Scoping Study of Condensation in Residential Buildings

Final Report

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Definitions

Absorption: The ability of a material to accept within its body, quantities of vapour or liquid, such as moisture.

Air Barriers: Control the unintended movement of air into and out of a building enclosure.

Air Change Rate: Abbreviated ACH (air changes per hour) or ac/h, it is a measure of the air volume added to or removed from a space (normally a room or house) divided by time (i.e., 2ACH = the volume of air in the room is fully exchanged by an equivalent volume of air coming into or out of the room in 30 minutes.

Air Leakage: Sometimes called infiltration and exfiltration, it is the unintentional or accidental introduction of air into a building assembly, typically through gaps in the building envelope.

Air Permeability: The unintended leakage of air through gaps and cracks in the external envelope of a building. It is measured as the volume of air leakage per hour per square metre of external building envelope ($m^3/h.m^2$) at a tested pressure of typically 50 pascals (Pa).

Airtight: Not permitting the passage of air or gas either inward or outward

Building Paper: An absorbent permeable membrane made from treated kraft paper placed under roof or wall cladding. Also known as Permeable Underlay.

Cavity: A horizontal inclined or vertical space within the roof or wall that provides a drained air gap separation between the protected insulated zone and the external cladding.

Condensation: The process by which a gas or vapour changes to a liquid form.

Cooler Side: The side of a structure with a lower temperature compared to the warmer side. The cooler side usually has a lower vapour pressure compared to the warmer side.

Counter Batten: A spacer of timber or steel fixed to a purlin or batten, which provides an air space between the cladding and any insulation or sarking.

Dew Point: The temperature at which water vapour condenses, which varies with the relative humidity and the air pressure.

Humidity: Water vapour suspended in the air. The state or quality of being damp.

Impermeable: A barrier preventing the passage of a liquid or vapour. Sometimes known as a Vapour Barrier. (It should be noted that in many countries have classes of vapour barrier. In this case they are often a vapour permeable barrier but have varying degrees of vapour permeability).

Indoor Air Quality (IAQ): is a term which refers to the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants.

Indoor Environmental Quality (IEQ): Refers to the quality of a buildings environment in relation to the health and wellbeing of those who occupy the space within it. IEQ is determined by many factors, including IAQ, lighting, and damp.

Internal Relative Humidity (IRH): Is the measurement of relative humidity within a defined enclosed space. This may be a whole building, an individual room or a surface within a building.

Interstitial Condensation: Condensation occurring within or between the layers of the building envelope.

Moisture: This is a complex term which can refer to a range of physical states of water, from vapour to a liquid and does include metastable (moisture in wood) state.

Permeable Membrane: Any sheet material that permits the passage of water vapour. Also known as Breather type or Permeable Underlay.

Relative Humidity (RH): The ratio of the mass of water vapour in a volume of air, compared to the value that saturated air could contain at the same temperature and pressure.

Sarking: Continuous sheets of OSB, plywood, chipboard, pliable membrane or similar material laid over the rafters below roof sheet.

Surface Condensation: Condensation occurring on visible interior surfaces within the building

Thermal Bridge: An element within the built envelope of lower thermal resistance which bridges adjacent parts of higher thermal resistance and which can result in localized cold surfaces on which condensation, mould growth and/or pattern staining can occur.

Vapour: water in a gaseous state

Vapour Barrier: There is substantial and inconsistent use if this term internationally. In this document the term vapour control layer is adopted.

Vapour Control Layer (VCL): A graded impermeable to permeable layer designed to control the passage of water vapour. Also known as a vapour check, vapour retarder or vapour barrier.

Vapour Permeable: A vapour permeable material permits the passage of moisture in vapour form but not moisture as a liquid.

Vapour Pressure: is the pressure at which water vapour is in thermodynamic equilibrium with its condensed state. In the context of this report, the water vapour pressure is the partial pressure of water vapour in any gas mixture in equilibrium within and around the built environment.

Vapour Resistance: The measure of the resistance to water vapour diffusion of a material or combination of materials of specific thickness. Vapour resistance is expressed in MN.s/g.

Ventilation: The exchange of air between two spaces, often between internal building environments and the outside. To replace noxious or stale air with fresh air. Air may be moved mechanically or via passive means.

Vent: Any means of provided ventilation to enclosed spaces, such as walls and roofs, the vent is the means by which a space is opened directly to external air supply.

Ventilated Air Space: A cavity or void that has openings to the outside air and placed so as to promote through movement of air, (i.e., enclosed subfloor space, wall cavity, roof space, gap between sarking and roofing material).

Ventilation Rate: The rate at which air within a building is replaced by outside air. The ventilation rate may be expressed as; a) number of times the volume of air within a space is changed in one hour (air changes per hour (h^{-1})), or b) rate of air change in litres per second (l/s)

Underlay: An absorbent permeable membrane that absorbs or collects condensation, or water that may penetrate the roof or wall cladding. Also known as Building Paper.

Water Activity: Represents the ratio of the water vapour pressure in a sample against the water vapour pressure of pure water under the same conditions. "Free" water is present when the water activity is 1 and beyond. Fungal growth is likely if the water activity exceeds 0.76.

Water Resistive Barrier: Is a thin membrane, (0.13 to 0.38 mm) which is intended to resist liquid water that has penetrated behind the exterior cladding.

Water Vapour: Water in a gaseous state, it does not need to be visible to be present in the air

Wicking: The movement of water through a porous material by capillary action.

Warmer Side: The side of structure with a higher temperature than the cooler side

Executive summary

This scoping report was instigated by the Australian Building Codes Board (ABCB) in response to concern raised by building regulation stakeholders that new Class 1 and Class 2 buildings were experiencing unacceptable levels of condensation and mould. The persistent presence of condensation in buildings is linked to negative impacts on human health and amenity, as well as building structural integrity. Many factors within the design, construction and building occupation can contribute to the presents of condensation. However, in Australia, recent changes in the type and complexities of the modern built fabric and increased consumer expectations of thermal comfort within Class 1 and Class 2 buildings may have led to the establishment of building typologies that may not always be suitably equipped to manage vapour pressure, condensation and mould. Since, condensation within buildings is a complex and inter-related phenomenon, any successful mitigation strategy must take a holistic approach to the problem.

This Scoping Report sought to identify the key issues that may contribute to condensation in Australian Class 1 and Class 2 buildings. Specific focus was given to any factors arising from building regulation within the legislative framework, which requires the ABCB to develop regulations within Volume One and Volume Two of the National Construction Code (NCC) which provide Safe and Healthy environments for building occupants. However, the NCC also relies on the quality of many referenced Australian Standards and technical documents. Within this context, the ABCB may be required to liaise and apply regulatory pressure on Australian Standards committees to improve relevant documents. Similarly, as the ABCB establishes national minimum requirements, it may need to provide assistance and guidance to industry stakeholders, State and Local Government and consumers.

This scoping report firstly analysed what causes the physical process of condensation, the Australian legislative framework for new buildings that may impact on the occurrence of condensation and mould. It must be noted that there is no regulatory requirement within the NCC to mitigate condensation and mould within new buildings. This is followed by summary analysis of the Nationwide Condensation Survey, another ABCB initiative. This voluntary survey, completed by design and construction industry based professionals and trades, confirmed that there is a national concern about condensation in buildings constructed since 2004. The concern may extend to before 2004, but the survey did not provide this option. The extent of the problem may include 40% of all Class 1 and Class 2 buildings. These findings were corroborated by industry representatives that took part in an industry consultation process, completed as a part of this report. The consultation process included Architects, Building Designers, Building Surveyors, Builders, Quantity Surveyors, Building Scientists and product manufacturers. Prior to the commencement of this task, the Tasmanian building regulator had funded research to explore condensation and mould occurrences within new Tasmanian Class 1 buildings. The findings of the 'Tasmanian experience' closely correlated with the data from the survey and comments obtained from the industry consultation.

To place Australia regulation within a broader international context, the building regulations of New Zealand, United States of America, Canada, United Kingdom and Europe were analysed for any regulation on condensation and mould. It was quickly established that most countries had included regulations pertaining to the mitigation of condensation and mould in the last ten to twenty years. In all cases, the regulation had evolved from simple statements to sections of up to 120 pages and often included reference to approved national standards documents. In the case of the UK, this included BS5250, which was first published in 1975, but has received significant expansion and amendment as the science associated with water vapour in buildings and vapour pressure management became more scientifically informed and precise. What was also evident from the review of international literature review and the review of building regulations was the very strong focus on two regulatory aspects, namely:

- Building durability, and
- Occupant health

The aspect of building durability was discussed extensively within the 'Tasmanian experience' and experiences in New Zealand that commenced more than a decade ago. All regulations had a strong focus on the need to keep all parts of the built fabric dry and free from mould. The aspect of occupant health has gained increasing international priority. A number of international studies have established a population-based link between condensation, mould and human health. The most comprehensive was conducted by The World Health Organisation – Europe established:

> *"Sufficient epidemiological evidence is available from studies conducted in different countries and under different climatic conditions to show that the occupants of damp or mouldy buildings, both houses and public buildings, are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma."*

This has been further verified by World Health Organisation recommendation in 2009, which identified that no safe thresholds can be recommended for acceptable levels of contamination with microorganisms. instead, it is recommended that dampness and mould-related problems be prevented in all buildings. The human health implications include asthma and other chronic diseases, at a time when Australia has very high rates of asthma per capita. Often included within the medical field of allergy and immunology, this significant awareness has lead international regulators to develop performance requirements for minimum indoor air quality and indoor environmental quality, which by default applies to mitigation of condensation and mould within subfloors, floors, rooms, walls, ceilings, roof spaces and roofing of all buildings.

The review of international regulations identified significant gaps, where Australian regulation has not kept pace with international expectations or the correlation between greater expectations for human comfort and its impact on vapour pressure differentials, or the inclusion of thermal performance regulations, which create greater differences between interior and exterior vapour pressures. All of which are likely to cause condensation and subsequent mould within Class 1 and Class 2 buildings in all climate types in Australia.

After considering what gaps needed addressing first, some draft regulatory suggestions were sent to a quantity surveyor to establish likely changes in construction costs for Class 1 and Class 2 buildings. The costs varied from $125 to nearly $5,000 for different actions. However, the experiences from Tasmania, New Zealand and the industry consultation process highlighted that the extensive costs currently being borne by owners of new homes, builders and the broader community to remediate the significant presence of condensation and mould. The annual medical costs that may be correlated within Australian for chronic disease treatment, which may have resulted from condensation and mould within buildings could well be in the billions. The occupants, who are often families cannot be forgotten. Rectification costs are significant. The rectification process places financial and other stresses on home owners. The Tasmanian Experience has shown the rectification costs are significantly more expensive, time consuming and stressful for homeowners, than the mitigation costs identified. Individual cases have included family breakdown, depression and other long-term health effects from living in houses with condensation and mould.

To mitigate the occurrence of condensation and mould from Australian Class 1 and Class 2 buildings, this scoping report has identified three stages of regulatory enhancement that should be adopted by the ABCB. These are explained and discussed within Part 9 – Scoping Report Recommendations. The measures are staged for 2019, 2022 and 2025 to align with the three yearly amendment cycle of the NCC. It should be noted that the recommendations for Stage 1, will not mitigate all occurrences of condensation and mould from new buildings. Only when all three stages have been applied can it be comfortably assumed that most instances of condensation and mould in new buildings has been mitigated. Unfortunately, this leaves a very large number of Australian Class 1 and Class 2 buildings that will continue to have built fabric and human health implications until remediation actions or building replacement has occurred.

As a closing statement two significantly different views became evident during the research associated with this report, namely:

- From Australia: *Condensation and mould are the fault of the building occupant and not the building*
- From all other developed nations: *Buildings are often not used as intended by occupants, so designers and builders need to err on the side of caution and adopt robust fail-safe built fabric solutions to eliminate the occurrence of built fabric and human health affecting condensation and mould.*

This difference in approach between Australia and the other developed countries reviewed in this report underpins an important distinction between which party is ultimately responsible for condensation, and what degree of governance over this matter is appropriate.

Purpose of this scoping report

Introduction

The Australian Building Codes Board (ABCB) commissioned the Scoping Report to determine the nature and extent of condensation in residential buildings (National Construction Code Class 1 and Class 2 buildings) and develop recommendations on the possible role of the National Construction Code (NCC) may play in the mitigation and risk reduction of condensation in residential buildings. Foundation documents for the Scoping Report included the ABCB Nationwide Condensation Survey responses and experiences from Tasmania and New Zealand. The full terms of reference are set out in Appendix 01. The terms of reference can be summarised as providing:

1. An analysis of the nationwide condensation survey responses
2. An analysis what may be causing any increase in condensation in Class 1 and Class 2 buildings
3. The nature and extent of the problem
4. How NCC requirements may be influencing risk of condensation
5. Any relationship between changes in NCC and increase of condensation forming
6. Gaps within the NCC which may influence risk of condensation
7. Capacity of industry / occupants to manage condensation risk
8. Approaches being used internationally and nationally to manage condensation risk
9. Apply the learnings of existing Tasmanian and New Zealand work around condensation risk.

Background

Incorrectly, condensation and mould have historically been an accepted part of the built environment within Australia. It has unfortunately become a ubiquitous part of bathrooms, wet areas and other habitable rooms within many homes. But in its hidden form it is also a problem within interstitial spaces, sub-floor zones and roof spaces As a result, and for a long time, condensation and mould has not been seen as a significant problem by home owners, but an accepted part of the domestic setting. However, in light of current international literature, regulation and medical awareness on this topic, the conditions within these buildings may have provided long term and significant structural degradation, and immunology and allergy health concerns for the occupants.

In response to a growing market based awareness, from occupants, construction trades, building designers and associated professions, the Australian Building Codes Board (ABCB) initiated the *Condensation Handbook 2011* which was significantly updated in 2014, and received minor revision in 2016 (ABCB, 2016a). The aim of the Handbook is to provide construction industry participants with non-mandatory advice and guidance on condensation in buildings. The Handbook consolidates current research and information around condensation risk and mitigation and the design and construction of 'dry' buildings.

The ABCB notes that the publication of the Handbook significantly increased traffic to their website, suggesting that interest in these matters extends beyond the community of building practitioners who work with the regulatory provisions of the NCC. During this same period, in response to new home-owner concerns, the Director of Building Control, Tasmanian Department of Justice, initiated a study into the occurrence of condensation in new homes. *The Investigation of Destructive Condensation in Australian Cool Temperate Buildings* was published in February 2016. Additionally, during the research period a number of other actions were taken, namely:

- the development and publishing a first version of the *Condensation in Buildings: Tasmanian designers' guide*, (with the assistance of the Tasmanian Fire Service),
- the provision of seminars across Tasmania with construction industry representative bodies, builders, engineers, building surveyors and building designers on the management of vapour within buildings.

This work provided the opportunity for considerable discussion and information exchange between a wide range of construction industry sectors and national product manufacturers. This work contributed to a growing body of anecdotal evidence that there was built fabric problems which related to condensation that was showing presence in all States and Territories of Australia.

This growing awareness led the ABCB to initiate the Nationwide Condensation Stakeholder Survey 2015-2016. The survey's aim was to gather evidence and feedback on the extent of condensation problems in Class 1 and Class 2 residential buildings, and the likely causes, as well as gain an understanding of industry's capacity to manage condensation risks. The Survey period was from late December 2015 to February 2016 and received 2664 responses.

Structure of scoping report

The Scoping Report seeks to addresses the Terms of Reference in the following way.

Part 1. Condensation in Buildings: provides an overview of condensation in domestic dwellings (Terms of Reference 2 and 3). This includes a discussion of the science of vapour formation, and the relationship between temperature and humidity factors that lead to mould and fungal growth and the role building construction plays in exacerbating or mitigating these conditions. Part 1 examines the reasons condensation risk may be increasing within the current Australian domestic housing sector and includes changes in building practice, building materials, regulatory change and changes in occupant patterns of use.

Part 1 also provides an overview of the key risk associated with condensation. These are identified as a risk to human health and a risk to building integrity. A summary of the review of international literature on each of these issues is provided and examples of the types of problems identified in Australia are discussed.

Part 2. Current Legislative Framework: provides an overview of the current Australian regulatory framework which may relate to condensation (Terms of Reference 4). As per the terms of reference the focus is on NCC Vol 1 and Vol 2. A summary of the key aspects of the NCC regarding condensation are identified and an analysis of critical changes to the NCC are provided.

The discussion, however, also examines critical regulation outside the remit of the ABCB to include state regulations around health and building control. Also current Australian Standards, non-regulatory technical document and Industry guides are also identified. A discussion on the role of these documents is included in the Gap analysis conducted in Part 5.

Part 3. Determining the Extent of the Problem: seeks to begin the process of determining the extent of the problem of condensation by analysing the results of the condensation survey

(Terms of Reference 1). An overview of key findings and a summary of the results is provided. A full analysis is provided in Appendix 02. The findings of the survey are used to inform the scoping report recommendations.

To further enhance the industry perspective of the problem, industry based stakeholders were interviewed individually and via representative group meetings. The aim of this additional process, was to give industry bodies the opportunity to discuss in confidence any issues regarding condensation that they may have identified. A full list of industry interviews is provided in Appendix 03. These interviews were also used to test a draft version of the scoping report's recommendations. Feedback from this process were integrated into the scoping report final recommendations.

Part 4. Residential Building Codes – An International Perspective: discusses a review of the residential building codes of four comparable countries (USA, Canada, UK, NZ) and examined regulatory framework within the EU member countries to highlight key issues (Terms of Reference 8). The Review was conducted using a matrix of key regularity components that the project team identified as drivers in effective regulation of condensation risk management and mitigation. This section concludes with a summary of the key findings of the international building regulation review, and a discussion of the findings in the context of the current Australian regulatory environment The full review is provided in Appendix 04.

Part 5. Potential Gaps in the Requirements of the NCC: provides a gap analysis of the NCC Vol 1 and Vol 2 (Terms of Reference 6). The findings of Parts 2, 3 and 4 are used to identify areas within the current regulatory system that may influence or not mitigate the occurrence condensation. This includes both aspects that are identified and areas that may not be addressed appropriately within current regulations. The regulatory response to condensation risk requires a holistic approach. As a result, Part 5 also examines aspects that sit outside the regulatory framework of the ABCB but which need to be addressed. This includes Australian Standards referenced by the NCC, State/Jurisdiction regulation, manufacturers literature and architectural (building design) documentation.

Part 6. Cost Benefit Analysis: provides an initial cost-benefit analysis of the proposed recommendations. As this is a scoping report, it is not a comprehensive analysis, but rather, through modelling of standard building designs, seeks to identify critical areas where additional costs are anticipated. This is quantified to the individual model house level only. Additionally, benefits of the proposed recommendations are also identified. Similarly, the benefits are discussed at the individual house level. Furthermore, the research from Parts 1 & 4 has identified significant building occupant health benefits, which is included as a significant benefit from improved regulation.

Part 7. Unintended Consequences and Further Research: provides an analysis of potential unintended consequences stemming from the proposed recommendations. This includes a summary of where, the project team believe, further research could be undertaken to progress the mitigation or condensation risk in Australia.

Part 8. Discussion and Conclusion: summarises the key findings that informed the development of the scoping report recommendations.

Part 9. Scoping Report Recommendations: is divided into three distinct sections, namely:

- Section 1: which outlines the approach taken to formulating the recommendations, the mechanisms by which the recommendations were structures, and the rationale behind a staged and targeted approach to implementation.

- Section 2: ranks the recommendations based on their likely impact for condensation risk management.
- Section 3: outlines each of the proposed recommendations with a supporting discussion.

