RAiNA
RAINSCREEN ASSOCIATION IN NORTH AMERICA

LITERATURE REVIEW REPORT
RAINSCREEN PERFORMANCE

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Introduction

This document is the result of a Performance Committee of the Rainscreen Association in North America (RAiNA) request for a literature review on rainscreen performance to provide a baseline of knowledge. At the end of this document is a comprehensive list of almost 400 pieces of literature relevant to rainscreen performance along with some brief comments. The information collected is grouped into 7 different categories, a summary of the state-of-knowledge is provided for each, and questions that could benefit from further research are provided.

Scope and Approach

RAiNA has recently defined a Rainscreen[1] Wall Assembly as

> an assembly applied to an exterior wall that consists of, at minimum, an outer layer, an inner layer, and a cavity between them sufficient for the passive removal of liquid water and water vapor.

The focus of the review was wall assemblies that meet this broad definition, the building science governing their performance, and testing and evaluation of them.

An important part of the work was selecting what kind of literature should be included. The performance of an enclosure wall is, of course, multi-faceted and includes aspects of structural performance, material durability, fire resistance, and aesthetics. Moisture control (primarily rain), specifically drainage and ventilation drying were to be a focus. A decision was made to exclude categories of information such as cladding attachment, thermal performance, and fire resistance along with aesthetics, and thermal bridging. However, many of the documents listed do cover some of these aspects—these documents are included because they offer valuable information or consensus about other aspects of rainscreen performance.

Although there are many overlapping categories of technical knowledge, seven primary categories of information were identified and used to collect and summarize the information.

- Topic 1 Rainscreen design guidelines / general cladding
- Topic 2 Drainage behind cladding, Water Resistive Barriers (WRBs)
- Topic 3 Ventilation & drying behind cladding
- Topic 4 Pressure equalization (benefits to structure and / or rain)
- Topic 5 Testing and evaluation
- Topic 6 Rain penetration mechanisms, all modes
- Topic 7 Climate and exposure influences

A summary of important findings for each of these seven topics is provided below.

[1] As rainscreen is a term that has not had a fixed definition over time or between different locations, many documents do not even use the term. Essentially the same definition has been proposed for inclusion in the 2024 International Building Code

A bibliographic list of reference documents is provided at the end of this report. Many of the sources referenced are technical papers, presented at technical conferences or in peer-reviewed journals, or reports by research organizations. Relatively few of the sources include books or industry guides, but these can be quite important because of their widespread accessibility and lasting permanence. Very few sources are from magazines or manufacturers' literature as these rarely include significant technical content. Some of the listed documents include standards for performance testing and evaluating rainscreen assemblies.

The bibliography provided at the end of this report include codes indicating which categorization they fall into (and often there is more than one). These two-character codes, designed to facilitate software searches, begin with the letter Z and end with the topic number.

Topic 1: Rainscreens and General Cladding

Early History of Rainscreens

Some of the concepts around rainscreens are not new, although not widely deployed in practise or described rationally and scientifically until more recently. For example, Vitruvius, in his *Ten Books of Architecture,* (Vitruvious 1914) written 2000 years ago, said

> *"…if a wall is in a state of dampness all over, construct a second thin wall a little way from it….at a distance suited to the circumstances….with vents to the open air….when the wall is brought up to the top, leave air holes there. For if the moisture has no means of getting out by vents at the bottom and at the top, it will not fail to spread all over the new wall".*

This certainly emphasizes ventilation drying and recommends a capillary break but does not discuss drainage, air barriers, or pressure equalization.

The true modern rainscreen literature begins with a 1946 paper by the Swede C.H. Johansson [1946][2]. This seems to be the first reference to a screen:

> *"...it is clearly unwise to allow walls, whether of brick or porous cement, to be exposed to heavy rain. They absorb water like a blotting paper, and it would therefore be a great step forward if an outer, water-repelling screen could be fitted to brick walls, with satisfactory characteristics from the point of view of appearance, mechanical strength and cost. This screen could be applied so that water vapour coming from within is automatically removed by ventilation of the space between wall and screen.*
>
> *If a rain screen of this type is used, the thermal resistance of the wall can be considerably increased for only a slight increase of expense, by employing one of the highly porous, thermally isolating materials now obtainable. With a highly porous layer between the actual wall and the rainscreen, the house would retain its good characteristics as regards heat capacity, sound isolation and fire risk."*

Many researchers in the post-war period accepted the merits of this multi-layer approach and began to do work on the concept. Hutcheon, in his seminal 1953 paper [Hutcheon

[2] References to specific literature or documents will take the common form of "[Author, year]" unless the sentence includes the author already, in which the reference will be "[year]". The bibliographic list at the end of this document is arranged alphabetically by author.

1953], Fundamental considerations in the design of exterior walls for buildings, he quotes directly from Johansson, but expanded the conversation to include other building performance factors, such as temperature differences, condensation, differential movement, etc. In Canada, Ball [1956] also introduced the idea of walls comprised of multiple layers.

Garden [1963], in his influential 1963 Canadian Building Digest, *Control of Rain Penetration* stated:

> *"In essence the outer layer is then an "open rain screen" that prevents wetting of the actual wall or air barrier of the building."*

He began the serious discussion of air pressures and pressure equalization but makes no mention of drainage.

In Norway, Svendsen [1967] produced a paper describing the two-stage weather tightening approach. In the figures of his paper (Figure 1) the term rain barrier (not rainscreen) is used and the term wind barrier (was air barrier meant?) on the exterior of the insulation is identified, with an interior vapour barrier. No drainage or water resistant "drainage plane" is identified.

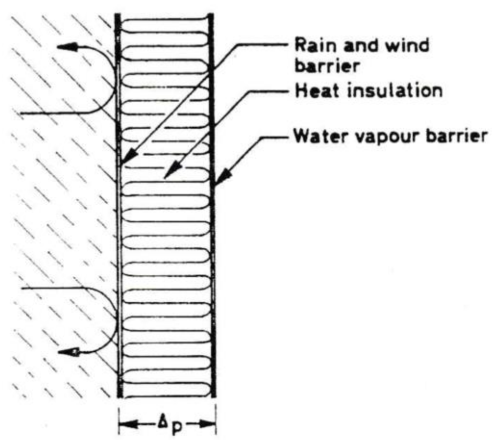


Fig. 2. The principle of one-stage seal.

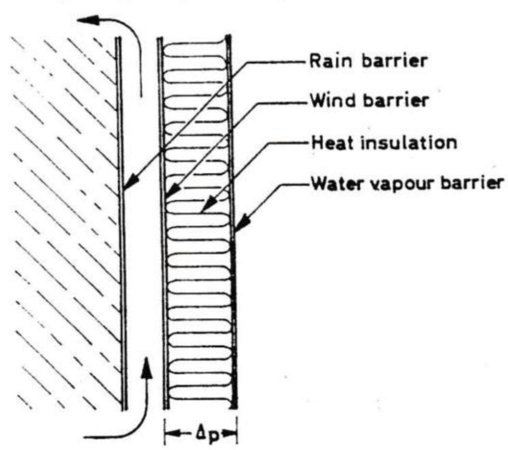


Fig. 3. The principle of two-stage seal.

Figure 1: Two-stage Weathertightness from Svendsen (1967)

By 1968, Birkeland [1968] had developed a concise understanding of the principles of rainscreens (although he applied the label to the cladding), one which was applied in practice to *joints*, not walls:

> *"On the basis of the knowledge of rain and wind penetration presented in this paper, a principle for designing weathertight joints is given. The rain and wind must be stopped separately. There must be an exterior rain screen, behind which is an air space that is ventilated so there is no wind pressure drop across the rainscreen. Behind the ventilated air space should be an airtight wind stop to prevent air from penetrating through the wall."*

Modern Rainscreen Era

A significant amount of knowledge about the performance of rainscreens was gained and documented prior to the 1970's. Most of this early literature focused on pressure-equalization, with ventilation and drainage rarely mentioned as strategies. This context must be understood when assessing performance today. A profound change in rain penetration control (and hence rainscreen design and research) occurred in North America between about 1990 and 2010. Building codes, design standards, even testing changed during this time to include dedicated water resistant layers and drainage as key elements. The same change is underway in Europe, but has only begun in some circles.

As rainscreens became an accepted and often preferred approach in research and academia, practical industry-focused guides began to be produced. This topic also included influential documents that provided recommendations for all kinds of enclosure walls or those that highlight rain control failures of walls.

In the early days of research (e.g. before 1960) rainscreen quickly took on the meaning of "pressure equalized" rainscreen. Today, the term often implies, but does not state, that a larger gap exists behind the cladding which is often ventilated. This change in use of the term and the lack of clarity and precision has caused significant confusion over time and between Europe and North America.

The curtainwall industry was an early adopter of the term rainscreen, and their explicit use of the rainscreen principle. American Architectural Manufacturers Association (AAMA) [1971] *The Rain Screen Principle and Pressure-Equalized Design Details of Three Recent Buildings*, was the first industry association guide followed by several other guidelines and recommendation documents. All of these relied heavily on Garden's [1963] 1963 Digest. Subsequent work by Latta [1973], Killip & Cheetham [1984] and others at NRC/IRC provided more science- and measurement-based advice for designers. This resulted in an internal report entitled *Review of design guidelines for pressure equalized rainscreen walls* [Baskaran & Brown 1992] which was widely disseminated in Canada.

The influential British book *Rainscreen cladding: a guide to design principles and practice* by Anderson and Gill [1988] fills the role of a design guide. This book identified the three approaches to rain penetration control – described as mass, fully-sealed, and rainscreen -- and then described pressure-equalized walls and "back ventilated" walls as separate rainscreen approaches. This document focused on pressure equalization performance, mentions ventilation, and rarely mentioned drainage or water resistant layers. The drawings in this guide (e.g., Figure 2) do not include water resistant layers, just cladding, insulation, structure, and interior finish.

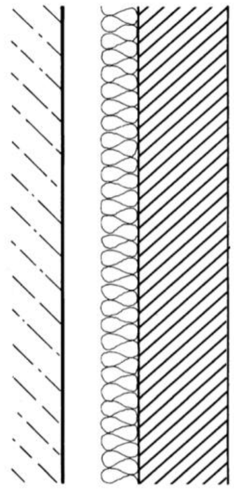


Figure 2: Rainscreen wall concept from Anderson and Gill [1988]

The AAMA released a slightly updated guide in 1996 (with an editorial revision in 2004) with advice that is also mentioned briefly in their 2005 *Curtainwall Design Guide* which continued to rely on research conducted before 1970. However, the updated 1996/2004 AAMA guide begins to apply modern language and understanding:

> *"Pressure equalization should not be confused, as some designers may do, with the more "conventional" and long accepted "theory of secondary defense," depending on a drainage system within the wall–a theory which, when properly applied, has also proven to be dependable".*

By 1999 the National Research Council of Canada's forty-years of research on the topic culminated in a concise document (hardly a design guide) by Brown et al [1999] that focused its recommendations on the "second-line of defense" and mentioned drainage as an important element alongside a passing mention of pressure-equalization as a rain control strategy. Very similar advice was given in Rousseau [1998]. This was a major change in emphasis. The focus on pressure-equalization as part of rainscreen recommendations that had been in industry guides such as Canada Mortgage and Housing Corporation publications [e.g., Drysdale 1991, Morrison Hershfield 1998] faded in the 2000's.

The term "rainscreen" does not occur in major North American building codes except in the explanatory appendices of the Canadian National Building Code (first in the 2005 NBCC and unchanged today) which mentions pressure equalization but does not discuss drainage, flashing, cavities, or ventilation. Rainscreen assemblies, are described in Appendix A (A-9.27) of the NBCC:

> *"… rainscreen assemblies include both a first and second plane of protection. The first plane comprises the cladding, which is designed and constructed to handle virtually all of the precipitation load. The second plane of protection is designed and constructed to handle only very small quantities of incidental water …"*

In Europe, the International Federation for the Roofing Trade [2018] has developed a *Guideline for Design and Installation of Rear-Ventilated Rainscreen Façades* document as recently as 2018. This guideline mentions the drainage function of the cavity in passing and explicitly states that "membranes" (assumed here to mean a Water Resistive Barrier

(WRB) or air barrier) are not required in properly designed and built assemblies. This is a major, even fundamental, difference in approach from the recommendations and codes in North America.

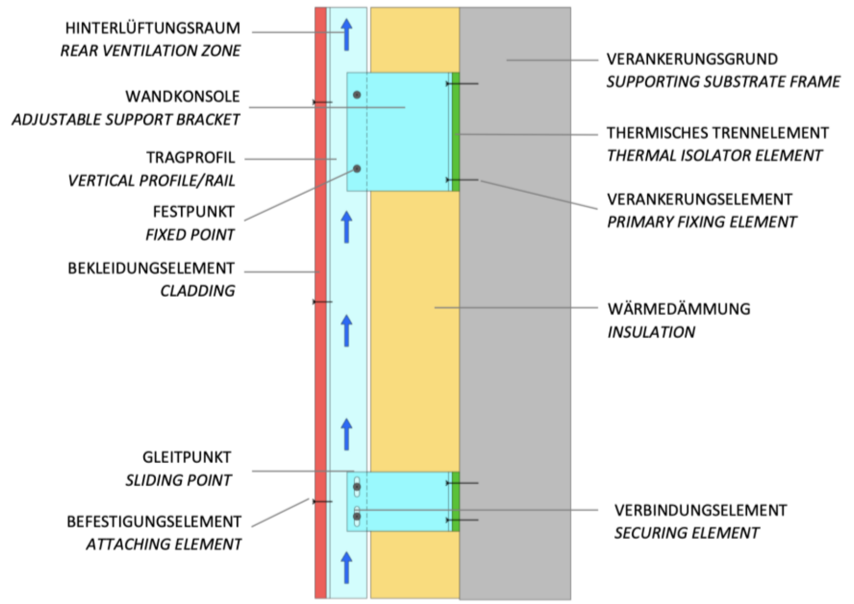


Figure 3: Definitions of "Rear-Ventilated Rainscreens" from IFD (2018)

Summary and Recommendations

When reviewing the literature is important to note that the terminology used at different times and by different countries must be borne in mind. Even today, the use of terms as common as WRB and air barrier can have different meanings in North America than Germany, and the way these terms were used has changed significantly. The RAiNA Definitions Committee is helping to reduce the uncertainty and imprecision of the language in future, but interpreting the true meaning of both current and historical terminology remains a challenge.

