Keeping walls dry

by Dale Kerr, B.Eng

Abstract

Water is the most significant factor in the deterioration of buildings. But walls can be designed to stay dry, or at least to limit wetting through the “4-D” strategies of *D*eflection, *D*rainage, *D*rying and *D*urability to such an extent that deterioration does not become an issue.

This article examines the many considerations that must go into the design of walls that “stay dry,” starting with the results of several CMHC studies that looked at the most common causes of building problems. The sources of moisture that can cause wetting of walls, including interior, exterior and construction moisture, are examined and methods of controlling each source are discussed. This article gives special emphasis to the penetration of rain, as rain is the leading cause of water problems in walls. Several design approaches are discussed for keeping walls dry, including drained cavity walls, simple rainscreen walls and pressure-equalized rainscreen walls.

Lastly, environmental data are presented that can be used to determine the severity of the environmental conditions to which the wall will be exposed; such data can be of use in determining what moisture control strategy should be employed.

Objectives

After reading this article, you should:

1. Understand the importance of details that are buildable, durable and easily maintained and the importance of communication during construction, and know several ways to improve both.
2. Understand the three sources of moisture in walls and the strategies that can be employed to limit them.
3. Understand the forces that push rain into buildings and the major ways building design influences rain penetration.
4. Understand the importance of designing buildings for the environmental conditions to which they will be exposed and know how to determine the severity of that environment.

Introduction

The cost of construction defects in highrise residential buildings has escalated significantly over the past several years; this is particularly evident in British Columbia. There have been several studies commissioned by CMHC over the past decade to examine the most common causes of building failures, including: *Construction Problems in Multi-family Residential Buildings*, (Drysdale Report);[1] *Wall Moisture Problems in Alberta Dwellings* (Alberta Study);[2] *Survey of Building Envelope Failures in the Coastal Climate of British Columbia* (B. C. Survey)[3] and *2001 Building Failure Study*.[4]

Even though each study looked at residential construction in different parts of Canada and both low-rise and high-rise residential construction were examined, the reports have all come to similar conclusions: Water is the most significant factor in the premature deterioration of buildings. Not only can water damage materials directly, for example, causing corrosion of metal or the chemical breakdown of organic materials like wood or drywall, it can also reduce the effectiveness of materials (like insulation) and it is the major factor in the growth of mold.

The reports identified contributing factors to moisture problems in buildings as:

· Lack of sufficient detail in the drawings,

· Lack of inspection during construction, and

· Lack of understanding of building science principles.

The reports also identified some specific aspects of construction that are more prone to moisture problems, including:

· Windows, doors and skylights (including their installation),

· Saddle flashings (where a saddle is defined as the transition of small horizontal surfaces, such as the top of a balcony guard rail or parapet wall, with a vertical surface, such as a wall),

· The perimeter of decks, balconies and walkways, and

· Precast concrete walls.

Table 1 is a more detailed summary of the problem areas identified in the *B.C. Survey*. Similar results were found in the *Alberta Survey* with problems in which windows and

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[1] Drysdale Engineering and Associates Limited. *"Construction Problems in Multi-family Residential Buildings"*. Canada Mortgage and Housing Corporation, 1991.

[2] Building Envelope Engineering Inc. "*Wall Moisture Problems in Alberta Dwellings".* Canada Mortgage and Housing Corporation, 1999.

[3] Morrison Hershfield Limited. *"Survey of Building Envelope Failures in the Coastal Climate of British Columbia".* Canada Mortgage and Housing Corporation, 1996.

[4] R. J. Burnside & Associates Limited. "*2001 Building Failure Study".* Canada Mortgage and Housing Corporation, unpublished.

penetrations accounted for a high percentage of the problem areas. The *B.C. Survey* found that 90 per cent of the problems investigated were related to interface details between wall components or at penetrations; only 10 per cent of problems were directly related to the basic wall assembly. All cladding types experienced performance problems, although the number of problems reported on stucco walls was substantially more than on other walls, and the cost of repairing damage to stucco walls is significantly higher on average. Again, the Alberta study had similar results. In general, buildings with simple details or those that contained fewer of the details associated with problems (such as exterior walkways or saddle connections) performed better.

In this paper, the recommendations of the CMHC studies will be examined. As well, the building science principles behind several moisture-control strategies will be examined.

The *Drysdale Report* determined that most problems could be traced to a lack of sufficient detail in the drawings and specifications, and more specifically to poor detailing. He went further in his report, suggesting that better drawings should help minimize the incidence of construction defects. The drawings and specifications are key communication tools, so they must be readable and understandable. The following are some recommendations made in the CMHC reports to help improve the quality of the drawings and specifications and to generally improve the lines of communication on the job site.

· It is essential to provide complete details for those components of the building envelope that most often fail, such as window, door and skylight installation, saddles (wall penetrations), intersections of decks and balconies with walls, perimeters of decks, etc. (see Table 1).

· The architect must continually seek feedback from the contractor to understand which details tend to be problematic. The contractor must also take some responsibility in ensuring this information is promptly relayed to the architect.

· Key details should be provided in a larger scale—a minimum of 1:5, but preferably 1:2. The larger scale will help ensure that there are no misunderstandings in reading the detail. The use of three-dimensional (possibly cut-away) details for key details is also recommended. Both these recommendations are made to improve clarity in the requirements.

· Drawings must be practical and reflect buildable details. For example, it is quite easy to draw a line that represents a membrane, indicating that the membrane should be used to air seal a window to the wall. However, in real life, membranes only bend easily in two directions, not three, so it may be difficult or impossible for the actual material to do what is shown by the two-dimensional line on the drawing. Consider the example in Figure 1. The design intends that the peel-and-stick air barrier membrane that is sealed to the block backup be sealed to the window frame. These membranes are sticky on only one side. However, this fact seemed to be forgotten when the line was drawn.

Problem description	# of problems	% of total
Windows		
No sealants at frame/cladding joint	10	5.2%
No sealants at corner mitre joints	12	6.2%
Poor flashing at head or sill	16	8.3%
Poor building paper installation	7	3.6%
Subtotal—windows	45	23.3%
Deck/Walkway/Balcony		
Poor Deck/Walkway/Balcony Waterproofing: Field	16	8.3%
Poor Deck/Walkway/Balcony Waterproofing: Junction with walls	17	8.8%
Subtotal Deck/Walkway/Balcony	33	17.1%
Horizontal Surface Flashings		
Poor Guardrail Saddle Joints	22	11.4%
Poor Guardrail Cap Flashings	13	6.7%
Poor Parapet Cap Flashings	8	4.1%
Subtotal Horizontal Surface Flashings	43	22.3%
Other		
Poor Base/Transition/Control Joint Flashings	15	7.8%
Poor Roof/Wall Joint Flashings	3	1.6%
Poor Eavestroughs/Downspouts	5	2.6%
Poor Concrete Slab/Wall Joints	5	2.6%
Poor Dryer Vents: Lint Plugged, Leaking in Wall	8	4.1%
Poor Vents: No Sealing or Flashing at Hood	8	4.1%
Poor Other Details	12	6.2%
Material/Installation Defects: Cladding, Weather Barrier, Sheathing	16	8.3%
Subtotal Other	72	37.3%
TOTALS	193	100.0%

Table 1— Problems Identified in the Survey of Building Envelope Failures in the Coastal Climate of British Columbia

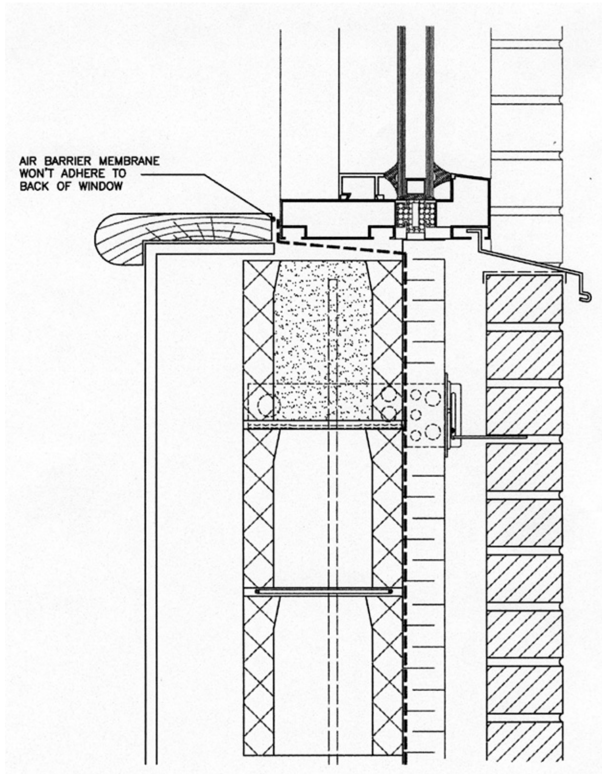

Figure 1—Example of an impossible-to-build detail.

· Designers should develop a bank of proven details that can be used on subsequent projects; however, that said, a one-size-fits-all approach should be avoided. Each detail in the bank must be reviewed and adapted as needed to ensure it is appropriate for each job and for the particular part of the building where it is to be used.

· It is not always sufficient to reference CSA or other standards on the drawings or in the specifications. Few contractors will be completely familiar with such standards and even fewer (if any) of the workers on site will have ever looked at a standard. So, to ensure that the work is completed in the expected manner, the pertinent issues with respect to the execution of the work, especially those related to details that most often fail, must be specifically stated in the documents. For materials, however, if compliance with a standard can be easily verified, reference to a standard is acceptable. For example, the specifications may state that a sealant to be used must comply with CAN/CGSB 19.24-M90, "Multi-component, Chemical-Curing Sealing Compound." This can be easily verified on site, as the sealant should state its compliance on its packaging.
However, it would not be appropriate to state in the drawings that the spacing of masonry ties must conform to CSA Standard A370, "Connectors for Masonry." As another example, it would not be sufficient to state that window installation must be in accordance with CSA A440.4, "Window and Door Installation." That standard provides several different methods for air-sealing the window to the wall-air barrier system. The contractor could essentially install the window in the manner of his choosing if the installation method is not specified more thoroughly in the construction documents.

· Acceptable and non-acceptable product equivalents should be identified Contractors often deal with a preferred material supplier and may be able to get volume discounts using their preferred supplier. However, the architect should maintain responsibility for material selection. If alternative products or suppliers are acceptable, the bid documents

should specify this to allow the contractor to prepare his best bid.
But more importantly, unacceptable materials must be noted, particularly if there are special circumstances on the particular project that make a normally fine alternative unacceptable. Listing unacceptable alternatives ensures that the contractor's bid is not passed on products that cannot be used.

· The construction documents should provide an indication of the water penetration strategy being employed (see further in this document for a discussion of alternative water penetration strategies). For example, if the intent was to create a face-sealed building for control of rain penetration, the contractor must understand this, so the appropriate level of care is taken to ensure all exterior seals are complete. The maintenance requirements must also be spelled out for the owner–occupant. Similarly, if the interior drywall is to be the air barrier (for control of interior moisture), the contractor must know this to ensure that extraneous holes in the drywall (such as an electrician or plumber might make) are to be avoided or sealed.

· Once the project is tendered and the actual materials and components to be used are established, shop drawings or working drawings must be developed from the generic drawings used for tendering. Again, the use of working drawings will help avoid any confusion during construction.

· The construction of details, whether shown on the drawings or not, is also a significant contributor to the poor performance of the as-constructed details. This fact indicates that better communication during construction is needed. The use of mock-ups is recommended to communicate the design intent of details likely to be problematic, particularly as they relate to sealing of air barriers at connections, and joints of different materials, such as the window-to-wall interface. The construction of the mock-up offers the opportunity to identify potential construction problems or material incompatibility problems before construction is well underway. It also provides a training opportunity for the on-site personnel. Lastly, the mock-up provides a benchmark for comparing actual construction to expected results.

The above recommendations should help in all aspects of construction, not just preventing moisture penetration. To understand how to keep walls dry, an understanding of how walls get wet is first needed.

Moisture penetration of wall assemblies

There are three things required to move water through an assembly:

1. A source of water,
2. An opening for the water to enter the assembly, and
3. A force to drive the water through the opening.

Moisture sources

Water in a wall can come from three sources: construction moisture, interior moisture due to occupant use, or exterior moisture.

Construction moisture

Construction moisture is moisture that is given off by new construction materials. While wood is supposed to have a moisture content no greater than 19 per cent when installed, this is often not the case. After construction, this excess moisture leaves the wood and becomes available for absorption-deterioration of other wall materials. Initial evaporation of excess water in concrete is also a great source of moisture during the building's first years. The efflorescence that often occurs on the surface of a new masonry building is visible evidence of evaporating construction moisture.

Little can be done to totally eliminate construction moisture. However, consideration should be given to providing some time for construction materials to dry before being closed in by wall, ceiling or floor finishes. Consideration should also be given in the design to allowing the construction moisture to escape from the wall to the exterior. For example, wood studs should not be enclosed in a double vapour barrier, such as polyethylene film on one side and EPS insulation on the other. The polyethylene and EPS would limit the opportunity for the wood to dry, and if it can't dry, deterioration will occur.

Interior moisture

Interior moisture comes from the people living in the building from perspiration, respiration and activities, such as bathing, clothes washing, or cooking. Health Canada recommends an interior relative humidity between 30 per cent and 50 per cent to prevent occupant discomfort and drying of mucous membranes; however, at the higher end of that range, condensation will occur on exterior walls and windows in winter. As a rule, interior moisture, measured as relative humidity, should not exceed 25 per cent to 35 per cent during the heating season to prevent condensation on windows. CSA Standard A440.1-00, "User Selection Guide to CSA Standard A440-00, Windows" recommends the humidity levels shown in Table 2 to minimize condensation on windows.

Where possible, interior moisture should be handled at the source using ventilation fans, such as kitchen and bathroom fans. In fact, there are provisions in the 1995 National Building Code of Canada (NBC) for exhaust appliances that must serve kitchen and bathroom areas.

The control of interior moisture that cannot be removed at the source requires an effective air barrier and an effective vapour retarder. The function of the air barrier and the vapour retarder are sometimes confused, especially as a single material is often used for both functions.

Outside air temperature	Inside relative humidity
-29°C or below (-20°F or below)	Not over 15%
-29°C to -23°C (-20°F to -10°F)	Not over 20%
-23°C to -18°C (-10°F to -0°F)	Not over 25%

-18°C to -12°C (-0°F to 10°F)	Not over 30%
-12°C to -7°C (10°F to 20°F)	Not over 35%
-7°C to 4°C (20°F to 40°F)	Not over 40%

Table 2—Recommended interior relative humidity levels to avoid condensation on windows (from *User Selection Guide to CSA Standard A440-00, Windows*).

Water vapour pressure

To understand the concept of water vapour pressure, think about an air molecule rapidly moving around inside a box. Every now and again, that air molecule will hit the side of the box, applying a pressure to the box. Now think of a huge number of air molecules doing the same thing. It is the molecules hitting the side of the box that creates the air pressure. Now add to that air some water molecules. Keep in mind that the molecules are very, very small compared to the size of the box and are very spread out within the box, so the air and water molecules act somewhat independently. The water molecules will hit the side of the box, just like the air molecules, and will create a pressure on the box, adding to the pressure created by the air molecules. The pressure created by just the water molecules is known as the partial pressure of the water vapour or just vapour pressure.