Part 1: Condensation in buildings

Overview

This part of the Scoping Report, provides an overview of condensation in domestic dwellings. The discussion includes an overview of the science of vapour formation, and the relationship between temperature, humidity and the factors that can lead to mould and fungal growth. The role that built fabric plays in exacerbating or mitigating these conditions is elaborated. This includes examples of the recent occurrences of condensation and mould in Australian buildings.

This is followed by a discussion about why condensation risk and occurrences of condensation and mould may be increasing within the current Australian residential buildings. This is linked to possible causes, including changes in building practice, building materials, regulatory change and changes in occupant patens of use.

The third section provides an overview of the key risk associated with condensation. These are identified as risks to building integrity, and risks to human Health. A summary of the review of international literature on each of these issues is provided.

The final section in Part 1, provides an overview of the current international literature on condensation, which is provided to assist in the identification of any patterns in the cause, frequency and mitigation of condensation. These patterns and trends were used to assist in developing a matrix, which was then used in the International Regulatory Review outlined in Part 4.

What is condensation?

Water exist in three states, as a liquid, as a gas and as a solid. Condensation is the point at which water vapour as a gas in the air converts to a liquid state. How condensation forms, changes, moves and interacts with physical objects is a complex process. However, some simple guiding principles, based in physics, can assist in predicting how moisture in the air, moves through and interacts with a building assembly.

Wherever there is air, there is water in that air in a gaseous state, this is known as vapour. All spaces within the building fabric, be it wall cavities, roof spaces, sub-floors and even within building products themselves, contain air and therefore some amount of water vapour. Vapour and vapour movement within the environment and within buildings is a natural and unavoidable process.

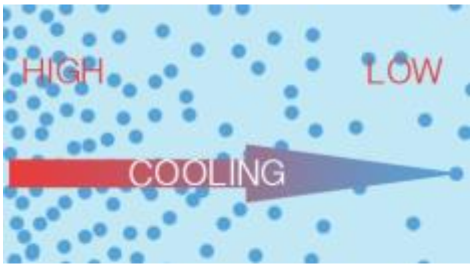

Figure 1 – Diagram of vapour pressure.

Water vapour's transition into condensation follows a simple set of rules. First water vapour will seek an equilibrium of vapour pressure difference. This movement of vapour is based on the conditions of the air, as shown in Figure 1. In essence, vapour will move from an area of relative high vapour pressure towards an area of low vapour pressure. Often there is a correlation between vapour pressure and air temperature.

The use of built fabric assemblages to enclose a space often creates variations between internal and external vapour pressures. The difference in vapour pressure will drive a physical and mechanical process where these two vapour pressures seek to be in equilibrium. This may happen via an open window, vapour diffusion through building materials, or via penetrations in the built fabric.

Having seen the mechanism for why vapour moves through the building assembly, we move to the second rule in the formation of condensation, that is relative humidity. As vapour moves from the warm side to the cold side of the material the air holding the water vapour cools. As the air cools its ability to hold water within it reduces. Hot air can hold more water vapour per cubic meter that cool air. If air cools, but the amount of water vapour within it remains the same, the relative humidity increases. If the air temperature continues to fall, it will reach a saturation temperature. Saturation temperature is when the air reaches 100% relative humidity and this coincides with dew point. At this temperature and below, condensation will form. Dew point temperature continually changes, as the physical system responds to air temperature, the amount of water vapour in the air and air pressure.

Therefore, throughout the built fabric vapour will migrate to equalise pressure differences. Warm air will move towards cool air, and its temperature will fall. If air temperature continues to fall the relative humidity of the vapour within it will rise. Depending on the amount of water in the air a point of saturation will occur, (dew point), and the vapour within the air will condense into liquid water, condensation.

Condensation within buildings

It is generally accepted that the human occupation of a residential building creates approximately 10 litres of water vapour per person per day. In a family home with four occupants, this equates to 40 litres of water vapour within the built fabric per day. This comes from people breathing, cooking, boiling a kettle, washing and bathing, indoor plants and pets.

As discussed above, the creation of the often distinctly different internal and external environments by a building enclosure, will establish differential air temperatures and vapour pressures. If, for example, the internal temperature is warmer than the outside temperature (a typical cool winters night) this will create a pressure differential between the inside and outside of the building. The vapour will migrate to equalise the vapour pressure difference. The vapour migration will carry the 40L of water vapour generated by the occupants with it. If the vapour comes in contact with a surface that cools it to a point where it reaches its dew point, condensation will form at that point. Similarly, in a hotter climate, where rooms are often cooled to a more comfortable temperature, the higher vapour laden outside air will drive vapour migration toward the cooler interior. Within the built fabric this may occur on wall surfaces, windows, within walls, on pliable wall and roofing membranes and on air-conditioning ducting and pipework.

Determining where and when condensation will form

The building science professions often illustrate the relationship of air temperature, relative humidity and dew point with a psychrometric chart, as shown in Figure 2 below. The horizontal axis represents dry bulb air temperature. The vertical axis represents humidity. The curved profile on the left side of the graph represents dew point or saturation temperature. In this figure the internal conditions are shown in orange, the external conditions are shown in green, the middle of the roof space is shown in red and the inside surface of the roof sarking is shown in blue. However, this psychrometric graph shows data from a new 'NCC compliant' house. A large amount of the data in blue is parallel to and against the line for dew-point, as described above, this indicates that the vapour in the air, and near to this surface would be condensing.

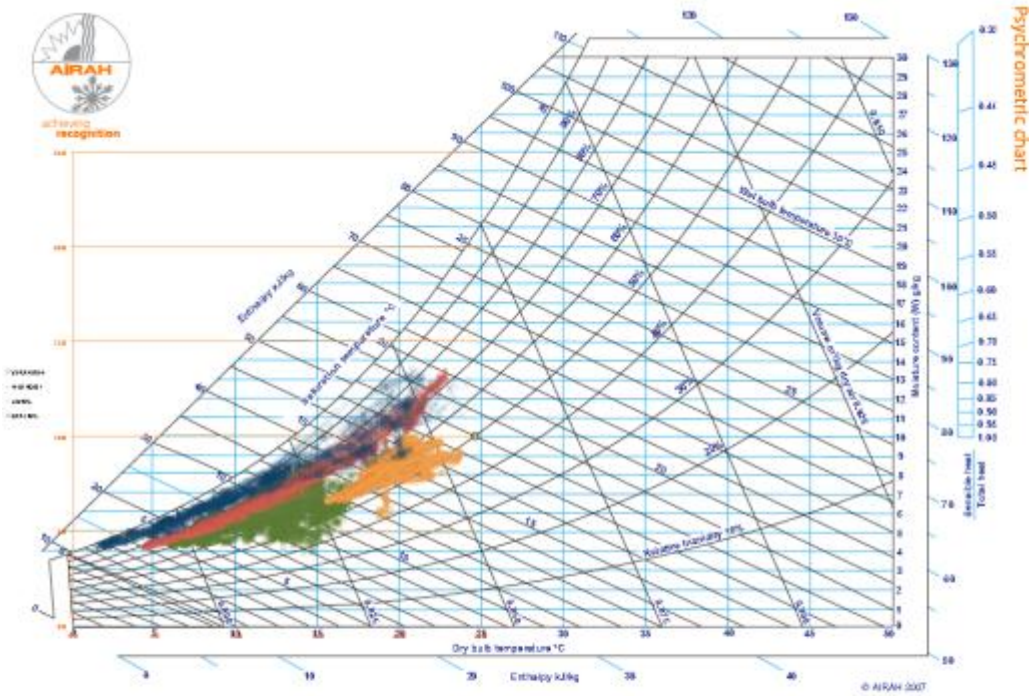

Figure 2 – Temperature and humidity measurements made in a Tasmanian house.

Why condensation forms in a building assembly

Figure 3 below illustrates a hygrothermal analysis of a typical residential wall system on a typical evening in Sydney. The wall system comprises an external masonry veneer wall, with a vented cavity, a vapour impermeable wall wrap, insulation and plasterboard.

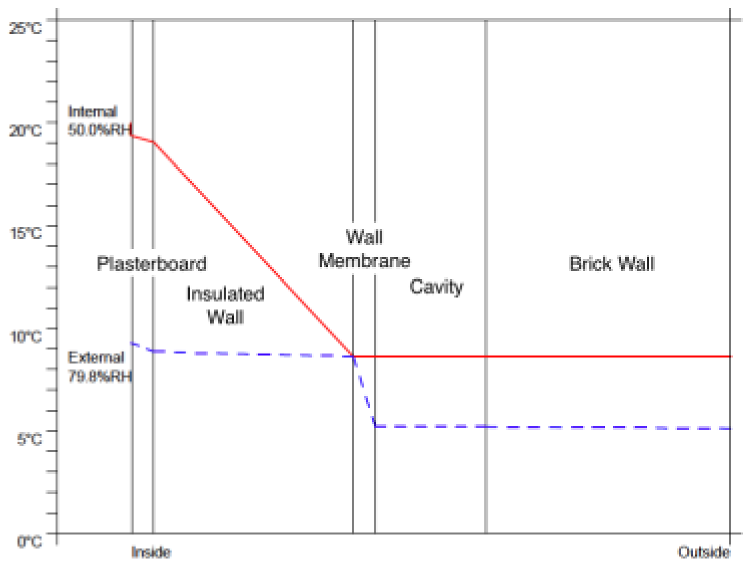

Figure 3 – Hygrothermal analysis of a masonry veneer wall system.

The red line shows how the temperature changes through the wall system between the site air temperature and the internal air temperature. The blue line represents dew point temperature. When the two lines meet, condensation is likely to occur. This illustrates that as the temperature drops between the interior and exterior surface of the wall insulation, the capacity for the air to retain vapour reduces. In this example the vapour migration is also hindered by the vapour impermeable wall wrap. When the temperature reduces to saturation, as discussed above with the psychrometric chart, the vapour condenses and becomes moisture. In the context of the analysis and discussion above, this could occur on:

- On the cool metallic surface of ceiling mounted and recessed light fitting,
- On the cool surface of a window pane,
- On the cool surface of a window frame,
- Interstitially within the walls, which may present itself through expanded timber trims around the window
- Invisibly in the walls, where timber framing and wall insulation batts may be sodden,
- Visibly on the interior surface of roof space sarking (for those that look inside a roof space),
- Visibly due to mould growth on the timber structure, (for those that look inside a roof space or behind plasterboard walls),
- Mould growth on internal walls, due to excessive moisture in the wall, and
- Moisture forming on the inside surface of an uninsulated floor.

The movement of vapour through the built fabric is called diffusion. Different materials have different diffusion rates, which can significantly affect the vapour pressure in different parts of the building assembly. However, the diffusion of vapour through the built fabric is only one component of water vapour transport. Accidental air leakage, through gaps, in the building fabric can represent a much higher proportion of uncontrolled vapour transfer into interstitial spaces or the interior of the house. The ABCB Condensation Handbook notes that 1m² of plasterboard allows 150g of water transfer via vapour diffusion each month. However, an unsealed average sized general purpose power outlet can allow 20kg of water vapour to leak into a wall space during the same time.

Additionally, if the path for vapour to diffuse through a building assembly is blocked by an inappropriate vapour control layer, the vapour pressure cannot reach equilibrium. If an inappropriate vapour control layer prevents the vapour from leaving the building, the amount of internal vapour keeps increasing, significantly raising the relative humidity within the house and within the walls and roof space. If any element within the built fabric is cool enough, the vapour will condense into moisture and the visible presence of water. The moisture can then fall or run as a liquid to pool and wet areas on surfaces and within the building fabric. If this occurs for a prolonged period, it has the potential to degrade structural materials and support the growth of mould.

Figure 4 below, shows an infra-red image of an insulated wall. The generally green coloured elements are close to room temperature. However, the light blue through to black coloured areas illustrate increased amounts of thermal bridging. The light blue areas signify the lower R-value of the wall framing compared to the areas of insulated wall. The darker blue sections indicate likely locations of unintended infiltration from the external wall wrap and/or uninsulated corners. The magenta to black sections highlight the common fault of air leakage combined with thermal bridging where wall framing meets the floor system. In the context of the above discussion, these locations can provide ideal environments for vapour to condense.

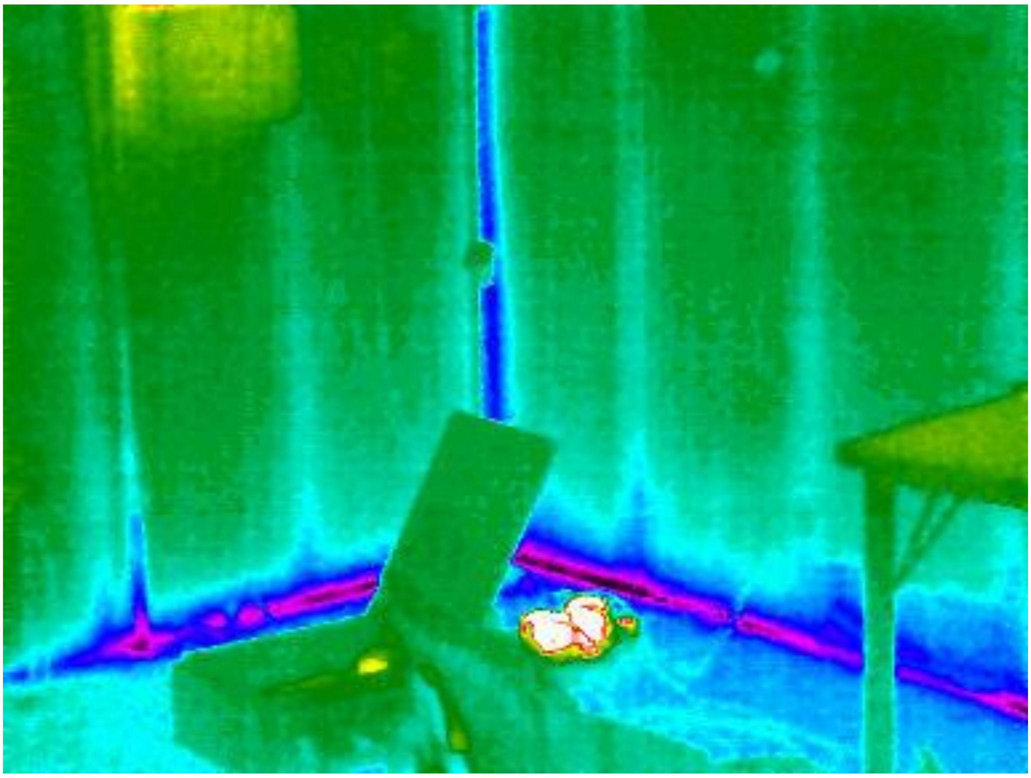

Figure 4 – Thermal bridging of external wall built fabric

Where mould is a concern, it should be noted that relative humidity is only an approximate indicator of the conditions, with water activity being a more accurate indicator of when conditions are conducive for mould growth.

> "Fungal growth is likely if the water activity exceeds 0.76 to 0.96, depending on fungal species, temperature, time, and composition of the material"
>
> (Kowalski, 2005)

The measure of water activity ranges from 0-1, and is similar to the measure of 0% to 100% for relative humidity, that it gives a factor to how much moisture can be held in a material until it reaches saturation, at which point and beyond, 'free water' is available on the material surface. Although water activity and relative humidity are conceptually similar, they are rarely of the same value. When a room has a relative humidity of 76% it does not necessarily equate to a 0.76 water activity within the walls. These values will coincide only if the material under consideration is at the same temperature as the air. This may be the case in a well-insulated part of the wall. However, there are many times the wall plaster may be influenced, and even dominated, by the cold external conditions, like the thermal bridging example discussed and shown above in Figure 4. This condition can be further exacerbated when the wall plaster does not benefit from direct space heating, like behind cupboards, sofas and beds. A material sample of lower temperature than the internal air will have a water activity higher than the equivalent relative humidity of the air. In an inadequately insulated room, one might find mould growth first occurring along cornices, skirting boards, top external corners of the ceiling and behind furnishing.

Condensation in different climate zones

As noted above, the enclosure of a space by a building fabric effectively creates two climates, an internal and external climate. This establishes a vapour pressure differential which essentially creates one of two scenarios, namely;

1. If the Internal temperature is warmer than the external temperature causing water vapour to migrate outward, and
2. If the internal temperature is cooler than the external temperature causing water vapour to migrate inward.

All building enclosures establish this dynamic between interior and exterior spaces, between unconditioned and conditioned spaces, between rooms with sunshine and those without, and between rooms with internal loads and those without. Each of these four scenarios combined with the two climate typologies listed above create differences in temperature between rooms in a house and between those rooms and subfloor zones, roof space zones and the external environment. Figure 5, below illustrates in a general manner of this vapour pressure principle.

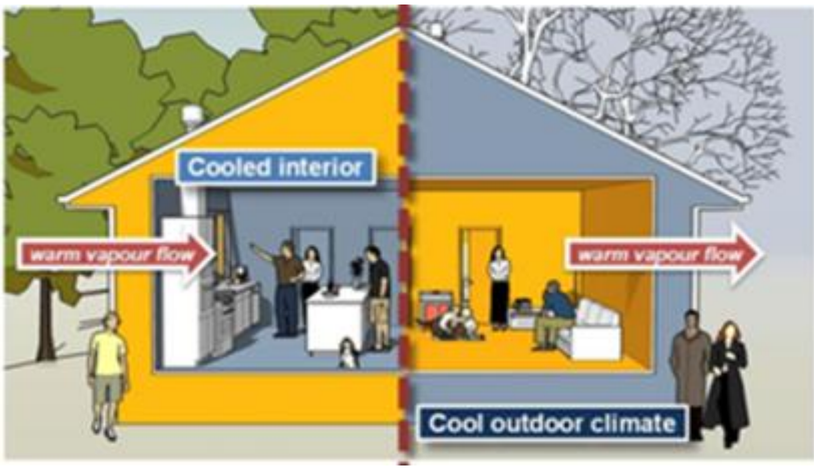

Figure 5 – Mass Air Movement as a result of temperature differences between internal and external environments. (From ABCB Condensation in Buildings Handbook Second Edition 2014)

An analysis of the complexity of the climatic conditions within each of the eight NCC climate zones, combined with thermal comfort expectations of house occupants creates the potential for water vapour to move in one direction or even two directions on a daily or even, hourly basis. Locations such as Townsville will normally have a single-direction water vapour migration system. However, other locations such as the western suburbs of Sydney, Brisbane, the Adelaide Hills and Alice Springs are all in climate zones that over a day and over a year can have a multi-directional water vapour migration system at play. All have the potential to experience periods of internal heating or cooling over a year. The key is how does the built fabric of buildings in these diverse climate zones manage water vapour pressure and mitigate the risk of condensation.

Condensation – examples of damage

The formation of condensation can be visible and cause damage to the surface and interior of linings and cladding. But it can also form invisibly within interstitial spaces, within subfloor zones, the floor structure, the wall fabric, the ceiling system or the roof/sarking system.

Figures 6 to 12 below show, examples of visible and invisible condensation with a home. All of these images are from new houses less than four months after completion and occupation.

