MOISTURE MOVEMENT IN BUILDING ENCLOSURE WALL SYSTEMS

J.F. Straube **E.F.P. Burnett**

ABSTRACT

Moisture is one of the most important factors affecting building envelope durability and performance, especially in cold climates. Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance.

Over the past five years, a group at a Canadian university has been involved in a number of studies involving the performance of full-scale exterior wall assemblies. This paper discusses moisture control and some of the results from the field monitoring of more than 30 wall panels exposed to the climate of southwestern Ontario over lengthy periods—well over a year. The panels were constructed of either 2 × 4 or 2 × 6 studs, with wood panel or exterior insulating sheathing, and with vinyl siding or brick veneer. Some wall panels had initially saturated lumber; others had warm, moist air pumped into the stud space, and all had an airtight inner poly/drywall layer.

Some aspects of the actual performance of the various walls are compared with anticipated response. The dynamic nature of hygrothermal behavior over representative weather periods is examined. It is demonstrated that the appropriate time interval must be used when analyzing or monitoring wall performance. The interaction of moisture storage, diffusion, temperature, solar radiation and air movement, and the influence of the air, water, and vapor flow characteristics of the sheathing and cladding—major variables in these studies—are discussed.

INTRODUCTION

In countries with cold climates, moisture is one of the most important factors affecting building envelope performance. Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance. In Canada, especially over the last 15 years, a great deal of time and effort has been devoted to the topic of moisture control.

Research on heat and mass transfer in building enclosure elements (wall and roof systems) is probably best conducted by a judicious combination of laboratory investigation, field testing, and theoretical modeling. Of these activities, field testing is undertaken the least, probably because comprehensive and accurate measurement of the performance of wall assemblies exposed to the natural environment is costly, involves a number of variables (controlled and uncontrolled), and requires a relatively long time. Field monitoring, however, has unique advantages in that the behavior of full-scale, near-real-wall enclosure assemblies can be monitored under actual climatic conditions. In addition to doing basic research and development, appropriate field monitoring can be used to validate theory, confirm laboratory testing, and demonstrate in-service performance, and thus also provide conformance testing for manufacturers, builders, and designers.

Since fall 1989, the Canadian group (BEG) has operated a full-scale, natural exposure test building dubbed the Beghut. Building envelope assemblies (e.g., walls, windows, doors) can be inserted and performance in the four cardinal directions can be assessed through monitoring, analysis, and observation. This facility permits the testing of full-scale assemblies under real-time, southwestern Ontario climatic conditions and, as such, constitutes a unique and valuable resource for the building industry.

A minimum of six panels can be installed in each side of the Beghut (24 total). Each test panel is approximately 1.2 m (4 ft) wide and 2.4 m (8 ft) high. Each panel is isolated (with respect to heat, air, and moisture) from the Beghut structure and neighboring panels. A pipe mast rising from the central peak of the roof supports a weather station at a height of 10 m (32.8 ft) above grade. The interior environment is controlled to provide constant temperature and relative humidity. In general, each wall panel is instrumented for temperature, relative humidity, pressure, and moisture content (e.g., for wood framing, sheathing, etc.).

Several projects have been conducted. The first project was directed at studying the ability of different wall assemblies with high built-in moisture levels (wet wood framing) to dry out. Other projects have been

J.F. Straube is a research assistant and **E.F.P. Burnett** is a professor of civil engineering and director of the Building Engineering Group at the University of Waterloo, Ont., Canada.

directed at validating wall response for computer modeling and developing new wall systems. A number of reports have been produced, some of which are proprietary. Valuable experience has been gained, and this paper documents some findings that may not be well known.

In this paper an attempt is made to synthesize the issue of moisture control and some results are presented from the field monitoring of different framed, residential wall systems exposed to the climate of southwestern Ontario. The focus is on screened, multilayer, framed wall systems, but much of the discussion can be extended to other envelope systems.

MOISTURE CONTROL

Moisture-related problems occur all too frequently in Canadian buildings. For a moisture-related problem to occur, it is necessary for at least four conditions to be satisfied:

- *Moisture* must be available.
- There must be a *route* or means in which this moisture can travel.
- There must be some *force* to cause moisture movement.
- The material(s) involved must be *susceptible* to moisture damage.

To avoid a moisture problem, one could choose to eliminate any one of these four conditions. To reduce the probability of having a problem, it often is advantageous to address two or more of these prerequisites.

Moisture usually is available from one or more of the following environmental sources:

- the exterior: water from precipitation (rain, ice, or snow melt) and water vapor;
- within the wall: built-in or stored water (wood, concrete, etc.), snow/ice, and water vapor; and
- the interior: water vapor.

Moisture can move into, through, or out of the envelope via:

- openings in materials (cracks, punctures, holes, pores, etc.),
- spaces or gaps at interfaces, and
- bridges and dams (ties, mortar, etc.).

The generic forces that, singly or in combination, cause moisture movement are kinetic energy (i.e., the wind), gravity (e.g., hydrostatic pressure and free flow), convection (thermal and moisture density differences), diffusion, air pressure, and surface tension (capillarity)

Different materials and assemblies are variously susceptible to different kinds of moisture-related damage. Measures (standards or criteria) are available for some of the following moisture-related concerns: discoloration (staining, "dusting," irregular wetting, etc.); deterioration (wear, drying out, etc.); decay, rot, or microbiological growth (air quality); corrosion; freeze-thaw degradation; and volume change (expansion, shrinkage).

VULNERABILITY

Whether a moisture-related problem actually occurs also is dependent upon three other considerations, each of which affects the probability of a problem occurring or, more generally, influences the level of risk associated with a moisture-related problem and its consequences. While the susceptibility of a material to a particular problem (e.g., freeze-thaw deterioration) may be measurable (e.g., standardized freeze-thaw tests and target criteria for acceptable performance), this measurement usually presumes or simulates conditions of use or exposure. How the practitioner actually chooses to use the material may make a problem more likely to occur. This vulnerability to a moisture-related problem may be considered to be a function of the potential for wetting, storage, and drying.

