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Heat, Air and Moisture Control Strategies for Managing Condensation in Walls

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Water, in liquid, vapour or solid form, is a major cause of building material deterioration. Interstitial condensation can contribute significantly to water accumulation in wall assemblies. Successful building design requires an understanding of moisture movement in building assemblies and techniques for managing moisture.

Building designers may attempt to manage condensation in exterior walls by means of a single element. Is it the thermal insulation? Is it the air barrier system? Is it the vapour barrier? Is it to include none of these elements, like fifty years ago? Research shows that no single material or system on its own will prevent excessive moisture accumulation within wall assemblies. Rather, effective moisture management comes from controlling heat, air and moisture transport (HAM) through the careful choice of materials properties. Failure to manage the transport of heat, air and moisture across the wall assembly can cause the following problems:

- Premature deterioration of building materials
- Accumulation of moisture condensate in wall cavities, leading to rot, corrosion or displacements of materials
- Mould growth on building materials
- Poor control over the indoor environment, e.g., cold draughts, low relative humidity, transmission of noise and pollutants between units or between indoors and outdoors
- Drop in performance and reduced service life of materials and systems
- High energy costs
- Condensation on the interior surfaces of windows (which is not discussed in this paper)

Stepping Back to Spring Forward

In the last thirty years, there have been major changes in the way buildings are designed, built and operated in Canada. For example, the energy crisis of the 1970s had a major effect on our building technology related to energy efficiency. As a result, in the late seventies much more thermal insulation was placed in exterior walls, and the need for a corresponding increase in airtightness had started to get recognition. However, most emphasis was still on the need for vapour diffusion control and vapour barriers were much emphasized in the industry. Electrically heated houses with no chimney became more common. Such changes in the operation of buildings affected the air pressure gradients across the exterior walls and ceilings and the direction of airflow – walls and ceilings were now more susceptible to air exfiltration through existing holes and imperfections in the wall assemblies.

The 1980s saw increased emphasis on the importance of air movement as the primary mechanism of moisture transfer across the building envelope. Requirements, performance evaluation and assessment for air leakage control were the subject of considerable research at several national agencies such as the Institute for Research in Construction (IRC) and Canada Mortgage and Housing Corporation (CMHC). Manufacturers, builders and developers introduced innovative approaches for airtightness at the "material" level as well as at the "system" level. For example, the Airtight Drywall Approach (ADA) uses a material commonly found in residential buildings – gypsum wallboard – to serve as the main air barrier element, but is innovative in the way the system is articulated over the enclosure to ensure continuity.

In the 1990s it was recognized that a systematic approach to the evaluation and assessment of air barrier systems was required and this work was carried out by the NRC's Canadian Construction Materials Centre (CCMC). The issue of the location of the air barrier system in relation to the thermal insulation and the distribution of vapour permeances across the wall assemblies was addressed as well.

Review of recent literature indicated that major recent failures of exterior walls in Canadian low-rise housing projects were mostly attributable to rain penetration resulting from faulty detailing, not to condensation of indoor moisture and air leakage. In the last three decades there have been significant advances in the understanding of moisture and environmental loadings and the properties of materials and systems, as well as their effects on performance and service life of building envelopes. Despite advances in building science, the introduction of new and innovative products and systems, increasing expectations of building occupants and new architectural designs for building envelopes create challenging issues of condensation control for builders, regulators, design professionals and building managers. Going back to basic building science principles to analyze the situations can be of great assistance in evaluating the available design options.

Factors That Affect Interstitial Condensation

Four conditions need to be in place simultaneously for water vapour to condense within a wall assembly (Figure 1): water vapour in the air, a force to move that water vapour through a path of least resistance to a location at a "cold enough" temperature for that moisture to condense.

Indoor moisture levels in the air (usually referred to as "relative humidity") are the result of occupants' activities, the operation of HVAC systems and natural ventilation, and, in early stages of occupancy, moisture absorbed into building materials during construction. *Forces* that move water vapour are differentials in air pressure or in vapour pressure across building elements. *Travel paths* are the result of building material properties and the ability of assemblies to exhibit discontinuities (holes, gaps, joints) present in building assemblies. *Temperature gradients* across materials and assemblies result from outdoor and indoor climates, the thermal properties of materials and the distribution of these properties between the several layers of the wall.

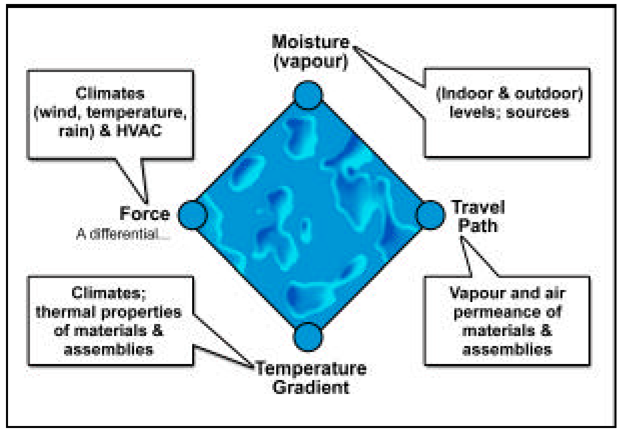

Figure 1. Four factors required for moisture to condense in interstitial places

These four factors are required for condensation to form on a cold surface; however, this does not necessarily imply that a moisture problem will develop, as this will depend also on how much water remains for how long in contact with moisture-sensitive materials. Traditionally the prediction through calculation methods that some moisture condensate – even an extremely small amount – could occur in a wall cavity has been a cause for concern (risk of deterioration). However, this assessment does not account for the drying/drainage ability of the wall assembly or for the possible ability of the building materials in question to tolerate short-term exposure to water. The quantity of moisture and the duration of its presence in the vicinity of moisture-sensitive materials have an effect on the risk of deterioration associated with condensation potential.

