UNIVERSITY of TASMANIA

MOISTURE ACCUMULATION AND MOULD GROWTH FOR 6 STAR AND 7 STAR HOUSING

Research Report 4: Final Report

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Acronyms

AAC	Autoclaved Aerated concrete
ABCB	Australian Building Codes Board
ACH	Air Change per Hour
ACR	Air Change Rate
ACR(1h)	Air Exchange Rate in 1 hour
BCA	Building Code of Australia (NCC was named Building Code of Australia between 1988 and 2010)
AEH	Air Exchange per Hour
AIA	Australian Institute of Architects
AIBS	Australian Institute of Building Surveyors
AIRAH	Australian Institute of Refrigeration, Air-conditioning and Heating
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
AS XXXX	Australian Standard
BRANZ	Building Research Association of New Zealand
BS XXXX	British Standard
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
CZ	Climate Zone.
DTS	Deemed to Satisfy provisions within the NCC
FWPA	Forest and Wood Products Australia
EA	Engineers Australia
EPW	Energy Plus Weather file format
HIA	Housing Industry Association
ICMB	International Conference on Moisture in Buildings (Hosted by University College London)
MI	Mould Index
MBAV	Master Builders Association of Victoria
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
OECD	The Organisation for Economic Co-operation and Development
RH	Relative Humidity
RMY	Reference Meteorological Year
UK	United Kingdom
US	United States of America
VBA	Victorian Building Authority
WDR	Wind Driven Rain
WHO	World Health Organisation
WUFI	Wärme Und Feuchte Instationär
VTT	VTT Technical Research Centre of Finland

Terms

Air Changes per Hour	This is the traditional method to quantify air quality and minimum rates of ventilation. This was originally achieved by conducting experiments with Tracer Gas to establish rates of air changes per hour within a room, or a building. Due to the complexity of this method and the development of building pressurisation testing in the 1970s, this method has generally been replaced by the ACR method.
Air Change Rate	This is based on the amount of infiltration and exfiltration that results through a building's external envelope, per hour. An internationally accepted 'rule-of-thumb' to convert ACRn50 to ACR/ACH/AEH is to divide the ACR value by 20 (ACRn50/20 = ACH). ACRn50 of 10 = ACH of 0.5.
ACRn50	This is based on the amount of infiltration and exfiltration that result from a 50 Pascal building pressurisation or depressurisation. This is different to the traditional ACH (air changes per hour), that exists in most older standards and regulation. Some documents may refer to AEHn50 and ACHn50, which are generally the same metric.
Air Exchange per Hour	The hygrothermal simulation software requires an input for AEH. For ACH values from 0.25 to infinite can be used within this function. When an AEH value becomes less than 0.25, a building is required to have mechanical ventilation for fresh air within habitable spaces. Within this context, the simulated AEH should not be less than 0.25.
Air Exchange Rate	This is a very similar term to ACH/AEH/ACR and is commonly used when calculating the required mechanical ventilation to ensure an adequate interior air quality. Typically, building simulation software include an ACR(1h) data input.
Building Code of Australia	Building Code of Australia – The NCC was called the Building Code of Australia between 1988 and 2010.
Bio-Hygrothermal	An analysis method that considers moisture and heat conditions, combined with material properties, that may promote mould growth on the surfaces of and within wall, floor or roof systems.
Built fabric	Built fabric refers to manufactured elements that are used to create constructed spaces, such as buildings, landscapes or a bush shelter.
Climate zone	The National Construction Code has eight climate types, whilst the Nationwide House Energy Rating Scheme (NatHERS) has sixty-nine climate types.
Dew point	When the relative humidity, discussed below, reaches 100%, the air can no longer hold the moisture in vapour form and the moisture condenses. A simplified formula to calculate the dew point temperature under normal conditions is; Td = T - ((100-RH)/5). Applying this formula to a room in a home when the interior temperate is 230C, and the relative humidity is 75%: Td = T – ((100 – RH) / 5) Td = 23 – ((100 – 75) / 5) Td = 18.00C Moisture will form on any surface within the room that is less than, or equal, to 18.00C. An example of this is phenomena is condensation of single glazed window or on a can of soft-drink that has just been taken out of a refrigerator.
Empirical Validation	The comparison of simulated and measured results to inform software calibration.
External wall system	All modern building envelopes incorporate several elements combined to make a system. For example, a brick veneer wall may include from the outside to the inside: A 110mm unpainted extruded clay brick,

	A 40mm vented air cavity, A 1mm pliable building membrane, A 90mm timber or steel wall frame that contains compressible wall bat insulation, A 10mm paper faced plasterboard board lining, and An Acrylic painted surface. Each of these elements will have different structural, durability, conductivity, water vapour resistivity, thermal capacitance and density properties. When considering the hygrothermal performance of a wall system, the flow of energy and water vapour needs to consider all these different physical attributes.
Hygrothermal	The combination of heat and moisture.
Interstitial	As described above, wall systems, (and floor and roof systems) comprise many elements with different physical properties. The space and materials between in the interior surface and exterior surface are classed as Interstitial. Interstitial mould growth, is mould growth that is occurring somewhere within the wall system.
Mould Index	Developed by Hannu Viitanen and Tuomo Ojanen, the Mould Index refers to the amount and mould that may grow on, and within a wall, floor, or roof system. It should be noted that most mould growth calculation methods can't calculate a MI greater than 5.0. For this reason, no graphs show a MI greater than 5.0.
NatHERS	Nationwide House Energy Rating Scheme
National Construction Code	"The National Construction Code is Australia's primary set of technical design and construction provisions for buildings. As a performance-based code, it sets minimum required levels for the safety, health, amenity, accessibility and sustainability of certain buildings." (ABCB 2022).
Relative Humidity	All air contains moisture in the form of water vapour. As air temperature increases, it can contain hold more water vapour, and as it cools, it needs to hold less water vapour. Generally, the term Relative Humidity indicates the amount of water vapour the air can contain. O% RH = no water vapour in the air, 100%RH = saturation or dew point conditions.
Thermal Bridge	All elements used to construct a floor, roof or wall system have a conductivity value. This is the rate at which a material conducts energy. Whilst steel has a very high conductivity value, insulation products have a very low conductivity value. Within a wall system some elements may have a higher conductivity value than others, leading to 'thermal bridges' within the built fabric.
WUFI	Wärme Und Feuchte Instationär, when translated means the transient calculation-based analysis of heat and moisture transport through elements and systems. An 'element' is an item (such as a concrete block), while a 'system' is a collection of elements that make up a component of a building envelope (i.e., Acrylic paint, plasterboard, insulation, building membrane, vented air space, extruded clay brick). The WUFI software was developed and owned by the Fraunhofer Institute of Building Physics (IBP). The Fraunhofer Institute is very similar in nature to the CSIRO in Australia. The WUFI software has undergone empirical validation in Europe, United Kingdom, Canada and the United States of America.
WUFI VTT	The WUFI software includes internationally tested and empirically validated 'add-ons' for graphing data, mould risk and corrosion risk. The WUFI VTT acronym stands for the WUFI software that incorporates the VTT Technical Research Centre of Finland's mould growth calculation method developed by Hannu Viitanen and Tuomo Ojanen.

1. Preamble

This research is not being undertaken to undermine or diminish the need for net zero homes and non-residential buildings. This research highlights the need for the co-development of energy efficiency, hygrothermal, weather proofing and ventilation building regulations. This research activity is conducted in response to national and Victorian concerns about the increased presence of moisture and mould within new buildings. The activities within this research project include the hygrothermal simulation-based assessment of mould growth risk in regulatory compliant 6 Star and 7 Star new homes in Victoria. The full Moisture Accumulation and Mould Growth research included four key outputs (to be delivered across 2022 and 2023), namely:

- Research report 1 - Moisture accumulation and mould growth risk for 6 Star housing,
- Research report 2 - Moisture accumulation and mould growth risk for 7 Star housing,
- Research report 3 - Enhancements to 6 Star and 7 Star external wall systems for Class 1 and Class 2 housing in Victoria, and
- Research report 4 – Final report, which summarises the research background, research methods, research results and recommendations (this report).

This report collates the key findings and recommendations from the research reports (Research Report 1, Research Report 2 and Research Report 3) that explored simulation-based mould growth risks that may be present in the external walls of Class 1 and Class 2 buildings, as constructed to the 6 Star and 7 Star energy efficiency standard and the health and amenity requirements of National Construction Code (NCC) 2019 [1, 2] and 2022 [3, 4]. Research Report 1 focussed on the external wall systems described within NCC 2019 to meet the 6 Star energy efficiency and condensation Deemed-to-Satisfy (DTS) requirements [1, 2]. Research Report 2 focussed on the external wall systems described within NCC 2022 to meet the 7 Star energy efficiency and condensation Deemed-to-Satisfy (DTS) requirements [3, 4]. Whereas research Report 1 adopted the DTS requirements for insulation and condensation, Research Report 2 applied the Nationwide House Energy Rating Scheme (NatHERS) [5] method to establish external wall insulation requirements and the DTS method for condensation requirements. Research Report 3 applied the same external wall systems that were simulated in Research Report 2, but then explored increasing water vapour diffusion properties of the weather resistive layer, adding a vented and drained cavity, and adding an interior membrane as actions to achieve a Mould Index (MI) of <3 and <1. Whereas NCC 2019 focussed on Condensation, NCC 2022 applied the internationally accepted Mould Index (MI) method, whereby in Australia, an external wall system should have a MI of <3.

The other key difference between Research Report 1, Research Report 2 and Research Report 3, is external climate data. Research Report 1 and Research Report 2 applied the NatHERS 2003 to 2021 Reference Meteorological Year (RMY) climate data, that did not include precipitation data. Research Report 3 applied the 2022 NatHERS RMY climate data, with hourly precipitation data added.

Mould growth in housing is internationally recognised as a cause of many short-term and life-long human health conditions [6-10]. Based on the international experiences and what was being observed in Australian buildings, concerned individuals, industry representatives and researchers have raised concerns since 2013. University of Tasmania research in 2019 highlighted that Australia had twice the Asthma rate of other developed nations that have had condensation and mould related building regulations for between two and six decades [11, 12]. For this reason, the first stage of regulatory development focussed on new clauses within Health and Amenity, and not Energy Efficiency sections of the National Construction Code. This is an important recognition of two key differences between condensation and mould growth, namely:

- Condensation occurs when the relative humidity reaches 100% or the mix of moisture in the air and air temperature reach saturation temperature.

- Mould growth occurs in areas of low ventilation when the relative humidity reaches 60% and in well-ventilated areas when the relative humidity is above 70% (e.g., a room may be well ventilated by cross ventilation when windows and doors are open but be poorly ventilated if only a single window is open. Similarly, the air in the middle of a room may be easily exchanged via ventilation, whilst low corners and areas around some furnishings or cupboards may be poorly ventilated).

This shows that mould growth occurs well before condensation occurs, and that a house may have no presence of condensation but have the visible and unhealthy presence of mould. The World Health Organisation states that the visible presence of mould within buildings has been linked to increases in medical conditions [13].

Within this context, this research has analysed the risk of surface and interstitial mould growth within typical external wall systems used in the construction of new housing in Victoria.

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2. Executive Summary

This report is the final report for the research activity that explored the simulation-based analysis of moisture and mould that may be occurring within the external wall systems of 6 Star and 7 Star houses in Victoria. A simulation approach is taken due to the urgency identified by design and construction professionals regarding the presence of mould and moisture in new homes. To date, most of the research in this area has been forensic analyses of homes that have concerning amounts of moisture and mould. Forensic analysis can be used to calibrate simulation tools, but not to inform change. Once a new home is constructed, owners often have a financial commitment with a financial institution for one of more decades. Similarly, the financial institution owns the building, until the loan has been paid. Whether it be the building occupants, the financial institution or the community at large, there is an expectation that a new home should have a life in excess of 50 years. However, since 2014 new homes in all Australian states and territories have had concerning amounts of moisture and mould on interior surfaces and within the interstitial spaces (external wall, subfloor and roof space systems).

International research since the 1930s has identified that when an interior air temperature and relative humidity are different to an exterior air temperature and relative humidity, water vapour diffuses through the external wall, floor and ceiling systems. If this water vapour is not managed, mould can grow, and moisture can form. Moisture and mould within building interiors and interstitial spaces has been known for decades to affect human health and lead to the decay of the building fabric. In 2009, the World Health Organisation stated that there should be no visible presence of mould within building interiors or interstitial spaces. Nath noted in 2018 that Australia had twice the Asthma rate of other OECD nations and Rickaby noted in 2021 that £1B of the UK National Health System expenditure could be attributed to treatment of occupants in mouldy housing.

As we heat and cool our homes, we create these differences in external and internal air temperature and relative humidity. But for reasons of thermal comfort and human health, this should occur. Buildings that have interior temperatures below 15°C or above 28°C have been found to impact human health. From a thermal comfort perspective, when people are reasonably sedentary, (i.e., sitting on a couch), we feel cool when the air temperature is less than 20°C and we will turn a heater on. Subject to our location in Australia, we may feel hot when the interior temperature is above 25°C and we will turn on the air conditioner. These expectations are not wrong, and in many developed nations, the interior thermostats for heating and cooling homes is set to 21°C for heating and 24°C for cooling. Many Australian workplaces use these same thermostat set points for employee and visitor/customer comfort.

In Australia, the focus of the National Construction Code on reducing heating and cooling energy in the recent years has not been for human health reasons, but as an action to reduce Australia's greenhouse gas emissions. This has led to a singular focus rather than a multi-faceted focus. The multi-faceted focus would respect that as we create well insulated and better sealed buildings we must consider not only the heating and cooling energy use, but we must also consider how we manage water vapour diffusion through the built fabric, how mould may grow when the relative humidity is above 60% in interstitial spaces, how moisture will form and the envelope systems must be designed to allow drainage and drying, and that the interior air quality (temperature, relative humidity, pollutants) needs to be maintained, such that the interior relative humidity does not exceed 70%. These differences rely on the minimum requirements within the weather proofing, energy efficiency, ventilation, and water vapour diffusion sections of the national building regulations.

Recently, Australia has adopted a similar regime with the first 'condensation' regulations included within the Health and Amenity clauses of NCC 2019, followed by some enhancements in NCC 2022. Whereas NCC 2019 focussed on condensation, NCC 2022 has moved the focus to a simulated MI value. Internationally a building envelope system that has a simulated MI of 3, or more, should not be constructed. In some nations, an envelope system with a simulated interstitial MI of 2, or more, should not be constructed. Envelope systems with a simulated MI between >1 to <3 generally require further analysis and investigation. Generally, a MI of 3 or more, indicates the visible presence of mould to the unassisted human eye.

In this research, hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) simulations have been completed for nine typical low rise residential external wall systems commonly constructed in Victoria. The use of hygrothermal and bio-hygrothermal simulation to inform building envelope design is quite common in North America, Japan, Korea, the United Kingdom, and many nations within Europe. Within this field, Australia is up to 70 years behind some other developed nations.

Research Report 3 identified that only 43% of non clay masonry NCC climate zone 4 and 69% of non clay masonry NCC climate zone 6-8 external wall systems, with a southern (non-equatorial) orientation, and an air change rate of ACR10@n50, met the minimum MI value of <3, as specified in NCC 2022. The clay masonry veneer wall systems, which already require a vented and drained cavity, showed 0% of NCC climate zone 4 and 25% of NCC climate zone 6-8 external wall systems, with a southern (non-equatorial) orientation, and an air change rate of ARC10@n50, met the minimum MI value of <3, as specified in NCC 2022.

The results from the hygrothermal and bio-hygrothermal simulations highlight the need for:

- Greater water vapour permeance properties of weather resistive pliable membranes, as climates become cooler and/or building air tightness is increased.

- The need for a vented and drained cavity, to ensure the moist cladding system does not contact the weather resistive pliable membrane, to allow outward-bound water vapour to leave the insulated envelope, and to promote ventilation to remove water vapour and assist in the drying potential of the external wall system.

- As buildings become more airtight there is the need to include an interior water vapour control membrane and automated mechanical ventilation.

Recommendations

The research has highlighted many aspects of hygrothermal and bio-hygrothermal considerations for existing and new buildings that need further development and application in Australia. These include, but are not limited to:

- The Tasmanian experience in 2014, identified the urgent need for training and awareness across the design and construction sectors. The state government instigated training activities via the HIA, MBA, AIBS, AIA, EA and other non-aligned groups. The first published design guide was published in 2014, with an update for 6 Star and 2018 and a further update for 7 Star planned for 2023. These measures significantly shifted the design and construction professions and avoided what appeared to be growing concerns regarding the significant presence of condensation and mould in new homes between 2010 and 2016. A similar approach is needed in Victoria.

- Detailed measured values of water vapour diffusion properties need to be printed clearly on packaging and material data sheets for all weather resistive pliable membranes. This will enable design and construction professionals to make better informed choices regarding the climatic suitability of weather resistive barriers.

- All external wall systems should demonstrate that a southern (non-equatorial) oriented wall system has a simulated MI of <3.0, and preferably less <2, as required in some other developed nations.

- This research has explored principles of increased vapour permeance, the addition of a vented and drained cavity and interior vapour control membranes. However, several wall systems did not achieve and MI of <3. Other aspects including increasing wall insulation, adding an over-cladding insulation product, increasing the vapour permeance of weather resistive pliable membranes and increasing ventilation capacity of the vented and drained cavity needs to be explored.

- A preliminary analysis of the relative humidity values within the 2022 NatHERS RMY climate files identified that some climates had extended periods of external relative humidity above 80%. This condition makes it difficult for the wall system to diffuse moisture in an outward manner. This leaves the need for either greater hygrothermal buffering inside the building and/or greater amounts of ventilation in the vented and drained cavity. As an example, in some countries a clay masonry veneer external wall is required to have five times (5 x) the ventilation capacity of a timber clad external wall system.

- There is a need for government to provide regulatory guidance in relation to the climate data required for this type of verification method. This is because different sources of RMY and EPW files provide very different values for all climatic inputs. At this stage, there is no perfect climate data file, but to ensure all certified users of transient hygrothermal simulation tools are using the same climatic inputs will provide design and construction professionals with repeatable simulation results.

- As noted in the conclusion, this research has used construction material physical properties from international databases. There is an urgent need for manufacturers to measure and provide physical properties of materials manufactured and used in Australia, and an opportunity for regulatory guidance to require this. This would include conductivity, density, porosity, specific heat capacity, water vapour diffusion resistivity, typical moisture content, moisture storage function and liquid transport coefficient. This would ensure that simulation results may better reflect how Australian materials perform.

- Within the ventilation, hygrothermal simulation and results sections, reference has been made to ventilation and relative humidity control. At this stage, there is no value prescribed within the NCC2022 or AS1668 regarding the maximum allowable relative humidity in buildings. Until a value is prescribed, there is no requirement to prove design and construction adequacy of the interior air quality. As the software used in this research applies the international expectation that interior relative humidity does not exceed 70%, these simulation results may be quite conservative when observed interior relative humidity conditions in Australian homes is considered.

- This research has highlighted the inter-relationship of Weather-tightness, Health and Amenity (condensation, ventilation and interior air quality) and Energy Efficiency (airtightness, wall insulation) regulations. There is a need for a careful and coordinated approach to the co-development of these areas of regulation.

These and other aspects are explored in the research results, results discussion, the conclusion and recommendations.

3. Introduction

The purpose of this research is to establish if new homes in Victoria are susceptible to moisture accumulation (condensation) or mould growth, within external wall systems that are built to a 6 Star or a 7 Star regulatory compliant pattern, and if so, explore enhancements to the way the external wall system is constructed to reduce mould growth risk. The National Construction Code (NCC) describes minimum methods and systems to meet regulatory compliance. Internationally and in Australia, there is a widely observed correlation between a) buildings that create significantly different temperature and relative humidity conditions between the interior and exterior environments, and b) susceptibility to moisture and mould on interior and interstitial surfaces. This section firstly introduces conditions for moisture on and in the built fabric, and how this might support mould growth. This is followed by a brief history of the application of energy efficient envelope requirements for Class 1 and Class 2 buildings, which is then followed by aspects of weather tight construction and ventilation. This will bring us to an introduction of hygrothermal and bio-hygrothermal calculation methods. Finally, an exploration of the principles of modern external walls, as published in other developed nations is explored.

Since 2008, national research conducted by the University of Tasmania has highlighted the connection between the energy efficiency regulations and the presence of condensation and mould in buildings. Since 2014, this has included the study of existing buildings and desktop based hygrothermal calculations and simulation [14-21]. At this early stage, it was identified that there was a causal link between moisture and mould in buildings and human health [18, 22]. This led to questioning of the non-transient simulations, and the adoption of transient simulation methods, which are described in more detail below. One of the recent University of Tasmania PhD projects explored condensation and mould risk that may exist in Hobart, Melbourne and Brisbane [23]. The research explored the changes in external wall system moisture and mould risks that have occurred between 2002 (pre-energy efficiency regulation) through to 2022 (7 Star regulation). That research highlighted the greater risk of moisture accumulation and mould growth in housing located in Melbourne. This made the university research team aware of the urgent need for a greater analysis of the specific needs for informed envelope (floor, external wall, and roof) systems for housing in Victoria.

This is not a problem unique to Australia. Similar experiences have occurred in most developed nations from the 1920s [24-27]. The main cause being the creation of indoor environments that are significantly different to exterior climates. There was some limited recent Australian research regarding the impact of excessive moisture on nail plate mechanical fixings in timber trusses [28, 29], but very little research on these matters has progressed. This is in contrast to international research [30-38] and the recent findings from the nationwide condensation survey commissioned by the Australian Building Codes Board [18], which identified that up to 40% of all new Class 1 and Class 2 dwellings constructed in the decade from 2006 to 2016, in all jurisdictions, had a concerning amount of condensation identified by the responding building design or construction professional.

The German standards system published its first moisture management guidelines in 1952 [39] with many updates since. In Australia the now defunct National Building Technology Centre, published three notes in 1964; NSB 32: House design for Australian cold-winter climates, NSB 61: Condensation in dwellings and NSB 78: Some condensation problems [40-42]. In the United Kingdom, the first British Standard was published in 1975 [43], which like the German DIN has had several updates. North America, including Canada, had their own challenges and the 'condo crisis' in during the 1980s and 1990s [44-49]. New Zealand's 'leaky building syndrome' which commenced in the 1990s, identified two key and often mis-diagnosed causes, namely moisture ingress and water vapour diffusion and many blamed the shift to performance-based building regulation [50-55]. Recent estimates have established that the leaky building syndrome in New Zealand has cost its economy more than NZD$46B [28, 29]. Recognising the need to inform design, rather than offer forensic advice, standards for the simulation of moisture and mould growth were developed and included within national standards like the German Standard DIN 4108, the British Standard BS5250 and the North American Standard ASHRAE 160 [56]. Within Australia, 2011 saw the publication he ABCB's Condensation in Buildings handbook, which provides non-mandatory advice and guidance [57], which has also received some updates. Recognising these trends, the Tasmania government sought advice from the University of Tasmania and published the "Condensation in Buildings – Tasmanian Designers' Guide" in 2014, with an update in 2018 and a further update to occur in 2023 [58, 59] . The application of the guide by the design and construction professions, has seen a significant shift in construction practices in Tasmania and the Australian Capital Territory.

Finally, the clauses regarding condensation within the NCC have been placed within the Health and Amenity section [1-4]. This location relates to the WHO's recommendation that no habitable spaces should include the visible presence of mould [7, 8]. Whilst Nath identified that Australia had twice the OECD average for asthma [11, 60], in 2021 research within the United Kingdom has identified that up to £1B per annum of the National Health Service budget can be attributed to the medical treatment of people living within 'wet' buildings [30]. For these reasons, we need to consider how aspects of moisture, energy efficiency, weather tightness, ventilation regulation may have impacted external wall system design and construction and methods we can use to simulate moisture and mould growth within external walls.

3.1 Moisture (water vapour and water)

This section explores aspects of moisture in buildings. It must be noted that moisture, in the forms of water and water vapour is all around us. Within the air, we quantify the amount of water vapour by the term's relative humidity or air moisture content. Within solid materials we refer to their moisture content. The movement of moisture into materials is the adsorption of water vapour, until they become saturated. The movement of water vapour into and out of materials and the air relates to differences in water vapour pressure. The other key aspect to water vapour is how temperature and relative humidity influence when water vapour condenses into water. This section will firstly explore an explanation of dew-point temperature, followed by water vapour pressure.

As mentioned above, all air and most materials contain moisture. The amount of moisture the air can hold is subject to the air temperature and barometric pressure. As air warms up, it can hold more water vapour, and as air cools down, it needs to reduce the water vapour content, which leads to moisture (condensate) forming. A simple example is when a cool drink in placed in a glass, and moisture forms on the cold surface of the glass. This moisture has condensed out of the air. Similarly, after a short period of time, as the drink has warmed up, the glass is once again dry; the mositure has evaporated back into the air. For several centuries, we have been aware of how water in the air may condense and form moisture on building surfaces and/or interstitially within envelope elements (floors, walls and roof spaces). The temperature term used for this reaction is dew point, or saturation, temperature. Saturation meaning the point at which the air can no longer hold moisture and the moisture in the air becomes dew, or condensate. A simplified equation to calculate the dew point temperature for different conditions is:

- $T_d = T - ((100 - RH)/5)$

Table 1 shows some dew point temperatures for different interior conditions. Three temperature conditions and three relative humidity conditions are shown. The three temperature conditions represent:

- 20°C: the NatHERS thermostat set point for the minimum temperature in living rooms and kitchens [5],
- 21°C: representing international benchmarks for household heating and cooling [3, 39, 43, 56, 61], and
- 23°C: representing the average measured temperature in new homes [19, 62, 63].

The three relative humidity conditions represent:

- 60% RH: the generally accepted maximum for ducted mechanical air- conditioning in office spaces [64, 65],
- 70% RH: representing values measured in many Australian homes [11], and
- 80% RH: representing values measured in many Australian homes, and the maximum accepted value in some countries before automated mechanical ventilation is required [56, 66].

What this data shows, for example, is that when a room is conditioned to 23°C and the relative humidity is 70%, any surface that is thermally bridged (glass, window frame, structural framing, gaps insulation, air leakage, etc) and has a temperature of ≤17°C, will have moisture condense out of the air onto thermally bridged surfaces. This is commonly observed on single glazing windows during winter. In the context of Victoria, the outdoor temperature is often 15°C or less.

Table 1: Examples of dewpoint temperature for conditioned interiors

Temperature (T°C)	**Relative Humidity (RH%)**	**Dew point T (Td°C)**
20	60	12
20	70	14
20	80	16
21	60	13
21	70	15
21	80	17
23	60	15
23	70	17
23	80	19

A common question is ‘where does the water vapour come from?” The water vapour contained in the air outside a home comes from ever-changing atmospheric conditions. A quick look at hourly recorded data available from the Bureau of Meteorology for Melbourne (http://www.bom.gov.au/products/IDV60901/IDV60901.95936.shtml), documents an ever changing condition for relative humidity and other measured items. In a home, the water vapour comes from our breathing, and activities we undertake. Whilst we are sleeping, our metabolic rate tends to be low, leading to a low expulsion of water vapour. When we are actively tackling housework, our metabolic rate is higher, leading to a higher expulsion of water vapour. This is one of the reasons why we need to regularly hydrate. Other activities like cooking, washing and bathing also add water vapour to the air in our homes. Nath [11] documented that a single person could contribute up to 8kg, or 8 litres of water vapour to a home interior in a single day. The only way to remove this water vapour is by ventilation and diffusion, which are explained in later sections.

By adding water vapour to the air, we change the pressure of the air. Reflecting back on the principles of dewpoint temperature discussed above, as the air in a new home is generally much warmer than that of an older uninsulated home, the air can contain a lot more water vapour. However, in Victoria the air outside the home is often cooler, meaning it would have a different amount of water vapour in the air. This difference is often referred to as the air's water vapour pressure. Water vapour pressure is measured in Pascals, and is how water vapour, in a gas form, exerts pressure.

Table 2 shows the calculated water vapour pressure for different temperature and relative humidity conditions. The mathematical process to calculate water vapour pressure is too long to show here. However, when the air temperature and relative humidity are known and the dew point temperature is calculated, as described above, there are many web-based calculators that can calculate the water vapour pressure (an example is: https://www.weather.gov/epz/wxcalc_vaporpressure). The table shows if the interior of a home is kept between 21°C and the relative humidity ranges from 60%RH to 80%RH, the interior water vapour pressure ranges from 1,496 Pascals to 1,935 Pascals. The two lowest rows have temperature and relative humidity values which are quite common external environmental conditions in Melbourne, where the mean minimum temperatures is 10.2°C and the mean relative humidity is 56% [67]. The water vapour pressure for this exterior condition is 758 Pascals. This highlights that a water vapour pressure inside the home could be between 738 (1496-758) and 1177 (1935 – 738) Pascals. Recognising the principles of physical equilibrium, this establishes a process where the higher interior vapour pressure is trying to equalise with the exterior lower vapour pressure. This process forces water vapour into the interstitial spaces, where it may be adsorbed by construction materials or continue to diffuse outward. The aim of water vapour permeable design is to eliminate materials that may restrict the ability for water vapour to leave the built fabric without causing mould growth and/or higher amounts of moisture coalescing and accumulating within the built fabric.

Table 2: Water vapour pressure for different temperature and relative humidity conditions

Air Temperature (°C)	Relative Humidity (%)	Dewpoint Temperature (°C)	Water Vapour Pressure (Pa)
21	60	13	1496
21	70	15	1703
21	80	17	1935
23	70	17	1935
23	80	19	2194
24	70	18	2061
16	55	7	1001
10	65	3	758

3.2 Mould

One of the less visible, quite destructive, and significantly impacting human health effects from moist housing are mould growth and mould spores within habitable spaces. Figure 1 shows the three conditions that support mould growth, namely relative humidity, temperature, and nutrients [68]. The greyed in section highlights the typical interior conditions for relative humidity and air temperature.

- Subject to relative humidity, mould will grow when the temperature is above 0°C.
- When the temperature is above 10°C and the relative humidity is above 70% the rate of mould growth increases.
- The overlap of measured temperature and relative humidity conditions observed within many homes is within the ideal range for mould growth.

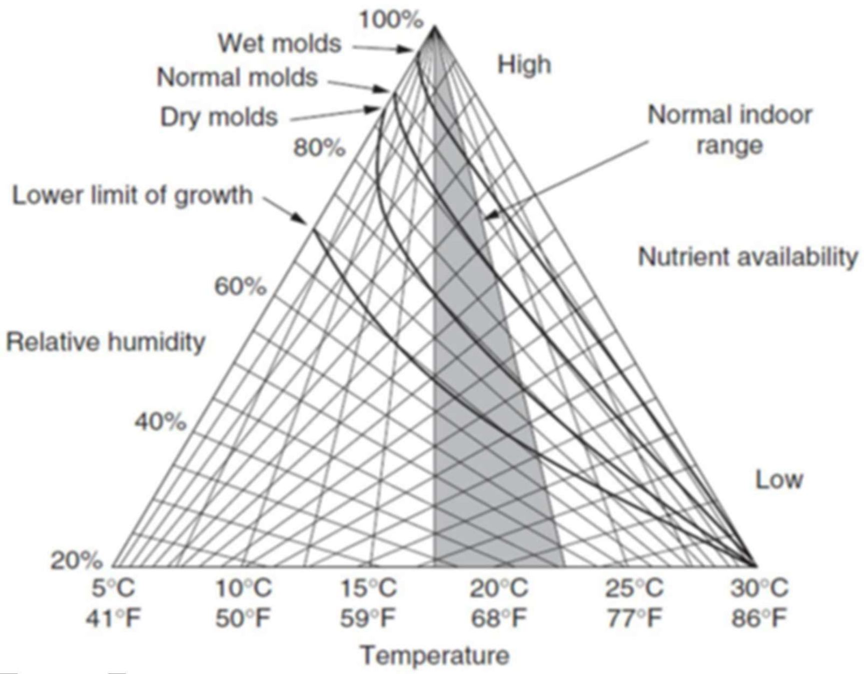


Figure 1: Conditions that support mould growth [68]

Figure 2, shows the observed and simulated temperature and relative humidity conditions within Australian homes between 2010 and 2018 [11]. This includes separate research activities conducted by the University of Tasmania [11, 12, 16, 17, 19, 69] and the CSIRO [63]. This mixture of simulated and measured interior environmental data is overlaid onto a simplified mould growth graph.

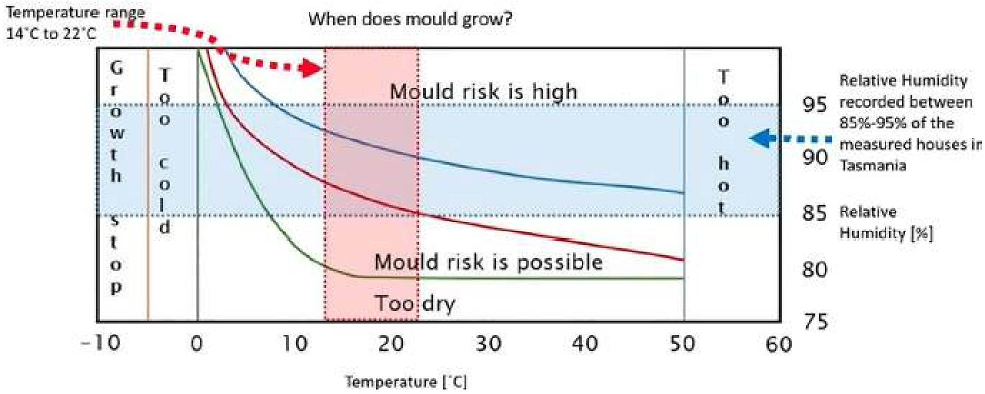


Figure 2: Rates of mould growth [70] and observed temperature and humidity conditions in homes [11]

The figure shows that the observed temperature in many homes was between 14°C and 24°C, the observed relative humidity in many homes was between 85% and 95%, and the combination of these interior temperature and relative humidity conditions provides an ideal environment for mould growth.

It is important to note that, subject to the amount of interior air movement and the comprehensiveness of the ventilation, the amount of ventilation required to remove excess water vapour and the environment needed for mould to grow can change. Research presented at the first International Conference on Moisture in Buildings (ICMB2021), at University College London, and the 2021 annual InnoRenew conference included research that documented mould growth within fully air-conditioned and ventilated museum buildings when the relative humidity was set at 60% [71, 72]. Even though the ICMB conference mentioned above is termed the first, conferences regarding the building physics and simulation methods on moisture and mould in buildings have occurred in other developed countries since the 1930s [24, 25, 27, 42, 49, 73-75]. What this research identified were the differences between areas of good air movement and areas where there was good mechanical ventilation versus other areas where the air was quite still. In many respects, this is not too different to many homes, where furnishings and methods of fresh air supply and exhaust will allow for some areas within a room to be well ventilated, and other areas that may include very still air spaces. This may suggest that relative humidity control in homes may need to be kept below 60%RH.

The critical issue surrounding mould growth and its impact on building occupants is internationally recognised. Mould spores within buildings are attributable to several short-term and life-long medical conditions [7, 11, 76]. Nath identified that Australia has twice the OECD average for Asthma rates per head of capita [11]. Research by Rickaby [77] noted that in 2020 the UK National Health Service medical care costs associated with annual treatment of occupants from damp or mouldy buildings was approximately £1 billion. In 2009, the international recognition of the significant impact that mould within buildings has on human health led the World Health Organisation, to state that no building should have a visible presence of mould growth [78].

Within the Australian regulatory context, there have been no regulatory requirements for condensation of mould until NCC 2019 [2, 79]. The first performance requirements and acceptable construction methods only applied to Class 1 and Class 2 buildings in NCC climate zones 6, 7 and 8. As Victoria includes NCC Climate zones 4, 6, 7 and 8, there was still no requirement to consider condensation and mould in locations classed as NCC climate zone 4. Additionally, the focus of these first requirements was on condensation.

NCC 2022 [3, 4] saw a significant and positive shift to a focus on mould growth, and greater water vapour permeance requirements of the pliable membrane when applied as a weather resistive barrier. Compliance with NCC 2022 Performance Requirement F8P1 is verified for an external wall assembly when it is determined that a MI of >3.0, as defined by Section 6 of AIRAH DAO7 [80], does not occur on interior, exterior or interstitial surfaces of components of the building fabric, from the 5th year after construction onwards. The water vapour diffusion properties of pliable building membranes have also been expanded to include climate zones 4 and 5, requiring a minimum AS4200 Class 3 water vapour permeance, and in climate zones 6, 7 and 8 a minimum AS4200 Class 4 water vapour permeance.