Wetting Potential

This potential depends largely upon exposure and thus location, e.g., the location of the relevant portion of the envelope on the building and the geographical location of the building. Exposure conditions, not only to rain but also to wind and sun, can be critical. For example, using a material that is not supposed to be susceptible to moisture damage (e.g., good quality, code-acceptable face brick) in locations with high wetting potential (e.g., at sills or at corners of high buildings) often leads to a problem.

Storage Potential

The ability of a material or an assembly to store moisture may be a critical consideration. Two particularly important features are how much moisture can be stored and for how long without crossing a performance threshold. For example, the storage capacity of wood allows significant amounts of moisture to be handled without causing a problem, whereas unprotected steel may corrode when exposed to small quantities of moisture for any length of time.

Moisture, in any form, can be *stored* in the enclosure in a variety of ways:

- retained in poorly drained areas in a wall (on mortar dams, in small depressions, by mortar droppings, etc.);
- adhered (as droplets or frost) to the surface of the sheathing, or at other interfaces;
- adsorbed on the face of a layer or on the surface of its constituent parts (e.g., on fiberglass filaments) of hygroscopic building materials;
- absorbed by porous materials (such as concrete, brick, fibrous batt insulation); and
- in the air within the enclosure element.

Drying Potential

The ability of a material or assembly to dry also is an important consideration. Diffusion of water vapor, air movement, desorption, capillarity, evaporation, and, of course, gravity drainage are all contributors to the drying process. Obviously, considerations of configuration, location, and exposure have an influence on the nature and rate of drying.

DRYING AND WETTING POTENTIALS

The difference in water vapor pressure between two locations across an enclosure element (e.g., interior and exterior environments, or any two interfaces) is the motive force for water vapor diffusion. The distribution of water vapor pressure also provides a good indication of what is likely to happen if there is any airflow in the same direction as diffusion.

Given some knowledge of the interior and exterior environments over the period of a year, it is possible to develop a measure of the potential for wetting and drying for the above-grade enclosure of a building in a particular location. Consider Figure 1(i), where mean monthly values for the exterior and interior ambient water vapor pressures have been plotted for the Beghut. Water vapor tends to diffuse inward for some of the time (during warm weather) and outward for some of the time (particularly in winter). Note that the use of mean monthly values of vapor pressure is an oversimplification. This is evident in Figure 1(ii), which shows the variability and range of the extreme daily vapor pressures over the same year. To assess how an enclosure is likely to perform under these environmental conditions, it is necessary to also consider the nature of the enclosure system.

In fact, Baker (1980) and others (Tobiasson and Harrington 1986; Condren 1982) have developed plots of the annual potential for wetting and drying for conventional low-slope, exposed-membrane (waterproof and airtight) roof assemblies. These potentials can readily be developed because the roofing membrane on these roofs can be assumed to be on the exterior and to be both the water and air barrier, as well as a vapor retarder for the assembly. Plots of the wetting and drying potential for exposed-membrane roofs can be generated by assuming that the temperature across the roofing membrane is uniform and equal to the exterior ambient value. Wetting below the membrane could occur when the exterior saturation vapor pressure drops below the interior vapor pressure. Drying of this condensate will occur when the saturation vapor pressure immediately below the membrane is greater than the vapor pressure inside the building. Because it reasonably can be assumed that there is no air leakage through the roofing membrane, the area difference between the exterior saturation vapor pressure and the interior vapor pressure is a relative indicator of the net potential for wetting and drying into and out of this type of roof assembly for a particular building and location.

Solar radiation and heat flow from the interior will raise the temperature of an exposed roof membrane, sometimes significantly above the outside ambient temperature. Accordingly, for more accurate results, the influence of solar radiation and heat flow should be incorporated in the development of wetting and drying potentials. Condren (1982) has attempted to make some provision for solar effects.

It is much more difficult to develop plots of the wetting and drying potentials for wall assemblies. Some differences need to be noted. By plotting the interior and exterior vapor pressures, as shown in Figure 1(i), it would appear that only the vapor drive between the interior and exterior environments is important. In a wall assembly, the critical (with regard to durability) vapor drive may occur between two interfaces other than the interior and/or exterior surfaces, and these other interfaces will have temperature and relative humidity values that differ from the values at the exterior and/or interior surfaces. Unlike roofs, the location of the vapor retarder in walls is likely to be close to the inside and, therefore, diffusion drying could occur in the winter and diffusion wetting is possible in the summer.

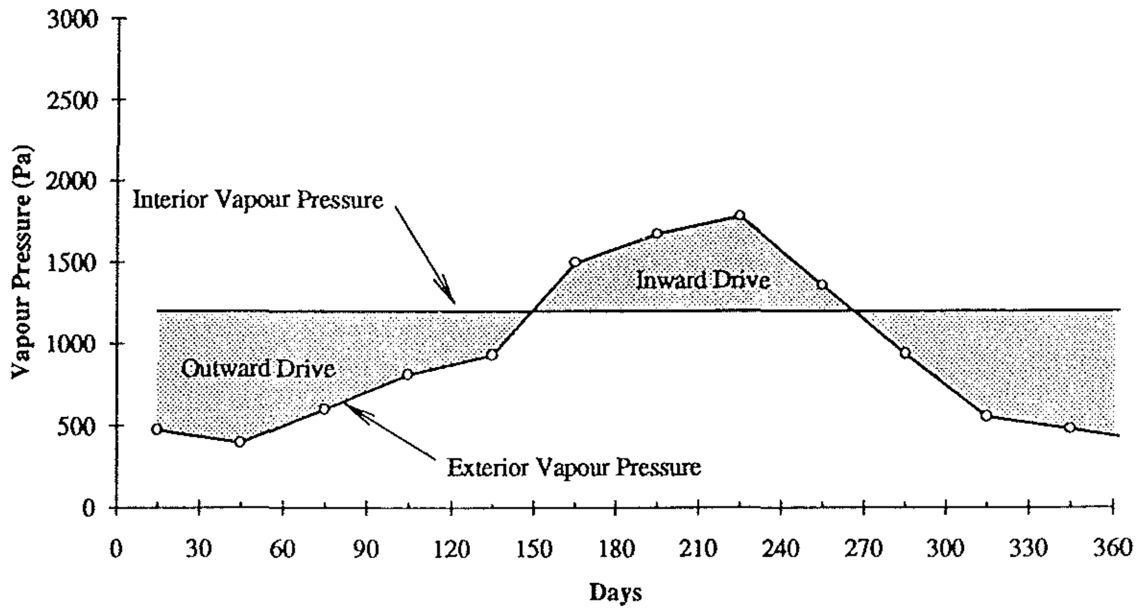
Unlike roofs, in walls air leakage is likely to occur and air leakage usually is a much more significant moisture transport mechanism than water vapor diffusion. Moreover, in walls, air leakage and vapor diffusion do not necessarily produce complementary effects. It follows that a different approach should be used for walls.