Until recently, there were few tools to help designers and researchers define the amounts and durations of those moisture loads for given climates and material properties and the associated risks. While simple prediction methods, such as dew point calculation using indoor and outdoor temperature and indoor relative humidity (RH), focusing on moisture diffusion might show that there is no risk, there could in fact be a risk of condensation. The current approach is to consider not only the wetting potential that can result from condensation but also the tolerance of the wall assembly to such wetting, in terms of drying potential of the wall assembly, the deterioration mechanisms at work and a more realistic representation of the climate to which the assembly will be exposed. IRC has used numerical modelling to provide useful comparative analysis of the effect of these parameters, and to provide guidance on the design of assemblies for condensation control.

More recently IRC has developed an integrated methodology to obtain reasonable inputs for numerical modelling analysis to compare wall responses to moisture loading, and has applied it to rain penetration problems (see the paper entitled *An integrated methodology to develop moisture management strategies for exterior wall systems*).

Mechanisms of Moisture Transport

Air movement and diffusion are the two transfer mechanisms of moisture in its gaseous form. These mechanisms of moisture transport may be combined with other mechanisms of transport of liquid moisture to carry moisture from outdoor to indoor or vice versa. For example, water may be absorbed at one face of a hydrophilic material, move through it by capillary action, and evaporate from its face to move towards another layer of the wall assembly. Let's now examine each mechanism.

Vapour Diffusion

The diffusion of water vapour through a material is a function of the ability of the material to provide a path for vapour transport (i.e., vapour permeance) and the presence of the force acting across the material (vapour pressure difference), which in turn depends upon the moisture content in the air on both sides of the material (Figure 2). The psychrometric chart can be used to obtain a quick estimate of the "vapour drive" across a material/assembly, based on the temperature and relative humidity prevailing on each side. In cold climates, the drive is normally from the interior to the exterior for the majority of the year, as indoor moisture content is much higher than outdoor content. Vapour permeance is a property inherent in a material of a given thickness and is expressed as the rate of transmission of water vapour in weight of water per Pascal of vapour pressure difference per unit time and per unit area of material (ng/Pa•s•m^2).

Vapour Barrier

To minimize moisture accumulation in the wall assemblies due to vapour diffusion, a material of low vapour permeance can be placed on the warm side of the assembly and be designated as the vapour barrier of the assembly. For best results, it is important that the vapour barrier covers the total area of the envelope, but it does not have to be tightly sealed. Several common building materials, such as polyethylene sheet, glass and metals, foil-back materials and wood-based materials like oriented-strand board (OSB) and plywood, exhibit low vapour permeance. In fact, 6-mil thick polyethylene sheet has been used as the designated vapour barrier, as well as an element of the air barrier system in most of the low-rise residential construction built in Canada over the last 20 years. Requirements for vapour barriers are different than for air barrier systems.[1]

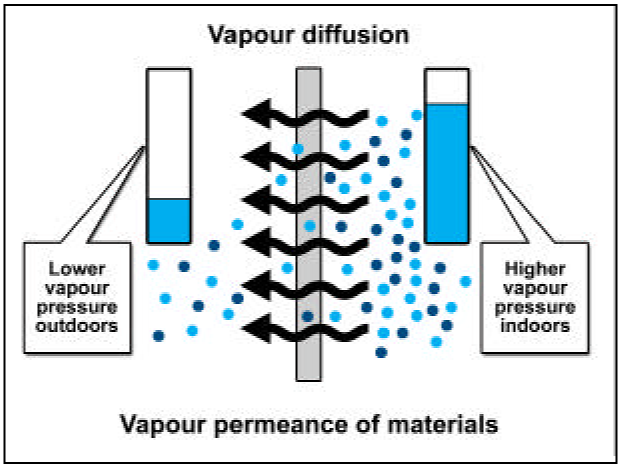

Figure 2. Vapour diffusion across a material or assembly

Air Movement

Air movement (air convection) is related to the ability of a material or an assembly to provide a path for airflow (i.e., defined by its air permeance in L/s•m^2 at 75 Pascals (Pa)) when an air pressure difference acts across it (Figure 3). Air pressure differentials across building elements are the result of wind action, temperature difference (also referred as stack effect) and the operation of mechanical systems in buildings. Air movement can result in through-flow across the wall assembly, also known as air leakage (Figure 3), which is the most significant means of moisture transport across a wall assembly. Another form of air movement is the partial flow of air through to certain elements within the wall assembly without penetrating right through to the exterior or interior (see section entitled "Not-Through Flow of Air Within the Wall Assembly"). In other words, a wall assembly with a perfect air barrier system could still experience lateral flow of air (often referred as wind-washing) or interior convection flow that can affect the condensation resistance of the wall assembly.