These enhanced requirements for external wall systems are starting to better reflect the responses to the 2016 nation-wide condensation survey [18]. As Victoria includes NCC climate zones 4, 6, 7 and 8, these enhanced clauses now require external pliable weather resistive membranes (when used) to have some form of water vapour permeance. The water vapour permeance values of Class 3 and Class 4 pliable membranes requires minimum water vapour diffusion properties of 0.143 µg/N.s and 1.14 µg/N.s respectively [81]. Table 3 shows data from AS4200 in µg/N.s and the equivalent converted water vapour diffusion resistance factors, which are used by the hygrothermal simulation software.

Table 3: AS4200 vapour diffusion classification and equivalent water vapour diffusion resistance factors

Class of water vapour permeance	**Vapour Category**	**Vapour permeance micrograms/N/second (µg/N.s)**		**Water vapour diffusion resistance factors**	
		Min (≥)	**Max (<)**	**Min**	**Max**
Class 1	Vapour barrier	0.0000	0.0022	90,909.0	No Maximum
Class 2	Vapour barrier	0.0022	0.1429	1399.6	90909
Class 3	Vapour permeable	0.1429	1.1403	175.4	1399.5
Class 4	Vapour permeable	1.1403	No maximum	No minimum	175.4

Buildings located in the temperate and cool-temperate climates of Victoria are increasingly warmer and more humid on the inside. Based on an understanding of the conditions for dew-point temperature and mould growth, it must be accepted that:

1. condensation, when RH is 100%, will occur somewhere within the built fabric,
2. subject to the amount of condensation that occurs, and its ability to return to a vapour form, this moisture may pose a long-term structural risk.
3. mould growth occurs in still air spaces when the relative humidity is higher than 60%.
4. interstitial spaces often have a relative humidity greater than 60%, which allows mould growth to occur,
5. the number of times when the relative humidity is <60% will affect the opportunities for mould growth to continue, or the mould growth to cease, prior to it becoming a human health, or structural decay concern.

3.3 Energy Efficiency

Prior to 2002, most Class 1 (stand-alone dwellings) and Class 2 (multi-residential buildings) had nil to limited insulation and no requirements for building airtightness. Similarly, there were no national requirements for a measurable thermal performance of the building envelope and its impact on heating or cooling energy use. As a component of Australia's pathway to reducing greenhouse gas emissions, one of the cost effective pathways that was identified was the reduction of likely energy needed to heat and cool Australian buildings [82]. The NatHERS was established in 1993 as a mechanism to quantify energy that may be used to heat and cool Australian homes [83, 84]. Research using the NatHERS simulation method established that most new housing had a NatHERS Star rating between 1 Star and 3 Stars [85, 86]. This indicated that a very large portion of energy used in Australian homes was to condition (heat or cool) interior climates to acceptable levels for habitation.

In 2003, the first set of Building Code of Australia (BCA) requirements in relation to envelope insulation, building sealing and glazing ratios were implemented [87]. In 2004, the NatHERS star rating system was applied to BCA 2004, where a compliant home generally had a Star rating score of 4 Stars [88]. In 2006, the minimum performance requirement within the BCA was increased to 5 Stars [89], a 6 Star requirement in 2010 [90], and a 7 Star requirement in 2023 [3, 4].

The NatHERS scheme applies internationally accepted principles for thermal comfort [5], which includes significant research from the University of Sydney. The scheme does this by applying:

- a minimum temperature at night for sleeping spaces of 15°C. This is based on significant international research regarding human health and illness from cool sleeping spaces,

- a minimum temperature for living room type spaces during typical occupation times of 20°C. This reflects extensive national and international research regarding the climatic adaptive thermal comfort expectations for a reasonable sedentary person being achieved at 21°C, and

- climatically specific cooling requirements for all room types. In the case of Melbourne, the cooling thermostat set point is 24°C, whilst in Townsville the thermostat set point is 28.0°C [5]. This is based on extensive national and international research regarding climate specific adaptive human comfort expectations and maximum temperatures for human health.

Table 4 shows the simulated heating and cooling energy allowances for Class 1 and Class 2 buildings located within NatHERS climate 21 (Melbourne). This table shows the reduction in simulated heating and cooling energy allowances for each Star rating, and the percentage reduction for each step, from 0 Stars to 10 Stars. Generally, a house with a 0 Star rating has interior and exterior conditions that are the same, whilst a 10 Star house requires no heating or cooling energy demand to maintain thermal comfort within habitable spaces. The table shows a 24.7% reduction in simulated heating and cooling energy use between a 4 Star and a 5 Star home. Similarly, the table shows a 27.2% reduction in simulated heating and cooling energy between a 6 Star and a 7 Star home. To achieve these savings in simulated heating and cooling energy use, the NCC has included requirements for floor, external wall and roof space insulation, glazing performance, and airtightness measures. Each enhancement to the minimum Star rating and the corresponding maximum energy allowance for heating and cooling has required increased amounts of insulation for floors, external walls and ceilings, combined with higher quality glazing and more airtight construction.

Table 4: Maximum NatHERS star-band based heating and cooling energy allowances for Melbourne and their respective energy reduction between Star-bands (MJ/m²)

	Estimated cooling/heating energy	Estimated energy reduction	Estimated energy reduction
1 Star	559		
2 Stars	384	175	33.3%
3 Stars	271	113	29.4%
4 Stars	198	73	26.9%
5 Stars	149	49	24.7%
6 Stars	114	35	23.5%
7 Stars	83	31	27.2%
8 Stars	54	29	34.9%
9 Stars	25	29	53.7%
10 Stars	2	23	92.0%

Nath [11] noted the general changes in simulated household interior temperatures between pre-2003 housing (1 to 3 Star housing) and modern 6 Star housing, as shown in Figure 3 and Figure 4. The X axis on these graphs represent the temperature within conditioned habitable rooms, whilst the Y axis shows the number of hours each temperature is achieved. Figure 3 for an uninsulated home, has a spread of room temperatures from 6°C to 36°C, the general shape of the data is somewhat a bell curve. By comparison the data in Figure 4, representing a 6 Star home, ranges from 10°C to 36°C, but with a strong concentration of data between 16°C and 22°C.

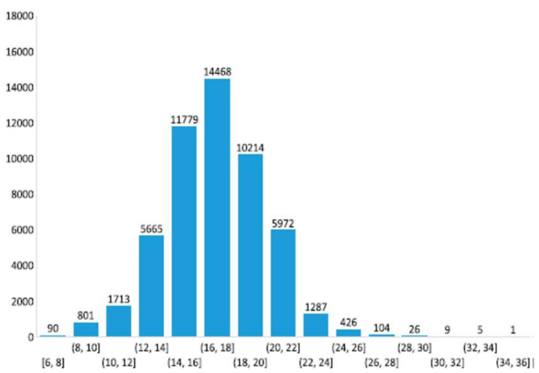


Figure 3: Habitable room temperatures pre-2003.

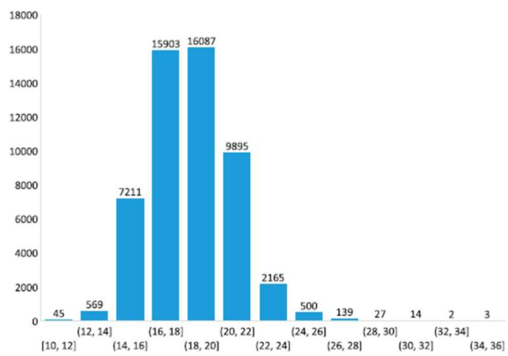


Figure 4: Habitable room temperatures: 6 Star home

This indicates that each improvement in building envelope thermal performance has created increased differences between the interior and exterior air temperature, relative humidity, and water vapour pressure. As discussed in the previous sections on moisture and mould, the concentration of room temperatures reflects a better building envelope for interior human thermal comfort, but from another perspective, it indicates that the air within the home now has the capacity to contain a lot more water vapour. By making the home more thermally comfortable, we have more than doubled the amount of water vapour contained within the air in the home. Additionally, many materials used to construct and furnish a home adsorb water vapour, and in some cases are referred to as seasonal hygrothermal buffers [91, 92]. The combination of an increased amount of water vapour in the air and an increased adsorption of water vapour by the building and its contents, creates a moister interior environment. Understanding the temperature and relative humidity in new energy efficient homes is critical to understand what may be happening to the durability of the built fabric located within interstitial spaces and/or the interior air quality. This is where the importance of the water vapour diffusion properties of external envelope components play a critical role.

Another aspect of energy efficiency has been the prevalence of foil type sarking products, that have historically been applied to the external walls. Most of these products are categorised as Class 1, water vapour impermeable, within the Australian Standard AS4200 [81]. The use of these products can partly be attributed to the Australian energy efficiency framework. These products were attributed high published R-Values, based on reflective insulation and not thermal resistance. Reflective properties mean they reflect a percentage of radiation. This is not to be confused with a normal R-value, where a material resists conductive gains and losses. Many of the high R-values were based on relatively still airspaces. However, in most applications there was either no air space, or the air space was affected by infiltration and exfiltration (ventilation). Many designers and builders applied these foil-based pliable membranes to external walls to achieve a higher R-value. But as discussed in the Hygrothermal and Bio-hygrothermal section below, these products are likely placing a plastic bag around the external walls of homes, trapping water vapour and leading to higher instances of condensation and mould.

The final aspect of energy efficiency is building airtightness. Historically, Australian buildings have been quite leaky [62, 63, 93]. NCC 2019 included a verification method that expected a new 6 Star home to have a maximum air leakiness of ACR10@n50 [2]. This equates to the number of times the air will change in a home due to differences in interior and exterior air pressure of 50 Pascals. A general rule of thumb is to divide the ACR@n50 value by 20, to establish a traditional Air Changes per Hour value. In this example, 10/20 = 0.5 air changes per hour. This indicates that in a modern 6 Star home, each room will have a passive and uncontrolled infiltration and exfiltration, which changes the air each room two times per hour. It is generally accepted that a habitable space does not need mechanical ventilation until the building airtightness is <5.0ACR@n50 [4, 94, 95]. However, North American researchers identified in the 1980s that when the air change rate drops below 9ACR@n50, greater attention needs to be paid to the water vapour diffusion properties of the external envelope [96]. It could be argued, that in Australia, our focus on 'build it tight' has not had a correlating focus on the water vapour diffusion properties of the materials selected for our external walls.

3.4 Weather-tightness

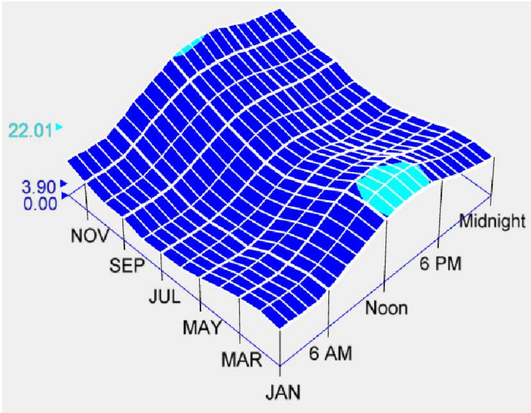
Weather tightness applies to both the building during construction and the building after construction. During the construction of a building, there is an expectation that the elements that may be affected by moisture and rain are protected. The common practice for the last few decades, has been to apply a pliable membrane to the exterior of the timber or steel frame such that all materials on the inside of the pliable membrane remain dry. Historically, this was the same foil type product that was also used to increase the R-value of an external wall system. The need for weather-tightness during construction is still very important but the types of pliable membranes used should consider climatically appropriate water vapour diffusion properties.

The other aspect is after construction weather-tightness. Within the Australian regulatory framework, the only external wall systems that require the cladding system to not touch the next layer of structure are clay masonry veneer (brick veneer), and cavity clay masonry (double brick) external walls [3, 4]. Internationally, direct fix cladding systems have been prone to a failure in weather-tightness, as best exemplified in the Canadian Condo [44, 45, 97-103] and the New Zealand Leaky Buildings crises [50-55, 104, 105]. Since the 1980s the term 'rain screen' has often been used to refer to the cladding system. There is no cladding system that stops all climate-based moisture from reaching the inner side of the cladding system. As each nation has had their own leaky buildings crisis, requirements have been added to the building regulations to include a vented and drained cavity behind the cladding system [18, 97]. The vented and drained cavity allows for mass air transfer to remove unwanted water vapour and for water to drain. Thus, any moisture that does penetrate the cladding system may leave the built fabric, without affecting the insulative or structural components of the building. This aspect requires attention in Australia.

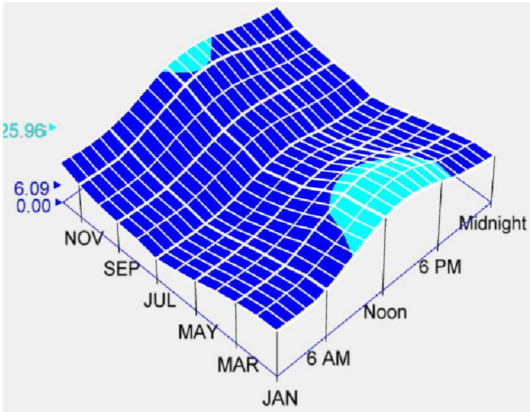
3.5 Ventilation

The aspect of ventilation is often forgotten. Ventilation of habitable spaces is included with the Health and Amenity section of the NCC [3, 4]. The performance requirement focusses on the need for fresh and unpolluted air within habitable spaces. The fresh air focusses on the need for air supply from outside the building and this promotes the stale and contaminated air to leave the building. The NCC requires a minimum of 5% of floor area as operable ventilation. But many challenges relate to this principle of occupant operated ventilation. Figure 5 shows in graphical form the average hourly temperatures for Launceston, Melbourne, western Sydney and Darwin. The dark blue shading indicates the outdoor air temperature is <20°C, the red shading indicates the outdoor temperature is above 27°C and the light blue shading indicates when the outdoor temperature is within the acceptable human comfort bandwidths. This reveals that in Melbourne, very few hours in a calendar year are suitable for a window to be open. If one does open a window, it may be closed shortly after, due to the cold draft it is creating. We can immediately see a conflict between the NCC's expectation for ventilation and the climates in which we live. Other developed nations that have recognised similar trends, have required mechanical ventilation. In more recent years, this has moved to enthalpy recovery ventilation. These systems measure the interior relative humidity and carbon dioxide levels and operate when needed.

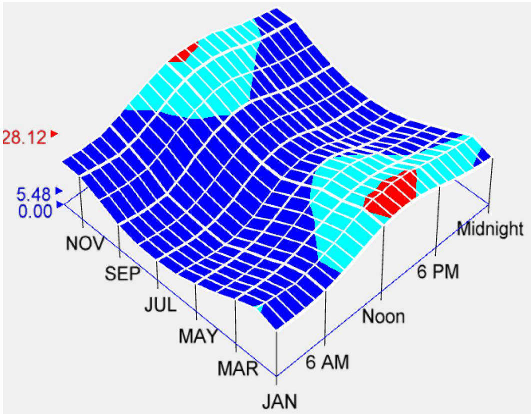
The requirement for kitchen, bathroom, laundry or sanitary compartment exhaust fans, seem to require a house to be less sealed, such that supply air is available for the exhaust fans to operate. If the minimum expected conditioned air temperature within most habitable room is 20°C [5, 61], it seems unlikely that occupants want this cooler outside air leaking into their living rooms. Some researchers and practitioner suggest that windows should be left open to provide air supply for the exhaust fans. This would only further compromise the interior thermal comfort and increase heating energy costs. These challenges highlight that we need to approach these matters in a much more refined manner [38]. It should be noted that building sealing and airtightness measures must be kept separate from ventilation that is required for interior air quality. Research from other developed nations has highlighted that the fast rate of air flow through older leaky buildings allowed for water vapour to leave the built fabric. However, areas of slow-moving air through a partially well sealed envelope have caused moisture to form, mould to grow and moisture to accumulate [106].



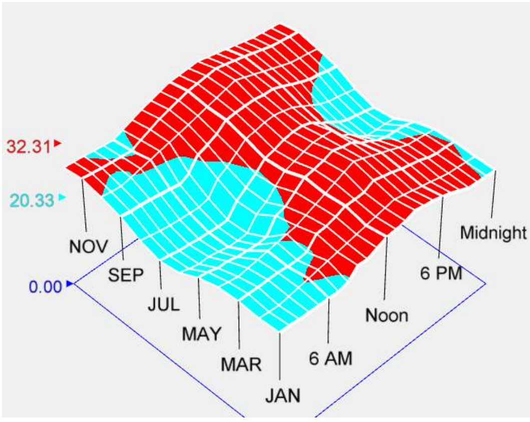
Launceston



Melbourne



Western Sydney



Darwin

Figure 5: Average outdoor temperatures for Launceston, Melbourne, western Sydney, and Darwin

This last note raises the issue of indoor relative humidity control. The NCC requires interior relative humidity to be managed. But there is no stated value (i.e., 70%) that a house interior should not exceed. Recognising that mould grows when the relative humidity exceeds 70%, there should be a requirement of that value. The software used to simulate the flow of heat and moisture through external wall systems has an inbuilt limit of 70%RH for the interior climate. This recognises the international expectation that the interior relative humidity does not exceed 70%. This is in quite contrast to the measured interior relative humidity conditions, as noted by Nath [11] and discussed earlier.

3.6 Hygrothermal and biohygrothermal calculation

Hygrothermal building physics is the study of heat and moisture movement within built spaces, and the diffusion of moisture, (and water vapour), through the built fabric. Bio-hygrothermal calculation uses the outputs from a hygrothermal calculation to assess the potential for mould growth. In this section, hygrothermal calculation will be discussed first, followed by bio-hygrothermal calculation.

Methods to calculate the hygrothermal (heat and moisture) performance of external wall systems have existed since the 1950s [107, 108]. The most common method, known as the Glaser-method, was developed in the 1950s by German scientist Helmut Glaser, was designed to calculate the amount of interstitial condensate that may form during a cold winter period. The Glaser method is a relatively simple condensation risk analysis method and has significant limitations and is therefore only useful under specific conditions. The British Standard (BS5250) [43] noted that more advanced methods, which are standardized in BS 15026, are available. An example of a result from a simplistic Glasser method calculation is shown below in Figure 6. This analysis is for a weatherboard clad wall system, comprising from left to right; 10mm plasterboard, 90mm insulated frame, 1mm vapour impermeable building membrane, 19mm weatherboard. The red line indicates the temperature profile through the wall. The dashed blue line indicates the dew point temperature profile through the wall. Where the red and blue lines cross paths, moisture will form. It is internationally recognised that this form of simplistic analysis may underestimate or overestimate any risk and does not provide adequate design or construction guidance [39, 43, 109].

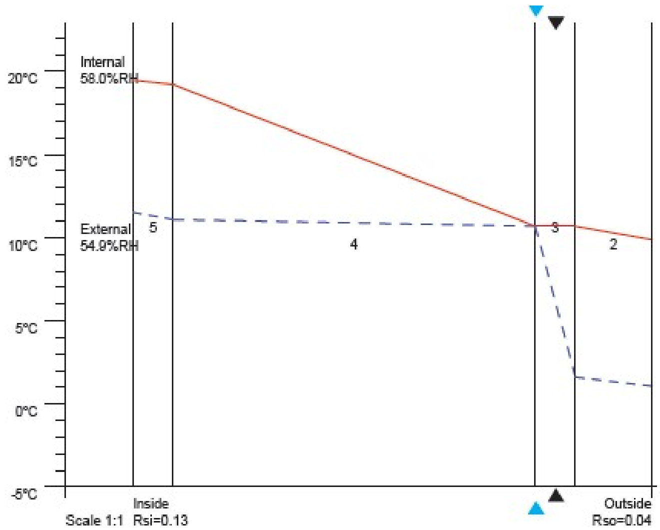


Figure 6: Example of a Glasser simplified method condensation risk analysis

Whereas this method initially only included a single calculation for winter, the method was expanded and improved over many years to include calculations for wetting and drying. This process allowed for the identification of the occurrence of moisture (condensation) and over time, the calculation of moisture accumulation. However, the method also had several limitations, including ignoring the "*hygroscopic effects, such as nonlinear dependencies of hygroscopic material properties, moisture storage, freeze-thawing mechanisms, liquid transport, latent heat, and transient nature of moisture loads at the boundaries."*[110, 111].

As computing capacity increased, these issues were addressed with ever increasing complexity in calculation methods [112, 113]. Modern software tools complete an hourly calculation, for a minimum of ten years. As these tools have evolved, international standards have also increased the minimum expectations for multi-year transient hygrothermal calculation methods [39, 43, 56, 114-116]. Several software tools have been developed and validated worldwide to assess the hygrothermal transport phenomenon through the built fabric considering the interior and exterior climatic conditions and the dynamic state of moisture and condensation. Amongst these software tools, very few integrate both thermal and hygrothermal functions between the internal and external environment. Künzel & Holm [117] emphasized that comprehending the hygrothermal methods in the building envelope requires the insight of water vapour control strategies that avert mould growth on the internal, interstitial, and external building surfaces.

For these tools to perform reasonably accurate calculations many types of input are required, namely but not limited to:

- Hourly exterior climatic data – air temperature, relative humidity, barometric pressure, wind speed, wind direction, global solar radiation, direct solar radiation, diffuse solar radiation, latitude, longitude, sun angle and sun altitude.

- Hourly interior climate data – temperature and relative humidity

- Physical properties of materials – conductivity, density, porosity, specific heat capacity, water vapour diffusion resistivity, typical moisture content, moisture storage function and liquid transport coefficient.

The outputs from these software tools include hourly temperature, relative humidity, and material moisture content within and on the surfaces of each material that is used to make an external wall system. Figure 7, shows a graphical result from a ten-year WUFI Pro transient hygrothermal simulation for a brick veneer wall. In this example the wall system comprising from left to right, 110mm extruded clay brick, 40mm vented cavity, 1mm pliable building membrane, 90mm insulated timber frame and 10mm paper-faced plasterboard. The upper section with the red line indicates the temperature profile between the exterior and the interior. The lower green shaded section shows the humidity range in between the exterior and the interior of the wall system. The blue shading at the bottom indicates moisture accumulation. An important aspect to view is the green relative humidity section. The relative humidity on the outside surface of the extruded clay brick, ranges from less than 20% to 100%. Times with 100% RH would be expected due to rain events. The relative humidity value within the vented cavity ranges from 40% to 100%. This is acceptable, as the vented cavity will remove water vapour and the cavity drainage would remove moisture. The relative humidity within the insulated timber frame ranges from 40% to 100%, with the highest relative humidity conditions on the inside surface of the pliable membrane. At face value, this raises two concerns requiring further analysis, namely:

- is there any moisture accumulation that would affect the durability of the timber framing, and

- a significant amount of the relative humidity condition is above 70% and this may support mould growth within the wall system.

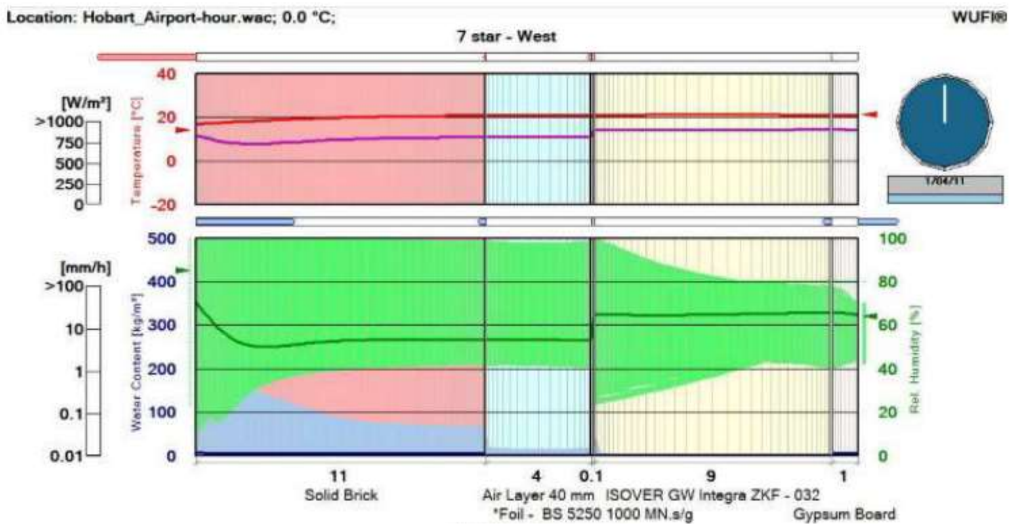


Figure 7: Example of WUFI Pro graphical simulation result [118]

The hygrothermal simulation output, for this wall system, in this climate zone, in this orientation, showed moisture forming, and moisture drying, leading to no ongoing accumulation of moisture. To understand if there is a risk of mould growth, a mould growth calculation must be completed.

Bio-hygrothermal calculation utilises the outputs from the hygrothermal calculation to calculate risks associated with mould growth. The development of calculation methods for mould growth generally occurred between 1940 and 1968 [119]. This period also included the development of the optical evaluation of rates of mould growth, which became known as the MI. These methods were further refined in the 1990s to assess the individual susceptibility of different construction materials, for example pine versus plasterboard. The VTT Technical Research Centre of Finland, was at the forefront of developing calculation methods and applying these to timber elements that are used in the construction of buildings [30, 70, 119-122]. These methods were then incorporated into BETA versions of transient hygrothermal software to estimate mould growth risk in 2005 [32, 123, 124]. Within the development of the WUFI suite of simulation tools, this became known as WUFI BIO, and was further improved over the following fifteen years.

The outputs for mould growth are generally available as a mould growth value, or a mould growth index (MI). The MI has been calibrated to reflect the World Health Organisation's recommendation that no habitable space should have a visible presence of mould [7, 8]. Recognising this human health risk Germany, the United Kingdom, Canada and the United States of America have included requirements that the calculated, or simulated, MI is <3.0 for a period of ten years [39, 43, 56]. Table 5 shows the international MI classification. An MI of <3.0 indicates the mould growth is not visible to the human eye. Whilst a MI that is ≥3.0 is the visible presence of mould. It should be noted that moulds are all around us in a microscopic state, and a MI ≤1.0 is generally termed safe. MI values that are >1.0 and <3.0 generally require further investigation, as slight changes in the material data, exterior climate or interior climate may significantly change the result. Relating this back to aspects of human health, no interior environment should have the presence of mould spores, or an MI that is ≥3.0. From a structural durability perspective, any structural element that is supporting ongoing mould growth will not be durable.

Table 5: Mould growth index (MI) [30]

Index (MI)	Growth rate	Description
0	No growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	<10% coverage of mould on surface (microscope)	Initial stages of growth
3	10%–30% coverage of mould on surface (visual)	New spores produced
4	30%–70% coverage of mould on surface (visual)	Moderate growth
5	>70% coverage of mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

Figure 8 below, shows the results from a bio-hygrothermal mould growth simulation using the WUFI VTT add-on. The graph shows the winter and summer seasonal growth and decay of mould respectively. The graph shows that the MI exceeds 3.0 in the fifth year and exceeds 4.0 in the tenth year. Applying the principles from Table 5, this wall system would support the growth and sporing of mould. Applying the verification method requirements from NCC 2022, this wall system is climatically inappropriate.

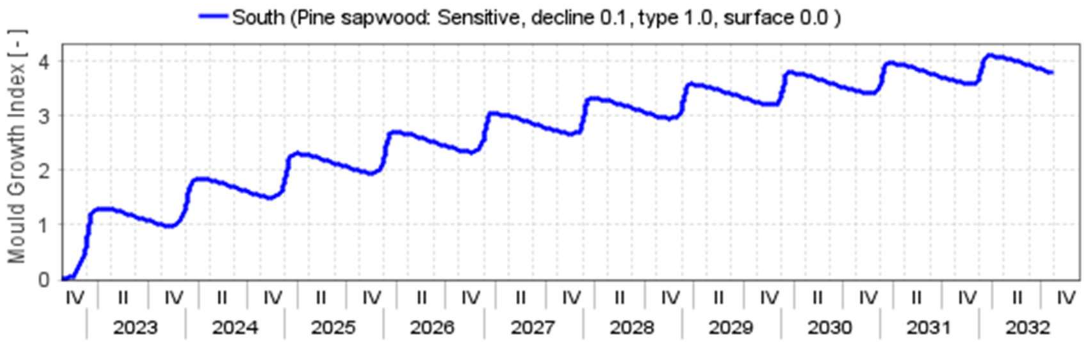


Figure 8: Example of WUFI VTT Mould growth calculation result

This type of building envelope design testing is increasingly occurring in other developed nations, including the requirement that interstitial spaces have a MI of <2.0 [36, 39, 43, 56].

3.7 Modern external wall systems

Since we started to create insulated buildings to shield us from the heat in summer or the cool of winter, nations have constructed many problem buildings. In response to these experiences, regulations have been developed to maintain appropriate indoor air temperatures and relative humidity conditions that do not compromise interior air quality and do not promote mould growth or condensation. This section includes some insights into approaches taken by other developed nations.

Since the 1990s, and as presented in Research Report 1, recommendations like those shown in Table 6 below have been established in other OECD nations [39, 43, 65, 114-116, 125-133]. These strategies highlight a few key aspects for high performance external wall systems, namely:

- establishing an airtight layer on the inside and outside of the insulation layer, and
- the inclusion of a vented and drained cavity between the cladding system and the next layer of the external wall.

Innovations, like the advent of European cavity brick construction in the late 19th century, were an attempt to disconnect the moist and cold outer brick from the dry and warm inner brick. This method of construction also demonstrated benefits in hot climates, where the hot outer brick was disconnected from the cool inner brick. When brick veneer construction commenced in the late 1920s, the same principle was adopted. These innovations occurred well before any insulation was added to external floors, walls of roof spaces of homes and sadly, many other styles of external wall system construction haven't adopted these principles.

Table 6: Condensation control strategies for the building envelope

Strategy	Aim	Measure
Management of moisture entry	Reduce air leakage	Air control layers
	Limit vapour diffusion	Vapour control layers
	Reduce moisture ingress	Water control layers
Control of moisture build-up	Increase the temperature of the condensing surface	Insulation on the exterior side of the condensing surface
	Permit accumulation which does not impact built fabric	High moisture capability at the condensing surface
	Allow moisture to leave	Provision of drainage planes outside the insulation layer
	Allow water vapour to leave	Provision of ventilation outside the insulation layer
Elimination of moisture	Encourage drying	Vapour permeable layers Capillary active layers Provision of ventilation outside the insulation layer
	Remove condensation	Provision of ventilation outside the insulation layer
Reduction of moisture load	Restrict moisture caused during the construction process	Use dry materials during construction Keep elements dry during construction
	Maintain interior relative humidity below 70%	Passive ventilation (supply and exhaust) Balanced mechanical ventilation

Prior to 2010, the Building Research Association of New Zealand (BRANZ) promoted the 4Ds of external envelope design and construction [134]. The 4Ds refer to an external wall system's ability to:

- Deflect moisture – the combination of macro and micro elements that deflect external moisture away from the structural and insulative elements of the external wall.
- Drain moisture – recognising that external moisture ingresses to the inside surface of the cladding system and outward moisture may form on the outside surface of the weather resistive pliable membrane, requires the inclusion of a drainage plan that allows the moisture to drain freely.
- Dry – recognizing that moisture will form in all wall systems, they need to be designed to promote drying. Through a recognition of external wall orientation, some may have solar radiation induced drying potential, while others may need significant ventilation to make up for the lack of solar radiation.
- be Durable – all external wall systems should be designed and constructed in a manner that meets the durability requirements of the national building regulations.

As much as the above focusses on external walls, in New Zealand, the same principles apply to roofs, eaves, gutters, window/door heads, window/door sills and subfloor zones of housing.

For a several decades regulators and researchers in North America have been exploring what is needed in a modern external wall system. The mixed government and industry funded Building Science Corporation has since published more than 140 technical notes. The first of these BSI 001, published in 2010 was called 'The perfect wall' [135]. This document followed trends from European research that had identified the need to consider the four control layers that must be continuous throughout the building envelope, namely:

- a water control layer
- an air control layer
- a vapor control layer, and
- a thermal control layer.

There are few key aspects to these principles. Firstly, none are called a barrier, as it was well accepted by 2010 that no system provided a perfect barrier, and elements needed to consider their role within a layer and to include redundancy. The second element is that the author equally advised that these principles be applied to floor and roof systems.

Most recently, collaborative research between the PassivHaus Institute and Fraunhofer Institute of Building Physics [38] established a rethinking of external wall system design, especially when applied to well insulated buildings. Within this framework, solar radiation is the first aspect on the wheel of principles, as experience has shown in cold climates that uncontrolled solar radiation overheats buildings and leads to cooling energy demand, even in winter. The five principles of external wall design are:

- Radiation control for the façade and fenestration systems, and external shading combined with interior blinds to manage daylight. As mentioned above, it is easy to overheat a well-insulated and airtight building. Small amounts of unwanted solar radiation can overheat building interiors.
- Air control for the external envelope system, establishing an airtight envelope and high efficiency balanced enthalpy recovery ventilation systems that manage interior air quality. A balanced system provides incoming air when exhausting stale air. This way, the air pressure within the home is unchanged.
- Thermal control, which applies principles of a continuous insulation layer with no thermal bridges. Most Australian housing has significant areas of non-continuous insulation and thermal bridges. This is an aspect that is starting to be explored in Australia.
- Dynamic performance control – recognising that no two consecutive hours are the same for the interior and exterior environments, building operate in a very dynamic environment. Items like wood, clay masonry and concrete act as hygrothermal buffers absorbing both moisture and energy during times of excess supply and releasing them at a later stage. This also requires us to consider how we condition (heat and/or cool) these dynamic interior environments.
- Moisture control – This aspect has two areas of focus. The first being the control of relative

humidity within a building to levels below 70% to minimise environments that support mould growth. The second, focusses on inward and outward-bound moisture. Like the NZ 4Ds this requires the acceptance of moisture forming in subfloor, external wall and roof space interstitial systems and how elements are designed to drain moisture and dry via a combination of solar radiation and ventilation.

These examples from very different locations in the northern and southern hemisphere highlight the principles of modern external wall system design and construction. The 4Ds from New Zealand have been promoted for fifteen years or more. There is a need for the external wall systems of residential and non-residential buildings in Australia to evolve, so that thermal, moisture, mould and durability concerns are addressed.

3.8 Summary

This background has provided an exploration of the internal and external elements that are creating a continuously changing dynamic environment that our external wall systems are required to manage. The confluence of water vapour, mould, condensation, energy efficiency weather tightness, interior temperature and relative humidity, ventilation, methods to calculate the flow of energy and moisture through external wall systems, and international trends in building envelope design have been explored.

Considering that new Class 1 and Class 2 buildings in Victoria are increasingly warmer and more humid on the inside, this requires an acceptance that (a) condensation will occur somewhere within the built fabric, and (b) subject to the amount of condensation that occurs, this may pose a long-term structural risk. However, well below the dew point condition (100% RH), mould will grow quite happily when the relative humidity is above 70%, and to date Australia has no regulatory requirements regarding the control of relative humidity within buildings or within the built fabric.

This highlights that a singular approach, within a single section of the national building regulations, does not adequately consider all the interactions that are occurring and how our external wall systems may manage of mis-manage moisture in water vapour and condensate form, leading to unwanted mould growth and built fabric degradation. To quantify potential risks of condensation and mould in new buildings, research options include:

- Empirical studies of exiting housing to validate computer simulation models – This is a very time consuming and costly exercise [136-139]. In the UK, Germany and US, buildings have been observed since the 1970s. We have no research of this nature in Australia.

- Forensic analysis of existing problem buildings to validate computer simulation models – This is often fraught with legal and human ethical issues [19]. Often it is linked to insurance claims or legal disputes, with very limited funds, which can significantly impact the impartiality and depth of the analysis.

- Building system simulation with empirically validated software to inform building envelope design. This has become the favoured method in many countries, due to its limited cost and research risks, and speed of analysis [118]. Internationally, several hygrothermal software tools have been developed through government funded research organisations and/or universities. Some of these tools have undergone empirical validation, (comparing simulation results to real buildings), for several decades.