Terminology varies significantly between different countries, different types of manufacturers, and different times of writing. Care must be taken to interpret information and the development of modern consensus definitions is a helpful step forward. The difference in terminology and rain control philosophy used by Europeans and Scandinavians should be resolved in some manner, possibly by striking an international working group.

There are no up-to-date and modern design guidelines in North America for designers and specifiers, particularly none that applies to opaque assemblies other than metal curtainwall frames. Such a guidance document would certainly be useful.

Topic 2: Drainage and Water Resistant Barriers

One of the cornerstones of modern North American building science is that enclosure walls use drainage as a strategy and hence include drainage planes (more properly, water-resistant barriers WRB's) to manage rainwater penetration through the cladding (Figure 4).

Based on the literature review, it should be noted that:

1) drainage as an explicit mechanism is a rather recent focus in design, and

2) many modern and successful enclosure systems such as Insulated Metal Panels, Insulated Glazing Units, Architectural precast concrete, low-slope membrane roofs[3], and below-grade waterproofing are all perfect barrier systems that do not rely on drainage to perform.

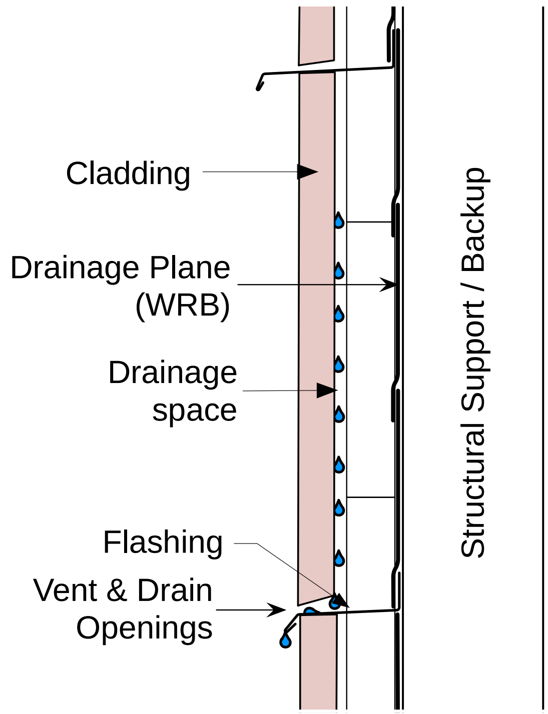


Figure 4: Conceptual Drained Wall

A limited awareness of the historical development of enclosure wall rain control has led to confusion about:

- the role of gaps behind cladding,
- the meaning of common terms such as WRB, and
- a belief that drainage is the only or best rain control strategy for all enclosure assemblies.

Some of the early researchers clearly understood the importance of gravity and the need for drainage. For example, the Norwegian scientist Isaksen [1965] was aware that water could cross an air gap at door and window penetrations and of the importance of drainage. He wrote:

> *"Our model tests showed that the air leakages had to be very great and concentrated if they managed to tear off water from surfaces. In the cladding case the water will run down on the inner side of the cladding and stick to it, it will not jump across the air space. It can, however, be led over to the back wall when the drainage is bad, i.e. via door- or window frames. A wind pressure potential across the air space is*

[3] Low-sloped roofs, of exposed membrane or protected membrane design, rely on the perfect barrier approach to rain control. Of course drainage can occur across the water control layer in all systems, face-sealed, mass, or otherwise, but by definition these systems do not require drainage to perform adequately as an enclosure system.

therefore not the reason for water penetration through the wall when the cladding has closed joints. A faulty design of drainage and/ or holes in the wind barrier are usually the main cause, the water simply flows into the wall by gravity".[4]

Herbert [1974] from the UK Building Research Establishment (BRE) wrote:

"It is important to realise that, however well they are designed and built, rain screen walls will allow some water to cross the cavity, and will also allow some water to drain down the back face of the screen."

Although this quote might suggest an emerging interest in drainage planes and water resistant barriers (WRBs), it is difficult to find any mention of a water barrier, water resistant material, or equivalent in the literature of that time.

Garden, who wrote early influential papers about pressure equalization and rain control [1963], was well aware of the importance of drainage, as he indicated in a research paper [Garden 1967]:

"It was recognized that in the United Kingdom a masonry wall would inevitably leak, thus cavity wall construction was adopted. With a properly drained clear space between two walls, the outer wall leaked as anticipated but the inner wall remained dry."

Not only was drainage little discussed, water resistant barriers (WRB) of any type were absent from the discussion and design drawings in this era. Garden also described effective rainscreens as "two-stage weather tightening" (adopting Svendsen's label, as many others did) with the help of case studies [Garden 1971]. Neither a water-resistant layer nor drainage is mentioned or labelled on the drawings he produced (Figure 5). The building paper widely used behind shingles in walls was labelled an air barrier, a label current building scientists would not use.

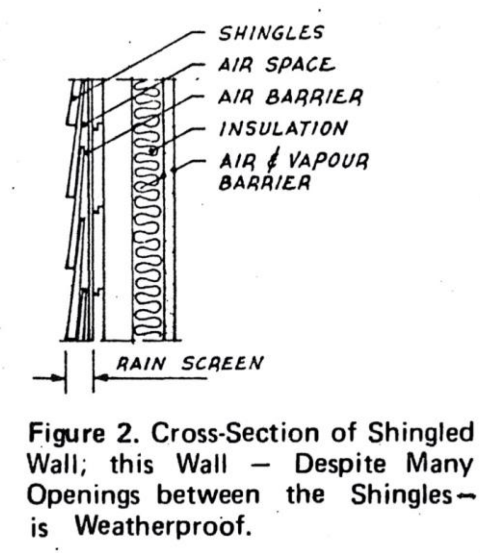


Figure 5: Drawing of a rainscreen from Garden (1971)

[4] Note "wind barrier" here is the building paper (common terminology in Scandinavia at the time), which is also assumed to be the primary air barrier – showing how language and performance expectations can be very different.

As another example, the drawings in Latta's Canadian design handbook [1973] shows an air barrier and an exterior "rain barrier": the water resistant barrier (aka drainage plane, or second-line of defense) assumed in modern walls and required by modern American and Canadian codes is conspicuously absent from drawings of this era.

An excellent representative example of the 1981 state-of-the-art comes from a Canada Mortgage and Housing Corporation (CMHC) advisory document by Plewes [1981]. Although the document takes care to document the needed components of a wall, and applies modern principles of building science, the drawings of masonry walls show no membrane applied as a drainage plane (Figure 5). The parged masonry inner-wythe was considered sufficient as both the air and water barrier (field experience showed it too often was not sufficient in situations with high exposure or poor workmanship [Cutlet 1980]).

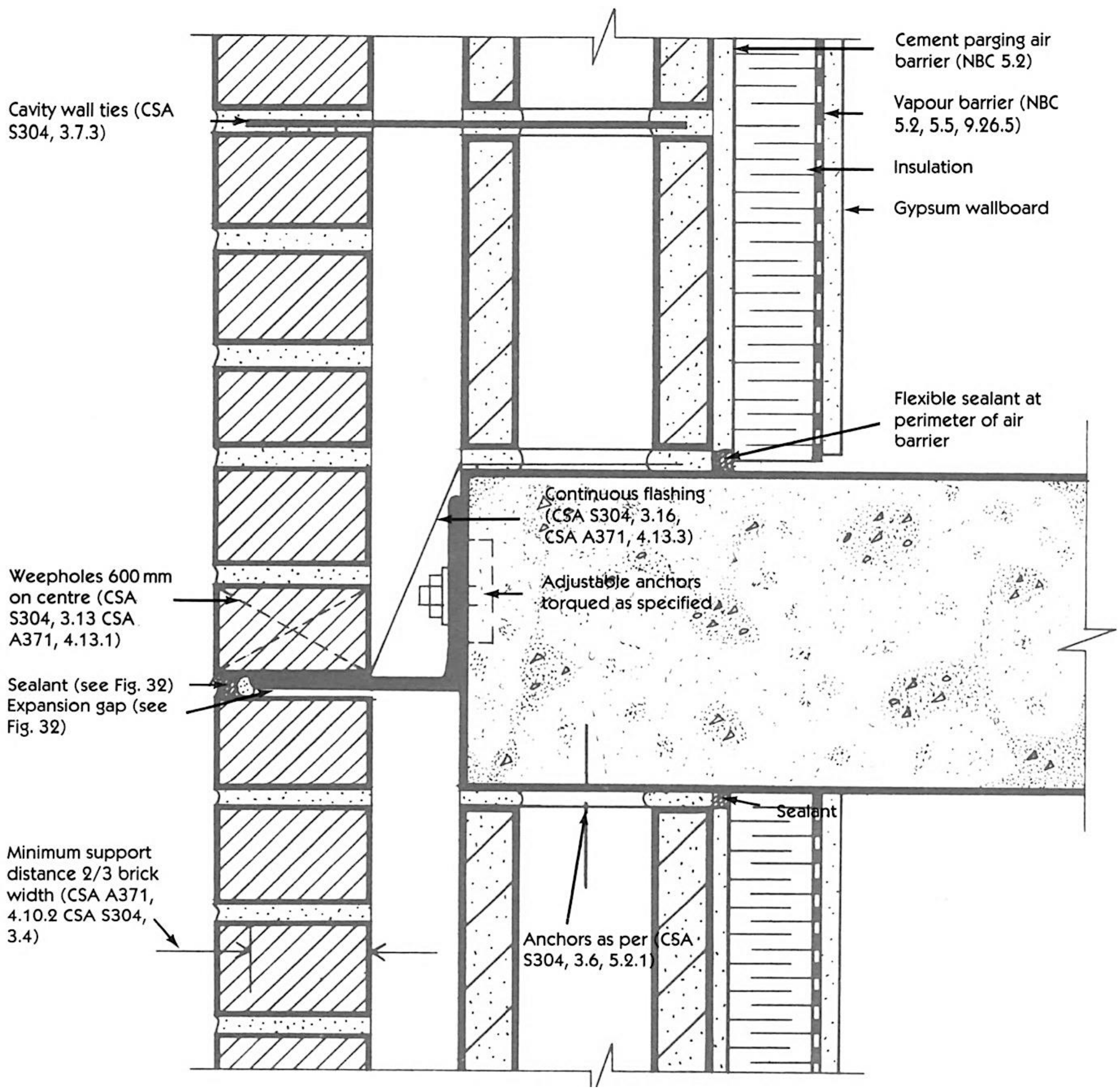


Figure 6: Note the careful and precise detailing (and code clauses) of masonry, weep holes, flashing, air barrier and vapor barrier, with no discussion of water resistant barrier or drainage [Plewes 1981]

A state-of-the art book by Ronald Brand (1990) showed excellent detailing, but focused on the need for an air barrier, a cavity to prevent water bridging, and pressure equalization. No water resistant barrier (WRB) or explicit drainage path was discussed or shown (although implicitly the flashings and air barrier membranes often provided that function). However, even at this date the role of pressure equalization as rain penetration control was beginning to be questioned:

> *"In the case of masonry, so much water leaks through the brick cladding with no pressure difference across it that it is doubtful pressure equalization would have much additional effect" (p. 178)*

A major change in rain penetration control thinking began in the 1990's when it became widely accepted that both air and water barriers were needed in all walls, whether ventilated or pressure-equalized, or, for that matter, whether they were rainscreen, barrier, or mass walls. Practitioners perhaps because of widely publicised rain control failures (in for example, North Carolina and Vancouver, B.C.) were driving drainage as the primary rain control strategy.

As early as 1990, practitioners such as Stephen Ruggiero of the leading building science firm Simpson Gumpertz & Heger identified that drainage was a critical factor in rain penetration control. Specifically, he stated [Ruggerio 1991]:

> *"Our experience in evaluating and testing various wall systems is that much of the leakage can be replicated by allowing water to flow over the wall system without application of a differential pressure across the wall, i.e., wind pressure".*

The importance of drainage was a key lesson learned by the wider North American industry from the failures that began to become prevalent in the mid-1980s, such as the Vancouver leaky stucco condo crisis and the North Carolina EIFS (Exterior Insulation Finish System) failures.

From 1990 publications begin to appear, again first from practitioners, about how one could measure and test drainage in walls [Krogstad 1990, Brown et al 1997, Karagiozis 2002]. The research into drainage continued in the early 2000's [Straube et al 2000, Smegal 2006, Straube & Smegal 2007, Onysko 2007] and has subsequently been picked up in Europe [Van Linden at al 2018, 2022].

It took until 2009 for Krogstad's method for masonry veneer walls to become an official ASTM Standard, C1715-09, whereas a method for EIFS drainage measurement (ASTM E2273) was approved as early as 2003 because of the pressing need created by the North Carolina EIFS failures.

The concept of a "second line of defense", usually provided by a water-resistant layer (most commonly a building paper or housewrap) was accepted as minimum performance and integrated into all major North American building codes over the period of about 1995 to 2003 for almost all wall types. Unlike "two-stage weather tightening", which ascribed different functions to the inner and outer layers, the second line of defence philosophy focused on a water-resistant layer behind the cladding (the first line of defense). The National Research Council of Canada's Institute for Research in Construction, a primary advocate of pressure-equalization, developed the new strategy and helped bring it into Canadian codes.