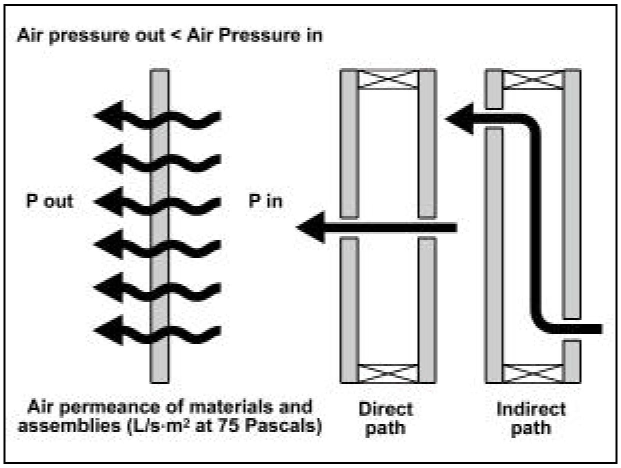

Figure 3. Air leakage across a material or an assembly

Air leakage across an exterior wall assembly can result in the transport of large quantities of moisture-laden air to a localized area of the assembly. The airflow characteristics are defined by the location of accidental air inlets and outlets and the path of least resistance between the two, the air permeance of building materials and the magnitude of the pressure differential acting on the assembly. Vapour diffusion is a slower process of moisture accumulation, and exhibits a more uniform pattern of distribution over a material.

IRC has developed advanced 2-D numerical hygrothermal modelling to study the interaction between air exfiltration and moisture accumulation in a simplified wall assembly.[2] Figure 4 shows the type of relationship established between air leakage, moisture accumulation and heat flow. The graph indicates that:

- For a band of low air exfiltration rates (less than 0.2 $L/s{\cdot}m^2$ at 75 Pa), moisture accumulation is very small.
- As the air exfiltration rate increases, moisture accumulation tends to increase in an exponential manner up to a point.
- Beyond a certain high rate of air leakage across the assembly, accumulation of moisture drops to zero. This is explained by the fact that exfiltrating air carries heat, along with moisture. As the rate of exfiltration becomes very high, the warm exfiltrating air warms up the exterior sheathing and raises its temperature above the dew point of the indoor temperature and hence no condensation occurs on it.

The results should not be used as absolute thresholds, as the output values will change with the input boundary conditions, i.e., the indoor and outdoor climates, as well as with the properties of the wall assemblies. This finding supports anecdotal field observations that older constructions built fifty years ago that operated with very high air leakage rates have experienced few condensation problems (Figure 4, Area D). More recent tighter construction with a somewhat increased control of air leakage is not "tight enough" to control condensation (Area C). Tighter construction in the neighborhood of 0.2 $L/m^2{\cdot}s$ at 75 Pa results in the least accumulation of condensate (Areas A and B). In Area A, the extra benefits of increasing the airtightness level are marginal in relation to the additional building complexity and quality control onsite for the execution of a tighter air barrier system.

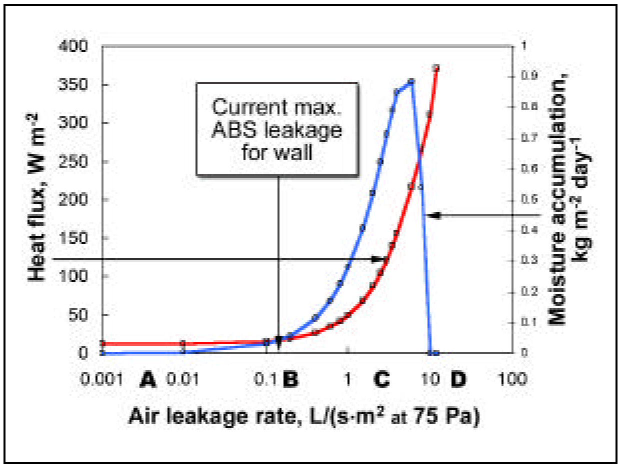

Figure 4. Type of relationship established between air leakage, moisture accumulation and heat flow

Air Barrier System

To minimize moisture accumulation in a wall assembly due to air leakage (infiltration or exfiltration), materials with the ability to restrict airflow effectively under air pressure differentials (such as those induced by wind) must be installed in a continuous fashion over the building envelope. The word "system" in air barrier system emphasizes the requirement for integrating different materials with the right properties over the building enclosure in order to create an effective continuous system, as opposed to simply employing a material with low air permeance.

Requirements for Air Barrier System

For the air barrier system (ABS) to perform its intended role, it must satisfy the following requirements.[3,4]

Low air permeance

Resistance to air flow is inherently a material property normally reported in $L/(s{\cdot}m^2)$ at a reference pressure differential of 75 Pascals (Pa). Extensive testing of a multitude of materials has been done in Canada, and results can be found in handbooks and documents discussing air leakage control.[5, 6, 7] A variety of materials exhibit low air permeance; for instance, polyethylene sheet, aluminum foil and certain non-perforated spun-bonded polyolefin membranes, modified bituminous membranes, gypsum wallboard, plywood and OSB cement panels, and insulation boards like extruded polystyrene foam.