Previous forensic research in Tasmania [16, 17, 19, 69, 140] and New South Wales [13, 141] identified common trends. However, as noted in points 1 and 2 above, this type of research takes a significant amount of time to complete, is quite expensive and is ethically questionable within peoples' homes.

Researchers at the University of Tasmania have utilised world leading non-transient (2013-2017) and transient (2017 -) hygrothermal and bio-hygrothermal simulation tools. The transient simulation tools used in this research have been internationally empirically validated by governments and industry. This has allowed for more than 200,000 simulations to be competed since 2017, which have shown results similar to conditions observed in buildings located in NSW, ACT, Victoria and Tasmania . The time that would be required to forensically analyse 200,000 homes is unquantifiable. Within this context, this research, as described in the methodology has explored simulation based hygrothermal and bio-hygrothermal risks associated with external wall systems commonly used in Class 1 and Class 2 buildings in Victoria.

4. Methodology

This section describes the methodology adopted for this research. This includes the selection of various forms of input data and simulation methods undertaken in this research. The software used in this research was the WUFI Pro one-dimensional (1D) hygrothermal analysis software that has been developed by the Fraunhofer Institute of Building Physics, and is in use by regulatory developers and researchers in Canada, United States, Japan, South Korea, New Zealand, Germany, France, Italy, Norway, Sweden, Finland, Poland, Bosnia, Austria, Belgium, Spain, United Kingdom, and Portugal. The basis for the simulation methodology used within this research combines the consideration of NatHERS thermostat settings, combined with collaborative method established by Nath and researchers from the Fraunhofer Institute of Building Physics in 2019 [118, 142]. More recently, the Australian Institute of Refrigeration, Air-conditioning and Heating (AIRAH) has entered a data sharing arrangement with the American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) and published DA-07- Criteria for moisture control in buildings [80], which is very similar to the ASHRAE Standard 160, of the same name [56]. The methodology described within ASHRAE Standard 160 and AIRAH DA-07 follows the same principles as developed by Nath.

4.1 External wall types

The research was guided by a Project Advisory Committee that included members from the four contributing organisations, namely:

- Victorian Building Authority (VBA)
- Master Builders Association of Victoria (MBAV)
- Commonwealth Scientific and Industrial Research Organisation, and
- Forest and Wood Products Australia.

After reviewing the eight wall types described within the Energy Efficiency section of NCC 2019 (3.12.1.1), it was identified that some of these wall types were extremely uncommon and that some wall types needed to be added. This led to the selection of the wall types, as shown in Table 7. In each case, the wall system composition was informed by data provided by the CSIRO, VBA and MBAV. Detailed data about these wall systems is available within the Appendices of Research Reports 1, 2 and 3.

Within this research there were three stages of analyses. Research Report 1 focussed on external wall insulation requirements as specified for 6 Star homes (2010 to 2022) and the permitted types of weather resistive pliable membranes. The insulation applied to the walls and the properties of the weather resistive pliable membranes applied the requirements within NCC 2010 to 2019 [2, 90]. Research Report 2 focussed on external wall insulation requirements as specified for 7 Star homes (2023 -) and the permitted types of weather resistive pliable membranes. The insulation applied to the walls utilised NatHERS simulations. More than 90% of new Class 1 and Class 2 buildings in Victoria apply the NatHERS methodology. As described in Research Report 2, each wall system was simulated until a 7 Star rating was achieved.

Research Report 1 and Research Report 2 identified significant simulation-based mould growth risks on non-equatorial (southern) orientated walls. To address these simulation-based risks, Research Report 3 took a three-pronged approach, namely:

- increase the water vapour permeance properties of the weather resistive pliable membrane layer

- add a vented and drained cavity between the cladding system and the weather resistive pliable membrane, and
- add a water vapour control pliable membrane to the interior side of the insulation layer (between the plasterboard lining and the timber frame).

Table 7: External wall systems selected for this research

No	Description	Rationale for selections	Described within NCC
1	Weatherboard clad with timber frame	This wall type comprises 20% of the Victorian Class 1 and Class 2 market.	Yes
2	Compressed fibre-cement sheet clad with timber frame	This wall type comprises 9% of the Victorian Class 1 and Class 2 market.	Yes
3	Clay masonry veneer with timber frame	This wall type comprises 61% of the Victorian Class 1 and Class 2 market.	Yes
4	Concrete blockwork masonry with timber frame	This wall type comprises 0.5% of the Victorian Class 1 and Class 2 market. Suggested to be retained due to class 2 buildings. The properties of this wall system are also very similar to those of a precast concrete wall commonly used in Class 2 construction.	Yes
5	Externally insulated clay masonry (reverse clay masonry veneer) with timber frame	This wall type is very rare, but due to its use to provide thermal mass in many award-winning eco-designer homes, this wall type be retained.	Yes
6	Extruded polystyrene cladding with timber frame	This wall type was common but current data uncertain.	No
7	Expanded polystyrene cladding with timber frame	This wall type was common but current data uncertain.	No
8	Autoclaved aerated concrete masonry cladding with timber frame	This wall type comprises 6% of the Victorian Class 1 and Class 2 market.	No
9	Flat metal cladding with insulated timber frame	This wall type comprises 2% of the Victorian Class 1 and Class 2 market. This can include products like sheet metal and thin composite steel and aluminium cladding systems.	No

This list is not exhaustive but relates to the time and financial resources attributed to this research. Due to timber framed external wall systems being at greater initial risk than steel framed wall systems, this research has focussed on insulated softwood timber framed wall systems. Condensation and mould growth does occur within insulated steel framed wall systems, leading to corrosion of steel elements and moisture transport through the external wall system, but this often takes longer to present significant health or structural concerns. Internationally, the focus is how to use natural, low embodied energy materials, like plantation timber, as a method of reducing long term carbon emissions and to provide some carbon sequestration.

This is the first research of its type, focused on Victoria, and there is a need for further research to explore other external wall systems used in housing in Victoria and their hygrothermal and bio-hygrothermal performance. As an example, the sheet metal system, as described in Wall System 9 is ‘flat steel’. Sheet metal and aluminium cladding systems come in a variety of flat, folded and rolled profiles. There is a need for extensive research exploring how each of these folded and rolled profiles manage cavity ventilation, moisture and mould.

4.2 External climate data

The selection of climates and climate data needed to consider both the climate zones within the NCC and the climate zones within NatHERS. Figure 9 shows the ABCB NCC climate zone map for Victoria. This map shows that Victoria has four 4 NCC climate zones, namely; climate zone 4, climate zone 6, climate zone 7 and climate zone 8. The NCC climate zones inform the minimum thermal resistance values for the external envelope. The minimum thermal resistance values establish how much insulation needs to be included within the external wall systems.

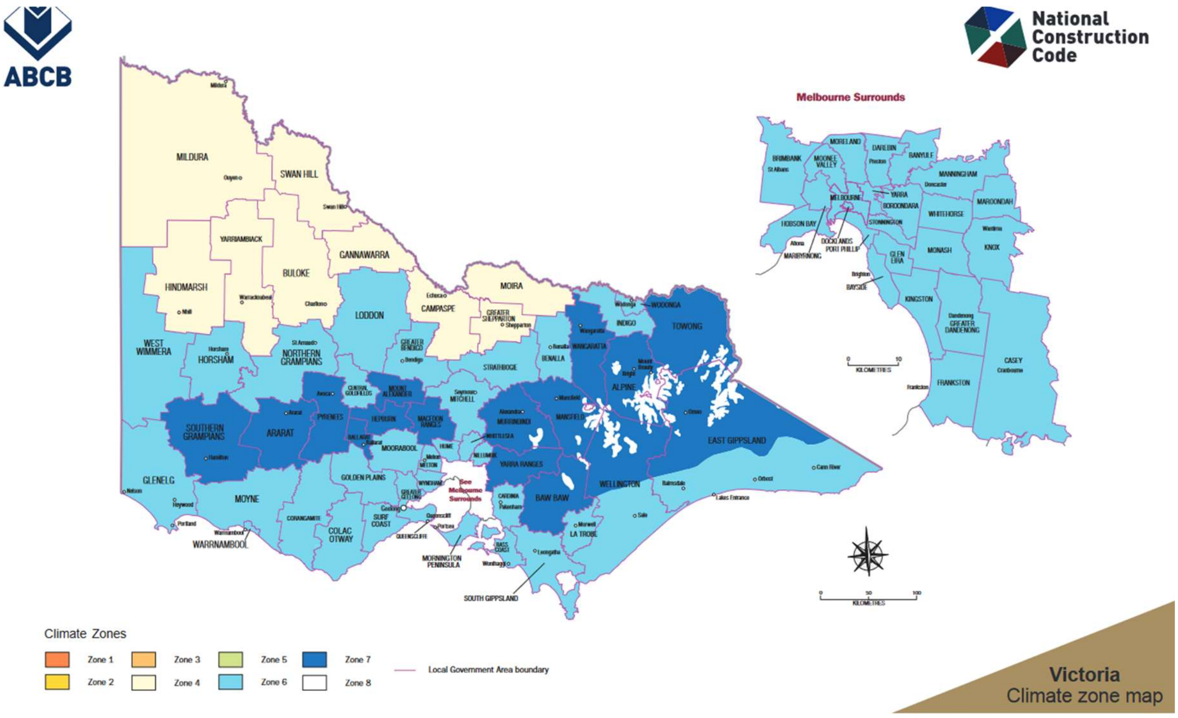


Figure 9: ABCB NCC Climate zone map for Victoria (ABCB 2022)

The second layer of climate data, as mentioned above, is the NatHERS climate zones. The NatHERS climate zone map, as shown in Figure 10, provides a greater recognition of regional microclimates and assigns climate zones based on historical records. However, even at this scale, it is difficult to understand the microclimate differences.

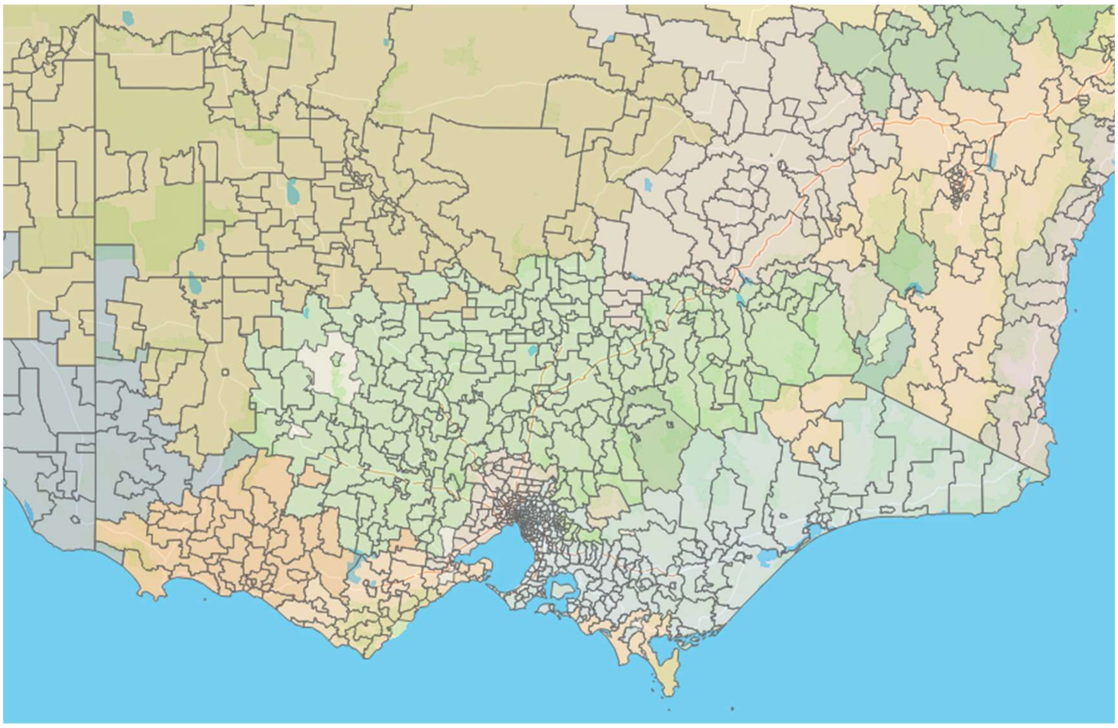


Figure 10: NatHERS Climate zone map for Victoria

The NatHERS climate zone data is allocated by postcode. In Victoria, there are 1,558 distinct localities with postcodes that are (mostly) sorted into 13 NatHERS climate zones. There is a slight anomaly where six of these postcodes are in areas of low housing density and are not assigned a NatHERS climate zone. These were eliminated in this research. Some localities straddle more than one NCC climate zone. These areas were replicated to compile a longer list of cross referencing Victorian localities and their corresponding postcodes with NatHERS zone and NCC climate zone, bringing the count to 1,726 localities.

The climate zone type analysis in Table 8 allowed the identification of how many localities are in each climate zone. NatHERS climates zones 20, 24, 25 and 69 were eliminated for this study because of their relatively small representation in terms of population and housing construction. This was further reduced as it was identified that NatHERS CZ 62 and CZ 64 are extremely similar, with a maximum allowance heating and/or cooling energy allowance of 125 and 127 mJ/m2.annum respectively. The NatHERS CZ 64 was selected due to the higher heating and cooling energy allowance.

Table 8: Victorian Localities in NatHERS and NCC Climate Zones

NCC CZ	NatHERS CZ												
	20	**21**	**22**	**24**	**25**	**27**	**60**	**61**	**62**	**63**	**64**	**66**	**69**
ALL	16	94	211	17	11	149	199	30	349	68	70	512	0
4	5	0	1	0	0	109	0	1	0	0	0	82	0
6	7	80	110	4	3	38	180	24	324	47	66	204	0
7	4	14	52	7	5	2	16	5	24	21	2	177	0
8	0	0	48	6	3	0	3	0	1	0	2	49	0

This established eight NatHERS climate zones, representing 1,682 postcode-based localities, as shown in Table 9.

Table 9: NatHERS climate zones selected for simulation.

NatHERS climate zone	Source of climate data	Number of postcodes using climate data	Percentage postcodes using climate data
21	Melbourne	94	6%
22	East Sale	211	12%
27	Mildura	149	9%
60	Tullamarine	199	12%
61	Mt Gambier	30	2%
63	Warrnambool	68	4%
64 (+62)	Cape Otway (+Moorabbin)	70+349=419	25%
66	Ballarat	512	30%
TOTAL		1682	100%

During this research the climate data specified for house energy rating use were updated. This led to the application of different climate data sets at different stages of the research, namely:

- Research Report 1 - 6 Star external walls - utilised EPW formatted 2003-2022 NatHERS Reference Meteorological Year (RMY) hourly climate data that did not include hourly precipitation data.

- Research Report 2 - 7 Star external walls - utilised EPW formatted 2003-2022 NatHERS Reference Meteorological Year (RMY) hourly climate data that did not include hourly precipitation data.

- Research Report 3 – 6 Star and 7 Star external walls - utilised EPW formatted 2022 - NatHERS Reference Meteorological Year (RMY) hourly climate data, with hourly precipitation data added.

It is widely recognised that Wind Driven Rain (WDR) is a critical factor leading to significant effects in the hygrothermal performance of building envelopes [38, 143, 144]. Moisture content in walls increases ten-fold when WDR is calculated in simulations [145] when compared to walls where WDR is ignored. The Australian RMY climate data provided by NatHERS for building simulation does not contain rain data. The effects of WDR are ignored in hygrothermal simulations if rain data is not provided, leading to results that show a much drier interstitial environment. In Australia, precipitation data is collected by the Bureau of Meteorology. The data can be purchased in its raw format and this research established significant gaps in data collection that required sourcing data from nearby locations, requiring the purchase of additional data sets. The NatHERS RMY climate file then needs to be reformatted into an EPW file and have the precipitation data added to the appropriate columns.

Recognising the differences in RMY data and the addition of hourly precipitation data led to significantly different results for the same wall systems between Research Report 1, Research Report 2 and the base cases in Research Report 3.

4.3 Interior Climate

The interior climates selected in this research adopted many of the principles outlined in ASHRAE Standard 160 [56], which is referenced by AIRAH DA-07 [80], that has been listed as a referenced document within the NCC 2022. Key parameters which were applied are shown in Table 10. NatHERS expects that habitable interiors are conditioned to acceptable thermostat set points [5]. This requires that the simulation consider air-conditioning which infers that the air inside the house is mechanically heated and cooled. The heating thermostat set point was universally set at 20°C, whilst the cooling thermostat set point varied subject to NatHERS climate zone.

Table 10: Key internal climate inputs

<table>
<tr><th>Aspect</th><th>Input selected</th></tr>
<tr><td>Mode of operation</td><td>Air-conditioning (heating and cooling)</td></tr>
<tr><td>Floating temp</td><td>Based on sum of cooling - heating</td></tr>
<tr><td>Cooling thermostat (°C)</td><td><table>
<tr><td>NatHERS CZ</td><td>Cooling</td></tr>
<tr><td>21</td><td>24.0</td></tr>
<tr><td>22</td><td>23.0</td></tr>
<tr><td>27</td><td>25.0</td></tr>
<tr><td>60</td><td>24.0</td></tr>
<tr><td>61</td><td>23.5</td></tr>
<tr><td>62</td><td>24.0</td></tr>
<tr><td>63</td><td>23.0</td></tr>
<tr><td>64</td><td>23.0</td></tr>
<tr><td>66</td><td>23.5</td></tr>
</table></td></tr>
<tr><td>Heating thermostat (°C)</td><td>20.0</td></tr>
<tr><td>Air exchange rate</td><td>User defined
0.5 ACH/10ACR@n50
0.375 ACH/7.5ACR@n50
0.25 ACH/5ACR@n50</td></tr>
<tr><td>Relative humidity cap</td><td>70%</td></tr>
</table>

The value for Air Change Rate (ACR) explored different measures of airtightness. As described earlier, the NCC [2, 4] requires a certain level of airtightness in new buildings. The verification method prescribes the building pressurisation/depressurisation method, often referred to as the blower door method. The maximum leakiness (infiltration/exfiltration) is specified as 10 ACR@n50. Applying the general rule of thumb [96] to covert the test method to passive leakage – 10 / 20 - infers a 0.5 air changes per hour within habitable rooms of buildings. The lower value for airtightness that was applied refers to the national and international standards which define the minimum building leakiness prior to the requirements for mechanical ventilation [95, 125, 146, 147]. This value is 5ACR@n20, (or 0.25 ACH). If a house is more airtight than 5ACR@n50 mechanical ventilation is required. Finally, recognising that researchers identified significant moisture and mould risks appeared when the measured infiltration was <8ACR@n50 [96, 148], the third variable assessed was 7.5ACR@n50 (0.375ACH).

The 70% relative humidity cap is an international setting based on the requirements for interior relative humidity control in other countries [38, 56]. This differs from measured data from Australian homes, as discussed previously, which is often higher than 70% [11]. This aspect will require further investigation and is one of the matters to be explored by the co-funded PhD student attached to this research.

4.4 Sample house plan

The hygrothermal simulation inputs include the cubic meterage of the building's interior and internally generated water vapour load. In this research, a house plan that has been used for several building thermal performance and hygrothermal analysis projects has been used [11, 12, 69]. As the hygrothermal and bio-hygrothermal analysis is only analysing the heat and moisture diffusion through an external wall system, the interior environmental conditions (air temperature, relative humidity, airtightness and interior water vapour loads) would be the same whether this was an external wall of a stand-alone house or the external wall of an apartment building. As noted on the house plan, the floor area (not including the garage) is 152.5m^2, with an interior volume of 366m^3. As the external envelope will face the four cardinal orientations, in Research Report 1 and Research Report 2, all wall types were simulated in a northern, eastern, southern and western orientation. As Research Report 1 and Research Report 2 identified the southern (non-equatorial) oriented wall as posing the highest risk of interstitial mould growth, only the southern (non-equatorial) orientation was assessed in Research Report 3. If the southern oriented wall system had a MI of <3, the north, east and west walls should also have a MI of <3. Due to the amount of interior air, a smaller four-bedroom house or apartment would have a higher the interior water vapour pressure, and a larger four-bedroom house or apartment would have a lower interior water vapour pressure.

Figure 11: Three-dimensional representation of the house

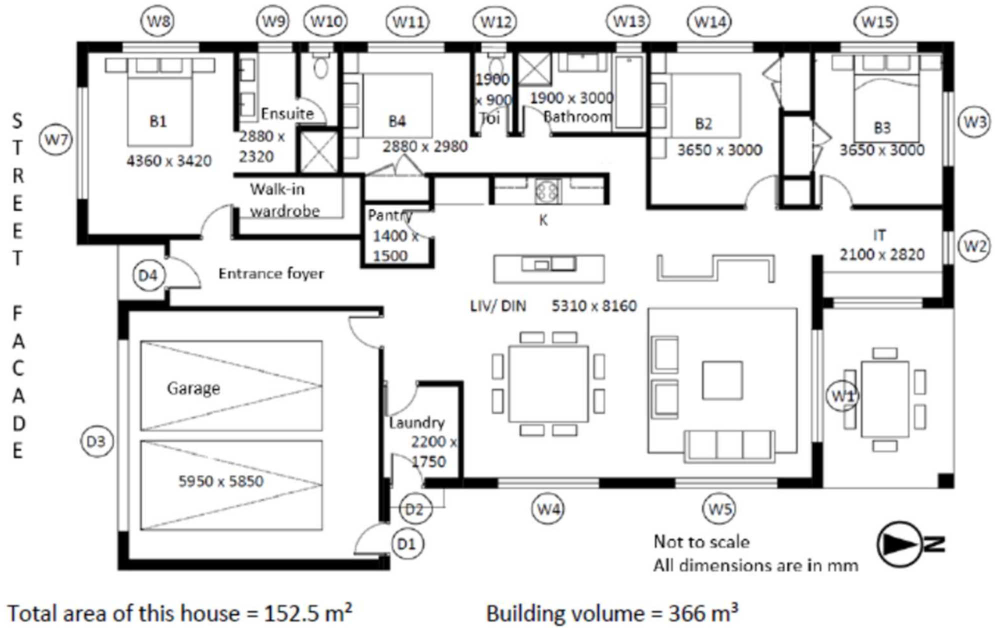


Figure 12: House plan (Not to scale)

4.5 Construction material physical properties

The sources of the physical properties of each element in the nine selected external wall systems was sourced from either:

- manufacturer's data, and/or
- NatHERS material properties database, and/or
- AIRAH Handbook [64].

A significant data gap was the water vapour diffusion properties for each material. In this research, this value was adopted from materials with a very similar conductivity (K) and density (kg/m3) values to other materials within international databases.

4.6 Hygrothermal and bio-hygrothermal simulation

In this research, the method adopted uses the WUFI Pro one-dimensional hygrothermal (heat and moisture) simulation program, that has been developed by a government funded research organisation, Fraunhofer Institute of Building Physics, Germany, and has been empirically validated by several nations and improved over more than 25 years [46].

The bio-hygrothermal (mould growth) simulation software used was co-developed by the Fraunhofer Institute of Building Physics and the Valtion Teknillinen Tutkimuskeskus (VTT) Technical Research Centre of Finland, and the Oak Ridge National Research Laboratory (USA). All three of these organisations have a similar government funding profile to the CSIRO in Australia. The mould growth software applies the MI method as described in the background section of this report.

In this research, adopting the principles of ASHRAE Standard 160 [56] and the most recent version of the German Standard DIN-4108 [39], hygrothermal simulations were completed for a ten-year period. Internationally, the minimum of a ten-year simulation period is increasingly being required due to the expected long-term performance of buildings [118]. The verification method in NCC2022 requires a simulation period greater than 5 years [4, 56, 80].The results from the ten-year hygrothermal simulations were then post processed by the WUFI VTT mould growth software. It should be noted that these two international standards provided regulatory verification in several other developed nations in Asia, North America and Europe.

The final aspect of the MI calculation process was the specification of the materials sensitivity to mould growth. As the wall systems being explored comprised a timber frame, and based on experiences and advice from New Zealand, north America and Europe, the Very Sensitive classification of Pine was selected. This also reflects the forensic analysis of wall systems in NSW, Victoria and Tasmania, where mould based degradation has occurred on the outside surface of the pine framing and not on the outside surface of the mould growth resistant glass-fibre insulation.

4.7 Summary

This section has described the methodology adopted for this research. This has included the selection of wall systems and their components (cladding, insulation, lining), the selection of exterior and interior climates, the selection of material properties for simulation purposes and the simulation method.

5. Results

This section contains the summarised results from each of the research reports. The results from Research Report 1, will be presented first, followed by Research Report 2 and Research Report 3. For more detailed results, please refer to each of the individual reports.

5.1 Results Summary Research Report 1 - 6 Star external wall systems.

Research Report 1, which involved 940 hygrothermal and 940 bio-hygrothermal simulations of the nine selected wall systems in eight NatHERS climates of Victoria. This report also applied built fabric variables for NatHERS Climate zones 4, 6, 7 and 8. The research included 532 simulations with an ACR of 10 and 408 simulations with an ACR of 5. As per the Introduction and methodology, an ACR of 10@n50 is the maximum allowed for a 6 Star home, as specified in the verification method for building sealing [1, 2].

The only wall systems that demonstrated moisture accumulation were the direct fixed (no cavity) extruded and expanded polystyrene cladding systems, located within NatHERS climate zone 63. The moisture accumulation occurred between the acrylic render and the polystyrene material. The report noted that in north America, these wall systems require a drainage plane between the render and the polystyrene.

Table 12 shows a summary of the MI results for the nine wall systems with insulation levels as specified within the DTS section of Energy efficiency and the weather resistive pliable membrane water vapour permeance as specified within the Health and Amenity section of NCC 2019. This included the no requirement for the water vapour permeance of the weather resistive pliable membrane for NCC climate zone 4 and an AS4200 Class 3 weather resistive pliable membrane form NCC climate zones 6-8. The results show that 22% of the wall systems simulated with an ACR@n50 of 10, had a MI of ≥3. The results for each wall system varied subject to wall orientation and the capacity for the cladding system to hold moisture. However, many of the external wall systems with an MI of ≥3.0 were southern oriented. When the ACR@n50 was reduced to 5, the number of wall systems with a MI ≥3 increased to 80%. These findings highlighted the need to understand the impact of airtightness and orientation on interstitial mould growth risks.

Table 11:Summary of bio-hygrothermal simulation results from Research Report 1

ACR@n50	Bio-hygrothermal simulation Mould Index value (MI)		
	<1	>1 to <3	>3
10 (ACH 0.5)	56%	22%	22%
5 (ACH 0.25)	5%	15%	80%

The discussion noted that these results could be conservative, as no hourly precipitation data had been included in the exterior climate data.

5.2 Results Summary Research Report 2 - 7 Star external wall systems.

Research Report 2 involved 594 hygrothermal and 594 bio-hygrothermal simulations of nine external wall systems within eight of the NatHERS climates for Victoria. The nine types of external wall systems comprised contemporary construction methods and materials and included adequate in-wall insulation to achieve a 7 Star rating from the sample house plan.

The only wall systems that demonstrated moisture accumulation were the extruded and expanded polystyrene cladding systems located within NatHERS climate zone 63. This occurred between the acrylic render and the polystyrene material. As noted above, in north America, when this system does not include a vented and drained cavity between the polystyrene cladding and the insulated timber frame, these wall systems require a drainage plane between the render and the polystyrene.

Table 12 shows a summary of the MI results for the nine wall systems with insulation levels as established for the 7 Star insulation requirements for NCC 2022. This included the requirement of an AS4200 Class 3 weather resistive pliable membrane for NCC climate zone 4 and an AS4200 Class 4 weather resistive pliable membrane form NCC climate zones 6-8. The results show that 86% of the wall systems have a MI of <3, as required in NCC 2022. When the ACR@n50 is reduced to 7.5 the number of wall systems with an MI of <3 reduces from 86% to 47%. Furthermore, when the ACR@n50 is further reduced to 5, only 5% of the wall systems have an MI of <3.0.

At a broad level, this shows that the performance of the wall systems at an ACR@n50 of 10 significantly improved due to the requirement for a more vapour permeable weather resistive barrier. But as the building becomes more airtight the number of wall systems with an MI >3.0 increases. This is important to note as many new homes in Victoria are more airtight than 10-ACR@n50.

Table 12: MI classification from Research Report 2 results

ACR@n50	Bio-hygrothermal simulation Mould Index value (MI)		
	<1	>1 to <3	≥3
10 (ACH 0.5)	70%	16%	14%
7.5 (ACH 0.375	20%	27%	53%
5 (ACH 0.25)	2%	3%	95%

5.3 Results Summary Research Report 3 - 6 Star and 7 Star external wall enhancements.

Research Report 3 included more than 4,310 hygrothermal and 4,310 bio-hygrothermal simulations of the nine external wall systems within eight of the NatHERS climates of Victoria. The base cases for each of the nine external wall systems applied the built fabric as described in Research Report 1 for the 6 Star systems and Research Report 2 for the 7 Star systems. Each wall system was then subject to enhancements that explored increasing the water vapour diffusion permeability of the weather resistive pliable membrane, adding a vented and drained cavity between the cladding system and the weather resistive pliable membrane, and adding an interior vapour control pliable membrane between the paper-faced plasterboard and timber framed structure.

Whereas Research Report 1 and Research Report 2 applied the 2002 to 2022 NatHERS RMY climate data that did not include hourly precipitation data, Research Report 3 included the 2022 NatHERS RMY climate data with precipitation data added.

In a similar manner to what was observed in Research Report 1 and Research Report 2, when ACR@n50 was set to 10, many wall systems documented a MI of <3.0 (NCC CZ4 . However, when the ACR@n50 was set to 7.5, wall systems generally required a vented and drained cavity and a more water vapour permeable weather resistive pliable membrane. When the ACR@n50 was set to 5.0, the most suitable wall systems often included a vented and drained cavity, a vapour permeable weather resistive pliable membrane and an interior pliable vapour control membrane.

The climate type that each wall system was located within also played a significant role. In the warmer climate types for Victoria, many external wall variations provided suitable results, especially for ACR10 and ACR7.5. However, in the cooler climate types for Victoria, the external wall systems that provided suitable results increasingly required a vented and drained cavity, a vapour permeable external membrane and an interior vapour control membrane.

Table 13 shows a summary of the simulation results for the nine external wall systems located within NatHERS climate zones 27, 61 and 66 and applying the principles of NCC climate zone 4. This table shows the impacts of increasing the water vapour diffusion properties of the weather resistive pliable membrane, the addition of a vented and drained cavity and the addition of an interior vapour control layer.

The blue highlighted cells indicate the application of NCC 2019, which shows that only 42% of the southern oriented walls systems simulated had an MI of <3. It should be noted that a shaded external wall system with a different orientation will perform in a similar manner to a southern oriented external wall. The purple highlighted cells indicate the application of NCC 2022, which shows that only 43% of the southern oriented walls systems simulated had an MI of <3. In both cases, as the airtightness increases, the number of wall systems with an MI of <3 significantly decreases. This table also includes values for simulations with an MI of <1. This inclusion recognises the international guidelines recommend deeper analysis for any wall system with calculated MI >1 but <3. A greater than 90% result is only achieved when the Class 3 (1398) weather resistive exterior membrane is combined with a vented and drained cavity and an interior vapour control layer, as shown in the orange shaded cell. Significantly, the best performing wall systems, as shown by the grey highlighted cells, only have 61% have an MI of <3, or 50% with a MI of <1, when the ACR@n50 is reduced to 5. This data demonstrates the need for further research to ensure all southern oriented external wall systems located within NCC climate zone 4 have a calculated MI of <3 and preferably <1.

Table 13: Summary of calculated MI values for southern oriented external wall system for NCC Climate Zone 4

Exterior membrane	Vented and drained cavity	Interior vapour control membrane	Percentage of simulations with a MI ⩽3				Percentage of simulations with a MI ⩽1		
			ACR10	ACR7.5	ACR5		ACR10	ACR7.5	ACR5
Class 1 (200000)	No	Nil	42%	8%	0%		42%	8%	0%
Class 3 (1398)	No	Nil	43%	17%	0%		40%	13%	0%
Class 4-1 (175.4)	No	Nil	57%	20%	3%		47%	10%	0%
Class 4-2 (100)	No	Nil	60%	20%	3%		47%	13%	0%
Class 4-3 (21)	No	Nil	60%	23%	3%		47%	17%	3%
Class 1 (200000)	Yes	Nil	24%	6%	0%		15%	3%	0%
Class 3 (1398)	Yes	Nil	33%	8%	0%		23%	8%	0%
Class 4-1 (175.4)	Yes	Nil	67%	54%	21%		62%	44%	15%
Class 4-2 (100)	Yes	Nil	74%	62%	38%		67%	56%	23%
Class 4-3 (21)	Yes	Nil	85%	69%	51%		74%	64%	51%
Class 1 (200000)	No	Yes	63%	25%	0%		50%	25%	0%
Class 3 (1398)	No	Yes	87%	60%	40%		67%	50%	27%
Class 1 (200000)	Yes	Yes	57%	33%	3%		43%	23%	0%
Class 3 (1398)	Yes	Yes	94%	89%	61%		94%	78%	50%

Table 14 shows a summary of the simulation results for the nine external wall systems located within NatHERS climate zones 21, 22, 27, 60, 61, 63, 64 and 66 and applying the principles of NCC climate zone 6 and 7. In a similar pattern to the NCC climate zone 4 results, this table shows the impacts of increasing the water vapour diffusion properties of the weather resistive pliable membrane, the addition of a vented and drained cavity and the addition of an interior vapour control layer.

The blue highlighted cells indicate the application of NCC 2019, which required the use of a Class 3 (1398) weather resistive pliable membrane and shows that only 63% of the southern oriented walls systems simulated had an MI of <3. It should be noted that a shaded external wall system with a different orientation will perform in a similar manner to a southern oriented external wall. The purple highlighted cells indicate the application of NCC 2022, which required the use of a Class 4 (175.4) weather resistive pliable membrane and which shows a reduction to only 53% of the southern oriented walls systems simulated had an MI of <3. In both cases, as the airtightness increases, the number of wall systems with an MI of <3 significantly decreases. However, when a vented and drained cavity between the cladding system and the weather resistive pliable membrane, as highlighted in green, 69% of the simulated southern oriented external wall systems had a MI of <3. When an interior vapour control membrane is added, as highlighted in grey, this increases to 96% for ACR@n50 of 10, 7.5 and 5.

Table 14: Summary of calculated MI values for southern oriented external wall system for NCC Climate Zone 6-7

Exterior membrane	Vented and drained cavity	Interior vapour control membrane	Percentage of simulations with a MI ⩽3			Percentage of simulations with a MI ⩽1		
			ACR10	ACR7.5	ACR5	ACR10	ACR7.5	ACR5
Class 3 (1398)	No	Nil	63%	42%	0%	46%	21%	0%
Class 4-1 (175.4)	No	Nil	53%	30%	1%	41%	18%	0%
Class 4-2 (100)	No	Nil	58%	30%	3%	45%	18%	3%
Class 4-3 (21)	No	Nil	59%	33%	4%	46%	20%	3%
Class 3 (1398)	Yes	Nil	53%	25%	0%	44%	9%	0%
Class 4-1 (175.4)	Yes	Nil	69%	52%	24%	61%	39%	19%
Class 4-2 (100)	Yes	Nil	78%	63%	39%	69%	55%	29%
Class 4-3 (21)	Yes	Nil	87%	75%	57%	77%	66%	55%
Class 3 (1398)	No	Yes	83%	75%	48%	73%	63%	29%
Class 4-1 (175.4)	No	Yes	89%	81%	60%	75%	68%	41%
Class 3 (1398)	Yes	Yes	97%	94%	84%	95%	91%	77%
Class 4-1 (175.4)	Yes	Yes	96%	96%	96%	96%	96%	96%

Table 14 also includes values for simulations with an MI of <1. This inclusion recognises the international guidelines which recommend deeper analysis for any wall system with calculated MI >1 but <3. The blue highlighted cells indicating the application of NCC 2019, which required the use of a Class 3 (1398) weather resistive pliable membrane and shows that only46% of the southern oriented walls systems simulated had an MI of <1. The purple highlighted cells indicate the application of NCC 2022, which required the use of a Class 4 (175.4) weather resistive pliable membrane and which shows a reduction to only 41% of the southern oriented walls systems simulated had an MI of <1. In both cases, as the airtightness increases, the number of wall systems with an MI of <1 significantly decreases. However, when a vented and drained cavity between the cladding system and the weather resistive pliable membrane, as highlighted in green, 61% of the simulated southern oriented external wall systems had a MI of <1. When an interior vapour control membrane is added, as highlighted in grey, this increases to 96% for ACR@n50 of 10, 7.5 and 5. This final result is much better than that documented above for NCC climate Zone 4 results.

