UNIVERSITY of TASMANIA

MOISTURE ACCUMULATION AND MOULD GROWTH FOR 7 STAR HOUSING IN VICTORIA

Research Report 2

Report authors: Dr Mark Dewsbury and Freya Su

Revision 04- 9 Dec 2022

Contents

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of this method and the development of building pressurisation testing in the 1970s, this method has generally been replaced by the ACR method.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^{0}C, and the relative humidity is 75%: Td = T – ((100 – RH) / 5) Td = 23 – ((100 – 75) / 5) Td = 18.0^{0}C

	Moisture will form on any surface within the room that is less than, or equal, to 18.0^{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
NatHERS portal	The NatHERS portal collects data regarding all Class 1 and Class 2 buildings that receive a Universal Certificate. Data includes a range of building materials and properties.
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 of Building Physics (IBP). The Fraunhofer Institute is very similar in nature to the CSIRO in Australia. The WUFI software has undergone empirical validation in Europe, United Kingdom, Canada and the United States of America.
WUFI VTT	The WUFI software includes internationally tested and empirically validated 'add-ons' for graphing data, mould risk and corrosion risk. The WUFI VTT acronym stands for the WUFI software that incorporates the VTT Technical Research Centre of Finland's mould growth calculation method developed by Hannu Viitanen and Tuomo Ojanen.

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 building regulations. This research activity is conducted in response to national and Victorian concerns about the increased presence of moisture and mould within new buildings. The activities within this research project include the hygrothermal simulation-based assessment of mould growth risk in regulatory compliant 6 Star and 7 Star new homes in Victoria. The full Moisture Accumulation and Mould Growth research 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,
- Research report 2 - Moisture accumulation and mould growth risk for 7 Star housing (this report),
- 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 mould growth risks that may be present in the external walls of Class 1 and Class 2 buildings, as constructed to the 7 Star energy efficiency standard and the health and amenity requirements of National Construction Code (NCC) 2022. This report highlights problems that may presently exist. Research Reports 3 and 4 will explore options to mitigate these risks.

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 [1-3]. 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 [4, 5]. 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 may be poorly ventilated).

This shows that mould growth occurs well before condensation occurs and also that a house may have no presence of condensation but have the visible and unhealthy presence of mould. The World Health Organisation states that the visible presence of mould within buildings has been linked to increases in medical conditions [6].

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.

This research was supported by the Victorian Building Authority through a research grant in association with financial and project advisory committee support from:

Dr Dong Chen (CSIRO)

Dr Phillip Alviano (Master Builders Association of Victoria)

Dr Alastair Woodard (Forest and wood Products Australia)

Prof. Hartwig Kuenzel (Fraunhofer Institute for Building Physics IBP)

The content represents the technical judgement of the authors and not necessarily that of the project sponsors.

1. Executive Summary

In 2008, the first meeting in response to New Zealand's 'wet-buildings' syndrome phenomenon [7-11] and the potential for parallel risks in Australia occurred between the University of Tasmania architectural science 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. Research Report 1 highlighted research showing that 40% of 2,662 survey responses from Australia's design and construction professions [5] found a concerning presence of condensation and/or mould in Class 1 and Class 2 buildings constructed between 2006 and 2016. The research report for that project included the statistical analysis of survey responses and a review of international experiences and regulatory development in other OECD nations. This report provided the Australian Building Codes Board with initial principles for regulatory consideration. This included a cost-benefit analysis and prioritisation of report recommendations [5].

As Tasmania has some of Australia's coolest climates, condensation and mould problems started appearing from 2010. Informal communications with members of the design and construction community of Victoria indicated that similar condensation and mould problems were becoming evident in Victoria. In Tasmania, the State's building regulator identified the need for 'better-than-code' design and construction guidance for the design and construction professions [12-16]. This led to an ongoing research program exploring theoretical and applied methods to understand the problems and recommend better design and construction practices [17-19]. The climates within Victoria range from somewhat milder than Tasmania through to Alpine climates. Where condensation and mould problems do already exist in 6 Star housing, it is likely that if building practices do not change, these problems will increase as houses become warmer, for longer periods of time, to meet the heating and cooling energy requirements of 7 Star Class 1 and Class 2 buildings.

Within this context, the aim of this research was to ascertain if an external wall system was constructed to achieve a 7 Star NatHERS simulation result, would the external wall system 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 594 hygrothermal, and 594 bio-hygrothermal simulations, of nine contemporary residential wall systems, within eleven Victorian NatHERS climates, with two NCC 2022 variations in pliable wall membrane variable (NCC 5 to 8, and NCC 2 to 4), and with an Air Change Rate of 10 (the maximum allowable for a 7 Star home), an Air Change Rate of 7.5 (as many homes are more airtight than an ACR of 10) and an Air Change Rate of 5 (which is the minimum permitted before mechanical ventilation should be installed).

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. 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 water vapour diffusion and ventilation and water drainage.
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 that significantly impact human health [1, 2, 20]. 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 3.0 or more [21, 22]. An MI of 3.0 or more is defined as having a visible presence of mould [23].

Of the 396 walls simulated with an Air Change Rate of 10, the maximum permissible building leakage (infiltration and exfiltration) rate within NCC 2022, 120 (30%) showed the need for a more detailed analysis or an unacceptable mould growth index. This indicates that nearly 30% of these external walls systems may be constructed as per the NCC 2022 requirements for Energy Efficiency (insulation & airtightness) and Health and Amenity (condensation) for Class 1 and 2 buildings [24-26]and may pose a high risk of an unacceptable level of mould growth.

Of the 99 walls simulated with an Air Change Rate of 7.5, which may better represent the airtightness of many Class 1 and Class 2 buildings, 79 (80%) showed the need for a more detailed analysis or an unacceptable mould growth index. This indicates that more than three quarters 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.

Of the 99 walls simulated with an Air Change Rate of 5 (the minimum permissible building leakage rate for infiltration and exfiltration before mechanical ventilation is required), 97 (98%) showed the need for a more detailed analysis or an unacceptable mould growth index. This indicates that nearly all 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 the three scenarios described above, there is reference to walls requiring further analysis. This indicates that the bio-hygrothermal simulation calculated a Mould Index greater than 1.0 but less than 3.0. 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, the hygrothermal and bio-hygrothermal simulation results may be quite conservative. This is the reasoning behind the DIN4108 [21] and ASHRAE Standard 160 [22] recommendations that further analysis is required, which would explore in greater detail the exterior and interior environmental factors and construction material properties.

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 7 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. 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.

3. 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.

4. A coordinated approach by the ABCB, NatHERS Administrator, appropriate researchers, and industry-based representatives, for the co-development of energy efficiency and hygrothermal regulations.

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

In 2010, the minimum performance requirement within the Building Code of Australia (BCA) was increased from a 5 Star to a 6 Star requirement [31]. The 2022 NCC has included a minimum 7 Star requirement for new Class 1 and Class 2 buildings. Each increase in NatHERS Star rating reflects a reduction in the estimated energy needs for household heating and cooling. Table 1 below shows the 2022 Star bands for the NatHERS climate of Melbourne. The values within the table are megajoules per square metre per annum (MJ/m^2.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. This shows that the improvement from 6 Stars to 7 Stars requires a 23.5% reduction for simulation-based energy to heat or cool a home. The 23.5% reduction in heating and cooling energy consumption relies on creating a more thermally efficient building envelope, which increases the differences between the interior and exterior surfaces of the external wall system.

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

	Estimated cooling/heating energy	Estimated energy reduction	Estimated energy reduction
1 Star	451		
2 Stars	302	149	33.0%
3 Stars	207	95	31.5%
4 Stars	128	79	38.2%
5 Stars	111	17	13.3%
6 Stars	85	26	23.4%
7 Stars	65	20	23.5%
8 Stars	45	20	30.8%
9 Stars	26	19	42.2%
10 Stars	11	15	41.7%

Research Report 1 included a simplified equation, as shown below, which can be used to calculate when the moisture in the air will condense under varying temperature and humidity conditions.

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

Table 2 below shows some dew point temperatures for different interior conditions. Three temperature conditions and three relative humidity conditions are shown. The three temperature conditions represent:

- 20°C: the NatHERS thermostat set point for the minimum temperature in living rooms and kitchens [32],
- 21°C: representing international benchmarks for household heating and cooling [21, 22, 33, 34], and
- 23°C: representing the average measured temperature in new homes [14, 35, 36].

The three relative humidity conditions represent:

- 60% RH: the generally accepted maximum for ducted mechanical air-conditioning in office spaces [37, 38],
- 70% RH: representing values measured in many Australian homes and [4],
- 80% RH: representing values measured in many Australian homes, and the maximum accepted value in some countries before automated mechanical ventilation is required [21, 22].

What this data shows, for example, is that when a room is conditioned to 23^0C and the relative humidity is 70%, any surface that is thermally bridged (glass, window frame, structural framing, gaps insulation, air leakage, etc) and has a temperature of ≤17^0C, will have moisture condense out of the air onto thermally bridged surfaces. This is commonly observed on single glazing windows during winter. In the context of Victoria, the outdoor temperature is often 15^0C or less.

Table 2: Examples of dewpoint temperature for conditioned interiors

Temperature (T^0C)	Relative Humidity (RH%)	Dew point T (Td^0C)
20	60	12
20	70	14
20	80	16
21	60	13
21	70	15
21	80	17
23	60	15
23	70	17
23	80	19

One of the less visible, quite destructive, and significantly impacting human health effects from moist housing are mould growth and mould spores within habitable spaces. Figure 1 shows the three conditions that support mould growth, namely relative humidity, temperature, and nutrients [39]. The greyed in section highlights the typical interior conditions for relative humidity and air temperature. Research Report 1 included data regarding the temperature and relative humidity conditions within Australian homes and highlighted the ideal mould supporting temperature and humidity conditions that were evident. The nutrient component within homes is provided by the dust that is created by human occupation. Within the interstitial spaces, materials like timber and construction dust also provide nutrients for mould growth. Most mould growth calculation methods require the selection of a construction system, which then allocates value for available nutrients for mould growth.