Structural capacity and rigidity

The air barrier system is intended to sustain all air pressure loads, wind loads being the single largest one (particularly gust wind). The system must be supported and fastened so that the wind load can be transferred to the structure without damage to itself or to other wall elements and without much increase in air leakage. Under such loads, the air barrier system should exhibit limited deflection as excessive deflection could displace other materials or open joints and increase air leakage. The structural capacity associated with the air barrier system can be provided by an element other than the airtight element of the ABS. For instance a sheet material acting as the airtight element can be sandwiched between two rigid sheathing panels in which case the panels become part of the air barrier system, and need to be designed accordingly.

Continuity

If only certain elements of the ABS meet the requirement for airtightness and discontinuities result in large holes and cracks, the ABS will not be effective, as paths of airflows can introduce an excessive amount of moisture accumulation locally. Field observations have indicated that junctions between components (e.g., wall/roof) or between dissimilar materials (e.g., lumber/concrete) are typical locations for discontinuities in the air barrier system. Continuity is without a doubt the most challenging requirement for air barrier systems. This is because their effectiveness depends on the interaction between the design of the building envelope and the practical considerations derived from field construction practices such as buildability, tolerances and construction sequencing by several trades.

Durability

Durability can be defined as the ability of a building material or assembly to perform its required functions over a period of time in the environment to which it is exposed. Durability is not only a matter of material property selection but also the severity of environmental exposure. The notion of inspection, maintenance and repairs during service life also plays a part in extending the service life of building elements. Building designers need to consider the severity of exposure during construction and during service life, as well as the level of access for inspection, maintenance and repairs.

The location of the air barrier system within the wall assembly has an effect on its level of environmental exposure as well as the level of accessibility for future maintenance and repairs.

- Introducing a layer of thermal insulation on the outside face of the ABS helps reduce thermal differential movements on ABS joints and minimize the wetting of ABS materials (e.g., due to convective air loops resulting in condensation).
- Placing the air barrier system on the interior side of the wall assembly makes it readily accessible for inspection and repairs (this can also make it susceptible to damage by the occupants). However, most air barrier systems are not directly accessible. When the air barrier system is accessible only through major disassembling of the walls, it should be designed and built to be more durable than accessible ABS systems. The location of the air barrier, as it relates to its vapour permeance, will be further discussed below.

FAQ on vapour barriers and air barrier systems

Q. Can an airtight element of the ABS be different than the designated vapour barrier?

A. Yes. Here are some examples: gypsum wallboard and spun-bonded polyolefin membranes.

Q. Can the designated vapour barrier be part of an ABS?

A. Yes. Examples: Foil-back gypsum board, polyethylene sheet, glass and metals, and elastomeric membranes.

Q. Is it a problem to have an air barrier element with low vapour permeance?

A. Not if its interior face is maintained above the dew point of indoor air.

Quantitative Requirements for the Air Barrier System

"Part 9 of the 1995 edition of the National Building Code (NBC) covers small buildings and houses. The only requirement for these buildings is that the air barrier system provides 'an effective barrier to air exfiltration under differential air pressure due to stack effect, mechanical ventilation and wind.' Part 9 does not contain quantitative requirements for allowable air leakage of either an air barrier system or the materials used to form it, or for its structural capacity and durability."[8] Part 5 of the 1995 NBC covers buildings that fall outside the scope of Part 9 and includes requirements for airtightness of the main element of air barrier systems, as well as some requirements for structural capacity and continuity. It requires a maximum air leakage rate for the main material of 0.02 L/s•m² at 75 Pa. Appendix A of the NBC 1995 (article 5.4.1.2) provides guidelines for the maximum air leakage rate for the air barrier system as a function of the severity of the indoor moisture level indoors: the higher the indoor relative humidity of the building, the higher the level of airtightness required. As the building envelope requires "an effective barrier to air exfiltration under differential air pressure due to stack effect, mechanical systems and wind,[7]" how is "effective" defined? Appendix A9.25.3.1 of NBC 1995 expresses it in the following way *"…Air leakage must be controlled to a level where the occurrence of condensation has to be sufficiently rare, quantities sufficiently small, drying sufficiently rapid to avoid material deterioration and growth of mould and fungi."* This brings forward a conceptual design approach that considers that some small amount of condensation may be acceptable as long as it dries quickly. The drying potential of materials within the wall assembly depends on the vapour permeance of the building materials and the driving force of the climate. Estimating the drying rates of wet assemblies for different climates has been done using numerical modeling.

