 *Weather conditions during second configuration tests.*

The fiberboard sheathing dried very quickly in the hot summer conditions in all of the test walls. The sheathing in the vinyl siding walls dried at similar rates as the brick veneer clad walls in the cool fall and dried faster in the cold winter conditions. The sheathing in the vinyl siding clad wall with SPBO dried faster than with AIF during the cool fall and cold summer conditions. The sheathing in the ventilated brick veneer clad wall with SPBO dried slightly faster than with AIF during the cool fall and at a similar rate in the cold winter. The sheathing in the ventilated brick veneer clad wall dried at a similar rate as in the nonventilated test wall under cold winter conditions.

Differences between the drying rates of walls with AIF and SBPO were consistently observed (Table 3 and Figure 9). The sheathing in the walls with SBPO tended to dry more quickly than the walls with AIF. Freezing and thawing conditions during high moisture contents explain the oscillating readings in the coldest part of the winter.

Condensation on the vapor barrier occurred in the walls following the September 2002 wetting (Table 4 and Figure 9). The walls with AIF experienced more solar-driven inward vapor drives from the fiberboard sheathing than the SBPO walls. The walls with SBPO sheathing membranes had significantly less hours of condensation occurrence than similar walls with AIF. Subsequent wettings, which occurred in cool or cold weather, resulted in essentially no condensation.

Histograms of hourly relative humidity measurements are plotted in Figure 10 for the batt space and in Figure 11 for the ventilation cavity space. The relative humidity in the batt space was over 90% for less than 5% of all hours for all walls. The nonventilated brick veneer clad wall tended to have the highest batt space relative humidity measurements. The vinyl siding clad walls tended to have lower batt space relative humidity measurements than the brick veneer clad walls.

Table 3. Second Wall Configuration—Drying Times and Hours of Wetness

Wall	Time for 10% moisture content drop in fiberboard			Inner stud MC (% of days)		
	4th Experiment Hot Summer	5th Experiment Early Cool Fall	6th Experiment Cold Winter	<=20%	20%-25%	> 25%
B20VF	4 days	29 days	83 days	97.3	2.7	0
B20NT	4 days	14 days	89 days	94.7	5.3	0
B20VT	4 days	15 days	80 days	100	0	0
V20VF	4 days	23 days	74 days	95.1	3.0	1.9
V20VT	4 days	14 days	53 days	100	0	0

In this setup with these weather conditions, the drying rates for the vented and ventilated brick veneer walls were similar, although the batt space of the nonventilated wall was significantly wetter and more affected by inward moisture redistribution. The smaller ventilation cavity size of the brick veneer relative to the first configuration walls should also be noted.

The nonventilated brick veneer clad wall (B20NT) exhibited a two-week period of high (>20%) inner stud moisture contents following the summer wetting. The ventilated wall with similar materials (B20VT) did not experience any high inner stud moisture contents. The ventilated brick veneer clad wall with AIFP experienced a week of high inner stud moisture contents following the summer wetting. The vinyl siding clad wall with AIFP sheathing membrane (V20VF) had a two-week spike in inner stud moisture content following the summer wetting. The vinyl siding clad wall with SBPO did not experience high inner stud moisture contents throughout the period.

Histograms of hourly relative humidity measurements are plotted in Figure 10 for the batt space and in Figure 11 for the ventilation cavity space. The relative humidity in the batt space was over 90% for less than 5% of all hours. The nonventilated brick veneer clad wall tended to have the highest batt space relative humidity measurements. The vinyl siding clad walls tended to have lower batt space relative humidity measurements than the brick veneer clad walls.

As expected, the ventilation cavity relative humidity measurements had a significantly larger number of relative humidity measurements above 90% RH than the batt space. The vinyl siding clad wall with SBPO (V20VT) had fewer hours of high humidity conditions (18%) than the V20VF (vinyl clad wall with AIF) wall (33%). The brick veneer clad walls had much higher relative humidity with 41% and 45% of measured values above 90% RH for the ventilated walls (B20VT and B20VF, respectively) and 62% for the nonventilated wall (B20NT).

DISCUSSION AND IMPLICATIONS

Perhaps the most important observation from these studies is that each of the test walls was subjected to nine separate wetting events with a total of 16 kg of water over three years, and all ended the program dry. The wood framing of several of the specimens was in perfect condition at the end of the program. This shows that it is possible in practical wood-framed wall assemblies to repeatedly dry significant (some would save excessive) quantities of water that may penetrate into the stud bay or sheathing. The results show that a certain magnitude and frequency of wetting, while by no means desirable, can be tolerated given a good design. In this experiment, highly permeable exterior sheathing was used, which clearly resulted in relatively high drying rates under some conditions. However, the results of previous field wall drying studies (McQuaig 1988; Forest and Walker 1990; Burnett and Reynolds 1991) with OSB and foam sheathing also demonstrated the significant potential for drying even in cold weather. This result is in direct opposition to the climate chamber study referenced earlier (Lawton et al. 2002). Clearly, the different results are due to the realistic boundary conditions used in our field study.