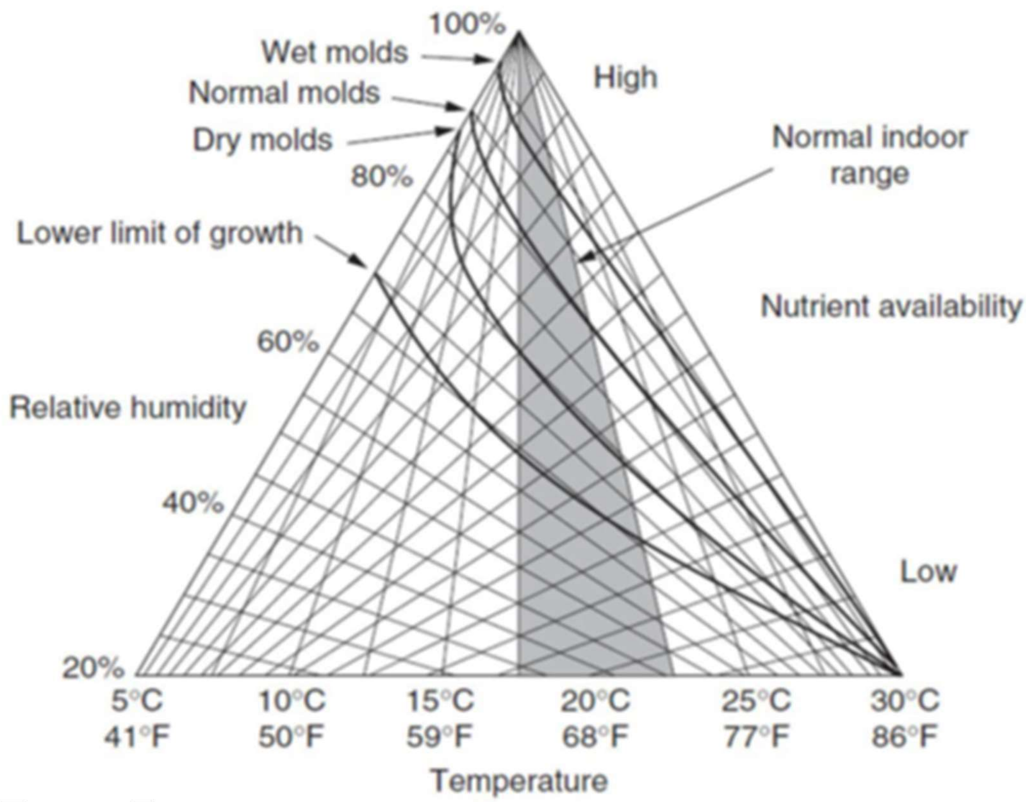

Figure 1: Conditions that support mould growth [39]

Within the Australian regulatory context, there were no regulatory requirements limiting condensation or mould until NCC 2019 [40, 41]. The first performance requirements and acceptable construction methods, designed to address condensation and mould were introduced in 2019 [40, 42], and only applied to Class 1 and Class 2 buildings in NCC climate zones 6, 7 and 8. Other developed nations have been establishing standards and regulations for more than 50 years [21, 33]. The NCC 2022 has enhanced some requirements and included more NCC climate classifications.

The NCC 2019 condensation and mould performance requirement has changed within NCC 2022 from a focus on moisture, as described in Research Report 1, to a focus on mould growth:

Compliance with Performance Requirement F8P1 is verified for an external wall assembly when it is determined that a mould index of greater than 3, as defined by Section 6 of AIRAH DAO7, does not occur on interior, exterior or interstitial surfaces of components of the building fabric, from the 5th year after construction onwards.

The water vapour diffusion properties of pliable building membranes have also been expanded to include:

(a) in climate zones 4 and 5, 0.143 µg/N.s: and

(b) in climate zones 6, 7 and 8, 1.14 µg/N .s.

These enhanced requirements for external wall systems are starting to better reflect the responses to the 2016 nation-wide condensation survey [5]. As Victoria includes NCC climate zones 4, 6, 7 and 8, these enhanced clauses now require pliable external wall membranes (when used) to have some form of water vapour permeance. The water vapour permeance values of 0.143 µg/N.s and 1.14 µg/N.s. refer to Class 3 and Class 4 properties, as described in AS4200 [43]. Table 3 shows data from AS4200 in µg/N.s and the equivalent converted water vapour diffusion resistance factors, which are used by the hygrothermal simulation software.

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

Class	Vapour Category	Min (≥) µg/N.s	Max (<) µg/N.s	Water vapour diffusion resistance factors	
				Max	Min
Class 1	Vapour barrier	0.0000	0.0022	No Maximum	90,909.0
Class 2	Vapour barrier	0.0022	0.1429	90909	1399.6
Class 3	Vapour permeable	0.1429	1.1403	1398.6	175.4
Class 4	Vapour permeable	1.1403	No maximum	175.4	No maximum

As discussed in Research Report 1, buildings located in temperate and cool-temperate Australia are increasingly warmer and more humid on the inside. Based on an understanding of the conditions for dew-point temperature, it must be accepted that (a) condensation will occur somewhere within the built fabric, and (b) subject to the amount of condensation that occurs, and its ability to return to a vapour form, this moisture may pose a long-term structural risk. However, as shown in Figure 1, well below the dew point condition (100%RH), mould will grow, and to date Australia has no regulatory requirements regarding the control of relative humidity within buildings. Since the 1990s, and as presented in Research Report 1, recommendations like those shown in Table 4 below have been established in other OECD nations [21, 22, 33, 44, 45].

Table 4: Condensation control strategies for the building envelope

Strategy	**Aim**	**Measure**
Management of moisture entry	Reduce air leakage	Air control layers
	Limit vapour diffusion	Vapour control layers
	Reduce moisture ingress	Water control layers
Control of moisture build-up	Increase the temperature of the condensing surface	Insulation on the exterior side of the condensing surface

	Permit accumulation which does not impact built fabric	High moisture capability at the condensing surface
Strategy	**Aim**	**Measure**
	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 hygrothermal and bio-hygrothermal simulation programs, that have been developed by a government funded research organisation, Fraunhofer Institute of Building Physics Germany, and has been empirically validated and improved over more than 25 years [46].

3. Hygrothermal analysis

Research Report 1 includes an introduction to hygrothermal analysis. This research adopts world leading transient (or dynamic) heat and moisture calculation methods. Please refer to Research Report 1 for detailed discussion of moisture and mould growth calculation methods. This form of hourly analysis calculates the inward and outward energy and moisture flows caused by conduction, convection, radiation, and water vapour pressure differentials. The water vapour pressure between the interior and exterior environments is continuously trying to achieve equilibrium.

Table 5 shows the calculated water vapour pressure for different temperature and relative humidity conditions. If the interior of a home is kept between 21°C and 80% RH, the interior water vapour pressure ranges from 1,496 Pascals to 2,194 Pascals. The two lowest rows have temperature and relative humidity values which are quite common external environmental conditions in Melbourne, where the mean minimum and maximum temperatures is 10.2°C and 19.9°C respectively, whilst the mean relative humidity is 56% [47]. The water vapour pressure for these two conditions are 758 and 1,001 Pascals. This highlights that a water vapour pressure differential of 1,436 Pascals could exist between the interior and exterior environments. This process is forcing water vapour into the interstitial spaces, where it may be adsorbed by construction materials or continue to diffuse outward. The aim of water vapour permeable design is to eliminate materials that may restrict the ability for water vapour to leave the built fabric without causing mould growth and/or higher amounts of moisture coalescing and accumulating within the built fabric.

Table 5: Water vapour pressure for different temperature and relative humidity conditions

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

This hourly hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) calculation over a ten-year period can identify simulation-based risks, exploring:

- Is there any moisture accumulation that would affect the durability of the timber framing and other materials within external envelope systems (floors, walls and roofs)?
- Is there a significant amount of the relative humidity condition above 70% that may support mould growth on, or within, the envelope system (floors, walls and roofs)?

The development of calculation methods for mould growth generally occurred between 1940 and 1968 [48]. This period also included the development of the optical evaluation of rates of mould growth, which became known as the Mould Index. These methods were further refined in the 1990s to assess the individual susceptibility of different construction materials, for example pine versus plasterboard. The VTT Technical Research Centre of Finland, was at the forefront of developing calculation methods and applying these to timber elements that are used in the construction of buildings [48-52]. These methods were then incorporated into BETA versions of transient hygrothermal software to estimate mould growth risk in 2005 [53]. Within the development of the WUFI suite of simulation tools, this became known as WUFI BIO, and was further improved over the following fifteen years. Recognising some of the limitations of WUFI BIO, software developers and hygrothermal researchers from Fraunhofer IBP and VTT Finland worked together to develop WUFI VTT [23, 54, 55].

The mould growth index (MI) has been recognised as the most appropriate metric for optical classification of mould growth. The principles of the mould growth index are explored in more detail in Research Report 1. Table 6 shows the different MI values and their optical properties. The World Health Organisation has published recommendations that no interior environment occupied by people should have a visible presence of mould [56]. Recognising this human health risk Germany, the United Kingdom, Canada and the United States of America have included requirements that the calculated, or simulated, MI is <3.0 for a period of ten years [21, 22, 33]. Within this research report, time series graphs have been used to show the calculated mould growth risk relative to the calculated Mould Index, over a ten-year simulation period.

Table 6: Mould growth index (MI) [49]

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%

4. Methodology

As described in Research Report 1, this research has used the WUFI Pro software for hygrothermal simulation and the WUFI VTT add-on for bio-hygrothermal simulation. The methodology adopted in this research combines the consideration of NatHERS thermostat settings, combined with a collaborative method established by Nath and researchers from the Fraunhofer Institute of Building Physics in 2019 [57, 58]. 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 has published DA-07- Criteria for moisture control in buildings [59], which is very similar to the ASHRAE standard of the same name [22]. The methodology described within ASHRAE Standard 160 and AIRAH DA-07 follow the same principles and parameters. Finally, the method described below only applies to the report - Research Report 2: Moisture accumulation and mould growth for 7 Star housing in Victoria.

4.1 External wall types

As described in Research Report 1, nine external wall types that are in commonly used in Class 1 and Class 2 buildings in Victoria were selected. The wall types are shown in Table 7.

Table 7: 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. The properties of this wall system are very similar to those of a precast concrete wall used in Class 2 construction.	Yes
5	Externally insulated clay masonry 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

The amount of insulation included in each of these 7 Star external walls systems is discussed below in section 4.4.

s the NCC classes Victoria as a heating only climate, the bulk of simulations only consider the impact of heating, whilst future research will consider impacts from heating and cooling.

The NatHERS thermostat settings differ from other international recommendations. Whereas NatHERS [32] has a 20°C heating thermostat setting, ASHRAE 160 and DIN4108 [21, 22] have a 21°C thermostat setting. Even though an interior thermostat setting of 21°C would provide a greater hygrothermal risk, this research has adopted the 20°C thermostat setting from NatHERS.