Figure 6 – Expanding timber elements resulting from excessive moisture in the built fabric

Figure 7 – 'Raining' windows resulting from excessive moisture in the built fabric

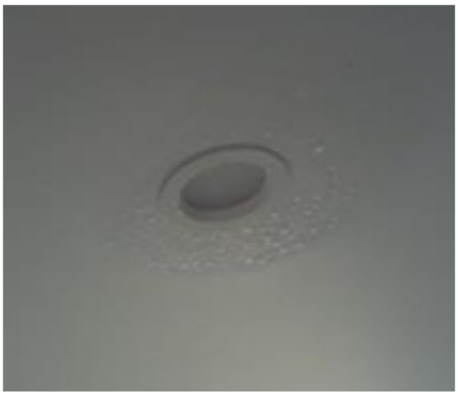

Figure 8 – Moisture forming around ventilated and uninsulated downlight

Figure 9 – Wet wall insulation, wet timber structure and mould growth within wall

Figure 10 – Mass Figure 8. Moisture on inside surface of roof sarking

Figure 11 – Mould growth in overly moist roof space

Figure 12 – Mould growth on wall resulting from excessive moisture in wall and moisture forming on uninsulated floor

What is driving possible condensation risk

There is anecdotal evidence of concern about condensation and mould in buildings dating back to the Israelite conquest of Canaan in c.1400 B.C. (Holy Bible: Old Testament). Similarly, several changes were made during the reconstruction works after the great fire of London in 1666. More recently, extensive research was completed in Europe and the America's before 1940, which examined materials and their likelihood to accumulate moisture in walls (Babbitt, 1939; Barre, 1940). This knowledge was coinciding with taller buildings, with greater occupancy ratios, better quality envelope construction and the inclusion of air-conditioning. This knowledge was often included in architectural and building science books and notes in common use at the time and in progressive design and construction manuals (CSIRO, 1962; van Straaten., 1967; CSIRO, 1970; Szokolay, 2008).

Historically, vapour pressure management and condensation risk analysis were taught within applicable technical and tertiary courses, which utilised Australian and international guidelines (Experimental Building Station, 1964; van Straaten., 1967; CSIRO, 1970). However, it appears that due to the general leakiness of historical Australian construction practises and the general 'de-sciencing' of many technical and tertiary training courses, which have often blamed pressures from funding arrangements, this critical component of built fabric design and construction has been removed from key learning outcomes and regulatory requirements.

This combination of simplified professional education, the desire and requirement for more complex building envelopes and the lack of guiding regulation, has established a significant knowledge gap between the technical considerations required to safely achieve more thermally efficient, structurally safe and healthy buildings and the current industry capacity of construction trades, building surveyors, environmental health officers, engineers and the building design professions. This gap has become clear nationwide. This is evidenced by the responses in the nationwide condensation survey and consultations with many levels of industry, government regulators and manufacturing undertaken for this report.

Whereas the Australian manufacturers and the design and construction professions appear to have 'forgotten' this integral component of building science, other nations have developed regulations, strict guidelines and national standards. One example is the British Standard 5250 - Code of Practice for the Control of Condensation in Buildings' (British Standards, 2011), which was first published in 1975. Similar requirements are detailed within the U.S. International Residential Code and the National Building Code of Canada. These are discussed in greater detail within the literature review.

Social and regulatory changes

Since 2004, and in response to building thermal performance requirements in the NCC, builders in states that require heating or cooling started to make buildings 'tighter' (ABCB, 2003; 2004; Nolan and Dewsbury, 2006; ABCB, 2007; 2010). Correspondingly at this early stage, a significant shift occurred, where houses started trending from principally unconditioned to conditioned (Dewsbury, 2011; Dewsbury, 2015).

However, this shifted the primary focus for the construction industry, which includes building designers (draftspersons, building designers and architects), building trades, engineers and building surveyors, from many other historical knowledge areas to the application of thermal performance requirements. It is one thing to specify a building should be more air-tight or have greater quantities of insulation within the envelope, but these simple actions create quite dynamic thermal differences within the built fabric, and in the context of condensation risk, significant differences in vapour pressure. Vapour pressure management is readily discussed in some permanently conditioned non-residential building projects and is often managed by the ducted air-conditioning system. However, even in the commercial construction sector, mechanical engineers have raised significant concern about uncontrolled air leakage and poorly designed built fabric systems and their impact on vapour and humidity management in new buildings. This indicates that in many Australian residential and non-residential buildings which are unconditioned, intermittently conditioned and permanently conditioned little to no consideration of vapour pressure management has been included within the design or construction stages.

Reasons for the significant differences are both historical and social. The majority of Australia's population generally live in temperate climate zones and they have historically accepted a greater range of daily internal environmental conditions. This provided considerable scope in how internal built environments operated and in particular the accidental passive management of vapour pressure. Other countries have significant populations living in more severe climatic zones than many parts of Australia. As a result, and when compared with Australia, there was a need to establish buildings that could provide a more appropriate indoor environment. This led to the earlier development building regulations and more climatically appropriate built fabric systems.

However, as evidenced in the significant increases in regulation, guidelines and standards, (including the occasional backflip), these nations have had their own steep learning curves about vapour pressure management, condensation risk management and the need to eliminate mould growth in all building typologies. In essence, they have decades of experience which Australia should learn from, however much of this has occurred in temperate and cool climates. Recent and ongoing built fabric suggestions for more hot and humid locations, such as Florida, in the United States, show that long term beliefs and practices for the most effective methods to manage vapour pressure are still evolving.

However, as Australian thermal performance requirements have been enhanced, the market (house occupants) have often demanded more thermally comfortable internal conditions, often combined with undocumented, installation of affordable heating and cooling systems after the initial construction. These expectations should not be ignored and in many instances they mirror the thermostat set points and hours of operation adopted by NatHERS and the NCC. Each of these changes on its own creates significant vapour pressure differentials, condensation risk and mould growth opportunities in all Australian climates. Recent research has even highlighted observations of new housing where financially able occupants operate the household reverse cycle air-conditioning seven days a week, twenty-four hours a day.

Whilst mortgage stressed, lesser financially able new home-owners are conditioning as little as possible (Dewsbury, Law, & Henderson, 2016).

To date, the regulatory response to these new types of conditioned internal residential spaces enclosed within often unconsidered and unregulated built fabric combinations, have created short and long-term consequences to built fabric durability and human health. Australian regulations have not responded with the same holistic, regulative and educative rigger as evidenced in other countries. The Australian regulatory approach has often relied on the market to address the issue, however, the current market, (which includes industry and consumers), is not sufficiently educated or correctly informed about condensation risk and its long term impact on built fabric and human health. There is a general 'acceptance' of mould. A general comment from medical practitioners in south-western Sydney, was that many homes have unhealthy amounts of mould. There is a lack of understanding of expected internal thermal performance characteristics and how they affect condensation risk and internal air quality. These conditions do not allow for the market to make informed decisions. It is not appropriate to assume that consumers will or should have the expertise to make informed decisions about condensation risk and its mitigation. Rather, like other industries, there needs to be a level of consumer protection built into the regulatory framework to address this legitimate knowledge gap.

Therefore, as now recognised by the ABCB

> *"Increasing levels of insulation and air tightness are changing the underlying building physics, less energy flow through the building fabric also means less moisture flow, so when the fabric gets wet, it is likely to stay wet longer. These circumstances suggest that condensation management strategies based only on established expectations, rules of thumb or narrow margins of safety are unlikely to stand the test of coming decades".* (ABCB, 2016a)

Condensation and risks to building integrity

The function of the NCC and building regulations are to protect occupants of buildings, whether they are the owner, a tenant or a visitor. Excessive moisture within a building can and will compromise long-term structural integrity and built fabric material performance. Similarly, moist environments will provide ideal conditions for mould to grow and spore freely, significantly impacting on human health. Within residential and non-residential buildings in South Australia, Tasmania, Victoria, the Australian Capital Territory and New South Wales, there has been a growing awareness of condensation and mould in buildings. This has come to the attention of the UTAS team via builders, building designers, structural engineers, mechanical engineers, house and building owners and tenants, building regulators and product manufacturers. All often after the 'magic bullet' to remediate an often complex problem. Some recent examples are illustrated and discussed below.

Figure 13 below, illustrate moisture content measurements from a new home. The house had been occupied for approximately four months when these measurements were taken from the softwood structural framing in the eastern and western walls. The southern wall had a values up to and greater than 18%. The accepted moisture content for softwood framing for long-term durability is between 6% and 7%. The moisture content within the timber framing was two to three times acceptable levels. In addition to the excessive moisture causing sodden framing and sodden (and ineffective) wall batt insulation, the performance of friction and shear connectors are significantly compromised. Likely causes of the excessive moisture included the use of vapour impermeable building wall wrap, no vapour cavity, inadequate roof space ventilation and significant thermal bridging. In this situation, like many others, extensive discussion, and argument, occurred as to who was responsible. At first, and as is common practice, the home occupants were blamed. After an independent consultant was engaged, the building designer, building surveyor, builder and subcontractors were all adamant that the architectural documentation and construction practises all complied with the requirements of the NCC. After extensive negotiation remediation was completed. For this new home, the tasks included removing sheet metal roofing, moisture and mould affected battens, moisture and mould affected blanket sarking system, sodden ceiling batt insulation, sheet metal cladding, vapour impermeable wall wraps, sodden wall batts and moisture affected internal timber reveals and trims. This process required the already mortgage stressed family to rent a second home for the many months during the deconstruction, drying time, mould removal and reconstruction processes. The remediation costs were in excess of \$40,000 for this $63m^2$ home. Additionally, and during this long and stressful process, the married couple separated and most of the family developed allergy and immunology conditions which in international literature has been linked to mould in buildings. The family were additionally advised by the family doctor to leave the building immediately, yet this advice was contradicted by an environmental health officer.

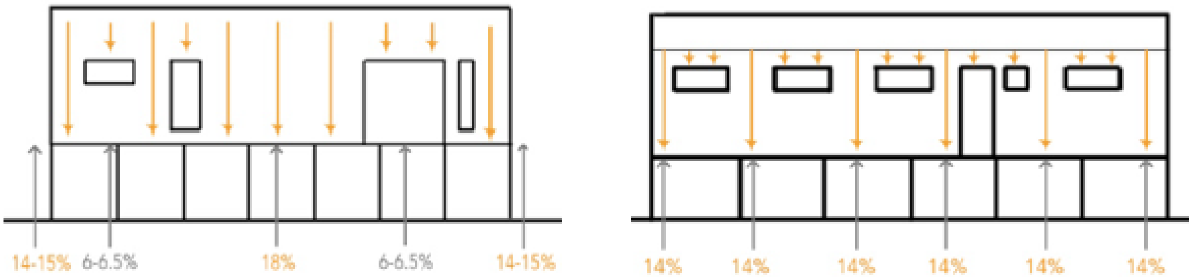

Figure 13 – Moisture content in east and west walls of six month old residence

Furthermore, in this case study, the discussion included concern about the structural durability of the timber structure. The continual expansion and contraction of the timber elements will have a significant impact of the serviceability of the friction and shear metal connections for all elements, which perform as structure, bracing and tie down functions. Metal shear connectors which are a common element in prefabricated stud wall and roof truss systems. These same connectors require a flush and tight fit between the wood products and the sheet metal fixing. The expansion and contraction of the wood, as it absorbs excess moisture and expands, followed by a period of drying will force the connector out of the wood leading to structural failure and significant harm to the building occupants (Leicester *et al.*, 2003; Nguyen *et al.*, 2008; Paevere *et al.*, 2008; Paevere *et al.*, 2009).

Figure 14 – Condensation on interior surface of double glazed window and condensation raining within roof

Figure 14 above, show condensation on a double glazed window and the inside surface of the sarking system in a new home. The owners of the new home raised concern after less than three months of new home occupation. The excessive moisture on the windows, interior walls and ceiling mounted downlights demonstrated the very high humidity levels within the home. Closer inspection revealed a very moist, foggy, dripping and mould affected roof space. This house had a 'breathable' vapour impermeable wall wrap system, inadequate roof space ventilation, vapour impermeable sarking and a very low pitched roof with a low solar absorptance sheet metal roofing. Like the example described above, all parties, including the architectural designer, building surveyor and builder were adamant that all aspects of the NCC had been complied with. After several months of negotiation, the roofing material, sarking system, mould affected battens and sodden ceiling batts were removed. After a period of drying, new ceiling insulation, roof space ventilation, sarking system and roofing were re installed. In this case the home owner was in shock, from the limited support provided by the building regulator and that all parties concerned who were accusing the home owner of causing the problem. This was a mid-sized modern two storey residence and remediation costs have never been advised.

Figure 15 – Condensation and mould inside roof space and condensation and mould on double glazed window and aluminium frame

Figure 15 above show a moisture and mould affected roof space double glazed window and aluminium frame. This like the two previous examples is from a new home shortly after construction. Whereas the two previous examples are from 2014, this house was constructed in 2011. In this example, the building regulators, building designer, building surveyor, builder, product manufacturers and insurance companies were in disagreement as to 'code compliance' and who should be responsible for the remediation activities for this significantly moisture affected timber framed new home.

At a recent national event organised by the Australian Institute of Refrigeration Air-conditioning and Heating (AIRAH) "Humidity Issues in Australian Climates Workshop", mechanical engineers from all parts of Australia met in Sydney. Many raised concern about the lack of built fabric permeability detailing knowledge and capability from architectural, construction and engineering professions. Many agreed that it was more a professional attitude for good construction outcomes, as the building regulations did not adequately cover this aspect of building durability and human health.

At this same event, a national importer of industrial sized hot air blower type fans advised that they could not meet the insurance demand for Victoria. When queried further it was established that the fans were being used in subfloors, house interiors and roof spaces as an attempt to dry-out the wet and mould affected interiors of many new homes.

In 2007, the Special Broadcasting Service (SBS) aired a series called 'Is Your House Killing You'. In this series one of the houses had significant mould growth. It was an older home, but no different to many other houses located in Sydney, with similar condensation and mould problems. In the series the family were required to leave the house for some time, whilst a professional mould removal team deconstructed elements of the house and provided remediation services.

Any quick internet search for Australian press articles that include condensation and mould in buildings will bring up hundreds of examples of public and private buildings. In all cases significant remediation, including deconstruction, reconstruction, costs and concerns about the occupant health have been discussed. This demonstrates a significant cost to the construction sector and/or building owners is currently being borne to make buildings safe and habitable. In many cases that the Tasmania team has looked at since 2010 privacy and confidentiality requests were included, as many settlements were made within the out-of-court environment, which has further hidden this issue from legislatures. Within this context there needs to be more data gathered on the true built fabric and human health costs that may be borne by the Australian community as a result of condensation and mould in both new and old buildings.

As a final comment at this point. Members of the UTAS research team are increasing being asked to inspect homes or additions constructed in the last ten to twenty years. These houses are showing the 'slow-burning' effect of long-term condensation and mould. Most have significant problems in subfloor zones and walls. To date some of these houses have, at the owners' expense, required significant deconstruction, remediation and reconstruction, whilst others have been demolished. Common patterns are appearing, where vapour impermeable or vapour semi-impermeable elements have been used, no vapour cavities for mixed fabric systems and significant thermal bridging. Examples include the use of direct-fix expanded polystyrene and sheet metal cladding systems, which are not allowing the buildings to breathe out the water vapour, and low pitched (<10 deg), sarked and sheet-metal clad roof spaces.

Health and amenity

The NCC provides regulation to protect the health and well-being of building occupants (ABCB, 2016b). For Class 2 residential buildings this is included in Volume 1 Part F: Health and Amenity and for Class 1 residential buildings this is included in Volume 2 Part 2.4 Health and Amenity. There is no mention or discussion of condensation and mould within these key sections of Volume 1 or Volume 2 of the NCC. This is in contrast to building regulations from other developed nations discussed later in the international literature review.

Internationally, there is agreement on the link between indoor dampness and respiratory disease. The adverse effect of dampness on respiratory health has been suspected for many years. Large cross sectional prevalence studies on both adults and children have confirmed a positive relationship between indoor dampness and specific respiratory symptoms such as asthma. This is a critical issue, as 1 in 10 Australians have asthma. Many Australian allergy and immunology researchers have raised concern about the prevalence of condensation and mould in Australian buildings and its likely, but to date unproven, correlation to Australia's high number of asthma sufferers. Asthma has a negative impact on people's lives with time taken from work, school, social activity and an ongoing need to take medication. There are also significant economic costs caused by the reduced productivity from missing work by suffers, carers of sufferers and the public cost of treatment.

There are a number of triggers for asthma but internationally, air quality is considered a key trigger. Given that people are now spending up to 90% of their time indoors, and two thirds of this time in their homes, internal air quality and the role played by the building fabric to manage this is significant. It is now well understood that, within buildings, the regular occurrence of relative humidity above 76% or the accumulation of moisture, on surfaces and interstitial spaces has the potential to promote mould growth that has the possibility of affecting the health of the building's occupants. This mould can be present on external surfaces, but due to its microscopic nature can be 'invisible' and located within walls, floor spaces or roof cavities.

The most important types of mould that trigger allergies are Aspergillus, Cladosporium and Alternaria. These are common moulds, however, when spores are breathed into the lungs there is no direct defensive mechanism against the spores or other compounds produced by mould. As a result, they are taken directly up by the body and it must act to defend itself against them. One of the more definitive studies of health impact of mould from damp buildings comes from the World Health Organisation (WHO Regional Office for Europe, 2009) in their Guidelines for Indoor Air Quality: Dampness and Mould, surmising that:

> *"Sufficient epidemiological evidence is available from studies conducted in different countries and under different climatic conditions to show that the occupants of damp or mouldy buildings, both houses and public buildings, are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma".*

According to the WHO

> *"as the relations between dampness, microbial exposure and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of contamination with microorganisms. Instead, it is recommended that dampness and mould-related problems be prevented."*

The WHO concludes by recommending that indoor temperatures be at least 18°C, even in the winter, particularly to avoid the health impact and burden on the immune system and the respiratory tract. At present there are no minimum or maximum indoor air temperatures prescribed by the NCC.

Other research in this area suggests increased risks of allergic rhinitis and asthma (Kercsmar & et al, 2006; Medicine, 2004; Mendell, Mirer, & Cheung, 2011; Pekkanen & et al, 2007). Although few intervention studies are available, their results show that remediation of dampness problems can reduce adverse health outcomes. More debilitating effects have been observed in the pioneering work by Ritchie Shoemaker who, in his clinical practise, has observed that on average 24% of the population have the genetic disposition to launch an excessive antigen response system and these patients suffer the consequence of the "friendly fire" of their innate immune response, he calls CIRS-WDB (Chronic Inflammatory Response Syndrome from Water-Damaged Building). He explains, this concept of magnification of host response is opposed to the idea from toxicology that the "poison is in the dose." We now know that this idea from toxicology has little bearing on mould illness, as indeed mould illness isn't toxicological at all, but is immunological instead. In extremely susceptible patients (with a Human Leukocyte Antigens of 4-3-53 or 11-3-52B) the health impairment can so substantially limit the major life activities of respiratory function, vascular function, and immune function, that some of these individuals qualified for disability under the American Rehabilitation Act (1973).

International research has established that once the human body's immunology and allergy capabilities have reacted to mould conditions, the internal trigger stays in place for most of one's life.

Awareness of health issues in current building practice

This research has found a significant knowledge gap between expectations in the medical field, where treatment in human immunology and allergy draws distinct qualified relationships to wet buildings and mould, and those of the design and construction industry. Similarly, personal interviews with Building Surveyors, Building Regulators and Environmental Health officers established a significant lack of knowledge within this field of expertise.

In one instance, a family received medical advice to immediately leave their home. Yet the EHO, who by legislation is the profession to provide advice to building surveyors and permit authorities, advised that the presence of mould was suitable for continued occupation of the house. This issue of inadequate governance and competency standards have been raised by mycologist (mould expert) Heike Kemp, who after the Brisbane flood said during an ABC interview, "If we actually had government involvement, that we had an Australian standard, not just a guideline, that we had mandatory courses that people who do mould courses, that they [referring to mould remediators] actually learn how to do it and that they need to have a minimum education" (ABC, 2011, Building owners face mould threat).

