UNIVERSITY of TASMANIA

MOISTURE ACCUMULATION AND MOULD GROWTH FOR 6 STAR HOUSING IN VICTORIA

Research Report 1

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Acronyms

AAC	Autoclaved aerated concrete
ACH	Air Change per Hour
ACR	Air Change Rate
AER(1h)	Air Exchange Rate in 1 hour
BCA	Building Code of Australia – The NCC was called the Building Code of Australia between 1988 and 2010
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
CZ	Climate Zone
FWPA	Forest and Wood Products Australia
MI	Mould Index
MBV	Master Builders Association of Victoria
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
RH	Relative Humidity
VBA	Victorian Building Authority
WDR	Wind Driven Rain
WUFI	Wärme Und Feuchte Instationär
VTT	VTT Technical Research Centre of Finland

Terms

AAC	Autoclaved aerated concrete – A light weight masonry product used to clad buildings.
ACH	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of this method and the development of building pressurisation testing in the 1970s, this method has generally been replaced by the ACR method.
ACR	Air Change Rate. 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. An internationally accepted 'rule-of-thumb' to convert ACR to ACH is to divide the ACR value by 20 (ACR/20 = ACH). ACR of 10 = ACH of 0.5.
AER(1h)	Air Exchange Rate in 1 hour – This is a very similar term to ACH and is commonly used when calculating the required mechanical ventilation to ensure an adequate interior air quality. Typically, building simulation software include an AER(1h) data input.
BCA	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.
CZ	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 23°C, and the relative humidity is 75%: $T_d = T - ((100 - RH) / 5)$ $T_d = 23 - ((100 - 75) / 5)$ $T_d = 18.0°C$

	Moisture will form on any surface within the room that is less than, or equal, to 18.0°C. 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
NCC	*"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 for 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.

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 and hygrothermal regulations. This research activity is 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 program includes four key outputs (to be delivered across 2022 and 2023), namely:

- Research report 1 - Moisture accumulation and mould growth risk for 6 Star housing (this report),
- Research report 2 - Moisture accumulation and mould growth risk for 7 Star housing,
- Research report 3 - Moisture accumulation and mould growth risk for 6 Star and 7 Star housing based on AusHygro 2 simulations, and
- Research report 4 - Moisture accumulation and mould growth risk for 6 Star and 7 Star housing based on AusHygro 2 simulations.

This report focusses on the requirements of Research Report 1, mould growth risks that may be present in the external walls of Class 1 and Class 2 buildings, which are constructed to the 6 Star energy efficiency standard and the NCC health and amenity requirements of 2019. This report highlights what problems may exist and later reports will explore options to mitigate these risks. Reports 2 to 4 will also explore these considerations for 7 Star housing.

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. One of the recent University of Tasmania PhD projects explored condensation and mould risk that may exist in Hobart, Melbourne and Brisbane. The research explored the changes in risk that have occurred between 2002 (pre-energy efficiency regulation) through to 2022 (likely 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 for housing in Victoria.

Mould growth in housing is internationally recognised as a cause of many short-term and life-long human health conditions. 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 [1, 2]. 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 reaches 75%. (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 by be poorly ventilated).

This shows that mould growth occurs well before condensation occurs and 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.

Within this context, this research will analyse 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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1. Executive Summary

In 2008, the first meeting to discuss the looming 'wet-buildings' syndrome for Australia occurred between University of Tasmania researchers, the Tasmanian government, the Australian Building Codes Board and Building Research Association of New Zealand. Based on the experiences of many developed nations and a lack of the application of their learned experiences within Australian regulatory development, there was an acceptance that as Australia increased envelope thermal performance requirements, our own 'wet buildings' experience would evolve quite quickly. By 2016, there was enough government and industry concern to prompt the Australian Building Codes Board to complete a nationwide condensation survey. The survey had 2,662 usable responses, from all Australian jurisdictions. The survey respondents advised that more than 40% of new buildings constructed in the last decade had a concerning presence of condensation and/or mould [2]. This led to the Australian Building Codes Board commencing actions to consider what may need to be considered from a regulatory perspective. As Tasmania has some of Australia's coolest climates, condensation and mould problems started appearing from 2010. By 2014, the number of regular enquiries from new homeowners, builders, building surveyors and design professionals to the State's building regulator, identified the need for 'better-than-code' design and construction guidance for the design and construction professions [3-7]. This led to an ongoing research program exploring theoretical and applied methods to understand the problems and recommend better design and construction practices [8-10]. The climates within Victoria range from somewhat milder than Tasmania through to Alpine climates, and there is a growing voice from homeowners, and the design and construction professions regarding concerning amounts of condensation and mould within Class 1 and Class 2 buildings.

Within this context, the aim of this research was to ascertain if an external wall system was constructed as described and specified with the current national building regulations (the National Construction Code), would these 6 Star external wall systems support or promote:

1. Moisture accumulation, that can lead to structural failure, and/or
2. Mould growth leading to unhealthy interior environments and decay of structural elements.

To explore these questions, this research conducted 880 hygrothermal, and 880 bio-hygrothermal simulations, of nine contemporary residential wall systems, within eight Victorian NatHERS climate zones, with three NCC 2019 climate zone insulation variables (climate zone 4, climate zones 6 and 7, and climate zone 8), and with an Air Change Rate of 10 (the maximum allowable for a 2019 6 Star home) and an Air Change Rate of 5 (as many homes are more airtight than an ACR of 10).

The simulation results, as shown in Section 5 and within the Appendices, show that aside from a few outliers there is no concerning amount of moisture accumulation with the analysed nine external wall systems.

It is important to note two key principles:

1. Moisture will form within external walls quite often, when the dew point temperature condition is achieved in each component (i.e., less than 12°C). The aim of modern façade design is to acknowledge this wetting condition, to minimise how much moisture may form and to promote a wall's ability to dry and remove the moisture via drainage and ventilation. A traditional brick veneer wall, which includes a vented cavity between the

clay brick and the timber frame, has applied these principles since the 1920s.

2. Whereas dew point temperature requires a relative humidity condition of 100%, mould will grow in ventilated spaces when the relative humidity is above 70% and in still air spaces when the relative humidity is above 60%. This indicates that you do not need to have a 'wet' building to have a 'mouldy' building.

The capacity for a building to be mouldy but not wet is exemplified by the results from the bio-hygrothermal simulations which were completed to ascertain if there is a risk of unacceptable mould growth. Mould growth on interior and interstitial surfaces leads to building decay, structural failure and mould spores significantly impact human health. The very small size of mould spores allows them to freely enter our blood stream via our lungs and the process of breathing. The World Health Organisation has advised that there should be no visible presence of mould within the built environment. An unacceptable mould growth index is any simulation with an MI of 3 or more. An MI of 3 or more is defined as having a visible presence of mould. Of the 532 walls simulated with an Air Change Rate of 10, the maximum permissible building leakage (infiltration and exfiltration) rate within NCC 2019, 230 (43%) showed the need for a more detailed analysis or an unacceptable mould growth index. This indicates that nearly half of these external walls systems may currently be constructed in a manner that poses a high risk of an unacceptable level of mould growth to construction requirements and climatic conditions.

Of the 348 walls simulated with an Air Change Rate of 5 (the minimum permissible building leakage rate (infiltration and exfiltration before mechanical ventilation is required), 327 (94%) showed the need for a more detailed analysis or an unacceptable mould growth index. This indicates that many of these external wall systems may currently be constructed in a manner that poses a high risk of an unacceptable level of mould growth due to construction requirements and climatic conditions.

In both scenarios described above, there is reference to walls requiring further analysis. This indicates that the bio-hygrothermal simulation calculated a Mould Index greater than 1 but less than 3. The software is simulating a 'Perfect Wall'. However, walls are rarely made perfectly and the environmental conditions inside and outside the wall system may vary, leading to an unacceptable amount of mould growth. Within this context, further analysis requires a deeper consideration of all environmental factors that may impact the wall system's long-term durability.

In all scenarios, the southern orientated external wall systems showed the greatest mould growth index values. Due to the solar radiation induced drying potential, the northern facing walls often performed much better, with a nil or lower mould growth index value. However, if one considers external wall shading from nearby buildings, eaves or landscaping, the minimum performance requirement should use the material arrangements such that the southern wall has a nil, or acceptable mould growth index. Within this context the recommendations of this research report are:

1. Each of the 6 Star wall systems needs to be modified such that the southern orientation shows either a nil, or an acceptable long-term mould growth index. This would include the specification of pliable building membrane water vapour diffusion resistance properties and the inclusion of a vented cavity for most external wall systems.

2. The next stage of the research includes 7 Star wall systems. The Council of Australian Governments (COAG) approved the NCC 2022 7 Star requirement for Class 1 and Class 2 residential buildings for adoption from 1 January 2023, (subject to Jurisdiction based adoption processes). When compared to a 6 Star home, a 7 Star home will have a

NatHERS simulation based 25% reduction in energy needed to heat or cool the habitable rooms. This will further increase the challenges of water vapour diffusion through the built fabric. The findings from the hygrothermal and bio-hygrothermal simulations of the 6 Star wall systems will need to be applied to the 7 Star wall systems.

3. A significant education program needs to be undertaken to inform design and construction professions of the risks evident in the simulation results. Since 2014, the Tasmanian government has actively engaged with the design and construction professions via training activities and two editions of the Tasmanian condensation design guide.
4. Further research must consider various aspects of airtightness and the climatically appropriate envelope elements to control water vapour diffusion such that concerning amounts of, or unacceptable amounts of mould growth do not occur.
5. There needs to be a coordinated approach by the ABCB, NatHERS Administrator, appropriate researchers, and industry-based representatives, for the co-development of energy efficiency and hygrothermal regulations.
6. This research is limited to the wall systems and inputs, as shown and discussed in the report body and Appendices. Changes to these inputs will change the results.

2. 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 in compliance with current regulations. The National Construction Code (NCC) describes minimum methods and systems to meet regulatory compliance. Internationally, and in Australia, the correlation between buildings that create a significantly different conditions (temperature and humidity), between the interior and exterior environments are more susceptible to moisture on building surfaces, interstitial condensation, and mould growth has been known for quite some time [11]. This introduction firstly provides a brief history of the application of energy efficient envelope requirements for Class 1 and Class 2 buildings. This is followed by an introduction to conditions for moisture on and in the built fabric, mould growth, reasons why the requirements are within the Health and Amenity section of the National Construction Code, and methods that can be used to ascertain risks for the built fabric and building occupants. As a point of reflection, it has been estimated that the leaky building syndrome in New Zealand has cost their economy more than NZD$46B [12, 13]. Furthermore, recent research within the United Kingdom has identified that up to 1 billion pounds per annum of the National Health Service budget can be attributed to the medical treatment of people living within 'wet' buildings [14].

Prior to 2002, there were no national requirements for a measurable thermal performance of the building envelope and its impact on heating or cooling energy use. However, the Nationwide House Energy Rating Scheme (NatHERS was established in 1993 as a mechanism to quantify energy that may be used to heat and cool Australian homes [15, 16]. Research using the NatHERS simulation method established that most new housing had a NatHERS Star rating between 1 Star and 3 Stars [17]. After the acceptance of climate change and the need to reduce greenhouse gas emissions, the improvement of building envelopes was identified as a 'low hanging fruit' in terms of the economic cost and the national benefit [18, 19]. In 2003, the first set of BCA requirements in relation to envelope insulation, building sealing and glazing ratios were implemented [20]. In 2004, the NatHERS star rating system was applied to Building Code of Australia (BCA) 2004, where a compliant home generally had a Star rating score of 4 Stars [21]. In 2006, the minimum performance requirement within the BCA was increased to 5 Stars [22], followed by a 6 Star requirement in 2010 [23]. The Council of Australian Governments has approved the adoption of NCC 2022 with a minimum 7 Star requirement for new Class 1 and Class 2 buildings from 1 January 2023. During each of these steps there has been a reduction in the simulation-based energy needs for household heating and cooling. Table 1 below shows the original (2019) and revised (2022) NatHERS Star bands for the NatHERS climate zone of Melbourne. The values within the table are megajoules per square metre per annum (MJ/m2.anum) for the heating and/or cooling of conditioned rooms. The percentage column shows the percentage of simulated heating and/or cooling energy reduced by each step. In the context of this research this data is quite important, as the reduction in heating and cooling energy consumption relies on creating a more thermally comfortable building interior, which increases the difference between the interior and exterior climates.

The NatHERS scheme applies internationally accepted principles for thermal comfort [24]. The scheme does this by applying:

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

- a minimum temperature for living room type spaces during typical occupation times of spaces of 20°C. This reflects extensive international research regarding the thermal comfort of a sedentary person being achieved at 21°C, and
- climatically applied cooling requirements for all room types. In the case of Melbourne, the cooling thermostat set point is 24°C. This is based on extensive international research regarding human health and personal thermal comfort experiences.

Table 1: Maximum NatHERS star-band based heating and cooling energy allowances and their respective energy reduction between Star-bands (MJ/m^2)

	2019				2022		
	Original star bands	**Energy Reduction**	**% Reduction**		**Revised Star bands**	**Energy Reductio**	**% Reduction**
1 Star	559				451		
2 Stars	384	175	31.3%		302	149	33.0%
3 Stars	271	113	29.4%		207	95	31.5%
4 Stars	198	73	26.9%		128	79	38.2%
5 Stars	149	49	24.7%		111	17	13.3%
6 Stars	114	35	23.5%		85	26	23.4%
7 Stars	83	31	27.2%		65	20	23.5%
8 Stars	54	29	34.9%		45	20	30.8%
9 Stars	25	29	34.9%		26	19	42.2%
10 Stars	2	23	92.0%		11	15	41.7%

Nath [1] 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 1 and Figure 2 below. 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. Whereas Figure 1 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 2 ranges from 10°C to 36°C, but with a strong concentration of data between 16°C and 22°C.

The concentration of room temperatures, from one perspective, reflects a better building envelope for human thermal comfort, but from another perspective, it indicates that the air within the home may be containing a lot more water vapour. Air with a temperature of 12°C and a relative humidity of 55%, contains five (5) grams of water per kilogram of air. Air with a temperature of 21°C and a relative humidity of 70%, which is a common condition in many Australian homes, contains eleven (11) grams of water per kilogram of air. 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 in the used to construct and furnish a home adsorb water vapour, and in some cases are referred to as seasonal hygrothermal buffers [25, 26]. 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 homes is critical to understand what may be happening to the durability of the built fabric and/or the interior air quality.

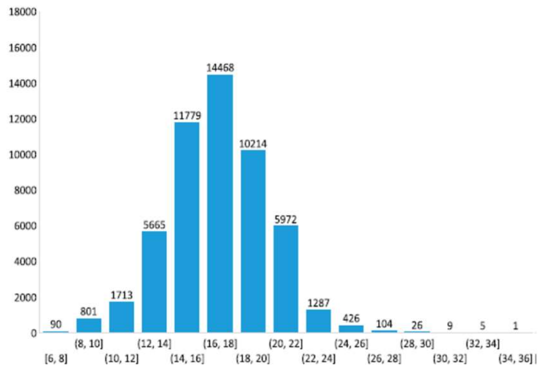

Figure 1: Habitable room temperatures pre-2003.