The ACR for the bulk of simulations has applied the maximum allowable value of ACR 10, as described in NCC 2022. Recognising that many new homes are more airtight than the minimum, the sensitivity analysis also explores the increased risk that may occur for ACR 7.5 and ACR 5. If a house has an ACR of <5, it is required to have mechanical ventilation.

4.2 External climate data

Research Report 1 identified eight (8) NatHERS climate types which accounted for most areas of development where Class 1 and Class 2 buildings may be constructed. A summary of this data is shown in Table 8. The climate types also need to overlay with the Climate classifications within the NCC. Figure 2 shows the ABCB NCC climate map for Victoria, which includes NCC climate zones 4, 6, 7 and 8. As mentioned above, NCC 2022 requires an AS4200 Class 3 membrane for NCC climate zone 4 and a Class 4 membrane for NCC climate zones 5 to 8.

Table 8: NatHERS climate zones selected for simulation

NatHERS climate zone	Source of NatHERS 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%

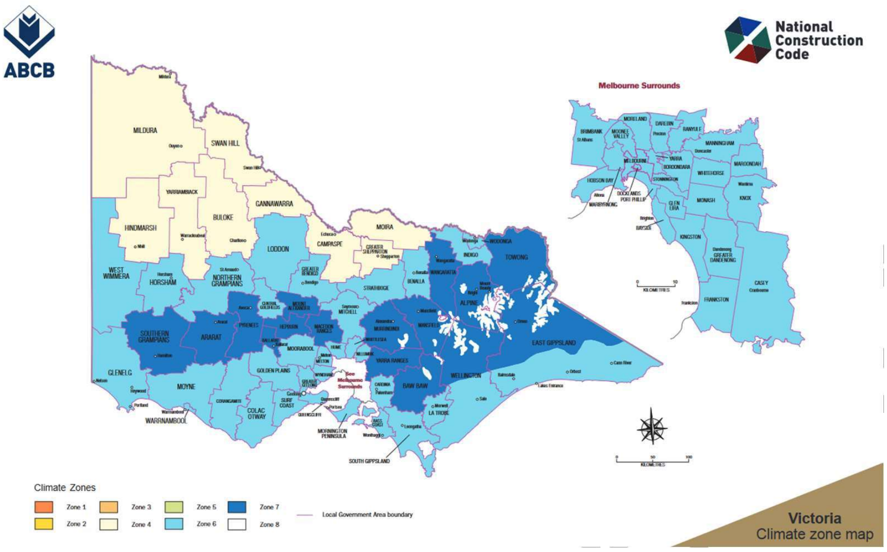

Figure 2: ABCB NCC Climate map for Victoria (ABCB 2022)

4.3 Interior Climate

The interior climates selected in this research adopted many of the principles outlined in ASHRAE Standard 160 [22], which is referenced by AIRAH DA-07 [59], that has been listed as a referenced document within the NCC 2022 [24-26].

Key parameters which were applied are shown in Table 9. The table includes two layers of simulation, namely bulk simulation input, which applies to all wall systems in all orientations and a sensitivity analysis based on air change rates (ACR). Research Report 1 clearly documented the higher calculated moisture and mould risks that were evident for all wall systems when they had a southern orientation. As the southern orientation poses the greatest risk, the ACR sensitivity analysis was only completed for the southern orientation.

Table 9: Key internal climate inputs

Aspect	Bulk simulation input		Sensitivity Analysis	
Mode of operation	heating only		Heated and cooled	
Floating temp	Based on sum of cooling - heating		Based on sum of cooling - heating	
Cooling thermostat (^{0}C)	NatHERS CZ	Cooling	NatHERS CZ	Cooling
	21	24.0	21	24.0
	22	23.0	22	23.0
	27	25.0	27	25.0
	60	24.0	60	24.0
	61	23.5	61	23.5
	63	23.0	63	23.0
	64	23.0	64	23.0
	66	23.5	66	23.5
Heating thermostat (^{0}C)	20.0		20.0	
Air exchange rate	User defined – 0.5 (=10 ACR)		User defined – 0.375 (=7.5 ACR)	
			User defined – 0.25 (=5 ACR)	
Relative humidity cap	70%		70%	

As the NCC classes Victoria as a heating only climate, the bulk of simulations only consider the impact of heating, whilst future research will consider impacts from heating and cooling.

The NatHERS thermostat settings differ from other international recommendations. Whereas NatHERS [32] has a 20°C heating thermostat setting, ASHRAE 160 and DIN4108 [21, 22] have a 21°C thermostat setting. Even though an interior thermostat setting of 21°C would provide a greater hygrothermal risk, this research has adopted the 20°C thermostat setting from NatHERS.

The ACR for the bulk of simulations has applied the maximum allowable value of ACR 10, as described in the NCC 2022. Recognising that many new homes are more airtight than the minimum, the sensitivity analysis also explores the increased risk that may occur for ACR 7.5 and ACR 5. If a house has an ACR of <5, it is required to have mechanical ventilation.

4.4 Sample house plan and external wall design

In this research, a house plan that has been used for several building thermal performance and hygrothermal analysis projects, and Research Report 1 [4, 17, 19]. 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 152.5m^2, with an interior volume of 366m^3.

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 interior water vapour pressure, and a larger four-bedroom house or apartment would have a lower interior water vapour pressure.

Figure 3: Three-dimensional representation of the house

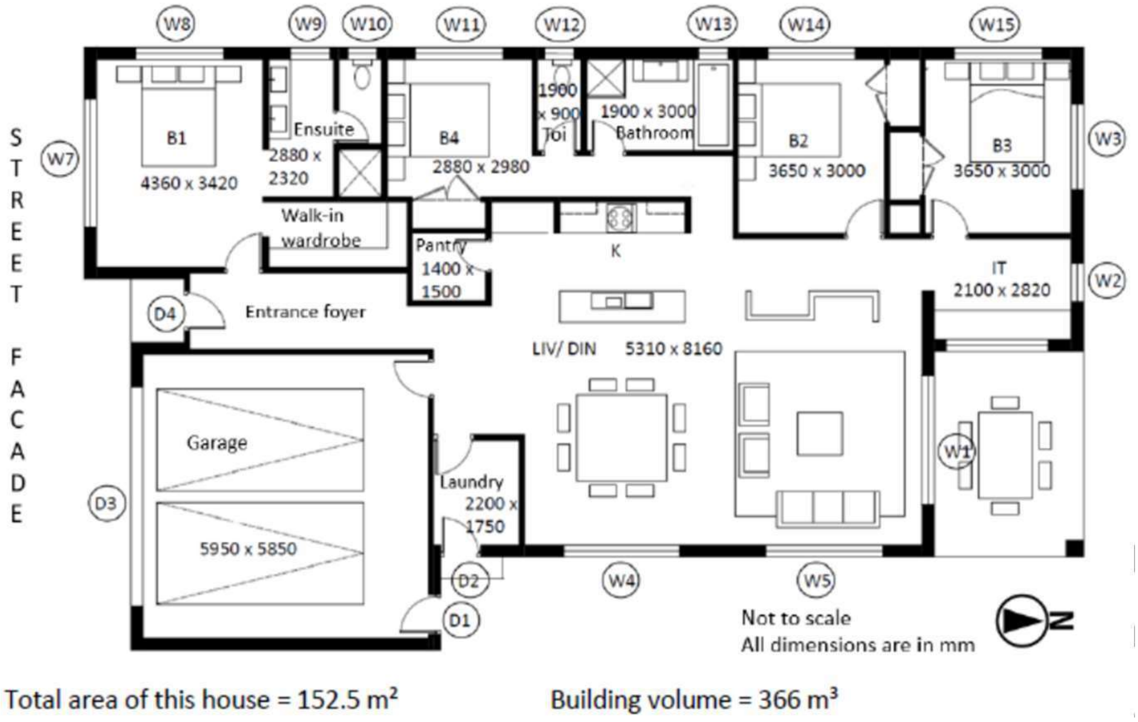

Figure 4: House plan (Not to scale)

To ascertain the amount of wall insulation that may be required for a 7 Star home, data from the NatHERS portal and advice from the project advisory committee was combined to establish a staged process. The data from the NatHERS portal identified that the insulation levels for many 7 Star designs was similar to that of 6 Star designs. The data from the portal also identified a lessening of the glass to floor area and an increased use of double glazing. As a comparison, when the minimum requirement of 6 Stars was adopted, most jurisdictions identified a reduction in the glass to floor area between 5 Star housing and 6 Star housing. This reduction appeared to be in response to managing the levels of wall insulation that may be required. For this report, two variations of 7 Star glazing were explored. Recognising that designers and builders will reduce glass to floor area ratios for 7 Star housing, the bulk of hygrothermal simulations adopted the wall systems that obtained a 21% glass to floor area ratio. A select group of southern orientated wall systems that included a 27% glass to floor area ratio were simulated to understand what challenges may exist with a higher insulated external wall system. The staged process that was used to quantify the amount of insulation on the external wall systems used the following methods:

Step 1: 6 Star 27% glass to floor area base model - Model the house plan, shown in Figure 4, with the AccuRate NatHERS accredited software. Include single glazing and standard wall and ceiling insulation products. This included single glazing and standard wall and ceiling insulation products, and ceiling batts and wall batts up to a value of R8.0 and R2.7 respectively. In most cases this achieved a 6 Star NatHERS result.

Step 2: 7 Star 21% glass to floor area base model - Model the house plan, shown in Figure 4, with the AccuRate NatHERS accredited software. Wall and ceiling insulation were increased to maximum values of R2.7 and R6.0, respectively. Both these insulation systems fit within contemporary timber framed structural systems. If the house had not achieved a 7 Star NatHERS rating, double glazing was added. The double glazing included four variations as shown in Table 10. Each of the selected windows comes from a national glazing business with distributors and retailers throughout Australia (in other words, 'off the shelf' glazing systems). The placement of improved glazing was first applied to the living rooms and kitchen area. If this still did not achieve the desired 7 Star result, double glazing was also added to the bedrooms. Preliminary simulations identified that adding double glazing to the non-habitable rooms, (Laundry, Water Closet, Bathroom and Ensuite), generally had an improvement of less than 0.05 Stars (1 MJ/m2.annum), so these rooms were generally left as single glazed. If the improved glazing did not achieve a 7 Star result, external wall insulation was increased above R 2.7.

