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TO **Mr. Antoine Habellion**
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ROCKWOOL -
Summary Report of Air Permeance and Wind Washing
DATE April 11, 2018

Dear Mr. Habellion,

As requested by ROCKWOOL, RDH Building Science Laboratories (RDH) is pleased to provide you with this summary report explaining the building science physics of wind washing, including some previous laboratory testing on the air permeance of stone wool insulation.

Yours truly,

[signature omitted for publication]

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Literature Review, and Research Summary on Wind Washing of Air Permeable Insulation

Introduction

Modern enclosure design favors the use of exterior continuous insulation (ci) over the supporting structure. This approach has long been favored by building science research because of its excellent thermal performance, condensation resistance, and enhanced durability provided to the materials installed inside of the insulation (Hutcheon 1964). More recently, this design concept has been championed as the "perfect wall" (Lstiburek 2007) shown in Figure 1.

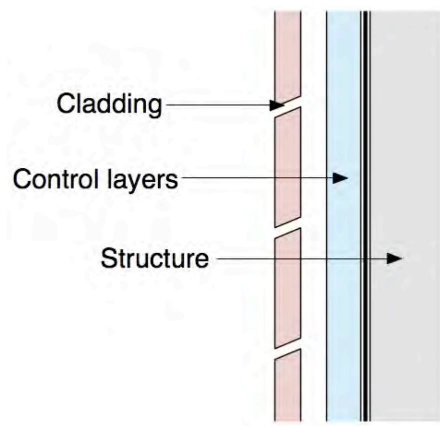

Figure 1: The "perfect wall" concept (Lstiburek 2007)

In a typical well-designed ci assembly, the air and water control (air barrier and water-resistant barrier) is a single membrane placed over the support structure and protected by a layer of continuous exterior insulation (Figure 2). In many enclosure walls, well-vented and even open-jointed cladding is installed over an air gap of ½" to 2" (12 to 50 mm) depth to provide a ventilated space behind the cladding and outside the continuous insulation. The flow of outside air through the gaps into the space behind the cladding – i.e., ventilation – is beneficial for encouraging drying of the back of the cladding and any undrained rainwater or condensation retained on or within the cavity.

Vents through and air gaps (i.e., cavities) behind wall cladding are a common feature of many new wall designs, and have been part of many traditional wall systems. The importance of these air gaps to the performance of walls has been a topic of significant research over the past few decades.

An air gap can provide (Straube 1995, 1998, 2005) a:

- Capillary break.
- Drainage path.
- Ventilation path (for removing moisture, not heat).
- Means of accommodating dimensional tolerances.
- Pressure chamber to enhance the pressure moderation performance.

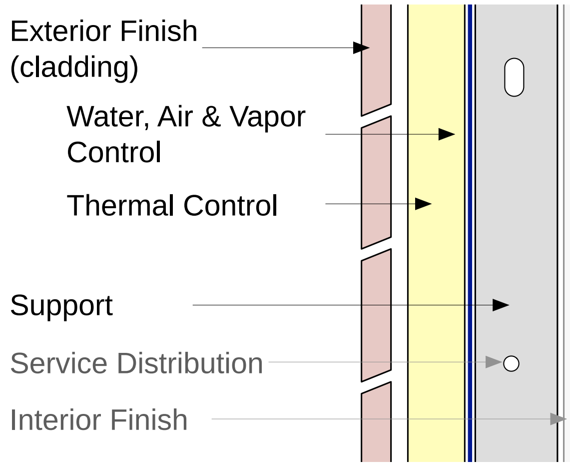

Figure 2: Modern enclosure wall with continuous insulation and exterior air and water barrier

Not all of these functions are needed in all wall designs and several functions can be provided by alternate means. Some of these functions are part of a wall's rain control strategy, helping to avoid wetting (e.g., a pressure moderation and capillary break) and/or improving drying (e.g., drainage and ventilation).

The depth of the air gap cavity varies from a few mm (1/8") to over 75 mm (3"). Vent area varies even more widely between different cladding systems. For example, masonry veneer systems have some of the lowest total vent areas (Van Straaten and Straube 2004a) and open-jointed panel cladding systems may have as much as 100 times as much vent area (Straube 1995).

As different systems have proliferated and become more widely adopted, a wide range of terms have been developed to describe them. The diversity and lack of precision can sometimes result in confusion, and hence some clarification may be useful.

A **drained cladding system** employs a specific rain control strategy: the cladding is assumed to allow water to pass, and a drainage layer (water-resistant barrier) and drainage gap (as small as a fraction of a millimeter) collect and drain the water back to the outside.

A **vented cladding system** is one which has openings that allow some degree of connection between the outdoors and the gap behind the cladding, but whose vent area and distribution is such that little to no airflow occurs, although diffusion is encouraged.