To elevate the importance of moisture, condensation and mould within buildings some nations, as exampled in the international literature review, have incorporated their respective national Health Act within the national construction codes.

Economic health impacts from mould in domestic buildings

Condensation and mould have a negative effect on internal air quality of the built environment. Within this context condensation and mould must be considered as health effecting pollutants. In environments where these pollutants are present, users and occupants are more likely to suffer respiratory diseases such as asthma. These diseases have the potential to negatively impact on their productivity. However, a range of factors can lead to an individual experiencing respiratory disease. To date, no substantial national study in Australia has been undertaken to determine what proportion of this economic impact of poor health is directly contributable to condensation in domestic buildings. This is not to say that no evidence exists. One example is the immunology and allergy department at the University of Western Sydney (UWS) Campbelltown hospital, where researchers are often called upon for symptom analysis and medical advice. Medical researchers from UWS, Melbourne University, Flinders University and the University of Tasmania have all raised concern about wet buildings and its correlation to indoor pollutants and poor indoor air quality. Due to the lack of national data, any economic impacts must be derived from the results of international studies.

There have been a number of studies into the impacts of condensation on buildings. There are also a number of population based studies examining the economic impact of respiratory disease such as asthma. A full list of papers reviewed for this report can be found in Appendix 05. However, the specific focus of this review was to examine research that attempted to extrapolate the economic impact from disease directly correlated to 'wet buildings'. Here the term wet building is used, which is the common terminology within the fields of human health and medicine, to encapsulate a range of building specific issues such as poor IAQ resulting from the presence of mould and fungal spoors, low ambient temperatures and high humidity levels. Everyone are factors that could be contributed to building design, building construction and building regulation.

A significant proportion of the research in this area looks at economic impacts from poor IAQ in workplaces and public buildings such as offices and schools (Sahakian *et al.*, 2008; Sahakian *et al.*, 2009; Fisk *et al.*, 2011a; b; Mendell *et al.*, 2013). Furthermore, and historically, the majority of research published in English from this field is conducted in the United States of America. However, there is extensive research in non-English medical journals and more recently China.

The most common approach to determining economic impact of dampness and mould exposures is by using an 'Attributable Fraction'. This is calculated by first, ascertaining the level of respiratory disease, such as asthma as a percentage of the population. Then, from additional studies that reported the prevalence of dampness and mould in homes these two data sets are combined to determine the proportion of asthma cases that are attributable to dampness and mould exposure. Due to the size and nature of population based studies, most of the literature reviewed modelling data around key indicators, such as average:

- hospitalisation days,
- income,
- medical expenditure,
- loss of earnings
- discomfort or disutility of illness.

There are two common methodologies for determining the economic impact of disease, willingness to pay (WTP) and cost of illness (COI). Both provide a different analytical tool to analyse a specific set of data and many studies reviewed used both as a comparison to highlight variations in cost associated to individual's action and behaviour.

Economic cost

The consensus from the international literature is that approximately 15–20% of the economic cost of several diseases and disease symptoms are associated exposures to poor IAQ resulting from dampness and mould (Mudarri, 2016). This analysis has shown that a large share of the Cost of Illness event that includes a hospitalisation is not borne directly by the individual, because hospitalisation costs are typically covered by health insurance or government. Average total Cost of Illness per hospitalisation are $US22,000 to $US39,000 (Au$29,000 to Au$51,000) (Chestnut *et al.*, 2006).

Within the United States, of the 21.8 million people reported to have asthma, approximately 4.6 million cases are estimated to be attributable to dampness and mould exposure in the home. By applying the attributable fraction, the national annual cost of asthma that is likely resulting from dampness and mould exposure in the home is estimated to be $US3.5 billion (Au$4.6 billion) (Mudarri and Fisk, 2007).

Rectification and improved IAQ costs

A number of studies attempted to estimate the cost of improving IAQ to mitigate health risks. In these studies, a connection was identified between recent changes in building methods resulting from regulatory change associated with improved building energy efficacy. Studies in this area found that there was a benefit in shifting from the promotion of energy efficiency in isolation, to an approach that promoted improving the indoor environment as a key proponent to improved energy efficiency (Fisk, 2000).

Summary of findings

There is a need to control moisture in both new and existing construction because of the significant and internationally accepted health consequences that can result from dampness and mould. The literature review found that in the populations studied, dampness and mould in buildings is a significant public health problem with substantial economic impact. It is argued that an increased awareness of these potential health and economic gains, combined with other factors, could help bring about a shift in the way we design, construct, operate, and occupy buildings (Fisk, 2000).

As noted above there has been no comprehensive analysis in Australia of the economic impacts of health related issues associated with condensation and mould in buildings. A simple extrapolation of cost can be made using the methodology outlined above. In Australia Asthma is estimated to cost the economy $AU28 billion per year. This includes health, productivity and other financial costs, and the burden of disease (Deloitte Access Economics, 2015). If the international data on poor IAQ resulting from dampness and mould is extrapolated, this would equate to 15-20% of all asthma associated costs would be attributable to 'wet buildings'. In Australia this would result in an economic cost of $AU4.2 – $AU5.6 billion per year.

Within this context of limited data from Australia, and for the purposes of this report, a very simplified means of determining an economic cost can be calculated. In Australia, although the number of people with asthma is well documented, and the economic cost has been studied in detail, as shown above. The proportion of Australian buildings considered to be 'wet' is still not known in any detail. However, it should be noted that BRANZ estimates that 25% of all domestic housing stock in New Zealand, which is stylistically very similar to Australian housing, suffer from condensation issues. Therefore, it could be conservatively accepted that 15-20% of Australian housing could be classed as suffering from health and amenity affecting condensation and mould, further confirming the economic cost of $AU4.2 – $AU5.6 billion per year, mentioned above.

Alternatively, another established way of estimating the burden of disease is the DALY, or Disability-Adjusted Life Years. In Europe, a conservative estimate for the range of exposure to "dampness" is between 10-25% (or a central value of 15%) of all dwellings. The range of exposure to "mould" in Europe is 5-25% (or a central value of 10%). For a target population of 140 million European children (0-14 years), the burden of asthma from indoor mould and dampness problems in the home environment account for estimated 55,842 DALYs based on the exposure prevalence of 10% of indoor "mould" in home environment and 69,462 DALYs based on the exposure prevalence of 15% of indoor "dampness" in the home environment (Braubach *et al.*, 2011). For reference, in 2011, there were 4.5 million DALYs due to premature death or living with disease or injury in Australia (Australian Institute of Health & Welfare, 2011, "Australian Burden of Disease Study - Impact and causes of illness and death in Australia"). The full burden of disease extends well beyond children suffering from asthma in homes, and can play a significant role in the development and presence of chronic disease, and is in need of research within Australian communities.

This estimated economic cost is only provided to give context when discussing the potential economic costs associated with the scoping report's recommendations. The report authors recommend a health cost analysis be undertaken to provide further guidance to the ABCB on the cost benefits of proposed recommendations for 2019 and beyond.

Condensation – International literature review

An international literature review was completed to provide an international perspective of experiences and regulatory changes that may have occurred in other developed nations. The aim was to ascertain if condensation and mould issues were evident, and if so, if it was a recent phenomenon or an ongoing issue within domestic buildings and building regulation. This literature review built on knowledge gained from previous research into condensation risk and mitigation for the Tasmanian government. A full list of references can be found in Appendix 04.

Condensation – not an isolated problem

Research has been undertaken into condensation risk in domestic dwellings in a range of countries. These have included the U.S.A., Canada, New Zealand, England, most European countries, ranging from Sweden and Demark to Greece, Italy and Spain, as well as former eastern bloc countries such as Estonia and Ukraine. A number of counties in Asia such as Japan, China, Singapore and Malaysia have also identified issues. Papers have also been published on issues in Brazil and South Africa. It is clear that, from an international perspective, the issue of condensation crosses all major climate zones and building typologies.

It is more difficult to ascertain if condensation has been a historical problem in all of these countries, or a problem that has only recently emerged, as a result of changing building practises. In some countries, such as Canada, there is research into condensation dating back to the 1930's. There are similar studies in the United States, Europe and England dating back to the 1950's. Other studies have suggested that issues of condensation date back further, with may identifying a need for rectification of older building stock, including historical buildings. The more recent proliferation of literature on condensation starting in the mid 1990's may have resulted from an increased envelope performance and an awareness of condensation as a contributor to poor health and building integrity. Internationally, research into condensation can be divided into two types, namely:

- Research into the causes of condensation problems, or
- Research into resolving condensation problems.

Both aspects, even though coming from different perspectives explore issues in built structures, thermal bridges and material properties for floors, walls, ceilings, subfloor zones, roof space zones and roof's, providing a reminder that vapour pressure forces apply in every direction equally. A significant shift in focus is observable in the European, Canadian and USA regulations where the focus has moved from built fabric systems, to indoor temperatures, to indoor air quality, to indoor environmental quality. This signifies a greater understanding of what is required within a building to provide adequate amenity within a healthy environment, of which condensation and mould is a key component.

Application in the Australian context

The considerable amount of international research into condensation causes and potential mitigation strategies provides the opportunity to draw on previously established viable solutions. Australia has a diverse range of climatic conditions and building typologies. However, the literature on condensation is comprehensive, ranging across all major climate types. The research from these other developed nations is also highly specific. They have tested very particular variables in building systems to determining responses to specific issues.

As a result, Australia does not need to re-invent the wheel. Considerable evidence-based research has already been conducted on a wide range of climate and building type responses to condensation. Any recommended solution or strategy should be tested before being implemented in the Australian context, however, this significant, and international, body of work on condensation, provides a substantial guide as to the possible solutions to test and the solutions that are likely to provide the greatest level of mitigation, in the most cost-effective way.

The literature review, as detailed in Appendix 04, highlights key areas in which condensation risk is identified and successful mitigation strategies have been implemented. This international perspective which has been balanced with experiences in Tasmania, Victoria and New Zealand have been used to critique current Australian building regulations and to develop a condensation risk matrix.

Part 2 - Current legislative framework

The review of the current legislative framework explores aspects that apply directly to the content of the NCC and to aspects that might become referenced by the NCC. Firstly, the overview of the current regulatory framework around condensation focuses on the NCC Volume One and Volume Two. From this a summary of the key aspects of the NCC regarding condensation are identified and the analysis provides some concepts for critical amendments or inclusions that may be required. This is followed by an examination of critical documents that can support and inform the application of the NCC, and include state regulations around health and building control, current or new Australian Standards, non-regulatory technical documents and industry/manufacturer developed technical guides. The information from this review provides key information for the Gap Analysis conducted in Part 5.

The NCC Volume One & Volume Two

The legislative framework to manage and control air quality, vapour pressure, moisture and mould within new Australian Class 1 and Class 2 buildings is the National Construction Code, with enforcement by each jurisdiction's 'Building Act'. The Building Acts generally establish a state building regulator, permit authorities and the role and responsibility for each profession involved in the design and construction of new buildings. The aim within this section is to provide an overview of the current regularity framework for Class 1 and Class 2 buildings in Australia.

National Construction Code Volume One

NCC 2016, Volume One stipulates a uniform set of technical provisions for the design and construction of larger scale buildings and other structures throughout Australia, which allows for variations in climate, geological and geographic conditions. Volume One contains the requirements for Class 2 to 9 (multi-residential, commercial, industrial and public) buildings and structures.

Within Volume One, Part F1 (Damp and Weather Proofing) makes no mention of a requirement to manage vapour pressure, or to limit moisture or condensation from forming within the built fabric, specifically:

- The term condensation is not used in Volume One.
- The term moisture is used, but only in reference to the management of moisture from the ground.
- In relation to vapour control, the term Sarking, which is a membrane placed above the roof space zone and under the roofing material, as:

> *"Sarking-type material - means a material such as a reflective insulation or other flexible membrane of a type normally used for a purpose such as water proofing, vapour proofing or thermal reflectance."*

However, there is no description in Volume One of what 'vapour proofing' is. Furthermore, within Section F, Health and Amenity F1.6 Sarking notes:

> *"Sarking-type materials used for weatherproofing of roofs and walls must comply with AS/NZS 4200 Parts 1 and 2."*

This is the Australian Standard 4200 relates to Pliable Building Membranes and Underlays.

There is no other requirement within Volume One with regard to vapour pressure, moisture, condensation or mould.

National Construction Code Volume Two

NCC 2016, Volume Two stipulates a uniform set of technical provisions for the design and construction of stand-alone or co-joined dwellings and other simple structures throughout Australia, which allows for variations in climate, geological and geographic conditions. Within Volume 2, Part 2.2 moisture is mentioned only as explanatory information. In Part 2.2: Damp and weatherproofing, Explanatory Information: Objective 0-2.2, It states: The Objective is to—

> *(a) safeguard occupants from illness or injury and protect the building from damage caused by—*
>
> > *(i) surface water; and*
> >
> > *(ii) external moisture entering a building; and*
> >
> > *(iii) the accumulation of internal moisture in a building; and*
> >
> > *(iv) discharge of swimming pool waste water;"*

As this statement is detailed as explanatory information, it is not a regulatory requirement.

Within the wet areas section, further non-regulatory information is provided within Part 2.4: Health and Amenity, Explanatory Information: Objective 02.4.1 Wet Areas, The Objective is to—

> *"safeguard the occupants from illness or injury and protect the building from damage caused by the accumulation of internal moisture arising from the use of wet areas in a building."*

The only regulatory requirement to consider moisture within the building appears within the Performance Requirement P2.4.1 Wet Areas, which states:

> *"To protect the structure of the building and to maintain the amenity of the occupants, water must be prevented from penetrating—*
>
> > *(a) behind fittings and linings; or*
> >
> > *(b) into concealed spaces,*
>
> *of sanitary facilities, bathrooms, laundries and the like."*

There is extensive guidance within the NCC on façade system design and the detailed construction of wet rooms to eliminate water, from the act of bathing or showering, entering the built fabric. Additionally, there is limited 'comment' that cooling systems and pipes may cause condensation. Within Volume Two, Section 3.12 there is a mention of condensation risk twice in the non-regulatory Explanatory Information for Table 3.12.1, Part 3.12.1.1 Building fabric thermal insulation.

National Construction Code summary

NCC (ABCB, 2016b) does outline the regulatory requirements for a number of areas that are linked to condensation; for example, ventilation, thermal efficacy, building sealing and air movement (see Table 1, NCC Comparison 2003 to 2016) (ABCB, 2003; 2004; 2007; 2010). The risk of condensation is highlighted in a number of 'Explanatory Information' boxes. Otherwise, there is no explicit guidance on the issues of surface condensation, interstitial condensation, mould growth and vapour pressure management within the principle Australian building regulatory document.

These omissions from the NCC establishes no regulatory requirement for the design and construction industries to manage vapour pressure, moisture, condensation and mould within new housing. Similarly, this omission affects the power of building regulators to question and inform design and construction practises which influence these conditions. As a result, many professions in the construction industry may take the lack of any regulation or guidance to assume (wrongly) that no design or construction responsibility is required around the control and mitigation of condensation risk in the built fabric.

Management of condensation outside the NCC

Regulation and management of condensation can extend beyond the remit of the Australian Building Codes Board to include referenced documents, state based regulations or other relevant Act's. Many Australian Standards are referenced by the NCC. Each has a particular focus and allows for a deeper discussion, explanation and prescribed design and construction practises to manage specific and related issues. At present Australia has no Standard which addresses condensation risk mitigation and vapour pressure management in residential or non-residential buildings. Additionally, many of the referenced standards illustrate construction methods that do not support vapour pressure management, condensation risk mitigation or thermal bridging. Similarly, as much as the Anti-Discrimination Act is actively integrated within building design and construction practices, Health Acts are not integrated as easily due to the state based nature the legislation.

Australian Standards

To complement the recommendations of the Scoping Report, a preliminary review of Australian Standards (AS) cited within the NCC Volume Two was completed. A full list of the reviewed standards, with a condensation risk commentary, is provided in Appendix 06. The aim of this preliminary review, was to identify standards with examples, diagrams, drawings or written explanations that refer to or have the potential to negatively impact the aspects of vapour pressure management, condensation risk and thermal bridging within the built fabric and building envelope. The review identified a number of specific references within the Standards that are inconsistent with the likely requirements the NCC may require to establish the broad coverage required to reduce condensation risk, namely:

- Performance specifications,
- Terminology,
- Definitions, and
- Explanatory diagrams

These inconstancies have the potential to create uncertainty, confusion or misinterpretation of minimum standards for design and construction. A Victorian audit into building permits dating from 2011 found over 70% of residential and commercial permits did not contain sufficient information to demonstrate compliance in at least 5 or more building technical or safety standards. However, the inconstancies between the needs of the NCC and the supporting Standards identified may be the result of a mismatch in amendment timing or a difference of desired or specific outcome. Within the context of condensation risk management, the Australian Building Codes Board will need to establish the objectives and drive the agenda, to ensure cohesion between documents.

A number of the Standards currently referred to in the NCC would likely require further review and possible revision if the Scoping Report's recommendations were adopted. Specifically, a revision of all Standards referenced by the NCC may be required to ensure the proper specification and application of air barriers and vapour control layers is addressed adequately. Additionally, it is recommended that the ABCB establishes and then oversees the adoption and integration of standardised terminology on moisture control. A coordinated revision strategy would reduce conflicting information between the standards and/or the NCC, reduce the occurrences of non-compliant construction and certification and provide a clear, consistent approach to mitigating condensation across all regulatory documents.

Public Health Acts

The Public Health Acts within each State and Territory are the primary legislative mechanism for auditing of buildings to ensure public health is maintained (see relevant State and Territory Legislation). At this stage and for most states, there is now a regulatory and management gap between building regulators and health professionals. Within this context the various Health Act's prescribe powers to Environmental Health Officers (EHO), who are generally employed by state or local governments. A general description of the powers granted to EHO's is the capacity to order premises to be vacated when they are unhealthy. However, there is a significant lack of clarity around the issue of mould or condensation and how and when this constitutes an 'unhealthy building'. For example, the Western Australian Department of Health provides a guide on Mould and Condensation in the Home, but it makes clear, in a rental property:

> *"Mould & mildew caused by structural faults or leaks should be remedied by the owner, but the tenant must ensure there is adequate ventilation & humidity is kept to a minimum to avoid mould problems in winter."*

How a tenant is to achieve this, especially in a complex case is unclear. For example, mould may be the result of incorrect built fabric arrangements, infiltration, or normal internal moisture loads. This statement within this government guide is in contradiction to regulations in other nations where the occupant of a house has no active responsibility to manage condensation and mould, further highlighting a distinct lack of understanding on these matters within Australia.

Within the professional workplace safety community, there are Occupational Hygienists who do appear to have knowledge in this field and provide advice about the interior environments of residential and non-residential buildings. But, in previous research and communications with concerned building regulators, several situations were noted where the EHO, who appears to have very limited knowledge in the field of mould and human-health, has made a determination that the presence of mould did not affect the safety of occupants. This has been in contradiction to medical professionals that established from exacting medical tests, that building occupants were suffering from immunology and allergy conditions related to the presence of excessive moisture and mould.

Within this context it could be argued that both the building and health regulatory legislation currently provide inadequate or no distinct guidance on vapour pressure management and its impact on excessive relative humidity, excessive moisture, surface condensation, interstitial condensation and mould growth within Australian buildings. It also highlights that professionals within both the Health and Construction industry sectors will need significant education about the conditions that lead to mould development in home, mould types and their likely impact on human health.

Non-regulatory guides and technical documents

In 2011 the Australian Building Codes Board released the first edition of the handbook Condensation in Buildings (ABCB, 2011). Many concerns were raised from the academic research and manufacturing industries that led to the second edition release in 2014 (ABCB, 2014). Many have still raised concern about climate specific shortcomings in the second edition, but most agree it is better than the first edition. However, and more critically, the handbook is a non-regulatory document and is only provided as information.