Using the requirements of the National Building Code and input from researchers and practitioners, the Canadian Construction Materials Centre endeavoured to develop a guide to evaluate air barrier systems for walls of low-rise buildings[4]. The maximum air leakage rate for air barrier materials is 0.02 L/s•m² at 75 Pa. The system air leakage for the walls is defined by the vapour permeance of the outer-most non-vented layer of a wall assembly exposed to a maximum of 35% RH indoors (Table 1). The data is based on hygrothermal numerical modelling done at IRC.[9]

Table 1. Permissible air leakage rates for the wall air barrier system (as a function of the vapour permeance of outermost materials of the wall assembly)

Water Vapour Permeance of the Outermost Non-vented Layer of Wall Assembly ng/(Pa·s·m²)	Maximum Permissible Air Leakage Rates for the Air Barrier System of the Walls (L/s·m² at 75 Pa)
15 <WVP <60	0.05
60 <WVP <170	0.10
170 <WVP <800	0.15
>800	0.20

The airtightness of the air barrier system is basically predicated by the wall's ability to dry to the outside, which is a function of the vapour permeance of the outer layers of materials of the wall. The lower the vapour permeance of the outboard materials, the tighter the air barrier system ought to be, as the wall assembly is expected to exhibit a lower drying ability to the exterior, hence increase the risk for a longer period of wetness into the wall. If the temperature of the material with low vapour permeance can be raised above the dew point temperature of indoor air, condensation on its face would be controlled, and the maximum permissible air leakage rate for the air barrier system selected from Table 1 could be increased by 0.05 L/s•m² at 75 Pa (up to a maximum of 0.20 L/s•m²).

Location of the Air Barrier System

In principle the air barrier system can be located anywhere within the wall assembly in order to control airflow across the wall. As mentioned before, from a durability perspective, it is desirable for the air barrier system to remain warm and dry. Installing thermal insulation on the outside face of the ABS helps avoid large thermal gradients across the ABS materials and joints, reduce thermal movement and associated stresses and reduce condensation potential on its inside face (irrespective of the vapour permeance of the airtight elements). This is not to say that the air barrier system should necessarily be on the interior side of the stud cavity. There are benefits associated with locating the ABS further to the outside (e.g., fewer discontinuities from electrical, mechanical and plumbing services). When placing the air barrier system closer to the outside, attention must be paid to the vapour permeance of the materials to be used.

IRC researchers have used computer numerical modelling to estimate that a material located on the cold side of the assembly, be it the designated air barrier element or not, that exhibits low vapour permeance (i.e., less than 60 ng/(Pa•s•m²) and an airtightness of less than 0.1 L/s•m²at 75 Pa, should be maintained above the dew point temperature of the inside air by means of placement of an insulation layer on the outside of this material.[9] The level of thermal insulation required for that purpose has been estimated as a function of the severity of the outdoor climate indicated by the Heating Degree Days for a given location and for a maximum indoor RH of 35% (Table 2).

¤ Heating Degree days can be found in Appendix C of the National Building Code of Canada 1995.

Table 2. Ratio of outboard to inboard thermal resistance as a function of HDD

Celsius Heating Degree Days (HDD)	Min. Ratio for Total RSI value outboard of material's inner surface to Total RSI value inboard of this surface
Up to 4999	0.20
5000 to 5999	0.30
6000 to 6999	0.35
7000 to 7999	0.40
8000 to 8999	0.50
9000 to 9999	0.55
10000 to 10999	0.60
11000 to 11999	0.65
12000 or higher	0.75

Evaluation of Air Barrier Materials and Air Barrier Systems

Several listings of building material properties provide the air leakage characteristics of generic building materials. Canadian Construction Materials Centre (CCMC) evaluation reports[†] provide technical data on proprietary products or systems in terms of meeting the intent of the code. At the time of writing this article, several breather-type sheathing membranes had been evaluated as air barrier materials and two insulation-based systems had been evaluated as air barrier systems.[10] To qualify as an air barrier material, the material needs to exhibit a maximum air permeance of 0.02 L/s•m^2 at 75 Pa. The material is not evaluated for its structural capacity or the effect of fasteners on its airtightness, as these properties have to do with the whole air barrier system. The evaluation reports can be found in the Masterformat Division 07273 of the Registry of Product Evaluations.

CCMC has also issued evaluation reports for two air barrier systems. The evaluation procedure is well described in IRC Construction Technology Update no 46.[*] The systems evaluated have been examined and evaluated to address issues of structural capacity, continuity at joints and junctions with other components, durability and buildability. These two air barrier systems use thermal insulation as the main airtight element of the exterior walls, i.e., extruded polystyrene boards and sprayed-in-place polyurethane foam. These air barrier systems are intended to be located on the exterior of the stud cavity. For this reason, their vapour permeance has an effect on the required properties of other elements of the wall assembly, such as the vapour permeance of the vapour barrier on the interior side of the wall assembly. It also affects the minimum thickness of the external insulating sheathing required to maintain its internal face above the dew point of the inside air. Limitations and uses related to the vapour permeance of the main air barrier elements are also presented in the evaluation reports.