The results for both NCC climate zone 4 and NCC climate zones 6 and 7 highlight that it is not just the water vapour permeance properties of the weather resistive pliable membrane that impacts the flow of water vapour through the external wall system. In both scenarios, when there was no cavity and the vapour permeance of the membrane was increased, the percentage of external wall systems with a MI of <3 decreased. It was only when the physical contact between the cold cladding and the weather resistive pliable membrane was removed by the inclusion of a vented and drained cavity, that the true benefit of the class 4 weather resistive pliable membrane became apparent. However, it should also be noted 97% of the simulated external wall systems showed that for houses with an ACR@n50 of 10 or more, a Class 3 (1398) weather resistive pliable membrane combined with a vented and drained cavity and an interior vapour control membrane provides an MI of <3. However, as the house becomes more airtight, the Class 4 (175.4) weather resistive membrane provides a better MI result in terms of air change rate and MI of <1.

5.4 Results summary discussion

The results from Research Reports 1, 2 and 3 highlight general trends that have been identified in other developed nations. Firstly, as greater differences are created in air temperature and relative humidity between the interior and exterior environments, greater attention needs to be paid to how moisture and mould risks are managed. Furthermore, as airtightness is improved in all buildings below 10 ACR@n50, even greater attention needs to be paid to the built fabric composition of the external wall systems, otherwise mould growth risks increase. The results also identified a few key considerations as discussed below.

Orientation and shading

Due to the solar radiation influenced drying potential, the northern orientation for many scenarios showed a nil MI, whilst eastern and western orientations of the same wall system had a MIs <1 and <3 requiring further analysis, and southern (non-equatorial) oriented external wall systems had MIs of >3, an unacceptable mould growth index. The NCC [2, 4, 79] does not differentiate external wall construction methods based on orientation. Within this context, the verification method, as described in NCC2022 should be applied to all southern oriented external wall systems to ensure an acceptable MI is achieved prior to construction approval. Furthermore, if an eastern, northern or western external wall system is shaded by a nearby structure, or building elements (i.e., verandah, eaves, or landscaping), its hygrothermal performance will be closer to that of the southern orientation, rather than its actual orientation.

Hygrothermal buffering

The results from Research Report 1 and Research Report 2, identified significant hygrothermal buffering benefits from the clay masonry veneer, concrete masonry and aerated autoclaved concrete wall systems. The climate data used for these simulations did not include hourly precipitation data. The results in Research Report 3 were significantly different, as these wall systems absorbed rain, and airborne moisture increasing their moisture content and showing higher MI values. This resembles recent experiences in New Zealand, Canada, the USA and Europe, where significant mould risk challenges have been identified in clay masonry veneer external wall systems. This aspect urgently needs more research in Victoria, as more than 60% of new homes comprise clay masonry veneer external wall systems.

Water vapour diffusion resistivity

When comparing the MI values between Research Report 1 and Research Report 2, the NCC 2022 requirements for an AS4200 Class 3 and Class 4 weather resistive pliable membrane within NCC climate zones 4 and 6-8 respectively, increased the number of scenarios with a MI of ≤ 3.0. Research Report 3 took this a step further and explored even more vapour permeable weather resistive pliable membranes (4-2 100 and 4-3 21). However, the climate data in these first two reports did not include hourly precipitation data, whilst the climate data used for Research Report 3 was different and included precipitation data. This revealed a decrease in simulated MI's of <3 until a vented and drained cavity was added. Once the vented and drained cavity was added, in all cases, the increased water vapour permeance increased the number of scenarios that had an MI of <3 and <1. The ability of a wall system to allow the water vapour to leave the built fabric is a critical component to promote wall drying capacity and reduce the risk of mould growth.

Vented cavity

Only three of the eight wall types described with Section 3.12 of the NCC 2019 and NCC 2022 require a vented and drained cavity. Two of these external wall systems were included in this research, namely, clay masonry veneer, and the externally insulated clay masonry wall systems. Generally, these two wall systems performed better than the other seven external wall systems that do not require a vented and drained cavity between the cladding system and the weather resistive pliable membrane. When a vented and drained cavity was added to those other seven external wall systems, the percentage of MI values <3 and <1 increased. However, it was also noted in Research Report 3 that the clay masonry and autoclaved aerated concrete external wall systems performed worse when the hourly precipitation data was added due moisture adsorption. Both the advantages of the vented and drained cavity and disadvantages of moisture adsorption issues with clay masonry construction follow principles and problems identified regarding modern external wall systems in the North America, Europe and New Zealand.

Airtightness

For the last five decades the principles of 'build-it-tight and ventilate-right' have been espoused by building energy efficiency experts in Australia, and elsewhere. This is an important aspect of energy efficient building design. However, as experienced in other nations and as demonstrated in this research, as the ACR@n50 is reduced to <10, we need to consider the elements that we use to make our external walls with even greater importance. The decrease in simulated MI values of ≤3, within Research Report 2, from 86%, to 47%, to 5% for ACR@n50 of 10, 7.5 and 5 respectively, highlight the importance of this aspect of energy efficient external wall system design.

Ventilation

The aspect of ventilation is not directly a component of this research. However, Research Report 3 introduced some challenges regarding the NCC's approach to natural ventilation and measured external air temperatures. Whether it be the inappropriateness of the external air temperature, concerns about personal security, noisy neighbourhoods, or other reasons, building occupants are often not opening windows or doors for ventilation. For decades, research has highlighted the high carbon-dioxide levels in many Australian buildings, yet we have still held onto a simplistic understanding about ventilation. This situation may have largely evolved due to our generally leaky buildings, which did not require the operation of windows, doors or mechanical ventilation systems for fresh air to enter, and stale air to leave, the building. Ventilation is a critical component for relative humidity control in buildings. The software used in this research has a relative humidity cap of 70%. This means that the interior relative humidity within the software never exceeds 70%. This cap relates to international standards, whereby the relative humidity within buildings should never exceed 70% due to risks associated with mould growth. However, data from observed conditions in Australian homes has identified significant periods when the relative humidity in Australian homes is greater than 70%. This increased interior relative humidity condition has not been explored in this research and should be considered in future research.

Software limitations

It should be noted that there are several limitations to the results from this research, including:

- The physical properties of the materials simulated. If the conductivity, density or water vapour diffusion resistivity properties of a material differ from those simulated in this research, the hygrothermal and bio-hygrothermal results will change. At this stage, there is no hygrothermal materials database for products used to construct external wall, floor, or roof systems in Australia.

- As per international requirements, the software has a cap on the interior relative humidity of 70%. However, as there is no requirement to control relative humidity in Australian homes, researchers have measured interior relative humidity conditions well over 70% and 80%. This would create a greater mould growth risk than what has been simulated in this research.

- The standard NatHERS RMY climate data does not include hourly rain data. As this research has shown, the inclusion of hourly precipitation data significantly impacts the hygrothermal and bio-hygrothermal simulations results.

- The NatHERS RMY data used in the research has applied average climate data. Simulations that include extreme weather events, or daily measured data, would create bias resulting in different moisture accumulation and mould growth results.

- If a home was heated to more than 20°C, the interior vapour pressure will increase, leading to greater vapour flow within the interstitial spaces of floors, external walls and roofs. Future research should consider warmer homes and intermittently conditioned homes.

- The software is simulating a 'perfect wall'. However, walls are rarely made perfectly. Subject to construction practices, a wall may be less or more insulated, may be less or more leaky, or may allow for the ingress of moisture. To address concerns about outward water vapour flow, advice from researchers at the Fraunhofer Institute of Building Physics advised not to include paint on the interior lining surface of the external wall models. This is a common simulation practice for buildings that do not include an interior vapour control layer. Aspects of gaps in wall insulation and greater amounts of inward moisture flow need to be explored further.

Several of the points described above would increase the risks associated with moisture accumulation and mould growth. Within this context, the results presented here may be conservative.

6. Conclusion and recommendations

This research has utilised one dimensional hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) simulation software to explore if code compliant external wall systems commonly constructed in Victoria may accumulate moisture or promote interstitial mould growth. Aside from a few instances of moisture accumulation between the acrylic render layer and polystyrene cladding systems, most of the external wall systems demonstrated nil moisture accumulation.

The post processing of the hygrothermal simulation results with the bio-hygrothermal software highlighted that many external wall systems, built in full compliance with 6 Star NCC 2019 and 7 Star NCC 2022 requirements did not meet the verification method described within NCC 2022, (i.e., they had a MI ≥3.0). This indicates they may be supporting unacceptable levels of interstitial mould growth, that may not become present to building occupants until a significant structural failure occurs or the smell of mould (and mould spores) emanates from the problematic external wall system .

The results from the hygrothermal and bio-hygrothermal simulations highlight the need for:

- Greater water vapour permeance properties of weather resistive pliable membranes, as climates become cooler and/or building air tightness is increased.

- The need for a vented and drained cavity, to ensure the moist and cool cladding system does not contact the weather resistive pliable membrane, to allow outward-bound water vapour to leave the insulated envelope, and to promote ventilation to remove water vapour and assist in the drying potential of the external wall system.

- As buildings become more air-tight there is the need to include an interior water vapour control membrane.

Recommendations

The research has highlighted many aspects of hygrothermal and bio-hygrothermal research that need further development and application in Australia. These include, but are not limited to:

- The Tasmanian experience in 2014, identified the urgent need for training and awareness across the design and construction sectors. The Tasmania state government instigated training activities via the HIA, MBA, AIBS, AIA, EA and other non-aligned groups. The first published design guide was published in 2014, with an update for 6 Star and 2018 and a further update for 7 Star in 2024. These measures significantly shifted the design and construction professions in Tasmania and minimized what appeared to be growing concerns regarding the significant presence of condensation and mould in new homes between 2010 and 2016. A similar approach is needed in Victoria.

- Detailed measured values of water vapour diffusion properties needs to be printed clearly on packaging and material data sheets for all weather resistive pliable membranes.

- All external wall systems should demonstrate that a southern (non-equatorial) oriented wall system has a simulated MI of <3.0, and preferably less <2, as required in some other developed nations.

- This research has explored principles of increased vapour permeance, the addition of a vented and drained cavity and interior vapour control membranes. However, several wall systems did not achieve and MI of <3. Other aspects including increasing wall insulation, adding an over-cladding insulation product, increasing the vapour permeance of weather resistive pliable membranes and increasing ventilation capacity of the vented and drained cavity needs to be explored.

- A preliminary analysis of exterior relative humidity conditions identified that some locations had a prolonged condition where the relative humidity was above 80%. In a similar manner to warm and humid climates, this makes it difficult for the external wall to remove water vapour. This leaves the need for either greater hygrothermal buffering inside the building and/or greater amounts of ventilation in the vented and drained cavity. As an example, in some countries a clay masonry veneer external wall is required to have five times the ventilation capacity of a timber clad external wall system. This aspect requires further investigation.

- The climate data that is used for this type of verification method should be provided by, or regulated by, government as different sources of RMY and EPW files have very different values for all climatic inputs. At this stage, there is no perfect climate data file, but to ensure all certified hygrothermal assessors achieve the same results, they should all be using the same climate files. Otherwise the design and construction industry will be further disenfranchised.

- The current NatHERS RMY climate data set does not include hourly precipitation data. In this research, hourly precipitation data was added for the simulations completed in Research Report 3. That report showed a significant increase in MI values when the rain data was included. There is an urgent need for hourly rain data to be added to the NatHERS RMY data set, for hygrothermal simulation purposes.

- Other nations have also established wet/dry, hot/cold RMY data sets. These have been developed so that external wall systems can be tested under different conditions. This type of climate data should be developed in Australia. This may include a multi-year climate files that provides a mixture of climatic variables.

- As noted in the conclusion, this research has used construction material physical properties from international databases. There is an urgent need for manufacturers to measure and provide physical properties of constructional materials in Australia. This would include conductivity, density, porosity, specific heat capacity, water vapour diffusion resistivity, typical moisture content, moisture storage function and liquid transport coefficient. This would ensure that simulation results may better reflect how Australian materials perform.

- Within the ventilation, hygrothermal simulation and results sections of this report, reference has been made to ventilation and relative humidity control. At this stage, there is no value prescribed within the NCC2022 or AS1668 regarding the maximum allowable relative humidity in buildings. Until a value is prescribed, there is no requirement to prove design and construction adequacy of the interior air quality. As the software used in this research applies the international expectation that interior relative humidity does not exceed 70%, these simulation results may be quite conservative when observed interior relative humidity conditions in Australian homes is considered.

- This research has highlighted the inter-relationship of Weather-tightness, Health and Amenity (condensation and ventilation) and Energy Efficiency (airtightness, wall insulation) regulations. A key aspect to this research is the rate of air changes per hour within a new Class 1 or Class 2 building. As mentioned above, the hygrothermal simulation software expects that interior relative humidity is kept below 70%. Law and Dewsbury have both identified that when applying the NatHERS method, many locations within Australia have limited times when a window or door should be opened. The Condensation section within Health and Amenity applies the AIRAH DA07 (ASHRAE160) simulation method that expects interior RH is kept below 70%. The Ventilation section within Health and Amenity includes relative humidity as one of the listed pollutants that must be controlled. The DTS ventilation method within the NCC prescribes the 5% of operable windows/doors for ventilation. However, operating these is likely to conflict with the conditions expected within the Energy Efficiency section. This is before aspects of better air sealing are considered. The hygrothermal simulation software uses the input term Air Exchange per Hour (AER). This represents a combination of building air-sealing (airtightness) and ventilation. That is, a building may have a measured air tightness of 2 ACR@n50 but is required to have a minimum ACR@n50 of 5, thus requiring a mechanical ventilation system of 3 AEH@n50. These aspects of the NCC should be co-developed such that they recognise contemporary construction and building occupant expectations.

- A key component of external wall design is the control of inward bound moisture. Guides developed in New Zealand, North America and Europe have established a language around control layers, deflection, and drainage. This aspect has not been explored in this research, but generally, control of moisture around penetrations in external walls (doors and windows) needs to be improved in Australia.

This research has also identified other aspects that need additional research including, but not limited to:

- the impacts from Class 1 and Class 2 buildings that are conditioned to above the minimum temperature of 20°C
- the impacts from Class 1 and Class 2 buildings that are not conditioned to the minimum temperature of 20°
- the impacts from Class 1 and Class 2 buildings that cool to temperatures lower than those specified by NatHERS
- the impacts from Class 1 and Class 2 buildings using intermittent conditioning (an aspect to be explored by the co-funded PhD attached to this research)
- the impacts from imperfect wall systems that allow greater amounts of inward moisture
- the impacts from imperfect wall systems that allow greater amounts of outward bound air and moisture to enter the external wall system
- the need for two dimensional hygrothermal and bio-hygrothermal analysis to explore impacts of thermal bridging at structural connections (i.e., floor/wall, wall/ceiling, window head/wall, window sill/wall)

Finally, the appendices attached to this report includes some documents from New Zealand and North America.

Appendix 1: BRANZ – The 4ds

Appendix 2: Building Science Corporation – BSI-001 – The perfect wall

Appendix 3: Building Science Corporation – BSI-022 - The star crossed lovers of building science: flanged windows and foam plastic

Appendix 4: Building Science Corporation – BSI-026 - They all laughed....

Appendix 5: Building Science Corporation – BSI-067 – Stuck on you

Appendix 6: Building Science Corporation – BSI-090 - Joseph Haydn does the perfect wall

Appendix 7: Building Science Corporation – BSI-091 - Flow-through assemblies

Appendix 8: Building Science Corporation – BSI-092 - Doubling down: how come double vapor barriers work?

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Cover: BRANZ scientist Steve McNeil in the BRANZ experimental building (see pages 44–48 and 62–63). Photo by Alan Wright.

THE 4Ds PRINCIPLES

Following the 4Ds principles will ensure that construction is robust and durable and will manage any water that impacts upon the building or penetrates the exterior cladding.

By Greg Burn, Structure Limited, Auckland (adapted from BRANZ *Building basics: Weathertightness*)

The external walls of all buildings should be designed and built following the basic philosophy for managing water known as the 4Ds – deflection, drainage, drying and durability.

Deflection – water impacting on the building exterior deflects off the face of the cladding. Water is deflected away from critical junctions in the cladding by specific deflection devices on the exterior of the building (such as a window head flashing). The style of the building can also aid deflection of rain away from building walls.

Drainage – any water that penetrates the exterior cladding must be drained back out from within the cladding assembly, down drainage paths that are specifically designed into the wall assembly. Water must be able to drain off the face of the building.

Drying – not all water will drain within a wall assembly – some will be absorbed by building components. Air needs to be able to circulate within wall assemblies to dry water absorbed by components. Wind and sun will dry water off the cladding exterior.

Durability – all components of a cladding and wall assembly need to be appropriately durable for the conditions and New Zealand Building Code durability requirements.

Deflection

The more a wall is exposed to water, the higher the risk of water penetration. Deflection devices protect the building exterior and critical junctions in the exterior, the primary one being the cladding.

Macro deflection devices are larger building features, like roof eaves and verandas, that shelter areas of wall and restrict the amount of water that impacts on these walls. Buildings with macro deflection devices, like wide eaves, have a lower risk of weathertightness failure than buildings with no eaves where the entire wall area is fully exposed – eaves deflect water and prevent it reaching the walls.

Micro deflection devices are smaller items such as window head flashings, window facings and inter-storey cladding flashings. These provide protection by deflecting water at a specific junction in the cladding (generally where water may penetrate if the junction is not protected).

Drainage

Drainage occurs down drainage paths assisted by gravity. Wall assemblies need to be designed and built to incorporate drainage paths that allow water that may have penetrated the exterior cladding to drain down and out of the wall assembly, ideally down the back of the cladding. Drainage paths lead to specifically designed gaps in the cladding that allow water to drain to the building exterior.

The exterior cladding and its finish coating also create drainage paths on the exterior surface that facilitate surface water drainage.

In direct-fixed cladding, the back of the cladding is in contact with the wall underlay so the wall assembly needs to be installed to ensure that water has the opportunity to allow limited drainage down the back of the cladding and face of the underlay.

In extreme conditions, water may also bridge the cavity in drained cavity cladding construction. Again, the wall underlay needs to be installed to facilitate gravity drainage on the face of the underlay.

Drying

Wall assemblies should be designed and built to allow air circulation within the assembly to dry out any water that has leaked in and been absorbed by building components, rather than drained. Wind and sun dries water from building exteriors.

Durability

The exterior cladding and components within the wall assembly require certain levels of durability and must meet the durability requirements of the Building Code. Claddings like brick veneer are very durable in their basic form – other cladding types may need an exterior finish to make them durable. For example, EIFS cladding is made up of a non-durable extruded polystyrene substrate that will deteriorate if it remains wet. (It

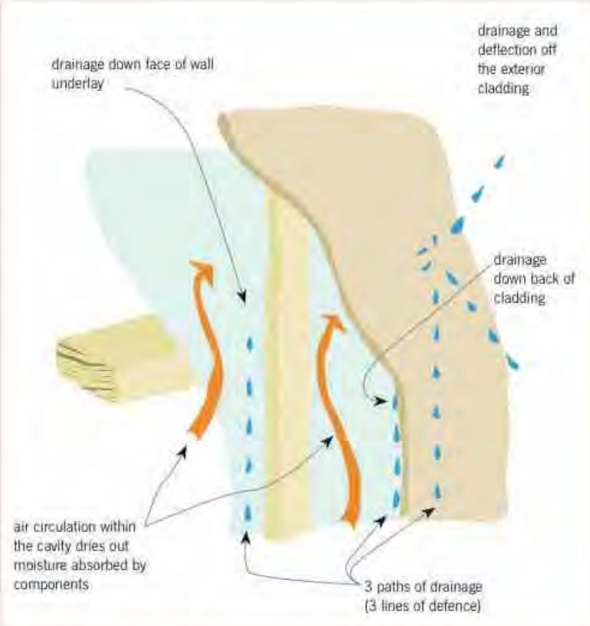

Figure 1: Deflection, drainage and drying with a drained and vented cavity cladding.

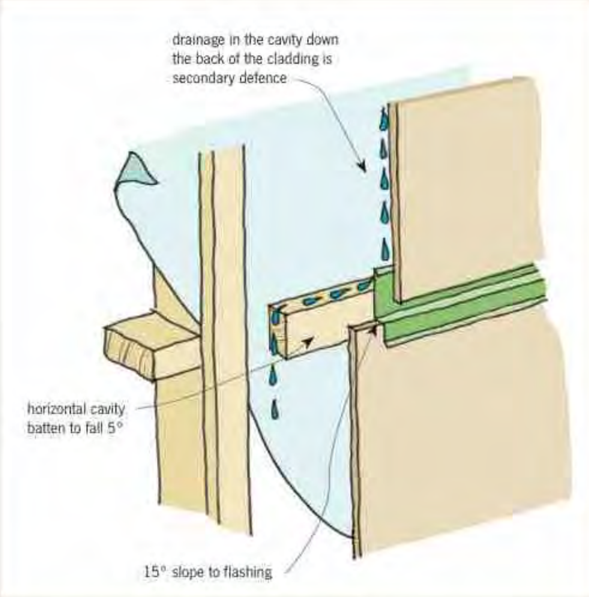

Figure 2: Drainage path as secondary line of defence – drained and vented cavity.

would also transfer moisture to the timber frame, which would decay if kept wet.) These systems rely on the face seal exterior paint or texture coating to keep water out and to be durable and weathertight.

Other components in the assembly require varying levels of durability. Treated timber framing will be durable if it remains dry, but it may rot if it is kept wet for long periods of time. Kraft-based wall underlays are durable but will deteriorate if they are kept wet, while synthetic-based wall underlays have greater durability.

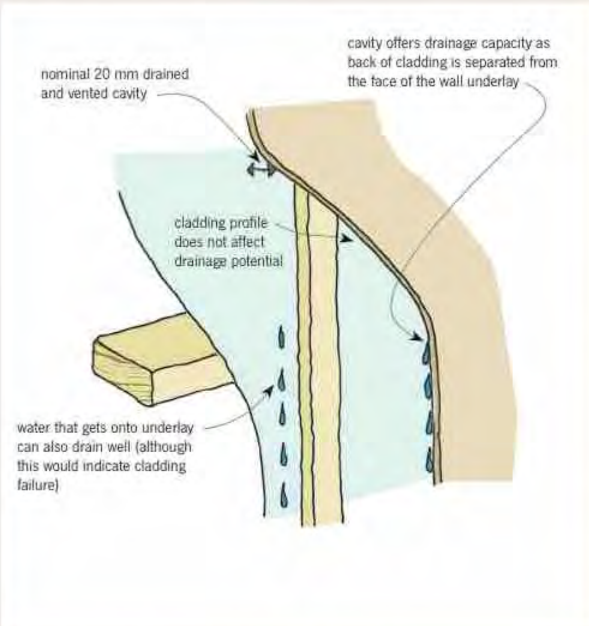

Figure 3: Drainage behind drained and vented cavity claddings.

Insight
The Perfect Wall

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

The perfect wall is an environmental separator – it has to keep the outside out and the inside in. In order to do this the wall assembly has to control rain, air, vapor and heat. In the old days we had one material to do this: rocks. We would pile a bunch or rocks up and have the rocks do it all. But over time rocks lost their appeal. They were heavy and fell down a lot. Heavy means expensive and falling down is annoying. So construction evolved. Today walls need four principal control layers – especially if we don't build out of rocks. They are presented in order of importance:

- a rain control layer
- an air control layer
- a vapor control layer
- a thermal control layer

A point to this importance thing here, if you can't keep the rain out don't waste your time on the air. If you can't keep the air out don't waste your time on the vapor.

The best place for the control layers is to locate them on the outside of the structure in order to protect the structure (**Figure 1**). When we built out of rocks the rocks didn't need much protection. When we build out of steel and wood we need to protect the steel and wood. And since most of the bad stuff comes from outside the best place to control the bad stuff is on the outside of the structure before it gets to the structure.

Also, after generations of building out of rocks folks somehow got the idea that they wanted to be comfortable – and they figured out that rocks were not the best insulation. I mean rocks are not that bad compared to windows – memo to architects: you can't build an energy efficient green building out of glass, but you can get design awards and we all know which is more important. Back to rocks, they are heavy and you need a lot of them to make the wall have any decent thermal resistance so we invented thermal insulation.

But where to put the insulation? If we put the insulation on the inside of the structure the insulation does not protect the structure from heat and cold. Remember we really do want to protect that darn structure – especially for the sake of making the structural engineers life more happy. Expansion, contraction, corrosion, decay, ultra violet radiation, and almost all bad things all are functions of temperature. So all the control layers go on the outside. Keep the structure from going through temperature extremes and protect it from water in its various forms and ultra violet radiation and life is good.

What about this air control thing? Well air can carry a lot of water and water is bad for the structure. So we have to keep air out of the structure as well because of the air-water thing – or if we let it get into the structure we have to make sure it does not get cold enough to drop its water. Now, just one other thing, tends to be important if you intend on living in the building or working in the building or keeping things safe in the building, we might want to control the interior environment. We especially ought to be concerned about what is in the interior air because when we are in the interior we tend to breathe it. Well, it turns out that we can't control air until we enclose air. So we need an honest to god airtight enclosure in order to provide conditioning such as filtration and air change and temperature and humidity control. And once again the best place to control this air thing is on the outside of the structure – but under the insulation layer so the air does not change temperature. Presto: the perfect wall. A water control layer, air control layer and vapor control layer directly on the

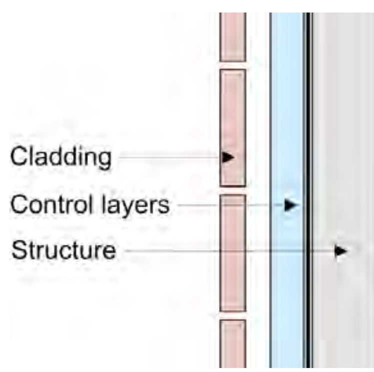

Figure 1: "The Perfect Wall"

In concept the perfect wall has the rainwater control layer, the air control layer, the vapor control layer and the thermal control layer on the exterior of the structure. The claddings function is principally to act a an ultra-violet screen. Oh, and architects might consider the aesthetics of the cladding to be important.

structure and a thermal control layer over the top of the other control layers (see **Figure 1** again).

This was figured out long before I was born – I think the Canadians figured it out first (1), but the Norwegians have some claims to this plus the Russians. I am going to go with the Canadians on this one because I am biased and proud of it. Also, I met Professor Hutcheon, and that is a story for the grandkids when I get some – memo to Christy and Andrew: so what's the delay here? For a more detailed discussion of the physics of all of this go to the old masters: Hutcheon and Handegord (2) and the new kids on the block Burnett and Straube (3).

In a beautiful bit of elegance and symmetry if you lie the perfect wall down you get the perfect roof (**Figure 2**) and then when you flip it the other way you get the perfect slab (**Figure 3**). The physics of walls, roofs and slabs are pretty much the same – no surprise (**Figure 4**). This insight was shone into a whole generation of practioners by Max Baker (4) when I was first getting started.

Notice in the perfect roof assembly the critical control layer or membrane for rainwater control and air control and vapor control is located under the thermal insulation layer and the stone ballast (i.e. "roof cladding") so that it is protected from the principle damage functions of water, heat and ultra violet radiation. Arrhenius* would be proud. Why we put the most critical control layers on roofs on the very, very top where they can be trashed by these damage functions never fails to amaze me. Yes, I know, they are easier to replace when they are located there. Standard answer for our disposable, unlimited resource available society.

Most problems in building enclosures occur where roofs meet walls. The classic roof-wall intersection is presented in **Figure 5** (will both credit and apologies to Max Baker). Notice that the control layer for rain on the roof is connected to the control layer for rain on the wall, the control layer for air on the roof is connected to the control layer for air on the wall…..and so it goes. Beautiful. And when it is not so…ugly.

* Dead, Nobel Prize Winner, no longer fashionable to study.

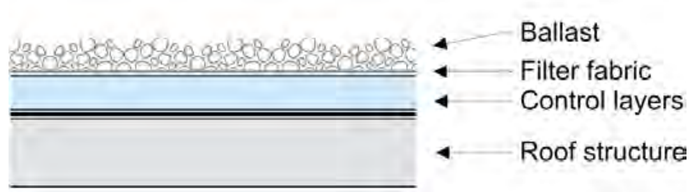

Figure 2: "The Perfect Roof"

The perfect roof is sometime referred to as an "inverted roof" since the rainwater control layer is under the insulation and ballast (i.e. roof cladding). Personally I don't view it as inverted. Those other folks got it wrong by locating the membrane exposed on the top of the insulation – it is they that are inverted.

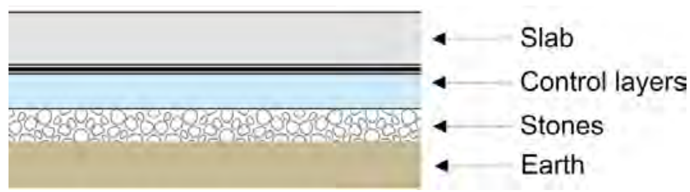

Figure 3: "The Perfect Slab"

The perfect slab has a stone layer that separates it from the earth that acts as a capillary break and a ground water control layer. This stone layer should be drained and vented to the atmosphere – just as you would drain and vent a wall cladding.

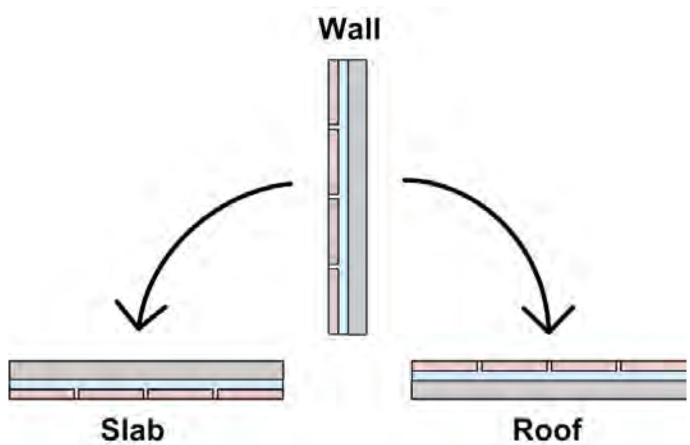

Figure 4: A Wall Is A Roof Is A Slab

The physics of walls, roofs and slabs are conceptually the same.

Time to put some meat on the bones of **Figure 1**. How should this perfect "conceptual" wall actually be built? Three ways. The best of the best of the best can be found in **Figure 6**. This is a very special wall. I refer to it as the 500-year wall for two important reasons:

- it represents 500 years of evolution; and
- it will last 500 years

It is the type of wall that you use for special buildings. Buildings that are passed down from one generation to the next. Museums, art galleries, courthouses, libraries. I call this wall the "institutional wall." It is sweet in that it can be constructed in any climate zone. The only thing that may be changed is the level of thermal insulation. My advice here is very simple: what ever you think the right amount of thermal insulation should be double it and shut up. If you love your kids don't argue with me.

A clever version of this first wall is where spray-applied closed-cell high-density foam is used to combine the four principal control layers in one material (**Figure 7**).

The second wall should be the "meat and potatoes" wall for commercial buildings. The wall every commercial building should use. The base wall that our infrastructure should depend on. So, no surprise I call it, yes you guessed it: the "commercial wall" (**Figure 8**). It has a conductive structure – metal studs. All of the insulation should – and must be located on the outside. It is a thermodynamic obscenity to insulate within a conductive structural frame. Again, you can build it

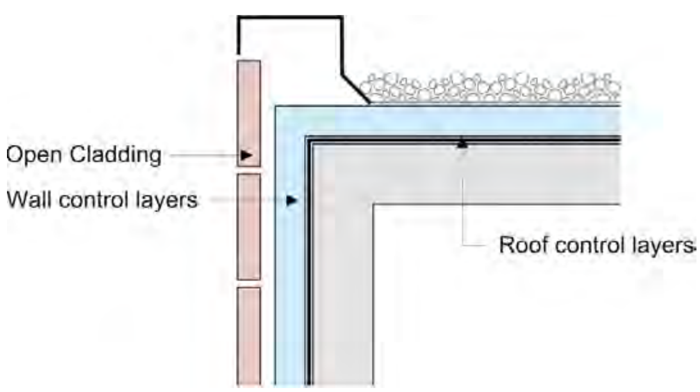

Figure 5: "The Roof-Wall Connection"

Notice that the control layer for rain on the roof is connected to the control layer for rain on the wall, the control layer for air on the roof is connected to the control layer for air on the wall… and so it goes.

anywhere in any climate location. Just consider the insulation levels (see above – particularly the part about loving your kids).

The third wall is the "residential wall" (**Figure 9**). Notice the structural cavity is insulated. That is because we are using a relatively non-conductive structural frame – the structure is wood and wood material based. Wood is not particularly conductive – that is why we do not have wood frying pans.

For this third wall to work almost everywhere (except Alaska and north of Flyn Flon** where we would not insulate even within a relatively non-conductive wood structural frame) we would split the thermal resistance of the insulation on the exterior of the structural frame with this insulation within the structural frame at least 50:50. So in an R-20 wall – at least R-10 or more on the outside of the non-conductive structural frame. And no vapor barrier on the inside of the assembly. Repeat after me, no vapor barrier on the inside of the assembly. We want the assembly to dry inwards from the control layers – and to dry outwards from the control layers. Always. Everywhere.

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(1) Hutcheon, N. B., CBD-50 Principles Applied to an Masonry Wall, Canadian Building Digest, National Research Council Canada, Ottawa, Ontario, Canada, February 1964.

(2) Hutcheon, N.B. and Handegord, G.O.; Building Science for a Cold Climate, National Research Council of Canada, 1983.

(3) J.F. Straube and Burnett, E.F.P.; Building Science for Building Enclosures, Building Science Press, Westford, MA, 2005 (www.buildingsciencepress.com)

(4) Baker, M.; Roofs, Multi-Science Publications, Ltd., Montreal, 1980.

** Home of Bobby Clark, hockey legend, no teeth

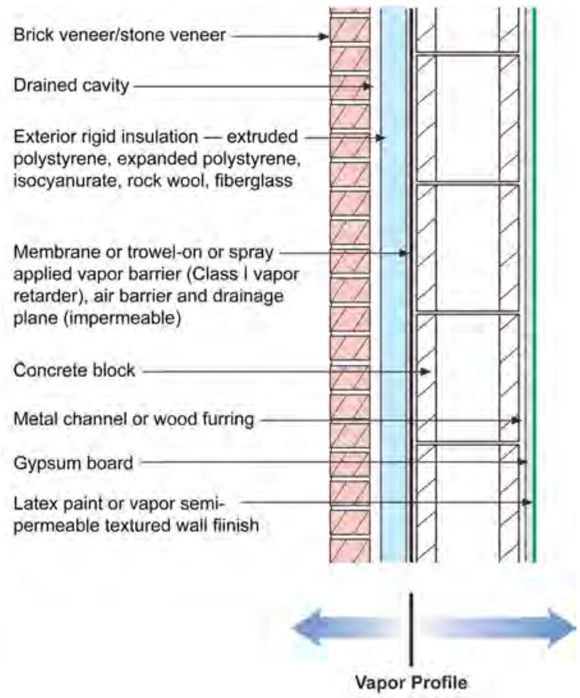

Figure 6: "The Institutional Wall"

The best wall that we know how to construct. Works everywhere in all climate zones.