Table 10: Glazing properties

	Name	Construction	U-Value	Solar heat gain co-efficient
1	Single Glazed	Aluminium SG 3Clr	6.5	0.66
2	Double Glazed 1	Aluminium DG 4/10/4	4.2	0.57
3	Double glazed 2	Aluminium DG 4/10Ar/4EA	3.5	0.53
4	Double Glazed 3	Aluminium DG 4/16Ar/4	3.2	0.53
5	Double Glazed 4	Aluminium DG 4/16/4CSClr	2.8	0.50

Step 3: 7 Star 27% glass to floor area base model – The same methods as described above for the 7 Star 21% glass to floor area ratio were adopted. Generally, the Stage 2 inputs were improved until a 7 Star NatHERS result was obtained.

Details of the envelope simulation properties are shown in Appendix 1.

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 [37].

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/m^3) 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 [22] and the most recent version of the German Standard DIN-4108 [21], 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 [58]. 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 Research Report 2. 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 7 Star Class 1 and Class 2 buildings, in the NatHERS climate zones of Victoria. Research Report 1 explored these same issues within 6 Star Class 1 and Class 2 buildings in Victoria.

5. Simulation Results

This section contains the summarised results for each of the nine selected 7 Star wall system hygrothermal and bio-hygrothermal simulations. The Appendices for each external 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 7 Star wall system are provided in a table format. The table lists each NatHERS climate zone and corresponding NCC climate zones. Each wall system has separate tables for hygrothermal (heat and moisture) and bio-hygrothermal (mould growth) 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 11 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 or equal to 3.0, (>1.0 to ≤3.0), will require further investigation.
- A MI greater than 3.0 (>3.0) does not achieve the minimum performance requirements in the preview version of NCC 2022 [26]. (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 [1, 21, 41]. Yet visible mould exists in many Australian homes.

Many of the MI simulation graphs within the Appendices show the seasonal patterns of moist conditions that promote mould growth during the cooler months and drier periods when the mould growth may recede or stay stagnant during the warmer months. This is a critical aspect to understand, as subject to the interior relative humidity and air temperature conditions explored in section 2 Introduction, the dewpoint temperature could be 19°C, or even higher.

This indicates that moisture may form and that the conditions in the wall would have a Relative Humidity much higher than 70%, required to promote mould growth.

Table 11: Mould growth Mould Index (MI) categories

Mould Index	Definition	Explanation [23]
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	$1 \leq$ MI < 2: invisible growth, recognizable only by microscope, and $2 \leq$ MI < 3: growth starts to become visible to the naked eye.
3.0 to >5.0	Unacceptable amount of mould growth was simulated	MI $\geq$ 3: growth is visible to the naked eye and starts covering the surface.

This research report explores moisture and mould growth risks that may be associated with external wall systems, or façade systems, that comply with the requirements from NCC 2022 that requires a minimum thermal performance requirement of NatHERS 7 Star. Research Report 1 explored these same issues but applied the built fabric requirements as described within Volume 2 Part 3.12 Energy Efficiency and Part 3.8.7 Condensation Management and Volume 1 Part F6 Condensation management of NCC 2019.

Mould Index simulation results

Research Report 1 provides a comprehensive introduction to Mould Growth Index graphs. Please refer to Research Report 1, for guidance.

However, further clarification regarding a simulated external wall system with an MI greater than 1.0 and less than 3.0 that is defined as requiring further investigation. This definition 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. Recognising wall shading, Nath [58] suggested that all walls that may be shaded, should be simulated with a southern orientation. This was further highlighted in Research Report 1, that showed the majority of southern orientated wall systems had mould growth indices above 1.0.

5.1. Timber cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star timber clad wall system. The complete set of MI graphs for this wall system are in Appendix 2.

Hygrothermal simulation (moisture accumulation)

Table 12 shows this external wall system, with an ACR of 10 and a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 12: Hygrothermal simulation results from 7 Star timber clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 13 shows this external wall system, with an ACR of 10 and a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 13: Hygrothermal simulation results from 7 Star timber clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 14 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022.

for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 14 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in seven of the eight (7 of 8, or 88%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in four of the eight (4 of 8, or 50%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 14 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in seven of the eight (7 of 8, or 88%) climates simulated and greater than 1.0 in the other two climates simulated.

Table 14 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 14: Bio-hygrothermal simulation results from 7 Star timber clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	<1.0	<1.0	>1.0	<1.0	>3.0	>5.0
22	<1.0	<1.0	>3.0	>1.0	>5.0	>5.0
27	Nil	<1.0	<1.0	<1.0	>3.0	>5.0
60	<1.0	<1.0	<2.0	<1.0	<3.0	>5.0
61	<1.0	<1.25	<4.0	>2.5	>5.0	>5.0
63	<1.0	>1.25	<4.0	>2.5	<5.0	>5.0
64	<1.0	<1.0	<1.25	<1.0	>3.0	>5.0
66	>1.0	>3.0	>4.0	<4.0	>5.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 15 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 15 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in two of the three (2 of 3, or 67%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 15 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater 3.0 in all three climates.

Table 15 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater 3.0 in all three climates.

Table 15: Bio-hygrothermal simulation results from 7 Star timber clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	<1.0	<1.0	>1.0	<1.0	>4.0	>5.0
61	<1.0	<2.5	>4.0	>4.0	>5.0	>5.0
66	>2.5	>4.0	<5.0	>4.0	>5.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 16 shows a summary of the 64 bio-hygrothermal simulations for this wall system. Of the simulations completed, this table shows that only twenty-one of the forty-four (21 of 44, or 48%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, nil (0 of 22, or 0%) had an acceptable amount of mould growth.

Table 16: Summary of Simulation results from 7 Star Weatherboard clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	**Number**	**Distribution**	**Number**	**Distribution**	**Number**	**Distribution**
Nil	1	2%	0	0%	0	0%
</=1.0	20	46%	0	0%	0	0%
>1.0 to <3.0	12	27%	1	9%	0	0%
3.0 to >5.0	11	25%	10	91%	11	8%
Total	44	100%	11	100%	11	100%

5.2 Compressed fibre cement sheet cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star compressed fibre cement sheet clad wall system. The complete set of MI graphs for this wall system are in Appendix 3.

Hygrothermal simulation (moisture accumulation)

Table 17 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 17: Hygrothermal simulation results from 7 Star compressed fibre cement sheet clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 18 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 18: Hygrothermal simulation results from 7 Star compressed fibre cement sheet clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 19 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 19 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in eight of the eight (8 of 8, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 1.0, requiring further investigation in three of the eight (3 of 8, or 38%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 19 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in three of the eight (3 of 8, or 38%) climates simulated and greater than 1.0 in one of the climates simulated.

Table 19 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 19: Bio-hygrothermal simulation results from 7 Star compressed fibre cement sheet clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	Nil	Nil	<1.0	<1.0	<1.0	<4.0
22	Nil	Nil	<1.0	<1.0	<1.0	>3.0
27	Nil	<1.0	<1.0	<1.0	>1.5	>5.0
60	Nil	<1.0	<1.0	<1.0	>1.5	>5.0
61	Nil	<1.0	>1.2	<1.0	>3.0	>5.0
63	Nil	<1.0	>1.2	<1.0	>3.0	>5.0
64	Nil	<1.0	<1.0	<1.0	<1.0	>3.0
66	<1.0	<1.0	>1.2	<1.0	>4.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 20 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 20 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in three of the three (3 of 3, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 20 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater 3.0 in all three climates.

Table 20 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater 3.0 in all three climates.

Table 20: Bio-hygrothermal simulation results from 7 Star compressed fibre cement sheet clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	Nil	<1.0	<1.0	<1.0	>3.0	>5.0
61	<1.0	<1.0	>4.0	>2.5	>5.0	>5.0
66	<1.0	<3.0	>4.0	>3.5	>5.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 21 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that only thirty-eight of the forty-four (36 of 44, or 82%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, two (2 of 22, or 9%) had an acceptable amount of mould growth.

Table 21: Summary of Simulation results from 7 Star compressed fibre cement sheet clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	**Number**	**Distribution**	**Number**	**Distribution**	**Number**	**Distribution**
Nil	10	23%	0	0%	0	0%
</=1.0	26	59%	3	27%	0	0%
>1.0 to <3.0	5	11%	2	18%	0	0%
3.0 to >5.0	3	7%	6	55%	11	100%
Total	44	100%	11	100%	11	100%

5.3 Clay masonry veneer with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star clay masonry veneer clad wall system. The complete set of MI graphs for this wall system are in Appendix 4.

Hygrothermal simulation (moisture accumulation)

Table 22 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 22: Hygrothermal simulation results from 7 Star clay masonry veneer clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 23 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 23: Hygrothermal simulation results from 7 Star clay masonry veneer clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 24 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 24 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in eight of the eight (8 of 8, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 1.0, requiring further investigation, in four of the eight (4 of 8, or 50%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 24 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in three of the eight (3 of 8, or 37%) climates simulated and greater than 1.0 in five of the climates simulated.

Table 24 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 24: Bio-hygrothermal simulation results from 7 Star clay masonry veneer clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	<1.0	<1.0	<1.0	<1.0	>1.25	>4.0
22	<1.0	<1.0	>1.0	<1.0	<4.0	>5.0
27	Nil	Nil	<1.0	<1.0	>1.0	>4.0
60	Nil	<1.0	<1.0	<1.0	<2.5	>5.0
61	<1.0	<1.0	>1.5	<1.25	>2.0	>5.0
63	<1.0	<1.0	>1.5	>1.0	>4.0	>5.0
64	<1.0	<1.0	<1.0	<1.0	>1.25	>4.0
66	<1.0	>1.0	>2.0	<1.25	>4.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 25 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 25 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in two of the three (2 of 3, or 67%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 25 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0 in all three climates.

Table 25 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 25: Bio-hygrothermal simulation results from 7 Star clay masonry veneer clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	Nil	<1.0	<1.0	<1.0	<3.0	>5.0
61	<1.0	>1.0	<4.0	>2.5	>5.0	>5.0
66	>1.0	>2.5	>4.0	>3.0	>5.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 26 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that only thirty-one of the forty-four (29 of 44, or 66%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, nil (0 of 22, or 0%) had an acceptable amount of mould growth.

Table 26: Summary of Simulation results from 7 Star clay masonry veneer clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	Number	Distribution	Number	Distribution	Number	Distribution
Nil	4	9%	0	0%	0	0%
</=1.0	25	57%	0	0%	0	0%
>1.0 to <3.0	12	27%	6	55%	0	0%
3.0 to >5.0	3	7%	5	45%	11	100%
Total	44	100%	11	100%	11	100%

5.4 Concrete block, internally insulated

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star concrete block, internally insulated, wall system. The complete set of MI graphs for this wall system are in Appendix 5.