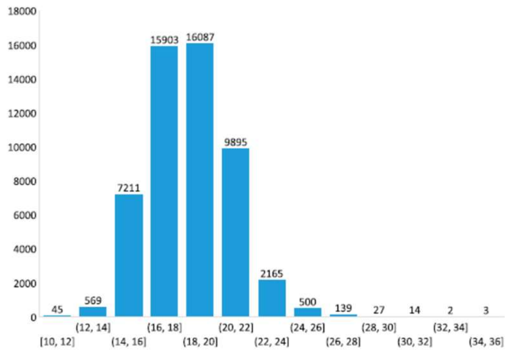

Figure 2: Habitable room temperatures: 6 Star home

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 :

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

Table 2 below shows some dew point temperatures for different interior conditions. What this data shows, for example, is that when a room is conditioned to 21°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 15°C, will have moisture condense out of the air onto thermally bridged interior surface. 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 2: Examples of dewpoint temperature for conditioned interiors

Temperature (T°C)	Relative Humidity (RH%)	Dew point T (Td°C)
21	55	12
21	65	14
21	70	15
21	75	16
21	80	17
24	65	17
24	75	19

Since the early 2000s, very little research has been done on the impact of excessive moisture on building structures and material durability. There was some limited Australian research regarding the impact of excessive moisture on nail plate mechanical fixings in timber trusses [27, 28], but very little research on these matters has progressed. This is in contrast to international research

[29-37] and the recent findings from the nationwide condensation survey commissioned by the Australian Building Codes Board [2], 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.

Innovations, like the advent of European cavity brick construction in the late 19th century was 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 1920's, 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.

One of the less visible, equally destructive, and significantly impacting human health effects from moist housing are mould growth and mould spores within habitable spaces. Figure 3 below, shows the observed and simulated temperature and relative humidity conditions within Australian homes between 2010 and 2018 [1]. This includes separate research activities conducted by the University of Tasmania [1, 3-5, 8, 10] and the CSIRO [38]. This mixture of simulated and measured interior environmental data is overlaid onto a simplified mould growth graph. The mould growth part of the graph shows that:

- 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.

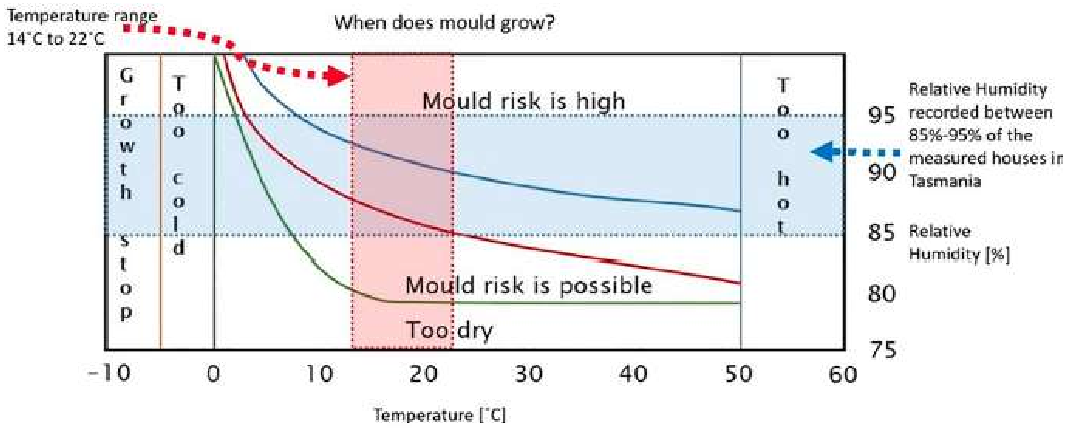

Figure 3: Rates of mould growth [39] and observed temperature and humidity conditions in homes [1]

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 1st 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% [40, 41]. What this research identified were the differences between areas of good air movement and areas where there was good mechanical ventilation but some 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. It should be noted, even though the ICMB conference mentioned above is termed the 1st, conferences regarding the building physics and simulation methods on moisture and mould in buildings have occurred in other developed countries since the 1930s [11, 42-48].

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 [1, 49, 50]. Nath identified that Australia has twice the OECD average for Asthma rates per head of capita [1]. Research by Rikaby [14] 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 one billion pounds. 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 [51].

Within the Australian regulatory context, there have been no regulatory requirements for condensation of mould until NCC 2019 [52, 53]. The initial performance requirement and acceptable construction methods only applied to Class 1 and Class 2 buildings in NCC climate zones 6, 7 and 8. By comparison to other developed nations, this may be up to 50 years too late, as many homes built prior to the introduction of energy efficiency regulations in 2003, and homes constructed between 2003 and 2019 have condensation and mould problems. It could be argued that the acceptable construction requirements introduced in 2019 may be inadequate. The NCC 2019 (Volume Two) performance requirement P2.4.7 states:

> *"Risks associated with water vapour and condensation must be managed to minimise their impact on the health of occupants." [52]*

However, the Acceptable Construction practice, as described in NCC 2019 Vol Two Part 3.8.7 [52] only requires that:

- a pliable membrane, if used in an exterior wall, must be a vapour permeable, and located on the exterior side of the insulation in NCC climate zones 6, 7 and 8,
- an unconditioned roof space must consider supply and exhaust actions for passive ventilation, and
- exhaust fan performance requirements for kitchens, bathrooms, laundries and sanitary compartments, if installed.

These simple requirements seem to ignore the nation-wide responses to the 2016 nation-wide condensation survey [2]. There are also contradictions within the requirements. The roof system requires the consideration of supply and exhaust openings, such that a passive ventilation system is achieved via stack ventilation. However, 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. Research from the University of Tasmania has highlighted that the measured climate data for Melbourne has shown that up to 88% of the 8,760 hours in a year may have an air temperature of less than 18°C [54]. If the minimum expected conditioned air temperature within most habitable room is 20°C [24, 55], 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 [37]. It should be noted that building sealing and air-tightness measures must be kept separate from ventilation 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 systems have caused moisture to form, mould to grow and in some cases, moisture to accumulate [56].

Considering that that new Class 1 and Class 2 buildings in temperate and cool-temperate Australia are increasingly warmer and more humid on this 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. Since the 1990s recommendations like those shown in Table 3 below have been established in other OECD nations [57-61].

Many practitioners and academics have been petitioning their state governments and the Australian Building Codes Board regarding the need to understand the breadth, depth and complexities of the condensation and mould problem in new housing, and how the current and future building regulations do or don't address these concerns.

To quantify potential risks of condensation and mould in new buildings, research options include:

- Empirical studies of exiting housing – This is a very time consuming and costly exercise [62-65]. 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 – This is often fraught with legal and human ethical issues [5]. 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 an empirically validated software. This has become the favoured method in many countries, due to its limited cost and research risks, and speed of analysis [66]. Internationally, several hygrothermal software tools have been developed through government funded research organisations and/or universities. Some of these of undergone empirical validation, (comparing simulation results to real buildings), for several decades.

Table 3: Condensation control strategies for the building envelope

Strategy	Aim	Measure
	Reduce air leakage	Air control layers

Management of moisture entry	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

In this research, the method adopted uses a hygrothermal and bio-hygrothermal simulation programs, that has been developed by a government funded research organisation, Fraunhofer Institute for Building Physics Germany, and has been empirically validated and improved over more than 25 years [67].

3. Hygrothermal analysis

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. As discussed previously, heat and water vapour are the two elements that are intrinsically coupled affecting levels of moisture and the occurrence of condensation and mould. Hygrothermal assessments consider numerous aspects such as environmental and climatic loads, indoor moisture level, interior relative humidity and temperature conditions, moisture accumulation of materials, and degradation processes.

Condensation risk analysis is a method to evaluate the possibility of condensation formation or moisture movement which may lead to moisture related problems within the built structure [4]. Techniques to recognise condensation risks were developed in the 1960s. The simplistic analysis by today's methods, provided an understanding that can then be used to develop a systematic and structured framework to deal with identified risks. The methods to assess condensation risk include steady state, non-transient and transient methods.

3.1 Steady-state and other non-transient methods

The "Glaser method" [68] is a calculation method to forecast interstitial condensation risk, taking place under specific environmental conditions. The Glaser method was developed in the 1950s by German scientist Helmut Glaser and has been in use since then. The main aim of this method is to assess condensation risk. This method is also termed the 'moisture profile method' or 'dew point method'. In the past, using this method, manual condensation risk assessments were done and were completed in a simplified way. The Glaser method does not take into consideration that:

- materials can be initially wet either due to accumulated moisture or rain
- materials can be hygroscopic
- mould growth
- water movement takes place due to the combination of both vapour and liquid flow
- moisture content affects the material properties
- solar radiation and long waved radiation affect the hygroscopic properties of the building material, and
- two-dimensional (2D) and three-dimensional (3D) flows of heat, air, and moisture are of significance.

Many Glaser method simulation tools have been developed which could complete twelve simplified calculations to establish annual patterns. These simplified calculations are completed based on monthly averaged temperature and humidity conditions.

The Glaser method is a relatively simple condensation risk analysis tool and so does have significant limitations and is therefore only useful under specific conditions. The British Standard (BS5250) [69] 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 4. 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 [59, 60, 70].

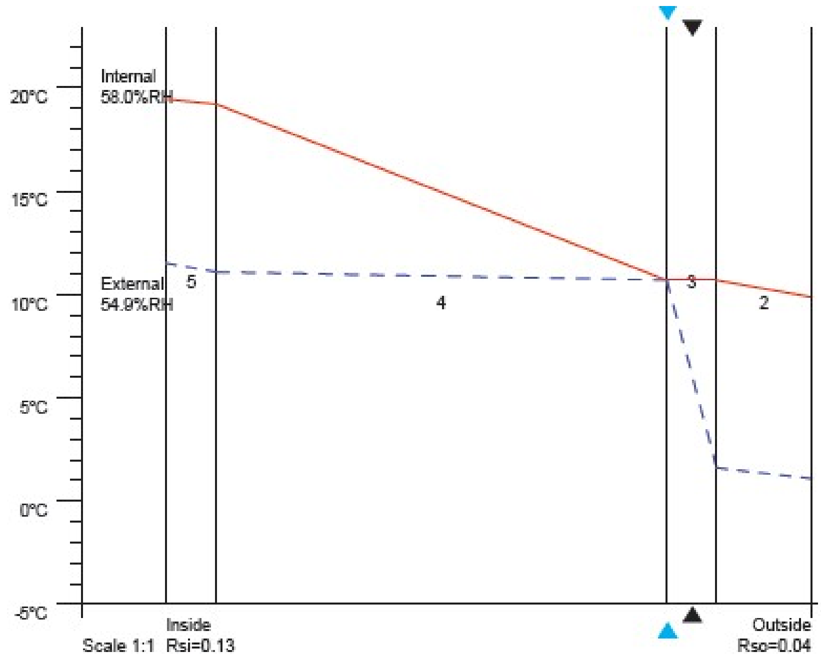

Figure 4: Example of a Glasser simplified method condensation risk analysis

Recognising these limitations, the international Standard (ISO-13788) [68] states that the simplified non-transient Glaser method does not consider some physical aspects that are required to understand moisture and mould growth in any detail. These limitations include:

- changes in material properties with the addition of moisture content
- capillary suction and liquid moisture movement within materials
- air movement from inside the building into the built fabric through cracks
- hygroscopic moisture capacity of materials
- building orientation
- risk of mould growth, and
- does not consider advanced material properties as applied within transient state simulation models.

3.2 Transient or dynamic state method

The more complex transient hygrothermal simulation tools simulate dynamic changes within the building envelope (walls, floors and roofs or building elements), on an hourly basis for the entire year, that is 8,760 times a year, (365 days x 24 hours), and can undertake simulations across several years. 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 [71] 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. This research uses the WUFI Pro transient hygrothermal simulation program developed by the German government funded Fraunhofer Institute for Building Physics in Germany, which has undergone significant international empirical validation.

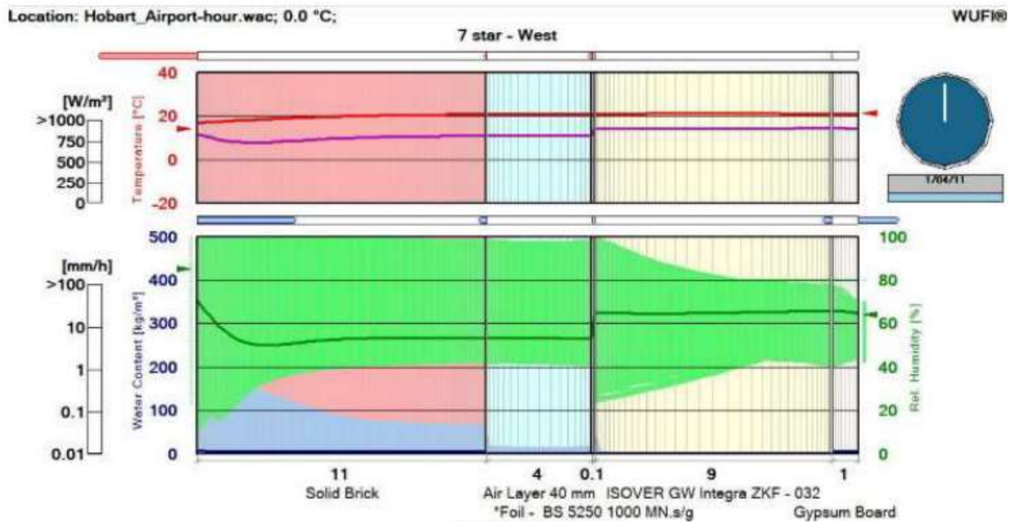

Figure 5: Example of WUFI Pro graphical simulation result [66]

Figure 5 above, 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. This graphical representation is from a ten-year simulation. An important aspect to view is the green relative humidity section. The relative humidity ion 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.

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 'add-on', as described below, must be used.

3.3 Mould growth calculations

There is extensive research conducted over many decades about the conditions for mould growth on and within the built fabric. Some transient hygrothermal software developers have liaised with the bio-sciences to develop mould growth interfaces for hygrothermal simulation software. The Fraunhofer Institute for Building Physics Germany, has co-developed WUFI Bio and WUFI VTT, as mould growth calculation add-ons to the WUFI Pro hygrothermal simulation program. The Mould Index method was developed in 1991 and has undergone extensive laboratory and forensic validation in Europe and North America [29, 31, 39, 72-76]. Table 4 shows that mould spores are produced when the MI is 3. Relating this back to aspects of human health, no interior environment should have the presence of mould spores, or an MI of 3.0. From a structural durability perspective, any structural element that is supporting ongoing mould growth will not be durable.

Table 4: Mould growth index (MI) [29]

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%

Both add-on calculation tools have been co-developed between Germany and Finland with co-operation from the United States [77]. The validation process has identified that the WUFI VTT add-on provides a more accurate simulation. Figure 6 below, shows the results from a hygrothermal simulation post processed mould growth calculation 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 Mould Index exceeds 3.0 in the fifth year and exceeds 4.0 in the tenth year. Applying the principles from Table 4, this wall system would support the growth and sporing of mould. This type of design testing methodology is increasingly occurring in other developed nations requiring that a wall system has a MI not exceeding 2.0 [35, 58-60].

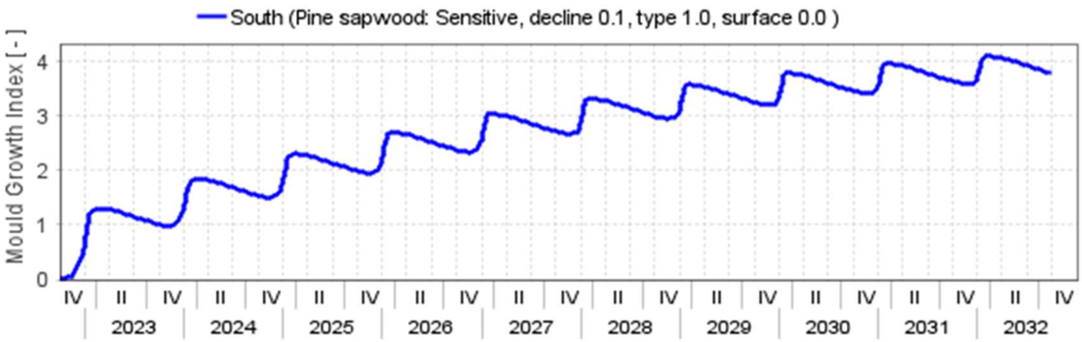

Figure 6: Example of WUFI VTT Mould growth calculation result

3.4 Summary

This section has set out to establish the framework for this research regarding condensation risk on new and energy efficient homes in Victoria. This has included an introduction the regulatory framework, causes of condensation and mould in all buildings, methods to calculate and simulate moisture in the built fabric and finally, methods to calculate mould risk.