It was noted in meetings with industry groups that there was a general awareness of the handbook and that the specific guidance and recommendations it provides on condensation are beneficial. However, the overwhelming concern about the handbook was that it was not a mandatory or regulatory document.

The international literature review highlighted the many manufacturer and industry-based documents in other countries. These documents operate within their relative building regulations and building standards but combine plain language with high quality and descriptive diagrams to guide design and construction professionals. As there is no framework of this nature at present in Australia, limited documents are available and their consistency and quality is questionable and provides confusion within the design and construction sector.

Summary

Any significant condensation mitigation strategy will need to be established by the Australian Building Codes Board, to enable a coordinated response that both recognises the key role of national regulation, as well as other regulatory and non-regulatory documents. This overview provides additional input for the Gap Analysis outlined in Part 5 of the Scoping Report.

Part 3 - Determining the extent of the problem

This section discusses what the extent of the condensation and mould problem may be with Australian Class 1 and Class 2 buildings since 2004. The first part discusses the analysis of the Nationwide Condensation Survey (the Survey). It provides an overview of key findings and summary of the results. A Full analysis of the nationwide condensation survey is included in Appendix 02. The second part of this section explores perceived industry capabilities. Through a series of stakeholder meetings, industry bodies, representatives and individuals were given the opportunity to discuss, in more detail and in confidence, any issues regarding condensation that they may have identified. A full list of industry contacts and meeting dates is provided in Appendix 03.

ABCB nationwide condensation survey and statistical analysis

The ABCB had received anecdotal evidence that indicated an increase in the presence of condensation was occurring in new residential buildings (NCC Class 1 and Class 2). Although sporadic, information was provided by a range of stakeholders, and focused on the visible signs of condensation. The information also suggested that the issue of condensation was being identified across a range of Australia climate zones. However, it was unclear if condensation, historically, had always been present in buildings, but was now simply becoming less accepted. Or whether condensation was a relatively new phenomenon, resulting from changes in the way people construct or use buildings, or changes to building regulation requirements and corresponding building practise.

As a result, in 2015-16 the ABCB undertook a survey to gather evidence and feedback on the extent of condensation problems and the likely causes, as well as gain an understanding of industry's capacity to manage condensation risk in new residential buildings. As part of the development of the Scoping Report all the raw data collected from the survey was analysed. As the paragraphs below only include key findings, a more comprehensive review of the findings is provided in Appendix 02.

Summary of survey analysis

There were 2,662 usable responses submitted between December 2015 and February 2016. The survey analysis is presented here in the context of questions raised in the *Approach to Marketing* document.

a. [The scoping study should include an analysis of the survey results… to holistically explore:] The issue of condensation in residential buildings and what may be causing any increase in condensation

Patterns of prevalence in Class 1 (houses) and Class 2 (apartments) were broadly similar. And from the point above, indicates a high occurrence of condensation. Likewise, response about comparison with 10–15 years ago, and with 2–5 years ago, were broadly similar, indicating a long-term problem that may be on the increase or building occupants are becoming more aware. This suggests a lack of effect of different versions of the NCC, since both time periods had similar responses. The survey does not provide evidence that the NCC amendments are directly responsible for condensation. It should be mentioned that it is a lack of evidence either way, i.e. that there is also no evidence that the NCC is not responsible for increasing the occurrence of condensation. In fact, the open-ended responses, taken together with the international literature review and discussions with informed industry representatives, indicate that increasing energy efficiency, bushfire legislation, occupant thermal comfort expectations and an industry wide lack of knowledge about vapour pressure management are commonly believed to be the causes for an increase in condensation.

The survey reveals a widespread perception that occupants are responsible for the management of condensation, but are often not doing enough, which contradicts regulation and expectations as discussed in the international literature review. More details are worth collecting in a follow-up survey, to understand what roles the industry expects occupants to play in condensation management.

b. The nature and extent of the problem(s) including climate specific considerations

The occurrence of condensation seems generally widespread. In summary, the overall magnitude of problems (as assessed by respondents) varies but does appear to be extensive enough to be of concern, (which based on the previous section about built fabric durability and human health is of a concern). The extent of problems was generally assessed as high, with about 40% of new buildings and existing buildings estimated to suffer from condensation. There were some variations in climate and state although not significantly different from the overall picture that condensation is a common occurrence across all of Australia.

Between the sub-categories of climate zones and states, it appears that state is a stronger predictor of how one would respond in the survey. This would be consistent with the state-based adoption of the Code and how practitioners see themselves identifying more with a particular state than a particular climate zone. However, many practitioners responded that they worked in various States, diluting some results.

c. Requirements within the NCC which may influence the risk of condensation forming,

Whilst this has not been particularly covered in the survey as a poll, the open-ended questions indicate that energy efficiency and occupant comfort expectations have been the primary drivers for greater air-tightness. This increased envelope tightness, when advanced without an accompanying vapour management plan, is the widely perceived problem behind increased condensation in many buildings.

d. Any evidence of a relationship between changes in NCC regulation and an increase in condensation forming in new residential buildings,

An attempt to categorise the respondents by state did not yield a clear trend in terms of regulatory changes and perceived increased occurrence of condensation. Whilst there is no evidence that regulation has increased condensation risk, it is also true to say there is no evidence to the contrary. In the text analysis of open-ended question, "energy efficiency" comes out at a very high frequency. In reading the responses, other indicators of a relationship to regulation are the adoption of tighter building enclosures to meet BAL ratings and inconsistencies in the Australian Standards.

e. Potential gaps in the requirements of the NCC, which may influence the risk of condensation forming,

This will be covered in greater depth in the literature review. The following response indicates that there are people in the industry who wish to see the NCC further developed with the best international practices.

> *"My opinion is based on anecdotal evidence as well as an understanding of the NCC and inconsistencies that I see in it. The NCC lags behind the rest of the world*

in the detail and specificity of its building code relating to energy efficiency. Some of the underlying building science informing the code is outdated. Materials and methods allowed and in some cases required by the building code have the potential to create surfaces within wall and roof assemblies that can lead to condensation." (Respondent 4395240564)

f. The capacity of the Australian building industry, and building occupants to manage condensation risk,

When it comes to managing condensation, the industry is inclined to implement various forms of ventilation. Commercial builders tended to be more cognizant with a larger variety of appropriate responses than residential-only builders. Performance-based solutions like hygrothermal analysis and orientation were unfamiliar to the majority of respondents. The industry also leaned towards design being the primary approach to managing condensation, followed by construction and building occupants. Of these, the average occupants were mostly seen to be unaware of their role in managing condensation risk. In the open-ended responses, there is a clear call for more education and information that is both easily understood and accessible.

Further recommendations

After being alerted to the issues, a well-designed and tested follow-up evaluation/survey may be advantageous in three to six years. Something that might be considered in the interim is a smaller stratified sample from the same frame (as an update) to spare all respondents from a follow-up request.

The suggested recommendations at the end of this report also draw on the professional knowledge gaps and built fabric performance misunderstandings that seem to be overly present in the survey responses (i.e., building physics v's rumour and conjecture).

Industry capability

In discussions with the ABCB is was agreed that it would be beneficial for the scoping report to explore issues raised in the survey in more depth through detailed discussions with building industry representatives. The aim was to ascertain the capability of the Australian building industry to manage condensation risk. Key groups were identified within the design and construction sectors that had a stakeholder role. Requests were sent to representatives. Not all groups responded. Industry engagement continued during the entire report writing time. Some industry responses are still being received, as the representatives are becoming more aware of what is occurring within their industry sector. Methods of communication included meetings, teleconferencing, and email exchange. These conversations also provided additional contacts and allowed for condensation risk management advice and resource to be fed to industry.

Of critical importance was the industry feedback provided for the draft version of the scoping report recommendations. This provided an opportunity to explore specific issues in depth and tested recommendations, allowed a cost benefit discussion on each recommendation, and helped to refine and amend recommendations so that they were practical and achievable. Below, a summary of the industry capabilities is provided. The full data from this task is provided in Appendix 03.

Many topics were discussed with the industry representatives but invariably discussion revolved around several issues, namely:

- building practices,
- industry awareness and capability,
- what climate zones and location problems are occurring and
- where in the built envelope these issues are occurring
- regulatory and legislative compliance,
- current education materials and strategies,
- product availability,
- terminology,

Each of these aspects is discussed briefly in the following paragraphs.

Industry capacity

The industry consultation has highlighted several concerns regarding the industry's capacity to manage condensation at the present time. It is clear there is a lack of understanding in the industry regarding the purpose of an air barrier system and specifically regarding built environment vapour management. Most were 'aware' of the issue, but across all parts of the industry there was significant variation in the level of understanding of which solutions are available, which solution to use and in which circumstance. For example, some had the capacity to outline in detail how vapour control was integrated into their building projects but this was rare. Others noted, the accepted use of a vapour management solution adopted by one jurisdiction, was resisted by other jurisdictions, even though they were very similar or even identical climate zones. This was leading to extensive confusion within the industry and for a range of 'sharks' to market after construction condensation 'fixing' approaches.

Others noted that, at an educational level, and due to attendance at technical college, some apprentices were aware of vapour control strategies, but were then being told on-the-job 'that's not how we do it here'. There also tended to be an acceptance of the use of the cheapest product, even if it was not environmentally suitable, rather than use products designed specifically for the climatically based management of built environment vapour and condensation risk.

It was clearly identified that there was a significant lack of understanding around how vapour control, thermal control and air control systems are different aspects of the built envelope and how systems applied must acknowledge priorities, but also how components interact with each other. A number of situations were reported in which air control was being used as vapour control, or thermal control was thought to also be managing vapour control. This was particularly apparent around the use of foil backed and foil blanket products. There was a concerning level of misunderstanding around the properties and functions of these reflective insulation products. There seemed to be a disconnect between the industry's understanding of the role and function of these products and the actual vapour, moisture and thermal control properties the products provided. This is further exacerbated by the different approach taken in Australia, to the accepted ventilated cavity values adopted elsewhere, and the confusion created by products that are vapour impermeable being labelled 'breathable'.

Industry awareness

The awareness of the building industry as a whole is critical to managing the condensation risk in residential buildings. Any building that establishes an internal environment that is different to the external environment is establishing vapour pressure differentials. Many materials can store moisture; some materials stop vapour from migrating through the built fabric. At any point in time, when dew point is achieved, vapour will condense. A case in point, is the concern raised by home owners in south western Sydney. The results from the survey showed that commercial builders are generally more aware than residential-only builders about condensation. However, it was difficult to establish exactly why this is the case. The Industry consultation process found that, generally, each respective role passes the responsibility onto other roles, from designers to builders and builders onto regulators (i.e., the designer draws plans and expects the builder to solve the problem, as ‘they are the builder’?)

According to the statistical analysis, it would seem that the industry considers occupants as being largely responsible for the management of condensation. This position is at odds with international understanding, expectations and regulation for vapour and condensation risk management, where occupants are considered to have active role in the management of condensation.

Industry consultation found that, overall, the management of condensation risk fell to the industry, although it remains debateable as to which part of the industry. It was agreed, that successful condensation mitigation must be part of the building fabric as a complete system. One that allowed the building to self-regulate through vapour permeable membranes and automated ventilation systems which exchange air and extract internal vapour loads. The mechanical ventilation approach is adopted in countries where envelope air-tightness regulations require less than 5 air changes per hour @n50. At present most new Australian housing is close to 15.4 air changes per hour @n50 (Ambrose and Syme, 2015).

Industry compliance

Industry feedback cited compliance as a major contributing factor to condensation problems. There are two primary types of compliance issue. Firstly, regarding regulatory and legislative compliance; and secondly, regarding compliance with manufacturer's installation specifications. Non-compliance with either of these types could contribute to condensation accumulation and result in financial liability on the part of the designer and/or builder. Furthermore, non-compliant construction will result in warranty exclusion. A building industry bulletin from 2014 showed the issue of condensation was apparent in Class 2 residential apartments and the ventilation system was blamed (Industry bulletin, 2014). However, further informal discussions called into question the capacity of the built fabric to passively managed standard apartment based water vapour loads.

According to an audit into building permits conducted by the Victorian Auditor-General’s Office, found as much as 76% of residential and commercial building permits had 5 or more compliance issues. How many of these may relate to condensation is unknown. Further studies and reports around Australia support the hypothesis that compliance lead to condensation problems or a reduction in energy efficiency.

However, an important point needs to be made. As mentioned above in the section on Legislative frameworks, there is no national building regulation requiring building designers, engineers, building surveyors, builders and sub-trades to consider and manage vapour pressure, or to provide a built fabric that mitigates condensation risk and does not promote the growth of human health affecting mould. This has established difficulties for building regulators, who are often contacted by designers, building surveyors, builders and home owners who are seeking advice. There is no regulation that stipulates the quality of built fabric permeability and air tightness, both of which are internationally required to minimise condensation risk. As mentioned above, the level of air tightness will determine if mechanical ventilation is required. In research by the CSIRO, (Ambrose and Syme, 2015), air tightness in new Australian housing varied from 1.4 ACH to 39 ACH @n50. Both the too air-tight and the extremely leaky houses provide significant risk for condensation and mould growth.

Discussions with representatives from a companies that provide reflective sarking systems commented that they rarely see reflective products installed correctly, absolving them from any insurance claims. Similarly, many industry respondents raised concern about the conflicting requirements of AS3959 (bushfire attack level) and the need for ventilated subfloors, cavities and roof space zones. Building Standards and Occupational Licencing (Department of Justice, Tasmania), established a working party of building scientists, builders, designers, surveyors and Tasmanian Fire Service, to develop a simple guidance document for the design and construction industry, which addressed the need for built fabric ventilation but also provided bushfire protection measures.

All these uncontrolled variables, which significantly impact the financial situation and health of owners and tenants demonstrate the need for national regulation.

Industry Education

It was noted in the Industry Consultation that the majority of the issues identified above were the result of poorly targeted, and at times inappropriate education strategies around condensation and vapour management. In the statistical analysis, 55% survey respondents were unaware that any educational materials existed. There was a general desire expressed for more educational materials to be created and circulated. For example, after a seminar on building products, feedback from industry professionals, (including architects, designers, builders, energy assessors, marketing and retail sales), there was a general desire for more information on condensation and moisture control. One of the events with the greatest amount of responses was held in south east Queensland. Specifically, there was a desire to establish what is compliant and for construction details that show simple solutions to technical problems. Attendees have asked to see local (climatic specific) examples of building practices that have succeeded or failed in relation to vapour management and condensation risk mitigation.

Others were concerned about the potential for detailing conflicts with AS3959 bushfire compliance. The seminar attendees included: architects, designers, builders, energy assessors, marketing and retail sales.

As the education and awareness of building occupants increases public awareness, the building industry will have to respond to market demands for increased energy efficiency combined with a moisture conscious design. Not only is the education of the industry important to increase the awareness about moisture control. It is also critical that national regulation stipulates appropriate performance requirements. According to one respondent from the scoping survey when answering question 18 ‘whose responsibility is it to consider condensation risk’,

> ‘*Governments need to write an Australian Standard to cover condensation and selection of materials… design should be assessed by the consultants doing the energy efficiency assessments…*’

In a preliminary review of the available education material, it was found that, other than the ABCB Condensation Handbook, little material exists. Furthermore, what material exists is commonly aimed at mould prevention but fails to address the source of the condensation causing problem. It was found that all states and territories have a factsheet or guide regarding mould, though few specifically mention vapour pressure management and condensation as a primary cause. There is little consistency between what information was included in documents from each jurisdiction. Access to the material was gained through the internet but not all factsheets were downloadable. There are no climate specific technical guides showing detailing tailored for the climatic requirements other than the Tasmanian BSOL booklet mentioned above. The Tasmanian government has identified the need to update this guide as a matter of urgency.

Summary of industry based recommendations

Industry representatives provided significant and valuable feedback on the scoping report's draft recommendations. This is outlined in full in Appendix 03. In summary the following key points have been used in drafting the final recommendations:

- Standardisation of terminology and general explanatory notation in all national and state guides and handbooks for professionals. Terms and definitions should be established by the ABCB.
- The inclusion of performance requirements (Building Regulation) within the NCC
- The development of an Australian Standard addressing condensation risk management
- Creation of technical guides that include construction detailing and methods of best practice for a number of cladding systems.
- State guides should include climate specific information and details should be created with this in mind.
- Education material delivered through relevant industry institution, unions, education providers as well as all levels of government.
- More guidance from manufacturers regarding best practice and explicit information regarding warranty exclusions if installations requirements are not meet.
- Creation of a model house guideline which specifies detailing for best practice construction and explains upcoming changes for each respective iteration of the NCC. For example, the guide for 2019 to show information and detailing to create a house of 2022 standards.

Part 4 - Residential building codes – an international perspective

A review of residential building regulations was conducted. From knowledge of key condensation causing mechanisms, a matrix of key regularity components was analysed from building regulations in the United States, Canada, United Kingdom, Europe and New Zealand. Key word and term searches relating to condensation risk were completed for each regulatory document. The findings are discussed below and in each case there is an overview of the regulatory framework, summary of relevant regulations and a contextualisation to the Australian NCC. References is made to sections of a regulations, to efficiently provide examples of specific approaches used to mitigate condensation, the way terminology is standardised and how a response is tailored to give climate specific outcomes. The full review of international building regulations is provided in Appendix 04. This section is then closed by a review of the Tasmanian experience, where short comings in regulation were identified as a key driver of condensation in all types of new buildings.

The review focused on the countries and regions mentioned above due to the ability to source, not just the regulations, but a range of supporting technical and specialised documentation, that were principally available in English. Some non-English regulations were also reviewed. The review of the US regulations included an examination of the national and state-based (Californian and Florida) jurisdictional regulations. California and Florida were chosen to establish what variation might exist between distinctly different climate typologies and for the climatic similarity to many parts of Australia. The review of European regulations focused on the European Union regulation. Some examples are then given on how individual member states have implemented these regulations.

Like Australia, a number of the regulations examined were national model codes. These are then implemented in whole, or with regional variations by state and local jurisdictions (USA, England, Canada, Europe). The primary focus of this review was the model national regulations. In each case elements of the regulations that provide regulatory requirement, performance or guidance have been extracted for discussion and comparison.

Each Regulation was analysed for regulatory changes that have evolved from the 1990's to 2016. This was to establish any key shifts, that might represent new understanding of vapour pressure management, condensation mitigation and mould eradication. Each regulation is analysed recognising building practices that are historically and geographically unique to that country or region. The analysis did not aim to compare specific building typologies and practices, rather, the reviewed examined key parts of each regulation that responded to issues of condensation internal moisture, humidity control, internal environmental control, air movement, and condensation related human health.

Specifically, each country's regulatory system was examined using the matrix developed from the key findings of the condensation literature review in Part 1 – Condensation in buildings. The Matrix is structured around the key headings, namely:

- Definition – is condensation defined in the regulations. If so how?
- Structure – how is condensation managed within the building fabric or envelope. This is divided into the sub-groups of Floor, wall and roof
- Internal Environment – The minimum and maximum internal temperature and air quality requirements (critical in avoiding dew point and condensation formation)

- Air Movement – the minimum ventilation rates and air-tightness controls (critical in reducing infiltration and condensation in interstitial spaces within the built fabric).
- Implementation – The Regulations examined were focusing on what was to be achieved. They often referenced other documents to detail on how to achieve the regulatory requirements. A review of these explanatory guides and reference was completed to assist in understanding how condensation risk has been mitigated.
- Compliance Testing – Regulations set minimum standard. The regulatory mechanisms used to ensure compliance and certification around condensation management were examined.
- Social Drivers – Many changes to regulations, around condensation, did not occur because of an identified long-term failure in building systems but rather, because of changes in social expectations around the internal built environment and energy efficiency. This broad heading aims to capture some of the wider context and motivations behind amendments to building regulations.