Hygrothermal simulation (moisture accumulation)

Table 27 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 27: Hygrothermal simulation results from 7 Star concrete block, internally insulated, wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 28 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 28: Hygrothermal simulation results from 7 Star concrete block, internally insulated, wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 29 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 29 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in seven of the eight (7 of 8, or 87%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in five of the eight (5 of 8, or 63%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 29 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated and greater than 1.0 in five of the climates simulated.

Table 29 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 29: Bio-hygrothermal simulation results from 7 Star concrete block, internally insulated, wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	<1.0	<1.0	>1.0	<1.0	>4.0	>5.0
22	<1.0	>1.0	>4.5	>2.5	>5.0	>5.0
27	Nil	<1.0	>1.0	<1.0	>4.0	>5.0
60	<1.0	<1.0	>3.0	>1.25	>5.0	>5.0
61	<1.0	>2.0	>4.5	>3.5	>5.0	>5.0
63	<1.0	>2.0	>4.5	>3.5	>5.0	>5.0
64	<1.0	<1.0	>1.5	<1.0	>4.0	>5.0
66	>2.0	>4.0	>4.5	>4.5	>5.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 30 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 30 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in two of the three (2 of 3, or 67%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 30 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater 3.0 in all three climates.

Table 30 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 30: Bio-hygrothermal simulation results from 7 Star concrete block, internally insulated, wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	<1.0	<1.0	<1.25	<1.0	>4.0	>5.0
61	<1.0	>2.0	>4.0	<4.0	>5.0	>5.0
66	<2.5	>4.0	<5.0	<5.0	>5.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 31 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that only eighteen of the forty-four (18 of 44, or 41%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, nil (0 of 22, or 0%) had an acceptable amount of mould growth.

Table 31: Summary of Simulation results from 7 Star concrete block, internally insulated, wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	Number	Distribution	Number	Distribution	Number	Distribution
Nil	1	2%	0	0%	0	0%
</=1.0	17	39%	0	0%	0	0%
>1.0 to <3.0	12	27%	0	0%	0	0%
3.0 to >5.0	14	32%	11	100%	11	100%
Total	44	100%	11	100%	11	100%

5.5 Externally insulated clay masonry (reverse brick veneer)

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star externally insulated clay masonry wall system. The complete set of MI graphs for this wall system are in Appendix 6.

Hygrothermal simulation (moisture accumulation)

Table 32 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 32: Hygrothermal simulation results from 7 Star externally insulated clay masonry wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 33 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 33: Hygrothermal simulation results from 7 Star externally insulated clay masonry wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 34 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 34 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in eight of the eight (8 of 8, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI of less than 1.0 in six of the eight (6 of 8, or 75%) climates simulated. This is due to the hygrothermal buffering and air cavity of this wall system.

Table 34 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0, requiring further investigation, in five of the eight (5 of 8, or 63%) climates simulated.

Table 34 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in five of the eight (5 of 8, or 63%) climates simulated.

Table 34: Bio-hygrothermal simulation results from 7 Star externally insulated clay masonry wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	Nil	Nil	Nil	Nil	<1.0	<1.0
22	Nil	<1.0	<1.0	<1.0	>1.0	>3.0
27	Nil	Nil	Nil	Nil	<1.0	<1.0
60	Nil	<1.0	<1.0	<1.0	>1.0	>3.0
61	<1.0	<1.0	>1.0	<1.0	>1.5	>3.0
63	<1.0	<1.0	>1.0	<1.0	>2.0	>3.5
64	Nil	<1.0	<1.0	<1.0	<1.0	>2.0
66	<1.0	<1.0	<1.0	<1.0	>1.5	>4.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 35 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 35 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in three of the three (3 of 3, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 1.0, requiring further investigation, in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 35 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in two of three climates.

Table 35 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 35: Bio-hygrothermal simulation results from 7 Star externally insulated clay masonry wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	Nil	Nil	<1.0	<1.0	<1.0	<4.0
61	<1.0	<1.0	>1.5	>1.2	>4.0	>5.0
66	<1.0	<1.0	>2.0	>1.2	>4.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 36 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that only thirty eight of the forty-four (38 of 44, or 86%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, six (6 of 22, or 27%) had an acceptable amount of mould growth.

Table 36: Summary of Simulation results from 7 Star externally insulated clay masonry wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	Number	Distribution	Number	Distribution	Number	Distribution
Nil	13	30%	0	0%	0	0%
</=1.0	25	57%	4	36%	2	18%
>1.0 to <3.0	6	13%	5	45%	1	9%
3.0 to >5.0	0	0%	2	19%	8	73%
Total	44	100%	11	100%	11	100%

5.6 Extruded polystyrene with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star extruded polystyrene (XPS) clad wall system. The complete set of MI graphs for this wall system are in Appendix 7.

Hygrothermal simulation (moisture accumulation)

Table 37 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows that the simulations in seven of the eight climates have a NIL value for moisture accumulation. The simulations for NatHERS climate zone 63 show moisture accumulation. This indicates that the seasonal wetting and drying of this wall system in NatHERS climate zone 63 did lead to moisture accumulation.

Table 37: Hygrothermal simulation results from 7 Star extruded polystyrene (XPS) clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Yes	Yes	Yes	Yes
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 38 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 38: Hygrothermal simulation results from 7 Star extruded polystyrene (XPS) clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 39 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 39 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in eight of the eight (8 of 8, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI of less than 1.0, in eight of the eight (8 of 8, or 100%) climates simulated. This pattern is due to the insulation being on the outside of the timber frame.

Table 39 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0, requiring further investigation, on five of the eight (5 of 8, or 63%) climates simulated.

Table 39 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 39: Bio-hygrothermal simulation results from 7 Star extruded polystyrene (XPS) clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	<1.0	<1.0	<1.0	<1.0	<1.0	>4.0
22	<1.0	<1.0	<1.0	<1.0	>2.5	>5.0
27	Nil	<1.0	<1.0	<1.0	<1.0	>5.0
60	<1.0	<1.0	<1.0	<1.0	>1.5	>5.0
61	<1.0	<1.0	<1.0	<1.0	<3.0	>5.0
63	<1.0	<1.0	<1.0	<1.0	>3.0	>5.0
64	<1.0	<1.0	<1.0	<1.0	<1.0	>3.0
66	<1.0	<1.0	<1.0	<1.0	>3.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 40 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 40 shows that this external wall system, with an ACR of 10, in all orientations, has an MI of less than 1.0 in twelve of twelve (12 of 12 or 100%) climates simulated. This pattern is due to the insulation being on the outside of the timber frame.

Table 40 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0 in two of three climates.

Table 40 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 40: Bio-hygrothermal simulation results from 7 Star extruded polystyrene (XPS) clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	Nil	<1.0	<1.0	<1.0	<1.0	>4.0
61	<1.0	<1.0	<1.0	<1.0	>3.0	>5.0
66	<1.0	<1.0	<1.0	<1.0	>3.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 41 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that forty-four of the forty-four (44 of 44, or 100%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, four (4 of 22, or 18%) had an acceptable amount of mould growth.

Table 41: Summary of Simulation results from 7 Star extruded polystyrene (XPS) clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	**Number**	**Distribution**	**Number**	**Distribution**	**Number**	**Distribution**
Nil	2	5%	0	0%	0	0%
</=1.0	42	95%	4	36%	0	0%
>1.0 to <3.0	0	0%	3	28%	0	0%
3.0 to >5.0	0	0%	4	36%	11	100%
Total	44	100%	11	100%	11	100%

5.7 Expanded polystyrene with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star expanded polystyrene (EPS) clad wall system. The complete set of MI graphs for this wall system are in Appendix 8.

Hygrothermal simulation (moisture accumulation)

Table 42 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows that the simulations in seven of the eight climates have a NIL value for moisture accumulation. The simulations for NatHERS climate zone 63 show moisture accumulation. This indicates that the seasonal wetting and drying of this wall system in NatHERS climate zone 63 did lead to moisture accumulation.

Table 42: Hygrothermal simulation results from 7 Star expanded polystyrene (EPS) clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Yes	Yes	Yes	Yes
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 43 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 43: Hygrothermal simulation results from 7 Star expanded polystyrene (EPS) clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	**East**	**South**	**West**
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 44 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 44 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in eight of the eight (8 of 8, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI of less than 1.0, in eight of the eight (8 of 8, or 100%) climates simulated. This pattern is due to the insulation being on the outside of the timber frame.

Table 44 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0, requiring further investigation, on four of the eight (4 of 8, or 50%) climates simulated.

Table 44 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (6 of 8, or 75%) climates simulated.

Table 44: Bio-hygrothermal simulation results from 7 Star expanded polystyrene (EPS) clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	<1.0	<1.0	<1.0	<1.0	<1.0	<3.0
22	<1.0	<1.0	<1.0	<1.0	>1.0	<5.0
27	Nil	<1.0	<1.0	<1.0	<1.0	>3.0
60	<1.0	<1.0	<1.0	<1.0	<1.0	<5.0
61	<1.0	<1.0	<1.0	<1.0	>1.5	>4.5
63	<1.0	<1.0	<1.0	<1.0	>1.5	>4.5
64	<1.0	<1.0	<1.0	<1.0	<1.0	<2.0
66	<1.0	<1.0	<1.0	<1.0	>1.5	<5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 45 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 45 shows that this external wall system, with an ACR of 10, in all orientations, has an MI of less than 1.0 in twelve of twelve (12 of 12 or 100%) climates simulated. This pattern is due to the insulation being on the outside of the timber frame.

Table 45 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1.0 in two of three climates.

Table 45 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 45: Bio-hygrothermal simulation results from 7 Star expanded polystyrene (EPS) clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	Nil	<1.0	<1.0	<1.0	<1.0	>4.0
61	<1.0	<1.0	<1.0	<1.0	<2.5	>5.0
66	<1.0	<1.0	<1.0	<1.0	>2.5	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 46 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that forty-four of the forty-four (44 of 44, or 100%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, five (5 of 22, or 23%) had an acceptable amount of mould growth.

Table 46: Summary of Simulation results from 7 Star expanded polystyrene (EPS) clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	Number	Distribution	Number	Distribution	Number	Distribution
Nil	2	5%	0	0%	0	0%
</=1.0	42	95%	5	45%	0	0%
>1.0 to <3.0	0	0%	6	55%	2	18%
3.0 to >5.0	0	0%	0	0%	9	72%
Total	44	100%	11	100%	11	100%

5.8 Autoclaved aerated concrete with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star autoclaved aerated concrete wall system. The complete set of MI graphs for this wall system are in Appendix 9.