Since the 1930s there has been an accepted linkage between differences between interior and exterior climates and condensation in buildings. Similarly, it has been accepted for many centuries that mould in the built environment affects human health. In modern times medical research has been able to define short-term and life-long medical conditions that are more present in people who occupy wet and mouldy buildings.

As economic data regarding building failures due to moisture accumulation is very limited, the pathway adopted by many countries, including Australia, is to implement new regulations within the Human health section of national building regulations. This method generally adopts a measure of mould growth as the performance requirement. The next section discusses the methodology of this research.

Significantly, in many other developed nations, the ongoing co-development of energy efficiency and condensation/mould related building regulations has been occurring since the 1970s. In Australia, this pattern of regulatory co-development has been lacking.

4. Methodology

As described in the introduction above, this research has used the WUFI Pro software for hygrothermal simulation and the WUFI VTT add-on for bio-hygrothermal simulation. Research by Nath, in collaboration with researchers form the Fraunhofer Institute for Building Physics, established the most appropriate methodology for hygrothermal and bio-hygrothermal simulations in Australia [66, 78]. 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 publish DA-07-Criteria for moisture control in buildings [79], which is very similar to the ASHRAE standard of the same name [58]. AIRAH DA-07 is referenced in NCC 2022 Volumes 1 and 2. In this research several factors for the methodology needed to be considered within the context of Class 1 and Class 2 6 Star buildings in Victoria, being external envelope types, external and internal climates, house design and construction material physical properties.

4.1 External envelope 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 5. In each case, the wall system composition was informed by data provided by the CSIRO, VBA and MBAV. This data is available in Appendix 1.

Table 5: External wall systems selected for this research

No	Description	Rationale for selections	Described within NCC
1	Weatherboard external wall construction	This wall type comprises 20% of the Victorian Class 1 and Class 2 market.	Yes
2	Fibre-cement sheet external wall construction	This wall type comprises 9% of the Victorian Class 1 and Class 2 market.	Yes
3	Clay masonry veneer external wall construction	This wall type comprises 61% of the Victorian Class 1 and Class 2 market.	Yes
4	Concrete blockwork masonry external wall construction	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) external wall construction	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 insulated timber frame	This wall type was common but current data uncertain.	No
7	Expanded polystyrene cladding with insulated timber frame	This wall type was common but current data uncertain.	No
8	Autoclaved aerated concrete masonry cladding with insulated 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

4.2 External climate data

The selection of climates and climate data needs to consider both the climate zones within the National Construction Code and the climate zones within NatHERS. Figure 7 below shows the ABCB NCC 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. This data can be viewed within Appendix 1.

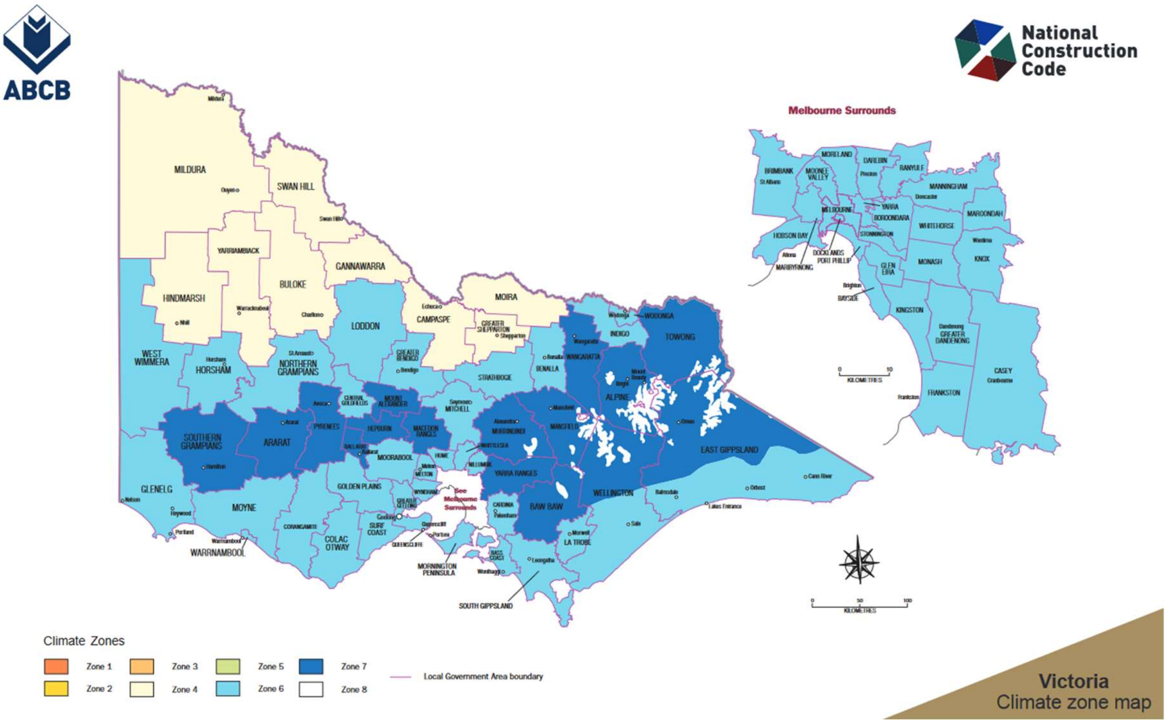

Figure 7: ABCB NCC Climate zone map for Victoria (ABCB 2022)

The second layer of climate data, as mentioned above, is the NatHERS climate zones. The NatHERS climate zone map, as shown in Figure 8 below, 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.

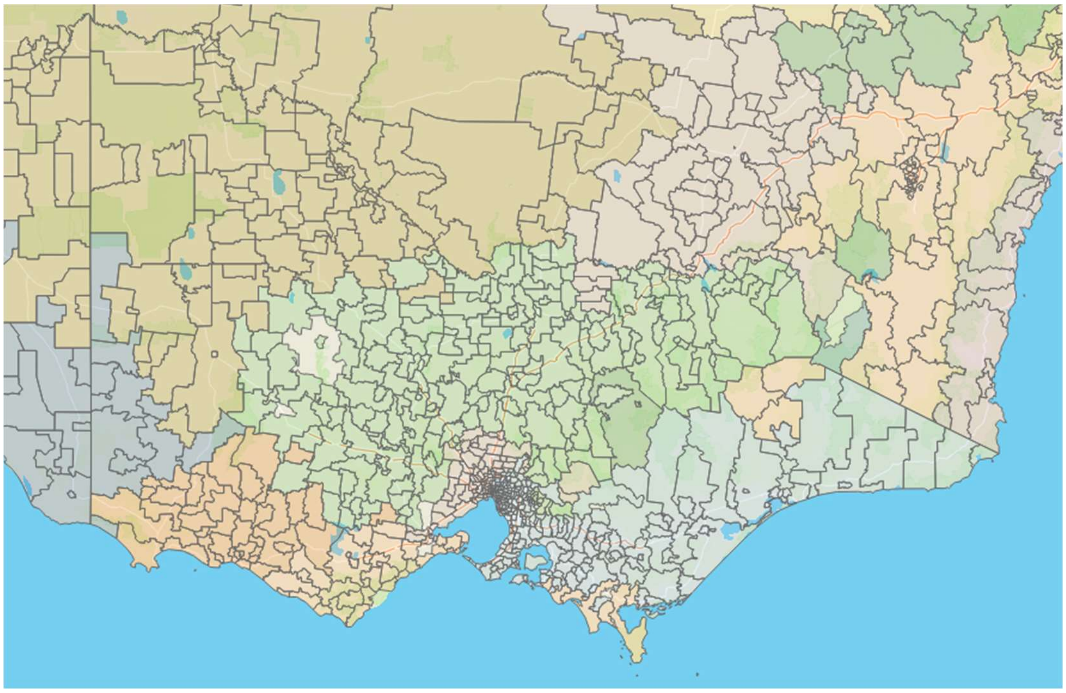

Figure 8: NatHERS Climate zone map for Victoria

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 for this this stage in the research. Some localities straddle more than one NCC climate zone. These areas were replicated to compile a longer list cross referencing Victorian localities and their corresponding postcodes with NatHERS zone and NCC climate zone, bringing the count to 1,726 localities.

Table 6: 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

The climate zone type analysis in Table 6 allowed the identification about 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. This established eight NatHERS climate zones, representing 1,682 postcode-based localities, as shown in Table 7 below.

Table 7: 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%

Compatible climate files for these NatHERS climate zones were obtained in *.epw format from US Energy Plus website. These files form part of the Australian government provided files for building energy simulation.

Rain in Climate Data

It is widely recognised that Wind Driven Rain (WDR) is a critical factor leading to significant effects in the hygrothermal performance of building envelopes [37, 80, 81]. Moisture content in walls increases ten-fold when WDR is calculated in simulations [82] when compared to walls where WDR is ignored. Australian 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 in climate data is not freely available. To replicate the type of simulation being conducted in industry, this part of the project will use climate data without rain. Recognising these differences, the moisture accumulation and mould growth findings in this report may be conservative. Due to the complexities regarding this aspect of the research, this additional analysis will be included 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 [58], which is referenced by AIRAH DA-07 [79], that has been listed as a referenced document within the preview version of the NCC 2022.

Key parameters which were applied are shown in Table 8 below. The value of 10 ACR/ 0.5 AEC is adopted from the verification method in the NCC [52]. Later reports will explore the risk that occurs if a house is made more airtight. The 70% relative humidity cap is an international setting based on the requirements for interior relative humidity control in other countries [37, 58]. This differs from measured data from Australian home, as discussed previously, which is often higher than 70% [1]. This aspect will be further investigated and reported in future reports.

Table 8: Key internal climate inputs

Aspect	**Input selected**	
Mode of operation	Air-conditioning (heating and cooling)	
Floating temp	Based on sum of cooling - heating	
Cooling thermostat (°C)	NatHERS CZ	Cooling
	21	24.0
	22	23.0
	27	25.0
	60	24.0
	61	23.5
	62	24.0
	63	23.0
	64	23.0
	66	23.5
Heating thermostat (°C)	20.0	
Air exchange rate	User defined – 0.5 (=10ACR)	
Relative humidity cap	70%	

4.4 Sample house plan

In this research, a house plan that has been used for several building thermal performance and hygrothermal analysis projects has been used [1, 8, 10]. 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, and interior water vapour loads) would be the same whether this was an external wall of a stand-alone house or the exterior wall of an apartment building. As noted on the house plan, the floor area (not including the garage) is 152.5m2, with an interior volume of 366m3. As the external envelope will face the four cardinal orientations, all wall types were simulated in a northern, eastern, southern and western orientation. The properties adopted from the house plan below (volume, airtightness, interior vapour load) would equally apply to an apartment the same size, in a multi storey building. 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 9: Three-dimensional representation of the house

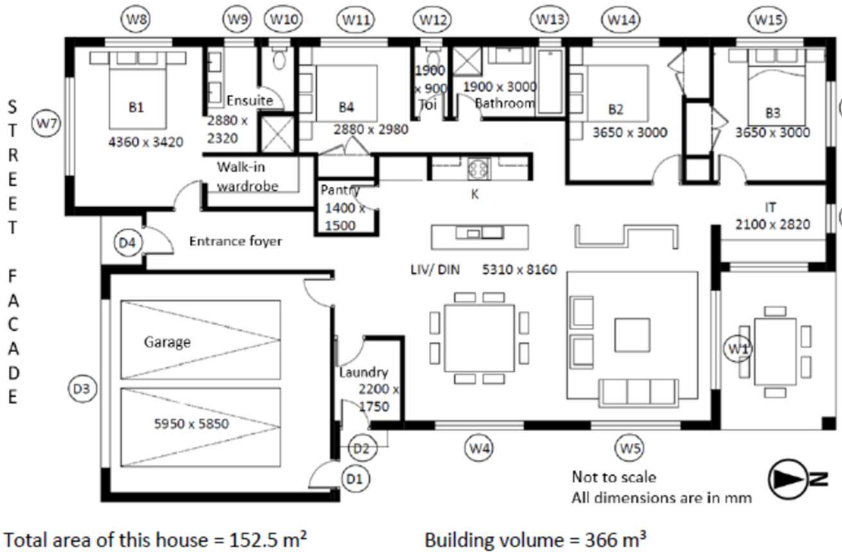

Figure 10: House plan (Not to scale)

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 [83].

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. This data is available in Appendix 1.

4.6 Hygrothermal and bio-hygrothermal simulation

In this research, adopting the principles of ASHRAE Standard 160 [58] and the most recent version of the German Standard DIN-4108 [59], 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 [66]. 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 North America and Europe.

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.

It is important to note that this report is focussing on the built fabric of 6 Star Class 1 and Class 2 buildings, in the NatHERS climate zones of Victoria. Research Report 2 will extend this methodology to include 7 Star Class 1 and Class 2 buildings in the NatHERS climate zones of Victoria.

5. Simulation Results

This section contains the summarised results for each of the nine selected wall system hygrothermal and bio-hygrothermal simulations. The Appendices for each wall type contain a more comprehensive compilation of mould growth Mould Index simulation results for each wall type. Each wall type will be addressed as a separate sub-section, namely:

- 5.1 Timber clad wall
- 5.2 Compressed fibre cement sheet clad wall
- 5.3 Clay masonry veneer
- 5.4 Concrete block with interior insulation
- 5.5 Externally insulated frame with interior clay masonry (reverse brick veneer)
- 5.6 Extruded polystyrene clad wall (XPS)
- 5.7 Expanded polystyrene clad wall (EPS)
- 5.8 Autoclaved aerated concrete masonry clad wall (AAC)
- 5.9 Sheet-metal clad wall

The results for each wall system are provided in a table format. The table lists each NatHERS climate zone and the corresponding NCC climate zone. Each table has columns for the hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) simulation results. The hygrothermal simulations calculate if there is moisture accumulation. If moisture has accumulated, this column will have a Yes, and if there is no moisture accumulation, the column will have a Nil. The bio-hygrothermal simulations calculate if the conditions within the wall system can promote mould growth. The mould growth Mould Index (MI) is presented in these results. In this research the bio-hygrothermal simulation results have been categorised as shown in Table 9 below, where:

- A MI of less than 1.0 (<1.0) may be suitable to construct if the MI does not increase.
- A MI that is less than 1.0 but has an upward trend may require further investigation.
- A MI greater than 1 but is less than 3.0 will require further investigation.
- A MI of 3.0 or more, is likely to be unacceptable in the NCC 2022 (It should be noted that some other developed nations require a MI no greater than 2.0).

What might surprise some readers, is that by international standards, the presence of visible mould growth is not acceptable [49, 53, 59]. Yet visible mould exists in many Australian homes.