The function of the vapour retarder is to resist the flow of vapour caused by a vapour pressure differential. A vapour pressure differential exists if the air on one side of the building envelope contains more moisture than the air on the other side. Nature likes a balance, so the moisture tries to move across the materials in the building envelope to create this balance, until the air on both sides have an equal amount of moisture. Of course, the exterior environmental conditions differ from the controlled interior environmental conditions so such a balance is never effectively achieved and there is always an imbalance or vapour pressure difference that attempts to drive moisture through the building envelope.

The rate of this moisture movement can be slowed by installing materials within the wall assembly that resist the flow of vapour. Materials installed at the side having the greater vapour pressure (usually the inside in a cold climate), such as polyethylene, foil-backed gypsum board and even certain paints, are effective at slowing the movement of vapour. If the vapour retarder is installed at a location in the wall assembly that will be at a temperature lower than the dew point temperature of the air, condensation will occur on the vapour retarder. To prevent this, the vapour retarder must be installed on the warm side of the insulation. In a cold climate, this will be on the interior of the insulation. Caution must also be taken to avoid the *double vapour barrier*, whereby there is another material, also impermeable to water vapour, further to the exterior than the vapour retarder. An example of a common detail where such a situation exists is in a typical window–wall system (see Figure 2), with exterior metal panels that are very good at resisting the flow of vapour.

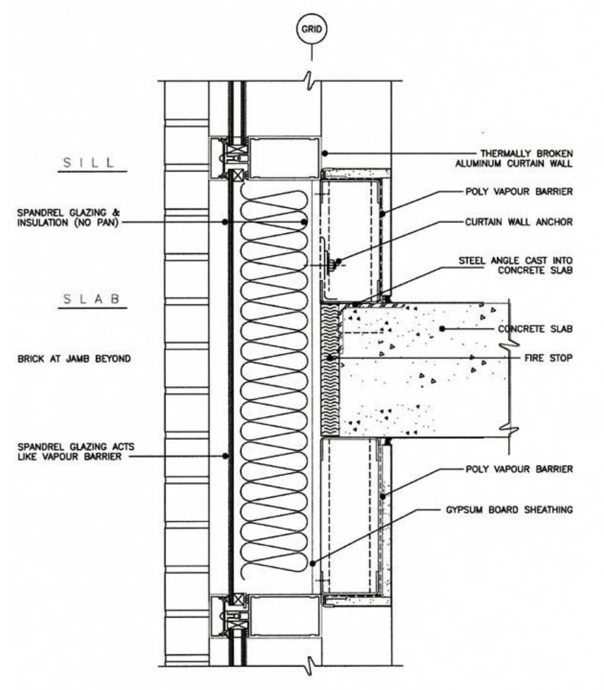

Figure 2—Example of a common detail resulting in a double vapour barrier.

Moisture migration via vapour diffusion is much less significant than that via air movement. Preventing airflow into or across the building envelope is crucial in controlling interior moisture because of the moisture that is carried within the air.

The function of the air barrier is to resist the flow of air across the building envelope, whether that flow is driven by wind, stack effect or fan pressurization. Air barriers must be designed to be airtight, continuous, structural (to resist wind loads) and durable, particularly if they are located within the wall assembly where they are not readily repairable. For further information on the subject of air barriers see *Guidelines for Delivering Effective Air Barrier Systems*,[5] *Design Considerations for an Air Barrier*[6] and *Air Pressure and the Building Envelope*.[7]

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[5] Knight, Kevin D. and Boyle, Bryan J. *"Guidelines for Delivering Effective Air Barrier Systems"*. Canada Mortgage and Housing Corporation, date unknown.

[6] Quirouette, Rick, Marshall, Sandra and Rousseau, Jacques. *"Design Considerations for an Air Barrier System"*. Canada Mortgage and Housing Corporation, 2000.

[7] Quirouette, Rick. *"Air Pressure and the Building Envelope"*. Canada Mortgage and Housing Corporation, to be published 2004.

Plumbing leaks are another source of interior moisture and the second most common source of water problems in buildings. Suggestions to avoid plumbing leaks in the building envelope include:

· Keep pipes out of exterior walls where they may be subject to freezing,

· Design to facilitate access for servicing, so leaks can be more readily discovered and more readily repaired, and

· Make use of watertight pans and drains (with adequately sized drainage holes) to control water leakage from equipment such as evaporation pans, washing machines or hot water tanks.

Exterior moisture

The control of exterior moisture requires an effective water-shedding surface and an effective moisture barrier. The term *water shedding surface* refers to the surface of assemblies, interfaces and details that deflect and/or shed most of the rain and water flow impacting on the wall. The moisture barrier (or water-resistive barrier) is the surface furthest into the wall from the exterior that can accommodate some exterior water without causing damage to interior finishes or materials within the assemblies.

Walls at- or below-grade

Exterior moisture is predominantly rain. However, other sources of exterior moisture include groundwater, surface runoff and melting snow. Most often, these sources affect walls at- or below- grade. These other sources can be minimized by:

· Keeping the basement above the water table,

· Ensuring the grade around the perimeter of the building slopes away (a five per cent or greater slope is recommended),

· Capping the backfill adjacent to the building with a low-permeability (high-clay content) soil extending 1.5 to 2.0 m (5 to 6.5 ft.) from the foundation to reduce water infiltration adjacent to the foundation,

· Ensuring there is adequate foundation drainage, including a drainage layer or drainage fabric adjacent to the foundation wall tied to a properly designed weeping tile and sump or storm system,

· Using the ability of the soil to absorb water and thus keep the water away from the wall, by minimizing paved areas, which do not absorb water,

· Directing runoff from eavestroughs and downspouts away from the building,

· Keeping wood and other sensitive materials at least 150 mm (6 in.) above-grade, and

· Placing a moisture barrier (asphalt coating, asphalt-impregnated building paper or closed-cell gasket) between wood framing and concrete or masonry and/or ensuring all wood in contact with concrete is pressure-treated.

Where hydrostatic pressure may develop in the soil (i.e., the groundwater table is above the level of the footings), it will be necessary to waterproof the foundation wall. Waterproofing is distinct from dampproofing, which only resists the diffusion of water vapour; waterproofing resists the movement of liquid water.

Ice dams

Melting snow does not only affect walls at- or below-grade. Sometimes melting snow on the roof can affect walls. This most often happens when ice dams form.

Ice dams are formed when heat from inside the building (and to a lesser extent heat from solar radiation) causes snow on the roof to melt. The melted snow runs down the roof to the cold edge, where it freezes again. As the process continues, layers of ice are built up, forming an ice dam. It is called an ice dam because the ice blocks further melt water from reaching the eavestrough. As a result, a pool of water can build up behind the ice, eventually backing up under the shingles, causing water damage to the roof and possibly to the interior walls (see Figure 3). Ice dams can be prevented by keeping the space below the roof as cool as possible, by adding insulation and especially by preventing warm air from leaking into the attic space.

The damage caused by ice dams can be minimized by installing an ice and water shield around the perimeter of the roof. In fact, the National Building Code requires eave protection to extend a minimum of 900 mm (3 ft.) up the roof slope from the roof edge for any roof constructed with shingles, shakes or tiles. Further, the extent of the eave protection must be at least 300 mm (12 in.) inside the inner face of the exterior wall.

There are exceptions where eave protection is not required, including over unheated spaces, where the roof overhang to the inner face of the exterior wall exceeds 900 mm, on roofs with a slope of 1:1.5 or greater and in regions with 3,500 or fewer degree-days. Heating cables can also be used to help melt the ice and create a clear drainage path to the eavestrough. However, this approach is only recommended as a remedial measure. The removal of ice once it has formed is not an easy task.[8]. It is far better to prevent the build-up of ice on the roof in the first place.

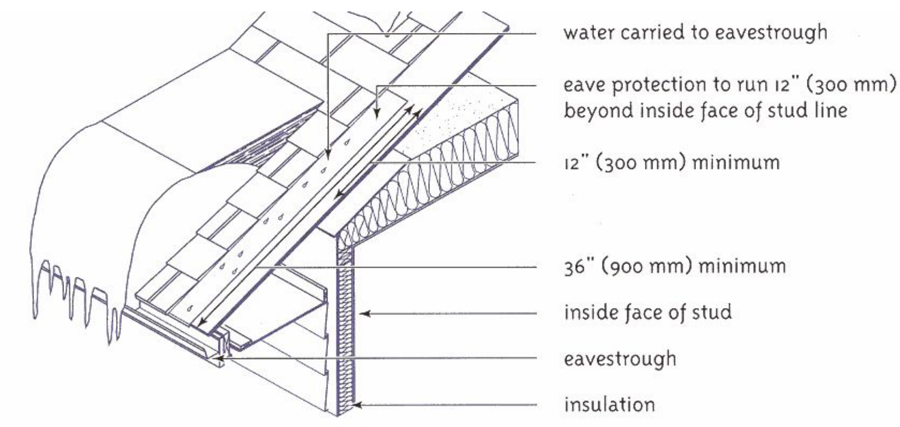

Figure 3 Formation of an ice dam (from *Air Quality in Interior Environments*[9])

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[8] "Removing Ice on Roofs". *About Your House*. Canada Mortgage and Housing Corporation, 1999.

Rain

All the *CMHC Reports* mentioned earlier identified rain as the major source of moisture problems in buildings, particularly within the first few years of occupancy. Before different rain-penetration control strategies can be developed, it is necessary to understand some of the physics behind rainfall, particularly since the amount of rain that actually hits a building varies over its surface.

The wind-flow pattern around a building affects how much rain is deposited at any location on the building. Wind direction is a factor, as windward-facing walls will be subject to more driving rain, while leeward walls will be protected.

Wind will typically blow most often from the same direction. Often, the most common direction of strong winds accompanying rain is significantly different than the general prevailing wind direction. The wind roses in Figure 4 illustrate this phenomenon. The wind rose shows the relative frequency of wind from the cardinal directions. The further the line from the centre of the rose, the more frequent is the wind from that direction. Note the differences between the wind rose for all winds (including wind during rain) and for only the winds accompanying rain. Designers may want to consider the direction of wind, particularly wind during rain, and perhaps adjust their sophisticated designs using strategies more tolerant of wetting on certain building orientations. Unfortunately, wind roses are not routinely published by Environment Canada and are not available for many cities, so such information is not always readily available.

[9] Garden, G. K. "Rain Penetration and Its Control". *Canadian Building Digest* 40. National Research Council Canada, 1963.

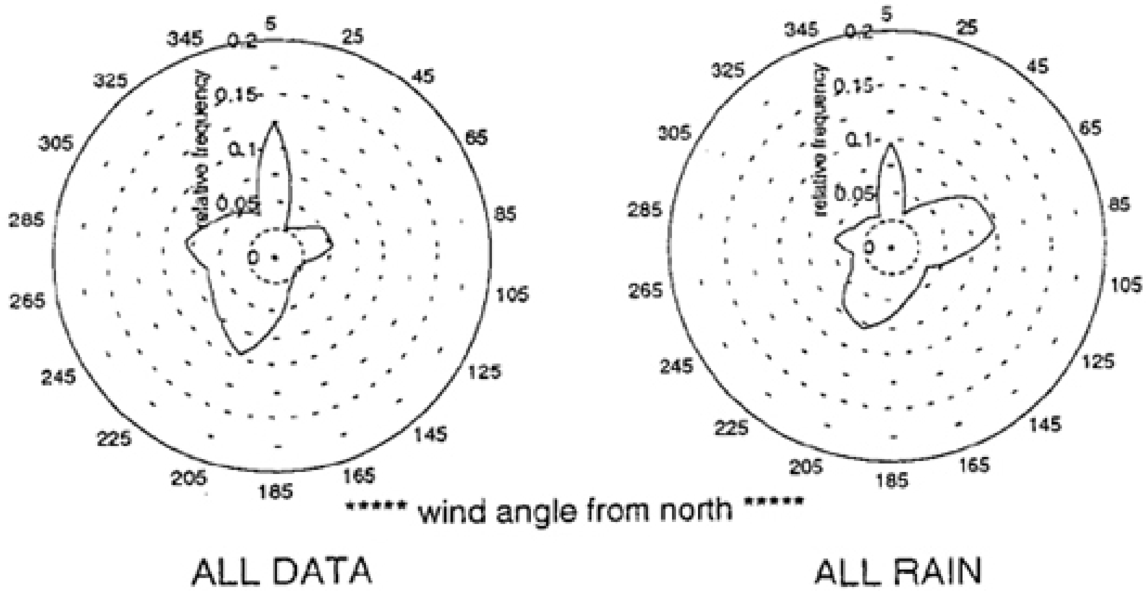

Figure 4—Wind roses for Ottawa, Ont. showing wind direction for all wind data and for wind during rain (from An *Exploratory Study of the Climatic Relationships Between Rain and Wind*[10])

Mean, or average, wind speeds are also consistently greater during rainy hours than during all hours. This indicates that the designer should not base design considerations solely on published mean wind speeds; instead, the designer should consider the mean wind speed during rain. On the other hand, extreme wind speeds are consistently smaller for rainy hours than for all hours. This is likely because there are more hours when it is not raining than when it is raining. An “extreme” is a rare event; therefore an extreme wind speed is statistically more likely to happen when it is not raining. While extreme wind speeds should be considered in structural design, designers should not base decisions about controlling rain penetration on extreme wind speeds.

The aerodynamics of wind flow around buildings also cause different areas of a single wall to be subject to different wind forces, especially in larger buildings. As wind parts to flow around and over a building, a cushion of high-pressure, but relatively still, air is created at the centre of the wall. This “dead spot” protects this area of the wall from driving rain. Wind accelerates around the side and top edges of the building, driving rain more forcefully against these parts of the wall, even driving rain upwards at the parapet. Figure 5 shows a typical wetting pattern for a multi-storey building. Studies have shown that these edges can receive more than 20 times and as much as 50 times more rain

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[10] Surry, D., Skerlj, P. F., and Mikitiuk, M. J. *An Exploratory Study of the Climatic Relationships Between Rain and Wind,* Canada Mortgage and Housing Corporation, 199

than the centre of the wall. This discrepancy in wetting intensity is greater for taller and narrower buildings.