The experimental results also provide clear evidence that ventilated walls dry faster and remain drier than similar unventilated walls, sometimes by a significant margin. Ventilation of the cladding may not benefit drying if the rate limiting step is moisture transfer through the sheathing membrane or the sheathing (see Figure 3). Ventilation of the brick veneer clad test walls was also effective in avoiding condensation and excessive stud moisture contents caused by solar-driven inward vapor diffusion. This would be true for almost all wall types, although it would have less practical significance for assemblies that have low vapor permeance sheathing or sheathing membranes.

The brick clad walls with vent openings at the bottom only (nonventilated) dried more slowly, experienced moisture conditions in the batt space close to or above damage thresholds, and suffered from more severe inward vapor drive condensation wetting. Physical inspection upon disassembly found much more mold growth and other signs of moisture damage in the nonventilated walls.

Hot weather drying (more accurately described as redistribution of moisture inward) of wetted sheathing was fast in all walls (i.e., under a week) and much slower and more dependent on wall design during cooler and more humid conditions.

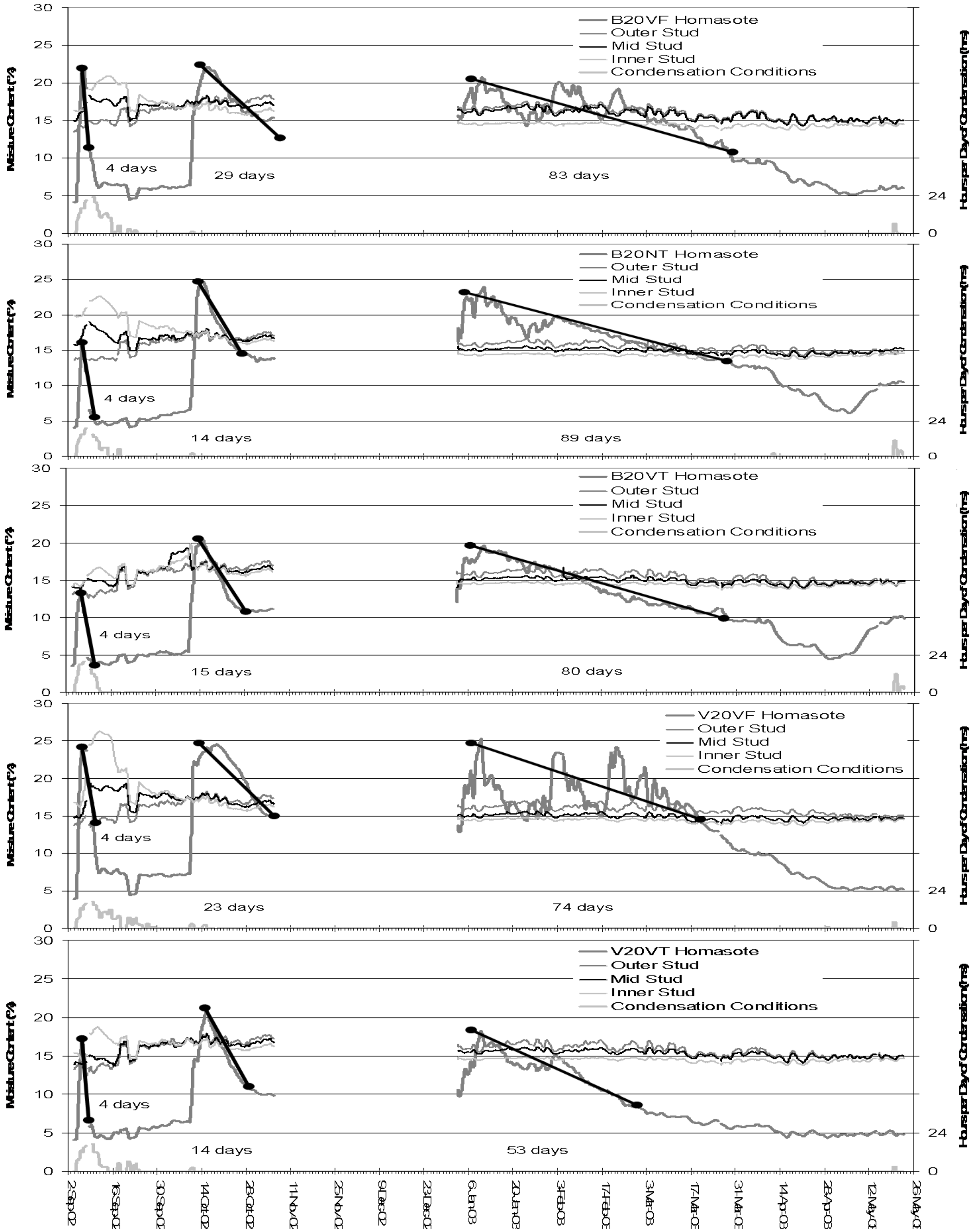

Figure 9 *Second configuration moisture content measurements.*

Table 4. Second Wall Configuration – Condensation Condition Occurrence

Experiment	B20VF		B20VT		B20NT		V20VF		V20VT	
	hrs	%	hrs	%	hrs	%	hrs	%	hrs	%
Fourth- Sept 4 / 02	163	17%	88	9%	109	11%	167	17%	106	11%
Fifth- Oct 10/02	0	0%	0	0%	0	0%	2	0%	0	0%
Sixth- Jan 2/03	6	0%	19	1%	18	1%	5	0%	3	0%

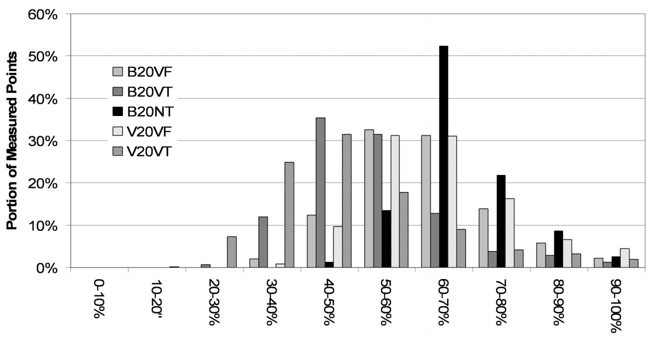

Figure 10 *Second wall configuration batt space relative humidity histogram.*

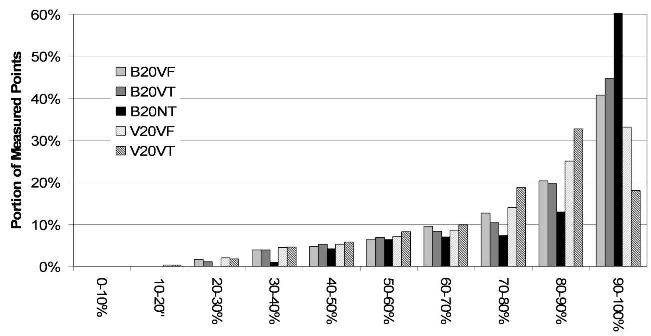

Figure 11 *Second wall setup ventilation cavity relative humidity histogram.*

In cold weather (less than about 0°C), the drying appears, unsurprisingly, to be predominately outward.