Hygrothermal simulation (moisture accumulation)

Table 47 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 47: Hygrothermal simulation results from 7 Star autoclaved aerated concrete wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 48 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 48: Hygrothermal simulation results from 7 Star autoclaved aerated concrete wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 49 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 49 shows that this external wall system, with an ACR of 10, all scenarios, except for one (CZ63 south orientation), have a MI of less than 1.0 (31 of 32, or 97%) for the climates simulated.

Table 49 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in one of the eight (1 of 8, or 13%), greater than 1.0 and less than 3.0 in three (3 of 8, or 38%) of the climate simulated, and less than 1.0 in four (4 of 8, or 50%) of the climates simulated.

Table 49 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 49: Bio-hygrothermal simulation results from 7 Star autoclaved aerated concrete wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
21	Nil	<1.0	<1.0	<1.0	<1.0	>3.0
22	<1.0	<1.0	<1.0	<1.0	>2.0	<5.0
27	Nil	Nil	<1.0	<1.0	<1.0	<4.0
60	Nil	<1.0	<1.0	<1.0	<1.0	>4.0
61	<1.0	<1.0	<1.0	<1.0	<2.5	<5.0
63	<1.0	<1.0	>1.0	<1.0	>2.5	<5.0
64	Nil	<1.0	<1.0	<1.0	<1.0	>3.0
66	<1.0	<1.0	<1.0	<1.0	>3.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 50 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 50 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in three of the three (3 of 3, or 100%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 1.0 in two of the three (2 of 3, or 67%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 50 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 1 in all three climates.

Table 50 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 50: Bio-hygrothermal simulation results from 7 Star autoclaved aerated concrete wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	**Bio-hygrothermal (Highest calculated Mould Index (MI))**					
	Air change rate 10 (ACR 10)				**Air change rate 7.5 (ACR 7.5)**	**Air change rate 5 (ACR 5)**
	North	**East**	**South**	**West**	**South**	**South**
27	Nil	<1.0	<1.0	<1.0	>1.25	>5.0
61	<1.0	<1.0	>1.5	>1.0	>4.0	>5.0
66	<1.0	>1.0	>2.0	>1.0	>4.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 51 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that thirty-eight of the forty-four (38 of 44, or 86%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, four (4 of 22, or 18%) had an acceptable amount of mould growth.

Table 51: Summary of Simulation results from 7 Star autoclaved aerated concrete wall system

	ACR 10		**ACR 7.5**		**ACR 5**	
Mould Index	**Number**	**Distribution**	**Number**	**Distribution**	**Number**	**Distribution**
Nil	6	14%	0	0%	0	0%
</=1.0	32	72%	4	36.5%	0	0%
>1.0 to <3.0	6	14%	4	36.5%	0	0%
3.0 to >5.0	0	11%	3	27%	11	100%
Total	44	100%	11	100%	11	100%

5.9 Sheet-metal cladding with insulated timber frame

This section presents the hygrothermal and bio-hygrothermal results for the 7 Star sheet-metal clad wall system. The complete set of MI graphs for this wall system are in Appendix 10.

Hygrothermal simulation (moisture accumulation)

Table 52 shows this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 52: Hygrothermal simulation results from 7 Star sheet-metal clad wall system NCC CZ6-8 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
21	Nil	Nil	Nil	Nil
22	Nil	Nil	Nil	Nil
27	Nil	Nil	Nil	Nil
60	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
63	Nil	Nil	Nil	Nil
64	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Table 53 shows this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, with an ACR of 10. This table shows all the simulations have a NIL value for moisture accumulation. This indicates that the seasonal wetting and drying of the wall did not lead to moisture accumulation within this external wall system.

Table 53: Hygrothermal simulation results from 7 Star sheet-metal clad wall system NCC CZ4 (ACR10)

NatHERS CZ	Hygrothermal (moisture accumulation)			
	North	East	South	West
27	Nil	Nil	Nil	Nil
61	Nil	Nil	Nil	Nil
66	Nil	Nil	Nil	Nil

Bio-hygrothermal simulation (Mould growth)

NCC Climate zones 6-8 with a Class 4 pliable wall membrane

Table 54 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 4 pliable wall membrane, as specified in NCC 2022 for NCC climate zones 6 to 8, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 54 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in five of the eight (5 of 8, or 63%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 54 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) of the climates simulated.

Table 54 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in eight of the eight (8 of 8, or 100%) climates simulated.

Table 54: Bio-hygrothermal simulation results from 7 Star sheet-metal clad wall systems NCC CZ 6-8 (ACR10, 7.5 and 5)

NatHERS CZ	**Bio-hygrothermal (Highest calculated Mould Index (MI))**					
	Air change rate 10 (ACR 10)				**Air change rate 7.5 (ACR 7.5)**	**Air change rate 5 (ACR 5)**
	North	**East**	**South**	**West**	**South**	**South**
21	<1.0	<1.25	<3.5	<2.0	>5.0	>5.0
22	<1.0	>2.0	<5.0	>4.0	>5.0	>5.0
27	<1.0	<1.0	>3.0	<1.25	>5.0	>5.0
60	<1.0	<2.5	<5.0	<4.0	>5.0	>5.0
61	>1.0	<4.0	>5.0	<5.0	>5.0	>5.0
63	<1.5	<3.5	<5.0	>4.0	>5.0	>5.0
64	<1.0	<1.50	<3.5	<2.5	>5.0	>5.0
66	<4.5	<5.0	<5.0	<5.0	>5.0	>5.0

NCC Climate zone 4 with a Class 3 pliable wall membrane

Table 55 shows the bio-hygrothermal mould growth simulation results for this external wall system, with a Class 3 pliable wall membrane, as specified in NCC 2022 for NCC climate zone 4, and an ACR of 10, 7.5 and 5. The mould growth simulation results for ACR 7.5 and 5 have only been completed for the southern orientation.

Table 55 shows that this external wall system, with an ACR of 10, in the northern orientation, has an MI of less than 1.0 in one of the three (1 of 3, or 33%) climates simulated. The table also shows that this external wall system, with an ACR of 10, in the southern orientation, has an MI greater than 3.0 in three of the three (3 of 3, or 100%) climates simulated. This difference is due to the differences in solar driven drying potential for the external wall.

Table 55 also shows that this external wall system, with an ACR of 7.5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 55 also shows that this external wall system, with an ACR of 5, in the southern orientation, has an MI greater than 3.0 in all three climates.

Table 55: Bio-hygrothermal simulation results from 7 Star sheet-metal clad wall systems NCC CZ 4 (ACR10, 7.5 and 5)

NatHERS CZ	Bio-hygrothermal (Highest calculated Mould Index (MI))					
	Air change rate 10 (ACR 10)				Air change rate 7.5 (ACR 7.5)	Air change rate 5 (ACR 5)
	North	East	South	West	South	South
27	<1.0	<1.0	>3.0	>1.0	>5.0	>5.0
61	>1.0	<4.0	<5.0	<5.0	>5.0	>5.0
66	<4.5	>5.0	>5.0	>5.0	>5.0	>5.0

Summary of bio-hygrothermal simulation Mould Index results

Table 56 shows a summary of the 64 bio-hygrothermal simulations, for this wall system. Of the simulations completed, this table shows that only eight of the forty-four (8 of 44, or 18%) wall systems simulated with an ACR of 10 had an acceptable amount of mould growth. For the southern wall systems simulated with an ACR of less than 10, nil (0 of 22, or 0%) had an acceptable amount of mould growth.

Table 56: Summary of Simulation results from 7 Star sheet-metal clad wall system

	ACR 10		ACR 7.5		ACR 5	
Mould Index	Number	Distribution	Number	Distribution	Number	Distribution
Nil	0	0%	0	0%	0	0%
</=1.0	8	18%	0	0%	0	0%
>1.0 to <3.0	11	25%	0	0%	0	0%
3.0 to >5.0	25	57%	11	100%	11	100%
Total	44	100%	11	100%	11	100%

6. Results Summary

The results section summarises the 594 hygrothermal and 594 bio-hygrothermal simulation of nine external wall systems within eight if the NatHERS climates of Victoria. The nine types of external wall systems comprised contemporary construction methods and materials that were established via NatHERS simulations to achieve a 7 Star rating for a sample house plan. 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^{0}C, and there are more than 1,000 heating degree days [42]. The heating thermostat setting was 20^{0}C as per the NatHERS protocol. The simulations included 396 with an ACR of 10, 99 with an ACR of 7.5, and 99 with an ACR of 5. An ACR of 10 is the maximum allowed for a 7 Star home, as specified in the preview version of NCC 2022 [24-26].

The hygrothermal simulations of most wall systems showed no moisture accumulation. Where moisture accumulation was simulated, it was within NatHERS climate zone 63 for the extruded and expanded polystyrene cladding systems.

Of the 396 bio-hygrothermal simulations with an ACR of 10:

- 276 showed a MI of NIL or less than 1.0 (70%)
- 64 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation (16%), and
- 56 showed a MI of 3.0 or more, indicating that these methods of construction may be climatically inappropriate (14%).

Of the 99 bio-hygrothermal simulations with an ACR of 7.5:

- 20 showed a MI of NIL or less than 1.0 (20%)
- 27 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation (27%), and
- 52 showed a MI of 3.0 or more, indicating that these methods of construction may be climatically inappropriate (53%).

Of the 99 bio-hygrothermal simulations with an ACR of 5:

- 2 showed a MI of NIL or less than 1.0 (2%)
- 3 showed a MI greater than 1.0 and less than 3.0, indicating these wall systems require further investigation (3%), and
- 94 showed a MI of 3.0 or more, indicating that these methods of construction may be climatically inappropriate (95%).

Table 57 shows a summary of the hygrothermal simulations of the nine external wall systems in 11 NatHERS and three NCC climates, based built fabric variables and an ACR of 10. An ACR of 10 is the maximum leakiness allowed as per the preview version of NCC 2022. The green shaded cells indicate that all four orientations had nil or an acceptable amount of mould growth. The orange shaded cells indicate that one or more orientations had an amount of mould growth requiring further analysis or an unacceptable amount of mould growth. This table shows that whilst two external wall systems (expanded and extruded polystyrene) may be suitable in all the simulated climate types, the other seven external wall systems may not be suitable in the simulated NatHERS and NCC climates.