To assess the wetting and drying potential of walls due to air exfiltration only, it can be assumed that water vapor in the air flowing from the interior will condense on the first surface that has a temperature less than the dew-point temperature of the interior air. Once this interface has been identified, it is relatively easy to plot the temperature for this interface, say, j, in a wall using the equation:

$$t_j = \frac{\sum R_{int...j}}{R_{total}} \cdot (t_{int} - t_{out})$$

The choice of the value for outside temperature (t_{out}) is important. While the monthly mean exterior temperature may be used, it should be borne in mind that the amount of condensation that theoretically will occur is dependent on this value. A second factor to consider is the influence of the sun. On walls exposed to the sun, the mean "exterior" temperature can be expected to be higher than exterior ambient. In masonry veneer walls, for example, solar energy will be stored and then released slowly. Thus, by increasing the mean temperature at the exterior, the sun can significantly reduce the potential for, and thus the amount of, condensation.

1. (i) MONTHLY MEAN VAPOUR PRESSURES
Waterloo 1990



1. (ii) DAILY EXTREME EXTERIOR VAPOUR PRESSURES
Waterloo 1990

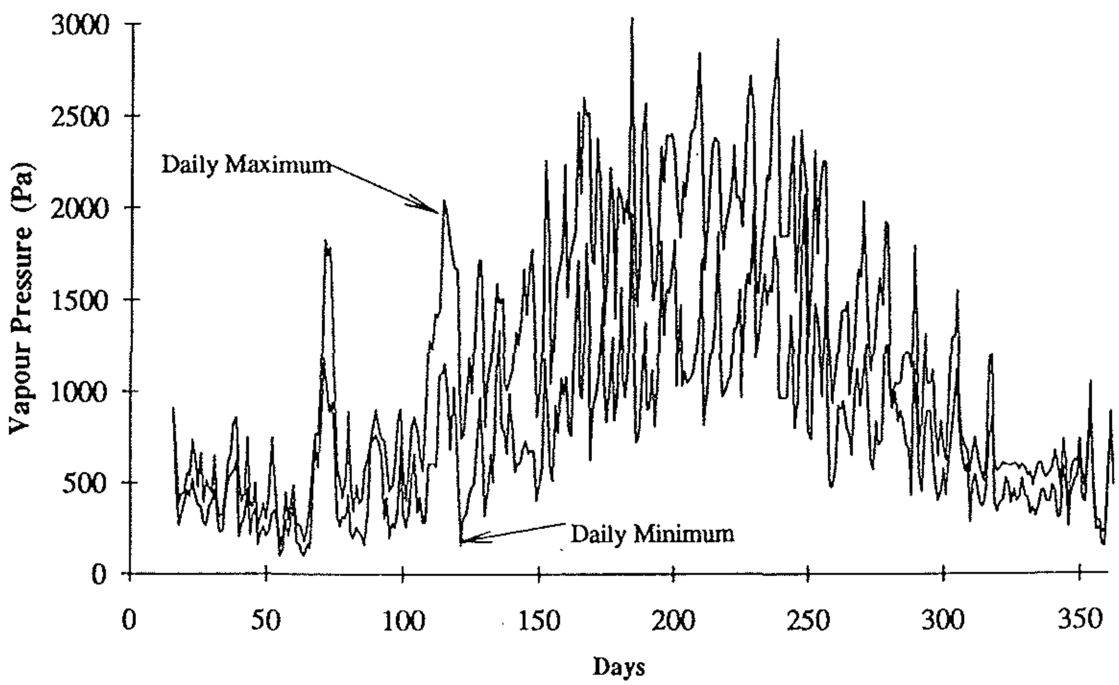


Figure 1 *Water vapor pressures over a year.*

Knowledge of the temperature and thus the saturation vapor pressure at the condensing interface and the vapor pressure of the indoor air permits the development of a plot of inward and outward vapor pressures. Figure 2(i), for example, was developed to illustrate the vapor drives to and away from the inside face of the fiberboard sheathing for an insulated 38-mm by 140-mm (2-in. by 6-in.) wood frame wall in Waterloo. In this example, monthly average exterior temperatures for Waterloo and 20°C interior air at 35% relative humidity (RH) have been used.

Predicting the amount of moisture likely to be transferred or the amount of condensation due to exfiltration is more problematic. For a specified air leakage rate and known interior environmental conditions, the rate of moisture accumulation can be calculated by assuming that the relative humidity of all of the exfiltrating air becomes 100% at the condensation plane. For a specific air leakage rate, the amount of exfiltration condensation can be evaluated. Figure 2(ii) is the plot for wetting and drying potential in terms of condensation due to exfiltration only. The wetting/drying axis in Figure 2(ii) has been normalized with respect to an airflow rate of 1.0 L/s per m^2 at a 10 Pa pressure difference; this is a representative average pressure difference across an envelope due to stack and wind effects. For instance, a recent cross-Canada air leakage survey of apartment buildings (Gulay et al. 1993) found wall leakage rates in the range of 0.25 to 3.8 L/s/m^2 at 10 Pa.