It is important to note that moisture accumulation and mould growth are two very different conditions. For moisture to accumulate, dew point temperature must be achieved, the wall be not allowed to dry, and moisture accumulates. However, as described in the introduction, mould will grow well when the relative humidity is above 70% for prolonged periods of time [73], and recent research has identified that in still air spaces, mould can grow when the relative humidity is above 60% [41]. Additionally, during the annual season cycle and even daily cycles, moisture may form and evaporate within the wall system. Unless the conditions (temperature and humidity) are kept above dew point, this process is unavoidable. For many parts of Victoria, dew point temperature may be 120 Celsius. This indicates that if a room is conditioned and a component of the envelope is at or below 120 Celsius, moisture will form. A key aspect of modern façade design is to accept this principle and design wall systems that promote drying, such that mould growth does not exceed acceptable levels and moisture does not accumulate.

Table 9: Mould growth Mould Index (MI) categories

Mould Index	Definition	Explanation [77]
Nil	No simulated mould growth was simulated	Nil mould growth
</=1.0	Acceptable level of mould growth was simulated	Mould growth just starting, invisible growth acceptable in indoor and interstitial spaces
>1.0 to <3.0	An amount of mould growth was simulated that requires further investigation	1 ⩽ MI < 2: invisible growth, recognizable only by microscope, and 2 ⩽ MI < 3: growth starts to become visible to the naked eye
3.0>	Unacceptable amount of mould growth was simulated	MI ⩾ 3: growth is visible to the naked eye and starts covering the surface

Many of the MI simulation graphs within the Appendices show these seasonal patterns of moist conditions that promote mould growth versus drier periods when the mould growth may recede or stay stagnant.

The research proposal for this stage of the research was to explore moisture and mould growth risks that may be associated with external wall systems, or façade systems, that comply with the requirements of the NCC 2019. Within the NCC 2019, a 6 Star home should have an air-tightness of ACR 10. However, the international standard for hygrothermal simulation expects an ACR of 5. In this report, many of simulations have been completed for both ACR 10 and ACR 5, as many homes achieve a lower ACR than the current requirement of ACR 10 [38].

Introduction to Mould Index simulation results

The Appendices include Mould Index (MI) graphs for all bio-hygrothermally simulated wall systems that show mould growth. For ease of reporting, these graphs are only included in the Appendices. Below, a few examples are provided with a short explanation about how to read the graph and what the graphs may infer.

Figure 11 below, shows the MI graph for the northern orientation of a compressed fibre cement sheet clad wall located within NatHERS climate zone 22 and NCC climate zones 6 and 7. The horizontal X axis of the MI graph indicates the ten years of simulation. The vertical Y axis represents the mould growth index MI. In this graph, the MI ranges from 0.00 to 0.020.

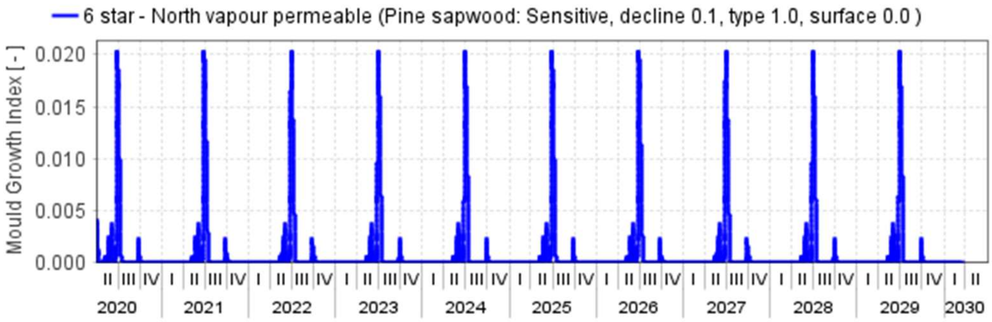

Figure 11: NatHERS CZ 22 / NCC CZ 6-7 northern orientation - mould growth within insulated timber frame

This graph shows a MI of 0 at the commencement of the simulation. It shows a calculated MI of 0.020 during the first winter. We can then see a dryer period and the mould receding until it reaches a MI value of 0.0. For each following winter and summer, the MI can be seen increasing to 0.020 and then receding to 0.0. This wall system, under these conditions, has an acceptable amount of mould growth.

Figure 12 below shows the mould growth index for the western orientation of the compressed fibre cement sheet clad wall in NatHERS climate zone 22 and NCC climate zone 8. This graph shows a MI of 0 at the commencement of the simulation. It shows a calculated MI of 0.5 during the first winter. We can then see a dryer period and the mould receding until it reaches a MI value of less than 0.01. During the next cooler season, the MI slightly exceeds the conditions of the first winter. Over the ten-year cycle of wetting, drying and mould growth, the MI reaches 1.0 in year ten. At one level, this wall system has a MI of less than 3.0. However, a more cautious approach may be to consider the fifty-to-seventy-year life of the building. The ten-year simulation shows an annual increase in the MI. A twenty-year simulation may reach an MI of 2.0, and a thirty-year simulation may reach an MI of 3.0. Considering these matters, the wall system should be further investigated.

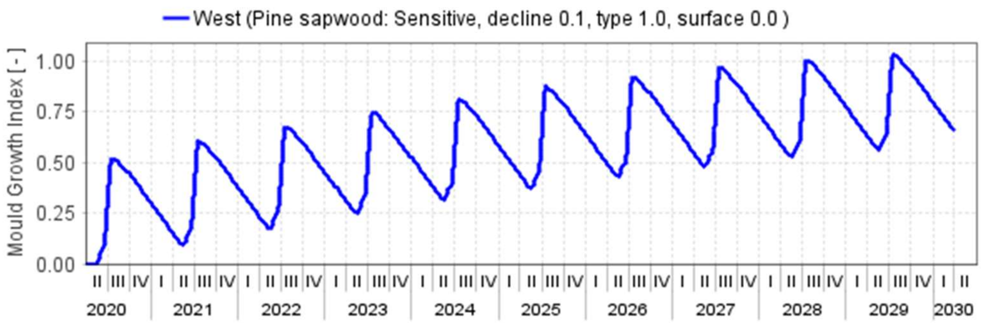

Figure 12: 6 Star compressed fibre cement sheet clad wall in NatHERS CZ22 / NCC CZ8, western orientation

The recommendation that all wall systems with an MI greater than 1.0 and less than 3.0 require further investigation, considers the differences between a computer simulation and a real building. Specifically, the hygrothermal and bio-hygrothermal simulations consider:

- perfect, error free construction
- receipt of orientation specific solar radiation
- no shading of the external wall system

- good ventilation around the external wall
- the interior relative humidity does not exceed 70%
- no air, water or water vapour leaks between the paper faced plasterboard and the external pliable membrane.

Any of these variables could significantly increase the amount of moisture and mould growth within a wall system, leading to an MI of 3.0 or more. For the case of wall shading, Nath [66] suggested that all walls that may be shaded, should apply a southern orientation within the simulation. As the non-equatorial southern wall often provides the worst simulated MI, this may be a wise choice.

Figure 13 below shows the mould growth index for the western orientation of a timber clad wall in NatHERS climate zone 22 and NCC climate zone 6 and 7. At first glance, this wall shows a mould growth index of less than 3.0. However, throughout the ten-year cycle, the MI continues to increase. Like the example discussed above, if it is planned that the wall system should be durable for fifty or more years, the MI may reach 3.0 before the 15th year. With this insight, this wall should undergo further investigation.

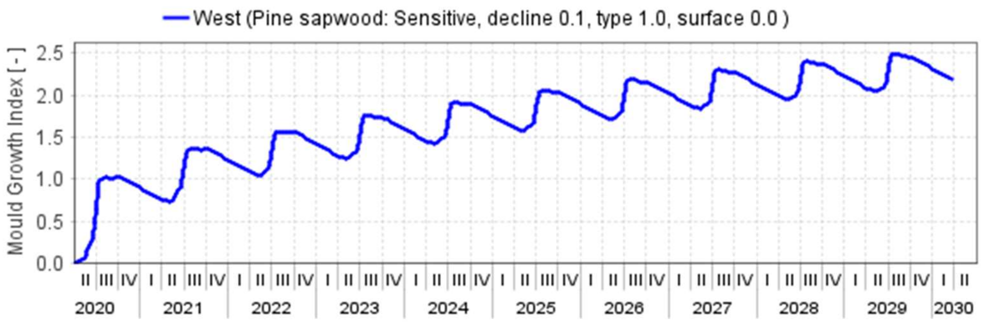

Figure 13: 6 Star weatherboard clad wall in NatHERS CZ 22 / NCC CZ 6-7, western orientation

Figure 14 below shows the mould growth index for a timber clad wall with a southern orientation in NatHERS climate zone 22 and the NCC climate zone of 6 and 7. The graph shows that during year 5, the MI exceeds 3.0. By year nine MI is exceeding 4.0. Applying the international conventions and changes for NCC, this wall system would not meet the performance requirements of NCC 2022.

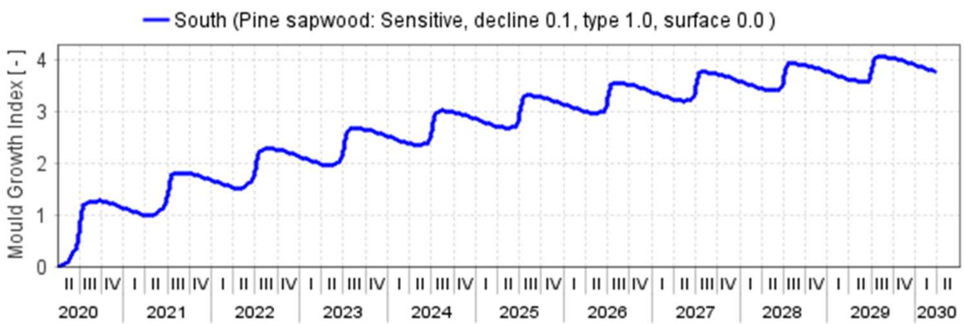

Figure 14: 6 Star weatherboard clad wall in NatHERS CZ 22 / NCC CZ 6-7 southern orientation

Figure 15 below shows the mould growth index for the southern orientation of a compressed fibre cement sheet clad wall in NatHERS climate zone 61 and the NCC climate zone of 4. This graph shows the MI exceeding 3.0 in the second year and reaching an MI of 5.0 from the third to tenth years. Applying the international conventions and changes for NCC, this wall system would not meet the performance requirements of NCC 2022.

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.

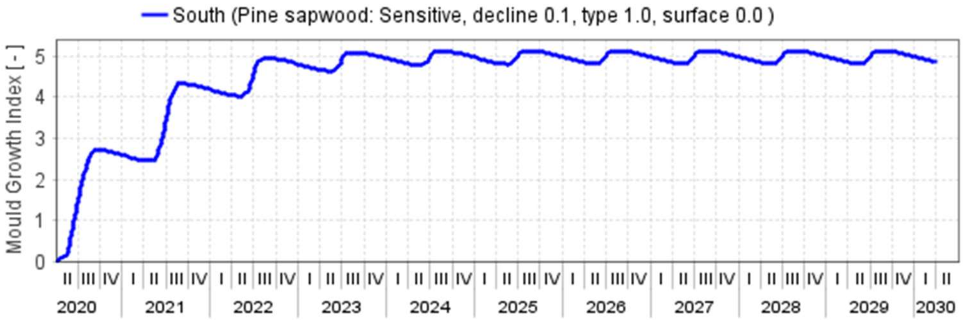

Figure 15: 6 Star compressed fibre cement sheet clad wall in NatHERS CZ 61 / NCC CZ 4 southern orientation

5.1. Timber cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star timber clad wall system. The complete set of MI graphs for this wall system can be seen in Appendix 2. Table 10 shows a summary of the results for simulations conducted with an ACR of 10.

Hygrothermal simulation (moisture accumulation)

Table 10 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth)

In Table 10, and similar tables for the other wall systems in this report, a coloured fill has been added to highlight the MI properties for each wall system, in each climate zone, within each cardinal orientation, where:

- green indicates a MI of Nil to <1.0,
- orange indicates a MI of 1.0 to <3.0, requiring more investigation, and
- red indicates an MI of 3.0 or more.

For example, in Table 10:

- NatHERS CZ 63, NCC CZ 6-7 North has a MI of <1.0, is classified as having a safe amount of mould growth and is shaded in green,
- NatHERS CZ 63, NCC CZ 6-7 East has a MI of >2.0, but <3.0, is classified as requiring further investigation, and is shaded in orange, and
- NatHERS CZ 63, NCC CZ 6-7 South and West have a MI of 3.0 of more, is classified as an unsafe amount of mould growth, and is shaded in red.

Table 10 shows that this external wall system has, for the southern orientation, an MI greater than 3.0 in ten of the fourteen (10 of 14, or 71%) NatHERS climate zones simulated. This is due to the lack of any solar driven drying potential. By comparison the northern orientation, which receives the greatest solar driven drying potential, ten of the fourteen (10 of 14, or 71%) NatHERS climate zone and built fabric variables simulated showed a MI of less than 1.0. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had one of fourteen (1 of 14, or 7%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western walls which can receive some solar radiation induced drying potential often have a higher MI than the northern orientation and a lower MI than the southern orientation.

The bio-hygrothermal simulations for NatHERS climate zones 27 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane within NCC 2019. In NatHERS climate zone 27, NCC climate zone 4, three orientations with a MI greater than 3.0, and the northern orientation requires further investigation. In NatHERS climate zone 66, NCC climate zone 4, all four orientations have a MI greater than 3.0.

For the NatHERS climate zones that correspond with the NCC 2019 requirement for a vapour permeable membrane, (climate zones 6, 7 and 8), there was generally a lower risk of mould growth. This is further divisible based on the finer grain of NatHERS climate zone, where:

- the warmer NatHERS climate zones had a lower risk (i.e., CZ21), whilst
- the cooler NatHERS climate zones had a higher risk (i.e., CZ61).

Table 10: Simulation results from 6 Star Weatherboard clad wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)				Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West	North	East	South	West
21	6-7	Nil	Nil	Nil	Nil	Nil	Nil	>1.5	Nil
22	6-7	Nil	Nil	Nil	Nil	Nil	>1.0	5.0	>2.5
22	8	Nil	Nil	Nil	Nil	Nil	Nil	>4.0	>1.5
27	4	Nil	Nil	Nil	Nil	>1.25	5.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil	Nil	Nil	>1.25	Nil
60	6-7	Nil	Nil	Nil	Nil	Nil	>1.0	>3.0	>1.5
60	8	Nil	Nil	Nil	Nil	Nil	Nil	>3.0	>1.25
61	6-7	Nil	Nil	Nil	Nil	<1.0	>2.0	>4.0	>4.0
63	6-7	Nil	Nil	Nil	Nil	<1.0	>2.0	>4.0	>3.0
64	6-7	Nil	Nil	Nil	Nil	<1.0	<1.0	>2.0	>1.0
64	8	Nil	Nil	Nil	Nil	<1.0	<1.0	<1.0	Nil
66	4	Nil	Nil	Nil	Nil	>4.0	>4.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil	2.5	>4.0	5.0	>4.0
66	8	Nil	Nil	Nil	Nil	>1.25	>4.0	5.0	>4.0

Table 11 shows a summary of the 56 bio-hygrothermal simulations, where 36% of the simulated wall systems had a nil, or an acceptable MI, 27% require further investigation and 37.5% had a MI greater than 3.0.

Table 11: Summary of Simulation results from 6 Star Weatherboard clad wall system ACR 10

	Simulation result		
Mould Index	Number	Distribution	Result
Nil	13	23%	No mould growth
</=1.0	7	12.5%	Acceptable level of mould growth
>1.0 to <3.0	15	27%	An amount of mould growth was simulated that requires further investigation
3.0>=	21	37.5%	Unacceptable amount of mould growth
Total	56	100%	

5.2 Compressed fibre cement sheet cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star timber compressed fibre cement sheet clad wall system. The complete set of MI graphs for this wall system can be seen in Appendix 3. Table 12 below shows a summary of the results for simulations conducted with an ACR of 10.