Non-proprietary air barrier systems are also commonly used. These have not necessarily been systematically evaluated for their performance, but track records of field application and experience by practitioners are also valuable assessment tools. A common approach for low-rise residential buildings has been to use a flexible membrane of very low air and vapour permeances (i.e., 6-mil polyethylene membrane) on the warm side of the assembly, to act not only as the vapour barrier but also as the designated airtight element of the air barrier system. In its air barrier role, the polyethylene membrane is coupled with other materials (e.g., gypsum wallboard, studs, batt insulation) which contribute to the structural capacity and rigidity of the ABS. Joints between two membranes of polyethylene as well as junctions at interfaces with penetrating components (e.g., floors, services, windows) need to maintain the continuity of airtightness and to exhibit a level of structural capacity and rigidity. For example, joints between two membranes of polyethylene will be stapled and sealed with acoustical sealant over a stud, and compressed by a sheet of gypsum wallboard, when the poly is meant to be part of the ABS. Several agencies have developed detailing for sealing joints and junctions using a polyethylene membrane as the basis for an “air-vapour barrier” in low-rise residential construction. In that type of construction, where the structural loads are low, the air leakage control characteristics of the “poly air-vapour barrier,” typically combined with rigid materials like interior gypsum wallboard, have shown a satisfactory performance record.

An innovative approach that makes use of the interior gypsum wallboard commonly used as interior finish in residential construction as a basis for both the air barrier

† CCMC Registry of Product Evaluations can be accessed on-line at http://irc.nrc-cnrc.gc.ca/ccmc/regprodeval_e.shtml
* CTU no 46 can be downloaded from IRC website at http://zone.nrc-cnrc.gc.ca/irc/reports/ctus/ctu46e.pdf

system and the vapour barrier is the Airtight Drywall Approach (ADA). The vapour barrier is either integral to the wallboard i.e., a foil-back gypsum board, or added on using several coats of paint on the interior side of the wallboard. Compressible gaskets and sealants are used to make the tight connections with other elements of the air barrier system.[13,14]

In both of these cases, as the air barrier system is installed on the interior side of the building envelope, the many joints and junctions present on the interior (e.g., electrical outlets, pipes, junctions with floors, foundations, cantilevered sections, top of partitions and party walls) present a challenge to its continuity.

"Not-Through Flow" of Air within the Wall Assembly

As mentioned earlier, other types of airflow, besides the type handled by the air barrier system, can affect the temperature regime of wall elements, possibly cooling them off below the dew point (wind-washing), or feeding moisture to a colder element (interior air convection loops). Little research has been done to quantify the effects of these phenomena, even though the research literature acknowledges its potential effects.[15,16] Considering the magnitude of the forces that cause these types of air flow, these are believed to be much less effective than air leakage through the assembly in causing condensation problems. However, designers need to account for these phenomena in the design of durable assemblies. It may be that materials designated for other functions will take care of such controls, or it may be that special measures will have to be taken.

Wind pressures may introduce lateral airflow patterns within a wall assembly (it could be the exterior side of an effective air barrier system as illustrated in Figure 5a). When cold air flows *over* the surface of a material, the material temperature drops, even though there could be thermal insulation in place against that surface. Wind-washing can affect the thermal value of low density insulation, short-circuit the performance of insulating sheathing, and cool down an air barrier system located towards the outside of the wall assembly (possibly below the dew point temperature). Corners and tops of walls, as well as horizontal assemblies like insulated floors separating an unheated garage from a living space above, or cantilevered living spaces, tend to be more susceptible to cold air circulation. The key to the control of this phenomenon is to increase the resistance to external airflow circulation.

This can be done by ensuring intimate contact between an air barrier system and an insulating sheathing (when these elements are on the exterior), or by introducing a secondary barrier to airflow (often referred to as a wind barrier or convection barrier) placed behind the cladding system. Breather-type sheathing membranes or low air permeance boards can be installed to reduce cold air circulation within the wall. Compartmentalizing the air space behind the cladding can also assist in reducing air circulation in that space. Vertical furring strips used in many cladding systems to create such an air space also act to compartmentalize the air cavity, and provide resistance to lateral airflow.

Another form of air circulation consists of interior convective airflow. Because of a temperature difference between the room and the outer portions of the wall, air flow could be initiated if openings are in place, even with a perfect air barrier system located on the outside (Figure 5b). It could transport indoor moisture to a