Dr Michael Lacasse, of Canada's National Research Council's Institute for Research in Construction (NRC/IRC), led a major project investigating the rain penetration resistance of residential systems in a methodical way, beginning in 1998. Lacasse reported on lab test results that showed a water-resistant barrier or “second line of defense” was needed even with a large cavity (i.e., 10 mm or more) behind the cladding.   He wrote [2003]:

> *“Interestingly, the IRC test results also indicated that even with the presence of this clear drained cavity behind the cladding, a small quantity of water could still find its way into the stud cavity.”*

and

> *“Even when an air space was present behind the cladding system, it was beneficial to ensure that the component of the assembly acting as second line of defence, be it a water-resistive membrane or a board stock material, be attached in a water-resistant manner.”*

His conclusions are in some ways a rediscovery of what Isaksen and Herbert concluded (see the earlier quotes from 1965 and 1974).

The awareness of the primacy of drainage over pressure equalization also focused attention on WRB (which was also sometimes called the underlay or the drainage plane). In the same Ruggiero article referenced above, the importance of a secondary plane of water tightness was highlighted and it was concluded this was more important than an air barrier (though one was still needed) for rain penetration control.

As early as 1997, Bill Brown, of NRC/IRC and previously the author of numerous publications focused on pressure equalisation, began to release a series of papers that investigated pressure equalisation, drainage, and rainwater management in general [Brown et al 1997]. He tested several enclosure wall systems with small drainage gaps (3 mm or 1/8” wide and smaller) and developed methods to measure drainage. Numerous peer-reviewed international research papers and university theses over the last 20 years have reported experimental results demonstrating that even gaps of less than 1 mm (1/16”) can be used to provide effective drainage -- Tonyan et al [1999], Straube et al [2000], Weston et al [2001], Smegal [2007], and van Linden [2018, 2022].

Although research has unequivocally shown that small gaps allow drainage, small gaps also may retain water at the bottom of a drainage space because of capillary forces. For gaps of 1 mm width this amounts to storage of up to 20 mm of water and thus 20 mL per meter length (less than one ounce per yard of wall length).

WRB and Building Codes

The first US building code to explicitly mention drainage and Water Resisitve Barrier (WRB) provisions was the 1999 National Building Code of the Building Officials of America (BOCA) which required:

> *The exterior wall envelope shall be designed and constructed in such a manner as to prevent the accumulation of water within the wall assembly by providing a water-resistive barrier behind the exterior veneer as described in Section 1406.3.6 and a means for draining water that enters the assembly to the exterior of the veneer...*

The first nationally adopted code in the United States was the International Residential Code of 2003. It also used the term water resistive barrier:

> *The exterior wall envelope shall be designed and built … to prevent the accumulation of water within the wall assembly by providing a water-resistive barrier.*

Unlike the US, the term Water Resistive Barrier does not occur in Canadian codes. The product category label of sheathing membrane is used in Part 9 of the code (prescriptive design), but the philosophy of a “second plane of protection” is embodied as a requirement in the NBCC starting from 2005.

> *“The second plane of protection shall consist of a drainage plane having an appropriate inner boundary and flashing to dissipate rainwater to the exterior.”*

The relevance of drainage was recognised[5] by the National Building Code of Canada in 1995, when it required [NBCC 1995]:

> 5.6.2.1 Except as provided in Sentence (2), materials, components, assemblies, joints in materials, junctions between components and junctions between assemblies exposed to precipitation shall be
>
> (a) sealed to prevent ingress of precipitation, or
>
> (b) drained to direct precipitation to the exterior.

This was further explained in the Appendix:

> A-5.6.2.1. Sealing and Drainage. Providing a surface-sealed, durable, watertight cover on the outside of a building is difficult. Where there is a likelihood of some penetration by precipitation into a component or assembly, drainage is generally required to direct the moisture to the exterior.

Summary and Recommendations

During the historical development of rainscreens the importance of drainage was recognized and the limited role of air pressures driving rain penetration identified. Today the North American building industry accepts that a WRB, integrated with flashing and weepholes, is a minimum requirement. However, there is a difference of philosophy in Europe, where large gaps are seen as sufficient to prevent the passage of rain water. This difference should be resolved and publicized.

A consensus outcome of drainage research over the last almost 20 years is that small gaps, e.g. in the order of 1 mm or 1/16”, can provide good drainage.

As water can be stored on and in materials lining the drainage gap, drainage tests on different types of walls can have very significant differences in results, differences that may have no impact on drainage performance. The method by which water is injected, the size of the specimen, the water application rate, and the duration of the test will have major impacts on the results. These differences require more research to understand. The ASTM E2273 test may be appropriate for EIFS, but its use for different assemblies that have absorbent materials lining the drainage path is questionable. Development of a more universal drainage effectiveness test would be desirable.

[5] The requirement for drainage was not identified in the 1990 NBCC.

Topic 3: Cladding Ventilation

Ventilation, the exchange of air in the cavity behind cladding with the outdoor air, is a strategy long used in both walls and roofs. However, the scientific study of ventilation, especially its ability to remove moisture from the cavity, was not considered seriously until relatively recently.

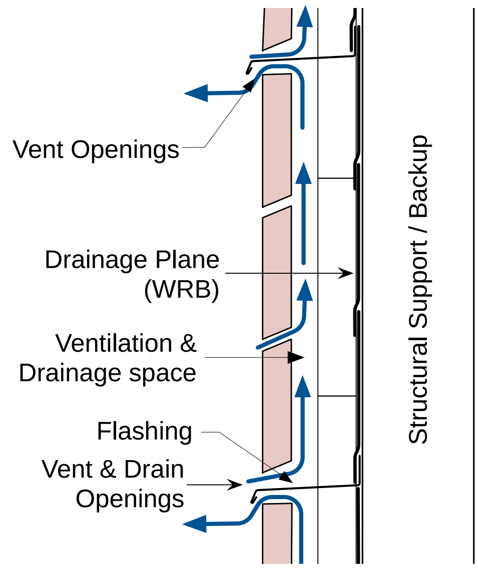


Figure 7: Ventilated and Drained Wall Cladding Concept

Some study of the ventilation was undertaken in Germany as early as 1973 by Schwarz [1973] and Frank [1973] followed by some seminal work by Popp [1980] and Kuenzel [1983]. A series of books about ventilated light-weight cladding were written in Germany [Liersch 1984] for practitioners but most of the guidance was related to implementing such systems under the then current building codes with only some detail about estimating ventilation airflow.

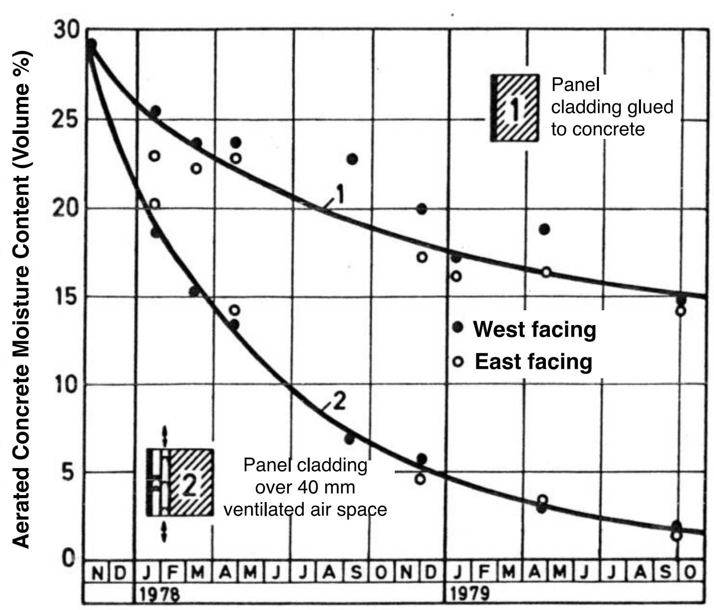


Figure 8: Field ventilation drying results [Popp 1980]

Although research demonstrating effective ventilation drying dates to at least 1940 [Rowley et al 1940, 1949] in North America, it was only in the 1990s that ventilation behind cladding began to be studied again as a potentially important drying mechanism by Ten Wolde [1992] and Straube & Burnett [1995, 1998]. A major multi-institutional study sponsored by ASHRAE [Burnett, Straube & Karagiozis 2004, Van Straaten 2003] combined field measurements, laboratory testing, and computer modeling to develop and validate methods that can predict airflow and the drying that can be generated.

A significant amount of experimental work has since replicated, validated, and extended this earlier work in New Zealand [Basset & McNeil 2006 and 2009], Europe [Falk & Sandin 2013, Nore et al 2005, Gudum 2004], and North America [Simpson 2010, Tariku 2011]. Research that does not challenge the wall with additional moisture (either by building walls with defects or injecting controlled water "leaks") tend to find little benefit of ventilation (Hansen 2002, Kehl et al 2010).

Field research and analysis shows that very small amounts of ventilation can bypass the vapor resistance of vapor impermeable claddings like metal and glass. Ten Wolde et al [1998] and Straube & Burnett [1995] developed theory to predict the equivalent vapor permeance of a cladding material as a function of ventilation and cladding material (Figure 9). Moisture storing cladding systems, such as those made of fibre cement and stucco, or enclosures sheathed with wood, can benefit from ventilation drying [Straube et al 2004, Finch & Straube 2007] at modest air flow rates. The volume needed for meaningful cooling of solar gains is very high and rarely effective in practical assemblies.

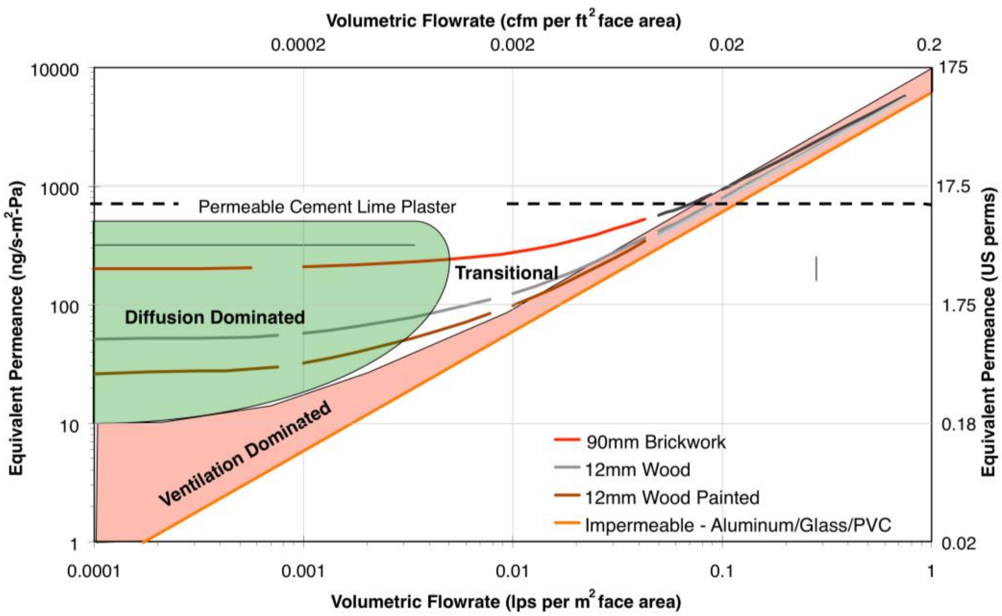


Figure 9: The relationship of ventilation flow and equivalent vapor permeance for different claddings [adapted from Van Straaten 2004]

For most wall systems the primary driving force driving ventilation air flow is solar buoyancy (which coincides with the majority of drying), although wind generates the highest peak pressures. The primary resistance to airflow, and hence the design element with the biggest effect on flow rates, are the vent openings and details.

It is important to note that there is a consensus in the literature that providing a vent only at the bottom of the cavity behind the cladding is not sufficient to achieve ventilation drying: a vent must be provided at the top and bottom to allow meaningful amounts of air to flow behind the cladding.

Although not well researched, analysis [Van Straaten 2003, Rahiminejad and Khovalyg 2022] strongly suggests that normal ventilation rates behind cladding systems has only a modest, usually negligible impact on R-value. Despite the limited research, the underlying physics of heat flow combined with a few physical measurements are unequivocal. Ventilation flow rates through most cladding systems are small enough, and the thermal resistance of even still air low enough, that ventilation of an airspace does impact the assembly value. Of course, if the same amount of airflow were to penetrate through the enclosure, rather than circulate behind the cladding, the impacts on enclosure thermal performance would be very significant and problematic.

3.1 Summary and Recommendations

Reasonable methods to predict ventilation air flow behind generic cladding have been documented, field validated, and replicated. It would be helpful to measure the behaviour of systems with complex (e.g., horizontal girts) and small air cavities to expand our knowledge.

There is little guidance on which systems require ventilation to perform acceptably, which benefit from ventilation, and which are not impacted. Although the research already conducted provides a wealth of information, it has not been summarized and placed in a general form for use by designers.

There is a useful collection of data on the nature and magnitude of air pressures that will drive ventilation air flow. However more field measurements of different systems on buildings with a range of exposures would be helpful to develop general consensus methods of prediction. The data already documented should be more widely disseminated.

Standard methods of measuring the resistance to airflow should be developed to allow for designers to select systems with the amount of ventilation desired or required.

Topic 4: Pressure Equalization

RAINA’s Definitions Committee recently defined pressure equalization as a performance state whereby the wind-induced pressures on the face of a cladding is exactly equalized by air pressure behind the cladding. This state is desirable both because a) it reduces the structural loads the cladding needs to be designed for and b) because it eliminates air pressure as one of the forces causing rain penetration of the cladding.

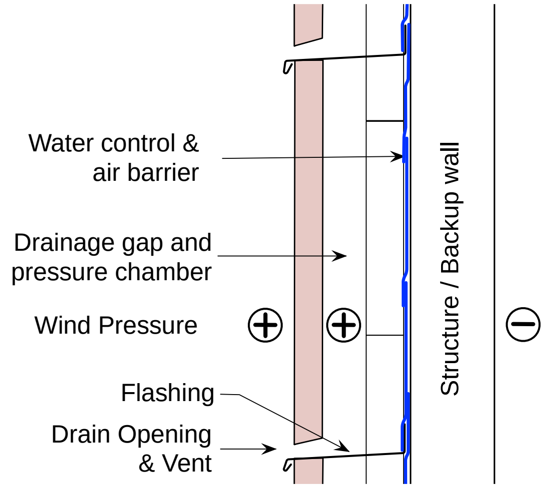


Figure 10: Conceptual pressure equalized wall concept

Garden, in his influential Canadian Building Digest *Control of Rain Penetration* [Garden 1963] stated that is pressure equalization could be achieved:

> *"In essence the outer layer is then an "open rain screen" that prevents wetting of the actual wall or air barrier of the building."*

He began the serious discussion of air pressures and pressure equalization, a topic investigated by many building research establishments in the 1960's (note, there is no mention of drainage or WRBs).