Hygrothermal simulation (moisture accumulation)

Table 12 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth)

Table 12 shows that this external wall system has a MI greater than 3.0 in ten of the fifteen (10 of 15, or 67%) NatHERS climate zones simulated.

Table 12: Simulation results from 6 Star compressed fibre cement sheet clad wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	<1.25	<1.0
22	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	4.0	>1.25
22	8	Nil	Nil	Nil	Nil		<1.0	<1.0	>4.0	>1.0
27	4	Nil	Nil	Nil	Nil		<1.0	<1.0	>2.5	<1.0
27	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	>1.0	<1.0
60	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	>3.0	>1.0
60	8	Nil	Nil	Nil	Nil		<1.0	<1.0	>3.0	<1.0
61	4	Nil	Nil	Nil	Nil		<1.0	<2.0	>5.0	>4.0
61	6 -7	Nil	Nil	Nil	Nil		<1.0	>1.0	>4.0	>3.0
63	6-7	Nil	Nil	Nil	Nil		<1.0	>1.0	>4.0	>2.5
64	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	>1.25	<1.0
64	8	Nil	Nil	Nil	Nil		<1.0	<1.0	>1.25	<1.0
66	4	Nil	Nil	Nil	Nil		>2.25	>4.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		<1.0	>3.0	>4.0	4.0
66	8	Nil	Nil	Nil	Nil		<1.0	>3.0	5.0	>4.0

Due to the solar radiation induced drying potential of the northern orientation, fourteen of the fifteen (14 of 15, or 93%) NatHERS climate zone and built fabric variables simulated showed a MI of less than 1.0 in this orientation. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had nil of fifteen (0 of 15, or 0%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western walls which can receive some solar radiation induced drying potential often have a higher MI than the northern orientation and a lower MI than the southern orientation. It should be noted that, regardless of orientation, if an external wall is shaded by an eave, nearby structure or other elements, the results for the southern orientation may better represent the hygrothermal conditions regardless of orientation.

The bio-hygrothermal simulations for NatHERS climate zones 27 and 66, which also includes the NCC climate zone 4, which does not require the use of a vapour permeable pliable membrane on walls (NCC 2019). In NatHERS climate zone 27, NCC climate zone 4, only the southern orientation had a MI greater than 1.0, requiring further investigation. In NatHERS climate zone 66, NCC climate zone 4, all four orientations have a MI greater than 3.0.

For the NatHERS climate zones that correspond with the NCC (2019) requirement for a vapour permeable membrane, (climate zones 6, 7 and 8), there was generally a lower risk of mould growth. This is further divisible based on the finer grain of NatHERS climate zone, where:

- the warmer NatHERS climate zones had a lower risk (i.e., CZ21), whilst
- the cooler NatHERS climate zones had a higher risk (i.e., CZ61).

Table 13 shows a summary of the 60 bio-hygrothermal simulations, where 48% of the simulated wall systems had an acceptable MI of less than 1.0, 22% had a MI greater than 1.0 and less than 3.0 requiring further investigation and 30% had a MI greater than 3.0.

Table 13: Summary of Simulation results from 6 Star compressed fibre cement sheet clad wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	0	0%	No mould growth
</=1.0	29	48%	Acceptable level of mould growth
>1.0 to <3.0	13	22%	An amount of mould growth was simulated that requires further investigation
3.0>=	18	30%	Unacceptable amount of mould growth
Total	60	100%	

-

5.3 Clay masonry veneer with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star clay masonry veneer external wall system. The complete set of MI graphs for this wall system can be seen in Appendix 4. Table 14 shows a summary of the results for simulations conducted with an ACR of 10, and Table 16 shows a summary of the results for simulations conducted with an Air Change Rate of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 14 shows that this external wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 14 shows that this external wall system has a MI of greater than 1.0 in nine of the fourteen (9 of 14, or 64%) NatHERS climate zones simulated.

Table 14: Simulation results from 6 Star Clay masonry veneer wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	<1.0	<1.0
22	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	>2.5	>1.25
22	8	Nil	Nil	Nil	Nil		<1.0	<1.0	>4.0	>1.25
27	4	Nil	Nil	Nil	Nil		<1.0	<1.0	<1.0	<1.0
27	6-7	Nil	Nil	Nil	Nil		Nil	<1.0	<1.0	<1.0
60	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	>1.5	<1.0
60	8	Nil	Nil	Nil	Nil		<1.0	<1.0	>2.0	>1.0
61	6-7	Nil	Nil	Nil	Nil		<1.0	>1.2	>3.0	>2.5
63	6-7	Nil	Nil	Nil	Nil		<1.0	>2.5	>3.0	>1.0
64	6-7	Nil	Nil	Nil	Nil		<1.0	<1.0	<1.0	<1.0
64	8	Nil	Nil	Nil	Nil		<1.0	<1.0	<1.0	<1.0
66	4	Nil	Nil	Nil	Nil		>1.0	3.0	>4.0	>1.2
66	6-7	Nil	Nil	Nil	Nil		>1.2	>2.5	>4.0	>3.0
66	8	Nil	Nil	Nil	Nil		>1.25	>3.0	>4.0	>3.0

Due to the solar radiation induced drying potential of the northern orientation, eleven of the fourteen (11 of 14, or 79%) NatHERS climate zone and built fabric variables simulated showed nil, or a MI of less than 1.0. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had five of fourteen (5 of 14, 36%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western walls which can receive some solar radiation induced drying potential often have a higher MI than the northern orientation and a lower MI than the southern orientation. It should be noted that, regardless of orientation, if a wall is shaded by an eave, nearby structure or other elements, the results for the southern orientation may better represent the hygrothermal conditions in that wall.

The bio-hygrothermal simulations for NatHERS climate zones 27 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane in NCC 2019. In NatHERS climate zone 27, NCC climate zone 4, all four orientations have an acceptable MI of less than 1.0. In NatHERS climate zone 66, NCC climate zone 4, two orientations require further investigation, and two orientations have a MI greater than 3.0.

For the NatHERS climate zones that correspond with the NCC 2019 requirement for a vapour permeable membrane, (climate zones 6, 7 and 8), there was generally a lower risk of mould growth. This is further divisible based on the finer grain of climate, where:

- the warmer NatHERS climate zones had a lower risk (i.e., CZ21), whilst
- the cooler NatHERS climate zones had a higher risk (i.e., CZ61).

Table 15 shows a summary of the 56 bio-hygrothermal simulations, where 55% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 27% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 18% had a MI greater than 3.0.

Table 15: Summary of Simulation results from 6 Star Clay Masonry Veneer clad wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	1	2%	No mould growth
</=1.0	30	53%	Acceptable level of mould growth
>1.0 to <3.0	15	27%	An amount of mould growth was simulated that requires further investigation
3.0>=	10	18%	Unacceptable amount of mould growth
Total	56	100%	

-

Generally, the results for this wall system, with an ACR of 10, are much better than many other wall systems examined in this research. This is due to the presence of the vented cavity between the pliable membrane and the clay brick.

Hygrothermal simulation (moisture accumulation) ACR 5

Table 16 shows that this external wall system, in all the simulated climate types, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 16 shows that this wall system has a MI greater than 1.0 in all fourteen (14 of 14, or 100%) NatHERS climate zones simulated. When compared to the ACR 10 simulations in Table 12, this wall system now has 52 of 56 (93%) scenarios where the MI is greater than 3.0.

Table 16: Simulation results from 6 Star Clay masonry veneer wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		<2.75	>5.0	>5.0	>5.0
22	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
22	8	Nil	Nil	Nil	Nil		>3.0	>3.0	5.0	5.0
27	4	Nil	Nil	Nil	Nil		<1.0	>4.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil		<1.0	>4.0	5.0	5.0
60	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
60	8	Nil	Nil	Nil	Nil		>2.0	5.0	5.0	5.0
61	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
63	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
64	6-7	Nil	Nil	Nil	Nil		>3.0	>4.0	5.0	5.0
64	8	Nil	Nil	Nil	Nil		>3.0	>4.0	5.0	5.0
66	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0

Table 17, shows a summary of the 56 bio-hygrothermal simulations, where 3% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 3% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 94% had a MI greater than 3.0. The dramatic difference in results between ACR 10 and ACR 5, highlight the need for improved envelope design measures for more airtight homes.

Table 17: Summary of Simulation results from 6 Star Clay Masonry Veneer clad wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	0	0%	No mould growth
</=1.0	2	3%	Acceptable level of mould growth
>1.0 to <3.0	2	3%	An amount of mould growth was simulated that requires further investigation
3.0>=	52	94%	Unacceptable amount of mould growth
Total	56	100%	

5.4 Concrete block, internally insulated

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star concrete block, internally insulated, external wall system. The complete set of MI graphs for this external wall system can be seen in Appendix 5. Table 18 shows a summary of the results for simulations conducted with an ACR of 10, and Table 20 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 18 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 18 shows that this wall system has only three out of fourteen (3 of 15, or 20%) NatHERS climate zones simulated where, for all four orientations, the MI is less than 1.0.

Table 18: Simulation results from 6 Star concrete masonry block internally insulated wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	6-7	Nil	Nil	Nil	Nil		Nil	>1.0	4.0	>2.0
22	8	Nil	Nil	Nil	Nil		Nil	>1.5	5.0	4.0
27	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	Nil	2.5	>1.0
60	8	Nil	Nil	Nil	Nil		Nil	>1.7	>3.5	>2.0
61	4	Nil	Nil	Nil	Nil		Nil	>1.5	>3.0	>2.0
61	6-7	Nil	Nil	Nil	Nil		Nil	>1.5	4.0	>3.0
63	6-7	Nil	Nil	Nil	Nil		Nil	>1.5	>3.0	>2.5
64	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>1.25	Nil
64	8	Nil	Nil	Nil	Nil		Nil	Nil	>2.0	>1.0
66	4	Nil	Nil	Nil	Nil		>1.5	>2.5	>3.0	>3.0
66	6-7	Nil	Nil	Nil	Nil		>2.0	>3.0	>4.0	>3.5
66	8	Nil	Nil	Nil	Nil		>3.0	>4.0	5.0	5.0

Due to the solar radiation induced drying potential of the northern orientation, twelve of the fifteen (12 of 15, or 80%) NatHERS climate zone and built fabric variables simulated showed nil, or a MI of less than 1.0. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had three of fourteen (3 of 15, or 20%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western orientated walls which can receive some solar radiation induced drying potential often have a higher MI than the norther orientation and a lower MI than the southern orientation. It should be noted that, regardless of orientation, if a wall is shaded by an eave, nearby structure or other elements, the results for the southern orientation may better represent the hygrothermal conditions in that wall.

The bio-hygrothermal simulations for NatHERS climate zones 27, 61 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane in NCC 2019. In all three NatHERS climate zones, due to the moisture storage capacity of the concrete blocks, the matter of an impermeable pliable membrane does not appear to create any significant difference in bi-hygrothermal results.

Table 19 shows a summary of the 56 bio-hygrothermal simulations, where 42% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 30% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 28% had a MI greater than 3.0. The dramatic difference in results between ACR 10 and ACR 5, highlight the need for improved envelope design and construction measures for more airtight homes.

Table 19: Summary of Simulation results from 6 Star Concrete Block wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	25	42%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	18	30%	An amount of mould growth was simulated that requires further investigation
3.0>=	17	28%	Unacceptable amount of mould growth
Total	60	100%	

Hygrothermal simulation (moisture accumulation) ACR 5

Table 20 shows that this external wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 20 shows that this wall system has nil out of fourteen (0 of 14, or 0%) NatHERS climate zones simulated where the MI is less than 1.0.

Due to the solar radiation induced drying potential of the northern orientation, three of the fifteen (3 of 15) NatHERS climate zone and built fabric variables simulated show a MI greater than 1.0 but less than 3.0, requiring further investigation.

Table 20: Simulation results from 6 Star concrete masonry block internally insulated wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
22	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
22	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
27	4	Nil	Nil	Nil	Nil		>1.5	>4.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil		>1.25	>4.0	5.0	5.0
60	6-7	Nil	Nil	Nil	Nil		2.5	5.0	5.0	5.0
60	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
61	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
63	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
64	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
64	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0

Table 21 shows a summary of the 56 bio-hygrothermal simulations, where 0% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 5% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 95% had a MI greater than 3.0. The dramatic difference in results between ACR 10 and ACR 5, highlight the need for improved envelope design measures for more airtight homes.

Table 21: Summary of Simulation results from 6 Star concrete block wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	0	0%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	3	5%	An amount of mould growth was simulated that requires further investigation
3.0>=	53	95%	Unacceptable amount of mould growth
Total	56	100%	

5.5 Externally insulated clay masonry (reverse brick veneer)

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star externally insulated clay masonry external wall system, which is often called reverse brick veneer. The complete set of MI Index graphs for this wall system can be seen in Appendix 6. Table 22 shows a summary of the results for simulations conducted with an ACR of 10, and Table 24 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed above in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 22 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 22 shows that this wall system has two out of fifteen (2 of 15, or 13%) NatHERS climate zones simulated where the MI is less than 1.0.

Table 22: Simulation results from 6 Star externally insulated clay masonry wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>1.5	1.25
22	8	Nil	Nil	Nil	Nil		Nil	Nil	>1.5	1.25
27	4	Nil	Nil	Nil	Nil		Nil	Nil	>1.2	Nil
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	Nil	1.2	Nil
60	8	Nil	Nil	Nil	Nil		Nil	Nil	1.2	Nil
61	4	Nil	Nil	Nil	Nil		Nil	>3.0	5.0	>4.0
61	6-7	Nil	Nil	Nil	Nil		Nil	1.0	>2.0	1.5
63	6-7	Nil	Nil	Nil	Nil		Nil	1.2	>2.5	1.5
64	6-7	Nil	Nil	Nil	Nil		Nil	Nil	1.2	Nil
64	8	Nil	Nil	Nil	Nil		Nil	Nil	1.2	Nil
66	4	Nil	Nil	Nil	Nil		>2.5	>4.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		Nil	>1.0	>2.5	1.5
66	8	Nil	Nil	Nil	Nil		Nil	>1.0	>2.0	1.5

Due to the solar radiation induced drying potential of the northern orientation, fourteen of the fifteen (14 of 15, or 93%) NatHERS climate zone and built fabric variables simulated showed nil, or a mould index of less than 1.0. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had two of fourteen (2 of 15, or 13%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western orientated walls which can receive some solar radiation induced drying potential often have a higher MI than the norther orientation and a lower MI than the southern orientation. It should be noted that, regardless of orientation, if a wall is shaded by an eave, nearby structure or other elements, the results for the southern orientation may better represent the wall conditions in that wall.

The bio-hygrothermal simulations for NatHERS climate zones 27, 61 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane in NCC 2019. In NatHERS climate zone 27, NCC climate zone 4, there is no discernible difference between the results with and without a vapour permeable membrane. However, climates 61 and 66 show some of the highest MI results.

For the NatHERS climate zones that correspond with the NCC 2019 requirement for a vapour permeable membrane, (climate zones 6, 7 and 8), there was generally a lower risk of mould growth. This is further divisible based on the finer grain of climate, where:

- the warmer NatHERS climate zones had a lower risk (i.e., CZ21), whilst
- the cooler NatHERS climate zones had a higher risk (i.e., CZ61).
-

Table 23 shows a summary of the 60 bio-hygrothermal simulations, where 53% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 37% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 10% had a MI greater than 3.0. This is a somewhat better result than some of the other wall systems examined in this research, and this is in part due to the air cavity between the externally insulated timber frame and the internal extruded clay brick wall, and the hygrothermal buffering properties provided by the clay brick.