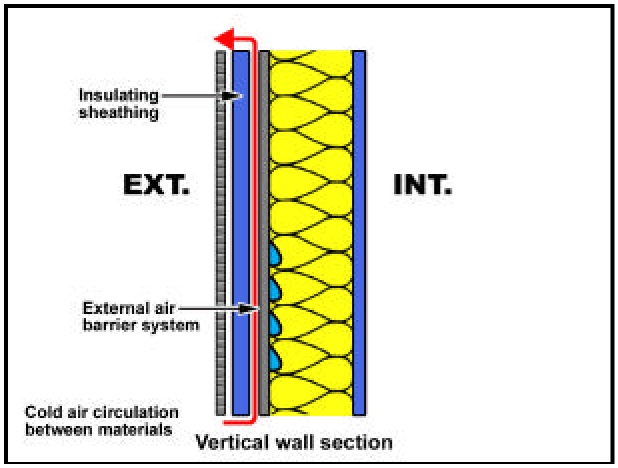

Figure 5a. One form of cold air circulation or wind-washing effect

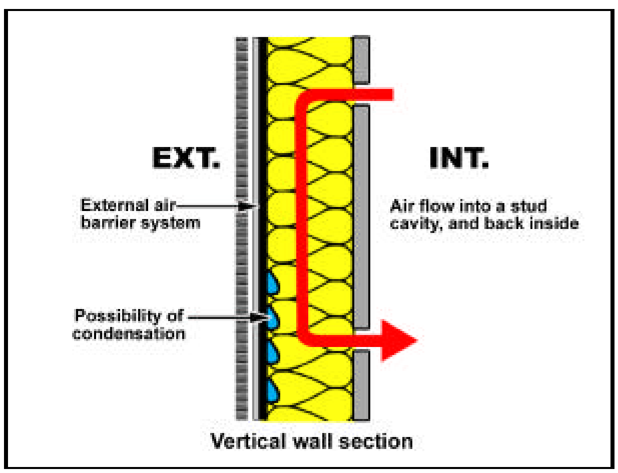

Figure 5b. Interior air convection loop

location below the dew point, possibly to an external air barrier element. The air pressures in this case are much smaller than what an air barrier system has to sustain, since the force is due to temperature difference alone. An element of low air permeance installed in a continuous manner on the interior side of the wall can minimize this phenomenon; it can be the air barrier system installed on the warm side, or a vapour barrier membrane. Installing the stud cavity insulation without leaving pockets of air is beneficial to minimize this phenomenon.[17]

Controlling Thermal Gradients for Minimal Interstitial Condensation

Although building envelope designers have little control over the prevailing indoor and outdoor temperatures for a construction, as the location of the project and the type of occupancy tend to dictate those, they can control the distribution of temperatures across the layers of the wall assembly for new construction. This temperature distribution depends on the thermal properties of the materials, their location within the assembly, as well as on air leakage. Figure 6 shows a schematic of temperature distributions for different locations of thermal insulation in the assembly, assuming air leakage is not considered. A designer might decide to keep the stud cavity warm and at a more or less uniform temperature (option C). Or, a designer might opt to take advantage of the stud cavity to insulate it, but also wish to raise the temperature of the studs to reduce thermal bridging (Option B).

For the control of interstitial winter condensation in a stud cavity or on exterior sheathing, placing thermal insulation on the exterior side of the wall assembly will raise the temperature of all the elements located on the interior side of this insulation (e.g., the exterior sheathing, studs and stud cavity, air barrier system and the vapour barrier material). As these elements are maintained at a higher temperature, the duration during which they lie below the dew point temperature of the indoor air will be shortened. This layer of insulation is usually rigid or semi-rigid insulation applied directly to the exterior sheathing, or sprayed-in-placed polyurethane foam. The higher the R-value of this exterior insulation, the shorter the duration for which the materials will be below dew point temperature. Indoor RH levels, air leakage rates, pressure differentials and climate conditions should be accounted for in a detailed analysis. Table 2 can be used to approximate the minimum amount of thermal insulation that should be placed on the exterior of the wall assembly to minimize condensation (assuming a max RH of 35% and an ABS air leakage rate of 0.1 L/s•m^2 at 75 Pa), as a function of the severity of outdoor temperature, expressed in heating degree days (HDD).

The use of exterior insulating sheathing can have a beneficial effect on reducing moisture accumulation in the stud cavity and on the exterior sheathing board, but its vapour permeance may have an effect on other requirements of the walls such as the level of airtightness of the air barrier system and the vapour tightness of the vapour barrier. The lower the vapour permeance of this material, the lower the permissible rate of air leakage of the air barrier system can be because the lower vapour permeance materials on the outside can reduce the drying potential of the assembly and, in fact, make the assembly less tolerant of moisture accumulation. IRC carried out research numerical modelling work on low permeance materials and developed the relationship presented in Table 2. If the insulating sheathing exhibits higher vapour permeance (i.e., above 800 ng/(Pa•s•m^2), it does not affect the level of airtightness required.

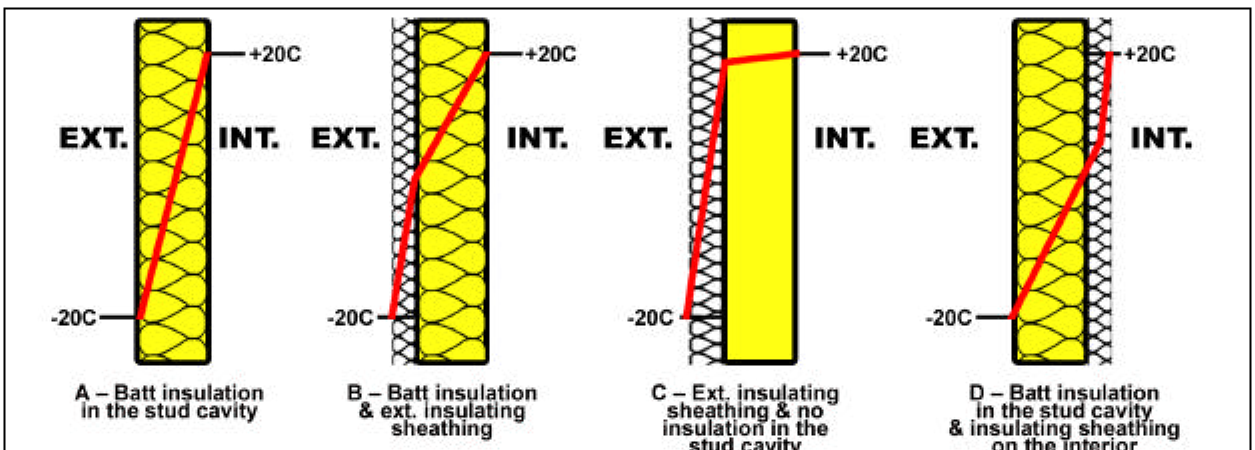

Figure 6. Examples of generic temperature gradients across a simplified wall assembly with no air leakage. The slope of the temperature drop will be related to the R-value of the materials.