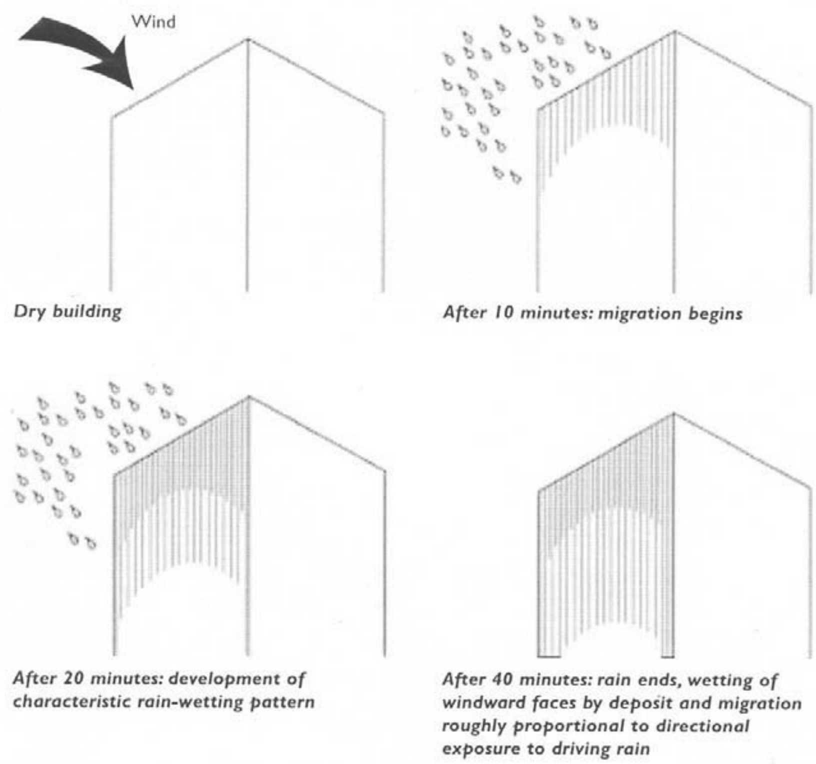

Figure 5—Typical rain wetting pattern on a multi-storey building (from *Rain Penetration Control: Applying Current Knowledge*[11])

Rain-wetting patterns on a building face also depend on the finishes used. Porous surfaces, such as masonry, absorb much of the water that strikes them and they release this water more slowly, through diffusion. Impervious claddings, such as metal and glass curtain walls, readily become covered with a film of water that flows down the wall surface. The accumulated flow can be significant by the time it reaches the bottom of a tall building. The downward flow is concentrated at vertical irregularities. Experiments have shown that the flow in narrow vertical depressions (i.e., joints) in a wall face can be many times greater than the average over the wall. Wind flow around corners and parapets can also draw water laterally and even upwards. This lateral flow can bring water to vertical joints, which are often quite vulnerable to leakage.

Understanding wetting and wind patterns, therefore, suggests some design solutions and precautions regarding rain penetration. Particular care should be paid to providing

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[11] Straube, John. *Rain Penetration Control: Applying Current Knowledge,* Canada Mortgage and Housing Corporation, 1999.

rain-resistant assemblies at the upper edge and corners of multi-storey buildings, and employing features such as cornices to direct rain off the building face. The design and construction of joints is critical in preventing rain penetration. Roof overhangs have long been effective in reducing rain exposure of low buildings, as shown by the *B. C. Survey*, which found a strong relationship between the width of eave overhangs and decreased frequency of rain penetration. Sloped roofs also ease windward wall wetting by reducing lateral wind, and hence water movement, at the wall–roof intersection.

Openings

Openings that permit the passage of water exist throughout the face of the building envelope—material pores, cracks, joints between materials or elements, etc. One approach to management of rain penetration is to locate both the water-shedding surface and the moisture barrier at the exterior of the wall. This approach, the *face-seal approach*, attempts to eliminate all openings at the exterior surface of the wall. The word attempt is used because it is impossible to completely eliminate all openings, especially over the long term. For all openings to be eliminated, the workmanship must be perfect, which is difficult to achieve given fabrication or job site inaccuracies and environmental conditions during construction. Further, even a perfectly constructed joint will suffer degradation over time due to thermal stresses, ultraviolet radiation, acid rain, etc.

Instead, better approaches to the design of the building envelope look to control the forces causing rain penetration.

Forces causing rain penetration

The forces that can move rainwater on the surface of a wall through openings are:

· Kinetic energy

· Capillarity and surface tension

· Gravity

· Pressure differences

Kinetic energy

Kinetic energy refers to the momentum of wind-driven raindrops. This force will carry raindrops directly through openings of sufficient size (see Figure 6). The raindrops can even be carried upwards. However, if there is no through path, rain cannot penetrate deeply into the wall by this mechanism alone. Thus, the use of cover battens, splines or internal baffles can protect intentional openings, such as drains and vents, from rain penetration by kinetic energy of the raindrops.

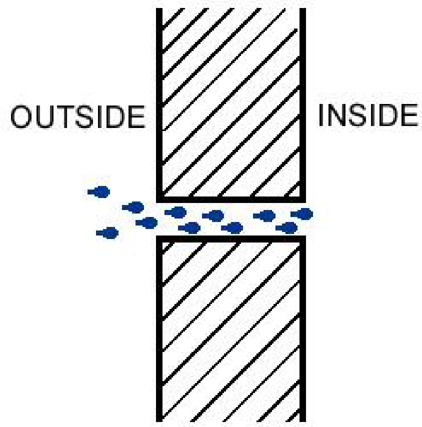

Figure 6—Rain penetration due to the kinetic energy of the raindrops.

Surface tension and capillarity

Water molecules are attracted to each other and to the surfaces near them. Cohesion refers to the molecular forces within the water and adhesion refers to the attraction of the water to adjacent materials (which varies with different materials). When water is dropped onto a surface, cohesion, adhesion, air pressure and gravity combine to determine the shape of water droplets or the thickness of the water film.

The forces of cohesion and adhesion also cause water to be drawn into a tube, crack or capillary, such as is found in porous materials like masonry. These forces can even draw water in an upward direction against the force of gravity. This phenomenon is referred to as capillary suction, capillary action or just "capillarity." The height to which the water will rise depends on the diameter of the capillary (the smaller the diameter, the greater the rise) and the material of which it is made (smooth materials, such as glass and aluminum, show the greatest rise).

Water will be drawn into a crack or joint until it reaches the capillary rise height for the given crack width and material (as shown in Figure 7). As long as there is a source of water, water will travel the full length of a horizontal capillary. The capillarity force is broken when the crack meets a much wider transverse space, such as the air space behind the masonry in a veneer wall or a capillary break (see Figure 8). A 10-mm (0.4 in.) gap is sufficient to interrupt capillarity in all common construction materials.[12]

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[12] Patenaude, Armand. *Migration of Water by Capillarity*, Canada Mortgage and Housing Corporation, 1993.

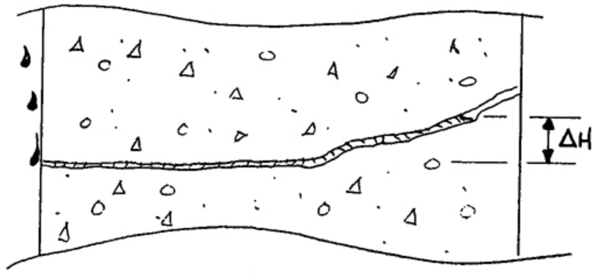

Figure 7—Water will progress within the crack until it reaches the capillary rise height (ΔH) (from Migration *of Water by Capillarity*[13])

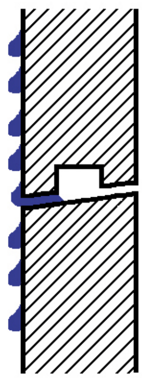

Figure 8—Example of a capillary break in a joint.

The adhesive and cohesive forces even allow water to cling to and flow along the underside of horizontal surfaces, such as soffits. Providing a drip on the underside of projections and overhangs is a common detail to break surface tension and prevent water from collecting or reaching the building face (see Figure 9).

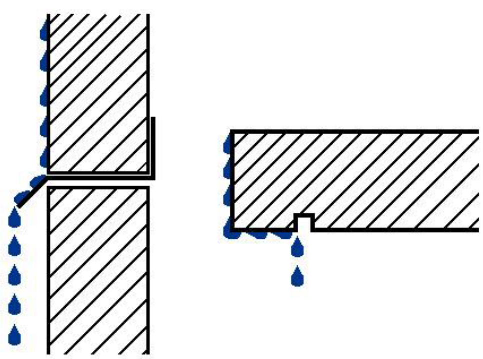

Figure 9—Two examples of drip edges.

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13 *Migration of Water by Capillarity*

Capillarity is usually the dominant force in water penetration of masonry. Capillarity will cause water to be drawn into masonry, even against gravity and an air pressure gradient, until the material is saturated. Other forces, such as wind pressure, gravity or kinetic energy may drive this absorbed water further through the wall. While capillary forces can act all through brick, testing of brick walls shows that most water penetration occurs at mortar joints, primarily through cracks at the mortar–brick interface. The water that has penetrated to the back of the masonry can be projected across the air space due to air pressure differences. Therefore, the air space must be of sufficient width to prevent this problem; however, further research is needed to determine scientifically what the minimum acceptable air space width is to prevent this. Adhesive forces can also cause water that penetrates masonry to flow across brick ties (or mortar droppings) to the inner wythe (possibly the air barrier).

Capillarity is also a factor in the design of windows. Consider this example (see Figure 10). The height of water in its natural state on a piece of pine is 3.4 mm (0.13 in.). The gap between the sash and frame of a pine window, therefore, should be at least 6.7 mm (0.26 in.) to avoid pine/pine adhesion. If the distance is greater than 6.7 mm and the space is filled with water, as soon as the water supply ceases, the water will drain off and it will attain its natural height of 3.4 mm. If the distance is less than 6.7 mm, capillarity forces will retain that water in the space and no drainage will occur; such prolonged wetting will lead to deterioration.

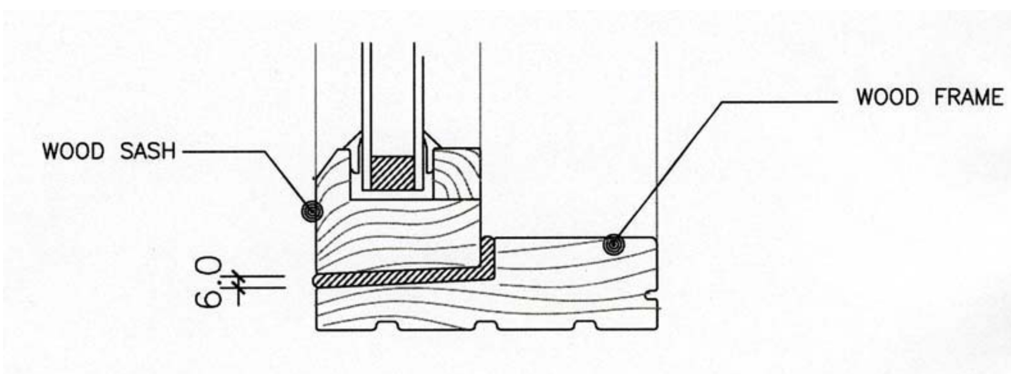

Figure 10—Example of water trapped between the sash and frame of a wood window due to capillarity (from Migration *of Water by Capillarity*[14])

As another example, consider the thickness of shims beneath a sealed glazing unit in a vinyl window (see Figure 11). The maximum vertical distance allowing adhesion between glass and PVC is 6.8 mm. Therefore if the shims are 6.8 mm or thinner, water will not drain out of the glazing cavity and will cause failure of the sealed unit. Note that the typical thickness of shims is ¼ inch, or 6.4 mm. This problem might be avoided by

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[14] *Migration of Water by Capillarity*

specify a thicker shim. A similar phenomenon may occur if the window's weep holes are not large enough. The distance allowing adhesion between two aluminum surfaces (natural finish) is 6.7 mm. If the weep hole is smaller than this, drainage will not occur naturally (i.e., without the application of another force to overcome the capillarity). Again, specifying a minimum size of weep hole may help prevent this problem.

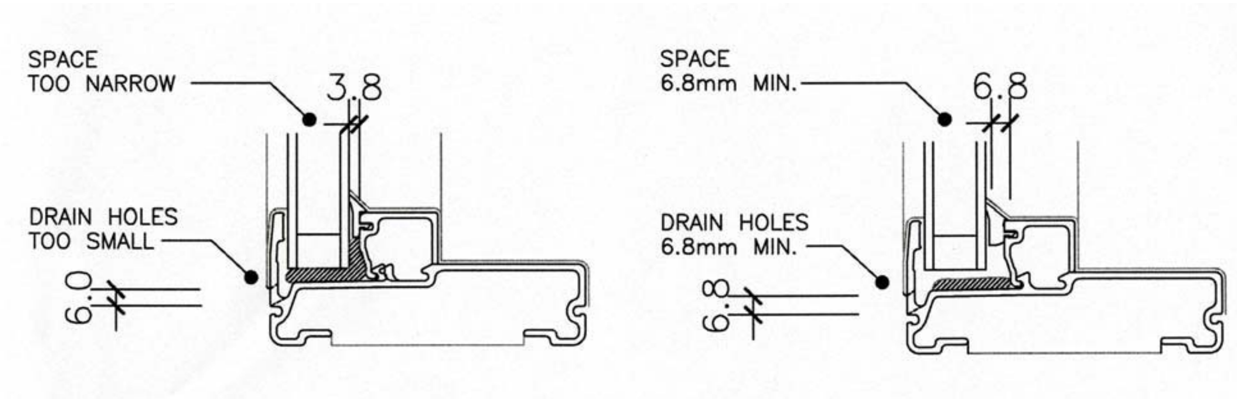

Figure 11—Window shim thickness and size of weephole can affect drainage of glazing cavity (from Migration *of Water by Capillarity*[15])

As windows have been identified as one of the key causes of water penetration of walls, consider one last window example. The bottom rail of a sliding window should be designed to minimize capillarity, as shown in Figure 12. With most current window designs, water infiltration in sliding windows is often generated by capillarity due to inadequate gap dimensions. Review window shop drawings carefully before accepting a manufacturer's product.

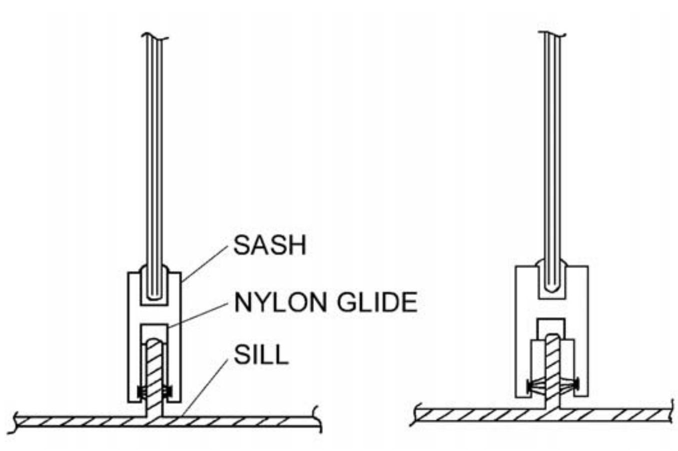

Figure 12—A wider sash track will help reduce capillary rise and water infiltration of sliding windows (from Migration *of Water by Capillarity*[16])

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[15] *Migration of Water by Capillarity*

As another example of the effect of capillarity, consider a finished basement, with a wood-framed wall on the interior of the basement foundation wall. Tests conducted at the Alberta Home Heating Research Facility[17] have shown that leaving a small gap under wood-framed walls reduced the amount of moisture absorbed by the bottom plate and allowed moisture (perhaps due to a crack in the basement wall) to escape from behind the panel more easily.

Gravity

Dealing with water movement due to gravity may seem elementary—simply avoid creating inward-and downward-sloping leakage paths or areas where water can pond or overflow drainage paths (see Figure 13). However, leakage due to gravity action still occurs all too frequently, sometimes due to errors in design or construction and sometimes due to cracks or other openings that develop after construction. However, gravity can be used to advantage in controlling rain penetration of walls. An air space immediately behind the wetted surface prevents water from flowing further inwards. Water reaching this space will cling to the inner face of the outer wythe and will run down the surface. Flashings can then be used to intercept and direct the flow of water to designed drainage paths.