The curtainwall industry grasped the rainscreen principle and pressure equalization early on, perhaps because they could benefit the most. The AAMA publication *The Rain Screen Principle and Pressure-Equalized Wall Design* [AAMA 1971] was a seminal document that informed many manufacturers and practitioners. Here the authors defined rainscreen "the *component"* as distinct from the rainscreen "the *principle".*

> *"The rain screen principle may be defined as a theory governing the design of a building enclosure in such a way as to prevent water penetration due to rain; in other words, a scientific approach to eliminating water leakage.*
>
> *What is referred to as the "rain screen" is the exposed outer skin or surface element of the wall, backed by an air space and so designed that it shields the wall joints from wetting. It is made resistant to water penetration, not by sealing its joints and openings but by eliminating the pressure differences – or equalizing the pressures – occurring on its inner and outer surfaces, while the primary wall joint seals are removed from this outer wall face to the inner part of the wall., where they are kept dry. Thus, instead of the joint seals being subjected to both water and wind pressure, a two-stage protection is provided; the rain screen shielding against water penetration and the joint seals only against air penetration".*

and ….

> *"It should be recognized, to begin with, that the terms "rain screen principle" and " pressure-equalized design," though closely related and, in fact, interdependent, are not strictly synonymous. The "rain screen" is only the outer skin or surface of a wall or wall element - the part exposed to the weather. The "rain screen principle" is a principle of design which prescribes how penetration of this screen by rain water may*

be prevented. Thus, the use of the rain screen principle is essential to achieving a pressure-equalized design, and conversely, a pressure-equalized design depends on this principle".

Pressure equalization began to be understood as only part of a wall design by Canada's NRC/IRC in a 1998 publication of entitled *Pressure equalization in rainscreen wall systems* [Rousseau and Brown,1998] which concluded:

> *"PER [*pressure equalized rainscreen*] walls are not only about pressure equalization across the rainscreen. Other forces are at work as well, not the least of which is gravity; their control is part of the PER wall strategy for rain penetration control in exterior walls. One should assume that some rain will enter at some time during the service life of any wall assembly; that water must be disposed of quickly. Drainage of the air compartment is an important feature; properly detailed and sloped flashings and drainage channels are necessary for that reason".*

Although not always written, and often forgotten by practitioners, there is in North America a wide-spread acceptance that pressure equalization cannot exist on its own as a rain control strategy as it can neither manage all rain penetration mechanisms nor does it perform perfectly all the time. Pressure equalization is always a complementary addition to the fundamental drainage approach to rain penetration control.

As noted in Topic 1 of this document, Baskaran of NRC [1992] summarized the state of the art in the early 1990s and proposed a series of research questions. Much was already known by that date, but additional research around the world has improved understanding of pressure equalization.

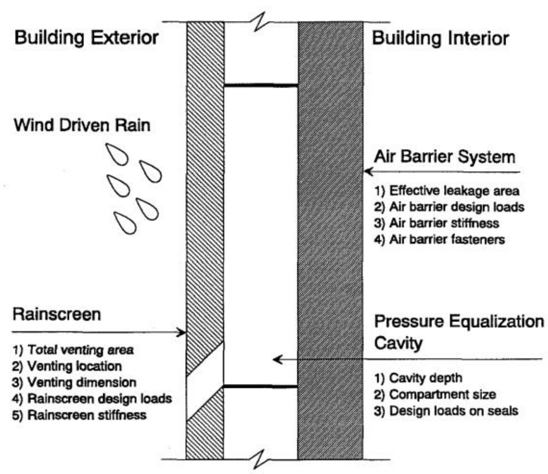


Figure 11:Components of a Pressure-equalized Rainscreen Wall from Baskaran [1992]

A complete and detailed field study of a high-rise building with a small chamber, very stiff, very airtight, and well compartmented assembly was conducted by Ganguli & Dalgliesh [1988]. They found:

> *During periods of high wind, maximum gust pressures (both inward and outward) ranged from 400-475 Pa (8.4-9.9 psf). However, the largest wind-induced pressure differences across the rain screen lasting several seconds or more were only 50-60 Pa (1.0-1.25 psf).*

Brown et al [1991] field tested an average quality (for the time) brick veneer steel stud system designed to be a rainscreen. Measured performance ranged from 35 to 65% pressure moderation. Field measurements of well-vented and compartmentalized brick veneers at the University of Waterloo studied performance in the frequency domain [Straube 2001]. He found good equalization at average pressures (over 95%) but poor (less than 50%) moderation of wind gusts. Kumar et al [2003] and van Bentum & Geurts [2015] measured the performance on a high-rise building and found similar results.

It can be concluded from essentially all laboratory and field studies that perfect pressure equalization at every moment is rarely achieved in practice. However, in some cases most of the instantaneous pressure difference acting on the enclosure may be equalized, leaving only a small and brief residual pressure difference.

Laboratory, simulation and field studies can be summarized to conclude that the degree of equalization (or pressure moderation) depends on two general classes of factors:

A. the enclosure system characteristics, and

B. the nature of the wind loading.

The enclosure system characteristics (A) can be further sub-divided into categories of characteristics that:

I. minimise the volume of flow required to achieve pressure equalisation, and

II. maximise the ease of flow of air into the chamber.

Factors included under the first category (I) of enclosure characteristics are:

1. air barrier leakage, or more precisely, the nature and magnitude of leakage;

2. the volume of air in the chamber;

2. the spatial extent of the chamber, i.e. compartmentalisation; and

3. chamber deformability (or stiffness, including the flexibility of both the cladding and the air barrier);

The second category of enclosure characteristics (II) includes factors such as:

4. venting, or more precisely the nature, magnitude, and spatial distribution of cladding air permeance; and

5. the air flow characteristics within the chamber.

The wind load characteristics (B) that affect pressure moderation are:

1. the mean pressure across the enclosure system;

2. the mean gradients (in two dimensions) across the exterior of each compartment;

3. the time-varying pressures across the system (i.e., speed of gusts); and

4. the instantaneous pressure field acting across the exterior of each compartment (i.e., the severity and duration of spatio-temporal pressure variations).

All of these four characteristics are strongly dependent on the building shape, size, orientation and the nature of the upwind topography

Figure 12 shows the well known fact that wind velocity at a point in space varies with time and can be described as a normal distribution upwind of the building (shown). The resulting pressure variations on a building face are similar but modified as they are influenced by building aerodynamics. The term turbulence intensity is defined as the standard deviation of the windspeed about the mean. Literature results suggest turbulence intensity can vary from below 10% to more common values of 25% or more.

A significant amount of the research literature found examines how to predict or test the pressure response of an air cavity to spatially uniform but time-varying exterior pressure. By the 1990's the National Research Council of Canada [e.g., Poirier et al 1992] and others [Alqhoury 1990, Ganguli & Quirouette 1987] were publishing the response of wall pressures to carefully controlled time-variant pressure waves.

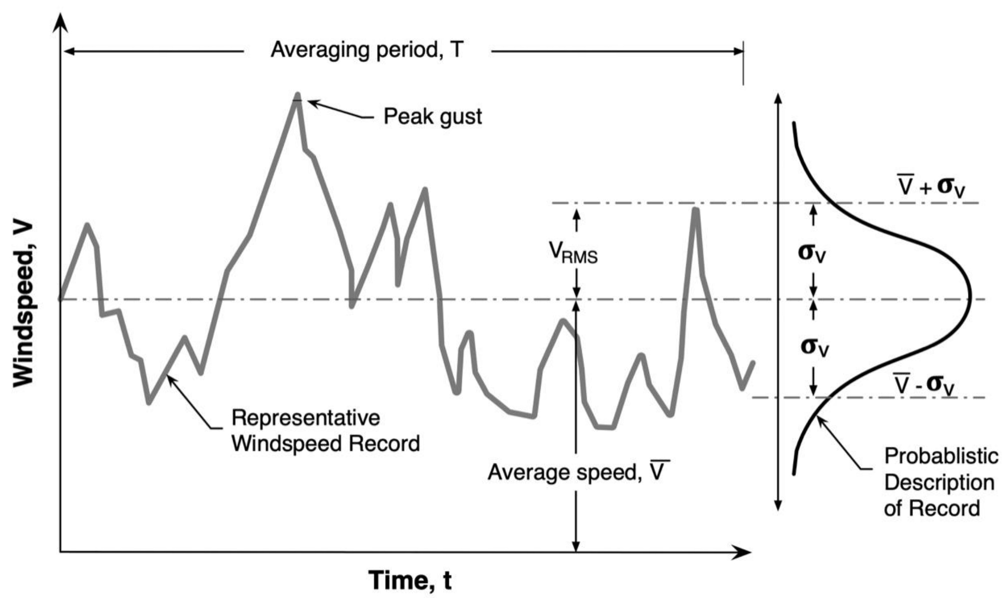


Figure 12: Example of the variation of windspeed at a point in space, and metrics used to describe this

That spatially-variable pressures (Figure 13) can influence the pressure experienced by a wall system, and hence its pressure equalization performance was known from relatively early times. For example, Dalgliesh and Garden [1968] described this challenge:

> *" … pressure equalization is not always achieved in a cavity which is open at two or more locations. The cavity must be closed at strategic locations to prevent air flow behind the outer screen. Knowledge of both the overall and local pressure variations is necessary for full exploitation of the principle of pressure equalization as a means of controlling rain penetration".*

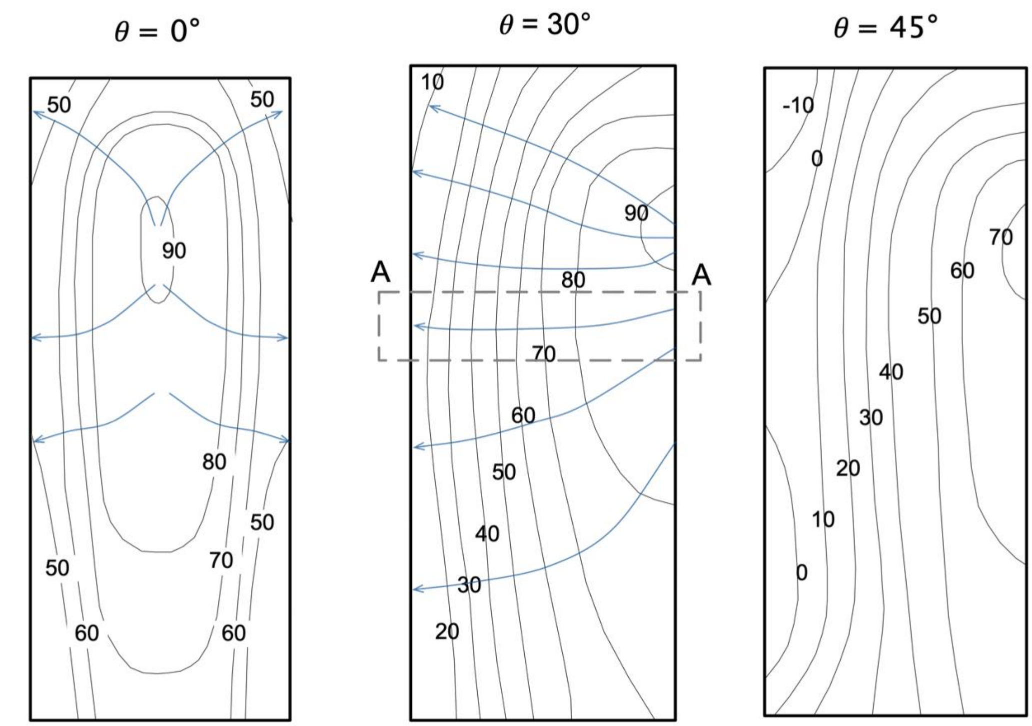


Figure 13: Average wind pressure over the face of a cuboidal building plotted as the percentage of total stagnation wind pressure for wind acting at 0˚, 30˚ and 45˚ to the face (adapted from ASHRAE)

Much more sophisticated methods and wind tunnel tests were used by Inculet et al [1996, 1997] to investigate compartmentalization. They proposed recommendations, but the stringent size limitations at the perimeter (1.0 m compartment size or less) meant these have not been adopted.

Measuring and reporting pressure equalization performance is more complex and challenging than might be assumed. The ratio of the pressure across the cladding to the total pressure across the wall is a good measure of pressure equalization. However, this measure varies significantly with the magnitude and direction of the applied wind pressure, the speed of the wind gust, the direction (negative or positive pressure) and the spatial extent of gusts. Hence, although the Pressure Equalization Factor (PEF) is likely the most commonly used term, its definition varies significantly between researchers. To respond to the major influence of wind gust duration, frequency-domain methods were developed (Inculet & Davenport 1994, Straube & Burnett 1997). While very effective for analysing complex field data, results in the frequency domain strictly only apply to specific wind directions for a given building shape and depend somewhat on wind speed.

4. 1 Summary

There is a consensus on the physical characteristics and environmental factors influencing pressure equalization performance. However, the relative impact of each factor cannot be predicted with as much confidence.

There is sufficient knowledge to calculate, with reasonable accuracy, the pressure equalization performance of a well-built sample when exposed to spatially uniform pressures dynamically varied as a sine wave. Current test methods (such as AAMA 508) impose spatially uniform and simple air pressure waves that do not correlate with measured field performance. Although research into the significant impact of spatially varying pressures has progressed in the last decade, predicting, and understanding field performance remains at an early stage.