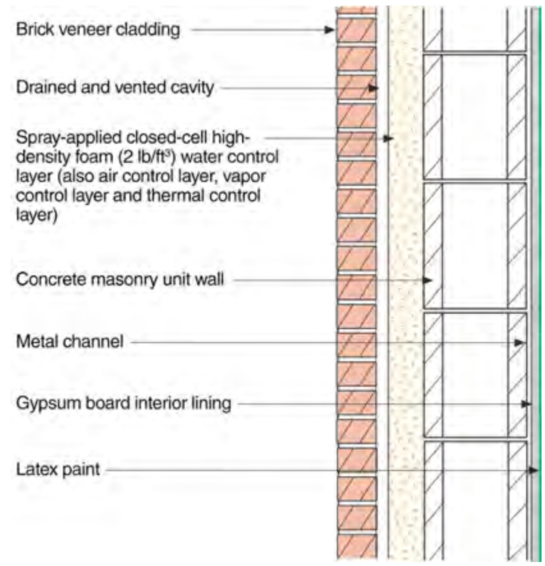

Figure 7: Clever Wall

One material combines four principal control layers.

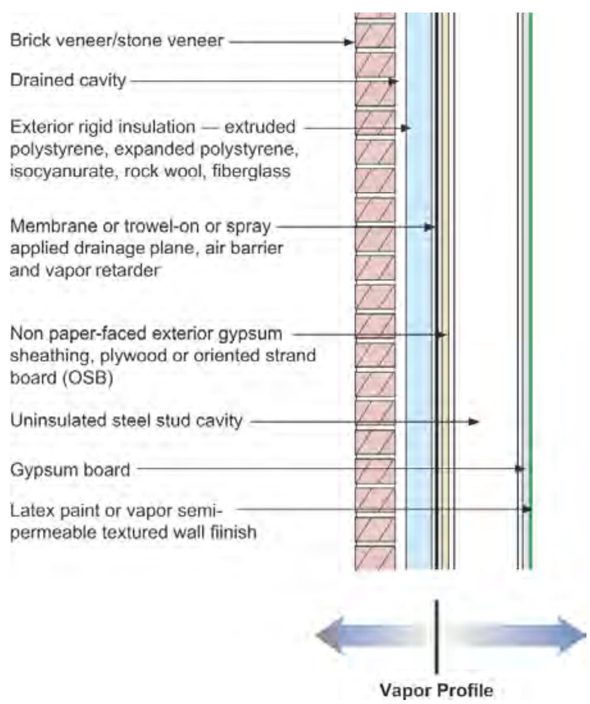

Figure 8: "The Commercial Wall"

The almost best wall we know how to construct. Affordable. Works everywhere in all climate zones.

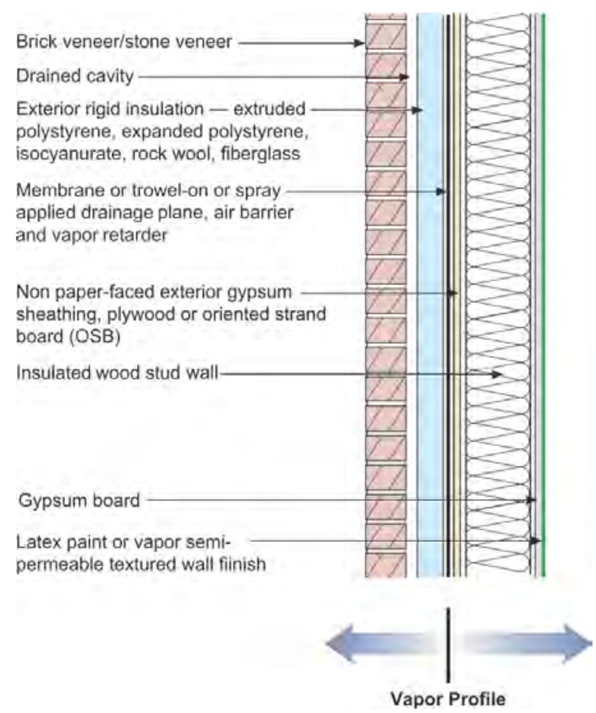

Figure 9: "The Residential Wall"

The best residential wall we know how to construct. Not cheap. Works almost everywhere – except in extreme cold climates where we would not insulate within the wood structural frame.

Insight
The Star Crossed Lovers of Building Science

Flanged windows and foam plastic insulating sheathing.

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

Sometimes I don't get it. Why would anyone deliberately recommend a thermal bridge when it is completely unnecessary? The window industry must hate the foam sheathing industry and as a result the foam sheathing industry hates the window industry. Yup, we have a vice versa. That is the only way I can explain it. Read on.

Anyone ever heard of a "ROESE"? Get used to it. It is a "rough opening extension support element"…."a projection" ("bump-out") or extension to the structural wall framing at the rough opening perimeter" according to "AAMA" and "WDMA" respectively the American Architectural Manufacturer's Association and the Window and Door Manufacturer's Association. According to AAMA and WDMA a ROESE is necessary when a flanged window is installed with walls sheathed with exterior continuous insulation – insulating sheathing – most typically foam plastic insulating sheathing.

A ROESE is not a ROSE is not a ROSE by any other name…it is a thermal bridge.[1]

Let's take a look at a ROESE in action. **Photograph 1** shows a wall sheathed with oriented strand board (OSB). The window openings are "picture framed" with a wood "bump out". The thickness of the wood "bump out" is intended to match the thickness of the continuous insulation to be installed later.

Photograph 2 shows the "bump outs" being "water proofed" with "peel and stick" flashing membranes. Note the primer being installed prior to the installation of the "peel and stick" flashing membranes. All good. All very good.

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[1] Apologies to William Shakespeare and Gertrude Stein. "Rose is a rose is a rose is a rose" comes from the 1913 poem "Sacred Emily" written by Gertrude Stein. "A rose by any other name would smell as sweet" comes from William Shakespeare's play Romeo and Juliet. Recall that Romeo is from the house of Montague and Juliet is from the house of Capulet. It can be argued that the Montagues and Capulets were the Elizabethan version of the Hatfield's and McCoy's. Note that the Hatfield's and McCoy's intermarried and regularly changed allegiances. On a completely unrelated topic Fortune Magazine announced the merger of Dow Chemical and DuPont on December 11, 2015.

Photograph 3 shows the windows being installed in the openings and a fully adhered water control layer being installed. The fully adhered water control layer is being integrated with the flashing membranes at the "bump out" openings. This is all good. Excellent, in fact. No water control issues. None at all. And no air control issues. So what is my problem? It is just that the wood "bump out" is a thermal bridge. What is the point of continuous insulation if we run a thermal bridge through it at every punched opening?

According to AAMA and WDMA the function of the "bump out" is to support the weight of the window and to "allow direct structural attachment of the window in order to transfer wind loads to the structure" when you install exterior continuous insulation. Seems reasonable. Except why now? Never needed this before. The building industry has only about 35 years of historical experience showing that this is not necessary. Installing flanged windows over foam sheathing goes back to Deep Purple and Smoke on the Water.[2]

Photograph 1 – ROESE In Action - The wall framing is sheathed with oriented strand board (OSB). The window openings are "picture framed" with a wood "bump out". The thickness of the wood "bump out" is intended to match the thickness of the continuous insulation to be installed later.

Photograph 2 – Water Proofing the ROESE - The "bump outs" are "water proofed" with "peel and stick" flashing membranes. Note the primer being installed prior to the installation of the "peel and stick" flashing membranes. All good. All very good.

Photograph 3 – ROESE Window Installation - The windows are installed in the openings and a fully adhered water control layer is installed. The fully adhered water control layer is integrated with the flashing membranes at the "bump out" openings. This is all good. Excellent, in fact. No water control issues. None at all. And no air control issues. So what is my problem? It is just that the wood "bump out" is a thermal bridge. What is the point of continuous insulation if we run a thermal bridge through it at every punched opening?

[2] Frank Zappa and the Mothers of Invention were performing at the Montreux Casino when a fire broke out due to a flare gun causing the roof to catch fire and inspired Deep Purple's "Smoke on the Water". In case you are wondering the opening riff is from guitarist Richie Blackmore.

Photograph 4 – Creep Testing - We have hung things off of foam sheathing to figure out long term creep performance.

Photograph 5 – Deflection Testing - We have hung things off of foam sheathing to figure out deflection and moments. We have sucked on windows installed over continuous insulation to understand wind loading. We have blown on windows installed over continuous insulation to understand wind loading. Others have done this. Lots of others have done this. Even the foam industry has done this.

We have hung things off of foam sheathing to figure out long term creep performance (**Photograph 4**). We have hung things off of foam sheathing to figure out deflection and moments (**Photograph 5**). We have sucked on windows installed over continuous insulation to understand wind loading. We have blown on windows installed over continuous insulation to understand wind loading. Others have done this. Lots of others have done this. Even the foam industry has done this. Testing and field experience show that "bump outs" are not necessary. Did the window industry just "wake up"? What problem are we solving? Besides having to learn origami and apply the knowledge at window-to-wall interfaces and door-to-wall interfaces?

Seems to me that you only need a ROESE if you want to wrap the exterior of the continuous insulation with a building paper or other non-adhered film water resistive barrier because the building paper or other non-adhered film water resistive barrier needs to be attached to something and you need extremely rigid backing behind the flange to get the sealant behind the flange to act as a gasket between the sheathing and the building paper or other non-adhered film water resistive barrier. You don't need to do this if you use the continuous insulation itself as the water control layer or if you install the water control layer behind the continuous insulation and the window is an "innie".

If the window is an "outie" and the water control layer is behind the continuous insulation you need a ROESE – and that would smell as sweet by any other name. Similarly, if the continuous insulation is mineral fiber insulation boards (aka "stone wool") – see "Windows Can Be A Pain", ASHRAE Journal, April 2015.

Now I do not have any problem with installing building papers or other non-adhered film water resistive barriers over continuous insulating sheathing. None at all. It is just that in many applications you do not need to. You can use the exterior continuous insulation itself as the water control layer. But I don't like tape at the joints. OK, you can go the building paper and non-adhered film water resistive barrier route. If I like the tape approach or the fully adhered membrane approach I don't need the ROESE.

I also do not have any problem with installing building papers or other non-adhered film water resistive barriers behind continuous insulating sheathing. None at all. It is just that you do not need to install a building paper or non-adhered film water resistive barrier if you don't want to. You can use the structural sheathing itself as the water control layer or install a fluid applied water control layer to the structural sheathing or install a fully adhered water control layer to the structural sheathing.

All of these options work. The options ought to be a design choice.

So let's assume that we actually have a problem with structurally attaching flanged window through exterior continuous insulation. Just for yuks go with me on this. How does the window industry recommend attaching non flanged windows? Straps. Straps baby…..straps (**Photograph 6**). In fact that is the only way to install windows in high wind zones and seismic zones regardless of the sheathing type (**Photograph 7**).

Photograph 6 – Straps - How does the window industry recommend attaching non flanged windows? Straps. Straps baby…..straps. Note in the photograph we are using straps with a flanged window. I can't see how this can possibly be an issue for the manufacturers of windows as they already allow the use of straps. In fact straps are the only means of attachment for non-flanged windows. How can adding straps to flanged windows not work? Exactly. There is no argument against this.

Photograph 7 – High Wind Zone and Seismic Zone Attachment – This window is in the high wind zone of coastal Florida. Straps make it work structurally. In fact that is the only way to install windows in high wind zones and seismic zones regardless of the sheathing type. Note that the thermal bridge goes away when straps are used.

So why not use straps to attach flanged windows through exterior continuous insulation and use the flanges for water management only? Easy peasy. The thermal bridge goes away. I can't see how this can possibly be an issue for the manufacturers of windows as they already allow the use of straps. In fact straps are the only means of attachment for non-flanged windows. How can adding straps to flanged windows not work? Exactly. There is no argument against this.

We regularly use straps with flanged windows for ultra-high performance wall assemblies.

Figure 1 illustrates bump outs and foam sheathing. **Figure 2** illustrates typical window installation with foam sheathing.

Figure 1 – Window Installation Sequence For “Bump Outs” And Foam Sheathing. The water and air control layer is the sheathing behind the continuous insulation. Note the “bump out” at the perimeter of the rough opening. Note the sloping sill. Note that the pan flashing can be liquid applied or a formable membrane. Note that the seams in the continuous insulation do not need to be sealed or taped.

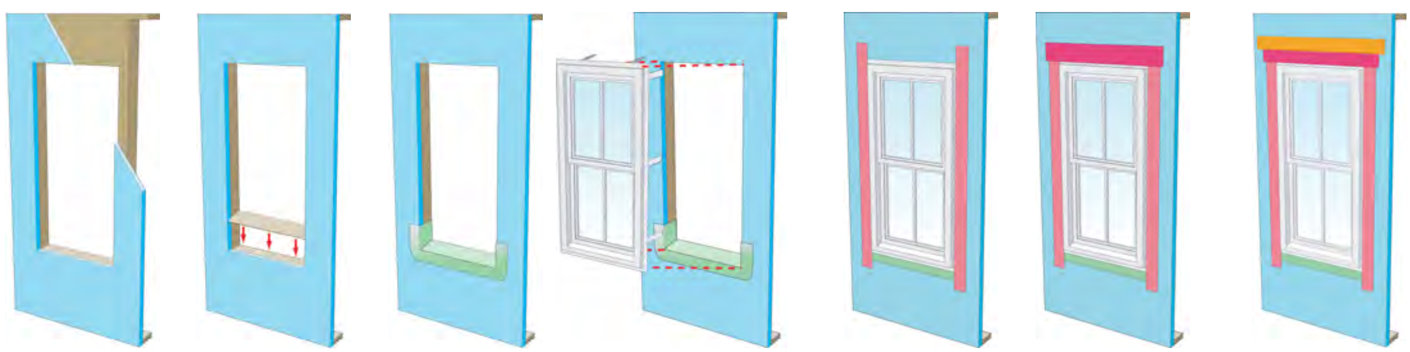


Figure 2 – Window Installation Sequence For Typical Foam Sheathing. The water and air control layer is the face of the continuous insulation. Note that the water control of the flanged window lines up with the water control of the face of the continuous insulation. Again note the sloping sill and that the pan flashing can be liquid applied or a formable membrane. Again note that sealant is not necessary behind the window flanges. And finally note that there is no wood behind the window flange – you don’t need any – the flange is seated directly over the continuous insulation – you attach the window to the framing with straps.

The NIST Net Zero Energy house in Gaithersburg, MD is one example ("Zeroing In – Net Zero Houses", ASHRAE Journal, October 2014). See **Photograph 8** and **Photograph 9**. In similar wall assemblies with 4 to 6 inches of continuous exterior insulation we line the opening with plywood or OSB "bumped out" the thickness of the continuous insulation (**Figure 3**). The "bump out" is "water proofed" with fluid applied flashing and integrated with a fully adhered membrane on the structural sheathing (**Figure 4**). A flanged window with straps is installed into the opening (**Figure 5**). In this case the "bump out" is an insignificant thermal bridge. The straps with the flanged window makes it all work.

It should not be a tragedy when flanged windows and foam plastic insulating sheathing are used together. The feuding families need to get reconciled. High performance windows need continuous insulation and continuous insulation needs high performance windows.

Photograph 8 – Net Zero House Strapped Window - We regularly use straps with flanged windows for ultra-high performance wall assemblies. The NIST Net Zero Energy house in Gaithersburg, MD is one example ("Zeroing In – Net Zero Houses", ASHRAE Journal, October 2014).

Photograph 9 - More Net Zero House Strapped Windows – The wall assembly has 4 inches of continuous exterior insulation. The window opening is lined with plywood or OSB "bumped out" the thickness of the continuous insulation. Note the air sealing around the straps.

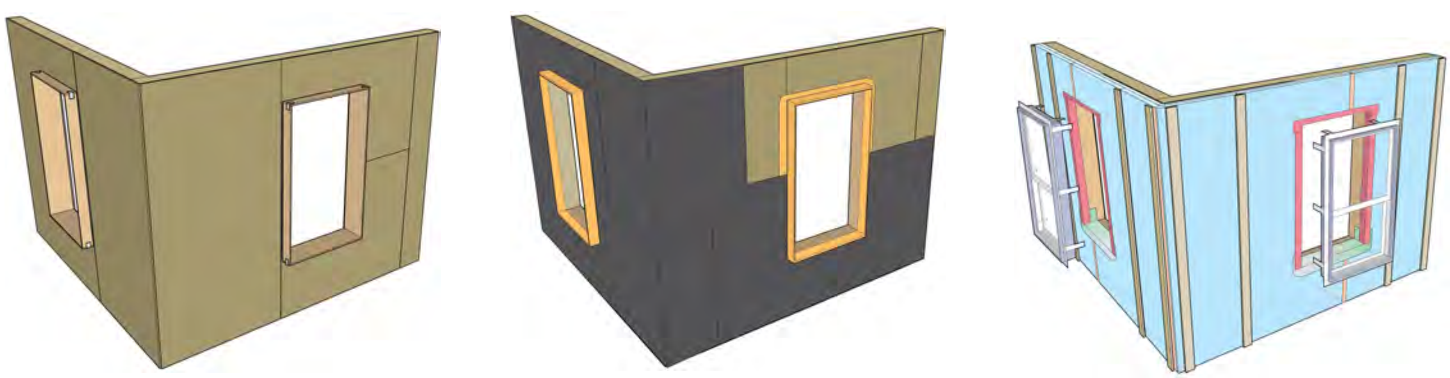


Figure 3 – Ultra-High Performance Wall – With 4 to 6 inches of continuous exterior insulation we line the window or door opening with plywood or OSB "bumped out" the thickness of the continuous insulation. **Figure 4 – Ultra-High Performance Wall Continued** - The "bump out" is "water proofed" with fluid applied flashing and integrated with a fully adhered membrane on the structural sheathing. **Figure 5 – Ultra-High Performance Wall Done** - A flanged window with straps is installed into the opening. In this case the "bump out" is an insignificant thermal bridge. The straps with the flanged window makes it all work. Easy peasy.

Insight
They All Laughed....

....at Fulton and his steamboat
Hershey and his chocolate bar....

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

OK, this is one of my all-time favorite songs. George and Ira Gershwin. Performed for the first time by Ginger Rogers. But everyone sang it…Bing Crosby, Frank Sinatra, Tony Bennett. Even Lady Gaga. But the all-time best was Ella and Louis. Yes, Ella Fitzgerald and Louis Armstrong. So where am I going with this? Hang on for the connections.

Robert Fulton, an engineer of course, developed a steamboat that actually worked ferrying passengers between New York City and Albany around 1800. Yes, I know, the English and the French[1] got there first, but Fulton actually made it work.[2] Steamboats, what a fabulous way to go. Distinctive sound. Anyway, a bunch of French dudes (aka "trappers") in the late 1820's traveling along the Yampa River in what is now Colorado heard a "chug chug" sound emanating from a natural mineral spring and promptly named the spot "Steamboat Springs".

Hard not to like Steamboat Springs if you are a skier. Buddy Werner was born and raised there. He was the first outside of the Austrians and the Swiss to win the Hahnenkamm downhill in Kitzbuhel. Mt. Werner is named after him. Billy Kidd lives there. Billy still skis while dangling his Olympic and World Championship silver and gold medals.

Lots of building is going on in Steamboat. Pretty cold place. Did I mention that skiers like it? Yup. That's why lots of building is going on in Steamboat. But all is not joy and cuddles in Steamboat. Damn codes. Confusion reigns. It shouldn't. The codes are pretty specific. Except they are written in "codease". A language that even "Authorities Having Jurisdiction" are having difficulty interpreting. Builders are nervous. Code Officials are nervous. Bad "juju"[3] in Steamboat.

Everyone should relax and take a Valium. The code is correct and backed by the physics and historic experience. So what is the code trying to say? Actually it is two separate codes talking about two separate things that are not incompatible.

The first code is the International Energy Conservation Code (IECC). It specifies the minimum thermal resistance or R-values of wall assemblies. Steamboat is in IECC Climate Zone 7. The 2015 IECC requires that walls built "prescriptively" if framed with 2x4 framing must have a minimum of R-13 cavity insulation coupled with a minimum of R-10 exterior continuous insulation (R-13 + 10). Alternatively, walls if framed with 2x6 framing must have a minimum of R-20 cavity insulation and a minimum of R-5 exterior continuous insulation (R-20 + 5).

The second code is the International Residential Code (IRC). It specifies the vapor control requirements of "prescriptively" framed walls. The 2015 IRC requires a Class I or Class II vapor retarder on the interior of a framed wall assembly (see Table I for Class definitions). An exception is provided allowing a Class III vapor retarder if a wall framed with 2x4 framing has a minimum of R-10 exterior continuous insulation (R-13 + 10) or if framed with 2x6 framing must have a minimum of R-15 exterior continuous insulation (R-20 + 15). Using exterior continuous insulation provides condensation control by elevating the temperature of the condensing surface (the back side/cavity side of the sheathing). We have been here before ("Confusion About Diffusion", ASHRAE Journal, December 2010).

[1] Denis Papin, Thomas Newcomen and James Watt.

[2] Fulton was a pretty amazing guy. A guy born on a farm in Pennsylvania who was commissioned by Napoleon Bonaparte to design the first practical submarine, the Nautilus, when he was not painting portraits and landscapes and designing torpedoes for the British Royal Navy. Yes, that "Nautilus". An American "Leonardo"…not DiCaprio, the real one. The Beach Boys memorialized him in their song "Steamboat….Don't worry mister Fulton, We'll get your steamboat rollin…" Thank you Dennis Wilson.

[3] "juju" is a spiritual belief system incorporating objects and spells used in religious practice as part of witchcraft emanating in West Africa currently being applied to wall assemblies by building officials in North America.

Table I – Vapor Retarder Class[4]	
Class I	Vapor Retarder: 0.1 perm or less
Class II	Vapor Retarder: 1.0 perm or less and greater than 0.1 perm
Class III	Vapor Retarder: 10 perm or less and greater than 1.0 perm
Test Procedure for vapor retarders: ASTM E-96 Test Method A (the desiccant method or dry cup method)	

The temperature of the condensing surface is controlled by the ratio of the thermal resistance exterior to the condensing surface compared to the thermal resistance to the interior of the condensing surface. A 2x6 wall needs more exterior continuous insulation to control the temperature of the condensing surface than a 2x4 wall. Hence the reason for the two different requirements in the IRC for condensation control between 2x4 framing and 2x6 framing.

In a 2x4 wall with cavity insulation of R-13 plus exterior continuous insulation of R-10 the total nominal thermal resistance is R-23. In a 2x6 wall with cavity insulation of R-20 plus exterior continuous insulation of R-15 the total nominal thermal resistance is R-35. Simple arithmetic yields the following similar ratios:

Exterior Insulation/ Total Insulation	Ratio	
2x4 framing	10/23	0.44
2x6 framing	15/35	0.43

How did the IRC pick a ratio of around 0.4 for IECC Climate Zone 7? It came from me. Yup. My fault. The point was to keep the condensing surface (cavity side of the exterior continuous insulation) temperature above 40 degrees F (5 degrees C) for most of the winter. To make the arithmetic work I picked the average of the monthly average outside temperature of the three coldest months for the exterior air temperature and an interior temperature of 68 degrees F (20 degrees C).

So where did the 40 degrees F (5 degrees C) come from? Trial and error and historical experience and field testing. The temperature represents the dew point temperature of 68 degrees F (20 degrees C) air at a relative humidity of 35 percent. I (and my team) spent a couple of million taxpayer dollars over a decade building test huts (**Photograph 1**), test buildings in the various climate zones and examining regional historic practice to develop this simple relationship.[5]

Photograph 1: Test Hut - A couple of million taxpayer dollars was spent over a decade constructing, instrumenting and managing test huts in the various climate zones.

Let's apply this to Steamboat Springs. The average monthly exterior air temperature for the three coldest months in Steamboat Springs is:

December	17.4 degrees F (-8.1 degrees C)
January	15.6 degrees F (-9.1 degrees C)
February	19.9 degrees F (-6.7 degrees C)
Average	approx. 18 degrees F (-8 degrees C)

So the average temperature difference between the inside and the outside over the three coldest months is (68 minus 18) approximately 50 F degrees (28 C degrees).

Now we need to figure out the average temperature of the condensing surface over the three coldest months. Take 10/23rds of 50 and you get 22 degrees. Add 22 degrees to 18 degrees and you get 40 degrees. Ta-da! How about that? The IRC gets it right for Steamboat Springs. Note that I am patting myself on the back here. Also note that the IRC has done all the calculations for you and presented them in a table. You don't have to do any calculations. You just have to know where you are building (that establishes the IECC Climate Zone) and whether or not you are framing with 2x4's or 2x6's. So stop with the dew point calculations already….

[4] Lstiburek, J.W., "Understanding Vapor Barriers", ASHRAE Journal, August, 2004.

[5] The U.S. Department of Energy funded the research through the Building America Program.

Let's go back to the two code requirements. For a wall framed with 2x4's the IECC requires (R-13 + 10) for the prescriptive minimum thermal resistance in IECC Climate Zone 7. For a wall framed with 2x4's the IRC requires (R-13 + 10) for condensation control when using a Class III vapor retarder. How about that? Both requirements are the same for 2x4 framing. Note that the IRC does not prevent you from using either a Class I or Class II vapor retarder as well when framing with 2x4's.

However, when we frame the wall with 2x6's the IECC requires (R-20 +5) for the prescriptive minimum thermal resistance in IECC Climate Zone 7 whereas the IRC requires (R-20 – 15) for condensation control when using a Class III vapor retarder. You want to stay with the (R-20 + 5)? OK, then you need a Class I or Class II vapor retarder. Don't want a Class I or Class II vapor retarder? OK, then you need to up the thermal resistance of the exterior continuous insulation. This is not a complicated code issue.

Let me restate it a little differently. With 2x4 framing in Steamboat Springs you can use a Class I or Class II or Class III vapor retarder and not be in conflict with either the IECC or the IRC. Pick one. With R-10 exterior continuous insulation all three work just fine. With 2x6 framing you can use Class I or Class II wherever you want. However, with Class III you need to go to R-15 exterior continuous insulation or higher to make things work under the IRC.

So what's the problem? Well, folks are not used to building with exterior continuous insulation in Steamboat…or in lots of other places for that matter. Until the 2015 IECC and 2015 IRC were adopted that standard way of building exterior walls in Steamboat did not utilize exterior continuous insulation (**Figure 1**). The "wall du jour" was a 2x6 wall framed with oriented strand board (OSB) and a 6 mil polyethylene vapor barrier on the inside (**Photograph 2**). The polyethylene vapor barrier is considered a Class I vapor retarder. Everyone was happy with this. The builders, the code officials, the lift operators and the bartenders, everyone. The wall could dry to the exterior if it got wet.

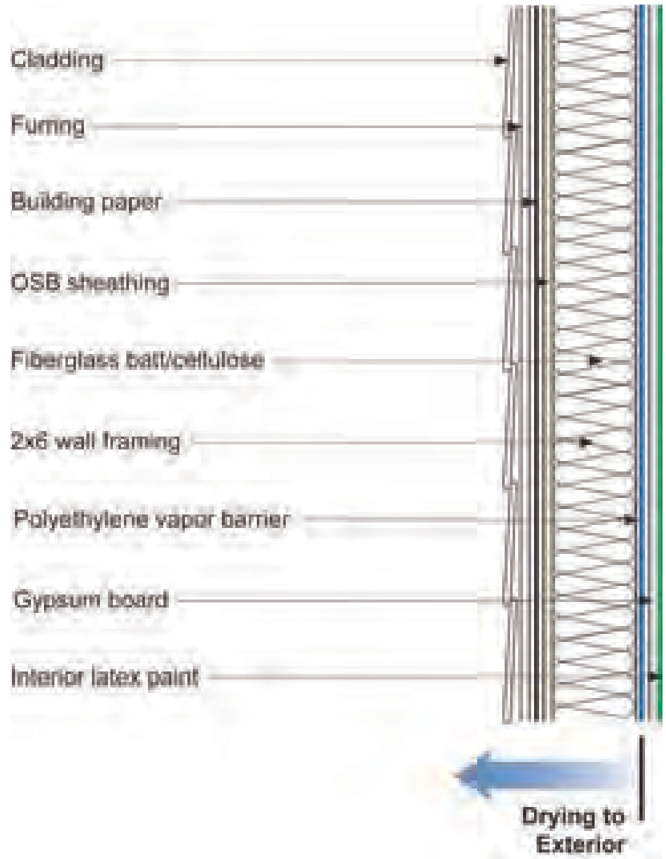


Figure 1: "Wall Du Jour" - 2x6 wall framed with oriented strand board (OSB) and a 6 mil polyethylene vapor barrier on the inside. The polyethylene vapor barrier is considered a Class I vapor retarder. Everyone was happy with this. The builders, the code officials, the lift operators and the bartenders, everyone. The wall could dry to the exterior if it got wet.

Photograph 2: Polyethylene Vapor Barrier – a "classic" Class I vapor retarder. Also a pretty darn good air control layer when installed with fastidious care…

Although it was not common, you could also install a Class II vapor retarder on the inside of the wall framing if you wanted to avoid the poly and still meet the code requirement for condensation control (**Figure 2**). The typical Class II vapor retarder was (and still is) a kraft faced fiberglass batt (**Photograph 3**). The Class II vapor retarder allowed inward drying in the summer time (we were here before as well, see Figure 4 from "How Come Double Vapor Barriers Work?", ASHRAE Journal, January 2016).

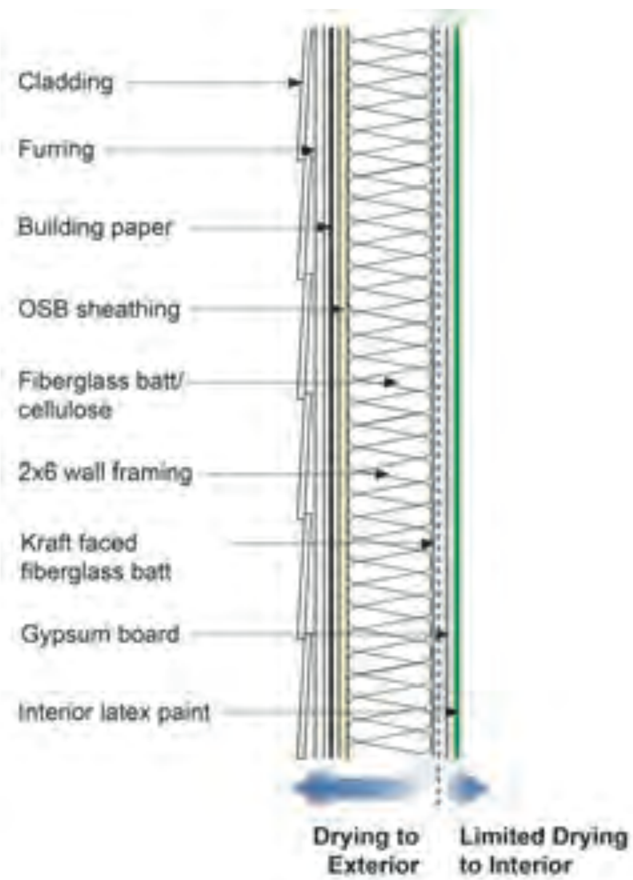


Figure 2: Class II Vapor Retarder - Although it was not common, you could also install a Class II vapor retarder on the inside of the wall framing if you wanted to avoid the poly and still meet the code requirement for condensation control.

Photograph 3: Kraft-Faced Fiberglass Batts - The typical Class II vapor retarder was (and still is) a kraft faced fiberglass batt. The Class II vapor retarder allows inward drying in the summer time.

Well, all that changed with the adoption of the 2015 codes. The builders had to use exterior continuous insulation. The big fear was would that prevent the walls from being able to dry to the exterior? Not if you used a vapor open exterior continuous insulation like stone wool/mineral fiber rigid insulation (**Figure 3**). If you used a vapor closed exterior continuous insulation like extruded polystyrene (**Photograph 4**) drying to the exterior was not possible. But drying to the interior was possible if you used enough exterior continuous insulation coupled with a Class III vapor retarder (**Figure 4**). We talked about this possibility already. Ah, but the R-15 required meant about 2.5 inches to 3 inches of exterior insulation and that was a pain. Not a lot of joy from the builders. Even the lifties and barflies were irritated.

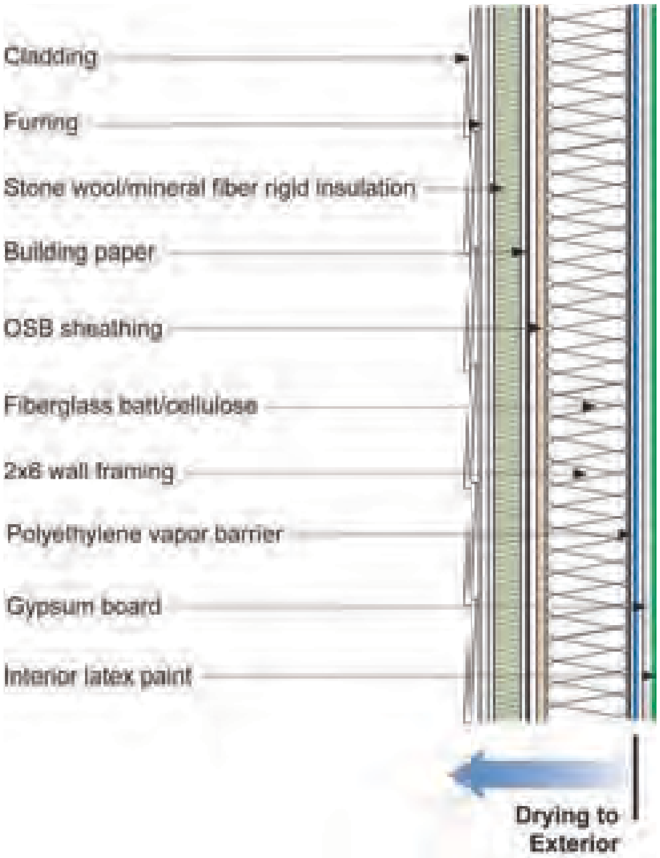


Figure 3: Vapor Open Exterior Continuous Insulation - Stone wool/mineral fiber rigid insulation allows drying to the exterior.

Photograph 4: Vapor Closed Exterior Continuous Insulation - If you used a vapor closed exterior continuous insulation like extruded polystyrene drying to the exterior was not possible.

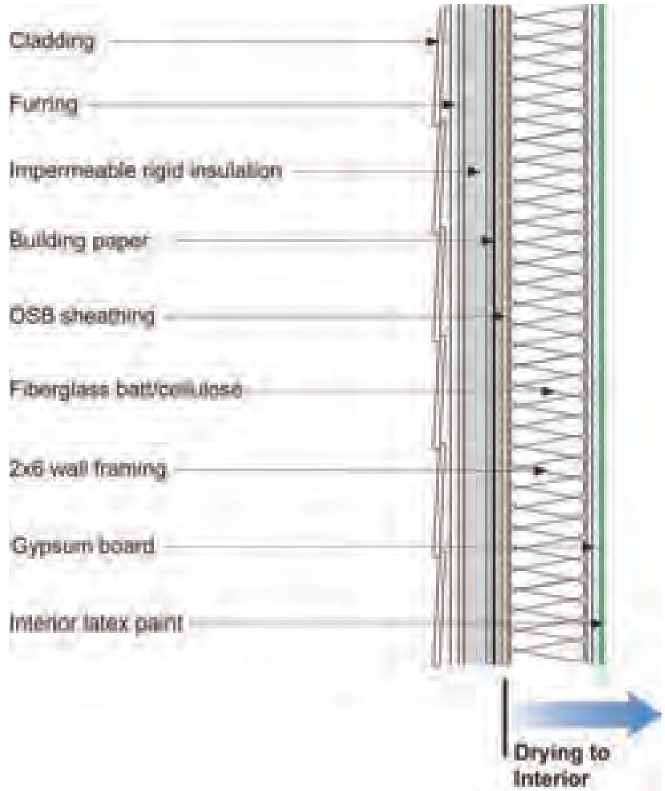


Figure 4: Interior Drying - Drying to the exterior is not possible with vapor closed exterior continuous insulation. But drying to the interior is possible if you use enough exterior continuous insulation coupled with a Class III vapor retarder.

Nothing however prevented anyone from using R-5 vapor closed insulation with 6 mil polyethylene on the inside (**Figure 5**). Yes, but that "creates" the evil double vapor barrier. Yes, but it has been shown to work all over the place. Relax. And again, as noted already, we have been here before ("How Come Double Vapor Barriers Work?", ASHRAE Journal, January 2016). But, apparently folks are unable to relax. So now what?