United States of America – the IRC

The International Residential Code (IRC) was developed in 2000 as a Model Code that jurisdictions can chose to implement in part or as a whole. Florida and California have adopted the IRC in full, with minor state specific amendments. The IRC encompasses all 1 to 2 family homes under 3 stories. It regulates a range of construction typologies and climates, zones and regulatory issues such as amenity and universal access. Provided below is a summary of the review of the IRC, using the Review Matrix. The full review of the IRC can be seen in Appendix 04).

Definitions

No definition of condensation

Structure

Floors: -

Minimum rates for sub-floor ventilation. Size and position of vents are also prescribed.

Walls

There was initially no mention of Vapour Barrier in IRC 2000. Vapour Barrier was included and defined by class in 2009. Vapour Barriers were placed in their own Section in IRC 2012. The regulation now stipulates:

> *"Class I or II vapour retarders are required on the interior side of frame walls in Zones 5, 6, 7, 8 and Marine 4"*

Furthermore, Section R703.2 External Walls requires

> *"Protection against condensation in the exterior wall assembly shall be provided."*

Air and vapour control location (internal or external side of wall system) is prescribed by climate zone.

Air and vapour control installation around the building and in regard to various building component is prescribed in detail (Table R402.4.1.1)

Roofs

Minimum ratio of ventilation size, location to roof space area is prescribed. This has changed over time providing more detail on vent type, size and location.

Roof space minimum ventilation area of a roof space is 1/150. This could be reduced to 1-300 if 50% of ventilation was located in the upper portion of the roof space (Section R806.2)

The use vapour barrier in roofs (sarking) was standardised in IRC 2012 to the use of specific classes in specific climate zones.

Air-impermeable insulation is only permissible as insulation in direct contact with the underside of the structural roof sheathing.

Internal environment

IRC 2012 introduced section N1101.9 (R302.1) - Interior Design Conditions. It mandates the interior design temperatures used for heating and cooling prescribed as maximum of 22°C for heating and minimum of 24°C for cooling.

Air movement

This has been amended over time. Section N1102.4.1 Building thermal envelope requires:

> "*The building thermal envelope shall be constructed to limit air leakage in accordance with the requirements of . . .Walls, ceilings, floors, crawl spaces basements and recessed lighting*"

Explanatory notes within IRC 2015 state the reason for this is:

> "*in response to International and U.S. research which identified leaking building fabric as a key location of condensation risk*."

Air-tightness – Minimum requirement for air leakage. (5 to 3 ACH@50 depending on climate zone)

Implementation

There are significant climate zone specific construction guides providing details for condensation mitigation. Comprehensive guides to designers, builders and home owners on the risks of condensation, and best practice advice on avoiding condensation risk.

Two clear 'portals' of information: The Environmental Protection Agency (EPA) focusing on issues of Indoor Air Quality (IAQ); and Building America, a division of the Department of Energy and Department of Housing and Urban Development.

Compliance testing

Air leakage testing (blower door testing) was introduced in IRC 2009 and expanded in IRC 2012 so that:

> *"The building or dwelling unit shall be tested and verified as having an air leakage rate of not exceeding 5 air changes per hour in Zones 1 and 2, and 3 air changes per hour in Zones 3 through 8."*

It is now mandatory for a new residential building to be pressure tested before it can receive an energy rating certification.

Social Drivers

The International Energy Conservation Code (IECC), like the IRC is a model code for minimum design and construction requirements for energy efficiency.

The IECC outlines a Model House. It is not compulsory, nor does it prescribe what design and construction methods should be used to achieve energy efficiency targets. It refers back to the requirements of the IRC.

Over time, the IRC has been amended so that the performance requirements set out in the IECC can be achieved in a way that mitigates condensation risk.

The IRC and lessons for Australia

A key finding of the review is that there has been significant refinement in how the issues of vapour pressure management and condensation is addressed and managed between, the development of the initial IRC 2000 and the current IRC 2015.

As condensation issues have been identified, mitigation strategies have been integrated into the IRC in a timely and coordinated way. This has responded to both specific climate based needs and building typologies.

As the IRC has developed there has also been a drive to use clear and constant language and terminology across the IRC and all supporting documents.

Also as the IECC and IRC requirements around building thermal performance changed, complementary changes were also made in other related sections of the IRC, to ensure condensation risk was minimised across all facets of the built fabric design and construction. *For example, IRC Chapter 7 – Wall Coverings,* provides an excellent example of the iterative process in developing regulatory responses to condensation. The initial definition in *IRC 2000* simply expressed the need to exclude moisture. However, *IRC 2006* progressed the definition to include vapour control, and by *IRC 2012*, the definition for wall assemblies have been separated into external and internal components and provide '*protection against condensation'*.

The United States, like Australia has diverse climate typologies. As a result, the way the IRC responds to climate specific issues is a good guide to the possible diversity of responses needed to mitigate condensation in the Australian regulatory context.

Like Australia, the IRC is a performance based system, setting minimum performance expectations but not prescribing how they are to be achieved. There is substantial supporting information provided to designers, builders and home owners on compliance with the IRC and how to respond to the issue of condensation in specific climates and building typologies.

Canada – The NBC

The Canadian National Building Code (NBC) is also a 'Model Code' that is adopted in-part or in-full by individual provinces and some municipalities. The NBC sets out basic prescriptive and performance requirements for building elements. It also covers basic building envelope and interior and exterior finishes and how they are to be constructed. The Code is divided into two key parts, namely:

- Division A, which defines the scope of the Code ('what' is expected).

- Division B, which contains acceptable solutions (commonly referred to as "technical requirements"). These are deemed to satisfy objectives and functional statements ('how' Division A is to be achieved).

Provided below is a summary of the review of the NBC, using the Review Matrix. The full review can be seen in Appendix 04.

Definition

The Objectives and the Functional Statements in the NBC make a clear link between prevention of illness of occupants and the management of indoor conditions, including vapour, moisture and mould.

The Objectives and the Functional Statements in the NBC make a clear the built fabric elements must perform the function of limiting moisture and condensation. Division A: Part 3 Functional Statements, Section 3.2.1.1:

> *"The building or its elements to perform the following functions . . Function 63 - To limit moisture condensation"*

Structure

Floors

Minimum sub-floor ventilation requirements and lining sub-floor surfaces

Walls

The NBC makes a clear distinction between the roles and functions of the 'first' and 'second' planes of weather protection.

The first (external layer) is a weather screen, the second (internal sheathing layer) controls minimum 'Ratio of Outboard to Inboard Thermal Resistance' for buildings to maintain the temperature and the relative humidity of the internal side of the rain screen above dew point (NBC Part 9.27.3.2).

The NBC provides a highly sophisticated description of materials, fixings, etc., and regulation of this second plan. Steady State Modelling is used to ensure this plane functions as required.

Roof

ALL roof spaces are to be ventilated (Part 9.19.1.2). The Ratio of vents to roof area is prescribed based on roof pitch (between 1/150 to 1/300). Roof Baffles are to be used to protect edge of insulation and guarantee roof space supply ventilation.

Internal environment

Depending on zone and function, Part 9.33.3.1. Indoor Design Temperatures require an indoor air temperature of not less than 15°C or 22°C.

Air movement

The NBC has significant requirements and measures to control condensation. Achieved by clearly defining conditioned and un-conditioned spaces. The role and function of thermal insulation, air barriers and vapour control.

As a result, NBC. Part 9.25.3.1 - Required Barrier to Air Leakage requires:

> "*include an air barrier system that will provide a continuous barrier to air leakage . . . sufficient to prevent excessive moisture condensation in such spaces during the winter"*

The NBC prescribes the use of a Vapour Control Layer (VCL) that is continuous and manages vapour diffusion through the built fabric and interstitial spaces. Additionally, the VCL shall protect the warm side of wall, ceiling and floor assemblies. Specifically, Part 9.25.4.1

Part 9.36.2.9 Air-tightness, prescribes that leakage of air into and out of conditioned spaces shall be controlled by a continues Air Barrier. With an Air Change per Hour (ACH) of 3.2 ACH@50 to 2.5 ACH@50, depending on the air-barrier system used.

Based on prescribed performance characteristics of materials and climate, Steady State Modelling is used to ensure condensation does not occur on the warm side of any building assembly.

Implementation

NBC is a model code and there is significant difference in building practice across regions and climate zones. Two key guides to builders are: Canadian Wood-Framed House Construction Guide and Canadian Home Builders' Association Builders' Manual.

Compliance testing

Part 9.36.5.10(10) allows for the 'design' air tightness calculations to be assigned for use in the energy model calculations until the actual air tightness has been measured via a mandatory blower door test on completion of build.

Social drivers

The EnerGuide Rating System requires a building pressurisation test to be performed after the house has been built, so that the 'as-built' results of the test are incorporated into the house performance rating.

The NBC and lessons for Australia

Within the NBC, condensation is clearly separated out from other forms of moisture and moisture risk. Condensation is a clear priority as it is identified as a risk at the Objective and Functional Statement levels. It is interesting to note that the Objective defines three key risk factors that must be managed to maintain occupant health, namely; indoor air quality, thermal comfort, and moisture. These are then referenced throughout the NBC as minimum expectations for compliance.

The more general description of 'moisture' is used in the Objective, but then, within the Functional statements moisture is divided up into its various components, such as ground, rain, and condensation.

The NBC provides the most comprehensive and sophisticated approach to Vapour Control Layers within the regulatory documents reviewed. It is noted that in some cases it is more prescriptive for elements like material selection.

However, the systematic approach and clarity used to outline the role and function of vapour control layer, air-tightness and thermal performance is significant. The separation of functions between First and Second Plans allows for a clear delineation of roles between external cladding and the 'internal' VCL. This delineation provides for the opportunity to clearly regulate the VCL and set minimum performance criteria to be achieved.

The clarity around regulating the VCL also allows for a steady state modelling. Designers and builders know what is the minimum requirement and post-build blower door testing ensures compliance with a well understood and logical set of minimum criteria.

Finally, Part - 9.36.5.3. Compliance stresses that it is not the occupant's role to manage vapour and condensation but the built fabric. It concludes vapour management:

> *.... is not dependent on occupant interaction.*

England - Building Regulations 2010

The Building Regulations 2010 (the Regulations) are national regulations with sub-variants for Scotland, Wales and Ireland. This report focusses on the Building Regulations as they relate to England. The Regulations contain definitions, procedures, and what is expected in terms of the technical performance of building work. Each section sets out the 'requirements' with which the individual aspects of building design and construction must comply in the interests of the health and safety of building users, of energy conservation, and of access to and use of buildings. England is unique when compared to the regulations reviewed from other countries as they continually refer to a specific British Standard that provides a comprehensive guide to the control of condensation. *BS5250 2011 – Code of Practice for the Control of Condensation in Buildings*. The standard provides information on:

> *"the risks associated with excessive humidity in buildings, notably mould growth and condensation, which can endanger the health and well-being of building occupants and the integrity of the building fabric."*

Provided below is a summary of the review of the building regulations and England and the code of practice for the control of condensation in buildings. The full review of these documents can be seen in Appendix 04).

Definition

There has been a definition of condensation in the Regulations since 2000.

However, this was re-written 2004. Schedule 1 of the Regulations now addresses the issue of condensation specifically in Section C2 – Resistance to Moisture:

> *"The walls, floors and roof of the building shall adequately protect the building and people who use the building from harmful effects caused by- . . . (c) interstitial and surface condensation"*

Structure

The Regulations provide minimum performance standard and basic information on how to achieve these standards for Floors, Walls and Roof. However, the Regulations quickly guides designers and builders to the referenced British Standards. So, for example,

> *"A Floor will meet the requirement if it is designed and constructed in accordance with Clause 8.5 and Appendix D of . . . the Code of Practice"*

The Code of Practice provides a comprehensive guide to the control of condensation. It makes a clear distinction between moisture types affecting buildings with the focus on condensation.

The Code of Practice describes the principal sources of water vapour, its transportation and deposition. It provides guidance on how to manage those risks during the design, construction and operation of buildings.

The Code of Practice is not a regulatory document in itself. But, a construction will meet the requirements of the Regulations if designed and constructed in accordance with the Code of Practice.

Internal environment

The Regulations require a minimum temperature be maintained depending on the function of the room at a minimum of 10 deg C.

However, the Regulations also prescribe that in regard to resistance to surface condensation and mould growth for Floors, Walls and Roofs, they need to be:

> *"designed and constructed so that the thermal transmittance (U-value) does not exceed 0.7W/m^{2}K at any point."*

Air movement & vapour control

The Regulations notes that one of the functions of ventilation is:

> *"... control of excess humidity arising from water vapour in the indoor air."*

The Regulations makes a distinction between air-infiltration (uncontrollable air exchange) and Ventilation (controllable air exchange)

The Regulations prescribed an air permeability of 10m^3/hm^2 at 50Pa for a domestic dwelling. The Code of Practice also recommended best practice of 5m^3/m^{2}h at 50 Pa.

To active this level of air tightness, the Regulations sight the Accredited Construction Details and The Code of Practice in regards to specific design and construction detailing. These are equivalent to 'deem to satisfy' that if used avoid the need for compliance testing (blower door testing).

The Construction details are comprehensive, and outline where and how a VCL should be used and information on how and why a specific construction detail mitigates the risk of condensation.

The Code of Practice provides a detailed definition of the minimum performance requirements and properties of any material used as a VCL.

If this level of Air-tightness is achieved then the Regulations require an extract ventilation rates, for a standard 3-bedroom house is prescribed at be 21l/s

Implementation

In regard to condensation mitigation The Regulations reference the Code of Practice. As noted above, compliance with the Code of Practice is considered to meet the requirements of the Regulations.

Compliance testing

Building pressurisation and depressurisation testing is required, unless the construction details outlined in the Accredited Construction Details and Code of Practice are included in the architectural documentation and are proven during construction.

Social drivers

The UK has had a rating system for building energy efficiency for some time. More recently, the Home Quality Mark (HQM) has been developed and implemented. This is a 5-star rating system that examines aspects beyond energy consumption to include broader issues that affect the Interior Environmental Quality and other social impacts.

The HQM was released after the latest revision of the Regulations. It will be interesting to note any changes in the structure, requirements, and terminology that may occur within the Regulations as a result of the introduction of the HQM system.

The regulations and lessons for Australia

The significant point of deference between England and other jurisdictions is the development of the code of practice for the control of condensation in buildings. It has a number of functions. The first being, that it enables the Regulations to focus on performance criteria. This allows the code of practice to provide extensive and evolving detail on the how and why of the performance criteria, and the how to meet the performance criteria.

The Code of Practice provides a comprehensive guide to the control of condensation. It, in a way, provides many of the same functions as the ABCB Condensation Handbook. It outlines why condensation is an issue, where and how it may be a risk, and provides a range of mitigation strategies based on various building types and construction typologies. The key difference being the code of practice is a regulatory document and a national standard, whereas the condensation handbook is non-regulatory.

The core of the code of practice establishes principles and a philosophy that feeds back into the wording and structure of the Regulations, like:

> *The occurrence of condensation is governed by complex interrelationships of factors*
>
> *Designers and builders need to integrate a range of principles to resolve condensation risk*
>
> *Buildings are often not used as intended by occupants and so a designers and builders need to err on the side of caution and adopt robust fail-safe built fabric solutions.*
>
> *Do not rely on users or mechanical solutions over the long term.*
>
> *When seeking to exceed minimum energy performance for a building, consideration must be given to the impact and risk to the condensation profile of that ....*

This last point is particularly salient. It highlights that any amendment to regulation requires a consideration of how that change may impact on current condensation risk and mitigation. The management of condensation must evolve with, in fact be embedded in, the regulatory process.

Also, the Accredited Construction Details provides an excellent guide to a set of construction details that meet minimum performance requirements, while still allowing designers the freedom to explore the most economic construction system.

This is done through the clear articulation of the vapour control layer in each detail. Specifically, the air control layer, thermal control layer and vapour control layer.

New Zealand - New Zealand Building Code (NZBC)

Background – the New Zealand experience

The New Zealand building regulations have been significantly redeveloped as a result of the 'Leaky Buildings' issue that occurred more than a decade ago. A problem that has cost the government, construction industry and government billions in remediation activities. Many of the problems that arose from 'leaky buildings' were related to a lack of appropriate building regulation. However, it should be noted that initially 'leaky buildings' was not a condensation related problem. It was a façade design and construction issue that allowed external moisture and water to enter and degrade the built fabric. However, during the early stages of 'leaky buildings' remediation, the issue of condensation and mould within new buildings became apparent and became a component of the leaky buildings program.

Like many of the recent experiences in Australia, condensation and mould was being found within subfloor zones, wall framing, internal spaces and roof spaces in New Zealand buildings. Aspects of ground moisture, subfloor ventilation and roof space ventilation were targeted quite quickly with some early positive outcomes. A distinct difference that existed between Australian and New Zealand was the use of craft-paper type vapour permeable building membranes. (Many of Australia's building membranes are vapour impermeable.) However, the management of vapour pressure through the built fabric soon became a priority with the need to ensure that all materials from the interior lining to the vapour control layer of the building membrane was vapour permeable. This process included the requirement for a vapour cavity in all construction systems. Most recently, (August 2016), New Zealand regulations have disallowed the use of foil products unless they meet very strict design and hygrothermal testing guidelines. In many respects, Australia may be 10 to 15 years behind New Zealand on this issue. As many Australian construction systems and climates are very similar to those of New Zealand, a sleeping condensation and mould problem may well start to make its presence felt within residential and non-residential buildings. This is best highlighted by the co-operation between the New Zealand BRANZ and UTAS teams which has compared images and data from condensation and mould affected buildings in New Zealand and Tasmania, often with identical causes and the corresponding presence of condensation and mould.

The New Zealand Building Code

The New Zealand Building Code (NZBC) contains the compulsory rules for building design and construction for New Zealand. Like the NCC the NZBC has both Acceptable Solutions and Verification Methods. The NZBC is divided into 8 clauses, (A through to H). Each clause addresses a specific aspect of the building regulations. Each clause of the NZBC is supported by Technical Guides that outline in detail the Acceptable Solutions and Verification Methods. It is in these Technical Guides that the detail on how to achieve the performance requirements of the NZBC are outlined in detail.

In regard to condensation, Clause E of the NZBC addresses the issue of moisture and is divided into three sub clauses, namely:

- E1 – Surface moisture
- E2 – External Moisture
- E3 – Internal Moisture

Provided below is a summary of the review of the NZB. The full review can be seen in Appendix 04.

Definitions

The NZBC provides a detailed definition of condensation. The Objective of Clause E3 Internal Moisture is to:

> *"(a) Safeguard people against illness, injury, or loss of amenity that could result from accumulation of internal moisture"*

As a result, under Section E3.2 - all buildings must be constructed to avoid the likelihood of:

> *"(a) Fungal growth or the accumulation of contaminants on linings and other building elements"*

Fungal growth (mildew)

> *"is avoided by minimising internal condensation.*"

Condensation is avoided or reduced by:

> *"maintaining the correct balance between interior temperature and ventilation. Insulation assists in maintaining interior temperatures at a suitable level"*

Structure

Section E3 of the NZBC makes no distinction between floors, walls and roofs, indicating that the provisions around condensation apply equally to all three built fabric systems.