No large difference in hygrothermal performance was found between the 20 mm and 50 mm ventilation cavity wall setups for the brick veneer test walls. Based on physical measurements of flow resistance and theoretical predictions, it was concluded that there likely was no significant difference in ventilation flow. The smaller cavity may have slightly reduced the ventilation rate, although the data are not conclusive. However, the hygrothermal behavior may have been dominated by the sheathing membrane permeance or the moisture storage properties of the brickwork.

The vinyl clad walls behaved as though they were very well ventilated. The fiberboard sheathing dried more quickly in the walls clad with vinyl siding than the walls clad with brick during winter and spring conditions. The vinyl and ventilated brick walls had similar drying rates and batt space conditions during summer and fall conditions. In general, vinyl clad walls were somewhat drier than similar brick clad walls because of higher solar-induced temperatures and lack of cladding moisture storage.

No fundamental difference in behavior was found between walls with vinyl siding cladding on strapping or contact applied.

As has been measured in several previous studies (e.g., Straube and Burnett [1998]), night sky cooling of the brick was not sufficient to cause ventilation wetting by condensation. The thermal mass of the brickwork causes the back of the brickwork to remain above the outdoor temperature even during very cold clear nights. Night sky subcooling of the lightweight vinyl cladding was measured in this study, although the number of hours during which this resulted in high (over 95% RH) behind-vinyl relative humidity was limited to the order of a few dozen per year. The hygric buffer capacity of the sheathing and heat flow from the inside appears to limit the impact of this phenomenon in these walls in this climate. Different results are likely for roofing (due to much greater subcooling).