Building "Forgiving" Wall Assemblies

A "forgiving" wall assembly is one that can tolerate some level of imperfection in the design and construction without unacceptable loss of performance or service life. This implies a conceptual approach to building envelope design, which expects imperfections, and aims for strategies to integrate second lines of defence to deal with their possible effects, while having a clear goal of acceptable performance and service life.

It may be that extensive field experience with a given design in a given climate has provided the practitioners involved with a high degree of assurance that "the system" works. When the conditions change, whether it is new and innovative designs, materials and systems or significant changes in climates (indoor or out), or the level of what constitutes "acceptable performance", a building science review of the proposed heat, air and moisture (HAM) control mechanisms should be done. The following section expands in this area.

To design a forgiving wall assembly, one needs to integrate "building science blocks" from the most simple to more complex levels, in an iterative manner as follows:

1. Characterize the indoor and outdoor environments that the walls will be subjected to: cold and dry, mild and wet, extremely cold most of the time, windy, in a city or on top of a hill, etc. What are the indoor climate requirements: relative humidity, temperature, mechanical ventilation and pressurization? Is the wall exposure severe, average or mild?
2. Analyze proposed wall assemblies to meet each functional requirement separately.

   Here are some of the questions that one should investigate in the design and review process.

   - What and where is the vapour diffusion control element (vapour barrier)?
   - What materials are part of the air barrier system? Where is the ABS located? Will it be in a warm and dry area of the wall, or a cold and occasionally wet area? What are its properties? Does it have low vapour permeance? Does it have the structural capacity to act as an ABS? Continuity is critical – work out the 3-D detailing for each junction, be it the wall/window, the wall/roof, top of partitions, party walls with other units. Ensure these typically high-risk of failure construction elements are not just improvised on site.
   - What rain penetration control strategy should be selected? How does it get incorporated with the cladding systems selected?
   - What elements need to be kept warm with the placement of thermal insulation? What are the properties of the different insulation materials to be used? Do they have low vapour permeance? What are their air permeance characteristics? How can thermal bridges be minimized?
3. Analyze the assembly from the point of view of interaction between material properties and their environmental exposure.

   Certain elements are put in place for condensation control but, in fact, they affect the performance of the wall at all functional levels, and vice versa. For instance, insulation materials are placed to control heat flow and the temperature of elements, but their vapour permeance will also affect vapour flow. Simply put, materials and assemblies are not aware that they have been designated "vapour barrier" or "air barrier element" or "thermal barrier"! They simply respond to the loads that they are exposed to with their properties. This may mean that certain materials end up carrying part of the loads intended to be sustained by another element, and that load distribution affects the wall performance in ways the designers may not have expected. Where are the materials of low vapour permeance located? What happens to the air leaking in and out (even effective air barrier systems leak)? How can the wall dry considering the properties of the wall layers? If drying is minimal, extra measures should be taken to ensure minimal wetting. Where are the materials with low air permeance? What if rainwater leaks into the wall? How can it get out again? IRC has investigated the drying of walls. The research indicated a greater risk of premature deterioration of moisture-sensitive elements due to frequent rainwater leakage into a stud cavity when the wall assembly included materials of low air and vapour permeance on the exterior and when the stud cavity was maintained slightly above freezing for long periods (which can be due to the climate or the presence of insulation on the exterior). This demonstrates the importance of integrating design for HAM with other considerations, be it rain penetration, smoke and fire control, or seismic requirements.
4. Integrate the challenges of buildability and construction into the design. What will be the weather conditions during construction? What should be done to ensure the walls are dry when they are closed in? Have innovative approaches been selected that the construction trades are not familiar with? Should a mock-up assembly be built on site for demonstration? What elements will need more quality control, and what tools will we use for this purpose?

Points to Remember

Modern construction techniques have made the management of moisture in wall assemblies more complex. The purpose of this paper is to minimize condensation in wall assemblies by employing heat, air and moisture control strategies. In addition, the design of wall assemblies must also address other crucial building science requirements such as rain penetration, fire resistance and the resistance of seismic and high-wind loads.

Airtightness, vapour permeance of building materials and thermal gradients are inter related factors that designers must consider equally to develop a wall assembly that does not accumulate much condensate and can dissipate it quickly – a forgiving wall. Wall elements tend to be labelled by their designated function (e.g., air barrier element, insulation), however their "other" properties can significantly affect the hygrothermal behaviour of the assembly.

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