In practice the role of pressure equalization as a supplement to drainage (and WRB's) rather than an alternative remains confusing to many architects and engineers. Education and consistent industry guidelines should be able to clarify this.

Topic 5: Testing and Evaluation

Managing rain penetration of building enclosures has been noted as a challenge from the beginning of recorded history. However, like most human endeavours, science began to be applied to the study and control of rain penetration in the 20th century. In the US, Fishburn [1938] produced a detailed early study that developed and reported on testing of masonry wall systems (the dominant solution then) and how the mass (storage) strategy of rain penetration control could be applied.

In much of North America and Europe three categories of test standards were developed: one for windows and doors, one for walls (usually masonry) and later one for curtainwalls. Even as early as the 1950s it was recognized that different test standards were needed for the two vastly different kinds of vertical enclosures: masonry walls and the glass filled windows installed within them.

In Canada Ritchie was investigating the use of small specimens for masonry walls in 1958, while Svendsen in Norway was working on a window test apparatus. Also in this year, the United States' Aluminum Window Manufacturers Association (AWMA) created a spray rack with a series of commercially available nozzles placed in a grid pattern.

Within 4 years, Birkeland and Svendsen [1962] reported on a complex Norwegian apparatus that moved spraying nozzles up and down a masonry wall to mimic wind-driven rain. Interestingly, his paper also reported extensively on the measured driving rain characteristics in that country.

By 1968 Sasaki and Wilson in Canada were proposing a standard window testing approach after comparing a number of spray rates and test durations: the 15 minute test using uniform spray grids became the standard for windows around this time. It is worth noting that their research showed that results were similar after 30 minutes of testing, but close enough that the practical value of a shorter duration of 15 minutes became the norm.

In 1967 the ASTM E331 *Tentative Method of Test for Water Resistance of Windows by Uniform Static Air Pressure Differential* was published for windows and three years later was modified to include application to curtain walls and doors. The standard has seen very little change since then and is at the core of most North American standards. ASTM E547, *Test for Water Penetration of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential* followed in 1975 and explicitly noted its application to curtainwalls.

As a result of this work two different groups of standards were developed, one for testing windows (e.g., ASTM E331, BS EN 1027) and one for testing masonry walls (e.g. ASTM E514). The British released BS 4315 Part 1 in 1968 for windows, and BS 4315 Part 2 in 1970 for masonry walls. Today, EuroNorms, prefaced with EN, provide standards for the entire European Union. Over time curtainwalls, which tend to be larger, include integrated structural resistance and accommodate movement, have developed their own series of standards such as AAMA 501.1-94 *Standard Test Method for Exterior Windows, Curtain Walls and Doors for Water Penetration Using Dynamic Pressure.* Omnibus standards such as Euro Norm 13830 *Curtain Walling* and AS/NZS 4284:2008 *Testing of building facades* include a series of tests to cover rain resistance, airtightness, structural properties, etc.

Laboratory rain penetration testing is most commonly conducted for compliance with specific project specifications (for large buildings) or local code requirements. Most rain penetration tests are intended to provide repeatable results in a laboratory environment rather than replicate performance in the field. This characteristic, repeatability, is critical for quality control testing and comparisons between systems. However, it is usually not possible to directly translate the results of laboratory performance to performance in the field and this is sometimes explicitly stated in test standards. Instead, using laboratory test data requires proper interpretation of the test results, and consideration of the imposed test conditions and the intended use of the assembly tested.

The concept of rain penetration testing is simple - water, simulating rain, and air pressures or air flows, simulating wind, are imposed on a specimen. However, within this basic construct there are many different test protocols and choices to be made. There are dozens of rain penetration test standards and protocols.

The factors that vary between different test protocols include:

- the nature and quantity of water application;
- the nature (dynamic, static, spatially uniform or variable) and magnitude of the air pressure difference; and
- the specimen to be tested, especially its size and the number of features included.

In addition, there are supplemental choices about design of the apparatus, including how observations of the performance are to be made (for example, whether these are limited to visual observations, or incorporate quantitative data) and, if the test is a pass/fail assessment of the assembly, the evaluation criteria to be used.

Each of the testing standards and protocols, although following the same basic approach, uses a different combination of experimental design choices.

Current research is highlighting the fact that existing test standards do not directly apply to drained and ventilated walls [Arce et al 2019, Krogstad 1990, Baskaran & Brown 1995, Bitsuamlak et al 2009, Matthews et al 1996]. Some drainage and cavity ventilation test standards for specific applications have been developed since 2000 (see Topic Z2 and Z3). For example,

- ASTM C1715-09 *Standard Test Method for Evaluation of Water Leakage Performance of Masonry Wall Drainage Systems*,
- ASTM E2925-19a. *Standard Specification for Manufactured Polymeric Drainage and Ventilation Materials Used to Provide a Rainscreen Function*, and
- ASTM E2273-18. *Standard Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies.*

Drainage testing methods for other cladding systems have not been standardized but developed and applied to many systems by researchers [Smegal 2006, Straube & Smegal 2007, Onysko 2007, Van Linden et al 2022]

Two relatively new standards have been developed that are directly relevant to rainscreens: AAMA 508 *Voluntary Test Method and Specification for Pressure Equalized Rainscreen Wall Cladding Systems and* AAMA 509 *Voluntary Test and Classification Method for Drained and Back Ventilated Rainscreen Wall Cladding Systems*. These standards both reference ASTM E331 for rain penetration resistance, and do not quantify or measure ventilation. AAMA 508 is the only standardized enclosure pressure equalization test method. This test method imposes a spatially uniform pressure of a single frequency and hence does not reflect our understanding of wind loads on pressure equalization described in Topic 4. AAMA 508 also defines failure as when water contacts the water resistant barrier (WRB) – all the effort invested in producing and testing WRBs is rendered irrelevant by the 508 standard.

Both standards require prescribed "failures" in the air barrier (that is, they imposed significant air leakage) as part of the specimen. While important developments, these two standards apply ideas from the 1980s (especially Gill & Anderson [1988]), do not address the importance of spatial variation, do not consider the way in which WRBs are commonly used today, and do not address ventilation at all.

5.1 Hygrothermal models

Evaluation of building enclosure assemblies is now commonly conducted with the air of hygrothermal models. ASHRAE Standard 160 provides some guidance for modeling rain penetration, which suggests water be added to layers within an assembly to predict its tolerance to rain leaks. Topic 6 provides a summary of the research that aims to estimate the magnitude of these leaks. Some research has also been conducted [e.g. Moore & Lacasse 2020] to guide the modeling of rain penetration and this work has highlighted the importance of understanding the magnitude and nature of the rain penetration (Topic 6) and environmental loads such a wind-driven rain and wind pressures (Topic 7).

5.2 Recommendations

New consensus standards are needed to address the current global move beyond perfect barrier (glass), mass (masonry), and perfect barrier with drained joint (curtainwall) systems towards drained and often ventilated enclosure walls. There is little to no research that answers how much water can pass the cladding and enter the drainage system or how much water on the Water Resistant Barrier is acceptable, or standards for defining the ventilation performance of a system.

Topic 6: Rain penetration mechanisms

As a primary goal of rainscreen systems is the control of rain penetration, the body of knowledge surrounding the physics and practicality of rain penetration was also reviewed. The literature categorized as Topic 6 relates in most cases to rain penetration mechanisms applied to rain screens, i.e., there is a focus on drainage and air-pressure driven penetration.

Garden [1963] again is a seminal paper that briefly listed six different mechanisms, a list that has been echoed countless times since. The original Garden document included dimensions for the openings for which the mechanisms applied: in most subsequent documents these relevant dimensions are missing. This is relevant as there remains confusion in practice about the role of capillary forces, gravity and air pressure in rain penetration.

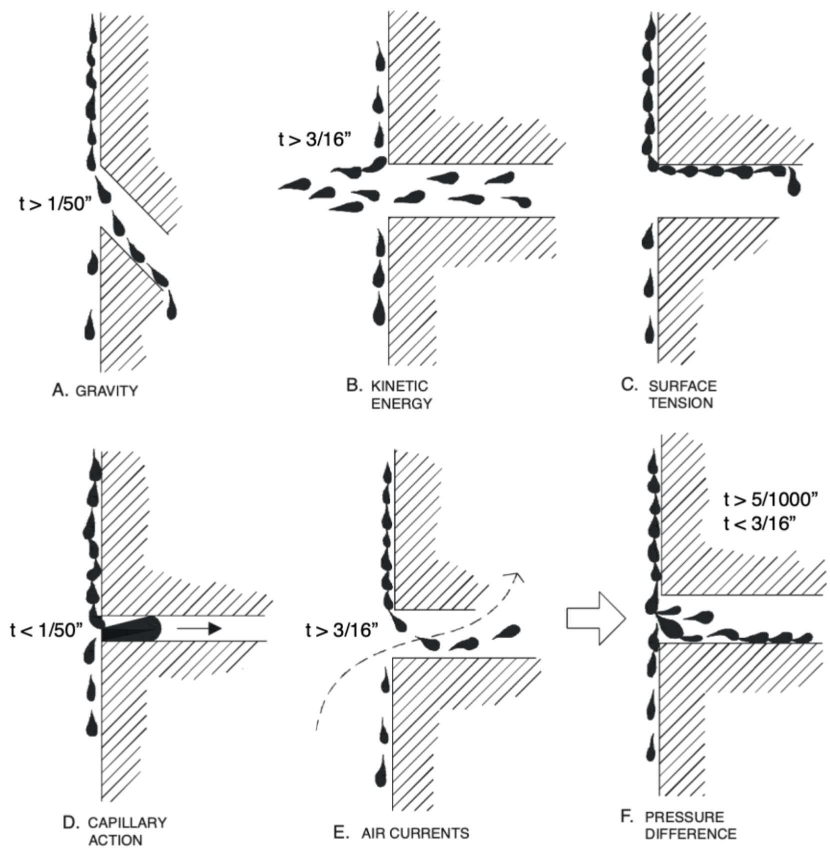


Figure 14: Rain penetration forces (adapted from AAMA [2004] and Garden [1963])

For a time, research into rain penetration of wall assemblies ignored the likelihood of gaps and imperfections. Around 2000, along with the embrace of drainage and second lines of defense Lacasse et al [2003, 2007, w/ Armstrong 2009], Sahal & Lacasse [2005], Salazano [2010], Lopez et al [2011], Ollson [2014, 2015, 2018], Ngudjiharto et al [2014], Ngudjiharto [2015], and many others began the investigation of leakage rates and factors influencing these through a range of common assemblies and defects. This research is different than many of the older references in that the more recent work attempts to quantify leakage rates, albeit usually under unrealistic levels of rain deposition and air pressure differences.

Research into the physics of rain penetration mechanisms has continued and is a current active area. Recent work of note has been done by Van den Bossche [2013] and his collaborators [e.g., w/ Janssens 2008, /w Lacasse 2012] and Lacasse et al [2003, 2007, w/ Hiroyuki 2009, van Linden 2022]. This work has explored the physics behind water penetration of cracks and openings in walls with and without air pressure differences. Although it may be surprising, the amount of water that might penetrate a known opening is difficult to predict with current knowledge [Stover et al 2022].

6.1 Summary

The basic mechanisms of rain penetration are well known to science, but not always well known to practitioners. There is a useful and growing body of research to provide leakage rates for common defects, but almost none of this data was collected with realistic combinations of likely rain and air pressures. Correlating test leakage rates and locations with natural field exposure leaks has not been undertaken at anything but the most general level. This lack may be the most significant knowledge gap in this topic.

Topic 7: Climate and Exposure

This is a major topic of study that is applicable to all types of building enclosures, structural design, cladding selection, paint choice, etc. However, the focus of the documents for the review in this category was rain deposition on walls (wind driven rain) and local wind pressure loads.

Driving rain has been scientifically studied for over a century. Modern English-language work by Lacy [1965] and others [Marsh 1977] (Figure 15) was widely used by researchers.

The research and experience was eventually developed into a British standard *BS 8104: Code of Practice for Assessing Exposure of Walls to Wind-Driven Rain* (and ISO 15927). Scandinavian and German research (e.g., Schwarz 1973, Frank 1973) were developing useful knowledge in parallel.

After a lull, research activity picked up with more detailed work aimed at estimating driving rain deposition on buildings. Work by Kuenzel [1994], Straube [1999], Straube and Burnett [2000], and Blocken and Carmeliet [2000,2004] formed the foundation of practitioner-friendly guidance developed by Straube and Schumacher [2005] and Cornick and Lacasse [2004, 2010]. Recently work has continued to study the impact of different building shapes (Figure 16) and overhangs on full-scale buildings in the field [e.g. Ge and Krpan 2007, Kubilay 2014, Ge and Stathopoulos 2017, Ge and Chiu 2017, Smegal et al 2014, Abu-Zidan et al 2021].

Wind pressure distribution on buildings is complex but has been studied for reasons of structural design for many years and has a rich body of scientific and engineering knowledge. Perhaps because of the focus on structural design, there is a surprising lack of clear consensus of what air pressures should be considered for driving rain penetration of facades. In the last decades the co-incidence of wind and rain, the intensity, duration and frequency of driving rain has begun to receive more attention [Tsimplis 1994, Sahal et al 2008, Van Den Bossche et al 2013, Xia et al 2021].