A **ventilated cladding system** uses relatively large vent openings to connect the outdoors to an unobstructed air gap behind the cladding in such a manner that air flows in one vent and out another via the air gap.

Figure 3 illustrates the differences between these three systems.

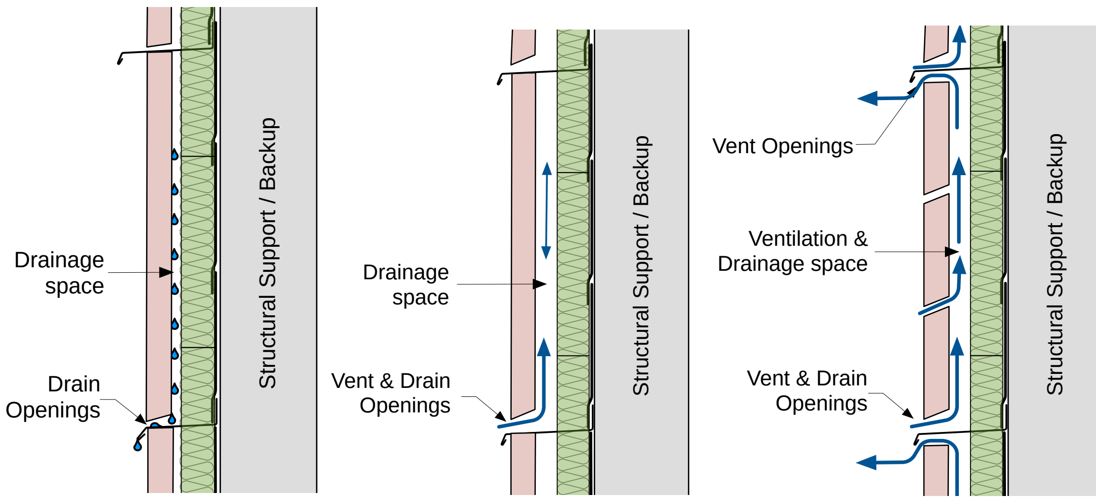

Figure 3: Drained (left), vented (middle), and ventilated (right) cladding systems

Wind Washing

Although ventilated cladding systems and continuous insulation have been in use continuously for over 50 years, the prevalence of this new method in North America has raised new questions about material selection and construction details to ensure good performance.

One of the concerns raised, especially with highly-vented and open-jointed cladding systems, is the risk of *wind washing*. Wind washing *is air movement driven by wind pressures through or behind the thermal insulation* within enclosures. Sometimes described as the “knitted sweater effect”, this bulk movement of air increases heat loss resulting in more energy consumption, greater risk of condensation on cooled surfaces, and higher space heating/cooling loads.

Wind washing airflows are driven by wind-induced air pressure differences which form over the face of a building (pressure gradients). Tall buildings and exposed sites experience the highest wind speeds. Wind pressures and gradients increase with the square of wind speed. The wind pressure gradients that drive wind washing are largest near building corners and parapets. Hence, wind washing is a serious concern at the corners of a building, where wind pressure gradients are large, although it can be a problem in the field of the wall as well. Figure 4 presents the typical shape of the pressure profile that forms around the corner of a building when the wind blows on one face.

In walls with vented cladding over air gaps, airflow will occur behind the cladding through the air gaps (Figure 5). This is desirable as it supports the drying objective of the air gap. However, if the airflow velocity rises too high, or if the material properties or assembly are improper, the airflow can pass through or behind the insulation and result in much more heat loss than assumed in design.

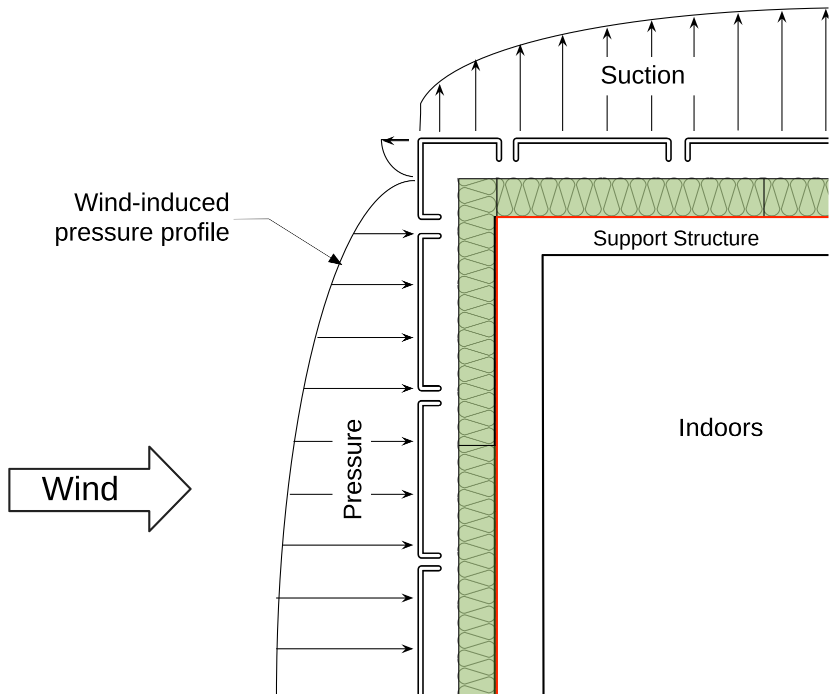

Figure 4: Typical pressure profile by wind action at a building's exterior corner