Table 23: Summary of Simulation results from 6 Star externally insulated clay masonry wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	32	53%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	22	37%	An amount of mould growth was simulated that requires further investigation
3.0>=	6	10%	Unacceptable amount of mould growth
Total	60	100%	

-

Hygrothermal simulation (moisture accumulation) ACR 5

Table 24, shows that this external wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 24 shows that this external wall system has nil out of fourteen (0 of 14) NatHERS climate zones simulated where the MI is less than 1.0.

Due to the solar radiation induced drying potential of the northern orientation, two of the fourteen (2 of 14, or 14%) NatHERS climate zone and built fabric variables simulated show a MI of less than 1.0, seven have a MI greater than 1.0 and less than 3.0 and five have a MI greater than 3.0. Except for two scenarios with an eastern orientation, all other bio-hygrothermal simulations of this wall system have a MI greater than 3.0.

Table 24: Simulation results from 6 Star externally insulated clay masonry wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		<1.0	>2.5	>4.0	>3.0
22	6-7	Nil	Nil	Nil	Nil		>1.5	>4.0	5.0	5.0
22	8	Nil	Nil	Nil	Nil		>1.0	>3.0	5.0	5.0
27	4	Nil	Nil	Nil	Nil		>1.0	>4.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>4.0	>3.0
60	6-7	Nil	Nil	Nil	Nil		>1.5	>4.0	5.0	5.0
60	8	Nil	Nil	Nil	Nil		>1.0	>4.0	5.0	>4.0
61	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
63	6-7	Nil	Nil	Nil	Nil		>4.0	>4.0	5.0	5.0
64	6-7	Nil	Nil	Nil	Nil		>2.0	>3.0	5.0	>4.0
64	8	Nil	Nil	Nil	Nil		>1.5	>3.0	>4.0	>4.0
66	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0

Table 25 shows a summary of the 56 bio-hygrothermal simulations, where 6% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 14% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 80% had a MI greater than 3.0.

This is a somewhat better result than some of the other wall systems with an ACR of 5.0. This is in part due to the air cavity between the externally insulated timber frame and the internal extruded clay brick wall, and the hygrothermal buffering properties provided by the internal extruded clay brick. However, when compared to this wall systems ACR10 results, it is once again evident that improved envelope design measures for more airtight homes may result in greater opportunities for interstitial mould growth.

Table 25: Summary of Simulation results from 6 Star externally insulated clay masonry wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	2	4%	No mould growth
</=1.0	1	2%	Acceptable level of mould growth
>1.0 to <3.0	8	14%	An amount of mould growth was simulated that requires further investigation
3.0>=	45	80%	Unacceptable amount of mould growth
Total	56	100%	

5.6 Extruded polystyrene with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star extruded polystyrene (XPS) with insulated timber frame external wall system. Extruded polystyrene has a very high resistance to water vapour diffusion. The complete set of MI graphs for this wall system can be seen in Appendix 7. Table 26 shows a summary of the results for simulations conducted with an ACR of 10, and Table 28 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 26 shows that this external wall system, in most of the simulated NatHERS climate zones, has a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall in most NatHERS climate zones did not lead to moisture accumulation within the wall system.

All four orientations of NatHERS climate zone 63, NCC built fabric variables for NCC Climate zone 6 and 7 showed moisture accumulation. The moisture accumulation occurred within the boundary of the acrylic render and the extruded polystyrene cladding. This would lead to a bubbling under the acrylic render. It should be noted that in some countries, a drainage medium is placed at this location within these types of walls. A drainage medium is not presently a requirement of NCC 2019.

Table 26: Simulation results from 6 Star extruded polystyrene wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
61	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
61	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
63	6-7	Yes	Yes	Yes	Yes		Nil	Nil	Nil	Nil
64	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
64	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 26 shows that this external wall system has a nil MI value for all NatHERS climate zones and orientations, including climate zone 63 where moisture accumulation was found. This is significantly in part due to the external insulation of the façade system. That is, the insulation is on the outside of the built fabric. This allows for the membrane and timber frame to stay warmer.

Table 27 shows a summary of the 60 bio-hygrothermal simulations, where 100% of the simulated wall systems had a nil, or acceptable MI of less than 1.0.

Table 27: Summary of Simulation results from 6 Star extruded polystyrene wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	60	100%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	0	0%	An amount of mould growth was simulated that requires further investigation
3.0>=	0	0%	Unacceptable amount of mould growth
Total	60	100%	

Hygrothermal simulation (moisture accumulation) ACR 5

Table 28 shows that this external wall system, in most of the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall in most NatHERS climate zones did not lead to moisture accumulation within the wall system.

All four orientations of NatHERS climate zone 63, NCC built fabric variables for NCC Climate zone 6 and 7 showed moisture accumulation. The moisture accumulation occurred within the boundary of the acrylic render and the extruded polystyrene cladding. This would lead to a bubbling under the acrylic render. It should be noted that in some countries, a drainage medium is placed at this location within these types of walls. A drainage medium is not presently a requirement of NCC 2019.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 28 shows that this wall system has nil out of fifteen (0 of 15, or 0%) climates simulated where the MI is less than 1.0.

Due to the solar radiation induced drying potential of the northern orientation, three of the fifteen (3 of 15) NatHERS climate zone and built fabric variables simulated show a MI of less than 1.0, nine had a MI greater than 1.0 and less than 3.0 and three had a MI greater than 3.0. Except for three other orientation and NatHERS climate zone scenarios, all other bio-hygrothermal simulations of this wall system have a MI greater than 3.0.

Table 28: Simulation results from 6 Star extruded polystyrene wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	1.25	>2.0	>1.5
22	6-7	Nil	Nil	Nil	Nil		>1.0	>2.0	>3.0	>3.0
22	8	Nil	Nil	Nil	Nil		2.5	>2.0	4.0	>3.0
27	4	Nil	Nil	Nil	Nil		Nil	Nil	>2.5	>1.5
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	2.5	Nil
60	6-7	Nil	Nil	Nil	Nil		>1.0	>2.0	>3.0	>2.5
60	8	Nil	Nil	Nil	Nil		>2.5	>4.0	5.0	5.0
61	4	Nil	Nil	Nil	Nil		>2.0	>3.0	>4.0	>3.5
61	6-7	Nil	Nil	Nil	Nil		2.0	>3.0	4.0	>3.0
63	6-7	Yes	Yes	Yes	Yes		>2.5	>3.0	4.0	>3.0
64	6-7	Nil	Nil	Nil	Nil		>1.0	>1.5	>2.0	>2.0
64	8	Nil	Nil	Nil	Nil		>1.5	4.0	>4.0	>4.0
66	4	Nil	Nil	Nil	Nil		>3.0	4.0	>4.0	4.0
66	6-7	Nil	Nil	Nil	Nil		>3.0	4.0	>4.0	4.0
66	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0

Table 29 shows a summary of the 60 bio-hygrothermal simulations, where 10% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 37% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 53% had a MI greater than 3.0.

This is a somewhat better result than some of the other wall systems with an ACR of 5 examined in this research. This is due to the insulation system being on the outside of the timber frame. Internationally, this is known as an externally insulated façade system. However, when compared to this wall systems ACR 10 results, it is once again evident that improved envelope design measures are needed for more airtight homes.

Table 29: Summary of Simulation results from 6 Star extruded polystyrene wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	6	10%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	22	37%	An amount of mould growth was simulated that requires further investigation
3.0>=	32	53%	Unacceptable amount of mould growth
Total	60	100%	

5.7 Expanded polystyrene with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star expanded polystyrene with insulated timber framed external wall system. Expanded polystyrene (EPS) is significantly more vapour permeable than extruded polystyrene. The complete set of MI graphs for this wall system can be seen in Appendix 8. Table 30 shows a summary of the results for simulations conducted with an ACR of 10, and Table 32 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 30 shows that this wall system, in most of the simulated NatHERS climate zones, has a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall in most NatHERS climate zones did not lead to moisture accumulation within the wall system.

All four orientations of NatHERS climate zone 63, NCC built fabric variables for NCC Climate zone 6 and 7 shows moisture accumulation. The moisture accumulation occurred within the boundary of the acrylic render and the expanded polystyrene cladding. This would lead to a bubbling under the acrylic render. It should be noted that in some countries, a drainage medium is placed at this location within these types of walls. A drainage medium is not presently a requirement of NCC 2019.

Table 30: Simulation results from 6 Star expanded polystyrene wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
61	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
61	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
63	6-7	Yes	Yes	Yes	Yes		Nil	Nil	Nil	Nil
64	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
64	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
66	8	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 30 shows that this wall system has a nil MI value for all NatHERS climate zones and orientations. This is significantly in part due to the external insulation of the façade system. That is, the insulation is on the outside of the built fabric. This allows for the membrane and timber frame to stay warmer.

Table 31 shows a summary of the 60 bio-hygrothermal simulations, where 100% of the simulated wall systems had a nil, or acceptable MI of less than 1.0.

Table 31: Summary of Simulation results from 6 Star expanded polystyrene wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	60	100%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	0	0%	An amount of mould growth was simulated that requires further investigation
3.0>=	0	0%	Unacceptable amount of mould growth
Total	60	100%	

Hygrothermal simulation (moisture accumulation) ACR 5

Table 32 shows that this wall system, in most of the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall in most NatHERS climate zones did not lead to moisture accumulation within the wall system.

All four orientations of NatHERS climate zone 63, NCC built fabric variables for NCC Climate zone 6 and 7 show moisture accumulation. The moisture accumulation occurred within the boundary of the acrylic render and the extruded polystyrene cladding. This would lead to a bubbling under the acrylic render. It should be noted that in some countries, a drainage medium is placed at this location within these types of walls.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 32 shows that this wall system has nil out of fifteen (0 of 15, 0%) NatHERS climate zones simulated where the MI is less than 1.0.

Due to the solar radiation induced drying potential of the northern orientation, six of the fifteen (6 of 15) NatHERS climate zone and built fabric variables simulated show a MI of less than 1.0, seven had a MI greater than 1.0 and less than 3.0 and two had a MI greater than 3.0. Except for four other orientation and NatHERS climate zone scenarios, all other bio-hygrothermal simulations of this wall system have a MI greater than 3.0. This result is slightly better than that for the extruded polystyrene clad wall system with and ACR of 5 and is due to the expanded polystyrene being water vapour semi-permeable, whilst the extruded polystyrene is water vapour impermeable.

Table 32: Simulation results from 6 Star expanded polystyrene wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>1.25	>1.0
22	6-7	Nil	Nil	Nil	Nil		Nil	>1.2	>2.5	>1.5
22	8	Nil	Nil	Nil	Nil		>1.5	>4.0	5.0	>4.5
27	4	Nil	Nil	Nil	Nil		Nil	Nil	>2.0	>1.25
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>1.2	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	>1.2	>2.0	>1.5
60	8	Nil	Nil	Nil	Nil		>2.0	>4.0	>4.5	>4.0
61	4	Nil	Nil	Nil	Nil		>1.5	>3.0	>4.0	>3.0
61	6-7	Nil	Nil	Nil	Nil		>1.0	2.5	>3.0	>3.0
63	6-7	Yes	Yes	Yes	Yes		>1.5	2.5	>3.0	<3.0
64	6-7	Nil	Nil	Nil	Nil		Nil	>1.0	>1.5	1.25
64	8	Nil	Nil	Nil	Nil		>2.0	>3.0	>4.0	>3.0
66	4	Nil	Nil	Nil	Nil		>3.0	>3.0	4.0	>3.0
66	6-7	Nil	Nil	Nil	Nil		>2.5	>3.0	>3.0	>3.0
66	8	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0

Table 33 shows a summary of the 60 bio-hygrothermal simulations, where 17% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 40% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 43% had a MI greater than 3.0.

This is a somewhat better result than some of the other wall systems with an ACR of 5. This is due to the insulation system being on the outside of the timber frame and the vapour permeability properties of the expanded polystyrene. However, when compared to this wall systems ACR 10 results, it is once again evident that improved envelope design measures are needed for more airtight homes.

Table 33: Summary of Simulation results from 6 Star expanded polystyrene wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	10	17%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	24	40%	An amount of mould growth was simulated that requires further investigation
3.0>=	26	43%	Unacceptable amount of mould growth
Total	60	100%	

5.8 Autoclaved aerated concrete cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star autoclaved aerated concrete (AAC) clad external wall system. The complete set of MI graphs for this wall system can be seen in Appendix 9. Table 34 shows a summary of the results for simulations conducted with an ACR of 10, and Table 36 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 34 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 34 shows that this external wall system has four out of fifteen (4 of 15, or 27%) NatHERS climate zones simulated where the MI is less than 1.0.

Table 34: Simulation results from 6 Star autoclaved aerated concrete wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
22	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>2.0	>1.0
22	8	Nil	Nil	Nil	Nil		Nil	Nil	4.0	>1.5
27	4	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
60	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>1.2	Nil
60	8	Nil	Nil	Nil	Nil		Nil	Nil	>2.5	>1.25
61	4	Nil	Nil	Nil	Nil		Nil	>1.0	>3.0	>2.0
61	6-7	Nil	Nil	Nil	Nil		Nil	>1.0	>3.0	>2.0
63	6-7	Nil	Nil	Nil	Nil		Nil	>1.0	>2.5	>1.5
64	6-7	Nil	Nil	Nil	Nil		Nil	Nil	Nil	Nil
64	8	Nil	Nil	Nil	Nil		Nil	Nil	>1.2	Nil
66	4	Nil	Nil	Nil	Nil		>1.2	>2.5	>3.0	>2.5
66	6-7	Nil	Nil	Nil	Nil		>1.0	>2.0	>3.0	>2.5
66	8	Nil	Nil	Nil	Nil		>1.5	>3.0	>4.0	4.0

Due to the solar radiation induced drying potential of the northern orientation, twelve of the fifteen (12 of 15, or 80%) NatHERS climate zone and built fabric variables simulated showed nil, or a MI of less than 1.0. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had four of fourteen (4 of 14, or 28%) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western orientated walls which can receive some solar radiation induced drying potential often have a higher MI than the norther orientation and a lower MI than the southern orientation.

The bio-hygrothermal simulations for NatHERS climate zones 27, 61 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane in NCC 2019. As much as each of these simulation results shows a MI greater than 1.0, this is not too different to many other of the simulations that incorporate a vapour permeable pliable membrane.

Table 35 shows a summary of the 60 bio-hygrothermal simulations, where 52% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 35% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 13% had a MI greater than 3.0. This low number of MI 3.0 or more simulation results may be due to the water storage capacity and the slight insulation properties of the AAC cladding system.

Table 35: Summary of Simulation results from 6 Star autoclaved aerated concrete wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	31	52%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	21	35%	An amount of mould growth was simulated that requires further investigation
3.0>=	8	13%	Unacceptable amount of mould growth
Total	60	100%	

Hygrothermal simulation (moisture accumulation) ACR 5

Table 36 shows that this external wall system, in most of the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall in most NatHERS climate zones did not lead to moisture accumulation within the wall system.

All four orientations of NatHERS climate zone 63, NCC built fabric variables for NCC Climate zone 6 and 7 do show moisture accumulation. The moisture accumulation occurred within the boundary of the acrylic render and the AAC cladding. This would lead to a bubbling under the acrylic render. It should be noted that in some countries, a drainage medium is placed at this location within these types of walls. A drainage medium is not presently a requirement of NCC 2019.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 36 shows that this wall system has nil out of fifteen (0 of 15, or 0%) NatHERS climate zones simulated where the MI is less than 1.0.