Table 57: Summary of bio-hygrothermal simulation results based on NatHERS and NCC climates ACR 10

Wall type	**Climate**										
	NatHERS/ NCC 6-7								**NatHERS/ NCC 4**		
	21	**22**	**27**	**60**	**61**	**63**	**64**	**66**	**27**	**61**	**66**
Weatherboard construction											
Compressed fibre-cement sheet											
Clay masonry veneer											
Concrete blockwork masonry											
Externally insulated clay masonry											
Extruded polystyrene cladding											
Expanded polystyrene cladding											
Autoclaved aerated concrete masonry cladding											
Flat metal cladding											

Table 58 shows a summary of the southern orientated hygrothermal simulations for the nine external wall systems in 11 NatHERS and three NCC climates based built fabric variables and an ACR of 7.5. Anecdotal evidence suggests that many new homes may be achieving and ACR of 7.5. The green shaded cells indicate that the southern orientated wall had nil or an acceptable amount of mould growth. The orange shaded cells indicate that the southern orientated wall had an amount of mould growth requiring further analysis or an unacceptable amount of mould growth. This table shows that all nine (9 of 9) of the southern orientated external wall systems may not be suitable in many of the simulated NatHERS and NCC climates.

Table 58: Summary of southern oriented bio-hygrothermal simulation results based on NatHERS and NCC climates ACR 7.5

Wall type	**Climate**										
	NatHERS/ NCC 6-7								**NatHERS/ NCC 4**		
	21	**22**	**27**	**60**	**61**	**63**	**64**	**66**	**27**	**61**	**66**
Weatherboard construction											
Compressed fibre-cement sheet											
Clay masonry veneer											
Concrete blockwork masonry											
Externally insulated clay masonry											
Extruded polystyrene cladding											
Expanded polystyrene cladding											
Autoclaved aerated concrete masonry cladding											
Flat metal cladding											

Table 59 shows a summary of the southern orientated hygrothermal simulations for the nine external wall systems in 11 NatHERS and three NCC climates based built fabric variables and an ACR of 5. Anecdotal evidence suggests that some new homes may be achieving and ACR of 5. The green shaded cells indicate that the southern orientated wall had nil or an acceptable amount of mould growth. The orange shaded cells indicate that the southern orientated wall had an amount of mould growth requiring further analysis or an unacceptable amount of mould growth. This table shows that all nine (9 of 9) of the southern orientated external wall systems may not be suitable in many of the simulated NatHERS and NCC climates.

Table 59: Summary of southern oriented bio-hygrothermal simulation results based on NatHERS and NCC climates ACR 5

Wall type	Climate										
	NatHERS/ NCC 6-7								NatHERS/ NCC 4		
	21	22	27	60	61	63	64	66	27	61	66
Weatherboard construction											
Compressed fibre-cement sheet											
Clay masonry veneer											
Concrete blockwork masonry											
Externally insulated clay masonry											
Extruded polystyrene cladding											
Expanded polystyrene cladding											
Autoclaved aerated concrete masonry cladding											
Flat metal cladding											

Key simulation findings

Orientation and shading

Due to the radiation influenced drying potential [45, 58, 60], 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. NCC 2022 does not differentiate construction methods based on orientation. Simulations should be able to demonstrate that the southern orientated external wall system constructed in compliance with Victorian building regulations (including the NCC 2022) should maintain an acceptable MI. This demonstrates that at this stage the aspect of wall orientation and its corresponding impact on moisture and mould is not addressed adequately within the NCC. This report provides evidence that many external wall systems, built in full compliance with the preview version of NCC 2022 requirements, can result in unacceptable levels of interstitial 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. This issue is neither explored nor qualified further within the present research.

Vented cavity

This report includes five of the eight external wall systems described within Section 3.12 of NCC 2022. Only three of the eight wall types described require a cavity between the cladding system and the wall structure, to allow the drainage of moisture and allow water vapour to leave the external wall system. The three wall systems are clay masonry veneer, cavity clay masonry and externally insulated clay masonry. Within this research, the only the clay masonry veneer and the externally insulated clay masonry external wall systems were analysed. A third external wall system, that is not described within Section
3.12 but is commonly used in Class 1 and Class 2 buildings, the autoclaved aerated concrete (AAC) panel cladding system, was analysed in this research. The manufacturers specification requires a cavity between the AAC panel and the building structure. In this report, these three wall systems which include a cavity for the drainage of moisture and the removal of water vapour performed better than other wall systems that did not include a cavity.

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.

Water vapour diffusion resistivity

The NCC 2019 only required the pliable membranes for a 6 Star Class 1 or Class 2 building to be of a AS4200 Class 3 in NCC climate zones 6, 7 and 8. The NCC 2022 for 7 Star Class 1 and Class 2 buildings requires a AS4200 Class 4 pliable membrane for NCC climate zones 6, 7 and 8. As discussed in the Introduction, and shown in Table 3, the water vapour diffusion properties for a Class 3 pliable membrane range from ≥0.1429 to <1.1403 µg/N.s, whilst a class 4 pliable membrane has a range from ≥1.1403, with no maximum. The minimum water vapour permeance of a Class 4 pliable membrane is ten (10) times greater than a Class 3 pliable membrane. This extra water vapour permeance is a significant improvement on NCC 2019, but as this report documents, this still leads to many of the bio-hygrothermal simulations having an unacceptable amount of mould growth.

The NCC 2019, had no vapour permeability requirement for pliable membranes for a 6 Star Class 1 or Class 2 building located in NCC climate zone 4. As discussed in the Introduction, and shown in Table 3, the water vapour diffusion properties for a Class 1 pliable membrane range from ≥0.0000 to <0.0022 µg/N.s, whilst a class 3 pliable membrane has a range from ≥0.1429 to <1.1403 µg/N.s. The minimum water vapour permeance of a Class 3 pliable membrane is sixty-five (65) times greater than a Class 1 pliable membrane. This is extra water vapour permeance is a significant improvement, but as this report documents, this still leads to many of the bio-hygrothermal simulations having an unacceptable amount of mould growth.

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.

Cladding insulation properties

Materials that provided insulation on the exterior of the insulated timber frame, like extruded polystyrene, expanded polystyrene and autoclaved aerated concrete performed well, as they allowed the timber frame to stay above dewpoint and mould growth conditions for longer periods of time.

Hygrothermal buffering

Materials like concrete, clay brick and autoclaved aerated concrete allow for daily seasonal adsorption and release of moisture. The externally insulated clay masonry (reverse brick veneer) wall system had a 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. Cross laminated, mass-timber and concrete elements are known for their hygrothermal buffering properties [60-63].

Airtightness

The NCC 2022 has a performance requirement that a new 7 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 [35, 36, 64]. As a result, many new homes have an ACR significantly less than 10. When the ACR was 10, 57% of the southern oriented wall simulations had an acceptable amount of mould growth. When the ACR was modified to 7.5, only 20 of 99 (20%) of the southern oriented wall simulations had an acceptable amount of mould growth. When the ACR was further modified to 5, only 2 of 99 (2%) of the southern oriented wall simulations had an acceptable amount of mould growth. This raises the relationship between two critical aspects of high-performance buildings, namely façade design and building mechanical ventilation.

As buildings increase in thermal performance the careful selection and installation of pliable building membranes on the interior and exterior of the external wall system becomes increasingly significant. This is to manage the rate and amount of water vapour diffusing through the external wall.

Building occupants may not open windows and doors for many reasons, including but not limited to noise, security, the external air temperature, the external wind speed, extended periods when working from home. In many homes, the failure of occupants to open windows and doors is a behavioural issue that contributes to a lower ACR. In the simulations completed in this report, the interior relative humidity has been capped at 70% due to the international nature of the software.

However, except for the openable window requirement in the NCC [40], there is no requirement to manage water vapour and relative humidity in Australian Class 1 and Class 2 buildings. As other nations have made their buildings more air-tight and acknowledged occupant limitations, there has been an increased use of enthalpy recovery ventilation systems to ensure the interior air quality and relative humidity are appropriately managed. In Australia, aside from Passive-house type projects, this level of interior air quality management is not common.

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 climate data used in the research has been sourced from the nationally certified average climate data sets that have been established for building energy rating (BER) and NatHERS simulation. This method follows the international practice of using BER climate data whilst countries explore what may be more suitable climate data sets for hygrothermal simulation. Additionally, a critical input as discussed in Research Report 1, is precipitation data. At this stage, the Australian BER climate files do not include hourly precipitation data. This would indicate that the simulation results in this report may be conservative, as rain absorption and penetration of the façade system has not been fully simulated. An external wall system that has less drying potential than what has been simulated in this report may support more mould growth or moisture accumulation. Research Report 3 will start to explore the inclusion of precipitation data.

  Current research at the University of Tasmania is exploring what may need to be considered for the establishment Australian climate data sets for hygrothermal simulation. This is outside the scope of this project.

- if a home was heated to more than 20^{0}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.

- Each of these actions would increase risks associated with moisture and mould.

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.

7. Conclusion and recommendations

This first stage of the research, as documented in Research report 1, examined if a 'code-compliant' external wall system for a Class 1 and 2 buildings constructed in accordance with NCC 2019 6 Star requirements, located within Victoria, may or may not promote moisture accumulation and/or mould growth. That report identified significant mould growth risk for the common wall systems used for Class 1 and Class 2 buildings in Victoria.

The focus of this second stage of the research examined if a 'code-compliant' external wall system for a Class 1 and 2 buildings constructed in accordance with NCC 2022 for a 7 Star home, located within Victoria may or may not promote moisture accumulation and/or mould growth.

This research report has identified that most of the hygrothermal simulations identified no risk of moisture accumulation.

However, the bio-hygrothermal simulations undertaken to ascertain if there is a risk of unacceptable mould growth presented a very different result. This report shows that 120 of the 396 walls simulated (30%) 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 10 to 7.5, of the 99 southern oriented walls simulated, 79 of 99 (or 80%) of the walls 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.

When the ACR was reduced from 10 to 5, of the 99 southern oriented walls simulated 97 of 99 (or 98%), of the walls 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.

Generally, but with a few exceptions, the bio-hygrothermal simulation results for the southern oriented version most external wall systems showed the greatest mould growth index, which leads to two branches of activity, namely research and regulatory intervention.

Research

1. Each of the 7 Star external wall systems simulated in this research needs to be designed and constructed or have regulations and guidance that require suitable design and construction such that the southern orientation shows either a Mould Index of nil, or less than 1.0. 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. As mentioned in the software limitations above, the BER climate data used in this research does not include hourly precipitation data. This could make the results in this report conservative, as the simulations may calculate dryer walls with a greater drying potential. There is a need to include hourly precipitation data. This will occur during the next stage of this research.

3. 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.

Regulatory Intervention

1. A significant education program needs to be undertaken in Victoria 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.