Floors

All sub-floors are to be ventilated

Walls

BRANZ provides considerable guidance on how to achieve thermal performance requiems, it is noted in E3 that insulation satisfying the energy efficiency requirements cannot automatically be assumed to meet the R-values for internal moisture requirements.

Roofs

The New Zealand Metal Roof and Wall Cladding Code of Practice is a code developed by the New Zealand Metal Roofing Manufacturers INC. It provides a comprehensive best practice guide for roofing and provides a large section about condensation mitigation.

It states that minimum roof ventilations should be:

> *"0.5 Air Change Rate per hour, or*
>
> *1m^2 net free ventilated area per 150m2 of ceiling area (ratio of 0.6%)"*
>
> (it should be noted that many other nations expect up to 4 air changes per hour in the roof space)

Additional vents must be provided if roof pitch is less than 15deg and roofs of less than 10deg should increase this ratio.

Internal environment

NZBC does not prescribe a minimum heating requirements for residential buildings. However, the Technical Guide notes:

"it is necessary and sufficient, for condensation control in winter, to keep interior temperatures 5°C to 7°C above exterior temperatures in a ventilated space."

This also creates confusion between vapour permeability and ventilation. This clause would indicate that windows must be left open, to enable condensation to be managed. This is significantly different in concept to the Canadian, USA and England regulations already reviewed.

Air movement and vapour control

The technical guides supporting the NZBC provides minimum requirements. These include: lapping and joint details for wall underlays. A wall underlay can be used as both a vapour control layer and an air barrier. It must have a vapour resistance of 7 MN s/g or less. This is a 'Low' vapour barrier under AS/NZS 4200.1.

Ventilation is similar to that in the NCC. Net openable area of no less than 5% of the floor area.

Implementation

BRANZ provides a range of quality research and technical guides that outline solutions for addressing condensation risk. Additionally, the Compliance Document 'Simple House' provides acceptable solutions, that if followed, provide compliance with the NZBC.

NZBC and lessons for Australia

The NZBC provides the most compressive definition of condensation found during the review process.

Its strength comes in its ability to move from a high level concept of protecting human health, logically down to mould as a consequence of condensation. The Definition also succinctly summarises the drivers of condensation around ventilation and internal temperature. However, as mentioned above, this places a reliance on ventilation, as opposed to passive built fabric vapour pressure management adopted in other countries.

A negative to this approach is that the 'definitions' are spread throughout several parts of the NZBC and other technical documents. This is due to the structure of the NZBC.

There may be benefit in consolidating the key components into one clear definition that then can drive the formulation of performance criteria, constant terminology and an integrated response to condensation risk.

European Union

The European Union (EU) has 28 member stats. The aim of this review was not to analyse all member states individually, rather to examine the overarching regulation of condensation risk at the EU level and look at member states for examples of implementation. The EU does not have a single unified building code that addresses all aspect of building construction. Each member state implements its own Building Code. There is significant diversity between each country's codes, reflecting different historical, social and climatic conditions. Provided below is a summary of the review of the EU Regulation. The full review can be seen in Appendix 04.

EU Regulation for built fabric

The most significant issue driving change, in relation to the issue of condensation, in EU building codes, is the aim to reduce energy consumption of buildings. This is driven by two documents, namely:

- The 2010 Energy Performance of Buildings Directive (2010 Directive), and
- The 2012 Energy Efficiency Directive (2012 Directive)

Neither Directive addresses condensation directly. However, it is noted that the changes they propose would significantly alter the current building systems in use through member countries. These changes will have a potentially negative impact on Indoor Air Quality

The EU recommends, but does not mandate a minimum and maximum indoor air temperature of 20 deg C and 26 deg C respectively (EN15251).

Likewise, Ventilation EN 15251 Annex B2, provides default values to use, if no national regulation is available. The minimum ventilation rate is based on floor area and requires between 0.05 to 0.1 l/(s·m2).

However, Germany divides ventilation into four types within its regulatory system. These are:

- Ventilation for protection against humidity - avoids damages caused by wet air
- Reduced ventilation - minimal hygienic requirements
- Nominal ventilation - active ventilation via window
- Intensive ventilation – extract air around cooking, washing, etc.

European Standard EN 13829 describes the measurement method of air permeability of buildings through fan pressurisation at an infiltration airflow rate at 50 Pa.

There is no consistency within the EU regarding infiltration rates. In Denmark, air leakage must not exceed 1.5 $l/(s \cdot m^2)$. Alternatively, Germany requires a maximum of 3 ACH@50 for natural ventilated houses, 1.5 ACH@50 for mechanically ventilated house and the Passivhaus standard limits air leakage to 0.6 ACH@50.

EU regulation of human health and amenity

The EU prescribes a strict regulatory framework around IAQ under Directive 2008/50/EC. At this stage, 'Microbial' pollutants are not contained in the directive. However, a review completed in 2013 argued that a more holistic approach to IAQ should be taken, in which a broader set of environmental and social health objectives are considered. When this update occurs non-dosed based pollutants such as mould are likely to be included.

The EU and the world Health Organisation (WHO) collaborated to produce the WHO - Guidelines for Indoor Air Quality: Dampness and Mould (WHO Regional Office for Europe, 2009). The WHO Guide identified that condensation, mould and poor IAQ were prevalent throughout Europe across all climate zones, and all building types. The Who Guide also provides a review and a synthesis of the epidemiological, clinical and toxicological evidence on the health effects of dampness and mould (page 63). The WHO Guide concluded that:

> *"Sufficient epidemiological evidence is available from studies conducted in different countries and under different climatic conditions to show that the occupants of damp or mouldy buildings, both houses and public buildings, are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma."*

The WHO Guide notes, energy conservation measures that are not properly implemented (tightened building envelopes, ventilation deficits, and improper insulation) contribute to the conditions associated with increased exposure to dampness and mould and the risks of adverse health effects due to biological contaminants of indoor air. The WHO Guide also noted that regulation of moisture generally focuses on entry during occasional events, such as water leaks, heavy rain and flooding. It argues that there is not sufficient focus on moisture which enter a building via incoming air, including that infiltrating through the building envelope or that resulting from the occupants' activities. The WHO Guide recommends:

- Persistent dampness and microbial growth on interior surfaces and in building structures should be avoided,
- Well-designed, well-constructed, well-maintained building envelopes are critical to the prevention and control of excess moisture and microbial growth
- Management of moisture requires proper control of temperatures and ventilation to avoid excess humidity, condensation on surfaces and excess moisture in materials

The principles of the WHO Guide have been reinforced by The Buildings Performance Institute Europe Report 2015 (Kunkel *et al.*, 2015), which recommended:

- IAQ and health should be considered to a greater extent in European building codes.
- Any increase in thermal performance, should also include minimum requirements for indoor air exchange and ventilation.
- The co-benefits of a healthy indoor environment should be taken into account when assessing the macroeconomic impact of energy improvement measures.

EU regulation and lessons for Australia

The EU regulation for built fabric highlights possible solutions available in the regulation of buildings as Australia increases then energy efficiency requirements for buildings. The regulation highlights that condensation emerges as a potential risk every time building fabric regulation is changed and how condensation mitigation must become imbedded within regulatory outcomes. A consistent set of themes throughout the EU regulations included:

- The need to ensure minimum and maximum indoor temperatures.
- Significant effort in making buildings to specified levels of air-tightness
- Highly sophisticated ventilation strategies
- Integration of building strategies to ensure good IAQ
- A move to a broader understanding of what makes a 'healthy' building with an increased focus on IEQ

The WHO Guide makes clear the link between condensation and negative impacts on human health. Its recommendations provide a set of core principles to manage vapour and condensation risk. The BPIE Report makes the salient point that IEQ should be part of any discussion around microeconomic benefits and regulation for energy efficacy in buildings.

Summary of international regulation findings for Australia

The international regulations reviewed covered a diverse set of climate typologies, providing a guide to the possible diversity of responses needed to mitigate condensation in the Australian regulatory context. Most regulations are a performance based, like current trends in Australian regulations, which establish minimum performance expectations but not prescribing how they are to be achieved.

The Regulations reviewed have all undergone an iterative process of review and reform to manage vapour pressure and mitigate the occurrence of condensation and mould. This process was driven by an improved understanding of condensation risk and the risks associated with improved thermal performance. Each regulatory iteration sought to improve and standardise terminology. Complementary changes were also made in other related documents, to ensure a consistent approach to condensation risk mitigation.

Definitions of condensation clearly separated it out from other forms of moisture and moisture risk. In all documents a clear link is made between condensation and its negative impact human health.

A consistent regulatory objective was the requirement that vapour control and condensation risk be managed passively, by the building fabric, (NOT the Occupant). To achieve this, the building fabric was often divided between first rain barrier and second internal vapour control layer. The internal layer was often broken into insulation, vapour control and air barrier control layers.

Certified accredited design and construction details documenting how to construct effective vapour control systems, to mitigate the occurrence of condensation and mould were often developed and provided by Regulators, National Standards or Industry Representative Bodies.

Steady state modelling was often required as a minimum measure to determine and manage condensation risk at the design stage. Many jurisdictions are increasingly requiring the use of dynamic hygrothermal modelling to establish climate and design specific, year round condensation risk assessments.

There are identifiable benefits from separating condensation into a clear Code of Practice (England). This method has provided a central, consistent, and dynamic document that can respond more quickly than a National Regulatory framework.

There was no consistent application of terms around Vapour Control Layer. Each regulation did define vapour permeability or vapour resistance, but there is no universally agreed approach to the description of VCL or measures climate based measures for vapour permeability of building components.

Building leakage has been identified as a critical point of condensation risk and mould growth. The uncontrolled air movement between the internal and external environments was often regulated and air-barrier construction details were provided. Most regulations mandated less than 10 ACH50. As buildings become more air-tight, passive ventilation is still prescribed, but recognition that mechanical ventilation is required in well-sealed buildings where infiltration is below 5 ACH50.

All roof spaces in all climate types require ventilation with either a minimum flow rate or a ratio of vent size to roof area.

Most countries reviewed provided extensive national education and explanatory documents for building occupants, building designers and the construction industry which discuss why condensation control is needed and how it can be managed.

The main driver changing building design, is energy efficiency. It is known to impact all aspects of the building, including risks associated with vapour management, condensation, moisture and mould. There is growing awareness of the need for an integrated approach for vapour control and moisture management with each step improvement in energy efficiency.

For several countries, the driving principle is now Indoor Air Quality. This is being driven by societies expectations for building thermal performance whilst still providing healthy interior environments. The management of mould and fungal growth are seen as a critical aspect of good IAQ. Additionally, IAQ is being treated with the same level of micro economic importance as energy efficiency, so that energy conservation, comfort enhancement and healthy indoor environment investments are mutually reinforcing.

The findings of the review can be summarised diagrammatically, as shown in Figure 16. As any regulatory system seeks to address fundamental aspects of building design and construction, aspects of structural durability, vapour pressure management, condensation risk mitigation and indoor air quality must be equally considered. The diagram shows where Australia likely sits with its international peers. The diagram shows the shift from simplistic views of thermal performance to the more integrated consideration of built fabric assemblages which provide high quality indoor environments. As Australia moves down the path of improved thermal efficacy and decreased ACH@50, it will need to also consider a broader, and more interconnected set of regulatory issues.

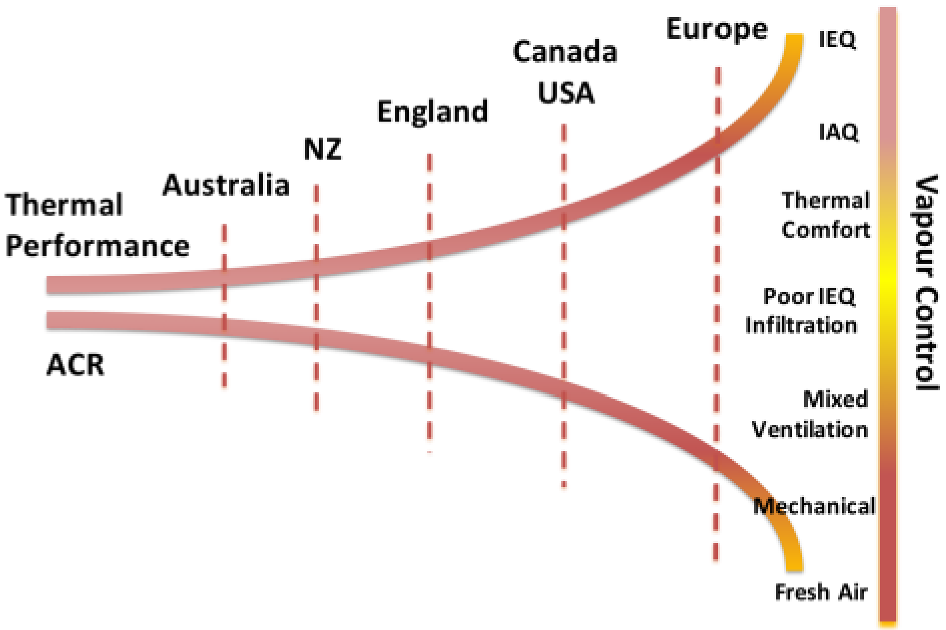

Figure 16 – Regulation, built fabric efficacy and indoor environmental quality

The Tasmanian experience

In 2005, a research team that included Professor Robert Vale and Professor Roger Fay and Dr Mark Dewsbury, were exploring design opportunities to provide a net zero energy house typology for a volume builder in Tasmania (Dewsbury *et al.*, 2006). Early in this process the team started to raise concern with regard to the proliferation of vapour impermeable building membranes in use in Tasmania and by association many other parts of cool temperate and temperate Australia.

This led to the development of a post-graduate research project which was advertised in 2007 (an investigation into the causes and effects of moisture in buildings). Unfortunately, after nearly a year of marketing no interest was shown and the funding was suspended.

This led to greater discussions and the provision of seminars around Tasmania in 2010, funded by Forest and Wood Products Australia. By this stage many new homes had been made more air-tight with vapour impermeable wall wrap systems. At the same time, individual building owners who were concerned about the condensation within their homes started to make contact with building thermal performance researchers at the School of Architecture and Design (University of Tasmania). Additional support from Forest & Wood Products Australia led to the publication of the technical guide: *Thermal performance for timber-framed residential construction: building comfortable and energy-efficient timber houses (Dewsbury and Nolan, 2015)*. The first draft of the technical guide was provided in 2011. As the first of its type in Australia, the guide underwent significant revision drawing on comment and input from a range of stakeholders. It is interesting to note that a range of contested issues and questions raised in the drafting process are now more widely understood and accepted within the industry.

From 2011 regular discussions commenced between the Tasmanian Building Regulator, UTAS, BRANZ and CSR Building Products. In response to these concerns CSR Building Products commenced a review of their product range, (and their vapour permeability properties) and corresponding recommended construction practises. Since that time CSR has been active in product development, product removal and building science research that has focussed on climatically appropriate built fabric systems.

During this period the Tasmanian Building Regulator was often raising concern with the ABCB, about the slow pace of change that was occurring within the NCC.

For Tasmania, condensation issues became a significant focus of concern in 2012. The building regulator started to receive regular enquiries from concerned home owners, building designers, building surveyors and builders. New houses with excessive amounts of condensation and mould were suddenly becoming more common place, or occupants were starting to be more concerned. This led to a multi-pronged approach, which included four tasks, namely:

- The establishment of a working group of building designers, building surveyors and building scientists which started to create awareness in Tasmania about the likely causes of the condensation and mould problems.
- In 2014, 2015 and 2016, the provision of government supported and industry based professional development seminars in all regions of Tasmania. These were targeted at building designers (including architects), engineers, building surveyors and builders. Well over 1,000 professionals attended these events.
- In 2015, the development of a simple design and construction guide for the design and construction professions. The A4 fold-out leaflet included ventilation and vapour permeable construction details for subfloors, walls and roof spaces and included non-BAL and BAL versions for each detail.

- In 2014, the detailed assessment and measurement of new homes that had excessive moisture, condensation and mould with subfloors, walls, interior rooms and roof spaces.

The detailed assessment of some new homes with extensive condensation was flooded with enquires from concerned new home owners. Thankfully, many builders made enquiries and some remediation actions were put in place during the construction process. The data and information gained from the case study houses led to a range of recommendations to the Tasmanian Building Regulator, namely:

- Until better information is available, all buildings in Tasmania, which may be heated, should use vapour permeable building wall wraps.
- Until better information is available, a minimum ventilation requirement for all unconditioned attic roof spaces in Tasmania should be applied. This would include supply air from eaves and exhaust air from gables and/or ridges. The minimum quantity of eave supply vents should be ½ half the rate specified within the NCC for enclosed-perimeter platform-floored subfloor ventilation, and they should be evenly spaced around the perimeter of the building. The ridge and/or gable vent area should equate to 40% of the eave supply vent area. Gable vents must be located as high in the wall as possible. (The required area for unconditioned roof space supply and exhaust ventilation will be revised once international regulations have been further evaluated.
- All cathedral style roof systems must have a supply and exhaust vent per cassette. This is the sealed space between each pair of rafters. However, if significant cross ventilation is provided between cassettes, this ventilation requirement may be varied to a similar quantity of vents as described in ‘2’ above.
- Under no circumstances should ceiling batt insulation and sarking system be in contact with each other.
- Sarking system must be installed as per manufacturers specified method for buildings in a cool and temperate climate.
- BSOL continue to provide state-wide and regular professional development training seminars which will present the basic design and construction principles that must be applied to provide vapour management, which will minimise the risk of condensation and subsequent mould growth within buildings.
- BSOL provide state-wide and regular professional development training seminars which present and discuss more advanced design and construction principles for vapour management which will minimise the risk of condensation and subsequent mould growth within buildings.
- BSOL, in collaboration with UTAS, Tasmanian Fire Service and key industry partners revise and redistribute the state based ‘Condensation in buildings: Tasmanian designers’ guide’ to all registered building practitioners.
- BSOL, in collaboration with UTAS, provide a written guide for building and related construction professions, which explains and provides guidance on construction practices that allow for vapour management within Tasmanian buildings.

- BSOL require that building application documentation includes architectural notes that describe the built envelope elements and/or systems that have been incorporated to manage vapour pressure, which will minimise condensation risk and subsequent mould growth in new buildings.
- BSOL should lobby the Australian Building Codes Board about the significant lack of regulatory requirement on design and construction practices to manage vapour pressure and minimise the risk of interstitial and internal condensation within the current National Construction Code. Section 2.2 (NCC Vol2 2015) included the objective to 'minimise the accumulation of internal moisture in a building'. However, there were no functional statements requiring the consideration of vapour pressure management or the minimisation of internal and interstitial condensation. This resulted in no requirement or discussion of these matters within the acceptable construction methods within Section 3. As of May 2016, this matter will be compounded, as the objective mentioned above is modified from a normative requirement to an explanatory statement. This results in no regulatory requirement to consider vapour pressure and condensation risk within buildings from May 2016.
- The current legislation names Environmental Health Officers, as the providers of advice regarding safe occupancy to occupants of buildings where mould is present, (The Tasmanian Public Health Act, 1997). It should be noted that this professional group does not fall within the bounds of BSOL. During this research it was established that knowledge of mould, mould types and their effect on human immunology and allergy was lacking within this professional group. Training needs to be provided to this professional group to enable correct and prompt advice to occupants of mould affected buildings.
- This research has focussed on matters pertaining to stand-alone and co-joined residential buildings. However, there is extensive industry based evidence of condensation problems occurring in non-residential and multi-residential buildings. Recommendations need to be developed which can guide designers and constructers of these other building typologies.