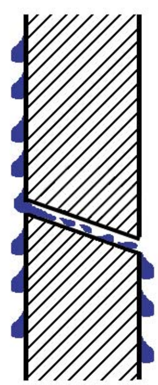

Figure 13—Gravity causing water infiltration.

It is also important to keep the concept of shingling in mind when designing to resist water penetration due to gravity; that is, overlapping construction materials so that the upper layer is overlapped on top of the lower layer. This is the way roof shingles work. One area where the concept of shingling is often forgotten is window installation. Most windows, particularly in Western Canada, now incorporate nailing flanges, rather than brick molds and drip caps. Typically, a wide strip of building paper is installed on the

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[16] *Migration of Water by Capillarity*

[17] Forest, Tom W. and Ackerman, Mark Y. *Basement Walls That Dry*. Canada Mortgage and Housing Corporation, 1999.

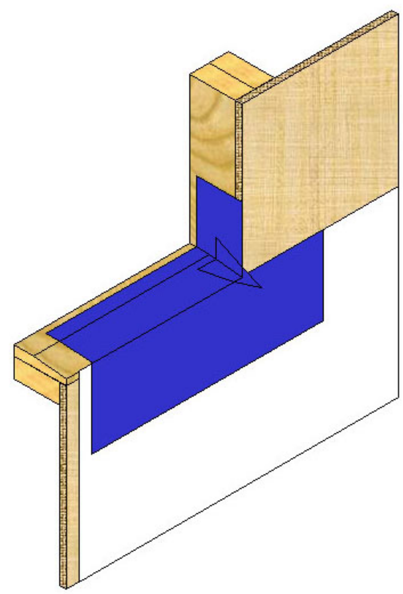
sheathing around the window openings, folded over at corners to speed and simplify installation. The folds create troughs that collect water. After the windows are installed, the building paper is lapped over the flanges and over the paper strip. This is appropriate at head and jambs, but at the sill, the lap leads water behind the building paper and into the wall. In some cases, flanges are taped or caulked to the paper strip with a corner bead along the edge.

The series of illustrations in Figure 14, which follows, shows a better installation approach.

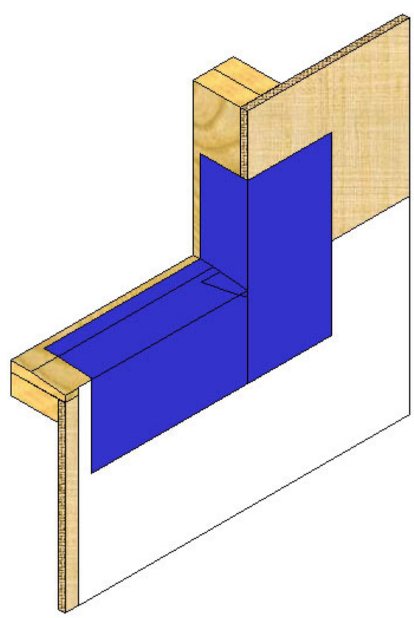
Figure 14a and b— Window installation with nailing flange showing proper overlapping of sheathing paper and flashing (from Water *Penetration Resistance of Windows.*[18]

Sheathing paper is installed under the window opening and then the sill of the window opening is covered with a sill membrane to prevent water that might leak through the window from entering the wall system below. This sub-sill drainage is a key benefit in preventing possible wetting of walls.

A separate *corner membrane* is used to ensure the corner is watertight (a).



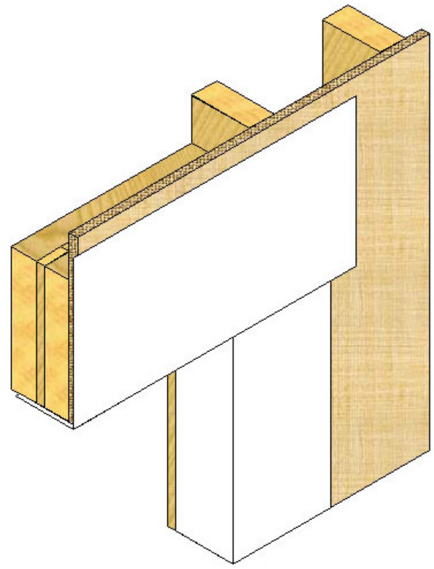
Next, the jamb membrane is added (b) such that it overlaps the sill membrane creating a shedding surface over the sill membrane.



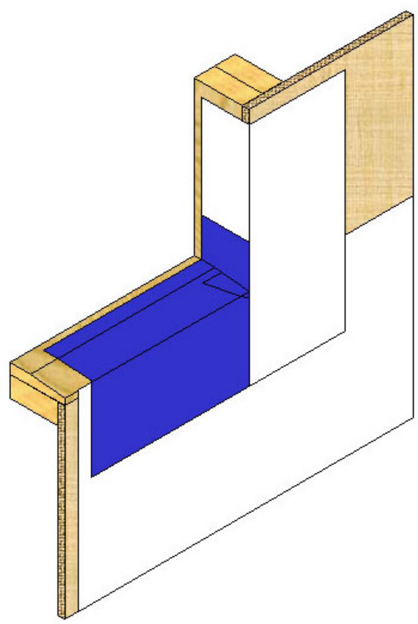
[18] RDH Engineering Limited. *Water Penetration Resistance of Windows—Study of Manufacturing, Building Design, Installation and Maintenance Factors*. Canada Mortgage and Housing Corporation, 2002.

Figure 14c and d— Window installation with nailing flange showing proper overlapping of sheathing paper and flashing (from Water *Penetration Resistance of Windows.*[19]

Sheathing paper that extends to the head of the window is then added over the jamb membrane (c).



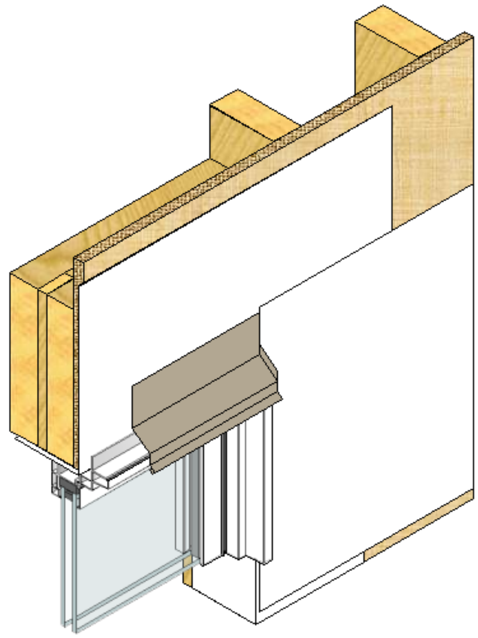
A strip of sheathing is added at the head of the window overlapping the jamb sheathing again to create a shedding surface (d).

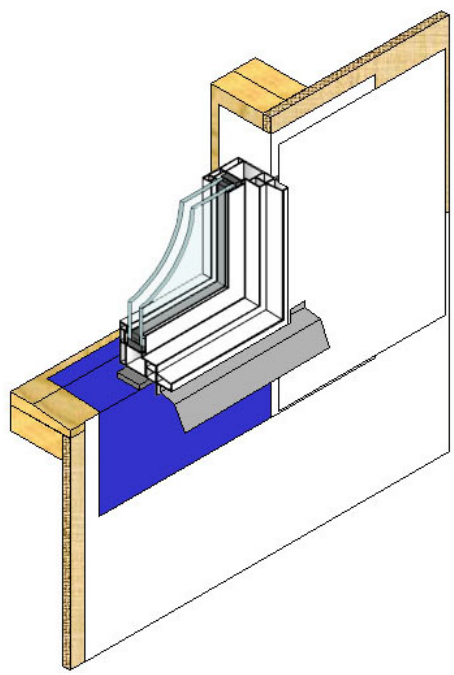


[19] RDH Engineering Limited. *Water Penetration Resistance of Windows—Study of Manufacturing, Building Design, Installation and Maintenance Factors*. Canada Mortgage and Housing Corporation, 2002.

Figure 14e and f— Window installation with nailing flange showing proper overlapping of sheathing paper and flashing (from Water *Penetration Resistance of Windows.*[20]

The window is then set into the opening on shims and secured into the opening by nailing through the nailing flange. Sheathing paper is installed at the jambs, overlapping the nailing flange, extending from the above the window head to below the windowsill. Flashings (or drip edges) are then installed at both the head and sill (e and f).

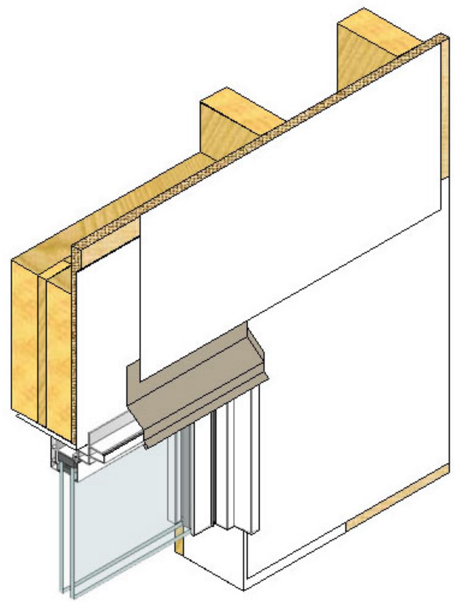




[20] RDH Engineering Limited. *Water Penetration Resistance of Windows—Study of Manufacturing, Building Design, Installation and Maintenance Factors*. Canada Mortgage and Housing Corporation, 2002.

Figure 14g — Window installation with nailing flange showing proper overlapping of sheathing paper and flashing (from Water *Penetration Resistance of Windows.*[21]

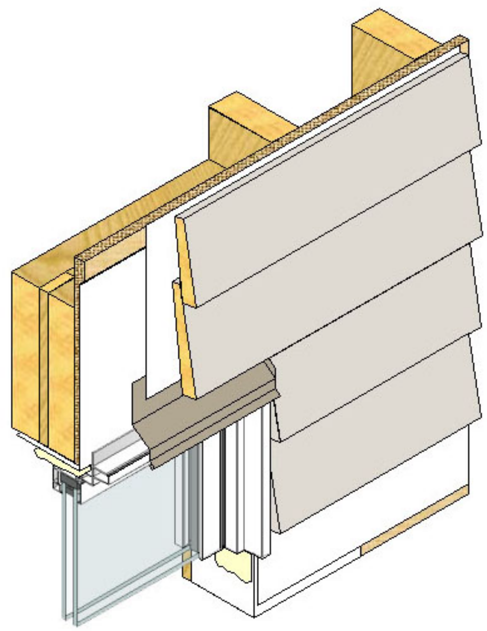
Another strip of sheathing paper is required at the head of the window to ensure water penetrating to the sheathing paper is directed to the front of the drip edge (g).

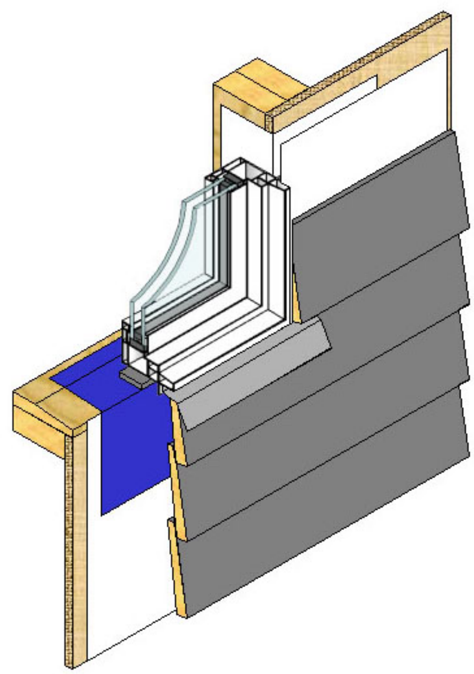


[21] RDH Engineering Limited. *Water Penetration Resistance of Windows—Study of Manufacturing, Building Design, Installation and Maintenance Factors*. Canada Mortgage and Housing Corporation, 2002.

Figure 14h— Window installation with nailing flange showing proper overlapping of sheathing paper and flashing (from Water *Penetration Resistance of Windows.*[22]

Lastly, the siding can be installed (h).





[22] RDH Engineering Limited. *Water Penetration Resistance of Windows—Study of Manufacturing, Building Design, Installation and Maintenance Factors*. Canada Mortgage and Housing Corporation, 2002.

Pressure differences

Pressure differences across the building envelope can be caused by stack effect, mechanical pressurization, barometric, thermal and wind. The net air pressure difference across the wall may be a combination of all these forces and may vary from one location to another. They have a significant impact, causing many of the moisture-related envelope problems.

Stack effect

Stack effect is caused by the difference in air density at different temperatures. In cold winter periods, the air inside a building is warmer (and less dense) than the outside air. There is a tendency for the warmer, lighter inside air to be pushed up and out of buildings, which generally causes an outward or positive pressure at the top of the building and a negative or inward pressure at the base of the building. In summer, the effect is opposite. The pressure caused by stack effect will be felt by the air barrier. Generally, stack effect is the most significant force causing air leakage in buildings because the size and direction of the pressure difference is sustained for months.

For further information on stack and other pressure effects, refer to *Design Considerations for an Air Barrier System*[23] and *Air Pressure and the Building Envelope*.[24]

Mechanical pressurization

Fans provide ventilation air for a building. In a highrise, these fans typically pressurize the corridors and impart a positive pressure to the corridors. Exhaust fans in the suite kitchens and bathrooms exhaust air and impart a negative pressure in these areas. Ventilation fans produce a small but significant air pressure difference across the building envelope and can impact on air leakage and the potential for condensation in the walls. However, mechanical pressurization does not significantly affect the potential for rain penetration, particularly if the building contains an adequate air barrier.

Wind pressure

Wind is of primary concern in controlling water infiltration, as the pressure difference due to wind is generally much higher and more variable.

Even a steady wind does not create uniform pressures across a building, as airflow patterns around building edges create varying wind velocities and forces. Air pressures due to wind will be positive on the windward faces of a building and negative (for example, suction or uplift) on the leeward side and often the roof.

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[23] Quirouette, Rick, Marshall, Sandra and Rousseau, Jacques. *Design Considerations for an Air Barrier System*. Canada Mortgage and Housing Corporation, 2000.

[24] *Air Pressure and the Building Envelope*

Cyclic pressures due to gusting winds can create significant variations over very short time periods. Air barriers that do not have the required structural strength will be damaged by high winds and will then allow uncontrolled air leakage into the wall area. In wall systems with impervious outer cladding, such as curtain walls, pressure differences may be the most significant force driving rain into the building.

Thermal and barometric cycling

The problems of the forces of stack, fan and wind pressure differentials can be accentuated by thermal and barometric cycling. Temperature and barometric cycling are not well understood, but contribute to moisture movement, and problems, in the cavities of building envelopes.

The critical influence of all of these forces is discussed in more detail in another article in this series entitled *Air Pressure and the Building Envelope.*[26] Several strategies to reduce these problems are discussed in the *Air Pressure* article. They include the placement of the air barrier on the in-board side of the insulation, to allow venting of moist air to the outside. In addition to this strategy, light coloured cladding, or the use of more massive cladding materials to increase the heat storage capacity of the wall can be used to reduce the bad effects of thermal cycling. The strategy known as the Dynamic Buffer Zone is also explained.