Accuracy is a concern. It is difficult to precisely evaluate how much moisture is transferred and stored due to exfiltration condensation. All of the moisture in excess of the saturation pressure (100% RH) may not be removed by condensation. Large or concentrated flows of warm air will tend to elevate temperatures near the flow path and thus reduce the amount of condensation. Depending on the flow rate and the nature of the flow path, some moist air may leak out of the wall assembly without contacting a condensation surface.

The process for deposition and accumulation of condensate and the process for the removal of condensate are not necessarily reversible. Evaporative drying due to air exfiltration is likely to be a much less efficient process than wetting because exfiltrating air in the summer is unlikely to reach 100% RH as it passes over a wetted layer in a wall assembly. Once a material is no longer saturated, exfiltration evaporation becomes an even less efficient means for drying (relative to the efficiency of the process of exfiltration condensation).

Although the assumptions for air leakage rate, etc., are likely to be only rough approximations, this approach does provide a rational basis for assessing the wetting and drying potentials of different wall assemblies for condensation due to exfiltration and diffusion. In fact, a commercially available computer program takes a similar approach in attempting to quantify wetting and drying in user-defined wall assemblies for several Canadian locations.

SOME FIELD RESULTS

Most of the walls tested in the Beghut to date were built with a near-perfect air barrier near the inside of the wall. Note that a perfect barrier may not be representative of many in-service walls, especially in older buildings, as this does restrict the role of indoor air as a source of moisture.

Solar-Driven Inward Vapor Drives

As is evident in Figures 1(i) and 2(i), in a fully conditioned building a significant inward water vapor drive exists over the warmer months of every year. However, the inward drive shown in Figure 1(i) significantly underestimates that which actually occurs because of the influence of solar radiation. Daily sol-air effects, when associated with moisture trapped behind vapor-impermeable cladding, can produce large, short-term, inward vapor drives whose magnitude can greatly exceed those outward-acting vapor pressure differences in winter (generally less than 1,000 Pa).

For a variety of reasons, moisture can be stored in the outer portions of a wall assembly. In cold weather, moisture, exfiltrating and diffusing through the inner layers of the enclosure assembly, may condense on the colder inner surface of the cladding or exterior surface of the sheathing. In the summer, a similar, but inward, situation can occur, especially in air-conditioned buildings. Moisture from precipitation or condensation also may be stored in and on the screen or cladding (especially wood products and masonry).

On a typical day the sun can warm the exterior surface of an exposed wall by as much as 30°C above the ambient. These relatively high temperatures generally will thaw frost and cause water stored in the materials to move. This process may cause drying of the cladding and can also generate high vapor pressures in the space immediately behind the cladding. Thus, stored moisture (within materials, on surfaces, or as vapor) near the outer surface will diffuse inward. If the vapor resistance of the exterior screen is higher than that for the outer layers of the inner wythe, significant volumes of vapor can be driven inward. Note that the exterior screen on many wall systems is relatively impermeable to water vapor diffusion (e.g., masonry veneer, vinyl siding, wood cladding, steel sheet).

As a practical example of this wetting phenomenon, consider the plots of the hourly average temperature and vapor pressure shown in Figures 3(i) and 3(ii) (Straube and Burnett 1993). These values were recorded on a sunny day in July in a brick-veneer-clad wood-frame wall panel sheathed with rigid fiberglass; this sheathing was placed immediately behind the brick veneer, i.e.,