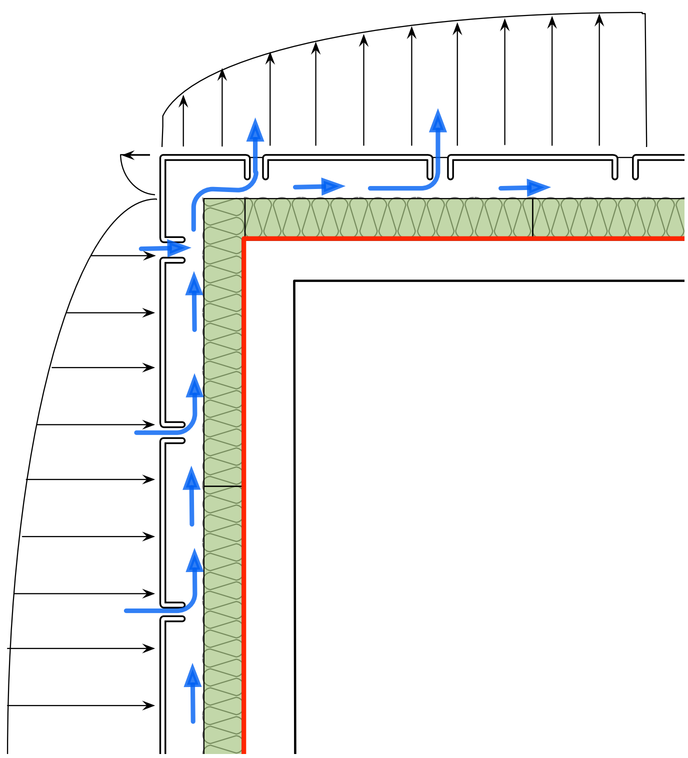

Figure 5: Airflow path through vented cladding and air gap

Two very different types of wind washing can occur: wind-driven airflow over and through air permeable (fibrous) insulation (Figure 6) and airflow behind insulation of all types (Figure 7). For air to flow behind the insulation, gaps must exist both behind the board and between joints to form a complete flow path.