Approaches to keeping walls dry

The 4-Ds provide a ready reminder of the strategies for keeping walls dry:

Deflection:	using features of the building to limit exposure of the walls to rain, such as overhangs and drips.
Drainage	Using design features that provide a means to direct water that does penetrate the wall back to the outside.
Drying	Using features that facilitate the drying of materials that get wet.
Durability	Using materials that are tolerant of moisture.

Deflection

Deflection is the first moisture control strategy to consider, since it can prevent water from hitting the wall (i.e., the source is controlled). If most of the water is deflected before it has a chance to impact on and/or enter the wall, then the need for the other requirements (drainage and drying) are significantly reduced.

A correlation has been found between rainwater damage to buildings and the size of roof overhangs; dwellings with smaller overhangs exhibit increased moisture damage to walls (see Table 3).

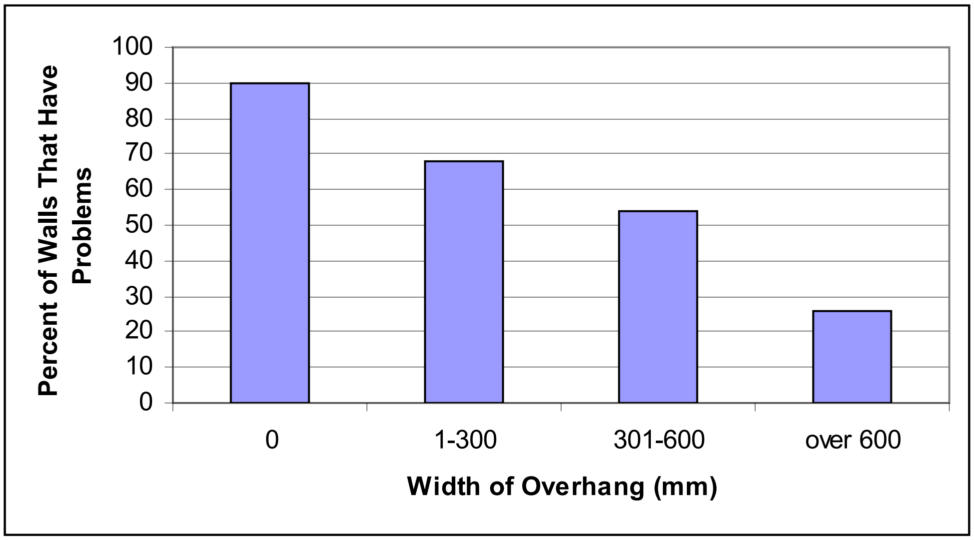

Table 3—Effect of overhangs on wall performance (from Survey *of Building Envelope Failures in the Coastal Climate of British Columbia*[25])

Research conducted in the boundary-layer wind tunnel at the University of Western Ontario also revealed that overhangs can have a significant impact on rain wetting of high-rise buildings. Figure 15 shows the wetting patterns on a model building with and without an overhang. The light coloured strips (yellow) on the models are made of water sensitive paper. When water hits the strip, the colour changes from light to dark (from yellow to red). The model on the left does not have an overhang. The concentration of wetting at the top of the building, and to some extent down the sides, is evident. The model on the right has an overhang. While the overhang has been significantly wetted, the building itself has remained dry, with the exception of the sides near the bottom of the building.

[25] *Survey of Building Envelope Failures in the Coastal Climate of British Columbia*

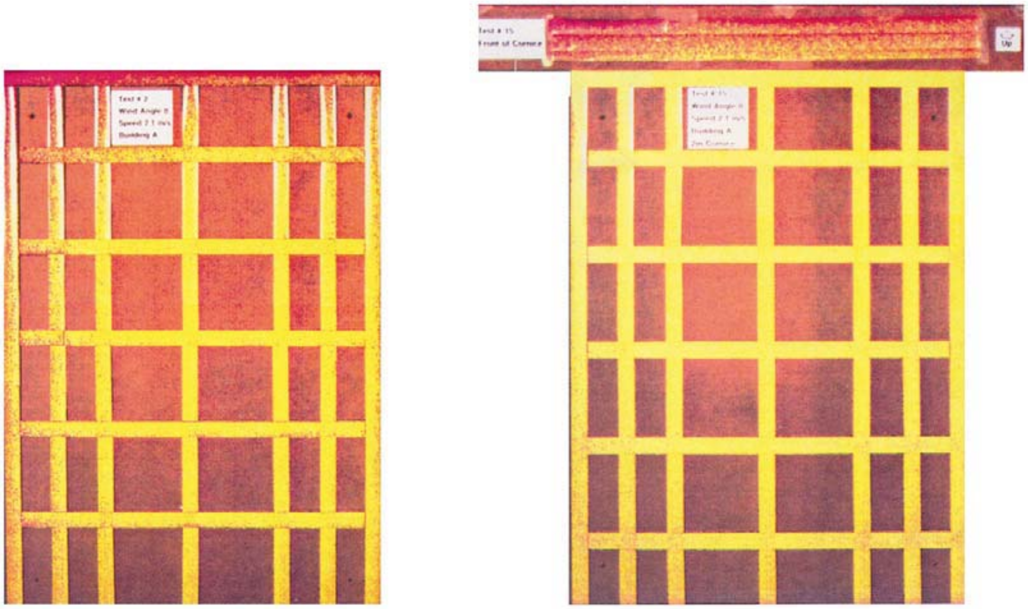

Figure 15—Wetting patterns on a model building with and without an overhang (from Simulation *of Wind-Driven Rain and Wetting Patterns on Buildings*[12]).

But while wide roof overhangs may be a good solution for small wood-frame structures, they are not practical for highrise buildings. However, design features, such as cornices and projections, can be used to help minimize rain wetting of buildings. The effectiveness of cornices has been demonstrated through a research project that explored the ability to predict the rain wetting on a building facade in Dundas, Ont. (see Figure 16).[26]

[26] Hangan, Horia and Surry, David. *Wind-Driven Rain Study for the Governor's Road Project*. Canada Mortgage and Housing Corporation, 1999.

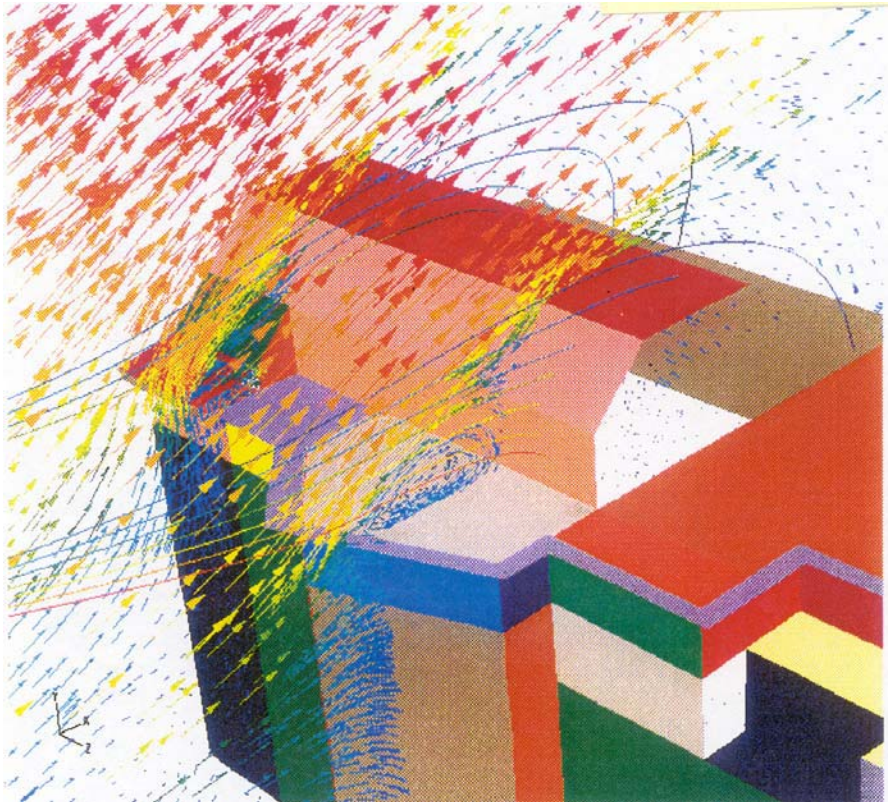

Figure 16—Result of simulation of rain patterns on a building in Dundas, Ont. (from *Wind-Driven Rain Study for the Governor's Road Project*[27])

Flashings with drip edges that direct water away from the face of the building are another form of deflection (see Figure 9). Drips on the underside of projections, such as balconies, also help keep water away from the face of the wall; the drip breaks the surface tension of the water, causing it to drip rather than to continue to run along the underside to the building. Drips should include sharp edges. Lastly, as previously mentioned, cover battens, splines or internal baffles are also useful in deflection.

Drainage

Drainage is the next most important principle. It is next to impossible to totally stop rain from impinging on the wall and to eliminate all openings in the surface, so it is inevitable that some water will enter the wall. Such water must be redirected out of the assembly by internal flashings. An air space in a wall assembly, between the water shedding surface and the moisture barrier, is generally required to provide good drainage. With most construction materials, cavities greater than 10 mm (0.39 in.) will drain freely under gravity; with smaller cavities, capillarity will restrict drainage.

Flashings are generally required:

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[27] *Wind-Driven Rain Study for the Governor's Road Project*

· at the top of exposed walls,

· at roof-wall junctions,

· within walls above doors, windows and other wall penetrations,

· at the foundation level to lead water out of the cavity and at each floor level in a multi-storey building, and

· at locations where water might enter the building through a juncture between two materials.

Most flashing problems occur at the joints and terminations of the flashings. When designing flashings that extend from interior to exterior of a wall system, the best way to ensure water cannot enter the wall at intersections in the flashing is to have a good slope, watertight joints and adequate end dams. End dams are required where there is the possibility of water entering the wall system at the end of the flashing. End dams should be watertight and have a sufficient height to prevent water overflow. When designing end dams, the number of joints that require sealant should be minimized to ensure a longer life. Figure 17 shows one method of making an end dam in a metal flashing without cutting the flashing, thus making the joint permanently watertight.

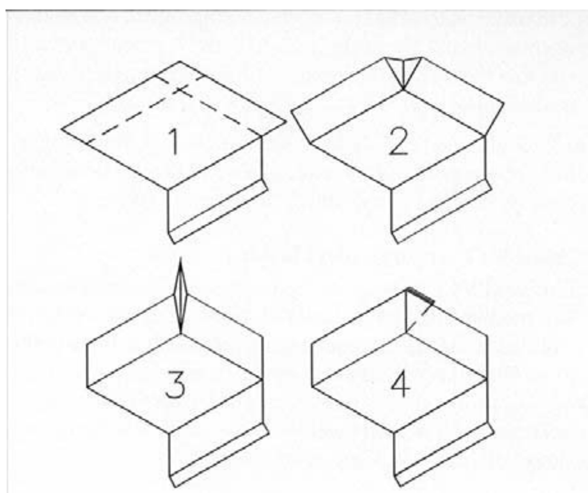

Figure 17—A method of making an end dam in a metal flashing without cutting the flashing (from Best *Practice Guide—Wood Frame Envelopes in the Coastal Climate of British Columbia*[28])

Drying

To prevent damage, any moisture that gets into the wall assembly and cannot drain quickly must be able to dry before it causes deterioration to the wall assembly. Since

[28] Morrison Hershfield Limited and RDH Engineering Limited. *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia"* Canada Mortgage and Housing Corporation, 1998.

moisture removal by drying is much slower than moisture removal by drainage, especially in humid weather, drying should not be relied upon to the same extent as a moisture control strategy.

If deflecting and draining strategies are ineffective, the last approach is drying the wall. The ability of a wall to dry depends on the amount of moisture already in the air and the amount of moisture the air is capable of holding (saturation). Air can only hold a certain amount of moisture at any given temperature. The warmer the air, the more moisture it can hold before it reaches saturation. The moisture content in the air can be expressed as relative humidity, which is the percentage of moisture in the air relative to the amount the air can hold at that temperature at saturation. For example, assuming temperature is constant, air at a relative humidity of 50 per cent is holding one half of the total amount of moisture it could possibly hold at saturation.

Another way to express moisture content is vapour pressure. Vapour pressure is the measure of the partial pressure exerted by water vapour in the total air mix (see sidebar on page __). The partial pressure of water is useful in moisture transport calculations, as the difference in vapour pressure is the force that leads to vapour diffusion—the movement of water vapour from a region of high vapour pressure to a region of lower vapour pressure.

The drying of walls is simply the movement of water molecules from a region of higher vapour pressure to a region of lower vapour pressure (such as evaporation). The greater the difference in vapour pressure between the two regions, the greater the drying potential. Temperature also affects the drying potential, as warmer air has the capability of holding more moisture than colder air. Therefore, the amount of water vapour in the atmosphere varies considerably between winter and summer.

The drying potential of walls also varies across Canada. Not surprisingly, the ability to dry in the coastal regions is low. Drying potential is also low in northern regions due to the colder temperatures. Parts of the Prairies, however, show a high capacity for drying. It is interesting to note that in Vancouver, the months with the greatest rainfall rates are also the coldest. This is a clear indication that drying is likely to be a problem in Vancouver. In such a situation, the design and construction of the wall is more critical than in other areas where drying potential is higher.

But the ability of a wall to dry also depends on the construction of the wall. If the wall is designed with exterior materials that are highly impermeable to vapour (see Table 4), such as vinyl or metal siding, or EIFS using EPS insulation, the wall will not have the ability to readily dry. In such cases, it is especially important to ensure that the design recognizes this and an approach that better facilitates deflection and drainage is employed; in these cases, more attention must be paid to the second line of defence, or the water-shedding surface. While the basic wall assembly does not appear to be a significant source of moisture ingress (the most significant source being joints and interfaces between materials), the basic wall assembly does contribute to moisture problems if it restricts the drying or drainage characteristics of the wall.

Relative drying speed	Common materials
Fastest	Fibreglass sheathing board, wood fibreboard
Relatively fast	Plywood and OSB (wood-based products)
Less fast	Extruded polystyrene
Least fast	Laminated polyisocyanurates

Table 4—Effect of overhangs on wall performance (from *Survey of Building Envelope Failures in the Coastal Climate of British Columbia*[29])

It is possible, in some cases, that the vapour pressure gradient is highest on the exterior side of the wall. In such a case, drying would tend to occur to the inside. However, this is not recommended as a design approach. In fact, since our building code requires the placement of a material of low vapour permeability (vapour retarder) on the inside of the insulation, drying to the inside will be inhibited.

Durability

Some materials are inherently more durable than others. For example, aluminum or other properly painted metals are generally more durable than wood-based products or materials such as sealants or gypsum board. In design, consideration should be given to the placement of less durable materials that will require repair or maintenance such that these materials are more readily accessible.

Durability by design also involves the use of assemblies and details that incorporate some redundancy. There is a need to incorporate some redundancy in design because all materials deteriorate with age and it is not possible to build with perfection. For example, installing a waterproof membrane around the bottom of the rough opening of a window and flashing the window provides some redundancy. As another example, installing a window in a protected environment, such as under a balcony projection or immediately beneath a large roof overhang, also provides some redundant protection

Wall design strategies

Solid or mass walls

Solid walls, such as solid brick, block, stone, concrete and solid timber, prevent rain penetration by shedding most water and absorbing the rest, which is released in drier periods. These walls, which were often load bearing, are not common in new construction because of their expense.