For walls exposed to above-freezing temperatures and direct solar radiation, a significant proportion of any water that penetrates the sheathing membrane layer is likely to be driven inward and may condense on cool vapor-impermeable interior layers. In the wall systems tested in this project (and observed in other projects and by other researchers), this mechanism caused the most damage by subjecting the studs to prolonged high humidities during the warm conditions necessary for damage. Inspections of the panels found that those walls that experienced the most condensation at the inner vapor barrier had the most mold damage.

Walls incorporating SBPO sheathing membranes dried slightly faster than those with AIF membranes. More significant to long-term performance was that the test walls with SBPO maintained significantly drier conditions within the batt space and framing and experienced less severe inward vapor drive wetting.

The properties of the sheathing membrane played a role in these tests. The vapor permeance of the #15 AIF used is lower than that of the U.S.-sourced SBPO. The measured ventilation cavity air RH conditions show that the sheathing membranes operated at over 90% relative humidity for large

(20% to 55%) portions of the time. It is suspected that a large portion of the outward drying occurs when the ventilation cavities are heated by the sun (since this greatly increases the difference in vapor pressure and increases ventilation by natural buoyancy). During these periods of the day, the relative humidity of the air in the cavity drops as the temperature rises. Hence, a large portion of the drying may occur during hours when the cavity is at lower relative humidities. Available data on the permeance of the sheathing membranes are plotted in Figure 12. The different curves for AIF are for three different manufacturers. SBPO and AIF have similar (and high) permeances at relative humidities of over 95%, but even at 80% to 90% RH the AIF permeances are an order of magnitude lower. Thus, during peak drying hours, the permeance of the AIF sheathing membrane is significantly lower than the SBPO. This would help explain the slower sheathing drying rates and the greater inward vapor drives in the AIF walls. The moisture storage capacity of the AIF, however, may dampen the response of the AIF RH relative to the cavity air RH.

CONCLUSIONS

The controlled experimental field study reported here results in a number of important conclusions for the wood-framed wall designs considered:

- Walls can dry outward significant amounts of any water that penetrates through the sheathing membrane layer, (provided the wall design allows for this).
- Fast-drying wall designs can be repeatedly wetted over several years and remain in almost perfect condition.
- Ventilation of walls (e.g., typical loose-applied vinyl siding or brick veneers with clear large vent openings top and bottom) encourages faster drying and significantly reduces the impact of solar-driven inward vapor drive condensation.
- The vapor permeance of sheathing membranes can play a role in the drying rate, although both of the membranes tested had reasonably high permeance values.
- Significant amounts of moisture can be redistributed from wet outer layers (sheathing or cladding) to the interior, driven by short-term peak solar radiation. The redistributed moisture can cause damage if sufficient moisture is available and prevented from drying to the inside.

Further research should be undertaken to confirm the predicted (from this study) impact of lower vapor permeance sheathings (such as OSB and plywood), low-permeance sheathing membranes, and low-permeance cladding systems (e.g., stucco, sealed metal panels, heavily painted wood clapboard, etc.). The role of solar-driven moisture redistribution and inward drying also deserves much more attention in all climates zones.

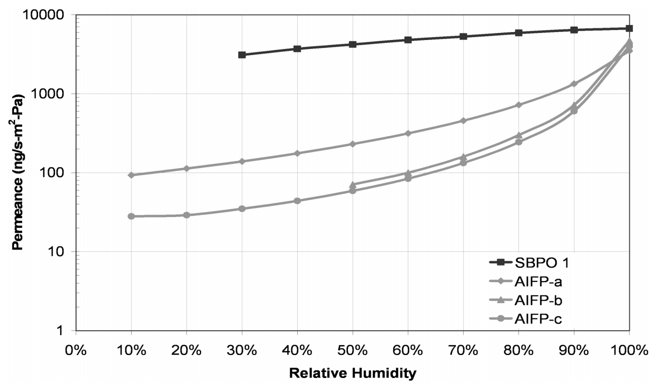

Figure 12 *Vapor permeance of SBPO and AIF (Kumaran et al. 2002).*

ACKNOWLEDGMENTS

ASHRAE and the National Science and Engineering Research Council of Canada must be thanked for their financial support of the work reported in this paper. Mr. Chris Schumacher's critical reviews and assistance during the experimental work were invaluable and are gratefully acknowledged. The paper's reviewers also added important insight and helped improve it.

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