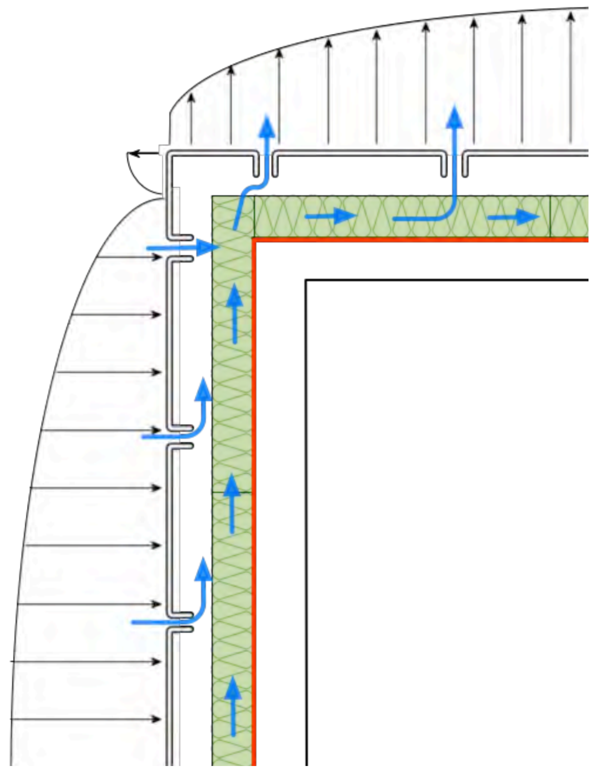

Figure 6: Wind washing – airflow passing through air permeable insulation

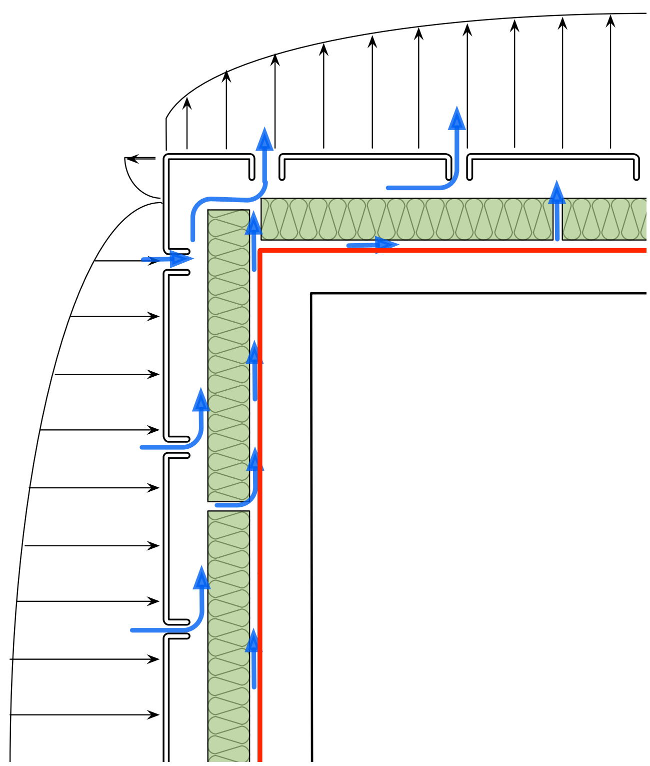

Figure 7: Wind washing – airflow passing behind and around insulation

The most common problem experienced in the field is airflow passing behind or around layers of insulation. Rarely is this a problem with materials or design: the insulation boards must be butted tight together and be pressed tight to the air barrier behind them on the warm side. Figure 8 is a photograph of a school under construction which was built with a ¼" (6 mm) gap behind the insulation for a significant proportion of the enclosure. This building did not experience in-service problems because the joints were butted tight and the cladding was vented sparingly (it was a vented and drained system).

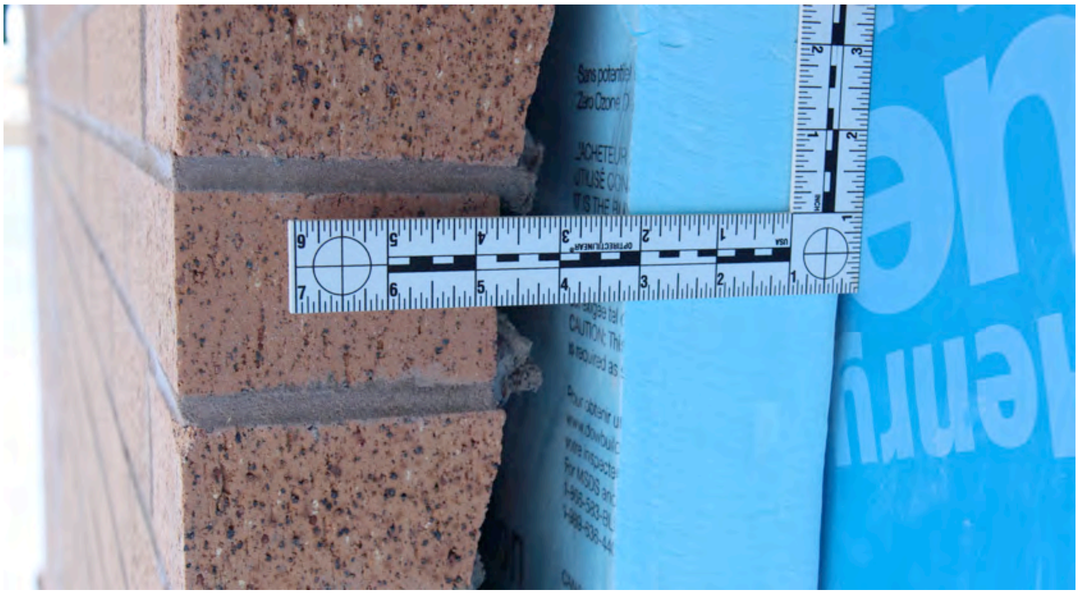

Figure 8: Actual air gap (1/4" or 6 mm) measured behind insulation on a school enclosure

Previous Wind Washing Research

Historically, wind washing was first identified as a performance concern in framed walls with air barriers located near the inside surface: e.g., gypsum wallboard or polyethylene sheet air-vapor barriers inside of low-density, air permeable fibrous insulation. Bankvall (1978, 1987a, 1987b) produced a series of papers that reported on wide-ranging Swedish research of the impact of airflow on insulation performance for such walls. Wind washing was identified as a concern for low-density insulation, but poor workmanship (i.e., large gaps between or around the insulation) or air leakage through the wall are required for significant impacts to thermal performance. Exterior "wind barriers" at the exterior sheathing layer were proposed and demonstrated to mitigate the effects.