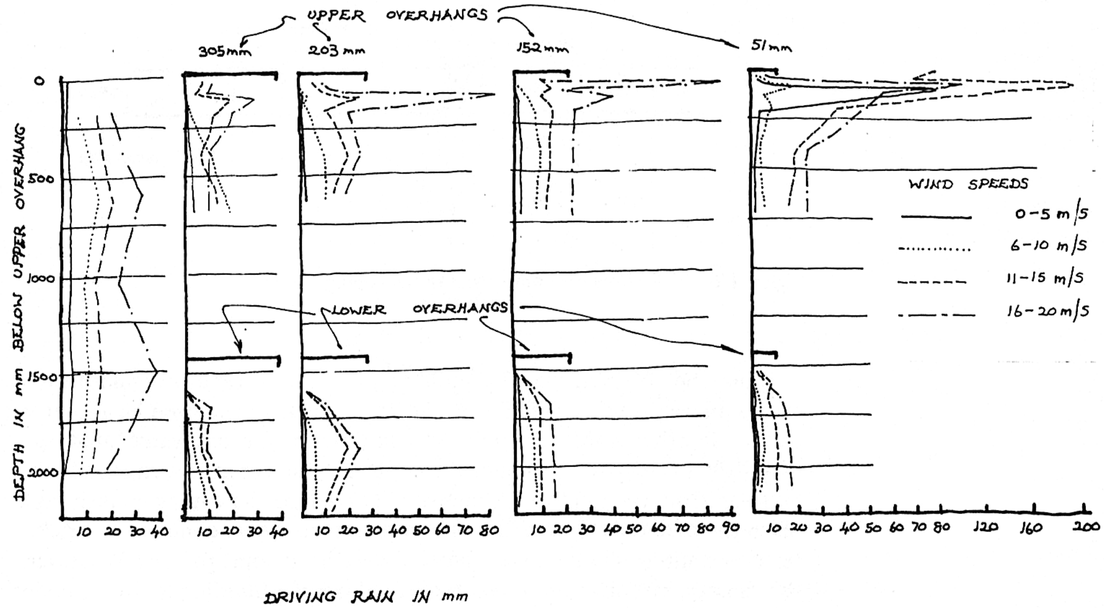


Figure 15: Early overhang sheltering research results from the UK [Marsh 1977]

The figure plots the amount of driving rain collected in a natural exposure test rig over time at different heights and when exposed to different wind speeds. Higher winds result in more rain water deposited, but the rain was concentrated at the top of wall, especially during high winds and with small overhangs.

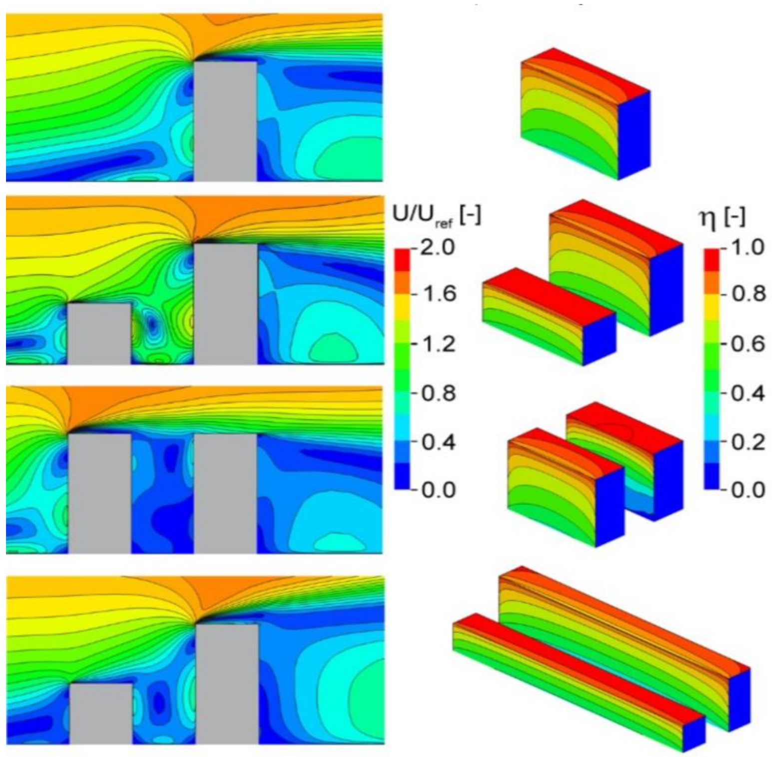


Figure 16: Example of driving rain shielding caused by interacting buildings [Carmeliet 2019]. Wind speed distribution on left, rain deposition on right.

The pressure levels chosen for structural design purposes, although widely available and standardized, are not very relevant to water penetration testing. Pressures for structural design purposes are by necessity, rare events (e.g., once-in-50 years) and short duration (a few seconds). If they are exceeded, even for a few seconds, the building can collapse, or at least sustain substantial damage.

Selecting air pressures for rain penetration testing is completely different. First, the likelihood of very high wind pressures coincident with driving rain is a statistically less likely event than just high wind pressures. Second, and more significantly, rain leakage is clearly tolerable for periods of time far longer than 3 seconds in fifty years. Even the worst hour every 5 or 10 years might be considered an unreasonably high target for glass and metal systems with no moisture storage. For opaque enclosure systems comprised of absorbent materials, such as wood, stucco, and masonry, leakage into moisture sensitive components (like wood or light gauge steel framing) may occur for as much as several hours every few months, provided sufficient safe storage capacity is available and drying is allowed to occur.

Although countries such as Canada (in the National Building Code) and New Zealand [Overton 2013] publish the pressures during the worst hour of wind-driven rain in five years, more frequent events (eg annually or semi-annually) are implicated in most in-service rain leakage. Little information is available for these more likely events to guide testing and evaluation. The research conducted shows that wind pressures during rainfall drop significantly for rain events that occur only one hour every second or fifth year (Figure 17).

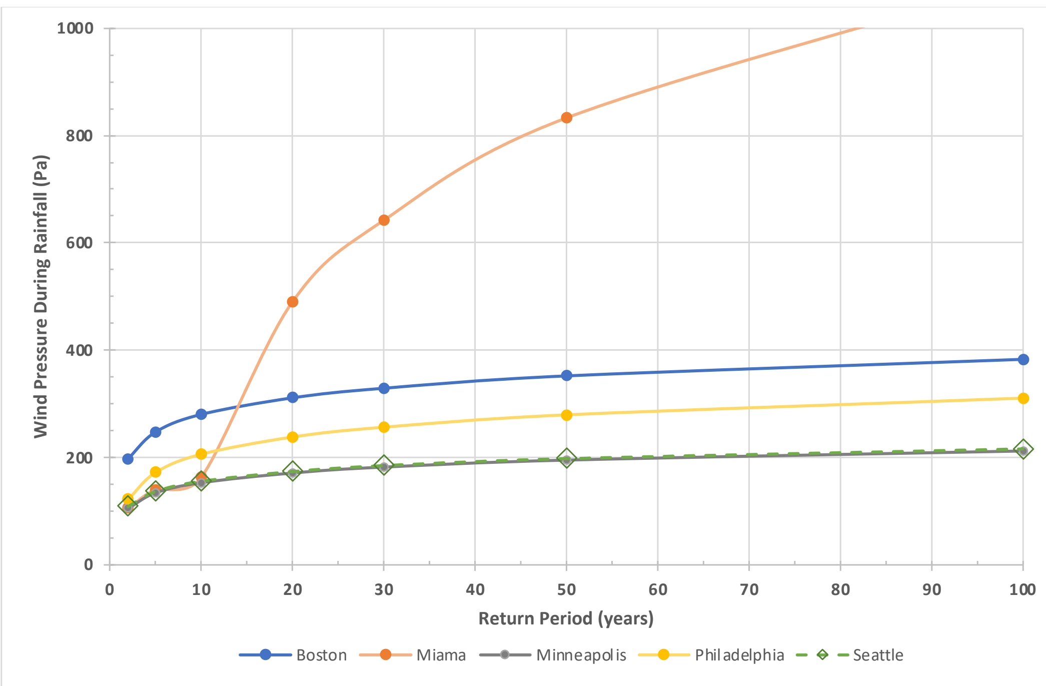


Figure 17: Wind pressure during rain as a function of return period for five US cities [adapted from Cornick & Lacasse 2010]

Selecting high air pressures as “proof” pressures for rain penetration testing is reasonable during product development and mock-up testing to provide assurance that the system under test will perform at the lower more likely pressures to be experienced in service.

However testing under pressures that are too high has the disadvantage that rain leakage paths and mechanisms that are different than in service can act, thereby disguising actual performance in the field. In practise it is usually much more fruitful to investigate the consequences of material aging (e.g., sealant debonding), workmanship errors (e.g., fishmouths), and structural movement (e.g., deflection cracks and bulging): it is difficult to “test” for these latter very practical issues.

7.1 Summary

Although precision is difficult to achieve, useful and practical estimates of wind driven rain deposition on facades are easy to create. Research continues to provide more detail regarding the influence of particular building shapes and features.

The air pressures that occur over a building façade are well understood, but the duration and magnitude of these pressures as they relate to return periods of interest for rain penetration are not well researched. Such data is needed and useful for the development of testing parameters but information for events more frequent than one hour every five years are difficult to find.

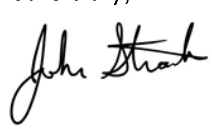
Although not thoroughly explored in the literature review, climate change is beginning to impact the frequency, intensity, and duration of wind and rain. The nature of this change and its significance for rainscreen wall design has not been studied at any depth but may become important.

Closure

This extensive literature search was wide-ranging and deep. However, there are certain to be documents not included that may be useful, especially those in languages other than English. Although the terminology and the focus of research and concern around the topic of rainscreens has changed over the years there is a large body of published research and knowledge. The volume of information in the documents listed is prodigious, but like all areas of study there remains a lack of consensus or clarity on many issues. Perhaps what is more surprising is that there is strong consensus on some topics that does not appear to be reflected in the knowledge of current practitioners and researchers.

We hope that this list of resources will help move research forward and provide the basis for practice guidelines.

Yours truly,



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encl. Rainscreen Bibliography

Rainscreen Bibliography

Searchable multi-factor codes.

- Z1 rainscreen design / general cladding
- Z2 drainage of water behind cladding, WRB
- Z3 ventilation & drying behind cladding
- Z4 pressure equalization – benefits to structure and / or rain
- Z5 testing / evaluation
- Z6 rain penetration mechanisms, all modes
- Z7 Climate and exposure influences

Use the search function in your pdf viewer, all references with an assigned code can be selected.

1. AAMA 508-21. *Voluntary Test Method and Specification for Pressure Equalized Rainscreen Wall Cladding Systems*. Z5

2. AAMA 509-22. *Voluntary Test and Classification Method for Drained and Back Ventilated Rainscreen Wall Cladding Systems*. Z5

3. AAMA. 1971. *The Rain Screen Principle and Pressure-Equalized Design Details of Three Recent Buildings.* CW-2-71 American Architectural Manufacturer's Association, Schaumburg, Illinois. Z1, Z4, Z5. This is a seminal publication that introduced pressure-equalization to many practioners, particularily curtainwall and window manufacturers. The mechanisms of rain penetration (essentially taken for Garden's earlier CBD) were outlined and definitons given. Z1, Z4

4. AAMA. 1996. *The Rain Screen Principle and Pressure-Equalized Wall Design.* CW-RS-1 American Architectural Manufacturer's Association, Schaumburg, Illinois. An update of the original 1971 AAMA document. Z4

5. AAMA. 2005. *Curtain Wall Design Guide Manual*. CW-DG-96. American Architectural Manufacturer's Association, Schaumburg, Illinois. Z1

6. Abu-Zidan, Y., Nguyen, K. and Mendis, P., 2021. "Influence of building shape on wind-driven rain exposure in tall buildings". *J Architectural Engineering*, 27(3), p. 04021027. Although based mostly on computer simulations this paper presents general information reinforcing the fact the tops ands edges of tall buildings receive much more rain than lower down. Z7

7. Alkhoury, E. 1990. "Window Rain Screen Evaluation". *Proceedings of the 5th Canadian Building Science Tech*., Toronto, Canada, March 1-2, pp. 240-257. Interesting paper that reports on measured pressure response of window frames to dynamic air pressures in the laboratory. Both good and bad PE performance of vented window frame designs are documented. Z4, Z5

8. Andersen, N.E., "Summer Condensation in an Unheated Building," *Proc. of Symposium and Day of Building Physics*, Lund University, August 24-27, 1987, Swedish Council for Building Research, 1988, pp. 164-165. The second significant literature mention of solar-driven vapor causing condensation in the summer on interior vapor retarders. The role of ventilation behind the cladding as a solution is not addressed. Z1

9. Anderson, J. M., & Gill, J. R. 1988. *Rainscreen cladding: a guide to design principles and practice*. Butterworth-Heinemann. Classic and influential book of its time—created the pressure equalized rainscreen and back-ventilated categories. Peak of the art just before awareness of widespread failures in North American practise change the conversation (to drainage and water resistant barriers) in the US and Canada. Z1, Z4

10. Anon. 2009. *Stucco in New Residential Construction - A Position Paper* Includes - Updates to Original Information. In: Division, B. I. (ed.). Woodbury, Minnesota: City of Woodbury. Z1, Z6

11. Arce-Recatalá, M., Garcia Morales, S. and Van den Bossche, N., 2020. "Pressure-equalised façade systems: Evaluation of current watertightness test standards used to assess the performance of enclosure components". *Journal of Building Physics*, *43*(5), pp. 369-397. A review of test methods with no critical analysis if any of the methods apply to field performance. Z5

12. Arce-Recatalá, M., García-Morales, S. and Van den Bossche, N., 2020. "Quantifying wind-driven rain intrusion: a comparative study on the water management features of different types of rear-ventilated facade systems". In *Proc of 12th Nordic Symposium on Building Physics.* A European paper that acknowleges air AND water barrier. Testing shows all systems are perfectly pressure equalized by the test conditions. Z4, Z5

13. Arce-Recatala, M.A., Morales, S.G. and Van Den Bossche, N., 2018. "Experimental assessment of rainwater management of a ventilated façade". *Journal of Building Physics*, 42(1), pp.38-67. Quote "Facades are not watertight systems in which the exterior surface of the cladding plays the role of the water shedding surface; the air space is the drainage plane; the exterior surface of the thermal insulation layer acts as water-resistive barrier, and the interior layer of the inner leaf is supposed to be the air barrier." Shows confusion/difference between European and North America views. Z5

14. Arce, Maria & Garcia-Morales, Soledad & Van Den Bossche, Nathan. 2019. "Pressure-equalised façade systems: Evaluation of current watertightness test standards used to assess the performance of enclosure components". *J of Building Physics*, Vol . Z4 Z5

15. AS/NZS 4284:1995. *Testing of building facades*. Z5. An omnibus test procedure including the application of cyclic air pressures during water spray to assess rain penetration resistance. Used mostly in Australia and New Zealand, often for curtainwalls.