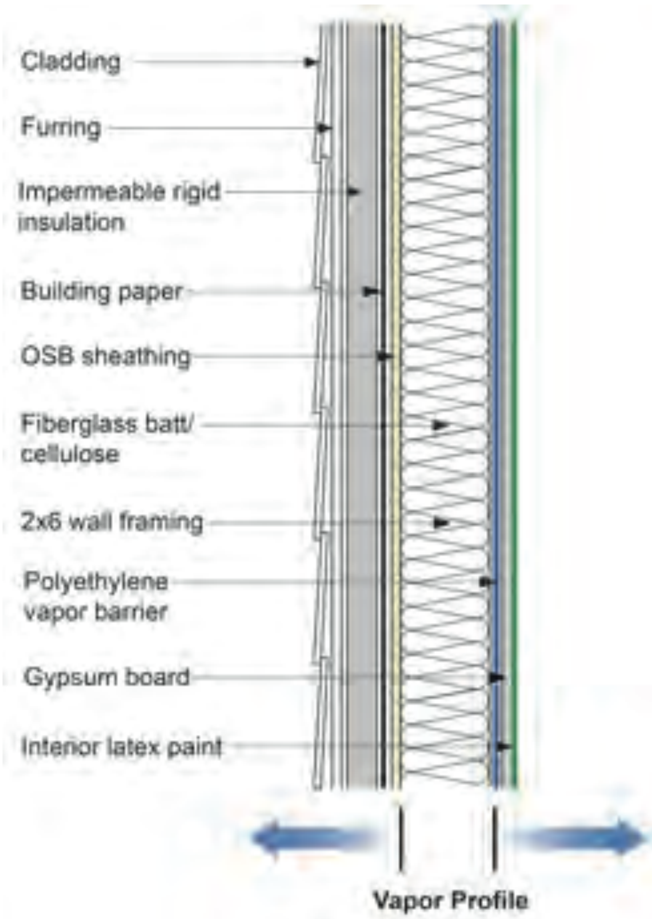
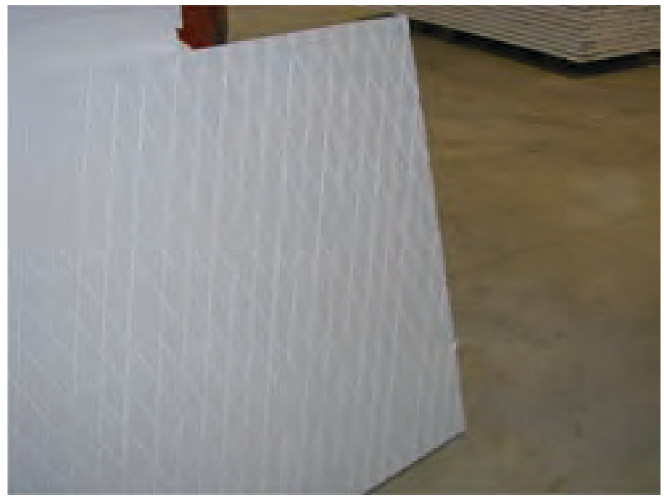


Figure 5: Double Vapor Barrier - Nothing however prevents anyone from using R-5 vapor closed insulation with 6 mil polyethylene on the inside. Yes, but that "creates" the evil double vapor barrier. Yes, but it has been shown to work all over the place. Relax. And again, as noted already, we have been here before ("How Come Double Vapor Barriers Work?", ASHRAE Journal, January 2016). But, apparently, folks are unable to relax.

Easy, replace the 6 mil polyethylene with a kraft faced fiberglass batt and keep the R-5 vapor closed exterior continuous insulation. Replace the Class I vapor retarder with a Class II vapor retarder. The IRC allows you to do this. Well, amazing as it seems, folks really like their 6 mil polyethylene in Steamboat. Go figure.

So can we make folks a little bit more comfortable with the 6 mil poly on the inside and the vapor closed exterior continuous insulation on the outside? Yes, of course. A little bit of magic and cleverness can come into play.

Back in the day, we found that cutting grooves into the continuous insulation (**Photograph 5**) or placing the continuous insulation over textured building papers (**Photograph 6**) to facilitate drainage also provided redistribution of moisture when the exterior continuous insulation was vapor closed (**Photograph 7**). (And, yes, we were also here earlier…"Joni Mitchell, Water and Walls", ASHRAE Journal, August, 2013).

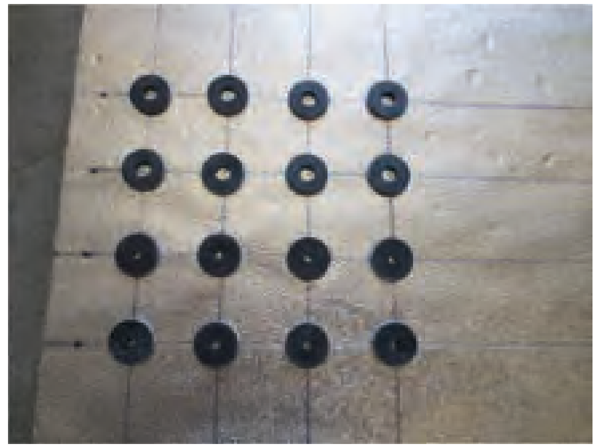


Photograph 5: "Groovy" - Cutting grooves into the continuous insulation to facilitate drainage also provides redistribution of moisture.

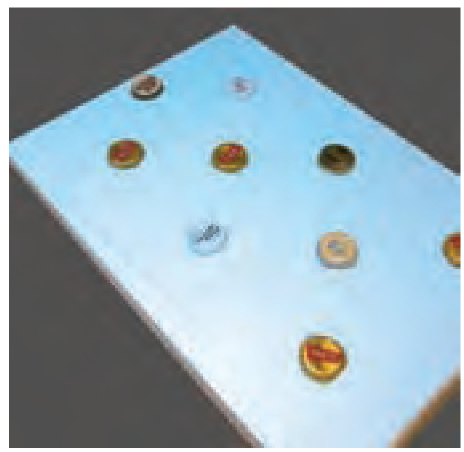
Photograph 6: Textured Building Papers - Placing the continuous insulation over textured building papers to facilitate drainage also provides redistribution of moisture.

Photograph 7: Vapor Closed Foil Faced Continuous Exterior Insulation – Note the draining building wrap providing redistribution of moisture. And, yes, we were also here earlier…"Joni Mitchell, Water and Walls, ASHRAE Journal, August, 2013).

We found that it did not take much to provide the drying to the exterior via lateral diffusion and some airflow – gaps of 1/32 to 1/16 of an inch had a huge positive benefit. Note that the spacing needed to be small to limit the reduction in thermal performance of the exterior continuous insulation.[6] Cap nails or washers proved to be pretty effective spacers (**Photograph 8**). This "rain screen" technology eventually led to the development of the "beer screen" (**Photograph 9**)…..So folks in Steamboat, keep that "chug, chug" thing going….



Photograph 8: Cap Nails/Washers - Gaps of 1/32 to 1/16 of an inch have a huge positive benefit. Note that the spacing needed to be small to limit the reduction in thermal performance of the exterior continuous insulation.



Photograph 9: Beer Screen - The "rain screen" technology eventually led to the development of the "beer screen"…..

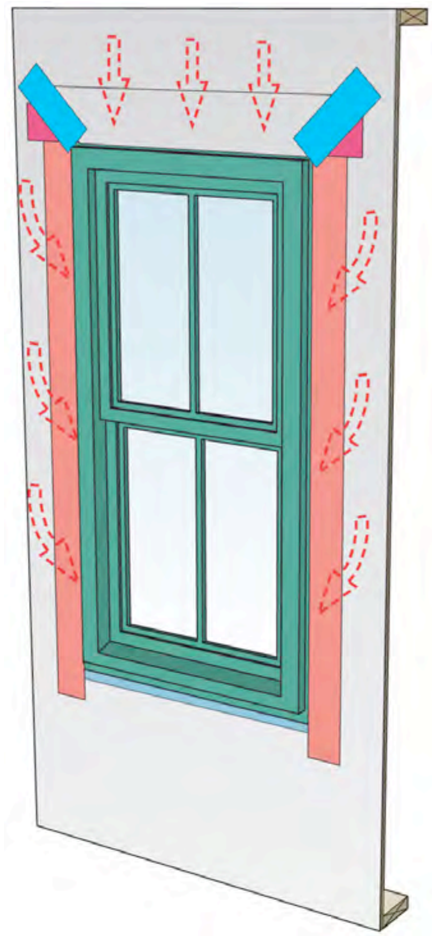
Ha, ha, ha!
Who's got the last laugh now?

[6] I am not allowed to tell you how I know this for reasons I can't get into…but trust me on this….you need to keep the gap less than 1/8 inch to limit the loss in thermal performance of the exterior continuous insulation below 5 percent….which is less than the loss in thermal performance that occurs due to the thermal bridging associated with attaching the cladding and continuous insulation itself….

Insight
Stuck on You

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek,
Ph.D., P.Eng., Fellow ASHRAE



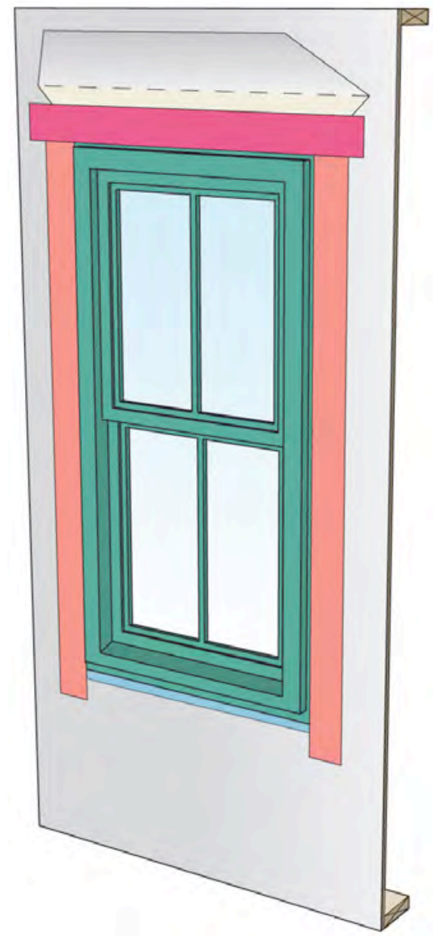


Figure 1: Water Entry at Window Opening (left) – It is important to address water running behind building wraps and housewraps at window heads and the sides of window openings. **Figure 2: Control of Water at Window Head** (right)– The top window flange is taped directly to the sheathing with "flashing tape." Note how the building wrap or housewrap is cut and folded upwards to expose the sheathing so that the "flashing tape" can be installed. Once the tape is installed, the flap is folded back down. This works exceptionally well.

One of the dirty little secrets that never gets talked about is that water leaks through building papers, building wraps and housewraps and runs down between them and the sheathings that they cover. The water enters through nail holes and staple holes and sometimes just through the field of the material if you have a poor product.[1] The good news is that the nail holes and staple holes don't leak too much and we know how to handle the incidental leakage.

In the field of the wall we don't care if things get a little wet as long as they can dry. We promote drying to the outside by leaving an air gap between the cladding and the building wrap or house wrap or water resistive barrier (wrb) or whatever we are calling this "thingy" this month. I like to call it the water control layer. Whatever. Anyway, the gap does not have to be very large—¼-inch to 3/8-inch works just fine. This gap also controls hydrostatic pressure.[2]

At penetrations such as windows and doors (**Figure 1**) we have learned to "scrape the water off the sheathing at the tops of the windows by taping the top flange of the window directly to the sheathing under the building wrap (**Figure 2**). This is a big deal. If we didn't do this, the water running behind the building wrap would wet the top of the window opening interior finish and folks would see it. We don't care if this water leaks through a joint in the sheathing in the field of the wall because the wet spot isn't seen by anyone. And if the wall is designed to dry either to the interior or exterior or both it does not

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1 We looked at some of the material properties of these products in "BSI-066: Holes and Leaks" (http://www.buildingscience.com/documents/insights/bsi-066-holes-and-leaks/view). What is bemusing to me is that of all of the myriad of material tests done to qualify these products such as resistance to hydrostatic head the entire point is missed in that the weak spot is the nail hole. If the tests made sense you would test the materials with nail holes and staple holes – a true system test.

2 We looked at this in "BSI-957: Hockey Pucks & Hydrostatic Pressure" (http://www.buildingscience.com/documents/insights/bsi-057-hockey-pucks-and-hydrostatic-pressure/view).

matter anyway.[3] Recall, that this amount of water is small.

At the sides of windows we use a "bedding joint." I love this term. A heavy bead of sealant is installed behind the flange of a window and it acts like a "gasket" smushing the building wrap against the sheathing limiting the water that can run sideways into the opening (**Figure 3**).

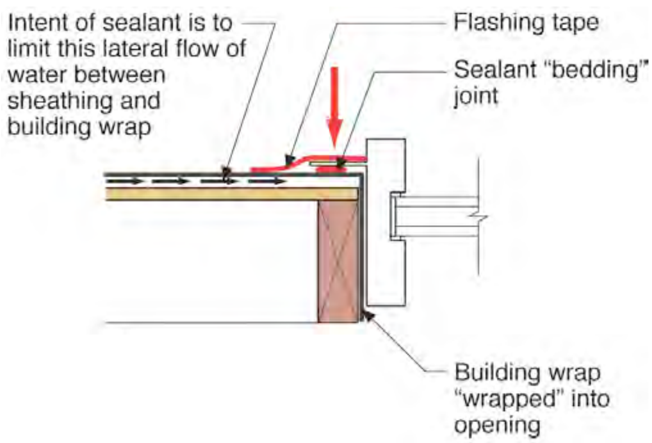


Figure 3: Control of Water at Window Jamb - A heavy bead of sealant is installed behind the flange of a window and it acts like a "gasket" smushing the building wrap against the sheathing limiting the water that can run sideways into the opening. The "red arrow" shows the "smush" direction created by screwing the window flange into the sheathing and frame opening.

And all of this works. And it works well. Building wraps and housewraps have a long history of successful performance. But understand that in order for them to work they rely on tapes and sealants—and by the way they leak… but not enough to get your knickers in a knot. All in all they provide a very robust system that is hard to beat cost wise and performance wise. Having said that there are limitations to the technology. The systems are not good for high rises because of wind loading. The wraps flutter and tear and can't take the wind load. And with complex geometries at "punched openings" trades need to learn "origami" to wrap openings. However, wherever there are limitations there are opportunities. More on this later.

Photograph 1: Gravity Lap Part I (left)– The flashing strips are layered shingle fashion. Horizontal bottom sill first. Vertical side jambs next. Horizontal head flashing last. Note the sealant used to provide water control layer continuity between the window unit and the flashing strips. **Photograph 2: Gravity Lap Part II** (right)– The rolls of building paper are installed horizontally shingle fashion. The vertical edge of the building paper is sealed to the edge of the window unit with more sealant. Any water that enters at that joint is expected to be controlled by running down the vertical "side flashing" or jamb flashing and out at the bottom. The width of the jamb flashing is problematic. That is why the flashing tape and housewrap detail at the window jamb flange shown in Figure 2 (and in Sidebar I) is such an improvement.

So what is wrong with just relying on a "gravity lap" (aka—layering things shingle fashion)? Gravity works, it is reliable, never needs maintenance and the politicians haven't figured out how to tax it….yet. Well, without some kind of sealant at vertical joints at "punched openings" gravity laps alone just do not work. Check out what we have to do at a window opening to try to make the gravity lap work (**Photograph 1** and **Photograph 2**). How wide do you have to make the vertical flashing at the jambs ("sides") to handle the flow where the building paper butts up to the window frame? This has never worked where it rains. So it is used where it doesn't rain—like Las Vegas and Phoenix. With the advent of building wraps and housewraps that can be taped these issues disappeared. It got even better when flashing systems became formable and flexible (**Photograph 3**). And better still when liquid applied systems were developed (**Photograph 4**).

In commercial and institutional buildings we have come to rely on fully adhered membranes and liquid applied membranes (**Photograph 5** and **Photograph 6**). By adhering directly to the sheathing the wind load issues become moot. And with no gap between the water

3 People seem to live in this fantasy world where they believe that walls don't leak. Almost all of them do. But it doesn't matter if they dry before any damage occurs. This balance between wetting and drying is a big deal and it is getting more complicated every day as we reduce energy flows across assemblies thereby reducing drying potentials. Having said that, we still have a lot of capacity and robustness left in most assemblies if we don't do stupid things like install vinyl wall coverings and plastic vapor barriers in climates that don't need them or assemblies that don't need them.

control layer and sheathing we don't have to worry about water that enters through fasteners wandering around between the two layers. But we had to learn a great deal about how to get the membranes to "stick." We found we had to "prime" concrete and masonry block surfaces to get things to stick. And when we had "reverse laps" we had figure out a way to "terminate" the lap–otherwise it would "fishmouth" and begin to peel away. In the early years it was so bad we used to call "peel and stick" membranes "stick and peels." When these products were first introduced in commercial buildings they had horrible reputations. Now they are the gold standard. But it took almost 20 years and major advances in adhesive technology.

This "terminate" the "reverse lap" thing is a big deal. There are a couple of ways we have learned to do this. In commercial buildings we often use "pressure bars" or a continuous bead of sealant to glue the top edge of the reverse lap to the underlying membrane or sheathing (**Photograph 7**). A pressure bar is just what it sounds like—a strip of

Photograph 3: Formable Flashing (above left) – Life got better when flashing systems became formable and flexible. This photo dates back a decade to when I got my first sample of flexible flashing to play with in my back yard. I thought it was the greatest invention since the transistor. Ok, so I am exaggerating - but only a little. Look at how beautifully a seamless under window flashing system is created. **Photograph 4: No Origami Here** (above right) – Today's liquid applied systems easily handle complex geometries seamlessly.

Photograph 5: Fully Adhered Membrane (above left) - In commercial and institutional buildings fully adhered membranes are the "gold standard." But it took 20 years. These are now true "peel and stick" systems when primers are used. **Photograph 6: Liquid Applied Membrane** (above right) - Becoming common now. Note the joint treatment – a tape reinforced mastic is installed at the joints first – then over coated with a liquid applied membrane creating as seamless, jointless system.

Photograph 7: Termination (left)– This "terminate" the reverse lap thing is a big deal. A continuous bead of sealant is used to glue the top edge of the reverse lap to the underlying membrane or sheathing.

Photograph 8: Wood Sheathing (above left) - Residentially we now use tapes on wood sheathings that have factory applied membranes factory bonded to them to provide water management and air management. **Photograph 9: Foam Sheathing** (above right) - Foam plastic sheathing panels are taped together creating a water-resistive barrier system. These systems are now around 20 years old. This image dates back to a subdivision development in Chicago in 1995. 3M was one of the first to develop acrylic based tape system for housewraps in the 1980's and they migrated to foam sheathings in the 1990's.

Photograph 10: Fifteen Year Old Tape (left) – This is my house. I took things apart at a few locations last summer to have a look at how things were working out. The tape, which is acrylic based, looks brand new and is sticking like it is brand new. The wood furring has aged, but not the tape. I am a believer. Wasn't that was a Monkey's hit recorded in 1966?

metal with a gasket attached to it that is mechanically fastened though the layers to the structure compressing a gasket to seal the reverse lap.[4] We have to thank the roofing industry for this technology. Nice job roofers.

Adhesives have come a long way in my lifetime. We glue planes together, cars together, bridges together and tissues together. And we have made them resistant to heat and ultra violet light and compatible with almost anything. But with all of the advances in materials science we have still not figured out how to get things to stick to mud, dirt and frozen surfaces. Let me repeat this because as good as things are there is no way to stick stuff to muddy, dirty, cold, wet and frozen surfaces. I should repeat it again, but you folks should just stop here, re-read the pervious sentence and think about it. Re-read it again. OK, now lets move on.

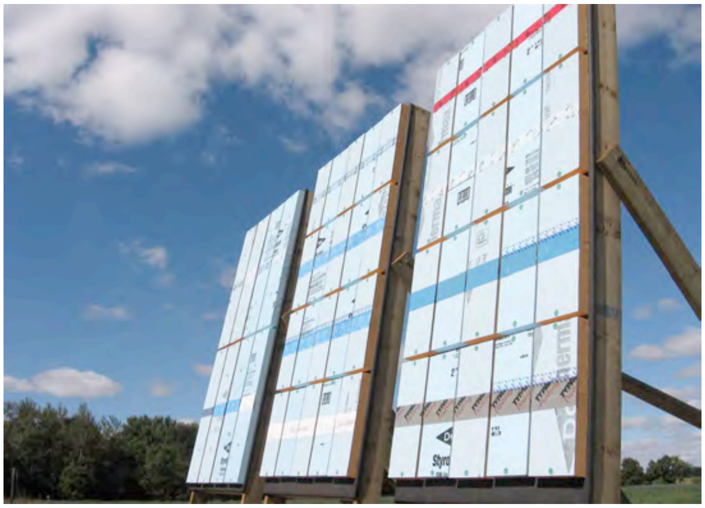
Residentially we now use tapes on wood sheathings (**Photograph 8**) and foam sheathings (**Photograph 9**) to provide water management and air management. So how well do these systems actually work? Now? Real well. In the early days? Not so good. The residential tape systems had to go through the same learning curve the commercial membrane systems went through.[5]

Tapes are typically a carrier sheet, which provides strength, and the adhesive which provides the "sticky." Carriers are often made of polyethylene or polypropylene, but can be made of aluminum foil or other materials. Flashing tape manufacturers are advancing the technology by fine-tuning both the carrier films ("facers") and adhesives.

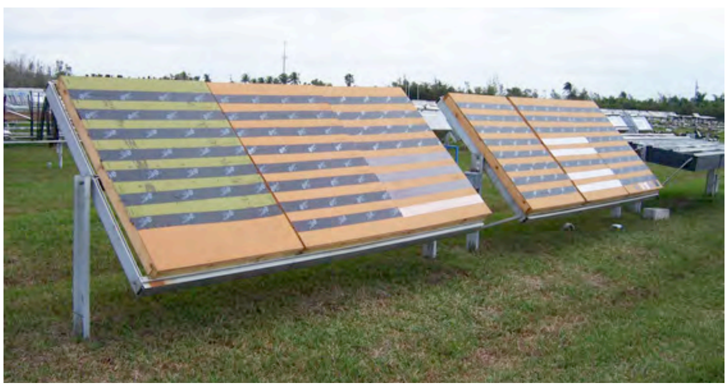
There are two basic groups of adhesives used in tapes—butyl and acrylic. Most butyl tapes are typically called "flashing" tapes and the acrylic tapes are typically called "sheathing" tapes. The butyl tapes are "thicker" and are "gooey" on the back. The acrylic tapes are very thin. The butyl tapes handle movement better than the acrylic tapes. The acrylic tapes "stick" better—they stick unbelievably well. The acrylic tapes are often used to "terminate" the top edge of a butyl tape. This is

4 A pressure bar and a gasket? Wow. Why is something so "serious" needed in a commercial building? Well, when you are up 20 floors the "loads" are an order of magnitude greater than when you are up 2 floors. And with commercial buildings the hygric buffering is significantly lower. "Hygric buffering"? Nice new popular phrase that means storage and redistribution. I can store a great deal of incidental water in wood framing and wood sheathing – I can't store squat in a steel stud or gypsum sheathing. A tiny leak in a high rise made out of glass and steel and gypsum that "sees" big "loads" is a much bigger issue than a tiny leak in a low rise made out of wood and wood products.

5 And the same learning curve the residential and commercial housewrap and building wrap folks went through. How easy folks forget the problems with UV exposure and surfactants and blow off and incompatibility with sealants. Today's systems are awesome, but 20 years ago they mostly sucked. Heck, even as recently as 10 years ago wood sugars, tannins and other surfactants drove folks crazy.



Photograph 11: Building Science Corp "Skunkworks" Exposure Facility – To test tape resistance to UV and heat and rain we stick them outside for years and watch them. The real world exposure testing is used to develop ("calibrate") short term "accelerated aging tests."



Photograph 12: Proprietary Florida Exposure Test Site - Not one of our sites. Lots of folks are testing things this way. Especially the folks who make things to sell. Nothing beats real world exposure.

Photograph 13: Horizon Homes Test Panel – You would be surprised at the number of homebuilders who are testing the stuff they plan to use to see how it works. Our rule-of-thumb is that if it works exposed like this for 2 years you are pretty much good to go.

necessary as butyl tapes can fishmouth—their top edge peels away or roll away over time—as such their top edge needs to be "terminated." This type of fishmouthing with acrylic tapes does not occur. Although most flashing tapes are butyl, advances in acrylic technology have allowed a limited number of acrylic tapes to function as both flashing tapes and sheathing tapes.

Today's tapes are resistant to UV and heat and rain. How do we know? We stick them outside for years and watch them and we also take apart older buildings that have used them to see how well they did (**Photograph 10**). Nothing beats real world exposure (**Photograph 11**, **Photograph 12** and **Photograph 13**). The real world exposure testing is used to develop ("calibrate") short term "accelerated aging tests."[6]

The term "acrylic" is deceptively simple and does not give justice to the evolution of the materials science behind it. Acrylic adhesives are based on acrylic polymer chemistry just like many high performance caulks and paints. The polymerization is "tunable" such that variables such as softness, hardness, low temperature flexibility and adhesion strength can be optimized. What all this means is that today's acrylic tapes can handle the movement of the wood based sheathings and foam sheathings—mostly because they move in tandem with the sheathings as opposed to fighting them—coefficients of expansion are "tuned" to the substrate. The elasticity of the adhesive compensates for the movement of the substrate due to changes in temperature and moisture content.

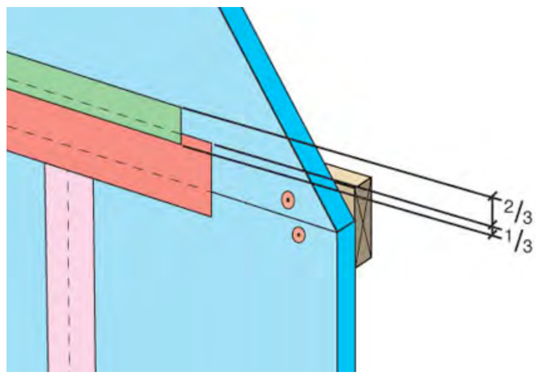
The "flashing" tapes are typically butyl rubber based (some are acrylic based as previously mentioned). The rubbers are synthetically produced and thus like the acrylics are also "tuned" to enhance performance. They are formulated compounds that allow you to add "tackifiers" to improve adhesion.

Both acrylics and butyl tape systems have UV stabilizers to address solar exposure and antioxidants to address long term aging which can change properties over time. In a twist to typical perceptions the tape systems tend to be as—or more durable—than the building wraps and housewraps they are adhered to.

6 I am old school. It is hard to beat taking a building apart after 15 or 20 years and having a peak. We have been doing this stuff for around 20 years and that is why I am now comfortable with the technology. The two decades of experience "tunes" the accelerated aging stuff and system evaluation stuff to the point where I now believe it. See the testing protocols and evaluation protocols in the References section of this column.

With any tape for it to function well it must be firmly pressed into place. This is particularly important with acrylic tape systems. They should be installed with a roller.

What's next? We see it already in the commercial side. Sealants and "paintable tapes" replacing tapes entirely. Installing a sealant in the joint and then painting over or spraying over the joint sealant. Sometimes a mesh reinforcing is used, sometimes not. Sometimes just a spray applied tape. How are they working out? Ah, a little too soon to tell with some systems. I like the sealant in the joint covered with a mesh reinforcing then all of this painted over. But then again I am old school on this stuff.



Photograph 14: More Termination (above left) - With flashing tapes we tend to terminate them two ways – with either a sheathing tape or a bead of sealant. A sheathing tape does not need to be terminated – it terminates itself. **Figure 4: Termination of Flashing Tape** (above right) – The "red" horizontal tape is a butyl based "flashing tape" that is "terminated" by a "green" acrylic based "sheathing tape."

Photograph 15: Reverse Lap (left) - With building wraps and housewraps the biggest single problem is making sure gravity laps are actually used. Look at the step flashing in this photograph. It should be "tucked under" the housewrap. Amazing as it seems reverse lapping is still the most common residential construction defect I see. Despite all the education and training in the world it still happens…go figure. In a delicious bit of irony, this type of defect is often fixed after the fact by a strip of flashing tape sealing the step flashing to the housewrap. The flashing tape is then "terminated" with a strip of sheathing tape at its top edge.

Back to this termination thing. With flashing tapes we tend to terminate them two ways—with either a sheathing tape or a bead of sealant (**Photograph 14** and **Figure 4**). A sheathing tape does not need to be terminated—it terminates itself.

At the end of the day taped sheathings work as well as building wraps and housewraps and vice versa. But there are limitations to both. With building wraps and housewraps the biggest single problem is making sure gravity laps are actually used. Amazing as it seems reverse lapping is still the most common residential construction defect I see (**Photograph 15**). Despite all the education and training in the world it still happens…go figure.

With tapes the biggest single problem is folks thinking they can stick them to muddy, dirty, cold, wet and frozen surfaces. You would think this is obvious. Again, amazing as it seems, folks keep trying to do it.

Check out ***Side Bar I*** and ***Side Bar II*** to see how to do it "right" with two of the more common "proven" approaches using either a housewrap or insulating sheathing as the water control layer.

The moral of this story is that when done well, there are a number of approaches that can work—but none of them work if put together wrong or put together dirty. With all these approaches the technology is not the problem, people are. Seesh. So folks, don't do stupid things and it will all be ok.

References

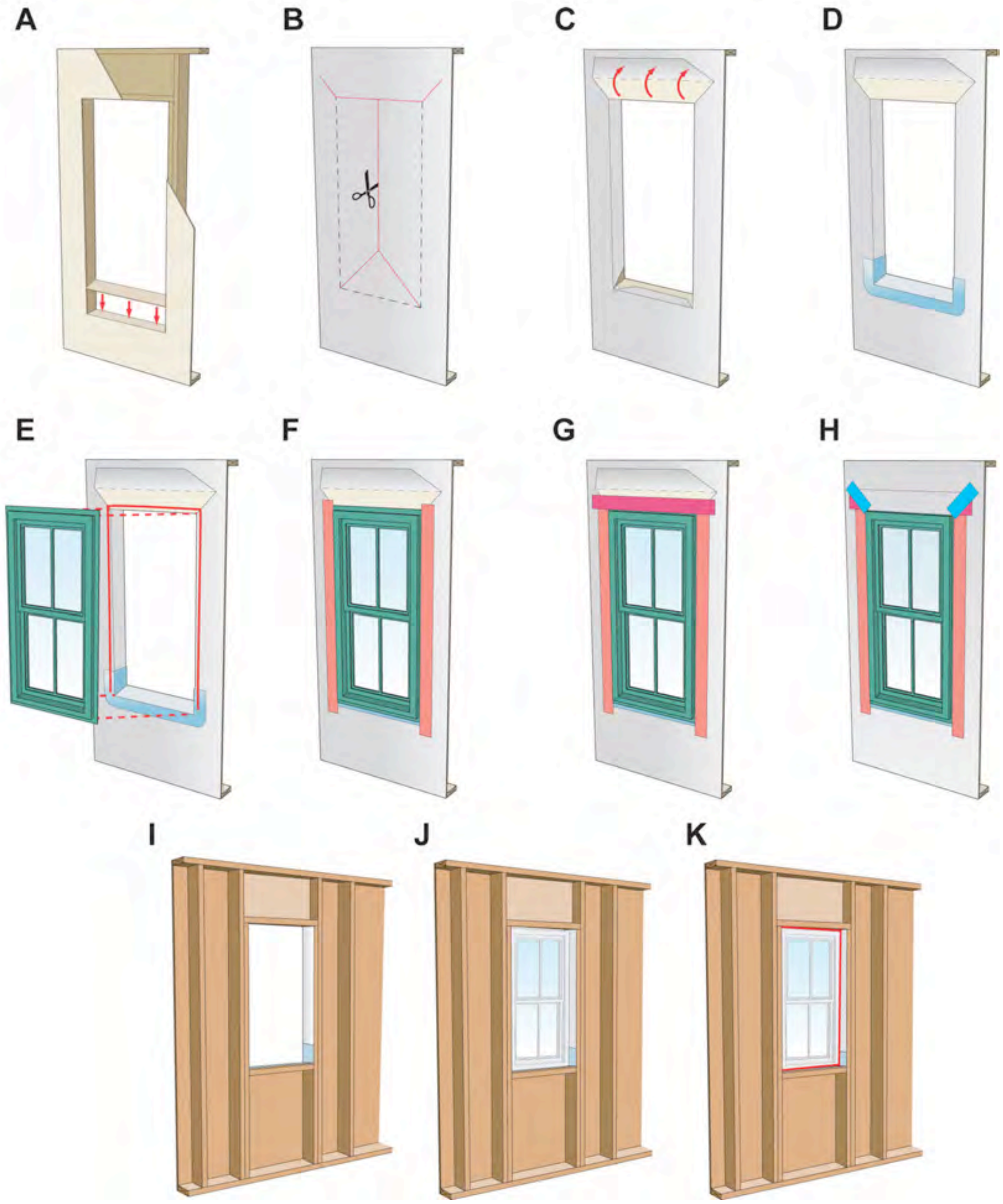
AC 71—ICC-ES Acceptance Criteria for Foam Plastic Sheathing Panels Used as Water-Resistive Barriers

AC 212—ICC-ES Acceptance Criteria for Water-Resistive Coatings Used as Water-Resistive Barriers Over Exterior Sheathing

AC 310—ICC-ES Acceptance Criteria for Water-Resistive Membranes Factory-Bonded to Wood-Based Structural Sheathing, Used as Water-Resistive Barriers

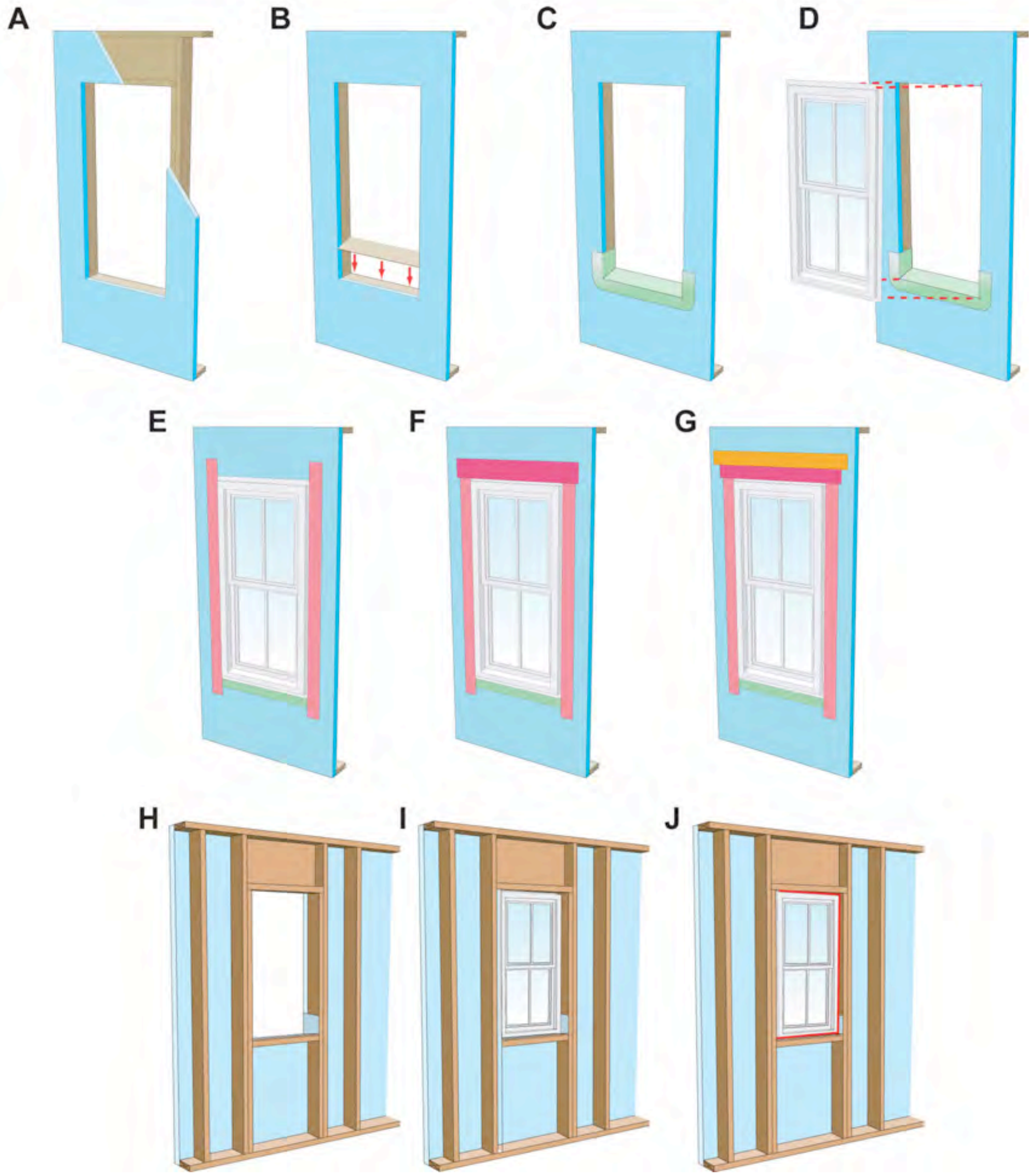
Grin, A. and J. Lstiburek; Guidance on Taped Insulating Sheathing Drainage Planes: Final Report, December 2012 http://www.buildingscience.com/documents/reports/rr-1301-guidance-taped-sheathing-drainage-planes/view.