However, there are many examples of this type of building envelope still in existence today, in relatively good condition, even after 100 or more years of service life.

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[29] *Survey of Building Envelope Failures in the Coastal Climate of British Columbia*

In these walls, the water-shedding surface is the exterior surface. The moisture barrier is also the exterior, as any water that penetrates the masonry reaches the interior. These walls rely on deflection, drying and durability for resisting water penetration as no internal drainage is provided. These walls are durable when saturated only when they stay warm. Should the temperature of wet masonry drop below freezing, the masonry could be subject to freeze-thaw deterioration. Care should be taken in retrofitting such walls, as changing their thermal regime could lead to failure.

Concealed barrier

The face-seal strategy is to eliminate all openings through which rain could enter the building. However, it is susceptible to deterioration as the exterior of the building envelope is exposed to the full effects of the climate, including ultraviolet radiation, water and temperature extremes. Further, if water does enter the wall system, it can become trapped; the typical low permeability of the exterior means there is little opportunity for drying.

Another approach is referred to as the *concealed barrier*,[30] in which there is an internal barrier to leakage. An example of this type of wall is a stucco wall with a water-resistant layer, such as building paper, behind the stucco. The stucco is the primary water-shedding surface, but it is porous and absorbs moisture; the building paper acts as the moisture barrier, providing resistance to capillary flow. In some cases, the concealed-barrier wall may include flashing at the base of the wall to direct water out. However, for all practical purposes, such a wall design should be considered face-sealed.

Drained cavity

The drained-cavity approach recognizes the likelihood that there will be openings in the exterior of the walls and that water will enter the wall system. In this approach, the water-shedding surface is separated from the moisture barrier. To prevent any water from getting all the way to the interior of the wall assembly, there is an air cavity or free-draining material inside of the outer layer (or wythe) of the wall.

Water that penetrates the outer layer (by capillarity or gravity) is prevented from going deeper into the wall horizontally by the moisture barrier. Instead, the penetrating water will drain (via gravity) down the cavity face and must then be directed out of the cavity by flashing. A brick-and-block cavity wall is an example of this type of wall. Since some water is expected to pass through the outer layer, the backup wall should have a second line of defence against moisture—a water-resistant material that can shed water down to a flashing at the base of the wall.

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[30] *Rain Penetration Control: Applying Current Knowledge*.

While a drained-cavity wall addresses the forces of gravity, capillarity and the kinetic force of the rain, it does not address pressure differences caused by wind—the dominant force causing rain penetration.

Simple or open rainscreen

The key difference between an open rainscreen design and a drained-cavity design is that the moisture-barrier layer in a rainscreen wall is designed as the air barrier. Since this surface is most airtight, it carries most of the pressure difference, minimizing the pressure difference across the outer layer (referred to as the rainscreen). This approach counteracts the force of the wind, which can drive water inwards, thus improving rain-penetration resistance of the wall. However, for this system to work well, the rainscreen must be must less airtight than the air barrier. To ensure this is the case, intentional openings, called vents, are designed into the rainscreen.

Another advantage with this wall design is that the air barrier is located at the inner layer where it is often easier to seal and where it is not exposed to the exterior environment (rain, ultraviolet, etc.), extending its expected service life. Examples of simple rainscreen walls include vinyl siding or overlapping wood shingles and shakes on wood-frame construction; in these wall types, small air spaces are created between the laps in the siding and the back-up board or strapping, effectively creating a vented outer rainscreen layer with an inner cavity.

While the simple or open rainscreen achieves a certain level of wind pressure control, the airflow through the entire wall cavity cannot respond to the continuous and rapid local changes of pressure during gusts of wind. Also, as wind pressures are distributed unevenly over walls, air will also flow laterally in the cavity to areas of lower pressure at the corners and top of the building. More control over the pressure differences caused by wind can be achieved with a pressure equalized rainscreen (PER) wall design.

Pressure-Equalized Rainscreen (PER)

The pressure-equalized rainscreen (PER) wall employs additional features in the design of the cavity to improve performance over a simple rainscreen wall design—namely, the use of compartments. Figure 18 shows how wind pressure varies over a building when the wind is at 90 degrees and 45 degrees to one face.

As the spacing of contours shows, wind pressure can be fairly uniform at the centre of walls, but steep gradients develop toward edges and at the roofline. A single wall may experience positive wind forces in one area and negative (suction) forces elsewhere, while corners may be subject to strong positive pressure on one side and strong negative pressure on the other. These pressure differences become greater as building height increases. If the cavity of a rainscreen wall has vents open to the outside in areas of unequal pressure, air will flow laterally through the cavity to areas of lower pressure. Pressure equalization will not occur in the cavity, and the pressure difference across the rainscreen can be very high, in fact, higher than if no vents were provided, especially at the corners.

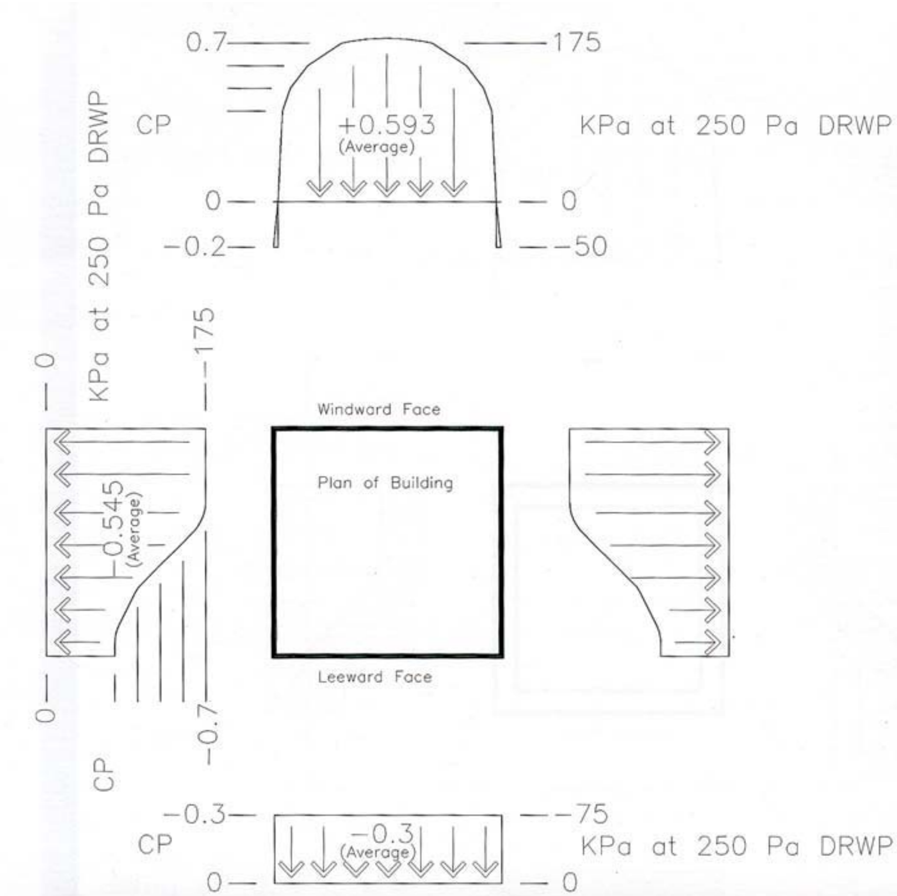

Figure 18— Wind pressures on building facades

To prevent this lateral air flow, the PER cavity is divided into compartments. At a minimum, the wall cavity must be sealed at all corners of the building and at the roofline, to prevent air from the windward face being drawn through to the negative pressure areas on the other faces. This approach should be adequate for small buildings.

In larger buildings, additional compartmentalization within a facade can address differences in pressure across the building face. The size of the compartments should be based on the extent of pressure variation across a given area. Therefore, smaller compartments are required at the edges of walls, while toward the centre of a building face, where pressure is more uniform, the compartments could be larger.

There is still much debate about the practicalities of actually achieving full pressure equalization because of the extreme variability of wind; so some refer to this approach as pressure modulation.[31]

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[31] *Rain Penetration Control: Applying Current Knowledge*

A much more detailed discussion on the design of pressure-equalized rainscreen walls, including design recommendations for compartment sizing and construction approaches, can be found in *The Rainscreen Wall System*[32] and *Rain Penetration Control: Applying Current Knowledge*.[33]

Two-stage joints

The *B. C. Survey* found only 10 per cent of the problems investigated were related to the basic assembly of the walls. Joints are typically the most vulnerable points of water entry in all kinds of wall construction, due to differential movement, sealant deterioration, etc. Similar to walls, rainscreen principles can be applied to the design of joints. A rainscreen, or two-stage, joint (see Figure 19) incorporates the same elements as a rainscreen wall:

· A cavity that is drained and vented to the outside,

· An outer weather seal or water shedding surface, and

· An inner seal, which is the primary air seal (and moisture barrier).

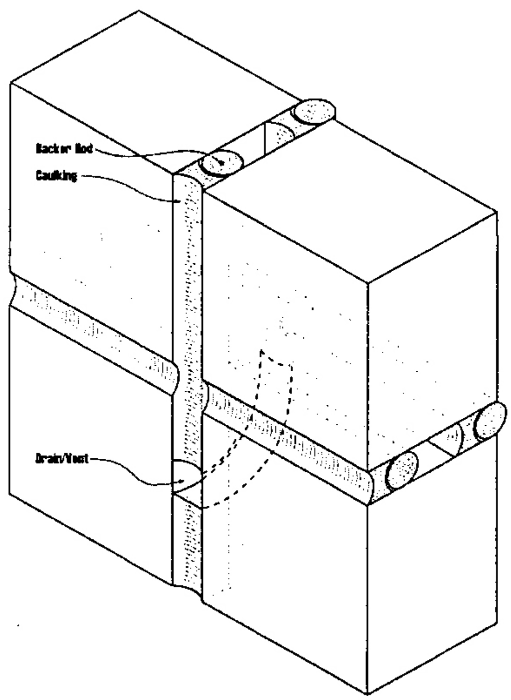

Figure 19—Example of a two-stage joint between face-sealed elements (from Rain *Penetration Control: Applying Current Knowledge.*[34]

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[32] Kerr Associates Technology Transfer. *The Rainscreen Wall System*. Canada Mortgage and Housing Corporation, 2001.

[33] *Rain Penetration Control: Applying Current Knowledge*

[34] *Rain Penetration Control: Applying Current Knowledge*

The same concepts discussed for walls are applied to such joints. The inner seal must be the most airtight seal and drainage must be provided from the joint cavity. The joint cavity must also be compartmentalized, especially near the corners of the building, for greatest effectiveness. Further information on two-stage or rainscreen joints can be found in *The Rainscreen Wall System*[35] and *Rain Penetration Control: Applying Current Knowledge*.[36]

Selecting a moisture control strategy

Table 5 is a suggested approach to assist in evaluating the potential performance of the moisture control strategies discussed above.

Exposure level	Face -sealed	Concealed barrier	Drained cavity	Simple rainscreen	Pressure-equalized rainscreen
High	Poor	Poor	Poor	Fair	Good
Medium	Poor	Poor	Fair	Good	Good
Low	Fair	Fair	Good	Good	Good
None	Good	Good	Good	Good	Good

Table 5—Performance expectations for exterior-wall moisture-control strategies (modified from Best *Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*[37])

The exposure level categories are somewhat arbitrary, but have been defined as follows:

· High—the wall is regularly wet under normal service conditions and is subject to significant exposure to wind driven rain.

· Medium—the wall is often wet under normal service conditions.

· Low—the wall is rarely wet under normal service conditions

· None—the wall is not wet under normal service conditions.

The performance expectation categories are also somewhat arbitrary, but have been defined as follows:

· Good—the wall assembly is likely to meet its expected performance criteria. This is low risk of failure occurring during the wall's intended service life, provided an appropriate maintenance is provided.

· Fair—the wall assembly may meet its expected performance criteria, although performance will be very dependent on quality of details, maintenance and local exposure conditions. There is a significant risk of failure within the expected service life of the wall.

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[35] Kerr Associates Technology Transfer. *The Rainscreen Wall System*. Canada Mortgage and Housing Corporation, 2001.

[36] *The Rainscreen Wall System*

[37] *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*

· Poor—the wall assembly is not likely to meet its expected performance criteria. This is an unacceptable risk of failure occurring during the expected service life of the wall.

Environmental factors

The first step in deciding which moisture control strategy to use for a wall system should be determining the environmental conditions or exposure level to which the wall will be exposed. The *B. C. Study* found that the wind exposure of those buildings without problems was on average lower than that of the "problem" buildings. A trouble-free wall design in one area may not perform adequately in another—the building science principles don't change, but the exposure conditions (heat, air and moisture) do.

The two key climate elements to consider with respect to rain penetration are wind speed and rainfall intensity. As wind affects both the amount of water hitting the building walls and is the major force driving the water inward, it makes sense to look at the wind pressure on the wall. It also makes sense to look at wind pressures during rainstorms. This is what the *Driving Rain Wind Pressure* (DRWP) represents.

Driving Rain Wind Pressure (DRWP)

Driving rain wind pressure (DRWP) data can be found for approximately 650 different locations across Canada in the *CSA A440.1 Standard, User Selection Guide to the CSA Standard CAN/CSA-A440-M90, Windows*.[38] The A440.1 Standard relates the DRWP for a given area with the level of water penetration resistance that should be specified for window selection. A similar approach could be used to determine an appropriate water control strategy for a wall.

DRWP data estimate the annual extreme mean hourly wind pressures (converted from wind speeds) associated with sufficient rain to cause leaks to occur. The 1/5 and 1/10 DRWP represent storms that have a 20 per cent and 10 per cent chance, respectively, of occurrence in any given year. Figure 20 is a graphical representation of DRWP for the 10-year return period.