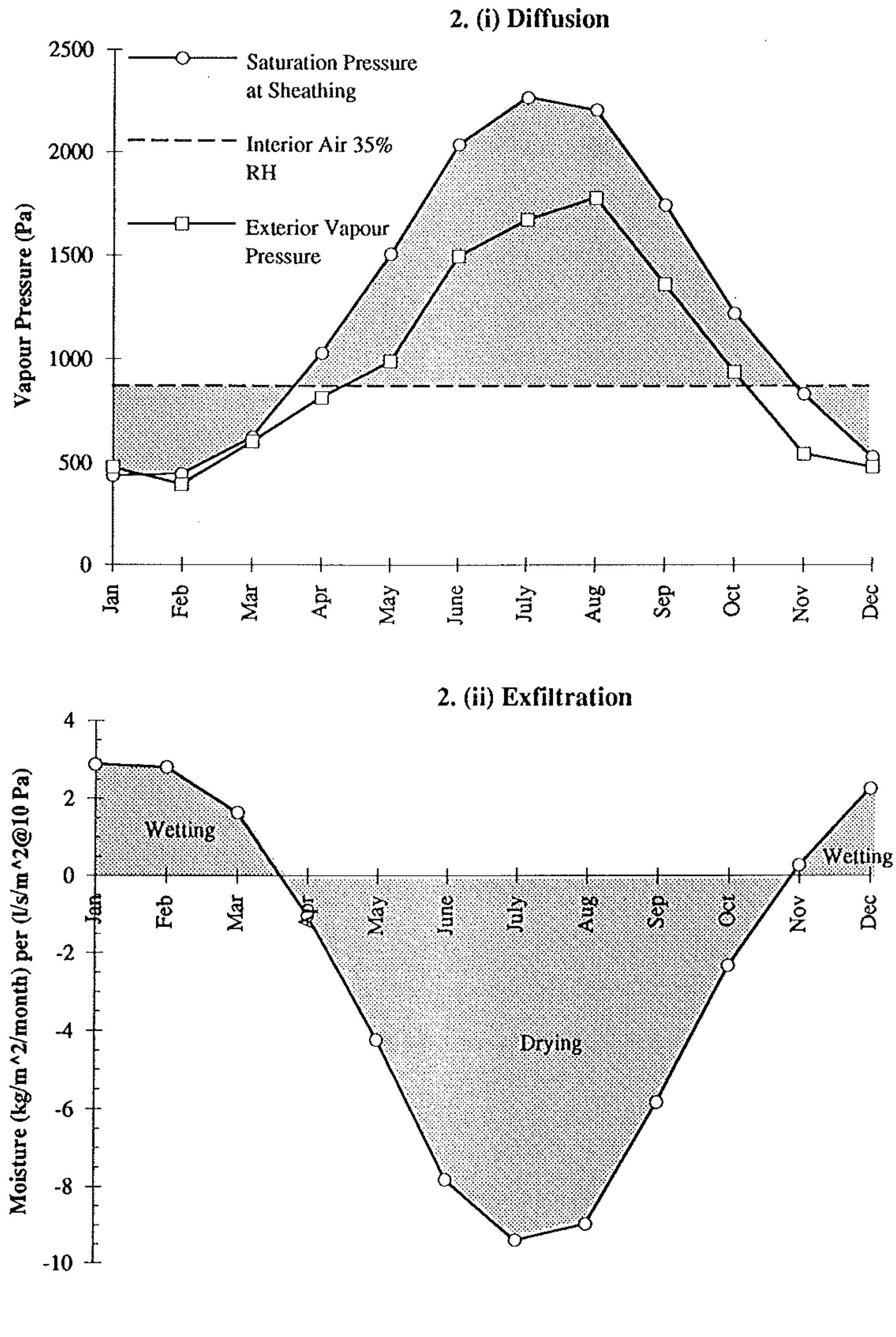


Figure 2 Temperature and vapor pressure variations for a representative day.

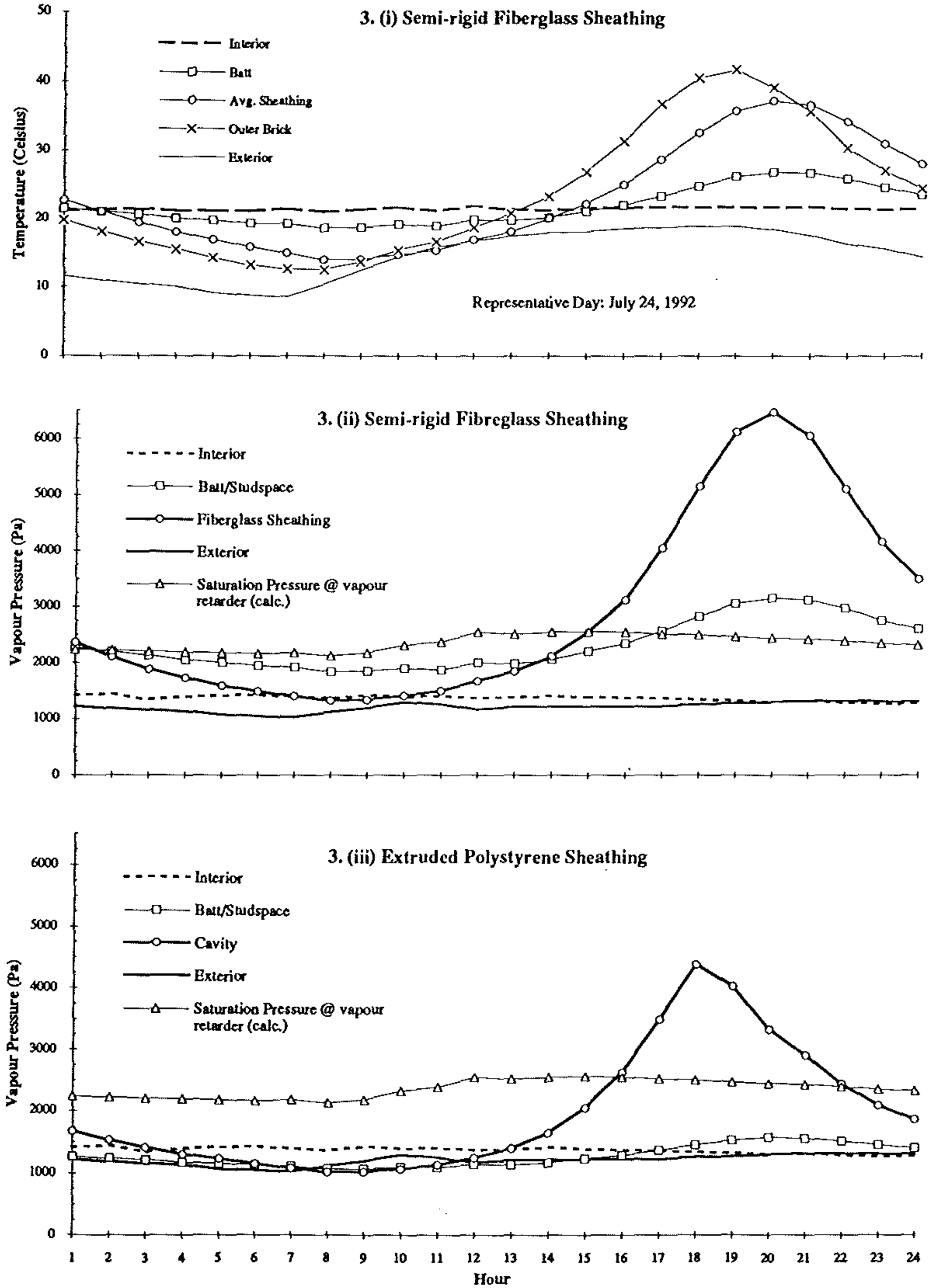


Figure 3 Representative wetting and drying potentials for a wall.

there was no clear cavity. This wall assembly had little vapor resistance within the wall downstream (exterior) of the interior poly vapor retarder. During the day, the vapor pressure in the sheathing increased (in step with the solar-induced temperature rise of the brickwork screen) to almost 6,500 Pa, while the vapor pressure within the stud space climbed to about 3,000 Pa.

As can be seen from Figures 1 and 2, in the winter the peak outward-acting vapor pressure difference is on the order of 1,000 Pa, even with exterior temperatures less than −20°C. Even in an air-conditioned building, the predicted vapor pressure difference acting across a wall in the summer will generally only be a few hundred pascals. Contrast this with the peak measured vapor pressure differences of several thousand pascals between two internal interfaces in each of the wall panels shown in Figure 3.