More than a decade after this work, Uvslokk (1996) presented further detailed field measurements of wind washing for similar wall construction: ventilated cladding, wood framing, interior air barrier and leaky or non-existent exterior sheathing. The research quantified the amount of airtightness required to protect cavity insulation, and reported on extensive field pressure measurements within ventilated gaps behind claddings. Hotbox testing replicated the field pressures and measured heat flow through walls insulated with 150 mm (6") thick batts made of 31.9 kg/m^3 (2 pcf) stonewool or 21 kg/m^3 (1.3 pcf) glass fiber. The results showed that some resistance to airflow was required exterior to the sheathing to protect insulation inside the stud cavity, and Scandinavia adopted exterior wind barrier performance requirements in wood-framed house construction.

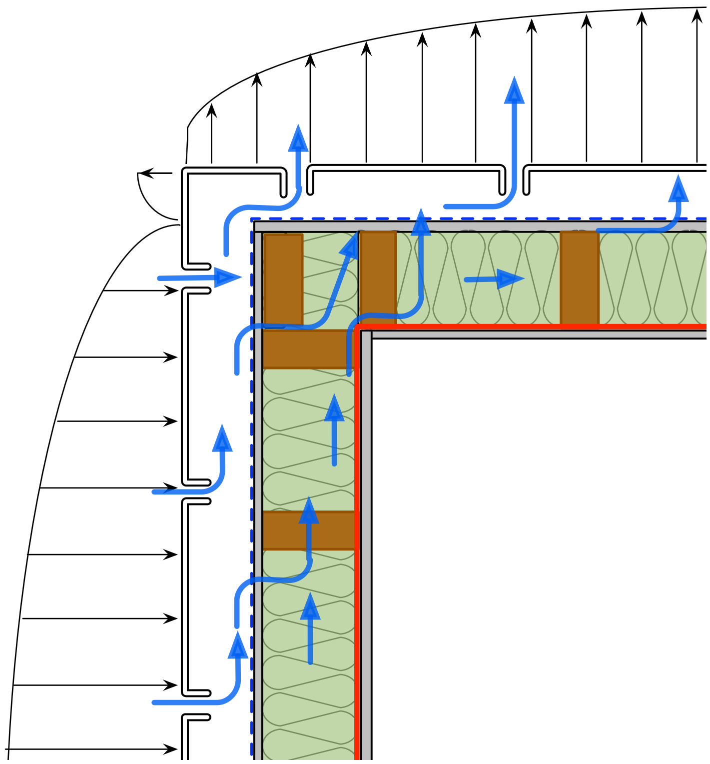

Figure 9: Wind washing flows through insulation within framed wall

Timusk et al. (1991) conducted applied research in the field and laboratory in Canada to identify the problem of wind washing within stud cavities filled with low-density fiberglass batt insulation for the case where the air barrier was located near the interior surface (polyethylene sheet in this case). They concluded that “deficiencies in the sheathing can lead to wind cooling of exterior corners, resulting in an increase of heat loss and, in houses with relatively high indoor relative humidity, in condensation and mould growth on wall surfaces.” The paper proposed and demonstrated via laboratory and field testing that “this can be controlled by moving the air barrier from its customary location on the warm side of the insulation to the cold side where it is easier to make continuous.” This was some of the first North American research that supported the move of the air barrier to the exterior of the wood framing.

Detailed research continued into understanding wind washing using increasingly sophisticated methods in the 1990’s. Silberstein (1991) conducted a laboratory hot box study (of heat loss) and field study (of air cavity velocities) and concluded: “forced convection does not significantly affect the thermal properties of the insulation under the air velocities usually found in the cavities, unless the construction mode and/or workmanship allow multiple air entry zones, or discontinuities in the insulation or in the internal air barrier.”

An extension and update of this research (Siberstein and Hens 1996) stated “To evaluate the effect of air flow along the insulation on the increase of the heat transfer across the material, one must consider: the velocity in the ventilation space (depends on the geometry and the pressure gradient along the airspace); the air permeability of insulation (depends on product homogeneity, density, and specific surface of fibres); the pressure gradient across the insulating material; and the air permeability of the roofing system.”

But again they concluded that windwashing would not be a material risk for normal applications.

The use of continuous insulation outside the support structure behind ventilated cladding had become very popular in Europe by the 1990's and hence research investigated this application to confirm that the previous research could be applied to this type of construction. Tanner (1996) reported on Swiss EMPA hot box research conducted in 1990. For mineral fiber insulations (glass fiber and stone wool) with densities between 20 and 62 kg/m^3 (1.25 to 4 pcf) and cavity air velocities of 0.3 and 1.0 m/s (60 to 200 fpm), there was "practically no influence" on the measured thermal performance. Hens (2007) summarized many years of field measurements behind vented brick veneer and concluded no wind washing effect was discernible for these poorly ventilated walls with exterior continuous insulation.