Due to the solar radiation induced drying potential of the northern orientation, two of the fifteen (2 of 15, or 13%) NatHERS climate zone and built fabric variables simulated show a MI of more than 1.0 but less than 3.0. The remaining orientation and NatHERS climate zone scenarios have a MI of 3.0 or more.

Table 36: Simulation results from 6 Star autoclaved aerated concrete wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
22	6-7	Nil	Nil	Yes	Nil		>4.0	5.0	5.0	5.0
22	8	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
27	4	Nil	Nil	Nil	Nil		1.5	>4.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil		>1.2	>4.0	5.0	5.0
60	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
60	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
61	4	Nil	Nil	Yes	Nil		5.0	5.0	5.0	5.0
61	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
63	6-7	Yes	Yes	Yes	Yes		5.0	5.0	5.0	5.0
64	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
64	8	Nil	Nil	Nil	Nil		>4.5	5.0	5.0	5.0
66	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0

Table 37 shows a summary of the 60 bio-hygrothermal simulations, where 0% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 3% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 97% had a MI greater than 3.0. The differences in ACR 10 and ACR 5 bio-hygrothermal simulation results for this wall system highlight the need for improved envelope design measures for more airtight homes.

Table 37: Summary of Simulation results from 6 Star autoclaved aerated concrete wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	0	0%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	2	3%	An amount of mould growth was simulated that requires further investigation
3.0>=	58	97%	Unacceptable amount of mould growth
Total	60	100%	

5.9 Sheet-metal cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 6 Star sheet-metal clad external wall system. This simulation data also mimics the results that would be obtained from a range of metal and aluminium cladding systems which would have very similar thermal resistance and water vapour diffusion properties. The other key matter regarding these simulations, is that they represent a flat pan simulation. Some metal products are installed as a flat pan, whilst others have varying depths of profile. The complete set of MI graphs for this external wall system can be seen in Appendix 10. Table 38 shows a summary of the results for simulations conducted with an ACR of 10, and Table 40 shows a summary of the results for simulations conducted with an ACR of 5. The relevance of these two ACR values is discussed in section 4.

Hygrothermal simulation (moisture accumulation) ACR 10

Table 38 shows that this wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 10

Table 38 shows that this wall system has nil out of fifteen (0 of 15, or 0%) NatHERS climate zones simulated where the MI is less than 1.0.

Table 38: Simulation results from 6 Star sheet-metal wall system ACR 10

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Nil	Nil		Nil	>1.2	>3.0	>1.5
22	6-7	Nil	Nil	Nil	Nil		Nil	>2.0	5.0	>4.0
22	8	Nil	Nil	Nil	Nil		Nil	>1.2	5.0	4.0
27	4	Nil	Nil	Nil	Nil		Nil	Nil	>3.0	>1.2
27	6-7	Nil	Nil	Nil	Nil		Nil	Nil	>3.0	>1.0
60	6-7	Nil	Nil	Nil	Nil		Nil	>2.5	5.0	4.0
60	8	Nil	Nil	Nil	Nil		Nil	>1.5	5.0	>3.0
61	4	Nil	Nil	Nil	Nil		>1.0	4.0	5.0	5.0
61	6-7	Nil	Nil	Nil	Nil		>1.0	4.0	5.0	5.0
63	6-7	Nil	Nil	Nil	Nil		>1.5	>4.0	5.0	>4.5
64	6-7	Nil	Nil	Nil	Nil		Nil	>1.5	>3.5	>2.5
64	8	Nil	Nil	Nil	Nil		Nil	>1.0	>3.0	>1.75
66	4	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		>3.5	5.0	5.0	5.0

Due to the solar radiation induced drying potential of the northern orientation, nine of the fifteen (9 of 15) NatHERS climate zone and built fabric variables simulated showed a MI of less than 1.0 in this orientation. Conversely, the southern orientation, that does not receive solar radiation for at least six months each year, only had nil of fifteen (0 of 15) NatHERS climate zone and built fabric variables with a MI of less than 1.0. The eastern and western orientated walls which can receive some solar radiation induced drying potential often have a higher MI than the northern orientation and a lower MI than the southern orientation.

The bio-hygrothermal simulations for NatHERS climate zones 27, 61 and 66, which also include the NCC climate zone 4, do not require the use of a vapour permeable building membrane within NCC 2019. The bio-hygrothermal simulation results for these three NatHERS climate zone scenarios are not dissimilar to results that include a vapour permeable membrane. This could be due to the vapour impermeable nature of the cladding system and requires further investigation.

Table 39 shows a summary of the 60 bio-hygrothermal simulations, where 18% of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 25% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 57% had a MI greater than 3.0.

Table 39: Summary of Simulation results from 6 Star sheet-metal wall system ACR 10

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	11	18%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	15	25%	An amount of mould growth was simulated that requires further investigation
3.0>=	34	57%	Unacceptable amount of mould growth
Total	60	100%	

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Hygrothermal simulation (moisture accumulation) ACR 5

Table 40 shows that this external wall system, in all the simulated NatHERS climate zones, has a nil value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within the wall system.

Bio-hygrothermal simulation (Mould growth) ACR 5

Table 40 shows that this wall system has nil out of fifteen (0 of 15, or 0%) NatHERS climate zones simulated where the MI is less than 1.0.

Table 40: Simulation results from 6 Star sheet-metal wall system ACR 5

NatHERS CZ	NCC CZ	Hygrothermal (moisture accumulation)					Bio-hygrothermal (Highest calculated Mould Index (MI))			
		North	East	South	West		North	East	South	West
21	6-7	Nil	Nil	Yes	Nil		5.0	5.0	5.0	5.0
22	6-7	Nil	Nil	Yes	Nil		5.0	5.0	5.0	5.0
22	8	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
27	4	Nil	Nil	Nil	Nil		>1.5	5.0	5.0	5.0
27	6-7	Nil	Nil	Nil	Nil		>1.5	5.0	5.0	5.0
60	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
60	8	Nil	Nil	Nil	Nil		>4.0	5.0	5.0	5.0
61	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
61	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
63	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
64	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
64	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	4	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	6-7	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0
66	8	Nil	Nil	Nil	Nil		5.0	5.0	5.0	5.0

Table 41 shows a summary of the 60 bio-hygrothermal simulations, where none of the simulated wall systems had a nil, or acceptable MI of less than 1.0, 3% had a MI greater than 1.0 and less than 3.0, requiring further investigation and 97% had a MI greater than 3.0.

The differences in ACR 10 and ACR 5 bio-hygrothermal simulation results for this external wall system highlight the need for improved envelope design measures for more airtight homes.

Table 41: Summary of Simulation results from 6 Star sheet-metal wall system ACR 5

	Simulation result		
Mould Index	**Number**	**Distribution**	**Result**
Nil	0	0%	No mould growth
</=1.0	0	0%	Acceptable level of mould growth
>1.0 to <3.0	2	3%	An amount of mould growth was simulated that requires further investigation
3.0>=	58	97%	Unacceptable amount of mould growth
Total	60	100%	

1. Sensitivity of wall systems

This sensitivity analysis provides a brief exploration of differences that can occur in the bio-hygrothermal simulation results subject to slight variations in the external wall components. This analysis explores the impacts of:

- pliable membrane water vapour diffusion resistivity
- the exclusion and inclusion of a vented cavity between the pliable membrane and the cladding system, and
- the impacts of airtightness.

The base wall system presented in this analysis comprises:

- 10mm paper-faced plasterboard lining
- 90mm insulated timber frame (R2.5)
- 1mm pliable building membrane, and
- 19mm timber cladding.

6.1 Water vapour diffusion resistivity

Figure 16 to Figure 19 explore the impact of the vapour permeability on the potential for mould growth within a wall system. Figure 16 includes an AS4200 Class 1 vapour impermeable pliable building membrane with a water vapour diffusion resistance factor of 1,500,000, which closely resembles many foil-based pliable membrane products. Figure 17 includes an AS4200 Class 3 pliable building membrane with a water vapour diffusion resistance factor of 90,909, which meets the NCC 2019 requirement for a vapour permeable wall membrane in NCC climate zones 6, 7 and 8. Figure 18 includes an AS4200 Class 4 pliable building membrane with a water vapour diffusion resistance factor of 175.4. Figure 19 includes an extremely water vapour permeable pliable building membrane, with a water vapour diffusion resistance factor of 18. It should be noted that an AS4200 class 4 pliable building membrane can have a water vapour diffusion resistance factor from 175.39 to 0. The pliable building membrane simulated in Figure 19 is not available in Australia.

Figure 16 shows that the MI exceeds 3.0 by the fourth year.

Figure 17 shows that the MI exceeds 3.0 the fifth year.

Figure 18 shows that the MI does not exceed 1.0 in the first ten years. However, due to the ever-increasing MI, this wall system would require further investigations.

Figure 19 shows that the MI never exceeds 0.20.

These four bio-hygrothermal simulations show the impact that the water vapour diffusion resistivity of building membranes on an external wall system's ability to diffuse water vapour. They demonstrate that the type of membrane used can significantly impact the likely mould growth in an external wall in the short and long-term.

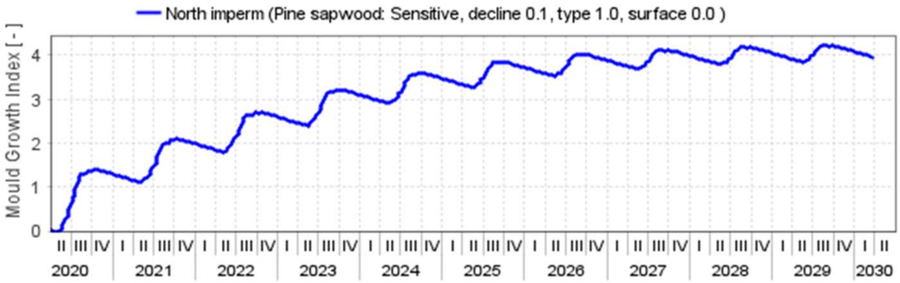

Figure 16: Timber clad wall, northern orientation, NatHERS CZ66, impermeable building membrane

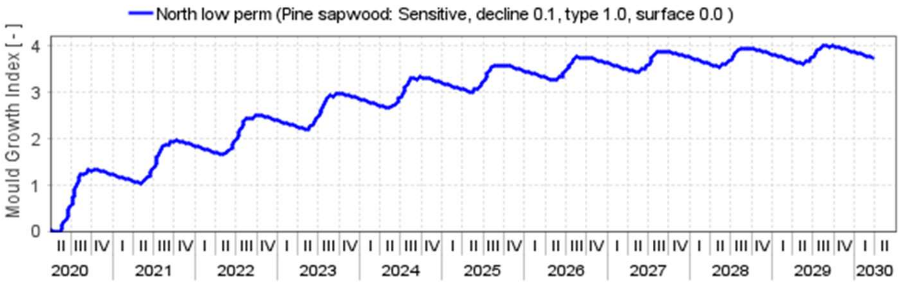

Figure 17: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 3 building membrane

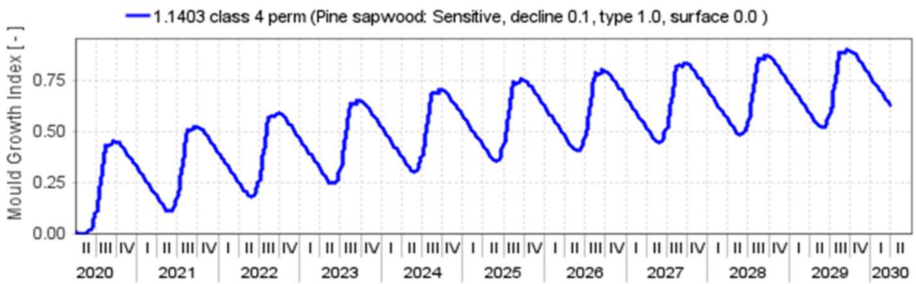

Figure 18: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 building membrane (1.1403 ug/N.s)

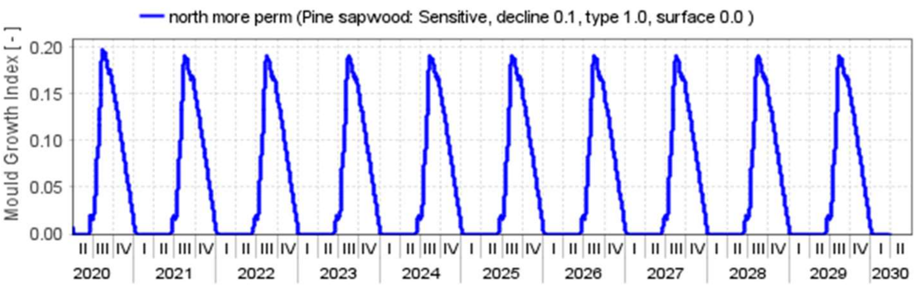

Figure 19: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 extremely permeable building membrane (not available in Australia)

6.2 Impact of vented vapour cavities

Figure 20 and Figure 21 show the impact of a vented cavity, between the pliable membrane and the external cladding system, on the potential for mould growth. In these two simulations, the pliable building membrane represents an AS4200 Class 4 product, with a vapour permeability of 1.1403 ug/N.s.

Figure 20 shows the bio-hygrothermal simulation results for the timber clad wall that does not include a cavity. The MI for this wall system does not exceed 1.0 but is increasing each year and would require further investigation.

Figure 21 is the same wall system but includes a vented cavity, which allows for the mass transfer of water vapour and the drainage of moisture. The MI for this wall system never exceeds 0.1 and is decreasing in value each year.

These two bio-hygrothermal simulations show the impact that a vented cavity , between the pliable membrane and the cladding, has on an external wall system's ability to diffuse water vapour. A well designed and constructed cavity will promote vapour diffusion and moisture drainage.

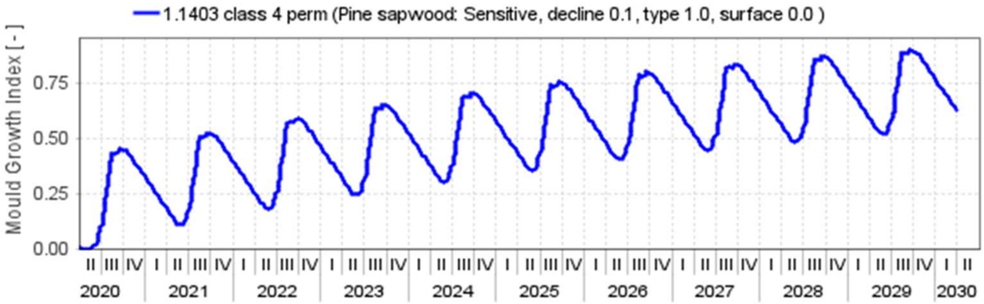

Figure 20: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s)

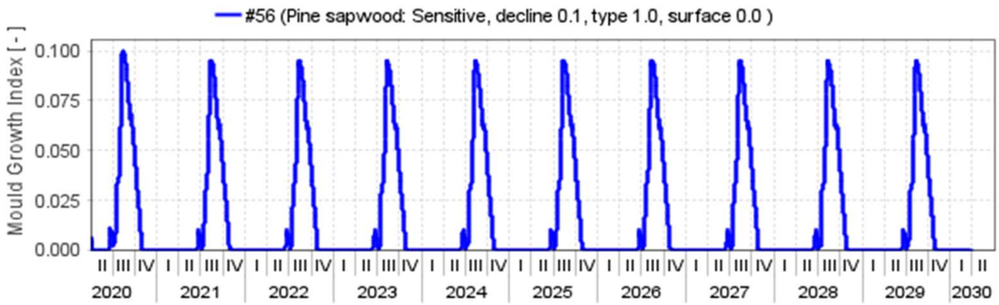

Figure 21: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s)

6.3 Impact of airtightness

Figure 22 to Figure 25 explore the impact of building airtightness on moisture and mould within external wall systems. As homes become more thermally efficient, airtightness plays a critical role for both energy and the control of mould growth. In an old and leaky home, the water vapour was removed by uncontrolled mass transfer. In an energy efficient home, it needs to leave via diffusion and timely ventilation-based mass transfer. Additionally, in temperate climates, as we better insulate our façade systems, the outer layers of the envelope become much colder. The wall system presented in Figure 22 to Figure 25 comprises:

- 10mm plasterboard
- 90mm insulated timber frame (R2.5)
- 1mm AS4200 Class 4 pliable building membrane
- 40mm vented cavity, and
- 19 timber cladding.