16. ASTM C1715-09. *Standard Test Method for Evaluation of Water Leakage Performance of Masonry Wall Drainage Systems*. Z5 Although developed by Krogstad of WJE around 1990, it became a standard much later.

17. ASTM E331-00(2023) *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors and Curtain Walls by Uniform Static Air Pressure Difference*. Z5

18. ASTM E514-20. *Standard Test Method for Water Penetration and Leakage Through Masonry*. Z5

19. ASTM E547-00(2016). *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Differenc*e .Z5

20. ASTM E1105-15. *Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls, by Uniform or Cyclic Static Air Pressure Difference*. Z5.

21. ASTM E2273-18. *Standard Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies*. Z5

22. ASTM E2925-19a. *Standard Specification for Manufactured Polymeric Drainage and Ventilation Materials Used to Provide a Rainscreen Function*. Z5

23. Baheru, T., Chowdhury, A.G., Pinelli, J.P. and Bitsuamlak, G., 2014. "Distribution of wind-driven rain deposition on low-rise buildings: Direct impinging raindrops versus surface runoff". *Journal of Wind Engineering and Industrial Aerodynamics*, *133*, pp.27-38. Wind tunnel study of rain deposition at very high wind speeds on low-rise building. Z7.

24. Baker, F. and Bomberg, M. 2005 "The Functional Requirements for Water Resistive Barriers Exposed to Incidental Water Leakage. Part 1: Classification of Membranes." *Journal of Testing and Evaluation 33*, no. 3 (2005): 1-4. Z5

25. Baker, F. and M. Bomberg 2005. "The Functional Requirements for Water Resistive Barriers Exposed to Incidental Water Leakage. Part 1: Classification of Membranes," *Journal of Testing and Evaluation* 33, no. 3: 1-4.

26. Balderrama JA, Masters FJ, Gurley KR, Prevatt DO, Aponte-Bermúdez LD, Reinhold TA et al. 2011. "The Florida Coastal Monitoring Program (FCMP): A review". *J Wind Eng Ind Aerodyn 99*(9): 979-995.

27. Ball, W.H., 1956. *Exterior Wall Construction.* Building Research Note #26, Division of Building Research, National Research Council, Ottawa, Canada, August. A very early paper that introduced the idea of multiple layers as a means of meeting the competing needs of Canadian enclosure wall. The basic ideas of a drained, ventilated and

pressure equalized (the latter term is not used, but the concept is described) air gap behind cladding is however espoused. Z1, Z2, Z3, Z4

28. Barrett D. 1998. *The renewal of trust in residential construction, Commission of inquiry into the quality of condominium construction in British Columbia*, Government of the Province of British Columbia. Z1

29. Baskaran BA, Brown WC. 1995. "Dynamic evaluation of the building envelope for wind and wind driven rain performance". *J Therm Insul Build Envelopes* 18: 261-275. Z4 Z5

30. Baskaran, A., 1992. *Review of design guidelines for pressure equalized rainscreen walls*. Internal Report 629. National Research Council Canada, Institute for Research in Construction. Although an internal report, this document was widely disseminated at the time and is still available on line. It summarized some of the recent field measurements and provided a good explanation of the state of research at the time. Z1, Z4

31. Baskaran, B. A., & Brown, W. C. 1992. "Performance of pressure equalized rainscreen walls under cyclic loading". *Journal of Thermal Insulation and Building Envelopes*, 16(2), 183-193. Presented some of the NRCC/IRC measured lab results of wall samples exposed to sinusoidal pressures of different magnitude and frequency. The results allowed for an understanding of Z4, Z5

32. Bassett, M. R., & McNeil, S. 2005. "The theory of ventilation drying applied to New Zealand cavity walls". *Proc of 2005 IRHACE Conference*, Nelson, New Zealand, 20-22 May 2005. Z3

33. Bassett, M. R., & McNeil, S. 2006. "Measured ventilation rates in water managed wall cavities". In *Proceedings from the 3rd International Building Physics Conference*, Montreal, Quebec, Canada pp. 403-10. This New Zealand BRANZ research measured ventilation in walls using tracer gas under natural conditions. The predictive equations of the Straube & Burnett (1995) research where shown to follow the observed trends. Z3

34. Bassett, M. R., Burgess, J. C., & Camilleri, M. J. 2003. "The weathertightness of window-to-wall joints–dependency on installation details". In *IRHACE Annual Conference*, Hamilton, New Zealand. Z1 Z5

35. Bassett, M. R., Overton, G., & McNeil, S. 2015. "Water management in walls with direct-fixed claddings". *Journal of Building Physics*, 38(6), 560-576. Z2 Z3

36. Bassett, M., & McNeil, S. 2009. "Ventilating wall cavities above windows". *J of Building Physics*, 32(4), 305-318. Z3

37. Bassett, M., & McNeil, S. 2009. "Ventilation measured in the wall cavities of high moisture risk buildings". *Journal of Building Physics*, 32(4), 291-303. Z3

38. Bassett, M., McNeil, S., & Bennett, J. 2009. "Drainage and Evaporation from Window Sill Trays". *J of Building Physics*, 32(4), 319-333. Z3 Z2

39. Beall, C. 2000. "Rain penetration in building envelopes." RCI *Interface* Magazine. Z1

40. Birkeland O. 1966. *General report on Rain penetration*. NBRI report on *RILEM/CIB Symp. on Moisture Problems in Buildings, Rain Penetration*, Helsinki, August 16-19.

41. Birkeland O. 1968. "The mechanism of rain penetration". *Weathertight Joints for Walls, Proceedings of the International Symposium*, held in Oslo, September 25-28,1967. "On the basis of the knowledge of rain and wind penetration presented in this paper, a principle for designing weathertight joints is given. The rain and wind must be stopped separately. There must be an exterior rain screen, behind which is an air space that is ventilated so there is no wind pressure drop across the rainscreen. Behind the ventilated air space should be an airtight wind stop to prevent air from penetrating through the wall." Z1, Z4, Z6

42. Birkeland, O. and Svendsen, S. 1962. "Norwegian Test Methods for Rain Penetration through Masonry walls". ASTM STP320. Z5, Z6

43. Bishop D, Webster CJD, Herbert MRM. 1968. "The performance of drained joints". Paper No. 64c, *Weathertight Joints for Walls, Proc. of the International CIB Symposium*, Oslo, 1967. Important early paper to discuss drainage as an important function, but focused on joints not walls. Z2

44. Bishop, R. C., & Bassett, M. R. 1990. *Weathertightness of Domestic Claddings.* Study report No. 22. Building Research Association of New Zealand. Z4. A research study of wall systems which applied air pressure and rain simulataneously. Z4, Z5.

45. Bitsuamlak GT, Chowdhury AG, Sambare D. 2009. "Application of a full-scale testing facility for assessing wind driven rain intrusion". *Build Environ* 44(12): 2430-2441. Z5

46. Blackall, T.N. and Baker, M.C. (1984). *Rain Leakage of Residential Windows in the Lower Mainland of British Columbia*, Building Practice Note, Division of Building Research, National Research Council of Canada, BPN-42, pp. 8, November. Z1

47. Blocken, B., Carmeliet, J., "Driving Rain on Building Envelopes—I. Numerical Estimation and Full-Scale Experimental Verification," J. of Thermal Insulation and Bldg Envelopes, Vol 24, No 4, 2000, pp. 61-110. Z7

48. Blocken, B., Carmeliet, J., "Driving Rain on Building Envelopes— II. Representative Experimental Data for Driving Rain Estimation," J. of Thermal Insulation and Bldg Envelopes, Vol 24, No 4, 2000, pp. 61-110. Z7

49. Bomberg, M., Pazera, M., & Onysko, D. 2005. "The Functional Requirements for Water Resistive Barriers Exposed to Incidental Water Leakage, Part 2: Testing Materials". *Journal of Testing and Evaluation*, 33(3), 1-7. Z2

50. Bomberg, M., Pazera, M., Zhang, J., & Haghighat, F. 2003. "Weather-resistive barriers: assessment of their performance". *Research in Building Physics: Proceedings of the Second International Conference on Building Physics*, Leuven, Belgium, 14-18 September 2003., p. 135. Z2

51. Bomberg,M., M. Pazera, and D. Onysko, "The Functional Requirements for Water Resistive Barriers Exposed to Incidental Water Leakage, Part 2: Testing Materials," *Journal of Testing and Evaluation* 33, no. 3 (2005): 1-7. Z2

52. Boyd, D.W., *Driving-rain map of Canada*, Technical Note No. 398, Division of Building Research, National Research Council, Ottawa, Canada, 1963. Z7

53. Brand, R. 1990. *Architectural details for insulated buildings*. New York: Van Nostrand Reinhold. An excellent practical guide to the design of building enclosures exhibiting best practises of the time. Pressure equalization discussed as the best means of controlling rain. Z1

54. British Standards Institution 1992. *British standard code of practise for assessing the expossure of walls to wind-driven rain*, BS 8104, British Standards Institution. Z7 The British standard based on Lacy (1965) work

55. Brookes, A.J. 1998. *Cladding of Buildings*. 3rd Edition. E and FN Spon, London. Some backkground of pressure equalized rainscreens, applied to joints mostly of many moden claddings. No direct discussion of air barriers or drainage planes and drainage is discussed for open joints behind cladding. Z1

56. Brown, N.G. and Ballantyne, E.R. 1972. "Watertight or weatherproof? Wind driven rain and the multi-storey building". Paper No. 6. Melbourne, Division of Building Research, CSIRO, 11 pp. *don't have X*

57. Brown, N.G. and Ballantyne, E.R., 1973. "Watertight or weatherproof—application of drained joint principles". In *Building forum* (Vol. 5, No. 1, pp. 2-8). Z2, Z4

58. Brown, W. C., Chown, G. A., Poirier, G. F., & Rousseau, M. Z. 1999. "Designing exterior walls according to the rainscreen principle". *Construction Technology*, 34, 1-8. This is a general design docoument that discusses drainage and drainage gaps, capillary flow in addition to pressure equalization Z1, Z2, Z4

59. Brown, W. C., Rousseau, M. Z., and Dalgliesh, W. A. 1991. "Field Testing of Pressure-Equalized Rain Screen Walls," *Exterior Wall Systems: Glass and Concrete Technology, Design, and Construction*, ASTM STP 1034, B. Donaldson, Ed., American Society for Testing and Materials, Philadelphia, pp. 59-69. Z4

60. Brown, W., Adams, P., Tonyan, T., & Ullett, J. 1997. "Water management in exterior wall claddings". *Journal of Thermal Insulation and Building Envelopes*, 21(1), 23-43. Z2, Z4. Still relevant study of drainage and pressure equalization of wall assemblies with and without defects.

61. Brown, W., Ullet, J., Karagiozis, A., & Tonyan, T. 1997. "Barrier EIFS clad walls: results from a moisture engineering study. *Journal of Thermal Insulation aand Building Envelopes*, pp. 206-226. Z2

62. Brown, W.C., Ullett, J.M, Dalgliesh, W.A. *Measured Pressure Equalized Performance of a Brick Veneer/steel Stud Assembly: Performance of Pressure Equalized Rainscreen Walls, a Collaborative Research and Development Project*. CMHC, June, 1995. Baskaran BA, Brown WC. 1995. "Dynamic evaluation of the building envelope for wind and wind driven rain performance". *J Therm Insul Build Envelopes* 18: 261-275. Z4 Z5

63. Brown, W.C., Ullett, J.M, Dalgliesh, W.A. *Measured Pressure Equalized Performance Two Precast Concrete Panels: Performance of Pressure Equalized Rainscreen Walls, a Collaborative Research and Development Project*. CMHC, May, 1995. Z4 Z5

64. Brozovsky, J., Nocente, A. and Rüther, P., 2023. "Modelling and validation of hygrothermal conditions in the air gap behind wood cladding and BIPV in the building envelope". *Building and Environment*, 228, p.109917. Z3

65. Building Research Establishment. 1967. *Joints between concrete wall panels: open drained joints*. BRE Digest 85. London: H.M.S.O., 6 pp.

66. Building Research Establishment. 1972. *Principles of joint design*. BRE Digest 137. London: H.M.S.O., 4 pp. Early paper that investigated research results and their impact on design of joints. This included general principles, dimensional tolerance, and etc pressure equalization.

67. Burgess, J. C. 1995. "Air pressure equalization in rainscreened joints by geometric alteration". *Building and Environment*, 30(1), 13-18. An early New Zealand study that investigated the influence of geometry – and hence drainage – as well as pressure equalization of joints. Z2, Z4.

68. Burgess, J. C., & McCardle, G. 2000. "Building cladding air pressure equalisation investigations—comparison between field results and a numerical model". *Building and Environment*, 35(3), 251-256. New Zealand's BRANZ provided some field measurements and predictions of a system installed on a multi-storey buildings.

69. Burnett, E. F. P., Straube, J. F., & Sloof, P., 1994. "The Relative Merits of Zero-Cavity Brick Veneer Walls". *Proc. of the 10th International Brick and Block Masonry Conference*, pp. 369-381. Z1

70. Burnett, E.F., Straube, J.F., Karagiozis, A.K., 2004. *ASHRAE 1091 –Synthesis Report and Guidelines*, ASHRAE, Atlanta. A comprehensive 1000 page study using field, laboratory and computer modeling approaches that demonstrated ventilation drying and inward vapor drives in the field, and provided a summary of how to calculate ventilation airflow rates, the influence of wind and stack effect, and ventilation Z3.