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[38] *An Exploratory Study of the Climatic Relationships Between Rain and Wind*

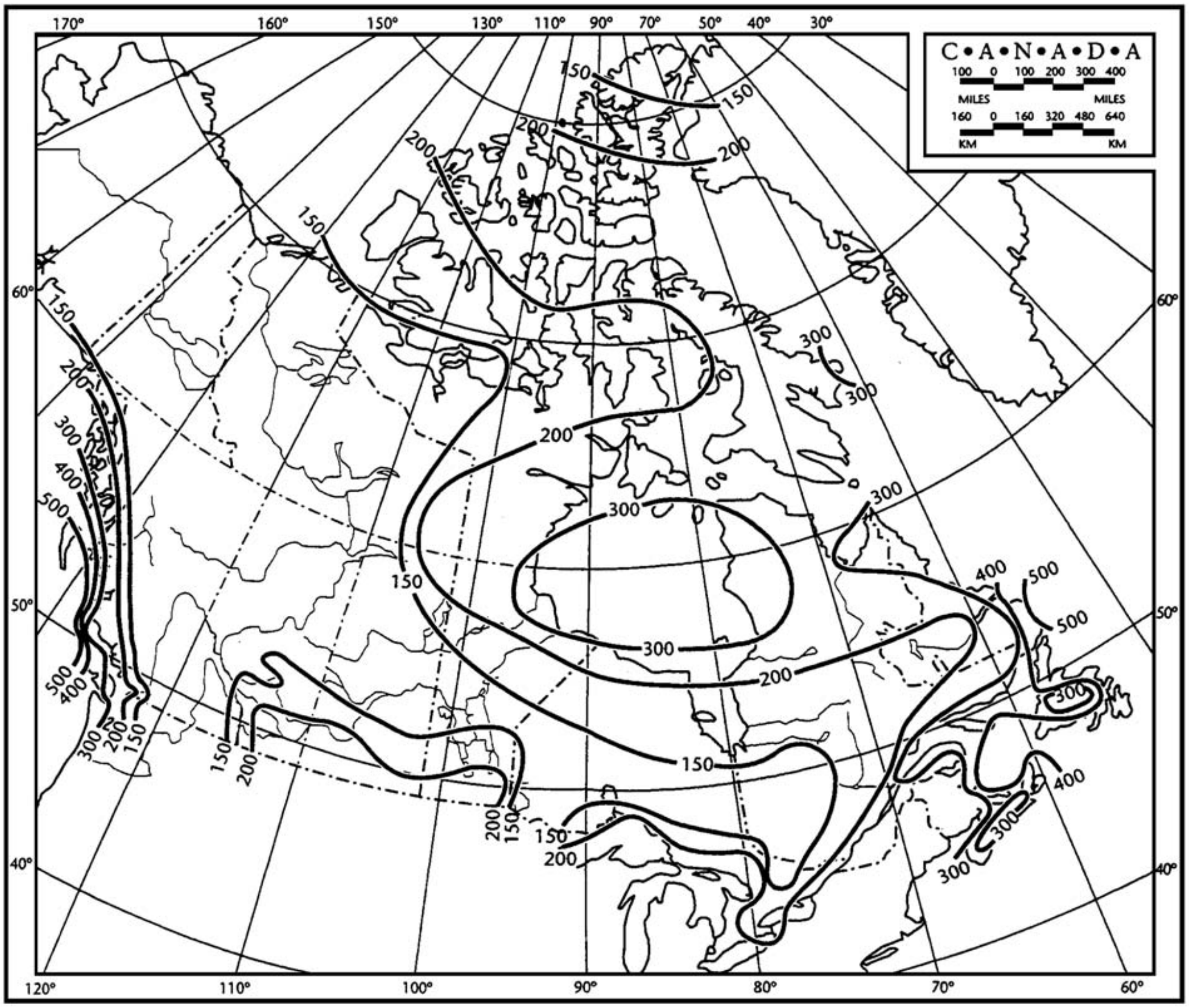

Figure 20—Map of DRWP for 10-year return period (from CSA *A440.1, User Selection Guide to CSA Standard A440*[39])

As the DRWP is reported at a height of only 10 m (33 ft.), a height coefficient—the same used for structural calculations—is used to factor the pressures for taller buildings (see Table 6). Note that the DRWP data are for wind in combination with rain and do not necessarily correspond to peak wind speeds used for structural calculations. It should also be noted that the DRWP values on the map were derived from measurements of wind in open, flat terrain and are represent the pressure in the central face of a building downstream of open, flat terrain. Higher or lower DRWPs may be experienced due to different local conditions, such as hilltops, bluffs or headlands or built-up areas. It may also be necessary to also consider building shape.

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[39] "*CSA A440.1-00, User Selection Guide to CSA Standard A440-00, Windows*". Canadian Standards Association, 2000

Height (m)	10	13	18	25	32	41	51	64	78	94	113
Height (ft.)	30.4	39.6	54.8	76.2	102.4	124.9	155.4	195.1	237.7	286.5	344.4
Height coefficient	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0

Table 6—Height coefficient for wind pressures

On larger projects that involve mock-up testing to confirm design and construction details, the DRWP can be used to establish testing loads for water penetration testing.

Annual *Driving Rain Index*

DRWP data are not indicative of frequency or duration of wind-driven rain exposure. For this purpose, the National Research Council has assembled an Annual Driving Rain Index (ADRI) for North America (see Figure 21). The materials and construction of a building determine whether peak load or annual exposure is more important. For example, in systems where *any* water penetration may lead to problems, such as face-sealed walls or windows, or where water is controlled by barriers such as upstands, peak loading is the most relevant design consideration. For assemblies that tolerate some water penetration and rely on a balance between wetting and drying, such as many masonry systems, annual exposure to rain is a more useful design parameter.

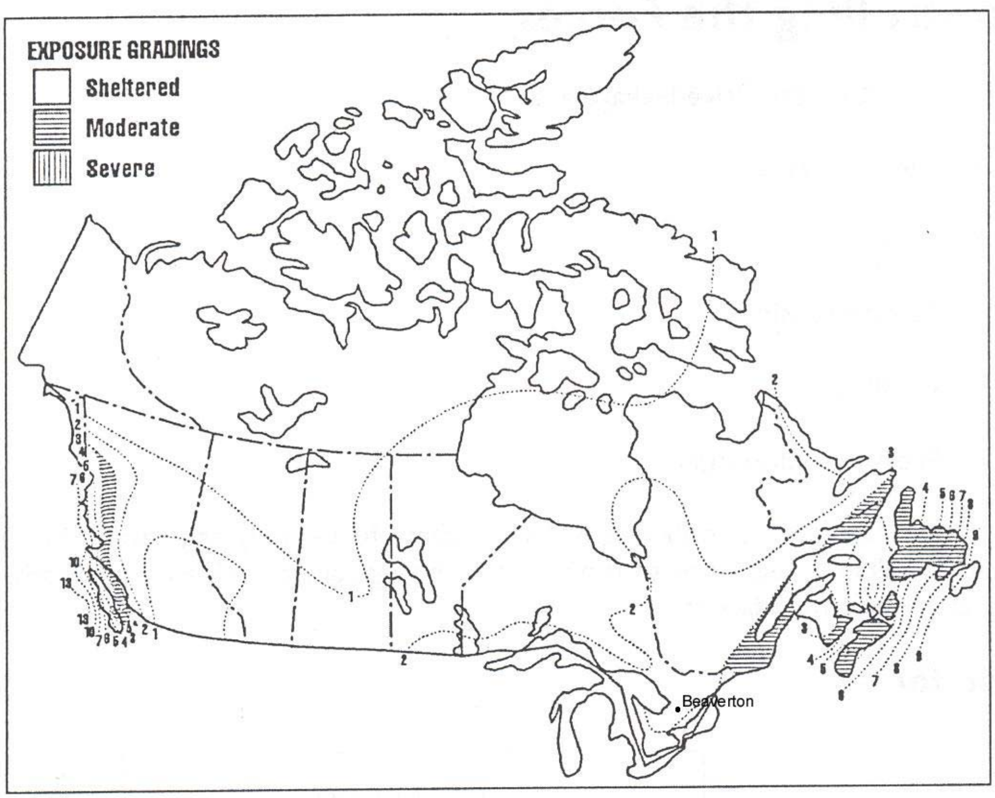

Figure 21—Map of Annual Driving Rain Index (ADRI)

Moisture Index

The National Research Council of Canada, as part of the MEWS Project (see sidebar) has more recently developed another index, the *Moisture Index* (MI). The Moisture Index is a combination of a Wetting Index, which represents the wind-driven rain to which a wall can be exposed, and a Drying Index, which represents the drying potential offered by the climate through evaporation.

The MI is intended to be a simple indicator of the severity of moisture loads inherent to the outdoor climate. MI varies between 0.0 and 1.414. The severity of the moisture load increases with MI, as indicated in Table 7.

MI	Severity of loads
MI ≤ 0.70	Zone 1—Low
0.70 ≤ MI < 0.80	Zone 2—Limited
0.80 ≤ MI < 0.90	Zone 3—Moderate
0.90 ≤ MI <1.0	Zone 4—High
MI ≥ 1.0	Zone 5—Severe

Table 7—Severity of environmental load, as indicated by Moisture Index

Using weather data from 300 locations in North America, an MI map of North America was developed (Figure 22).

The MEWS Project

The Institute for Research in Construction of the National Research Council of Canada, with a number of industry partners, has completed a four-year research project entitled *Methods for Evaluating the Moisture Management of Wood-Frame Wall Systems*, or MEWS. The main emphasis of the MEWS project was to predict the hygrothermal responses of several wall assemblies that are exposed to North American climate loads and a range of water leakage loads. Researchers used a method based on both laboratory experimentation and 2-D modelling with IRC's mathematical computer model, *hygIRC*.

The research has resulted in a methodology leading to design considerations for improved moisture management strategies for any wall assembly in any geographic region in North America.

The MEWS project makes full use of IRC's *hygIRC*, benchmarked against many sets of laboratory experiments, for predicting the hygrothermal response of the wall as a whole, as well as at localized, vulnerable areas of the wall.

The MEWS project developed new knowledge on the following fronts:

· Climate characterization for North America, in terms of moisture loads imposed on a wall;

· Typical practice of design and construction of walls with different cladding systems in place;

· Estimation of quantity and distribution of water ingress into the wall assembly, in relation to climatic loading;

· Characterization of hygrothermal properties of materials; and

· Selection of indicators of the hygrothermal response of the wall.

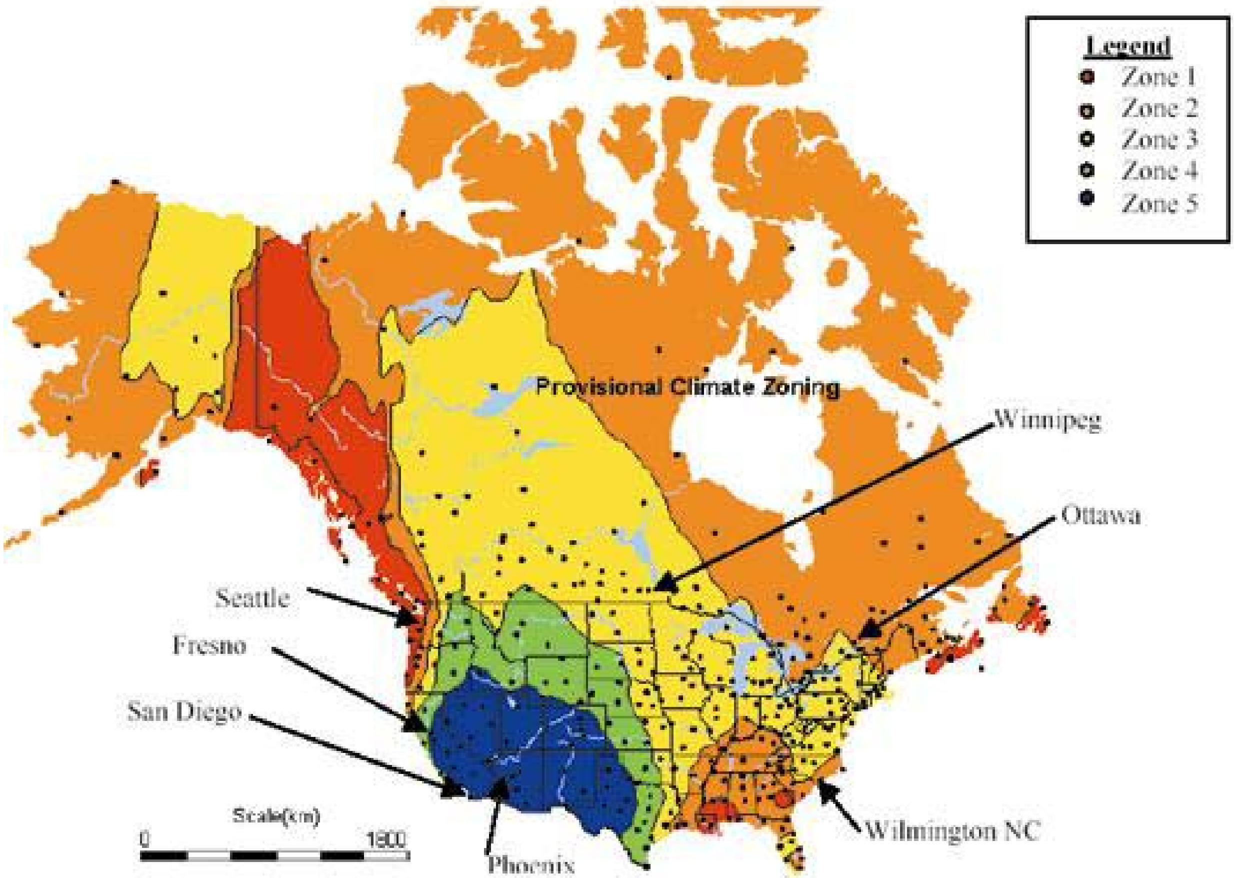

Figure 22—Map of MI (from Defining *Climate Regions as a Basis for Specifying Requirements for Precipitation Protection of Walls*[40])

Design factors

The determination of exposure involves the consideration of both environmental and design factors. At present, the Building Code provides a limited amount of information

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[40] Cornick, S. M. and Chown, G. A. *Defining Climate Regions as a Basis for Specifying Requirements for Precipitation Protection for Walls*. NRCC-45001. Institute for Research in Construction, 2001.

with respect to exposure conditions through climatic tables, including wind pressures and temperature extremes; some additional environmental factors are discussed above.

Design factors, however, are much more difficult to quantify, and are more related to micro-exposure conditions, such as the impact of overhangs and local topography. Design factors range from building orientation to how the building and its components deflect water. While these factors are much more difficult to quantify, some approaches are provided below.