Figure 3(iii) shows a plot of vapor pressure over the same day for another wall constructed with a vapor-resistant sheathing of extruded polystyrene instead of the vapor-permeable fiberglass (in Figure 3[ii]). Although the vapor pressure in the cavity is high, little moisture is transferred inward to the stud space and there is little danger of condensation because of the low vapor permeance of the polystyrene.

Therefore, solar-driven inward vapor drives several times larger than outward-acting winter vapor drives can be expected to occur in screened walls. These inward drives may cause condensation on the interior vapor retarder, especially in air-conditioned buildings. The presence of a relatively vapor-impermeable layer near the outside of the assembly (e.g., extruded polystyrene) will reduce the potential for significant quantities of warm weather condensation due to diffusion.

Periodicity and Variability

Another important point to note is the influence of short-term climatic variations. Some effects would not be evident if monthly or even daily averages were to be used. Monthly averages, and certainly any values that ignore the influence of the sun, will distort the results of any performance prediction. For instance, the monthly means shown in Figure 1(i) hardly reflect the actual range and variability shown in the plot of daily values presented in Figure 1(ii).

For the test wall whose response over one warm day is shown in Figures 3(i) and 3(ii), the vapor pressure of the interior environment had an average value of about 1,400 Pa. The average saturation vapor pressure (2,500 Pa) at the poly vapor barrier can be calculated using the average measured temperature at this point. The daily average vapor pressure measured in the stud space was about 2,250 Pa. Thus, an analysis based on daily mean measurements would indicate that condensation would not occur. On an hourly basis, however, condensation is predicted to occur over about seven hours during the day. Considering the small vapor resistance of the sheathing used (rigid fiberglass with a polyolefin housewrap), the volume of condensate is likely to be significant. In fact, over the period of several summer months, the wood framing in this test panel became saturated and staining and mold appeared.

Therefore, to understand and accurately predict envelope behavior it is sometimes important to consider the variability of the exterior environment and the significant influence of solar radiation. The lightweight, framed wall assemblies often used in North America are especially sensitive to short-duration variations in temperature and moisture.

Dynamic Responsiveness

Normally wood framing is assumed to respond slowly to exterior variations; therefore, daily averaging would seem to be appropriate. If a wall is sufficiently air and vapor permeable, however, the air in the stud space can react quickly to exterior weather changes. On the other hand, the moisture conditions in the stud space of a wall with a vapor-retardant sheathing respond more slowly to exterior weather changes. Hence, the dynamic responsiveness of the wall can play a significant role in its long-term behavior. Conversely, reducing the dynamic responsiveness of the stud space in a wall by using a sheathing with low vapor permeability also means that the framing, once wetted, dries out more slowly. Consider the drying performance of three different wall assemblies with built-in moisture (initially saturated wood framing).

Figure 4 presents three plots of measured daily average wood moisture content over a four-week period soon after installation (Burnett and Reynolds 1991); this was in the winter with a strong diffusion-driven drying potential. These three wood-framed wall systems with insulated sheathing were constructed with initially wet (moisture content of more than 30%) wood framing. The walls that were built with the more air- and vapor-permeable fiberglass product allowed the built-in moisture to escape more quickly than the wall sheathed with extruded polystyrene. Note, however, that all these walls performed satisfactorily with regard to the handling of the built-in moisture.

In the wall with low-vapor-permeability, extruded polystyrene sheathing, the built-in moisture was eventually removed by airflow through the ship-lapped joints between the sheets. If wintertime air exfiltration deposited moisture in the wall, the net moisture content of the wood in this type of wall might be higher than in a wall that was more vapor permeable. In the summer, the reverse would be true, especially for air-conditioned and masonry-clad buildings. Indeed, the wood moisture content in the extruded-polystyrene-sheathed wall panel remained almost constant, whereas in the other wall