Sidebar I: Installing Windows in Housewrap Openings



A) Install beveled wood siding in frame wall opening at sill to create slope; (B) "I" cut in housewrap; (C) Fold housewrap in at jambs and sill; housewrap at head temporarily folded up; (D) Install formable flashing at sill; (E) Install sealant bead at head and jambs; install window plumb, level and square; (F) Install flashing tape at jambs; (G) Install flashing tape at head; (H) Fold housewrap down at head; tape in place with sheathing tape; (I) Interior view prior to window installation; (J) Interior view after window installation; (K) Air seal window around entire perimeter on interior with sealant and sealant backer rod

Sidebar II: Installing Windows in Insulating Sheathing Openings



(A) Insulating sheathing installed over frame wall; (B) Install beveled wood siding in frame wall opening at sill to create slope; (C) Install formable flashing at sill; (D) Install window plumb, level and square; (E) Install flashing tape at jambs; (F) Install flashing tape at head; (G) Install sheathing tape over flashing tape at head to terminate flashing tape; (H) Interior view prior to window installation; (I) Interior view after window installation; (I) Air seal window around entire perimeter on interior with sealant and sealant backer rod

Insight
Joseph Haydn Does The Perfect Wall

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

With the "perfect wall" we were here way back when (BSI-001: The Perfect Wall). The perfect wall has four control layers outside of the structure:

- a water control layer
- an air control layer
- a vapor control layer
- a thermal control layer

These are typically covered with a drained cladding (**Figure 1**). No mystery here. The most common manifestation of the perfect wall is a steel framed wall sheathed with exterior gypsum board (**Figure 2**).

The control layers are listed in order of importance. All are important, but not equally important. The ranking comes from historic experience and the underlying physics. Controlling water in the liquid form (rain and ground water) has been the focus of master builders and architects for generations. Controlling air is a much more recent focus – less than a century. When considering water and air I can pretty much assure you I have never gotten a call at 2 a.m. from an angry client yelling "my building is leaking air…my building is leaking air". The corollary, however, is too often true for many in the industry. There should be no doubt, the water control layer is much more important than the air control layer. Take note ABAA[1].

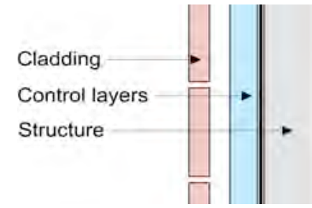


Figure 1: Perfect Wall—Control layers located exterior to the structure.

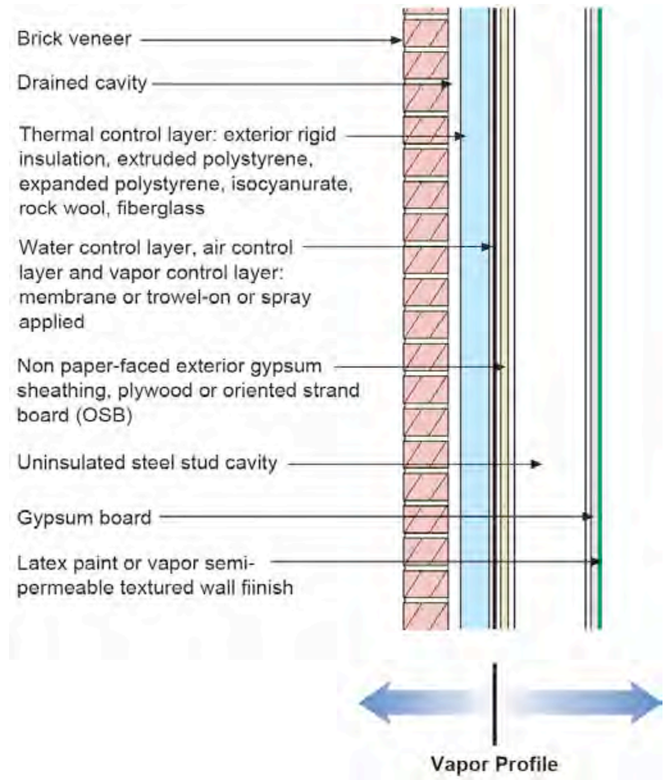


Figure 2: Typical Perfect Wall—The most common manifestation of the perfect wall is a steel framed wall sheathed with exterior gypsum board. Note the vapor profile at the bottom. Drying occurs to the interior from the bold line and to the exterior from the bold line in all climates.

Controlling vapor is even more recent – only a generation or two. Air movement transports significantly more water in the vapor form than does vapor diffusion and therefore air control is more important than the control of molecular water vapor transport "vapor diffusion". "Air barriers" are more important than "vapor barriers".

Thermal control dates back millenniums – but getting it wrong has rarely led to durability failures. The thermal

1 ABAA stands for "Air Barrier Association of America" not to be confused with ABBA the Swedish musical group. I am of the opinion we should have had a WBAA "Water Barrier Association of America" before we had an ABAA but I have learned the hard way that physics and logic should never get in the way of marketing.

control layer failures have been typically limited to comfort issues and operating cost issues. Hence, thermal control layers are listed last on the control layer "priority" list[2].

In the last decade we have gotten pretty good at combining the water control layer, air control layer and vapor control layer into a single layer that can be a film or coating or membrane or a sheet good. We have also gotten pretty good at wrapping the exterior of all this with the fourth control layer – the thermal control layer.

This configuration, with the thermal control layer outboard of the water, air and vapor control layers, allows the assembly to be constructed in all climate zones: cold, mixed, hot and humid or dry. Even better, this configuration allows this assembly to enclose all interior environments in all climate zones: office, commercial, residential, institutional, pools, museums, art galleries, data processing centers. The sole exception being refrigerated buildings and cold storage facilities. In such assemblies the location of the thermal control layer is "flipped" with the other control layers – the thermal control layer now becomes located on the interior of the other three control layers. More about this later.

In cold climates locating the vapor control layer on the interior of the thermal control layer results in this layer remaining warm therefore controlling condensation from occurring due to interior moisture sources.

In hot climates locating the vapor control layer on the exterior of the structure allows the drainage of condensation to the exterior – condensation that may occur on the exterior surface of the control layer due to exterior moisture surfaces. This condensed water is handled in the same manner as penetrating rainwater. Note that the water control layer and vapor control layer are in the same location and are typically the same material.

In mixed climates the configuration addresses interior moisture loads during the heating season in the same manner a similar assembly addresses interior moisture loads in cold climates. During the cooling season the configuration addresses exterior moisture loads in the same manner a similar assembly addresses exterior moisture loads in hot climates.

Note the vapor profile at the bottom of **Figure 2**. Drying occurs to the interior from the bold line and to the exterior from the bold line in all climates. For this reason, this configuration or assembly is referred to as the "universal wall" or the "perfect wall". It works in all climate zones for all interior environmental conditions with the exception noted.

The cladding is drained. Again, we have been here before (BSI-057: Hockey Pucks & Hydrostatic Pressure). The function of the drainage is to control hydrostatic pressure that may result from penetrating rainwater.

In this assembly a myriad of products work successfully. Almost any exterior insulation works and almost any sheet good, spray system or trowel applied membrane works.

Channeling Joseph Haydn

All is good with the universe and we are done right? Well, no. There are variations on a theme[3]. One of the variations of the "perfect wall" is an insulated metal panel.

Insulated metal panel systems are a "pre-manufactured" version of a "perfect wall" (**Figure 3**). With insulated metal panel systems the vapor profile is slightly altered from that of a traditional "perfect wall". Drying to the exterior occurs from the exterior face of the insulated metal panel system in all climate zones. Drying to the interior occurs from the interior face of the insulated metal panel system in all climate zones.

Note that the exterior face of the insulated metal panel system functions as the water control layer, air control layer and vapor control layer. Now, for the twist—the interior face of the insulated metal panel system also functions as an air control layer and vapor control layer. This dual location of both an air control layer and vapor control layer allows this assembly to function successfully for refrigerated buildings and cold storage facilities in all climates. This is the reason insulated metal panel systems "own" this segment of the business.

2 We can also calculate and model the thermal control layer much better than the other control layers. If we can calculate them and they are unimportant the building code tends to obsess over them. The code is full of U-values and R-values and pretty much silent on water control except for a generalized "be good" and "good luck".

3 *Variations on a Theme* by Joseph Haydn was composed by Johannes Brahms. A fabulous piece of work. Brahms attributed the theme – the melody—to Haydn and credited him accordingly. Although, today, there is doubt that Haydn was the original source. So for us the "Perfect Wall" is the melody of building science and it is attributed to Professor Neil Hutcheon.

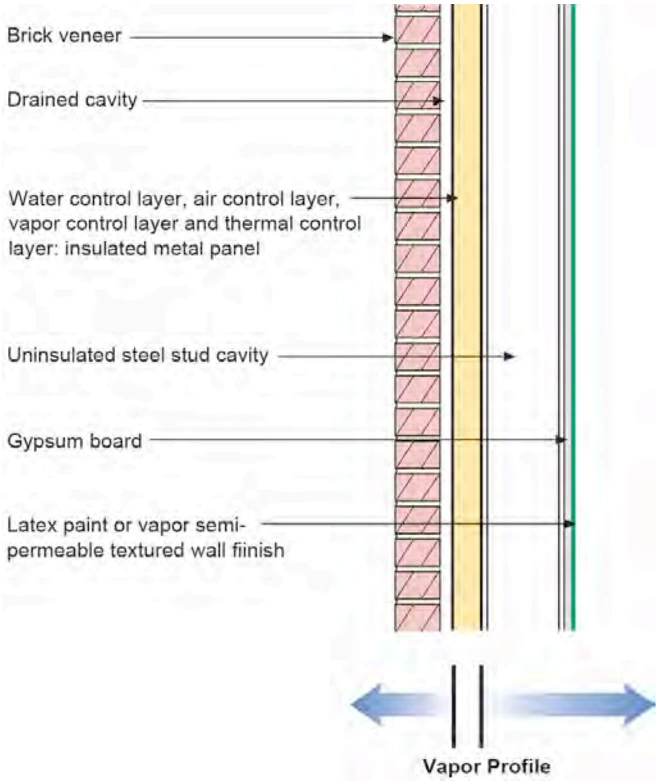


Figure 3: Insulated Metal Panel—A "pre-manufactured" version of a "perfect wall". With insulated metal panel systems the vapor profile is slightly altered from that of a traditional "perfect wall". Drying to the exterior occurs from the exterior face of the insulated metal panel system in all climate zones. Drying to the interior occurs from the interior face of the insulated metal panel system in all climate zones.

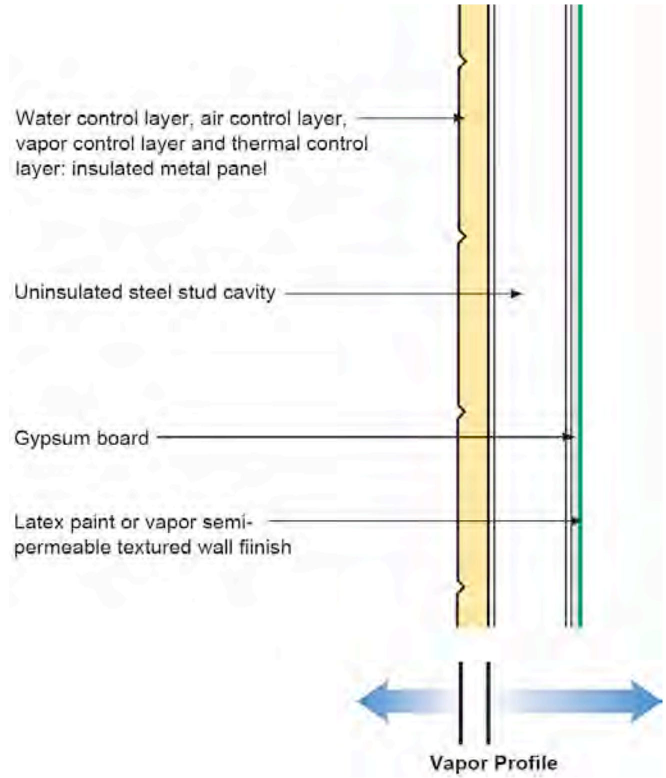


Figure 4: "Face-Clad"—The traditional cladding is omitted and the exterior face of the insulated panel becomes the cladding. With this approach insulated metal panel systems "channel" precast concrete panel systems.

Insulated metal panel systems get even simpler. Check out **Figure 4**. The traditional cladding is omitted and the exterior face of the insulated panel becomes the cladding. With this approach insulated metal panel systems "channel" precast concrete panel systems. The results are impressive (**Photograph 1** and **Photograph 2**).

From our previous look at the perfect wall we noted that the same approaches can be applied to roofs – the argument being that similar loads and the same laws of physics apply (**Figure 5**).

The traditional configuration for the control layers of a compact roof assembly is presented in **Figure 6**. Control layers are provided above and below the thermal control layer. The typical roof membrane functions as the water control layer, an air control layer and a vapor control layer above the thermal control layer – the "insulation". A second membrane or layer or layers are provided below the thermal control layer – the "insulation" – and the function of this membrane or layers is to function as an air control layer and vapor control layer. The intent is to keep the "rain" and "air" and "vapor" from getting into the assembly from the top ("outside") and to keep the "air" and "vapor" from getting into the thermal control layer from the bottom ("inside"). This configuration also works in all climate zones and for all interior environmental conditions – even for refrigerated buildings and cold storage facilities.

Note the vapor profile of the compact roof assembly. Drying occurs to the interior from the lower membrane and to the exterior from the upper roof membrane in all climate zones.

Insulated metal panel roof systems are a "pre-manufactured" version of a compact roof assembly (**Figure 7**). With insulated metal panel roof systems the vapor profile is identical to that of a traditional compact roof. Accordingly, as is the case for traditional compact roofs, insulated metal panel roof systems also work for refrigerated buildings and cold storage facilities in all climates.

Photograph 1: Insulated Metal Panel System I—Concrete frame infilled with metal framing and clad with insulated metal panels.

Photograph 2: Insulated Metal Panel System II—Completed building with both insulated metal panels and glazing installed.

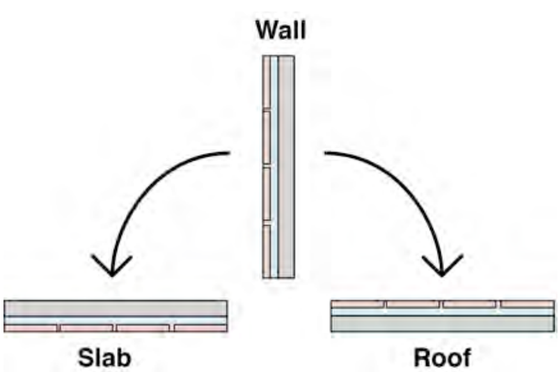


Figure 5: Walls Are Roofs Are Walls—The same approaches can be applied to both walls and roofs – the argument being that similar loads and the same laws of physics apply.

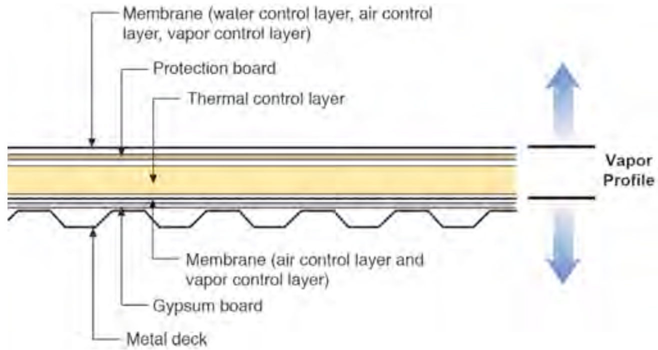


Figure 6: Compact Roof Assembly—Control layers are provided above and below the thermal control layer. The typical roof membrane functions as the water control layer, an air control layer and a vapor control layer above the thermal control layer – the "insulation". A second membrane or layer or layers are provided below the thermal control layer – the "insulation" – and the function of this membrane or layers is to function as an air control layer and vapor control layer. The intent is to keep the "rain" and "air" and "vapor" from getting into the assembly from the top ("outside") and to keep the "air" and "vapor" from getting into the thermal control layer from the bottom ("inside").

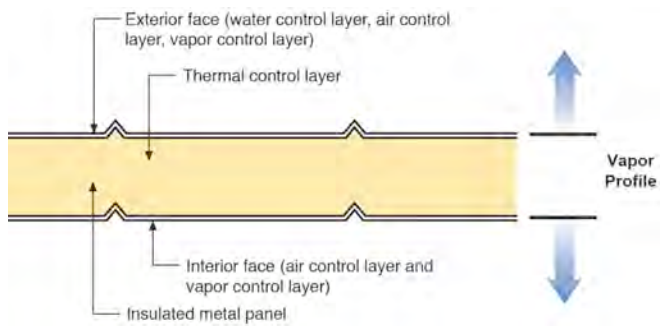


Figure 7: Insulated Metal Panel Roof—A "pre-manufactured" version of a compact roof assembly. With insulated metal panel roof systems the vapor profile is identical to that of a traditional compact roof. Accordingly, as is the case for traditional compact roofs, insulated metal panel roof systems also work for refrigerated buildings and cold storage facilities in all climates.

It's All About the Joints

In panel systems joints are required to meet the same control requirements, as assemblies are required to meet in the field of the wall or the field of the roof – namely provide:

- Water control continuity
- Air control continuity
- Vapor control continuity
- Thermal control continuity

Fundamentally the water control layer of a panel should be connected to the water control layer of an adjacent panel. The air control of a panel should be connected to the air control of an adjacent panel. The vapor control of a panel should be connected to the vapor control of an adjacent panel. And finally the thermal control of a panel should be connected to the thermal control of an adjacent panel.

Figure 8 illustrates the fundamental principles for insulated metal wall panels. Water control layer continuity is provided by a "flashed" and drained joint. The upward "tongue" of the lower panel functions similarly to the elevated vertical leg of a "metal flashing". The exterior horizontal gap between upper and lower panels facilitates drainage at the panel joint (**Photograph 3**).

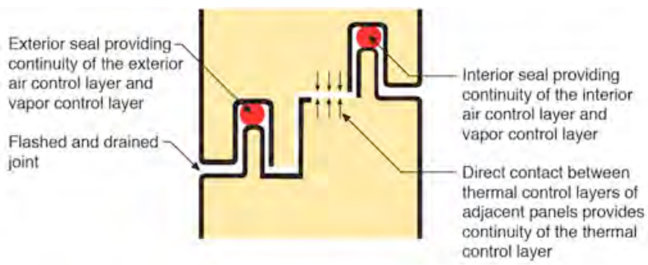


Figure 8: Wall Panel Joint—Water control layer continuity is provided by a "flashed" and drained joint. The upward "tongue" of the lower panel functions similarly to the elevated vertical leg of a "metal flashing". The exterior horizontal gap between upper and lower panels facilitates drainage at the panel joint. Air and vapor control continuity is provided by sealant joints. Note that insulated panel systems have both interior and exterior air control and vapor control layers. As such they require both an interior and exterior seal. Thermal control continuity is provided by direct contract of the adjacent panel thermal control layers.

Photograph 3: Insulated Metal Wall Panels—The upward "tongue" of the lower panel functions similarly to the elevated vertical leg of a "metal flashing".

Air and vapor control continuity is provided by sealant joints. Note that insulated panel systems have both interior and exterior air control and vapor control layers. In many insulated metal panel assemblies where wind, rain and exterior humidity loads are low the outer seal is omitted. In refrigerated buildings the inner seal is omitted to allow the joint to dry inwards.

Thermal control continuity is provided by direct contact between the thermal control layers of adjacent panels. The thermally conductive exterior and interior metal panel faces are broken at panel edges. The metal faces do not wrap continuously around panel edges thereby providing a thermal break.

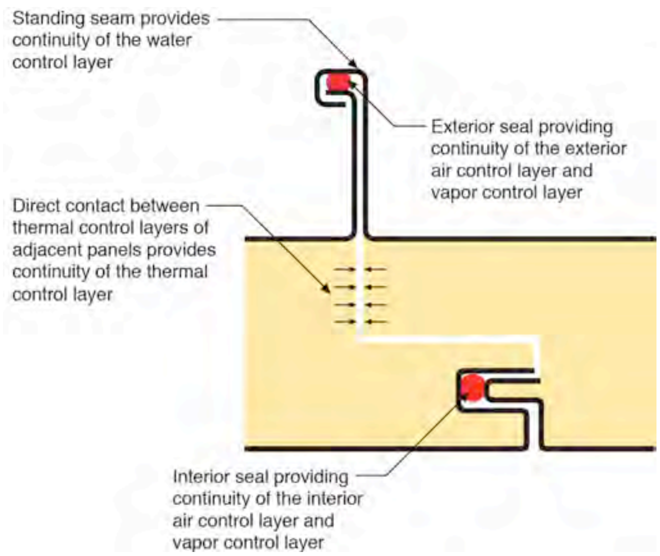


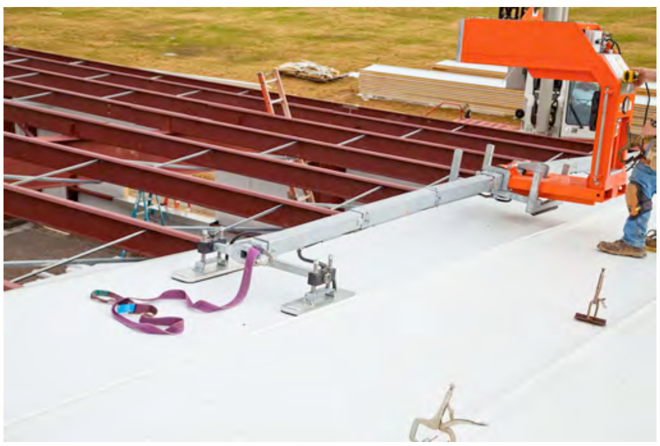
Figure 9: Roof Panel Joint—Water control is provided by a "standing seam" and gravity. Air and vapor and thermal control are addressed similarly to those of wall panels.

Figure 9 illustrates the fundamental principles for roof panels. Water control is provided by a "standing seam" and gravity (**Photograph 4** and **Photograph 5**). Air and vapor and thermal control are addressed similarly to those of wall panels.

Check out **Figure 10** for wall panels and **Figure 11** for roof panels. Note the panel mounting clips for both wall assemblies and roof assemblies are attached over the thermal control layer where the thermal control layer acts as a thermal break.

What about retrofit? Can you use an insulated metal panel system as a retrofit strategy for uninsulated masonry buildings? Yes. With retrofit approaches it is common to apply a fluid water and air control layer

Photograph 4: Insulated Metal Roof Panel—Installation of roof panels "crimping" the "standing seams".



Photograph 5: Insulated Metal Roof Panel—Positioning the roof panel during installation.

directly to the masonry (**Photograph 6**) and have the insulated metal panels only provide the thermal control function and cladding function (**Photograph 7**).

Photograph 6: Retrofit Metal Panel—With retrofit approaches it is common to apply a fluid water and air control layer directly to the masonry. Note the sheet membrane transition between the field of the wall and the replacement glazing system.

Photograph 7: Retrofit Metal Panel—Insulated metal panels only provide the thermal control function and cladding function.

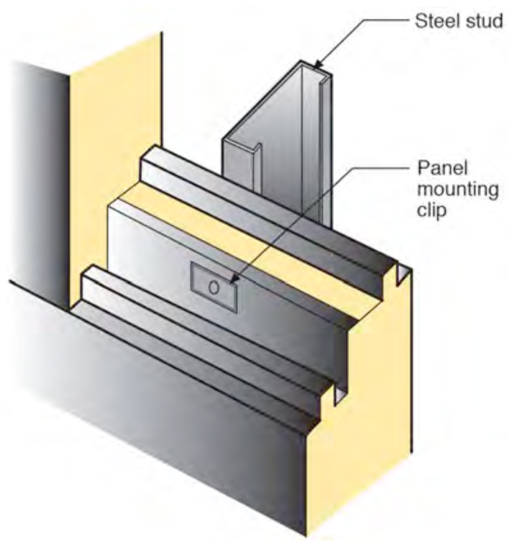


Figure 10: Wall Panel Mounting Clip—The thermally conductive exterior and interior metal panel faces are broken at panel edges. The metal faces do not wrap continuously around panel edges thereby providing a thermal break.

Pan Out?

Panel manufacturers over the past couple of generations have innovated their way into building enclosure systems that work in all climates and even more impressive—work with pretty much any interior condition from refrigerated buildings, ice rinks, natatoriums to standard commercial buildings. Apparently the systems have "panned out"[4].

4 Prospectors separate and recover valuable minerals by swirling dirt or crushed rock in a pan of water. Hence "pan out" has come to mean "to succeed".

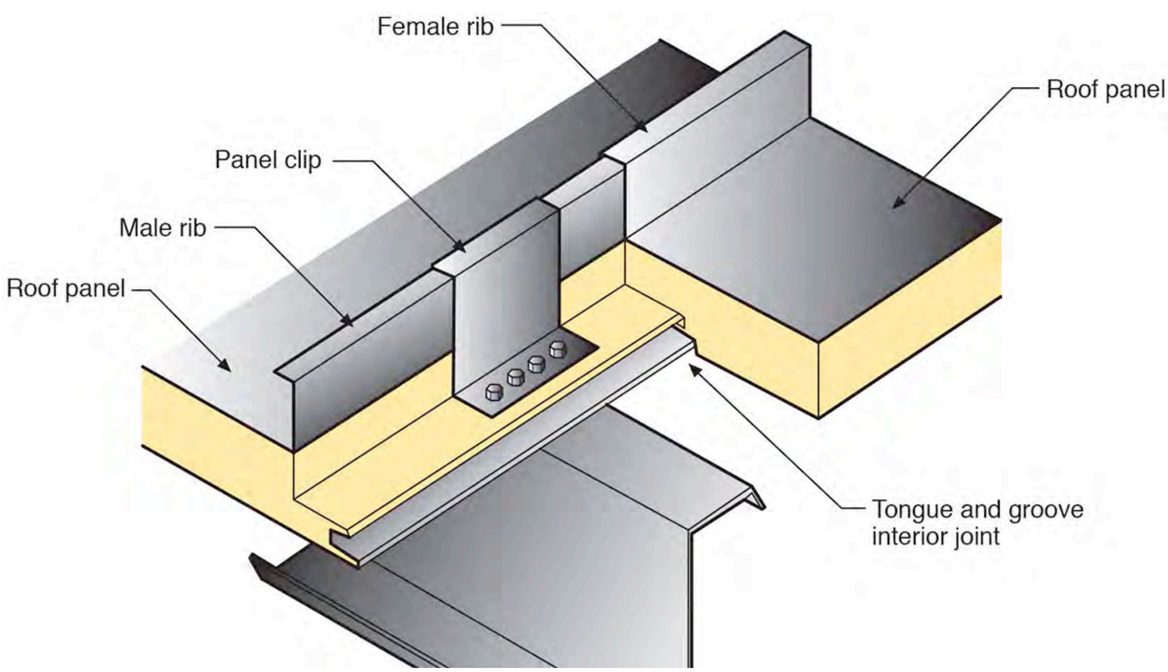


Figure 11: Roof Panel Mounting Clip—Again, as for wall panels, the thermally conductive exterior and interior metal panel faces are broken at panel edges.

Insight
Flow-Through Assemblies

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

A wall is supposed to keep the outside out and the inside in. That is the way things are supposed to work. Check out the "perfect wall" (**Figure 1**). We have our water control layer, our air control layer, our vapor control layer and our thermal control layer all in the right places. The wall dries outward from the vapor control layer and dries inward from the vapor control layer. All is right with the universe[1].

The premise relating to the vapor control layer in the "perfect wall" is that it is for all intents and purposes completely impermeable—a true "vapor barrier".[2] That way "stuff" from the inside can't get out and "stuff" from the outside can't get in. By "getting out" we really mean getting into the wall from the inside and damaging it. By "getting in" we really mean getting into the wall from the outside and damaging it.

But do we even need the vapor control layer at all? Heresy. What if we took Figure 1 and turned it into **Figure 2**? Would it still be "perfect"? Yes, pretty much. Some folks have the audacity to say that it is even more "perfect". A more "perfect" "perfect wall"? Perhaps. The premise now becomes instead of stopping "stuff" from getting into the wall from the inside let it go completely through the wall to the outside.

If "stuff" gets into the wall isn't it better to let it get all the way out rather than kick it back in? Yes, I can live with that argument if the "stuff" actually makes it all the way "out". How we let the "stuff" get out matters. If the "stuff" doesn't get all the way out you shouldn't let it get in or if it does get in you need to make sure bad stuff doesn't happen like have it change phase or if it does you need to make sure you kick it back before it causes problems[3].

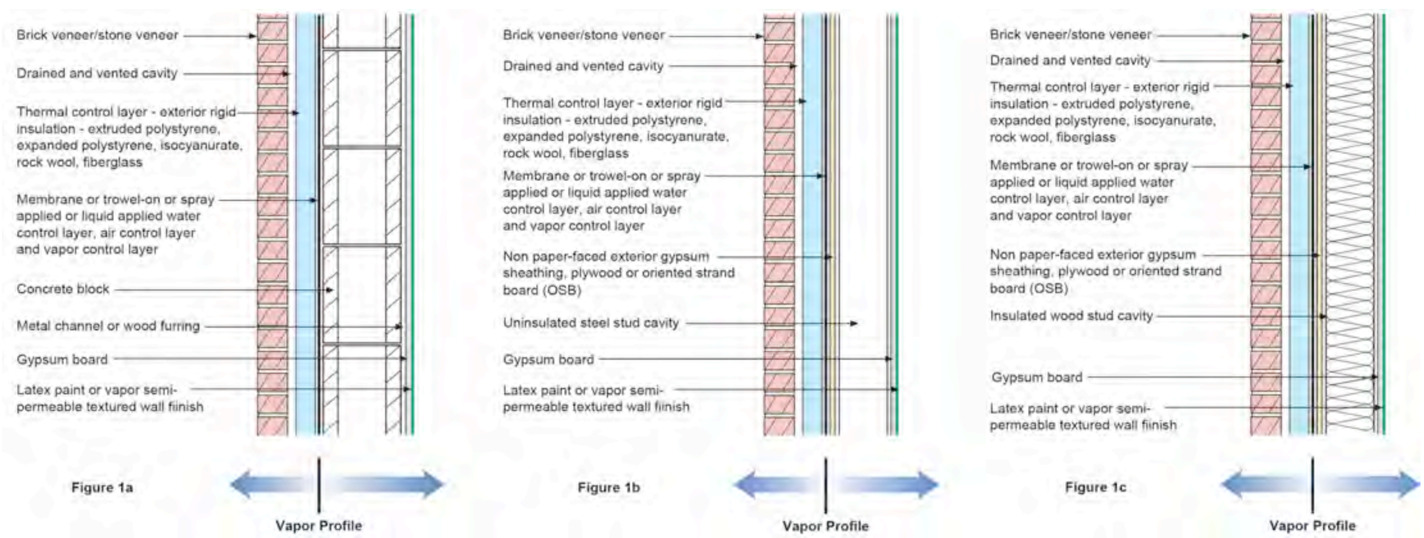


Figure 1: The "Perfect Wall"—We have our water control layer, our air control layer, our vapor control layer and our thermal control layer all in the right places. The wall dries outward from the vapor control layer and dries inward from the vapor control layer. All is right with the universe.

1 Our first column "BSI-001: The Perfect Wall".

2 Less than 0.1 perm (60 ng/(Pa-s-m^2)), a Class I vapor retarder as defined by the model codes.

3 Or "pull it" though sheathings or other layers in the liquid form quickly enough so it gets to the outside before it causes trouble on the inside. In the old days with plywood and fiberboard sheathings we would get frost and condensation on their interior surfaces but this change in phase from the

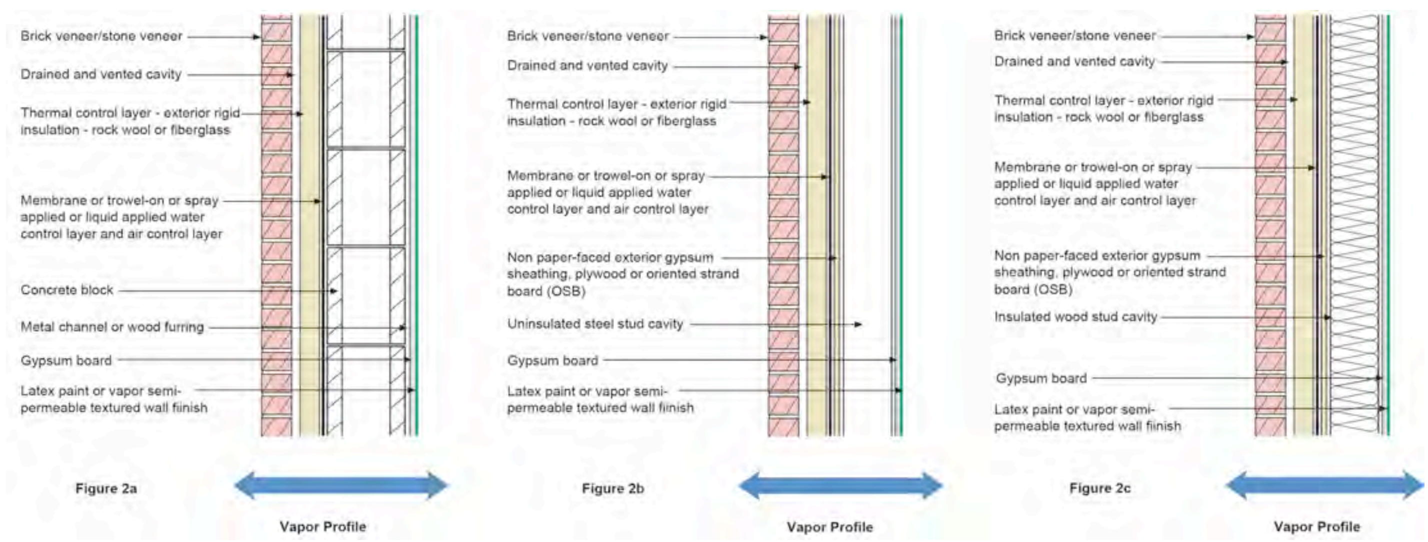


Figure 2: The More Perfect Perfect Wall? Can it be so easy that all we have to do to make the perfect wall more perfect is leave out the vapor control layer?

The "stuff" of course is water in one of its most tricky forms: "vapor". But what about "stuff" from the outside? Yeah, that too. Rainwater getting in from the outside can be real trouble. Most of us believe that when this happens it is better for the assembly to be able to "dry" in both directions—so vapor barriers on the interior of wall assemblies that leak rainwater are a problem. Of course the easy answer to this is don't have the wall assembly leak rainwater. Yeah. Right.

Can it be so easy that all we have to do to make the perfect wall more perfect is leave out the vapor control layer? Ah man, why do you ask these types of questions? Go irritate someone else. The answer is yes. Sorta. Kinda. But not always.[4]

When you have non-extreme environmental loads and continuous insulation on the outside. The answer is yes. What is a non-extreme environmental load? This means an enclosure enclosing an office or house or apartment rather than a natatorium, museum, hospital or art gallery[5]. So for natatoriums, museums, hospitals or art galleries stick with the perfect wall with a vapor control layer.