2. 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.

List of Appendices

References

1. WHO, *Damp and mould: health risks, prevention and remedial actions*. 2009, WHO Regional Office for Europe.
2. Holst, G., et al., *Household dampness and microbial exposure related to allergy and respiratory health in Danish adults.* European clinical respiratory journal, 2020. **7**(1).
3. British Standards, *BS5250 - Code of Practise for condensation in buildings*. 2002, British Standards: London.
4. Nath, S., M. Dewsbury, and J. Douwes, *Has a singular focus of building regulations created unhealthy homes?* Architectural Science Review, 2019.
5. Dewsbury, M., et al., *Scoping study of condensation in residential buildings: final report*. 2016, Australian Building Codes Board.
6. WHO Regional Office for Europe, *WHO guidelines for indoor air quality: dampness and mould*. 2009, Germany: World Health Organisation.
7. May, P., *Performance-based regulation and regulatory regimes: the saga of leaky buildings.* Law & Policy, 2003. **25**(4): p. 381-401.
8. Howden-Chapman, P., et al., *Retrofitting houses with insulation to reduce health inequalities: aims and methods of a clustered, randomised community-based trial.* Social Science & Medicine, 2005. **61**: p. 2600-2610.
9. Stahlhut, D., *Decay fungi from New Zealand leaky buildings: isolation, identification and preservative resistance*, in *Biological Sciences*. 2008: The University of Waikato.
10. McGregor, A. *Calamities, corrosion, ;eaky buildings and the law*. in *Corrosion and Prevention*. 2008. Wellington, New Zealand.
11. Bassett, M. and S. McNeil. *Drained and vented cavity walls – measured ventilation rates*. in *IRHACE Conference 'Institution of Refrigeration, Heating and Air Conditioning Engineers,*. 2005. Nelson, New Zealand.
12. Dewsbury, M. and T. Law. *Recent increases in the occurrence of condensation and mould within new Tasmanian housing*. in *50th International Conference of the Architectural Science Association 2016*. 2016. Adelaide.
13. Dewsbury, M. and T. Law. *Temperate climates, warmer houses and built fabric challenges*. in *International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016*. 2016. Sydney: Procedia Engineering.
14. Dewsbury, M., T. Law, and A. Henderson, *Investigation of destructive condensation in Australian cool-temperate buildings*. 2016.
15. Dewsbury, M., Y. Foo, and T. Law, *Renovating a pre-1980s weatherboard home: what about condensation?*, in *Australasian Building Simulation Conference 2017*. 2017, AIRAH: Melbourne.
16. Dewsbury, M., et al., *Condensation RIsk Mitigation for Tasmanian Housing (draft report)*. 2017, University of Tasmania: School of Architecture and Design. p. 73.
17. Dewsbury, M., et al., *Condensation RIsk Mitigation for Tasmanian Housing (final report)*. 2018, University of Tasmania: School of Architecture and Design. p. 69.
18. Law, T. and M. Dewsbury, *The unintended consequences of building sustainability in Australia*, in *Sustainable development research in the Asia-Pacific region: education, cities, Infrastructure and buildings*, W. Fihlo, J. Rogers, and U. Lyer-Raniga, Editors. 2018, Springe International: Switzerland. p. 525-547.
19. Nath, S., M. Dewsbury, and K. Orr. *Is new housing a health hazard?* in *Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association*. 2018. RMIT University: The Architectural Science Association and RMIT University.
20. Brambilla, A. and A. Sangiorgio, *Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk.* Renewable and Sustainable Energy Reviews, 2020. **132**.
21. Deutsches Institut Fur Normung E.V. (German National Standard), *DIN 4108-4: Thermal insulation and energy economy in buildings - Part 4: Hygrothermal design values*. 2020: Germany.

22. ASHRAE, *Standard 160-2016 - Criteria for Moisture-Control Design Analysis in Buildings (ANSI Approved)*. 2016: Atlanta.
23. Viitanen, H., et al. *Mold risk classification based on comparative evaluation of two established growth models*. in *6th International Building Physics Conference, IBPC 2015*. 2015. Elsevier, Energy Procedia.
24. ABCB, *Preview: Housing provisions standard: energy efficiency and condensation provisions*, Australian Building Codes Board, Editor. 2022: 2022.
25. ABCB, *Preview volume two building code of Australia: Energy efficiency and condensation provsions*, Australian Building Codes Board, Editor. 2022: Canberra.
26. ABCB, *Preview: volume one building code of Australia energy efficiency and condensation provisions*, Australian Building Codes Board, Editor. 2022: Canberra.
27. Rogers, T., *Preventing condensation in insulated structures.* Architectural Record, 1938: p. 109-119.
28. Dyer, P., *Something rotten in the state….* Architecture New Zealand, 2021.
29. Dyer, P., *The story of New Zealand's leaky buildings disaster*. 2019: David Bateman Limited.
30. Rickaby, P., *The long road to quality assured, moisture-safe retrofit in the UK*, in *International conference on moisture in buildings 2021*. 2021: University College London.
31. ABCB, *The Building Code of Australia*. 2010, Australian Building Codes Board.
32. NatHERS Administrator, *Nationwide House Energy Rating Scheme Software Accreditation Protocol*. 2019: |Canberra.
33. British Standards, *BS 5250: Management of moisture in buildings – code of practice*. 2021.
34. ASHRAE, *ASHRAE Standard 55: Thermal environmental conditions for human occupancy*. 2013.
35. Ambrose, M., et al., *The evaluation of the 5-star energy efficiency standard for residential buildings*, CSIRO, Editor. 2013: Canberra.
36. Ambrose, M. and M. Syme, *House energy efficiency inspections project: final report*. 2015, CSIRO: Canberra.
37. AIRAH, *AIRAH Technical handbook*. 6th ed. 2021: The Australian Institute of Refrigeration, Aircondioning and Heating.
38. ASHRAE, *2017 ASHRAE Handbook Fundamentals (SI Edition)*. 2017, Atlanta: ASHRAE.
39. Clarke, J., et al., *A technique for the prediction of the conditions leading to mould growth in buildings.* Building and Environment, 1999. **34**(4): p. 515-521.
40. ABCB, *The National Construction Code: Volume 2*, A.B.C. Board, Editor. 2019: Canberra.
41. ABCB, *The National Construction Code: Volume 2*. Building Code of Australia Class 1 to Class 10 Buildings. 2016, Canberra ACT: The Australian Building Codes Board. 576.
42. ABCB, *The National Constrcution Code: Volume 1*, A.B.C. Board, Editor. 2019: Canberra.
43. Standards Australia, *AS4200.1: Pliable building membranes and Underlays - Materials*. 2017.
44. Horner, E., *IEQ applications:indoor dampness and health.* ASHRAE Journal, 2017. **59**(1).
45. Overton, G., *Vapour control in New Zealand walls*. 2016: Porirua, New Zealand.
46. Schwab, R., *25 years of the WUFI® program family*. 2021, Fraunhofer Institute for Building Physics IBP.: Holzkirchen.
47. Meteorology, B.o., *Climate statistics for Australian locations: summary statistics Melbourne regional office*. 2022: http://www.bom.gov.au/climate/averages/tables/cw_086071.shtml.
48. viitanen, H., *Modelling the time factor in the development of mould fungi - the effect of critical humidity and temperature conditions on pine and spruce sapwood.* Holzforschung (Wood research and technology, 1997. **51**(1).
49. Viitanen, H. and A. Ritschkoff, *Mould growth in pine and spruce sapwood in relation to air humidity and temperature*. 1991, The Swedish University of Agricultural Sciences, Department of Forest Products.: Uppsala.
50. Viitanen, H., *Factors affecting the development of mould and brown rot decay in wooden material and wooden structures*, in *Dept. of Forest Products*. 1996, Swedish University of Agricultural Sciences, .

51. Hukka, A. and H.A. Viitanen, *A mathematical model of mould growth on wooden material.* Wood Science and Technology, 1999. **33**: p. 475-485.
52. Viitanen, H., et al. *Modelling mould growth and decay damages*. in *Healthy Buildings 2000*. 2000.
53. Krus, M., D. Rösler, ., and K. Sedlbauer, *Mikrobielles wachstum auf fassaden–hygrothermische modellierung.* Altbauinstandsetzung, 2006. **11**: p. 61-74.
54. Krus, M., M. Seidler, and K. Sedlbauer, *Comparative evaluation of the predictions of two established mould growth models.* ASHRAE Transactions, 2010. **116**.
55. Vereecken, E., D. Saelens, and S. Roels. *A comparison of different mould prediction models*. in *Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*. 2011. Sydney: IBPSA.
56. WHO, *Guidelines for Indoor Air Quality: Dampness and Mould*, R.O.f. Europe, Editor. 2009, World Health Organization: Denmark.
57. Nath, S. and M. Dewsbury. *The use of an innovative hygrothermal simulation method to develop built fabric recommendations for southern Australia*. in *Revisiting the role of Architecture for 'Surviving' Development: 53rd International Conference of the Architectural Science Association 2019.* 2019. IIT Roorkee, India: Architectural Science Association (ANZAScA).
58. Nath, S., et al., *A bio-hygrothermal mould growth analysis of typical Australian residential wall systems*, in *The 54th International Conference of the Architectural Science Association (ANZAScA) 2020*, A.G. Ali Ghaffarian oseini, and Nicola Naismith, Editor. 2020, Architectural Science Association: School of Future Environments, Built Environment Engineering, Auckland University of Technology, Auckland, NewZealand. p. 1-10.
59. AIRAH, *DA-07 Criteria for moisture control in buildings*. 2020, Australian Institute of Refigeration, Air-conditioning and Heating: Melbourne.
60. Kuenzel, H. and M. Dewsbury, *Moisture control design has to respond to all relevant hygrothermal loads.* UCL Open: Environment, 2022.
61. Slimani, Z., et al., *Use of the buffering capacity of the building envelope for the reduction of the rate of air exchange.* 6th International Building Physics Conference (Ibpc 2015), 2015. **78**: p. 1531-1536.
62. Ali, M., et al. *Moisture condensation on building envelopes in differential ventilated spaces in the tropics: quantitative assessment of influencing factors*. in *IBCC 2016*. 2016.
63. Woloszyn, M. and C. Rode, *IEA Annex 41, MOIST-ENG: Subtask 1 – Modelling Principles and Common Exercises (Final Report)*. 2007, International Energy Agency.
64. Department of Industry, *Your home: Australia's guide to environmentally sustainable homes*. 5th ed. 2013, Canberra: Australian Government, Department of Industry.