Figure 22, which includes an ACR of 15, which is 50% more than expected with a 6 Star house, has a MI of less than 0.0025.

Figure 23, which includes an ACR of 10, the maximum permitted by the verification method in NCC 2019, has a MI just over of 0.20.

Figure 24, which includes an ACR of 7.5, which is common in many new homes [38], has a MI greater than 2.5 and would require further investigation.

Figure 25, which includes an ACR of 5.0, which has been observed in some new homes [38], has an MI greater than 3.0 in the first year.

These four bio-hygrothermal simulations show the impact that the building airtightness has on the internal vapour load that the external wall system must manage. They demonstrate that as a building becomes more airtight, different methods must be used to assist in the management of water vapour within the walls, such that mould growth is not supported. This may include the need for an interior pliable membrane between the plasterboard lining and the insulated timber frame.

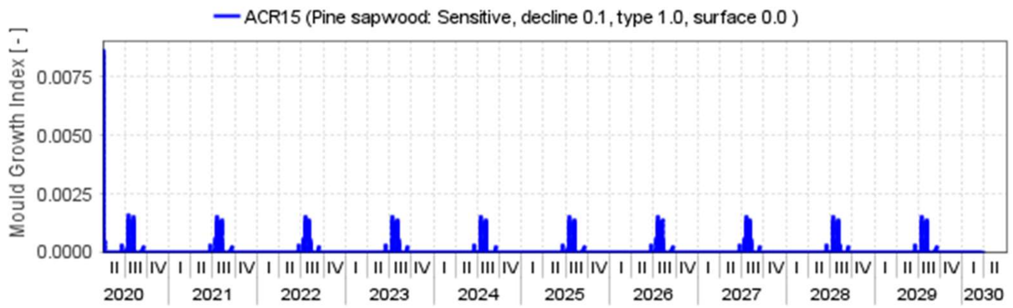

Figure 22: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s) ACR 15

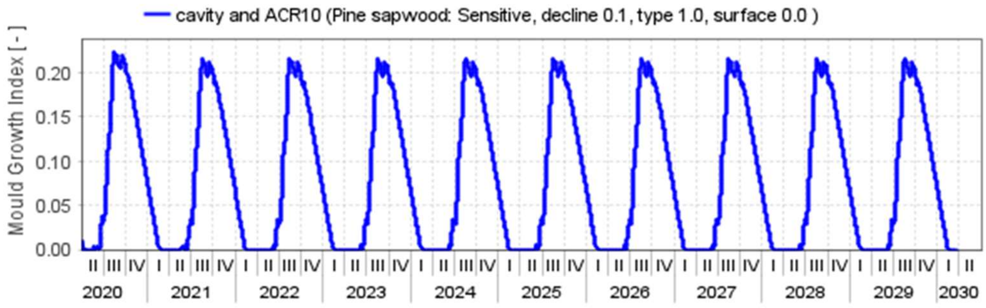

Figure 23: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s) ACR 10

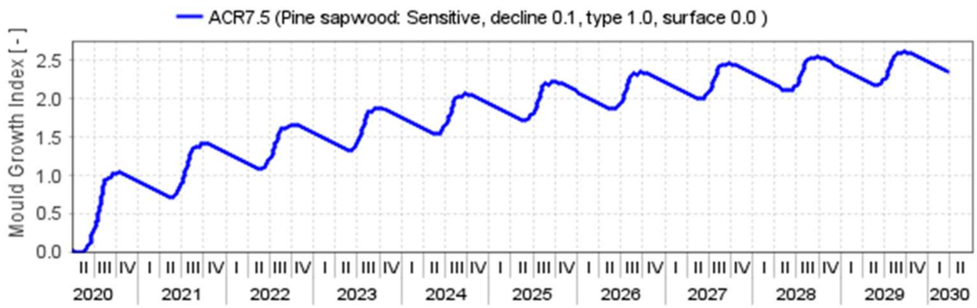

Figure 24: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s) ACR 7.5

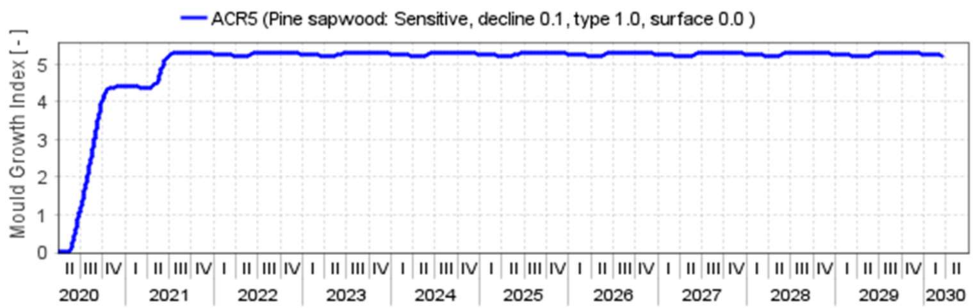

Figure 25: Timber clad wall, northern orientation, NatHERS CZ66, AS4200 Class 4 permeable building membrane (1.1403 ug/N.s) ACR 5.0

6.4 Results Summary

The results section summarises the hygrothermal and bio-hygrothermal simulation of 940 external wall systems within eight if the NatHERS climate zones of Victoria. The nine external wall systems comprised contemporary materials and materials that were compliant with the requirements of the NCC 2019 for 6 Star housing. The simulations applied a heating only parameter, in line with NCC expectations for NCC climate zones 6, 7 and 8 where the average maximum January temperate is less than 30°C, and there are more than 1,000 heating degree days [84]. The heating thermostat setting was 20°C as per the NatHERS protocol. The simulations included 532 with an ACR of 10 and 408 with an ACR of 5. An ACR of 10 is the maximum allowed for a 6 Star home, as specified in the verification method for building sealing [52].

The hygrothermal simulation of most wall systems showed no moisture accumulation. Where moisture accumulation was simulated, it was within the boundary of exterior cladding and acrylic render systems.

Of the 532 bio-hygrothermal simulations with an ACR of 10:

- 299 showed a MI of nil or less than 1.0
- 119 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation, and
- 114 showed a MI of 3.0 or more, indicating that these methods of construction may be climatically inappropriate.
- Of the 408 bio-hygrothermal simulations with an ACR of 5:
- 21 showed a MI of nil or less than 1.0
- 63 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation, and
- 324 showed a MI of 3.0 or more, indicating that these methods of construction may be climatically inappropriate.

The results of the simulations of the nine external wall systems in 14 to 15 NatHERS climate zone and built fabric variables, with an ACR of 10, showed that:

- the timber clad system had one NatHERS climate zone where all four orientations had an acceptable MI
- the compressed fibre cement sheet clad system had nil NatHERS climate zones where all four orientations had an acceptable MI
- the clay masonry veneer system had five NatHERS climate zones where all four orientations had an acceptable MI
- the concrete block, internally insulated, system had three NatHERS climate zones where all four orientations had an acceptable MI
- the externally insulated clay masonry system had two NatHERS climate zones where all four orientations had an acceptable MI

- the extruded polystyrene clad system had fifteen NatHERS climate zones where all four orientations had an acceptable MI
- the expanded polystyrene clad system had fifteen NatHERS climate zones where all four orientations had an acceptable MI
- the autoclaved aerated concrete cladding system had four NatHERS climate zones where all four orientations had an acceptable MI, and
- the flat pan metal cladding system had nil NatHERS climates zones where all four orientations had an acceptable MI.

From these simulations some pertinent matters are evident.

Orientation and shading

Due to the radiation influenced drying potential, the northern orientation for many scenarios showed a nil mould growth index, whilst other orientations of the same wall system ranged from requiring further analysis to an unacceptable mould growth index. The NCC 2019 (and the NCC 2022) does not differentiate construction methods based on orientation. Within this context, it should be a requirement to able to be demonstrated to relevant parties that the southern orientation has an acceptable MI prior to construction approval. At this stage the aspect of wall orientation and its corresponding impact on moisture and mould is not addressed adequately within the NCC 2019 (and NCC 2022). This report provides evidence that many external wall systems, built in full compliance with NCC 2019 requirements, can result in unacceptable levels of mould. Furthermore, if an eastern, northern or western external wall system is shaded by a nearby structure, verandah, eaves, or landscaping, its hygrothermal performance will be closer to that of the southern orientation, rather than its actual orientation.

Cladding insulation properties

The extruded and expanded polystyrene cladding systems performed well under the ACR 10 scenario. This is due to their insulation properties. Externally insulated façade systems have been internationally identified as the most suitable forms of moisture and mould free construction. However, as building airtightness increases there is a need for additional vapour control measures, as was made evident by the ACR 5 bio-hygrothermal simulation results.

Hygrothermal buffering

The externally insulated clay masonry (reverse brick veneer) internally insulated concrete block and autoclaved aerated concrete external wall systems had a marginally better performance than the timber, compressed fibre cement sheet and flat metal cladded external wall systems due to their ability to act as a hygrothermal buffer. Hygrothermal buffers are materials that can adsorb water vapour, which can reduce the vapour pressure on boundary materials. Cross laminated, mass-timber and concrete elements are known for their hygrothermal buffering properties.

Water vapour diffusion resistivity

The simulations included NCC climate zone 4, which allows for the use of vapour impermeable membranes. Some of these wall systems with a vapour impermeable membrane performed worse than their NCC climate zone 6 and 7 counterparts (that required the use of a AS4200 Class 3 vapour permeable membrane). The sensitivity analysis in Section 4.10 showed the bio-hygrothermal simulation results from a wall system with vapour permeable AS4200 Class 1, Class 3 and Class 4 products, and a wall system with an extremely vapour permeable Class 4 product (though this latter product is currently not available in Australia). The MI decreased significantly as the pliable membrane vapour permeability increased. 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 require a vented cavity. Within this research, the only external walls that included a vented cavity space were the clay masonry veneer and the externally insulated clay masonry wall systems. The sensitivity analysis within Section 5.10 included two simulations of a timber clad wall system. The simulation that included no cavity had a MI requiring further investigation, whilst the system that included a cavity had a MI of less than 1.0. Internationally, cavities are required for many external wall systems. In Australia, this aspect needs more analysis and should be the focus of further analysis and development, to reduce the risk of unacceptable levels of mould growth in external wall systems.

Airtightness

The NCC 2019 has a performance requirement that a new 6 Star home have an airtightness value not greater than ACR 10. This value has been used as a baseline for all simulations. However, governments, practitioners and homeowners have spent the last two decades exploring how to improve the airtightness of homes. As a result, many new homes have an ACR less than 10 [38]. The sensitivity analysis in Section 4.10 included four simulations of a timber clad wall system which includes an AS4200 Class 4 permeable pliable building membrane. The simulations for the nine external wall systems included an ACR of 10 and an ACR of 5. All the simulated external wall systems showed a significantly higher MI for ACR of 5, when comparted to and ACR of 10. Many of these wall systems showed an MI of 3.0 or more in all scenarios.

The sensitivity analyses further extrapolated the effect of airtightness by showing an external wall system simulated with an ACR of 15, 10, 7.5 and 5. Whereas the wall with an ACR of 15 showed a minimal MI, for each step in reduced ACR (improved airtightness), the MI increased from less than 1.0 to more than 3.0. Other nations have required other measures, such as interior pliable membranes, to control water vapour entry into external wall systems. As the envelope insulation and air tightness measures increase, a more comprehensive method to manage water vapour diffusion through external walls will be required.

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 water vapour diffusion resistivity value of a material is higher than what has been simulated, the element may then trap more water vapour within the wall system leading to mould growth and/or moisture accumulation.

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%, This would create a greater mould growth risk than what the software can simulate.

The NatHERS climate zone data used in the research has applied average climate data. Simulations that include extreme weather events would create different moisture accumulation and mould growth results.

If a home was heated to more than 20°C, the vapour load within the home would increase.

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 more or less leaky, or may allow for the ingress of moisture.

The last four 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 first stage of the research project was to examine if a ‘code-compliant’ external wall system for a Class 1 and 2 buildings constructed in accordance with NCC 2019 requirements, located with Victoria may or may not promote moisture accumulation and/or mould growth.

The research presented here shows that aside from a few exceptions, the simulated wall systems with an ACR of 10 did not support or promote moisture accumulation.

However, the bio-hygrothermal simulations to ascertain if there is a risk of unacceptable mould growth presented a very different result. This report shows that 233 of the 532 walls simulated (44%) with an ACR of 10 had an MI greater than 1.0, requiring the need for a more detailed analysis, or an unacceptable MI of 3.0 or more. This indicates that these wall systems, constructed in this manner may be climatically inappropriate.

When the ACR was reduced from ACR 10 to ACR 5, to simulate the more likely airtightness of new homes in Victoria, 387 of 408 walls simulated (95%) showed the need for a more detailed analysis or an unacceptable MI. This indicates that these external wall systems, constructed in this manner may be climatically inappropriate.

In all cases the southern oriented external wall systems showed the greatest mould growth index, which leads to two branches of recommended further activity, namely research and regulatory intervention.

6.1 Research

Each of the 6 Star external wall systems simulated in this research needs to be designed and constructed in a manner such that the southern orientation shows either nil, or less than 1.0 Mould Index. This would include the specification of pliable building membrane water vapour diffusion resistance properties and the inclusion of a vented cavity for most external wall systems.

The next stage of the research includes 7 Star external wall systems. The data gained from the 6 Star external wall system hygrothermal and bio-hygrothermal simulations is to be applied to the 7 Star wall systems.

The climate data used in this research was sourced from the NatHERS climate database. This aspect of suitable climate data for hygrothermal simulation needs further research, to ensure that the data being used to simulate hygrothermal and bio-hygrothermal processes is suitable and appropriate.

Further research must consider various aspects of airtightness and the climatically appropriate envelope elements to control water vapour diffusion such that concerning amounts of, or unacceptable amounts of mould growth do not occur.

6.2 Regulatory Intervention

A significant education program needs to be undertaken to inform the design and construction professions of the risks evident in the simulation results. Since 2014, the Tasmanian government has actively engaged with the design and construction professions via training activities and two editions of the Tasmanian condensation design guide.

As identified in this research, and the experiences in Europe, United Kingdom, North America, Japan and New Zealand, there is a need for the coordinated co-development of regulations regarding building envelope thermal performance and hygrothermal design.

7. List of Appendices

Appendix 1: Detailed hygrothermal input data

Appendix 2: Hygrothermal simulation results – Timber cladding

Appendix 3: Hygrothermal simulation results – Compressed fibre cement sheet cladding

Appendix 4: Hygrothermal simulation results – Clay masonry veneer

Appendix 5: Hygrothermal simulation results – Concrete block, internally insulated

Appendix 6: Hygrothermal simulation results - Externally insulated clay masonry

Appendix 7: Hygrothermal simulation results – Extruded polystyrene cladding

Appendix 8: Hygrothermal simulation results – Expanded polystyrene cladding

Appendix 9: Hygrothermal simulation results - Autoclaved aerated concrete cladding

Appendix 10: Hygrothermal simulation results – Flat metal cladding

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