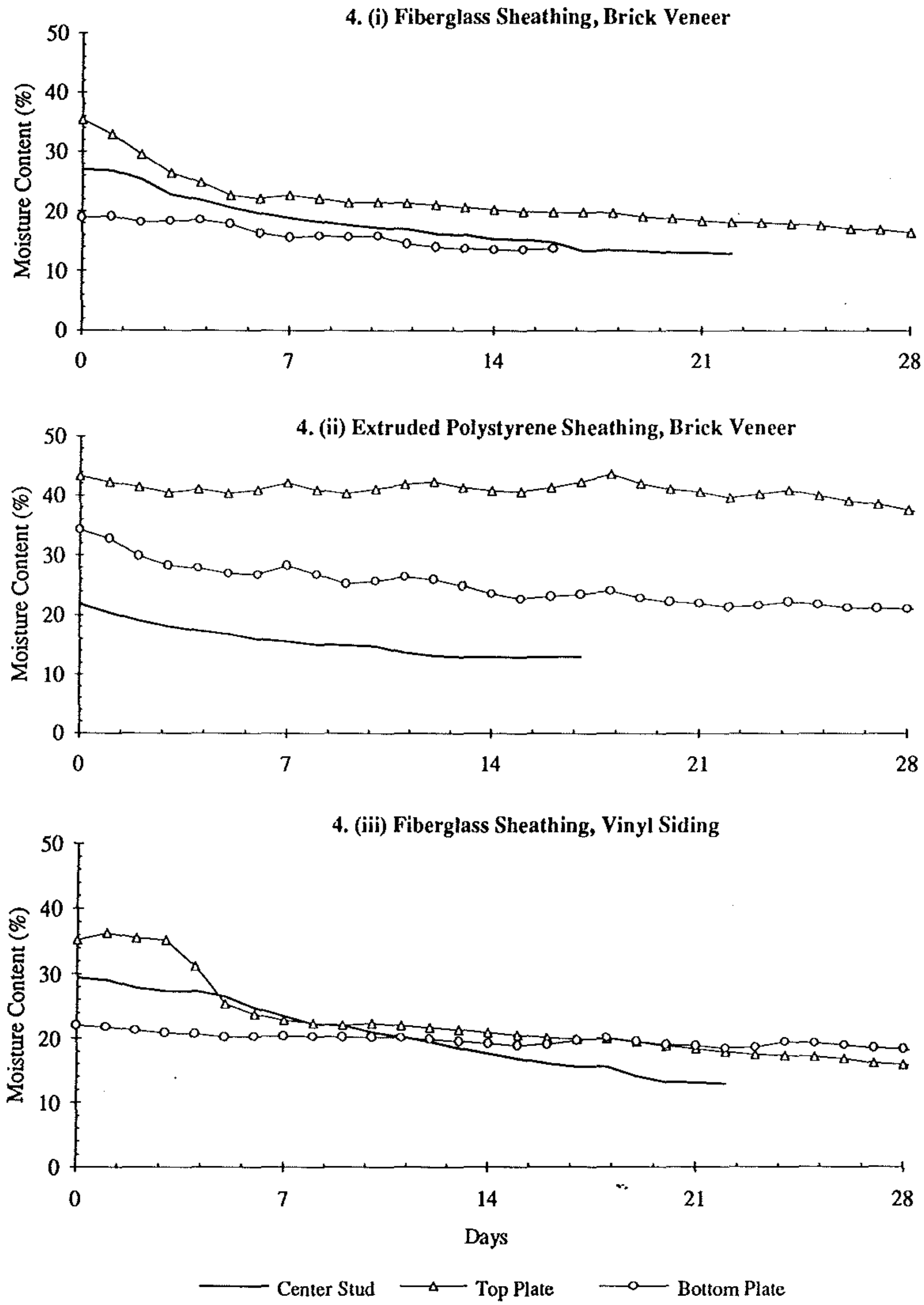


Figure 4 *Daily average wood framing moisture contents for three different wall assemblies.*

panel the wood framing behind the fiberglass sheathing responded to the changes in the exterior and gained moisture over the summer. Clearly, responsiveness and storage capability are important design considerations for walls.

A wall may have a net drying potential but may not have sufficient capacity for moisture storage, and thus high levels of moisture content and relative humidity may be maintained. The greater the volume of wood or other hygroscopic materials available within a wall, the greater the moisture storage capacity. If the surface-to-volume ratio is high (e.g., sheet products), the material will be able to absorb or discharge moisture quickly. Wood-based sheathings such as fiberboard, waferboard, and plywood are examples of good accumulators and distributors of moisture. When a drying potential exists,

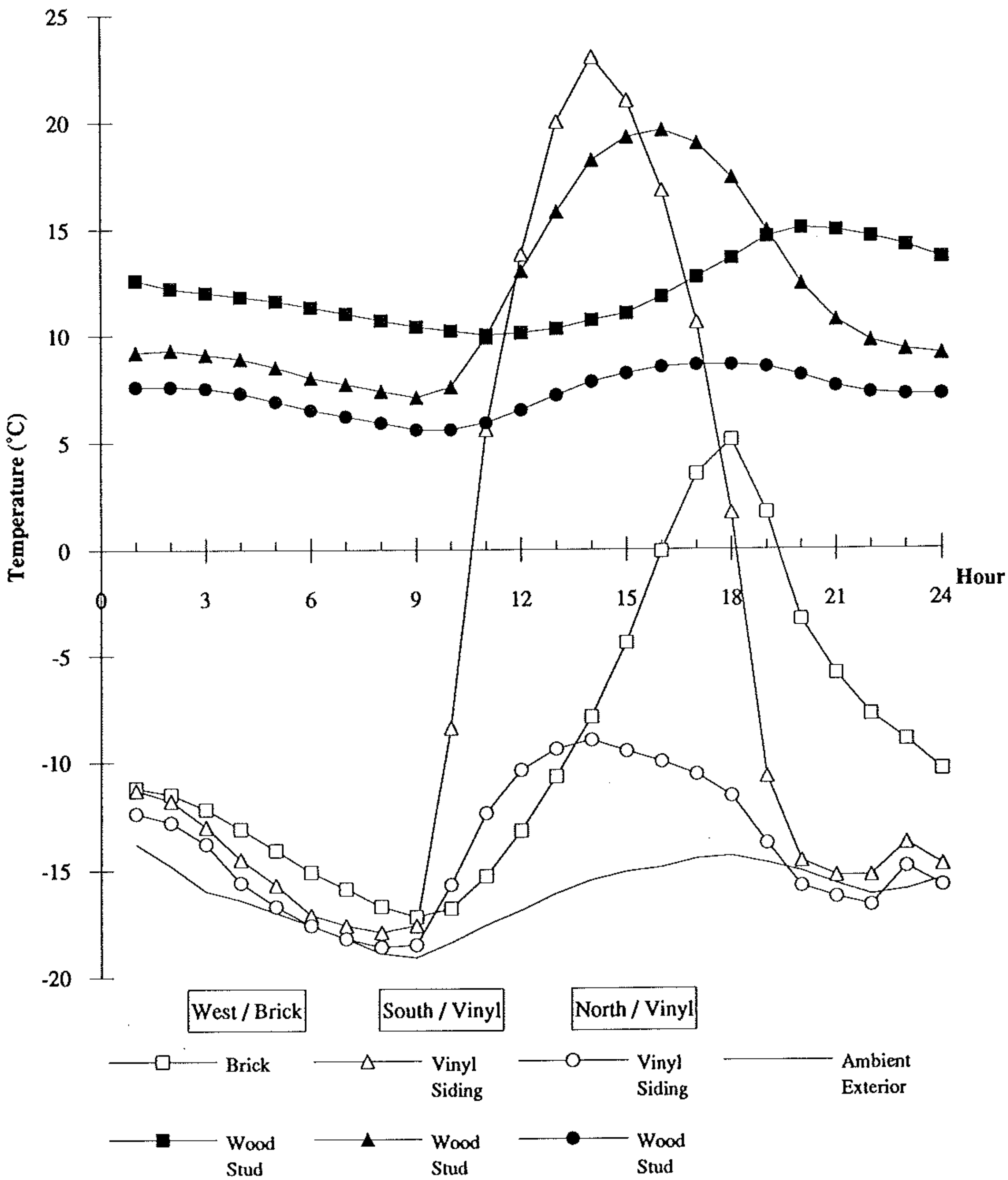


Figure 5 Temperature variations in three different wall assemblies.