Wind washing can still be a practical problem in the field. Cummings and Withers (2012), for instance, provide examples of wind-driven flows through low-density batt insulation used in knee-wall construction when the insulation is not installed in contact with the air barrier. However, the focus of most research in Europe and North America has shifted to the positive role ventilation plays in drying, as the role of wind washing appears to be well answered.

It should be noted that a recent computational fluid dynamics (CFD) computer model study (Doggett and Brunjes 2016) reported quite different results: the predicted airflow velocities were much higher than measured in the field and wind washing was predicted to significantly increase heat losses (up to 42%). These results are at odds with essentially all the physical measurements in the lab and the field reported above, and perhaps are most useful as a cautionary tale of how computer models, regardless of their complexity, can result in wildly inaccurate predictions if not validated against actual measurements.

Airflow Behind Ventilated Claddings

The rate of airflow through air gaps directly behind cladding relates to the potential thermal impact due to wind washing. Hence, this section reviews the airflow velocity that might be expected. Significant research has been conducted to understand the air velocity, as the air change rate of the air gaps relate directly to the potential for drying that is a primary goal of providing air gaps[1].

Comprehensive and practical early work was documented by Liersch (1981) but was based on little research. Subsequently, the airflow through the cavity behind ventilated cladding has been studied theoretically (Straube and Burnett 1995, Anderson 2000, Straube et al. 2004, Davidovic et al. 2012, Stoval and Karagiozis 2004) and measured in both the lab (Van Straaten and Straube 2004b, Smegal and Straube 2004, Smegal 2006, Straube and Smegal 2007, VanStraaten 2004) and the field (Schwartz 1973, Kuenzel and Mayer 1983, Jung 1985, Gudum 2003, Van Straaten and Straube 2004a, Falk and Sandin 2013, Nicolajsen 2016).

In some of the most sophisticated testing, BRANZ measured ventilation rates behind numerous cladding systems mounted on a test hut using tracer gas (Basset and McNeil

[1] Unfortunately, some of the research related to wall drying often does not directly measure or report the velocity.

2009) and validated the theoretical estimating methodology developed earlier by others (Straube and Burnett 1995, Straube et al. 2004).

Finally, Van Straaten et al. (2016) recently outlined the range of air gap velocities that could be expected for a wide range of building types, exposures, and cladding designs.

In almost all cases reported in the literature (Table 1), ventilation velocities and air change rates have been measured for intentionally ventilated walls, with relatively large vents, large clear cavities, and vent openings located at the top and the bottom of the air gap or at all joints (open-jointed cladding). Typically, in-service ventilated walls with discrete vent holes (usually 3/8" to 1" in dimension [3 to 25 mm] spaced 0.3 to 0.9 m [1 to 3 feet] apart at both the top and bottom of an air gap) tend to have an order of magnitude (and more) less airflow and often velocity cannot be measured, and air exchange is measured instead (Sandin 1991, Hens 2007). This means that the cavity airspeed experienced by typical vented wall assemblies in-service will be much less than the cavity airspeeds in Table 1.

TABLE 1: SUMMARY OF VELOCITIES MEASURED IN THE FIELD BEHIND CLADDING BY VARIOUS RESEARCHERS

REFERENCE	CLADDING AND EXPOSURE	WINDSPEED (m/s)	CAVITY AIRSPEED (m/s)
Schwartz (1973)	Open slots to 40 mm cavity behind smooth panels in 18-storey building	0-8 m/s	0.2-0.6 m/s
Künzel and Mayer (1983)	Open slots to 20 mm cavity behind smooth panels in 3-storey building	3 m/s	0.06-0.16 m/s
Nicolajsen (2016)	Open slot, 3 m tall panels, 1-storey building	0-10 m/s	0-0.2 m/s
Gudum (2003)	Top and bottom slot to 25 mm clear cavity in small 1-storey test building	0.7-2.1 m/s	0.12-0.27 m/s
Falk and Sandin (2013)	Open slots to 25 mm cavity behind smooth panels in 1-storey test building	0-5 m/s	0.15-0.30 m/s

RDH Measured Thermal Impact of Wind Washing

An experimental program was undertaken to confirm the existing scientific understanding of wind washing and demonstrate that modern building insulation products could perform well. Inspiration was taken from a previous experimental apparatus described by both Yarborough (1983) and Silberstein (1991), with improvements in measuring accuracy and control.

The measurement concept is simple: air is drawn over a 1625 mm (64") length and 48" (1.2 m) width of guard heater before reaching a 406 x 406 mm (16"x16") square meter section, d, where the heat flow is measured. A uniform temperature is imposed across the sample and the heat flow measured at the meter section for a wide range of velocities. Van Straaten et al. (2016) outlines more details.