Exposure Category Nomograph

One process for simplifying the determination of exposure is the Exposure Category Nomograph (Figure 23). This approach is suggested in the *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*.[41]

[41] *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*

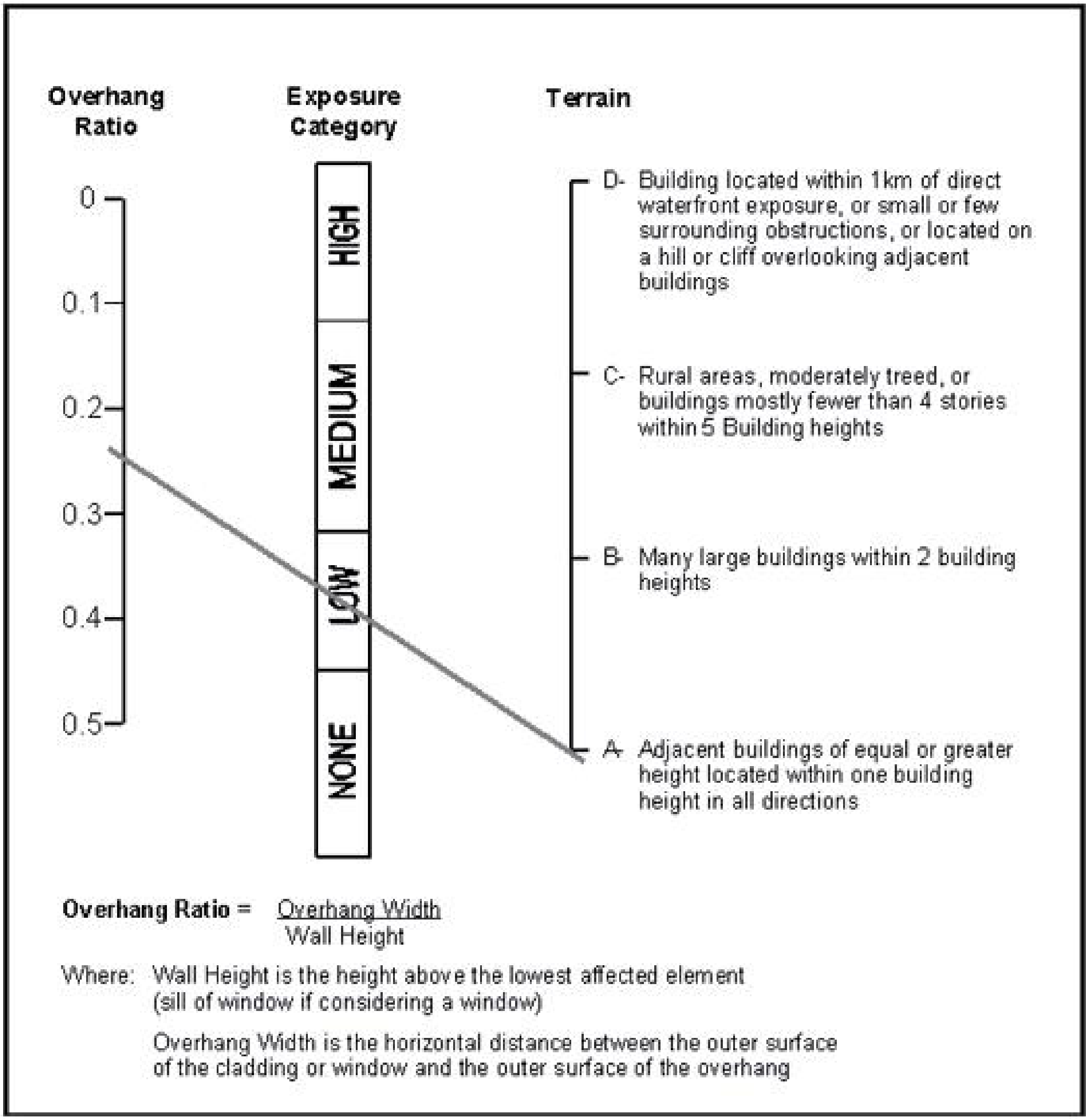

Figure 23—Exposure Category Nomograph for B. C. (From *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*[42])

This nomograph, which was developed for British Columbia, assumes that the climate is severe. It relates the overhang ratio and the terrain to an exposure category. Overhang ratio is defined as:

[42] *Best Practice Guide: Wood Frame Envelopes in the Coastal Climate of British Columbia*

$$\text{Overhang Ratio} = \frac{\text{Overhang Width}}{\text{Wall Height}},$$

where *Overhang Width* is the horizontal distance between the outer surface of the cladding and the outer surface of the overhang (while an overhang is usually created by the roof, it could also be created by other features, such as awnings or balconies), and

Wall Height is the height above the lowest affected wood element (therefore would not include concrete foundation wall height).

A straight line drawn between a calculated overhang ratio and an appropriate terrain description will pass through the Exposure Category bar to obtain an Exposure Rating. The example shown by the dotted line in Figure 23 represents a situation with an overhang Ratio of 0.3 and a Class C terrain, generating an Exposure Rating of Medium. The Exposure Rating can then be used to select a wall moisture control strategy using Table 5.

This particular nomograph has been developed for the severe climate of British Columbia, so it cannot be used in all areas; however, the concept could be expanded to other climates.

Computer modelling

There are a number of complex computer models available for predicting the hygrothermal (moisture and temperature) response of a wall, including EMPTIED, WUFI and *hyg*IRC.

EMPTIED

EMPTIED (Envelope Moisture Performance Through Infiltration, Exfiltration and Diffusion) was developed by CMHC. The program makes many simplifying assumptions to make it practical for designers to use to compare the relative effects of different climates, indoor conditions, wall materials and airtightness on wall performance.

Because of the simplifying assumptions, it does not predict or explain absolute amounts of moisture in a wall and it does not consider moisture storage or moisture wicking due to capillarity. However, it does offer an excellent comparative tool. For example, if you have a wall design that you know from experience performs well in particular conditions, you can ask what will happen to performance if you build it in another city with a different climate, humidify the interior in winter for comfort or add insulation. On the other hand, if you have a wall that is not performing well, EMPTIED can help you compare possible solutions. A free copy of EMPTIED can be obtained from CMHC by sending an email to splescia@cmhc.ca

WUFI

WUFI was developed at the Oak Ridge National Laboratory in the United States. It allows realistic calculation of one-dimensional heat and moisture transport in multi-layer building components exposed to natural weather. The program uses measured weather data, including driving rain and solar radiation, thus allowing realistic investigations of the behaviour of the components under exposure to natural weather. The program has been extensively validated with field studies. WUFI can be used for developing and optimizing building materials and components. For example, WUFI can be used for assessing:

· the drying time of masonry with trapped construction moisture;

· the danger of interstitial condensation;

· the influence of driving rain on exterior building components;

· the effect of repair and retrofit measures; and

· the hygrothermal performance of roof and wall assemblies under unanticipated use or in different climate zones.

A free research and education version of WUFI is available for download at www.ornl.gov/sci/btc/apps/moisture/. The program is directed at manufacturers of building products, consultants, designers, engineering offices and experts in the field of hygrothermics. Proper application of WUFI requires experience in hygrothermics and some basic knowledge in the use of numerical calculation methods and is not suited to use by general practitioners. However, there are consultants who can be retained to perform these analyses.

hyg*IRC*

IRC's two-dimensional computer model, *hygIR*, was used in the MEWS project to predict the hygrothermal response of a full-scale, one-storey wall over two years. The computer program predicts the real-time response of the wall to changing environmental conditions and hygrothermal loads.

For the simulation, the outside of the building envelope is subjected to hourly weather variations, including temperature, relative humidity, solar radiation, wind speed and direction and rain; the inside of the building envelope is subjected to changing temperature and humidity conditions. The program also accounts for other types of moisture and thermal sources, such as those due to unintentional air leakage through openings and cracks, rainwater entry from wind-driven rain, rising damp from the ground and in crawl spaces, and moisture deposition as a consequence of thermal bridges. The program then simulates the response of the changing environmental conditions and produces information on temperature and relative humidity distributions within the building envelope assembly and how they will change with time.

The *hyg*IRC program is complex and not suitable for use by general practitioners. However, early in 2004, IRC planned to release a one-dimensional version of the program for general use by design professionals and contractors. The 1-D *hyg*IRC model was built to facilitate case studies, allowing users to readily conduct *parametric* studies—studies in which several parameters are changed one at a time to gauge the sensitivity of the wall response. In other words, the 1-D *hyg*IRC facilitates "what if" scenarios, such as "what if the stucco cladding was replaced with acrylic stucco?" It can be applied to a variety of climatic conditions.

RHT Index

A novel concept, called RHT Index, was also developed during the MEWS project, utilizing the *hyg*IRC computer program. Part of the long-term performance of any wall assembly is the localized hygrothermal response of any of its components and material layers, particularly when there is a defect in the wall system.

The RHT (Relative Humidity and Temperature) Index captures the duration of the coexistence of moisture and thermal conditions that are ***above*** a set of threshold levels at a specific location in the wall assembly. The theory is that the wetter and the warmer the conditions at a certain location, the more likely deterioration will occur. In the MEWS Project, the wood framing and the sheathing board were looked upon as the critical layers most susceptible to moisture deterioration. The threshold levels established for the RHT Index depend on the physical process that is of interest in regard to the durability of any selected material in the wall.

For example, a combination of 95 per cent or higher RH and 5°C or higher temperature (called RHT95) was determined to be of relevance to the growth of wood decay fungi; a combination of 80 per cent or higher RH and 5°C or higher temperature (called RHT80) was determined to be of relevance to mold growth and corrosion. The higher the RHT Index, the greater the potential for moisture-related deterioration. Table 8 provides some RHT95 values for a number of North American cities for a stucco wall with OSB sheathing.

City	Moisture Index	RHT95
Ottawa	0.93	1536
Phoenix	0.13	655
Seattle	0.99	2290
Wilmington	1.13	3213
Winnipeg	0.86	1337

Table 8—Examples of RHT95 for different cities for one type of stucco wall

The RHT Index can provide information that can help in choosing the building materials and type of wall assembly to use, as well as in determining the need for location-specific construction details (See Figure 24). For example, different wall materials can be simulated to determine which material offers the highest potential (i.e., the lowest RHT Index) for long-term moisture performance. This information becomes useful to a building designer, for example, in choosing a building material from a pool of available materials. It can also help to determine the relative benefit of additional construction details, such as a drainage cavity behind the exterior cladding or an overhang to deflect wind-driven rain.

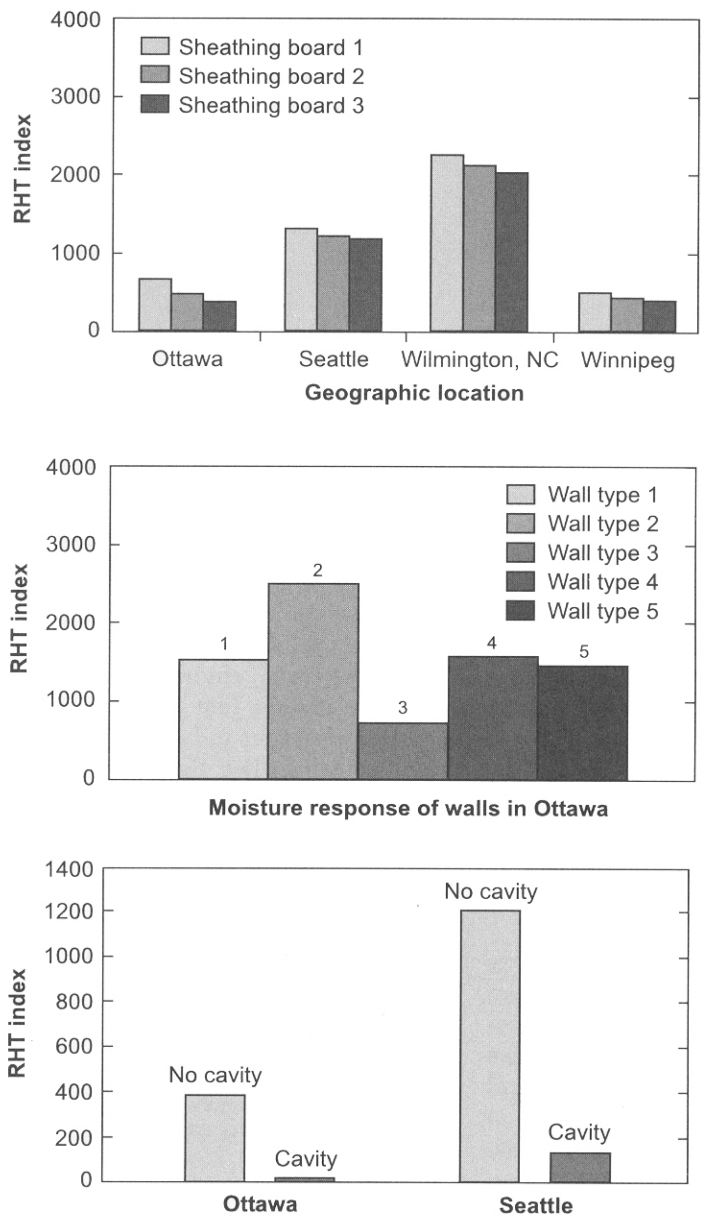

Figure 24—Examples of the use of RHT Index to compare materials, wall types and vented *vs.* unvented cavities (from "MEWS Project Produces Long-term Moisture Response Indicator," *Construction Innovation*[43])

Bringing it all together

So, the question remains: Given the available information, how can it be used to help in the design of a building that stays dry? Consider the following example.

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[43] Institute for Research in Construction. "MEWS Project Produces Long-term Moisture Response Indicator". *Construction Innovation*, Volume 8, Number 1, March 2003.

Beaverton, Ont. is about 100 km, or an hour's drive, northeast of Toronto on the eastern shore of Lake Simcoe. A developer expects that Beaverton will become the next favourite vacation spot for the large population in the Greater Toronto Area due to its accessibility and beaches. The developer has plans to build a 10-storey high-rise resort on a bluff on the shores of the lake.

The terrain to the east of the proposed project is relatively open, with expanses of cleared farmland and some forested areas. Lake Simcoe lies to the west of the proposed site. Unfortunately, *wind roses*, or wind direction diagrams, are not available for Beaverton. From personal experience, however, the architect knows that the wind usually blows from the southeast, but that when it is raining, most of the wind comes from the northwest.

In deciding what water penetration strategy to use in the design of the building, the architect examined the maps of DRWP, ADRI and MI (Figures 20, 21 and 22, respectively), and determined the following:

- DRWP—150 to 200 Pa
- ADRI—Level 3 (Sheltered)
- MI—Zone 2 (Limited Severity of Load)

Based on this information, the architect has determined that Beaverton has a relatively Low Exposure Level, especially when compared to other locations in Canada. Referring to Table 5, the architect determines that a drained cavity, simple rainscreen or pressure-equalized rainscreen wall would be suitable for the location.

However, the local topography must also be considered. The proposed site of the hotel is on a bluff that is exposed to the very open terrain of Lake Simcoe on the west. Further, most of the driving rain comes from the west. Therefore, the architect feels that he should consider his particular location to have a Moderate Exposure Level rather than a Low Exposure Level. Therefore, he has decided that a simple rainscreen design should be used.

The architect has also gathered the following information about the climate of Beaverton from the CSA A440.1 Standard:[44]

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[44] *CSA A440.1-00, User Selection Guide to CSA Standard A440-00, Windows*

Latitude	Longitude	1/5 DRWP @ 10 m	1/10 DRWP @ 10 m	1/10 hourly wind pressure	2.5% January design temperature
44 deg. 26 min.	79 deg. 09 min.	120 Pa	160 Pa	0.24 kPa	-24 °C

The proposed building will be 10-storeys, or approximately 32 m (105 ft.) high. Applying the height coefficient of 1.4 (from Table 6), the architect determines that the design driving rain pressure should be at least 224 Pa (160×1.4). The architect has decided to specify that the cladding system must pass a water-penetration-resistance test at a pressure difference of 225 Pa.

If they want to further refine their designs, the selection of materials and their arrangement, architects can now submit their preliminary designs for analysis using a computer program, to refine. For further information about envelope design, the reader is invited to review the other technical articles that are part of this series at http://www.cmhc-schl.gc.ca/en/imquaf/himu/himu_002.cfm

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Questions

1. Water is the most significant factor in the premature deterioration of buildings. What are the three key contributing factors to moisture problems in buildings? Provide an example of a typical situation representing each of these contributing factors.
2. What specific aspects of buildings are more prone to moisture problems? Select one of these aspects and discuss how you might address it to help prevent moisture problems.
3. List and discuss five ways to improve the quality of drawings and/or improve the lines of communication on the job site.
4. What are the three sources of water in a wall system? Describe ways of controlling interior moisture sources.
5. Discuss the similarities and differences between an air barrier and a vapour barrier.
6. What are the 4-Ds? Describe each one and its strategy for preventing moisture deterioration of walls.
7. Several different water management strategies are presented in the paper. Select one and discuss its advantages and disadvantages and provide an example of a situation where the strategy would be appropriate.

There are several environmental factors that could be considered in the design of a wall system, including wind pressure, wind roses, driving rain wind pressure, annual driving rain index, and moisture index. Select one environmental factor and describe how you might use it in the design of your buildings with respect to keeping walls dry. Are there other environmental factors that you might want to consider?