these same materials can quickly release the moisture. Typically, in a wall the wood-based sheathing product will have a volume comparable to that of the wood in the framing. A wall with wood sheathing and wood framing has the ability to transfer and store considerable quantities of moisture without generating a problem

Cladding Type and Wall Orientation

To this point, only walls screened with brick veneer have been discussed. Although vinyl is completely impermeable to air and moisture flow, the joints and small openings (weepholes and vents) in vinyl siding systems allow for some moisture movement. Figure 4 illustrates the results of the initial four weeks of testing for three wall panels constructed with wet framing lumber. These panels differed only with regard to their screen (brick veneer and vinyl siding) and sheathing (fiberglass board and extruded polystyrene).

Figure 4(iii) shows the variation in wood moisture content for a wall clad with vinyl siding and sheathed with fiberglass board. Comparing this figure with Figure 4(i) there is little evidence to indicate that the use of vinyl siding instead of brick veneer has any significant influence on the drying rates of the framing lumber. However, vinyl siding (like steel cladding) cannot store moisture, whereas masonry (and wood cladding) can. It follows that moisture movement inward, especially that due to solar-induced vapor diffusion, may be less significant for vinyl siding. Note, however, that the low thermal mass of vinyl siding (and sheet steel cladding) results in higher peak temperatures that occur for shorter periods.

Figure 5 (Burnett 1992) plots the variation in temperatures in the screen and the wood framing in three different wall panels over a cold but sunny day in February. Apart from orientation and screen, these test panels were identical. The plot clearly shows that, even on a day with an average exterior temperature of −16°C, the south-facing vinyl siding can reach a temperature of almost 25°C. The north-facing vinyl siding exhibited a temperature increase to about 8°C above ambient from reflected radiation; it also decreased to below the ambient outside temperature at night due to radiation to the sky. The brick veneer temperature on the west face increased to about 5°C (some 20°C above ambient) but it gains and then loses this heat much more slowly than the vinyl; six hours after reaching its peak temperature the brickwork is still 8°C above ambient, whereas the vinyl siding reached the temperature of the outside air four hours earlier.

The influence of the cladding temperature on the wood framing temperature can also be seen in Figure 5. The wood framing is affected by the screen, and the amplitude and lag in temperature also reflects that of the screen. The average daily temperature of the framing is substantially more variable in the vinyl-clad south-facing panel. Over the winter, the average temperature of the wood framing in the brick-clad panel remained fairly constant, at about 5°C above ambient. On the particular day shown in Figure 5, while the wood studs in the vinyl-clad south wall reached a higher peak temperature (19°C) than the framing in the brick-clad west wall (16°C), the daily average for the wood in the brick-clad west wall (13.9°C) was greater than that for the vinyl-clad south wall (10.3°C). In the vinyl-clad north wall, the average stud temperature was only 7.2°C, almost 7°C colder.

These differences in temperature affect the moisture content of the wood framing. The higher the temperature, the higher the vapor pressures that can be generated and hence the greater the potential for moisture movement outward by diffusion. Higher mean temperatures in the stud space are advantageous for both moisture control and energy conservation.

CONCLUSIONS

To ensure moisture control in the performance of enclosure assemblies, it is necessary to consider all the likely sources of moisture, all the means or routes for transport of moisture, and all possible motive forces, as well as susceptibility to a moisture-related problem. Furthermore, consideration of the potentials for wetting, storing, and drying of moisture will permit an assessment of the vulnerability of the assembly to moisture-related problems.

Experience with the field monitoring of wall assemblies indicates the following.

- Solar-driven, inward vapor-pressure drives can, during the day in warm weather, be several times greater than outward-acting, wintertime vapor drives. Warm-weather moisture diffusion must be considered as a potentially damaging moisture transport mechanism. The use of exterior sheathings with a low vapor permeance can be effective in reducing the potential for damage due to inward vapor drives.
- When analyzing the building envelope, especially lightweight framed assemblies, the appropriate time interval must be used even for relatively simple predictive calculations. Using monthly or even daily average data can result in significant errors and misleading results.
- Some wall assemblies respond faster to the weather than others, and the choice of sheathing material(s) has a significant influence on wall performance.
- It needs to be emphasized that cladding and orientation choices are both important behavioral parameters.

REFERENCES

Baker, M.C. 1980. *Roofs*. Montreal, P.Q.: Polyscience Publications Inc.

Burnett, E.F.P. 1992. *The Ontario wall drying project: Phase 2.* Ottawa, Ont.: Canada Mortgage and Housing Corporation.

Burnett, E.F.P., and A. Reynolds. 1991. *The Ontario wall drying project.* Ottawa, Ont.: Canada Mortgage and Housing Corporation.

Condren, S.J. 1982. Vapor retarders in roofing systems: When are they necessary? *ASTM STP 779, Moisture Migration in Buildings,* pp. 5-27. Philadelphia, Pa.: American Society for Testing and Materials.

Gulay, B.W., C.D. Stewart, and G.J. Foley. 1993. *Field investigation survey of airtightness, air movement and indoor air quality in high-rise apartment buildings summary report.* Ottawa, Ont.: Canada Mortgage and Housing Corporation.

Straube, J.F., and E.F.P. Burnett. 1993. Zero-cavity and DPV wall project—Draft report for Canada Mortgage and Housing Corporation. Unpublished.

Tobiasson, W., and M. Harrington. 1986. Vapor drive maps of the U.S. *Thermal Performance of Building Envelopes III.* Atlanta, Ga.: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.