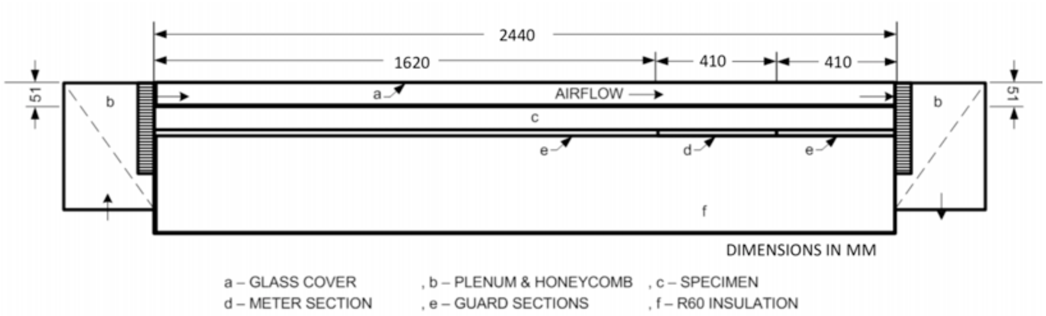

Figure 10: Schematic section of wind washing test apparatus

A number of different mineral fiber insulations (both glass fiber and stone wool) with densities from 16 kg/m³ (1 pcf) to 128 kg/m³ (8 pcf) were tested. As a comparison an expanded polystyrene (EPS) foam board with an airtight laminated plastic film was tested.

The loss in thermal resistance (in RSI) is plotted for each sample in Figure 11 as a function of air gap air speed between zero and 1 m/s (near the top of the likely range of velocities expected based on the literature review). It can be seen that only the low-density fiberglass batt (FG) products exhibit a measurable impact: about a 5-8% reduction in thermal resistance. The impact on the other stone wool (SW) products is small, close to the range of error of the equipment. Regardless, the reduction is at most RSI0.03 (R-0.2).

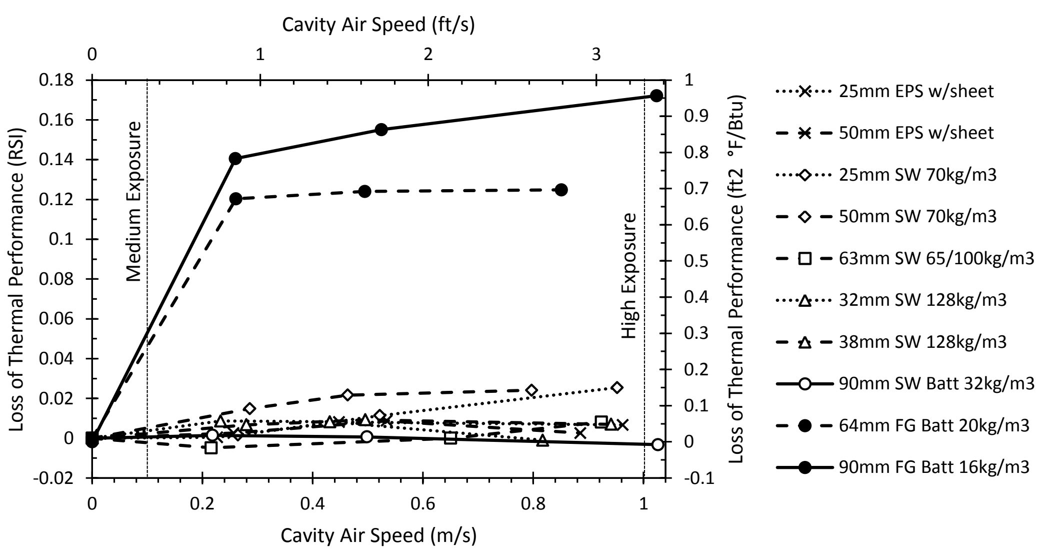

Figure 11: Measured impact of wind washing from laboratory measurements (R-value= RSI*5.678)

This study has both verified previous research by others and extended the results to align more directly with modern materials and practice in North America.

Mitigating Wind Washing Risks

The extensive research, spanning many decades, presented above indicates that wind washing can occur, but can also easily be avoided. Poor design choices, inappropriate materials, and bad workmanship can result in poor performance in some situations. Several strategies that can reduce wind washing risk are shown in Figure 12.