71. Butt, T. K. (2005). "Water resistance and vapor permeance of weather resistive barriers". *Journal of ASTM International*, 2(10), 1-15 and ASTM STP1484. Z2

72. Carmeliet, J. Kubilay, A. Allegrini, J Derome, D. 2019. "New Developments in Understanding Wind-driven Rain Deposition on Building Envelopes and its Consequences". *Proc. Thermal Performance of the Exterior Envelopes of Whole Buildings XIV* (pp. 582-590). American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

73. Choi, E.C. and Wang, Z., 1998. "Study on pressure-equalization of curtain wall systems". *J Wind Engineering and Industrial Aerodynamics*, 73(3), pp. 251-266. A laboratory study of curtainwall spandrel panels and pressure equalization that varied the important variables of vent area, backpan stiffness, etc. Test methodology and laboratory performance results are explained. Z4, Z5

74. Chown, G. A., Brown, W. C., & Poirier, G. F. (1997). *Evolution of wall design for controlling rain penetration*. Construction Technology Update No. 9. Institute for Research in Construction, National Research Council of Canada. Z1 Z4

75. CMHC, *Survey of Building Envelope Failures in the Coastal Climate of BC*. Report by RDH & Morrison-Hershfield for CMHC, Ottawa, Nov. 1996.

76. Cope, A.D., Crandell, J.H., Johnston, D., Kochkin, V., Liu, Z., Stevig, L. and Reinhold, T.A., 2013. "Wind loads on components of multi-layer wall systems with air-permeable exterior cladding". In *Advances in Hurricane Engineering: Learning from Our Past* (pp. 238-257). Detailed wind tunnel study of vinyl siding over wood framed walls. Although well vented, the siding experienced about 65 to 75% of the peak wind loads acting on the entire wall. Z4.

77. Cope, A.D., Crandell, J.H., Liu, Z., and Stevig, L., 2014. "Wind loads on fasteners used to attach flexible porous siding on multi-layer wall systems". *J. Wind Eng. Ind. Aerodyn.* 133, 150-159. Wind tunnel study of fastener loads for vinyl siding over wood framed walls. Concludes that loads on the cladding can be assumed to act directly on the fasteners. Z4.

78. Cornick, S.M. and M. A. Lacasse 2010. "An Investigation of Climate Loads on Building Façades for Selected Locations in the United States." *Journal of ASTM International* Vol. 6, No. 2, pp. 1-33. Z7

79. Cornick, S.M. and M. A. Lacasse, 2004. "A Review of Climate Loads Relevant to Assessing the Watertightness Performance of Walls, Windows and Wall-Window Interfaces," *Performance and Durability of the Wall-Window Interface*: ASTM STP 1484, B. G. Hardman, C. R. Wagus and T. A. Weston, Eds., ASTM International, West Conshohocken, PA and *Journal of ASTM International*, no. 10, pp. 1-15. A good example of work that considers wind pressure coincident with rainfall at return periods more likey to be considered for rain penetration control. Z5 Z7

80. Cutlet J.F. 1980. *Recommended details and general information to overcome water penetration and vapor movement in exterior masonry wall systems*. City of Toronto Masonry Water Penetration Study Committee, 30 pp. A historical document that documented in good technical detail the moisture and rain penetration problems of high-rise Toronto apartments during the 1970's. Z1, Z6. *

81. Dalgliesh,W.A. and Garden,G.K. 1968. "Influence of wind pressures on joint performance". *Proceedings of the International Symposium Weathertight Joints for Wall*, held in Oslo, Norway, September 25-28, 1967. CIB Report No. 11, NBRI Report 51C, January 1968, pp. 329-331. "Rain penetration of joints can be prevented by providing sufficiently large openings in the outer screen so that the air pressure on both sides becomes equally high. However, the wind pressure on all sides of the building is not the same; a certain flow-off around sharp edges will occur. Therefore, pressure equalization is not always achieved in a cavity which is open at two or more locations. The cavity must be closed at strategic locations to prevent air flow behind the outer screen. Knowledge of both the overall and local pressure variations is necessary for full exploitation of the principle of pressure equalization as a means of controlling rain penetration. This paper examines some of the pressure variations caused by corners and projections." Z4

82. Davison, J.I. 1979. *Rain penetration and design detail for masonry walls*. Building Practice Note 13. Ottawa: National Research Council Canada, Division of Building Research, 8 pp. Z1

83. Davison, J.I. 1979. *Rain penetration and masonry wall systems*. Building Practice Note 12. Ottawa: National Research Council Canada, Division of Building Research, 5 pp. Z1 Z6

84. Davison, J.I. 1980. *Workmanship and rain penetration of masonry walls*. Building Practice Note 16. Ottawa: National Research Council Canada, Division of Building Research, 6 pp. Z1 Z6

85. Derome D, Desmarais G, Thivierge C. 2007. "Large-scale experimental investigation of wood-frame walls exposed to simulated rain penetration in a cold climate". *Proc of Thermal Performance of the Exterior Envelopes of Whole Buildings X Conference*, December 2-7, Clearwater Beach, FL, U.S.A., ASHRAE. Z2 Z1

86. Drysdale, R.G. and Suter, G.T. 1991. *Exterior Wall Construction in High-Rise Buildings: Brick Veneer on Concrete Masonry or Steel Stud Wall Systems*.Canada Mortgage & Housing Corporation, 206 pp.. A state of best practise guide of the time for a common wall system of the time. There is no requirement for drainage or water resistant layers behind cladding. Z1, Z2

87. Durst, C. S.,1960. "Wind speeds over short periods of time". *Meteor. Mag*, 89(1056), pp. 181-187. This is an early and still relevant paper that provides the scientific basis for adjusting hourly average wind speeds (and pressures) to shorter-term gusts of more interest to structural design and pressure equalization. Z4

88. Edgar, J., Brown, W.C., and Rousseau, J., 1996. "Noncombustible, Pressure-Equalized Rainscreen Technology to Reduce Leaking in EIFS" *Exterior Insulation Finish Systems (EIFS): Materials Properties, and Performance.* ASTM STP 1269, P. Nelson and R. Kroll Eds. American Society for Testing and Materials. Z4

89. Edgar, J., 1999. "Performance of Source Drainage External Insulation Finish System at the Window/Wall Junction". *Journal of Thermal Envelope and Building Science*, 23(1), 57-77. Z2

90. Eppell, F.J., 1980. "State of the Art Report: Rain Penetration of Masonry", *Proc. Second Canadian Masonry Symposium*, G.T. Suter and H. Keller Eds., June 9-11, Ottawa, Canada, pp. 521-536.* Z1 Z6

91. Eppell, F.J., 1983. "A Report on a Cross Canada Survey of Rain Penetration Risk in Masonry Buildings", *Proc. Third Canadian Masonry Symposium*, J. Longworth and J. Warwaruk Eds., June 6-8, Edmonton, Canada, pp.31-1 - 31-15.*

92. Falk, J., & Sandin, K., 2013. "Ventilated rainscreen cladding: Measurements of cavity air velocities, estimation of air change rates and evaluation of driving forces". *Building and Environment*, 59, 164-176. This is a Swedish study that followed on the North American (Burnett et al, Straube) and New Zealand studies (BRANZ) with basic confirmation. Z3.

93. Falk, J., Molnár, M. and Larsson, O., 2014. "Investigation of a simple approach to predict rainscreen wall ventilation rates for hygrothermal simulation purposes". *Building and Environment*, 73, pp. 88-96. Z3.

94. Fazio, P., S.R. Mallidi, D. Zhu, 1995. "A quantitative study for the measurement of driving rain exposure in the Montreal region", *Build. Environ.* 30 (1) 1–11. Z7.

95. Finch, G., Straube, J., Hubbs, B. and Eng, P., 2007. "Hygrothermal performance and drying potential of wood frame rainscreen walls in Vancouver's coastal climate". *Proc. 11th Canadian Conference on Building Science and Technology*, July. Z3. Field measurements of the dynamic response of walls and the role of ventilation. Z3.

96. Finch, G., Straube, J.F., 2007. "Ventilated Wall Claddings: Review, Field Performance, and Hygrothermal Modeling", *Proc. of ASHRAE Buildings X*, Clearwater, FL. Comparison of field measured hygrothermal performance with computer modeling, providing guidance for ventilation drying. Compare with Falk & Sandin 2013. Z3.

97. Fishburn, C.C, Parsons, D.E., Petersen, P.H. 1941. *Effect of Outdoor Exposure, on the Water Permeability of Masonry Walls*. NBS BMS Report 76, August. One of the first large rain penetration of walls testing studies published in the US. Z5, Z1

98. Fishburn, C.C, Watstein, D., Parsons, D.E., 1938. *Water Permeability of Masonry Walls*. NBS BMS Report 7. October. Oldest serious scientific study of rain penetration that lead to ASTM E514 standard testing. Z5

99. Frank, W., 1973. "Einwirkung von Regen und Wind auf Gebäudefassaden" *Berichte aus der Bauforschung*, Verlag Ernst & Sohn, pp.17-40. Z7. This german study investigated driving rain deposition and wind influences on building facades.

100. FVHF. *Planning and Constructing Rear-Ventilated Rainscreen Façades*. Guideline of Fachverband Baustoffe und Bauteile für vorgehängte hinterlüftete Fassaden, Berlin, 2018.

101. Ganguli, U., & Dalgliesh, W. A. 1988. "Wind pressures on open rain screen walls: Place Air Canada". *Journal of Structural Engineering*, 114(3), pp. 642-656. Probably still the best documented field study of pressure equalization in a high-rise building. An excellent enclosure design that performed very well. Z4

102. Ganguli, U., & Quirouette, R. L. 1987. "Pressure equalization performance of a metal and glass curtain wall". *CSCE Centennial Conference Montreal*, Quebec, May 19- 22, Vol. 1, pp. 127-144. A rare example of a measure pressure response of curtainwall. Z4

103. Garden GK. 1963. *Rain penetration and its control*. Canadian Building Digest, Division of Building Research, National Research Council, CBD40, pp. 401-404. This is a seminal and widely distributed digest that introduced pressure equalization to a wide audience. Drainage was not explicity mentioned and water resistant barriers had not yet been labelled, but it remains a good introduction. Z1

104. Garden, G. K., 1967. "The Problem of achieving weathertight joints". *Weathertight Joints for Walls, Proceedings of the International Symposium*. Oslo, Norway, September 25-28. A discussion of how two-stage joints and pressure equalization can be used to manage rain penetration. Z2, Z4

105. Garden, G.K. 1968. *Look at Joint Performance*. Canadian Building Digest 97. National Research Council Canada, Division of Building Research, 4 pp.

106. Garden, G.k., 1968. "Some experience with joints" . *Weathertight Joints for Walls, Proceedings of the International Symposium*. Oslo,Norway, September 25-28, 1967. CIB Report No. 11, NBRI Report 51C, pp. 249-250.

107. Garden, K. 1971. "Rain and Air Leakage at Joints" *Industrialization Forum*, vol.2 no.4 July p. 7-12.

108. Gavanski, E., and Kopp, G.A., 2012. "Effects of pressure equalization on the performance of residential wall systems under extreme wind loads". *J. Struct. Eng.* 138, 526-538. This paper considers how much load reduction pressure equalization may provide during the extreme wind events that govern most cladding design. Z4

109. Ge, H. and Krpan, R., 2007. "Field measurement of wind-driven rain on a low-rise building in the coastal climate of British Columbia". *In Proceedings of the 11th Canadian conference on building science and technology*, March, Banff, Alberta. One of the few field measurements of wind-driven rain deposition useful for understanding the relative scale of rain penetration load. Z7.

110. Ge, H., Chiu, V. and Stathopoulos, T., 2017. "Effect of overhang on wind-driven rain wetting of facades on a mid-rise building: Field measurements". *Building and Environment*, 118, pp. 234-250. A unique field study of wind driven rain deposition impacted by overhang dimensions. Z7.

111. Ge, H., Nath, U.D. and Chiu, V., 2017. "Field measurements of wind-driven rain on mid-and high-rise buildings in three Canadian regions". *Building and Environment*, 116, pp.228-245. Z7.

112. Gerhardt, H.J. and Janser, F., 1994. "Wind loads on wind permeable facades". *Journal of Wind Engineering and Industrial Aerodynamics*, 53(1-2), pp.37-48. Field and wind tunnel measurements that showed the positive impact of compartmentalizing cavities at the corners of buildings and the possible wind load reductions on cladding. Z4

113. Gerhardt, H.J. and Kramer, C., 1983. "Wind loads on wind-permeable building facades". *Journal of Wind Engineering and Industrial Aerodynamics*, 11(1-3), pp.1-20. Some of the earliest wind tunnel research into pressure equalization of ventilated facades and load reductions, including the impact of corner sealing compartmentalization. Z4.

114. Geurts, C. P. Bouma, P. W., Aghaei, A. 2005. "Pressure equalisation of brick masonry cavity walls". In *Proceedings Fourth European-African Conference on Wind Engineering*. A very brief paper that descreibes field measurements of pressure equalization of brick cavity walls. Turbulence and spatial variations are shown to be important and significant gust pressures are partially (30-50%) moderated. Z4

115. Gigla, B. “Protection of masonry veneer walls against driving rain”. *Mauerwerk*, Dec 2017, 21(6), pp. 391-398. Another representative European paper discussing rain penetration control that shows No WRB is used, and full reliance is placed on cavities and flashing. Z2

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needed for thin 5 mm cladding. Not much about claddings, a focus on joints. A clear acknowledgement of drainage needed. Z1, Z2, Z4

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126. Herbert, M.R.M., and Harrison, H.W. 1974. *New ways with weatherproof joints*. Current Paper 90174. Garston, England: Building Research Establishment, 12 pp Z2 Z4

127. Hutcheon, N.B. 1953. "Fundamental Considerations in the Design of Exterior Walls for Buildings." *Proc. 47th Annual Meeting of the Engineering Institute of Canada*, Halifax, NS, May. A fundamental paper about modern multi-layer wall design. Z1.

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LITERATURE REVIEW REPORT
RAINSCREEN PERFORMANCE

RAINA
RAINSCREEN ASSOCIATION
IN NORTH AMERICA