Not so fast. What does continuous insulation mean? Use the requirements in the International Energy Conservation Code (**Table 1**). Note that these are "conservative". You could get away with less…but… following the table is easy because you don't have to argue with the "authority having jurisdiction". You want to argue? Okay, I like your attitude. If you go there you are going to need to do some convincing (see BSI-089: WUFI—Barking Up the Wrong Tree?). Here is a hint—don't push the argument into "very cold" and "subarctic/arctic" climates (**Figure 3**).

Table 1: Ratio of Continuous Insulation to Cavity Insulation

IECC Climate Zone	Minimum Continuous Insulation/Cavity Insulation Ratio
Marine 4	0.2
5	0.35
6	0.5
7	0.7
8	0.95

What about when you have non-extreme environmental loads but you don't have continuous insulation on the outside? It gets a little bit more restrictive. In cold climates you need some kind of interior "vapor throttle". What is a cold climate? Think "Chicago" south and "Milwaukee" north as a kind of dividing line. The International Energy Conservation Code (IECC) is more

vapor form to the liquid or solid form would not usually get us into trouble because the liquid phase water (or frost when it melted) would be wicked into the sheathings via capillarity where it typically got redistributed and eventually found its way to the outside surface where it could evaporate or diffuse to the exterior.

4 Great "consultant" answer.

5 These enclosures are typically operated at high interior humidities (50 percent or higher year round) and pressurized.

Figure 3: Hygrothermal Regions—Note that IECC Climate Zones 7 and 8 are considered "very cold" and "subarctic/arctic".

specific. IECC Climate Zones 6 and higher require a vapor control layer. You can use a "smart" vapor barrier which is a type of "vapor throttle" and make a flow through assembly work without continuous insulation in these climate zones. But you need something to reduce the vapor flow rate from the interior if you do not have continuous insulation on the outside.

For all "flow-through" assemblies you need a ventilated cladding system over your continuous insulation or exterior sheathing to let moisture that is passing through the continuous insulation or sheathing and the respective water control layers and air control layers to get around the cladding. You don't need much of a space for most claddings. I recommend a minimum of $^{3}/_{8}$ inch (9.5 mm). We had this discussion before (see BSI-086: Vitruvius Does Veneers—Drilling Into Cavities).

When we get to reservoir claddings like brick veneers and very vapor open sheathings coupled with very vapor open water control layers and air control layers you need a bigger air space—1 inch (25 mm) for brick—and with stucco go with paint coupled with a drainage mat and the $^{3}/_{8}$ inch. Again, we had this discussion before (see BSI-087: Chubby Checker and the "Fat Man" Do Permeance). Why a bigger air gap and why the paint? Ah, vapor can flow inward as well as outward. With a rain-

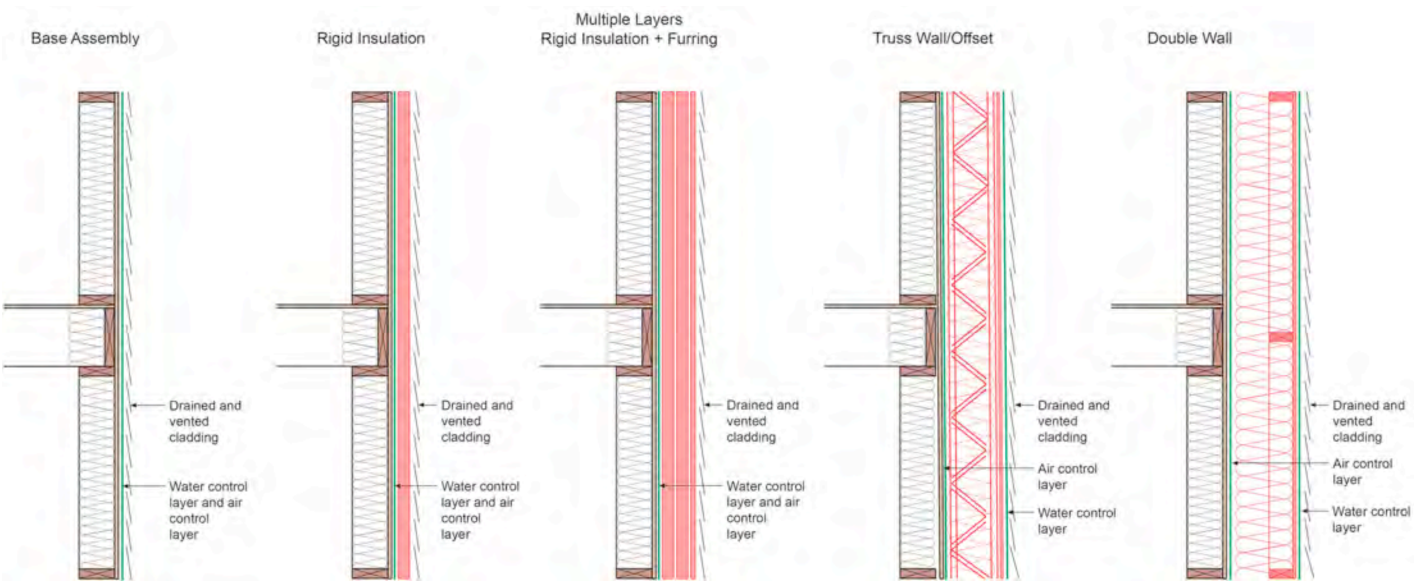


Figure 4: Flow-Through Assemblies—Various configurations of flow-through assemblies. The "base" assembly is limited to IECC Climate Zones 5 and lower unless an interior vapor throttle such as a "smart vapor barrier" is used. The "rigid insulation" assembly and "multiple layers" assembly are constrained by Table 1. The "truss wall offset" and "double wall" need a mid assembly "throttle" in IECC Climate Zones 5 and higher (we have been here before, see BSI-087: Chubby Checker and the "Fat Man" Do Permeance).

wetted reservoir cladding coupled with incident solar radiation and air conditioning we get inward drive. We either have to throttle this inward drive down or we have to uncouple the cladding with a ventilated air space or we reduce the size of the reservoir by painting the cladding or by using additives that reduce water absorption. All of these approaches work.

Figure 4 shows the various configurations of flow-through assemblies. The "base" assembly is limited to IECC Climate Zones 5 and lower unless an interior vapor throttle such as a "smart vapor barrier" is used. The "rigid insulation" assembly and "multiple layers" assembly is constrained by **Table 1**.[6] The "truss wall offset" and "double wall" need a mid assembly "throttle" in IECC Climate Zones 5 and higher (we have been here before, see [BSI-087: Chubby Checker and the "Fat Man" Do Permeance](#)).

So how do these assemblies look like? They ought to look familiar (**Photograph 1**, **Photograph 2** and **Photograph 3**). We sure have been building lots of them historically in places where it is not ugly cold in the winter. Most houses and office buildings have traditionally been "flow-through" assemblies with vapor permeable water control layers[7] and no interior vapor barrier.

6 It is not much of a constraint, but folks, at least look at the table just to make me happy? I am tired of listening to the "but I have a great ventilation system and no interior moisture " argument. Remember that I am the guy folks call when things don't work and I don't like having to say "I told you so".

7 I never liked the term "wrb" or "water resistive barrier" or its even more annoying cousin "weather resistive barrier". I grew up with "building papers". Then they became "house wraps" except when they were "building wraps". Now they are also called "combined air barrier wrb's". See [BSI-024: Vocabulary](#).

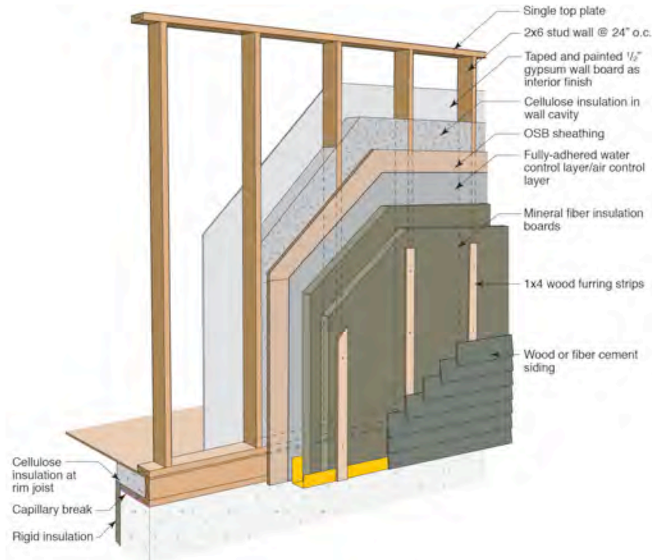


Figure 5: Vapor Permeable Exterior Rigid Insulation—We are beginning to see vapor permeable exterior rigid insulation—"continuous insulation" in the parlance of the model codes. The vapor "openness" of these rigid insulations allows us to extend "flow-through" assemblies to places where it actually is ugly cold in the winter.

The big change is **Figure 5**. We are beginning to see vapor permeable exterior rigid insulation—"continuous insulation" in the parlance of the model codes. The vapor "openness" of these rigid insulations allows us to extend "flow-through" assemblies to places where it actually is ugly cold in the winter.

Photograph 1: Residential—Fully adhered vapor permeable water control layer and air control layer. Yes, one material or product can do both things. Note the now typical oriented strand board (OSB) sheathing—a semi-vapor permeable material—an "external vapor throttle".

Photograph 2: Commercial/Retail—Fluid applied vapor permeable water control layer and air control layer installed over a vapor permeable glass faced gypsum board.

Photograph 3: Multifamily—Sheet vapor permeable water control layer and air control layer. The “classic” air infiltration barrier that also controls rainwater installed on the exterior of vapor permeable sheathing such as glass faced gypsum board.

Insight
Doubling Down: How Come Double Vapor Barriers Work?

An edited version of this Insight first appeared in the ASHRAE Journal.

By Joseph W. Lstiburek, Ph.D., P.Eng., Fellow ASHRAE

Huh? Blasphemy. Yeah, well, in some assemblies, it is actually a pretty good idea. The most famous "double vapor barrier" of them all is a classic compact flat roof. Check out **Figure 1**. The roof membrane on the "top" is clearly a vapor barrier. In fact, it is almost a "perfect" vapor barrier. And the membrane on the "bottom" is also a vapor barrier. The "bottom" membrane's primary function is that of an air barrier but it's material characteristics are such that historically it has also been a vapor barrier.

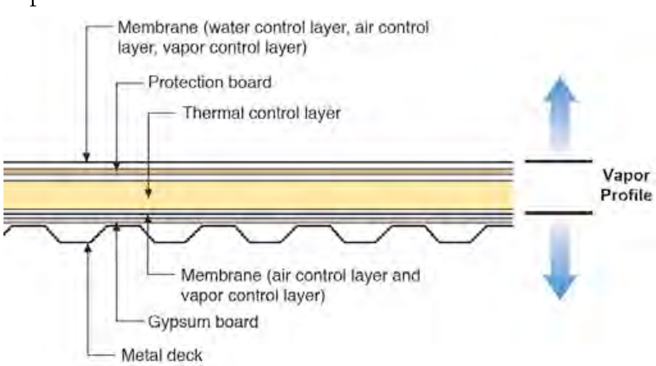


Figure 1: Classic Compact Flat Roof—The most famous "double vapor barrier" of them all. The roof membrane on the "top" is clearly a vapor barrier. In fact, it is almost a "perfect" vapor barrier. And the membrane on the "bottom" is also a vapor barrier. The "bottom" membrane's primary function is that of an air barrier but it's material characteristics are such that historically it has also been a vapor barrier.

The misunderstanding of the difference of this "vapor barrier" versus "air barrier" function in compact flat roofs goes back generations. We still have, to this day, roofing consultants, manufacturers and architects referring to this lower membrane as a vapor barrier rather than an air barrier. In fairness, it actually has been a vapor barrier, but its more important function has been that of an air barrier.[1]

So, in classic compact flat roofs we have double vapor barriers. And we have had them for a long time. And in millions upon millions of square feet of roofs. How come they work? Easy. They are pretty much "perfect" double vapor barriers and double air barriers. The upper and lower membranes are both airtight and vapor tight. Note that the airtightness is more important.[2] Moisture can't get into the assembly from the top and moisture can't get into the assembly from the bottom and that is why these roofs work.[3]

Compact flat roofs have some interesting history. When they were "black" and fully adhered they did not need air barrier "bottom" membranes in most climate zones. You could get away without a "bottom" membrane up to International Energy Conservation Code (IECC) Climate Zone 5 in commercial office buildings and warehouses – places with low interior moisture loads – if you had a "black" membrane. Note we are not talking museums, hospitals, indoor swimming pools and the like.

Interior moisture would travel upward hit the underside of the black roof membrane stop and then be driven back down when the black membrane got hot. And that back membrane would get real hot. Real, real, real hot – 180 degrees F hot. That thermonuclear sphere 93 million miles away gives off quite a bit of energy. We had ping-pong water. It went up and then got bounced back due

1 Semantics are important here. If you misname things you don't understand things. This lower layer can be vapor open and the roof assembly would still function in the majority of applications but there is no way that this layer can be air leaky and function in the majority of applications.

2 OK, OK, the upper membrane also has to be watertight. Yes, I know that is the point of having a roof. In making the upper membrane watertight you also make it airtight. The same folks who install the upper membrane also usually install the lower membrane and do it just as fastidiously. Note that "fastidiously" is the new "anal". The vast majority of flat roofs don't leak water and therefore the vast majority of flat roofs also don't leak air – when they also have a lower membrane.

3 Yeah, but what happens when they leak? They get wet, that's what happens. And they can't dry. So what happens? Well, you walk the roofs every couple of years and find if or where they are wet and leaking and take them apart and dry them and fix them and move on. We have been doing this longer than I have been alive and I remember when Elvis was thin and the Maple Leafs won Stanley Cups.

to solar radiation. Life was easy. Then membranes became "white". They didn't get so hot. White membranes were "cool" – 120 degrees F cool. The interior moisture that traveled upwards didn't get bounced back as much and we began to have problems even in office buildings and warehouse roof assemblies. We now needed air barriers. We put them in and the problems disappeared. Note that these air barriers were almost always vapor barriers.

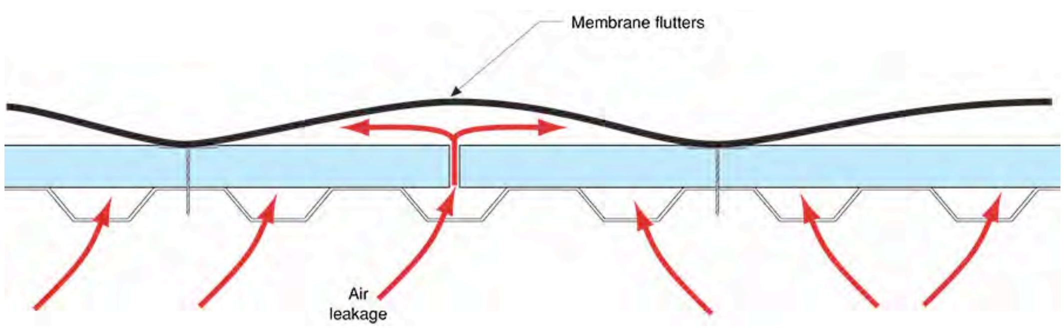


Figure 2: Fluttering Roof Membrane—When a mechanically attached roof membrane experiences suction or uplift from wind air is pulled into the roof assembly from the building interior if an underside air barrier is not present.

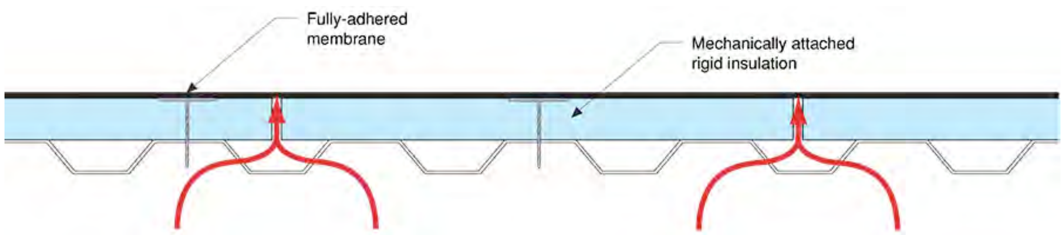


Figure 3: Fully Adhered Roof Membrane—The suction wind load is taken almost completely by the fully adhered roof membrane if an underside air barrier is not present.

So where does the fully adhered part come into play? Check out **Photograph 1** and **Figure 2**. We were here way back when ([BSI-019: Uplifting Moments—Roof Failures]). With a mechanically attached membrane and no bottom side air barrier the roof membrane "flutters". This does not happen with a fully adhered membrane (**Figure 3**) or with a bottom side air barrier. With a bottom side air barrier the wind load that a roof membrane "sees" is now "shared" between the lower membrane and the upper membrane. Blow-offs are reduced. This is a good thing.

Photograph 1: Missing Air Barrier—With a mechanically attached membrane and no bottom side air barrier the roof membrane "flutters".

So lets go back to **Figure 1**. The "vapor profile" clearly is one of a "double vapor barrier" and it works. It works fabulously well and has done so for a very, very long time in all the climate zones. So much for the "common wisdom" of never having "double vapor barriers". Yeah, but roofs don't count[4]. What about walls?

Let's look at walls with "double vapor barriers". Some work, some do not. The reasons why are important. Check out **Figure 4**. A "classic" wood frame wall with foam sheathing – a wall that we have been building in cold climates for 40 years. The foam sheathing on the exterior is clearly a vapor barrier. And the sheet polyethylene on the interior is also clearly a vapor barrier. The "vapor profile" is that of a "double vapor barrier". I grew up with this wall in Ontario - 2x6 wall with R-5 foam sheathing (**Photograph 2**) coupled with unfaced fiberglass batt cavity insulation covered with an interior 6 mil poly air/vapor barrier (**Photograph 3**). This wall is currently being built all over Minnesota and Wisconsin. It is still being built in Ontario. And it works. We know that it works because we have been building it for so long without problems. So why does it work? The

4 I love the "roofs don't count" comment from folks when you crush them with an obvious fact that destroys their argument. Apparently, the physics are different in roofs and walls. Actually, not, but the assemblies are somewhat different as we shall see.

reasons are somewhat different than the discussion we just had with compact flat roofs. Not completely different, but somewhat different.

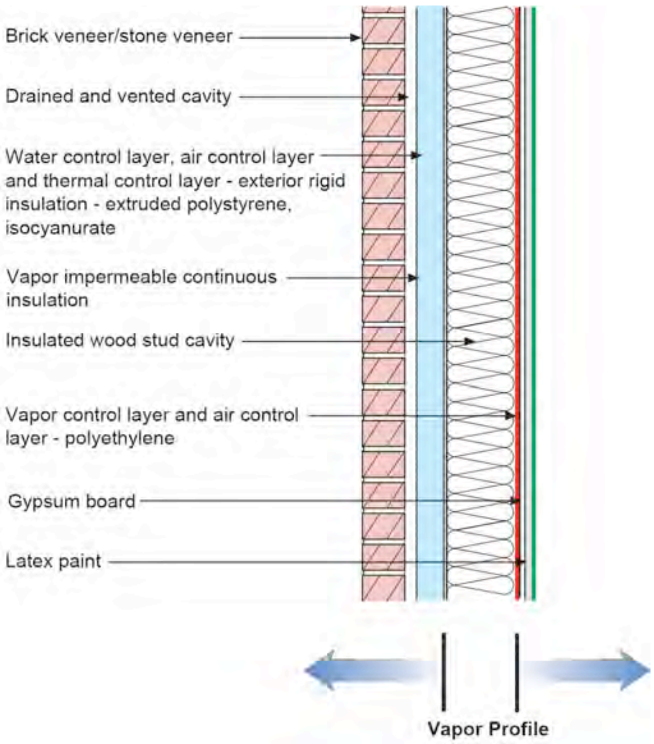


Figure 4: Double Vapor Barrier Wall Assembly That Works—The “vapor profile” is that of a “double vapor barrier”. We know that it works because we have been building it for so long.

Photograph 2: “Classic” Wood Frame Wall With Foam Sheathing—A wall that we have been building in cold climates for 40 years. The foam sheathing on the exterior is clearly a vapor barrier. The “vapor profile” is that of a “double vapor barrier”. I grew up with this wall in Ontario—2x6 wall with R-5 foam sheathing and a plastic interior air/vapor barrier.

Photograph 3: Interior Polyethylene Vapor Barrier—The sheet polyethylene on the interior is clearly a vapor barrier. In this assembly it is also acting as an air barrier (air control layer).

The best place to start on understanding this wall is look at walls with double vapor barriers that do not work. We were also here way back when (BSI-054: High Risk Walls). **Figure 5** illustrates a double vapor barrier wall that does not work. So what’s going on in this wall? The outer precast (the exterior vapor barrier) is significantly more airtight than the interior polyethylene sheet (the interior vapor barrier). It gets worse. The interior surface of the outer precast is also “cold” during the heating season as it has pretty much no thermal resistance. We have an “air leakage” problem coupled with a cold “condensing surface” problem. Note that we did not have the air leakage problem in the compact flat roof assemblies we looked at.

It is not typically possible to the make both the inside and outside of walls perfectly airtight. This is different than our ability to make the top membrane and bottom membrane of compact flat roofs more or less perfectly airtight. Walls are more complex than roofs. If we built walls the same way we built roofs it would be a different story. We do not. We have windows. We have architects. We have gazillion claddings. Argh!

If the outside is “leakier” than the inside we reduce the risk. And if the condensing surface temperature is warmer we reduce the risk. And finally, if the interior moisture loads are not extreme, we reduce the risk. So houses with foam sheathing in cold climates with interior vapor barriers with good interior air sealing that are not humidified and pressurized to hospital and art gallery performance metrics work.

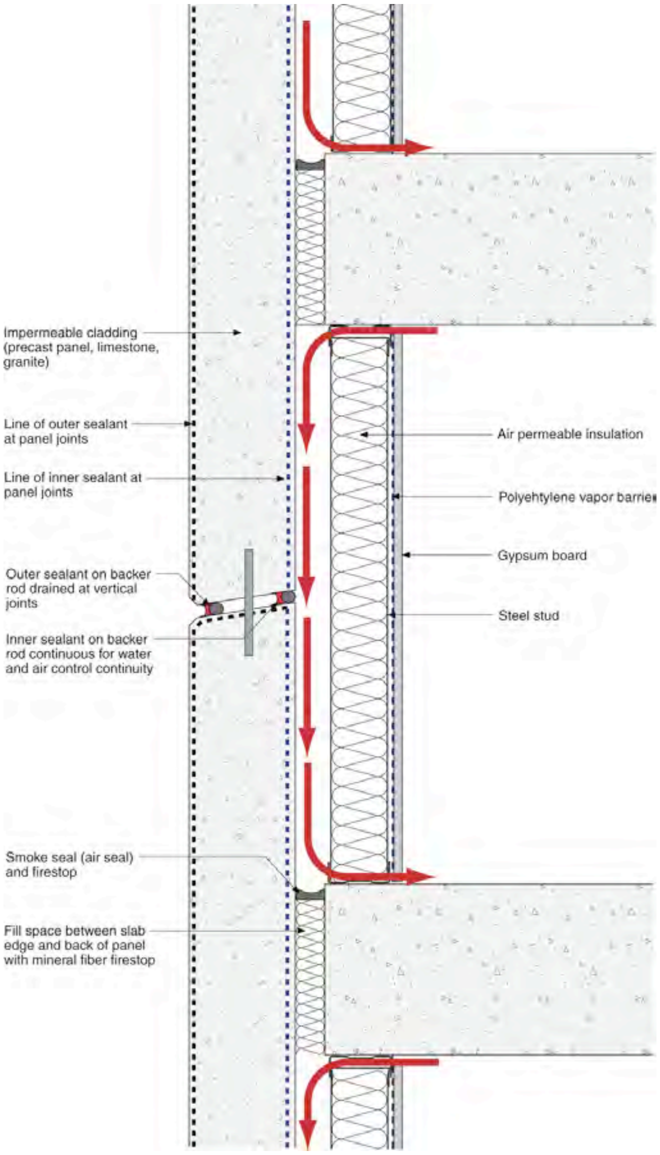


Figure 5: Double Vapor Barrier Wall Assembly That Does Not Work—The outer precast (the exterior vapor barrier) is significantly more airtight than the interior polyethylene sheet (the interior vapor barrier). It gets worse. The interior surface of the outer precast is also "cold" during the heating season as it has pretty much no thermal resistance. We have an "air leakage" problem coupled with a cold "condensing surface" problem.

Figure 6 illustrates what is typically going on. The interior poly is never "perfect" but it is pretty, pretty darn good. You don't believe me go visit some building sites in Minneapolis and Mississauga and Menomonie. Note that the exterior foam is never "perfect". It is pretty darn good, but not as good as the interior poly. And even better, the foam has a thermal resistance. Not much moisture condenses and the stuff that condenses dries outward. We know this because the walls have been working. And we have been measuring them. In lots of places over many decades.[5]

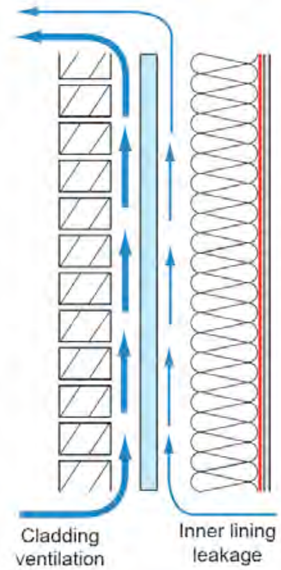


Figure 6: Why The Wall Works—The interior poly is never "perfect" but it is pretty, pretty darn good. Note that the exterior foam is never "perfect". It is pretty darn good, but not as good as the interior poly. And even better, the foam has a thermal resistance. Not much moisture condenses and the stuff that condenses dries outward.

Let me remind everyone once again that the key to these walls is the airtightness and vapor tightness of the interior lining. If you don't have an "interior" air barrier and an "interior" vapor barrier your exterior vapor barrier is going to have to have a lot more thermal resistance to control condensation. We were here before (BSI-049: Confusion About Diffusion). The model codes recognize this and provide guidance on how to construct walls without interior vapor barriers or air barriers in cold climates.

Let's look at two wall assemblies with "double vapor barriers" that have powerful historical track records (**Figure 7** and **Figure 8**). The difference between the two is that one uses polyethylene as both the air barrier and vapor barrier (in "Joe speak" this is would be the air control layer and the vapor control layer) and the other uses the interior gypsum board as the air barrier (air

5 This is another place where field experience and field measurements disagree with most hygrothermal analysis if the air component is not included. See "BSI-089: WUFI—Barking Up the Wrong Tree?".

control layer) and the facing on fiberglass batt cavity insulation as the vapor barrier (vapor control layer).

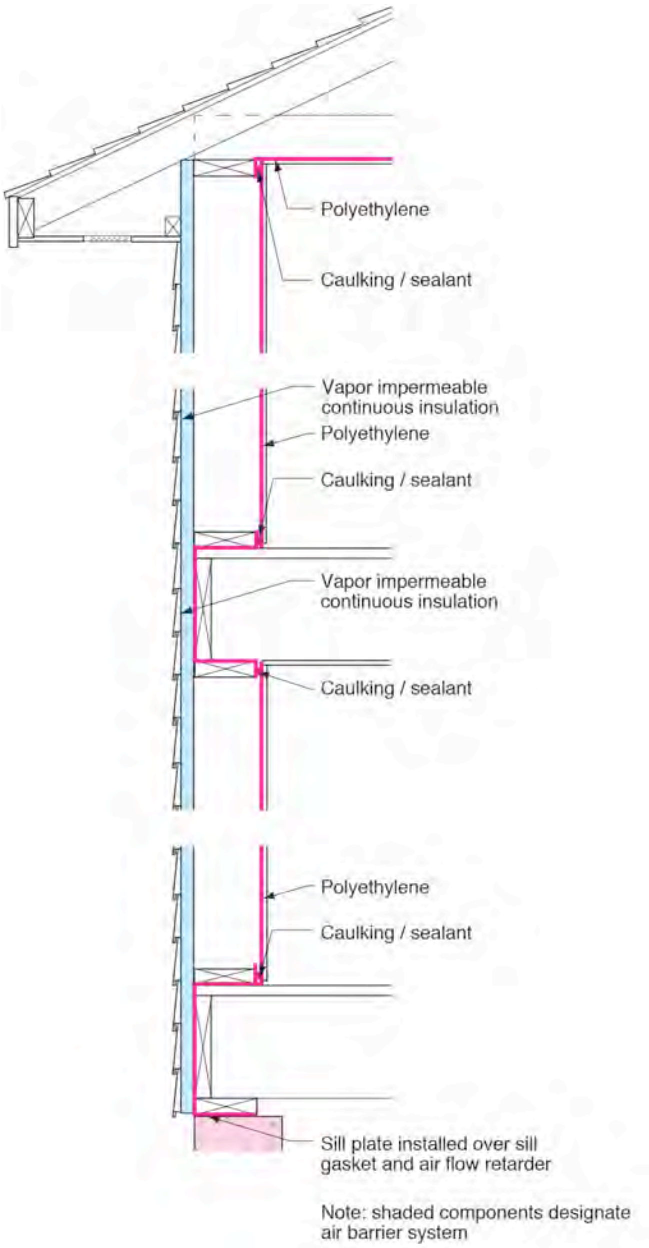


Figure 7: Poly Air/Vapor Barrier—This assembly uses polyethylene as both the air barrier and vapor barrier (in "Joe speak" this is would be the air control layer and the vapor control layer).

Using the kraft facing (**Photograph 4**) on the fiberglass cavity insulation as the vapor control layer takes advantage of the change in vapor permeance of this layer as a function of relative humidity (**Figure 9**). Kraft-faced insulations were the original "smart vapor barriers".

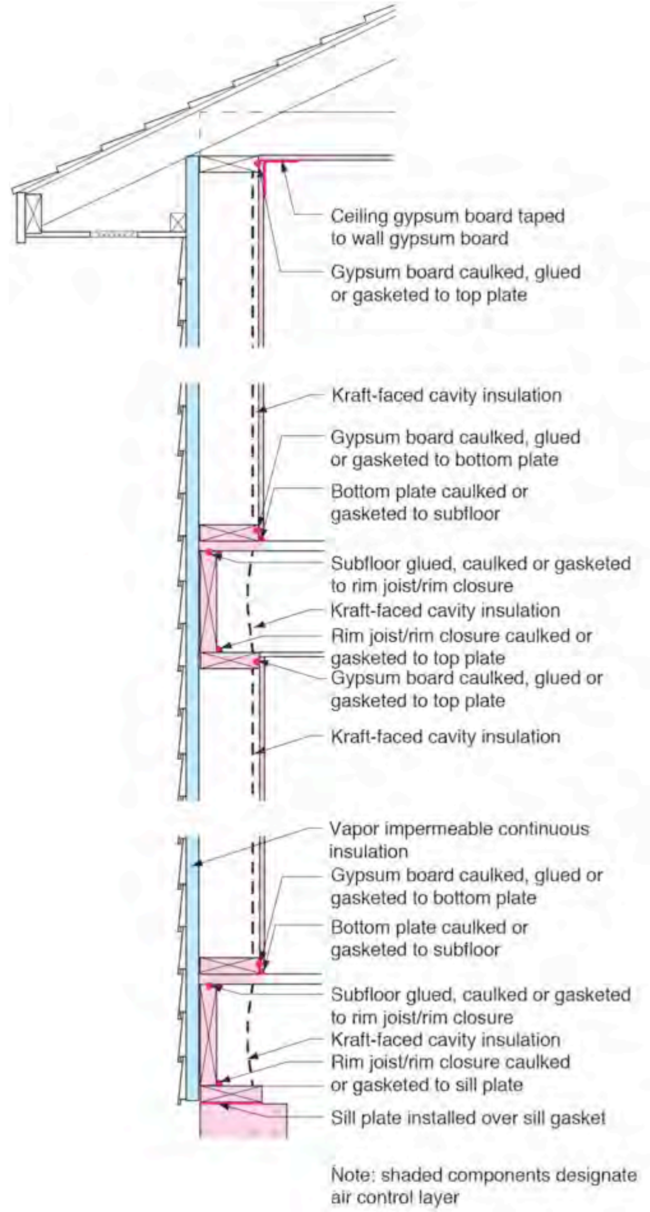


Figure 8: Drywall Air Barrier—The interior gypsum board is the air barrier (air control layer) and the facing on fiberglass batt cavity insulation is the vapor barrier (vapor control layer).

During the heating season most homes (and most buildings) have interior relative humidity in the 20 to 35 percent range. In this range the kraft facing performs as a Class II vapor retarder. During the summer most homes (and most buildings) have interior relative humidity in the 60 percent and higher range causing the kraft facing to "open" from a vapor resistance perspective. We can accomplish the same thing with some paint systems and some plastic membranes (aka "smart vapor barriers"). With this approach we only have a "double vapor barrier" during the winter – we don't have one during the summer.

Photograph 4: Kraft Faced Fiberglass Batts—The facing is the vapor control layer. Note that the Kraft facing does not function as an air barrier (air control layer).

Note that the kraft facing does not function as an air barrier (air control layer). This approach needs to be coupled with "fastidious" air sealing of the interior gypsum board ("the air drywall approach"). We were here earlier as well (BSI-084: Forty Years of Air Barriers—The Evolution of the Residential Air Barrier).

So where are we with all of this? Yes, double vapor barriers are counter-intuitive but they do work – within the limits noted above – especially the points about humidified and pressurized buildings and control of condensing surface temperatures[6]. Recall that we have been focusing on cold climates in this discussion. For the record I do not have heartburn with interior vapor barriers in cold climates. Nor should all of you. But I do have heartburn with interior vapor barriers in hot climates and mixed climates and pretty much any place with lots of air conditioning.

6 One final point, and this goes for all wall assemblies not just ones with double vapor barriers, don't close them up when they are wet. Ah, without the poly on the inside the wall can dry to the inside you say. Do you seriously think covering up a wet wall with a paper-faced sheathing like drywall is a good idea?

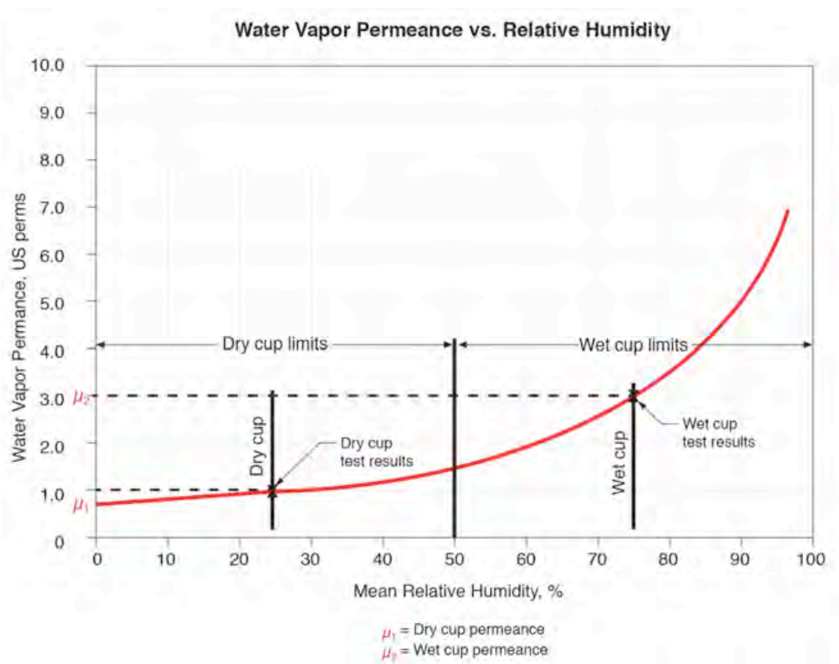


Figure 9: Vapor Permeance vs Relative Humidity—Kraft faced insulations were the original "smart vapor barriers". During the heating season most homes (and most buildings) have interior relative humidity in the 20 to 35 percent range. In this range the Kraft facing performs as a Class II vapor retarder. During the summer most homes (and most buildings) have interior relative humidity in the 60 percent and higher range causing the Kraft facing to "open" from a vapor resistance perspective.