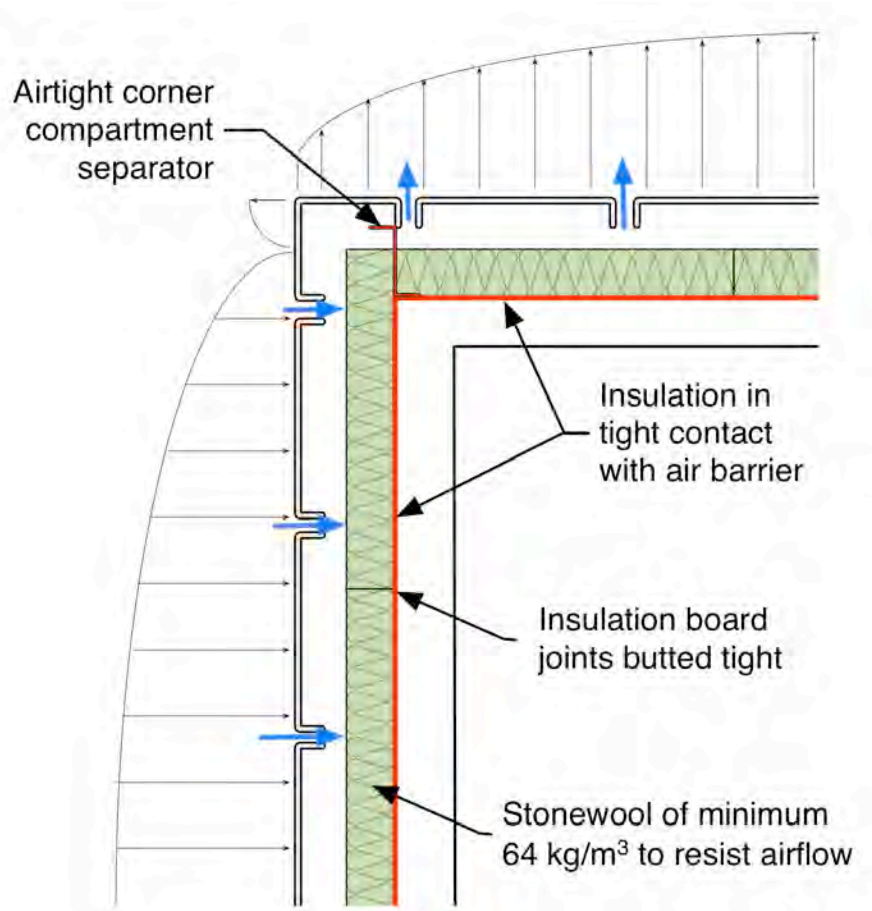

Figure 12: Several strategies to minimize the risk of wind washing are available

Conclusions

This extensive review of past field and physical laboratory research has reinforced several strong conclusions. Many researchers from different countries working in different decades have developed a solid understanding of the nature and rate of airflow behind ventilated claddings. To a lesser but considerable extent, the impact of wind washing on the thermal performance of insulation is understood. All of the physical testing (in the lab and the field) shows that the airflows expected in ventilated claddings will only have a meaningful impact on thermal performance if:

- Insulation is low density and high permeance (in practical terms, this means fibrous insulation of around 1 pound per cubic foot or 16 kg/m^3 density or less), or
- Exterior insulation is not placed in substantial contact with the air barrier (which is often also a water barrier) or to a far lesser extent has large gaps between the boards.

The velocities of airflow in the air gap behind ventilated cladding will generally be below 200 feet per minute (1 m/s) in almost all types of buildings, exposure, weather conditions, and cladding designs. Less exposed and lower-rise buildings and systems with less venting than full open joints are likely to see velocities much lower than this, perhaps in the 20 fpm (0.1 m/s) range even during windy conditions.

Although one computer modeling study of ventilated claddings conducted without field validation reached different conclusions, this can safely be discounted until careful validation of the modeling with field measurements is completed.

There is no risk to wind washing of low density insulation inside the wall cavity if there is an air control layer to the exterior of the sheathing.

In all practical designs airflow through the air barrier system (air leakage) is a much larger and more significant factor, which requires and deserves attention during design and construction.

Recommendations for Practice

The literature review leads to several well-supported recommendations for practice for enclosure assemblies that use exterior continuous insulation behind vented or ventilated cladding systems:

- Place exterior insulation in tight contact with the air barrier to avoid airflow through small gaps behind the insulation[2]. This can be a challenge for stiff board insulations, and hence more pressure, flatter substrates, or more flexible boards may be needed.
- Avoid large gaps (over about 1/8") between boards of insulation (which can lead air to any gaps behind the insulation).
- Avoid very high air permeance products for well-ventilated claddings with large ventilation gaps, that is, specify stone wool products with a density of more than about 64 kg/m^3 (4 pcf) or a dual density product.
- Designers should avoid over-ventilation and excessively large air gaps. The benefits of ventilated gaps diminish rapidly as the gap increases in size above about 1" (25 mm). Large vent areas and large ventilation gaps incur the risk of additional direct rainwater entry, increase problems with animal infestation, and have higher risks of fire spread among other disadvantages.

Sincerely

[signature omitted for publication]

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[2] Special systems, such as drained EIFS and draining housewrap behind board insulation, use small, under 1/8" air gaps, to provide drainage behind the insulation. For these to perform, the cladding should be vented only (not ventilated) and corner separators should be used (implicitly provided in most of these systems).

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