As condensation within buildings has been identified as a national problem by several manufacturers,

- Develop, with interstate or national assistance, and within the next twelve months, a condensation risk matrix, which will enable a 'Deemed-To-Satisfy' or a 'Performance Based Solution' for vapour pressure management to minimise condensation risk and subsequent mould growth within residential buildings.
- Develop, with interstate or national assistance, and within the two to four years, a software based condensation simulation tool, which would integrate the NatHERS climate files and simulation output data from accredited building simulation tools to provide a full year (8760 hours) and room specific condensation risk assessment for residential and commercial buildings.
- Finally, although not a deeply explored task within this research, the correlation between mould in buildings and its impact on human immunology and allergy has Australian and international acceptance. Many countries have strict regulations within their building codes concerning condensation and mould. These international examples, which focus on the need for appropriate

vapour pressure management, need to be evaluated in the context of contemporary issues in Australia.

Correlation between many of these recommendations and regulatory requirements of the other building codes discussed above are evident.

Has the situation in Tasmania improved – YES. There are many less telephone calls to the building regulator. However, many new buildings are still being constructed with no consideration of the items listed above. However, the UTAS team still receives regular telephone enquiries and requests for a building inspection. The challenge is the lack of regulation. The challenge when facing specific home owners' experiences of built fabric condensation issues is the lack of clarity in the regulatory space. This leaves the home owner in an uncertain position as they are often financially unable to remediate the built fabric. Even in September 2016, the UTAS researchers have met with builders who still believe that the condensation and mould problem is the fault of the home owner and not the built fabric. A growing number of telephone calls are coming from owners of houses that were built up to 15 years ago. These houses often have vapour impermeable wall wraps, inadequate roof space ventilations, roofing material thermally bridged to sarking, ceiling batt insulation and wall framing and direct fixed vapour impermeable cladding systems providing thermal bridging to the interior surface of wall wrap systems. Recently, some houses have required significant demolition and reconstruction.

Discussions with industry partners in this research have identified very similar built fabric problems occurring Class 1 and Class 2 buildings in South Australia, Victoria, ACT, NSW, and Queensland.

Part 5 - Potential gaps in the NCC, which may influence the risk of condensation

This section seeks to identify how current regulatory requirements within NCC Volume One and Volume Two may influence the risk of condensation. Thus includes a review of changes in the NCC, any relationship between changes and an increased risk of condensation and regulatory gaps that may allow condensation and mould to occur in new buildings. The gap analysis is an examination of potential issues regarding: the current regulatory requirements, inconsistencies across current regulations, and potential issues arising from the absence of regulations. The current NCC and associated Australian Standards and relevant complementary documentation has been outlined in Part 2. The gap analysis is a structured discussion exploring regulatory 'gaps' when compared to the international literature review, international building code review and condensation problems that have been witnessed in Australia.

The discussion commences with a review of condensation in NCC from 2003 to 2016. This provides an overview of reform to the NCC since the introduction of minimum energy efficiency requirements. It is not a comprehensive review, rather it is targeting specific regulation relating to condensation. This will be followed by an examination of NCC 2016 using Comparison Matrix that was used in the review of international building regulations in Part 4. The aim is to identify overarching regulatory strategies within the NCC and provide an opportunity for of comparison with the international regulations reviewed.

This gap analysis also uses the findings of the Nationwide Condensation Survey and the findings of the industry consultation, outlined in Part 3 of the report, to highlight and then analyse any gaps in the NCC. This is followed by a summary of the findings and their likely link to the Scoping Reports recommendations.

A second gap analysis examines the Australian Standards referenced in the NCC with regard to condensation issues. The gap analysis identifies potential shortcomings, with a specific focus on AS3959, which has been identified as a key standard in condensation risk and mitigation management.

Review of condensation in NCC from 2003 to 2016

The term condensation is used four times in the NCC 2016 Volume Two. Two of these references are in *Part 3.12.5.3 - Heating and cooling ductwork*. Another in P*art 3.12.4.1 - Air movement*, which links condensation to mould growth, but this reference addresses the inappropriate use of evaporative cooling in humid locations.

In Part 3.12.1.1 (c) ii - Building fabric thermal insulation Explanatory Note 2, includes a good description of condensation risk and human health. But the discussion is limited to artificially cooled buildings and the need to place a vapour barrier on the humid, or generally warm side of the insulation. It is not clear why this risk of condensation is limited to a cooled building.

A full comparison of NCC Volume Two, from 2003 to 2016 can be seen in Appendix 07. It is clear from this table how minimal any change has been to the NCC in regard to condensation.

Since 2003 a number of parts within the NCC have referenced components, which affect condensation mitigation, such as air-tightness, ventilation, insulation and moisture control.

However, during this thirteen-year period there has been no correlation and linking discussion and performance requirements, which co-address the need for vapour control, and condensation, moisture and mould mitigation.

This lack of change or evolution within the NCC from 2003 to 2016 has the potential to significantly impact on the ability of new Class 1 and Class 2 buildings to appropriately manage condensation risk. As the built fabric of new buildings has changed to improve thermal performance, other important changes to the built fabric, such as vapour control, air-barriers and ventilation rates, are not keeping pace with change. As a result, under current NCC provisions the risk of interstitial condensation risk may be increasing.

There are a number of other issues within the NCC, which affect condensation mitigation. There is no clear definition of condensation. The term moisture specifically refers to liquid moisture risk, as made clear in the explanatory notes for Part 2.2. The term moisture vapour is used interchangeably with humid air and condensation. In NCC 2016 this description of moisture was moved from a non-regulatory Objective to a non-regulatory Explanatory Information, significantly hampering any discussion of condensation related to building regulation compliance. In many of the industry meetings that were conducted as a part of this task, there was sense of general concern about this lack of regulation and guidance.

Section P2.4.5 Ventilation does not discuss ventilation as a component of condensation mitigation. Management of humid air is part of IAQ (an objective of the part) but in itself it is not a contaminant. Humid air does have the potential to generate environments for microorganisms to accumulate and so should be managed via effective ventilation strategies. This part does not reference any minimum flow rate for ventilation that would achieve its objective.

Section 3.12.1.1 Building fabric thermal insulation provides explanatory information regarding the use of reflective foils. The general statement around condensation, mould and risk to health is sound. However, it is limited to artificially cooled buildings, whereas it should apply to all buildings. It is also unclear if the risk being identified is only present when using reflective insulation.

The Explanatory Note goes on to suggest a fully sealed vapour barrier may need to be installed on the more humid, or generally warmer, side of the insulation. There is no explanation as to what constitutes a vapour barrier. The issue arises as to which Australian Standard would be referenced when specifying a ‘vapour barrier’. This is also challenged by recent changes in Florida, where there has been a shift back to vapour permeable buildings due to condensation and mould problems in intermittently conditioned and fully conditioned buildings, which had previously required a vapour impermeable vapour control layer.

The development of insulation requirements in roof and ceilings, as prescribed in *Table 3.12.1.1a* has established a steady increase in the climate dependent minimum R-Values prescribed for roof and ceiling insulation from R2.2 - 4.3 in NCC 2003 to R3.1 - 6.3 in NCC 2016. This change has the potential to significantly alter conditions in the roof space and the vapour pressure interaction between the conditioned and unconditioned spaces.

Additionally, the focus in many countries has been insulation of the conditioned space. The current description for the roof space allows for ineffective and unproductive insulation to be placed against the roofing material, above what is supposed to be a well vented and unconditioned roof space, promoting a greater loss of cooled or heated conditioned energy from the rooms below.

The Explanatory Notes provide some information on this, but there are areas of inconsistency. For example, *Note 1* - recommends ventilation only for climate zones 1 to 5. This would be out of step with current research that suggest un-vented roof space in cool climate zones require ventilation to manage condensation risk.

The second part of *Note 1* implies that ventilation of skillion type roof spaces is difficult and seems to suggest it is not recommended, once again contrary to minimum prescribed practice in other countries. However, it is not clear if this only refers to the warm climates described at the beginning of the Note, or to all climate types. *Note 4*, is correct that consideration should be given to surrounding environmental features when considering a roof ventilation strategy. But it is unclear if the risks identified refer only to climates zones 1 to 5 or all climate zones.

Substantial research has been conducted on the risk of vented versus unvented roof spaces in humid climates. It finds that a roof space can never be made truly air-tight. This has established that there is significant risk of moisture build up around the air infiltration site as humid external air 'leaks' into and remains in roof spaces, causing immediate built fabric degradation (Building America 2014).

Part 3.12.3.5, construction of roofs, walls and floors requires construction to minimise air leakage, but there is no description of what constitutes a minimised air leakage.

Examination of NCC 2016 using comparison matrix

As can be seen in Table 1, below, when using the comparison matrix, there are significant differences, (gaps), between the NCC Volume Two and the reviewed codes when addressing the issues of condensation. Provided below is a discussion of the NCC around the key components of the Matrix when compared to the analysed international regulations.

Definition

NCC 2016 Part 2.2 Damp and Waterproofing - provides an explanatory note regarding moisture. However, the Functional Statements attached to this statement make clear that the term moisture is used here exclusively to mean liquid water. Therefore, the NCC does not provide any definition of condensation. This is in contrast with the reviewed regulations. There are benefits to having a high level regulatory requirement, which provides recognition that human health, structural durability and material performance is impacted by moisture and that this definition separates moisture and condensation. Such a definition would recognise that there are clear and persistent structural and human health threats from the formation of condensation within buildings. Recognition of condensation risk, at this high level, gives legitimacy and clarity to any subsequent parts of the regulations that specify where and why vapour pressure, water vapour, condensation, uncontrolled moisture and mould should be managed.

Table 1: Comparison Matrix - International Regulation and NCC Volume Two

REGULATION CHARACTERISTIC	UNITED STATES O AMERICA	UNITED KINGDOM	CANADA	NEW ZEALAND	EUROPE	AUSTALIA
Name of Regulation	International Residential Code 20	Building Regulation 2010	National Building Code of Canada 201	New Zealand Buildi Code	The 2010 Energy Performance of Buildings Directive and the 2012 Energ Efficiency Directive	National Constructi Code 2016 Volume – Class 1 and Class Buildings
Definition of Condensation or Internal Moisture		x	x	x		
Structure						
Suspended Floors						
Air Barrier	x	x	x	x		
Dedicated Vapour Control membrane	x	x	x	x		
Seal Penetrations and holes in VCL	x	x	x	x		
Water impermeable Ground Cover	x	x	x	x		x
Minimum Ventilation	x	x	x	x		x
Walls						
Dedicated Air Barrier membrane		x	x			
Dedicated Vapour Control membrane	x	x	x	x		
Penetrations and holes in VCL (managing leakage)	x	x	x	x		
Breathable Sarking / Sheathing / rain screen	x		x			
Roof						
Sarking layer	x	x	x	x		x
Dedicated Vapour Control membrane	x	x	x	x		
Penetrations and holes in VCL (managing leakage)	x	x	x	x		
Ventilation rate Cool Roof construction	x	x	x	x		
Ventilation Rate Hot Roof construction	x	x		x		
Vent Size / Vent Net Area	x	x	x	x		x
Baffels	x		x			
Thermal Comfort or IAQ						
Min / Max Internal Temperature					x	
Min Ventilation Rate/ Net Area	x	x	x	x	x	x
Air-Tightness / Air Change Rate	x	x	x			
Mechanical Ventilation	x	x	x		x	
Compliance						
Static State Model	x	x		x		
Dynamic Model					x	
Blower Door Test	x	x	x		x	
Implementation						
Key Reference Documents / Constructio						
Recognition of Condensation as Health issue	x	x	x	x	x	x
Condensation risk linked to Energy Effici requirements	x	x	x	x	x	x
Provide Guide to:						
Vapour Control	x	x	x	x	x	
air-tightness	x	x	x	x	x	x
Ventilation	x	x	x	x	x	
Thermal Bridges	x	x	x	x	x	x
Social Drivers						
Condensation part of IAQ assessment included in rating matrix		x			x	
Education om Condensation Risk and mitigation						
Builders	x	x	x	x		x
Designers	x	x	x	x		x
Home owners	x	x	x	x		x

The industry consultation highlighted the confusion that exists on this matter with state and local government based regulators, unsure of how to deal with the issue of condensation and mould. A precise set of definitions and requirements within the NCC would assist in removing this confusion. Specifically, feedback often placed responsibility for humidity control, solely on the occupant, (whether an owner occupier or a tenant). However, this is at odds with international expectations and NCC's own objectives around health and amenity. A clear definition of condensation, may assist in re-prioritising condensation management.

An excellent example of a definition is Canada's NBC.

> *The Objective of the NBC is to:*
>
> *". . . limit probability of exposure to an unacceptable risk of illness due to indoor conditions. . . caused by — contact with moisture. . . (by) . . .limit moisture condensation"*

Like the NCC, the NBC has a primary objective to ensure human health in the built environment. However, the NBC separates out the issues of moisture into risk factors that include water as condensation.

England makes similar separations on the definition of moisture to include the risk of condensation. New Zealand and the United States do not make the distinction in the Objectives parts of their respective codes. However, the NZBC is structured in a way that the descriptor of specific risk of condensation is within the Guide for the Functional Statement E3. It states:

> *"Fungal growth (mildew) is avoided by minimising internal condensation. Condensation is avoided or reduced by maintaining the correct balance between interior temperature and ventilation. Insulation assists in maintaining interior temperatures at a suitable level"*

Structure

Sub-floors

There is a level of consistency between the regulation of sub-floor ventilation in the NCC and other reviewed regulations. All codes require a ratio of vents to floor area and sealing of damp floor spaces.

Walls

England and Canada both use a Steady State model and a Vapour Control Layers to manage the risk of condensation in wall space. The NCC does not require any hygrothermal or steady state modelling of wall systems to ensure that dew point is not reached within the wall system. The lack of modelling gives rise to a potential situation in which walls systems are designed and constructed that allow for condensation to occur, rather than wall systems that actively and appropriately mitigating condensation risk. It should be noted that some nations are in the process of adopting dynamic hygrothermal analysis tools due to the accepted limitations and risks associated with steady state dew point analysis.

The United States and New Zealand specify the use of a climatically appropriate Vapour Control layer. The type and placement of the VCL in all countries is prescribed in detail and determined by climate zone. There is no consistent description of what constitutes a VLC between countries. But each references a country specific standard or definition.

The NCC provides no description of a VLC and no standard is referenced to provide a consistent set of terms or definitions of vapour permeability or vapour resistant products that may constitute a VCL. An Explanatory Note for Part 3.12.1.1 references ‘vapour barrier’, but this is in the context of reflective insulation acting as a vapour barrier. No detailed description is given as to, how the vapour barrier performs, or the level of resistance provided or needed, and critically, if a ‘vapour barrier’ is needed in this context at all.

In discussions with the BRANZ Building Performance Research Team, it was established that foil products have now been disallowed as membranes in cavities. This may apply to walls and roofs. BRANZ have identified foil products in particular locations as providing a significant condensation risk.

The United States and Canada separate walls into different components. This separation allows for a more sophisticated regulatory response to specific wall components. The United States separates walls types into internal and external. The management of condensation can then be managed regarding where, how and what type of VCL is used in a specific climate zone. Canada separates walls into first and second planes. The first (external layer) is a weather screen, the second (internal sheathing layer) controls minimum *‘ratio of outboard to inboard thermal resistance’*. Again significant detail is given in the NBC on this specific part of the wall system and its role in managing condensation.

Roofs

Industry consultation highlighted a range of knowledge in the drivers behind condensation risk in roof spaces. A number of industry representatives are taking steps to address specific issues, but this is ad-hoc and even they sought grater clarification on ventilation systems and ventilation rates. There is also a growing market for mechanical as opposed to passive ventilation systems. If a new home is having a mechanical ventilation system installed to manage roof space vapour, who will maintain this equipment, provide failure base alarms and warrant the product for a set period of time with coordinated equipment replacement program?

Significant industry feedback provided a worrying level of misunderstand about condensation in roofs. Many sighted incorrect information as ‘industry norm’, others sighted construction systems and the use of specific products, that, from an international perspective are known to contribute to risk. As noted above, roof ventilation requirements within the NCC are limited, inconsistent and open to interpretation, which is significant contrast to the reviewed regulations.

In contrast, Canada’s NBC states in Part 9.19, all roof space are to be ventilated. Both Canada and the United States make a distinction between roof structure and roof space. Both are regulated separately. Although New Zealand does not specify this within the NZBC, it is detailed in the referenced roofing industry guide. Additionally, England, Canada and the United States separate regulation of roof ventilation into ventilation of the drainage plane (the space between roof sheet and sarking), and ventilation of ‘roof space’ between sarking and insulation. This highlights that both the roof space and the space between sarking and roofing are ventilated spaces, and not still air.

The IRC still allows ‘non-vented’ roof space however, the construction methods required to achieve this are extensive and there were attempts to remove this option from the IRC 2015. However, for this interim period the IRC progression of ever increasing clauses as it attempts to regulate this issue. Over time the sub-clauses detailing requirement has grown from a few lines to a few pages. The current approved method requires the use of a sophisticated thermal and vapour control system. This is stark contrast to the comment in Note 1 from Table

3.12.1.1a of the NCC. When this is considered, the NCC might be promoting the occurrence of condensation.

Internal environments.

All regulations reviewed provided climate type based minimum levels of thermal insulation. All provided detail on the need to make the thermal layer continuous around conditioned internal spaces. The NCC does have a similar requirement. All but New Zealand prescribe minimum internal temperatures that must be maintained for human health. Some also specify the maximum internal temperature. All linked the maintenance of minimum and maximum internal air temperatures to condensation mitigation.

There were significant differences in prescribed minimum temperatures between climates and countries. The minimum temperatures were used to model energy use, heating system size and insulation requirements. By establishing these temperature boundaries, a condensation risk analysis can be completed. At present, the NCC does not have a discussion at this level, creating difficult situation for any steady state or dynamic dew point and condensation risk analysis can be compromised. In Europe, countries have or are in the process of requiring dynamic condensation risk modelling. This is further supported by the EU Directives specifying requirements for Indoor Air Quality, which include air temperature, humidity, moisture and mould.

Air movement and ventilation

All regulations reviewed provided minimum ventilation rates for habitable spaces. All provided requirements to vent air out of internal space. Like the NCC, all based ventilation rates on floor area and used operable windows as a primary ‘natural’ ventilation system. There is significant complexity when attempting to summarise the ventilation part of the reviewed regulations. Each is significantly different from the other making direct comparison difficult. However, some general comments can be made. All noted that as a building becomes more air-tight, ventilation as part of the condensation mitigation strategy is important. None recommend a specific ventilation strategy but they do separate ventilation into different types, namely:

- Background ventilation
- Natural Ventilation
- Mechanical ventilation

Others use different terms, but the key concept is the recognition that management of condensation in thermally efficient buildings is complex. Furthermore, and specifically, when air-tightness is <5 ACH@50, mechanical ventilation is recommended or required. The mechanical system is required to equally provide fresh air and to assist in household humidity management. This is a critical benchmark to be aware of. Most Australian Class 1 and Class 2 buildings are significantly leakier than the 5 ACH50. However, some early leaders in low energy homes may be creating very air-tight internal spaces that should have mechanical ventilation as a code requirement.

Additionally, whether the system is passive built fabric or a mechanical system, most regulations stipulate they must operate without the active participation of occupants. The NCC recognises a range of potential ventilation systems, but does not make clear any link between specific ventilation strategies and condensation mitigation. Other than New Zealand, all regulations prescribed a level of minimum air change rates. Based on climatic variables, air change rates vary from 8 to 3 ACH50. Europe is already prescribing 0.6 ARC for housing seeking high-energy ratings.

The NCC does not prescribe a minimum or maximum ACH@50. This is out of step with all comparable countries. It is clear from the review that prescribing an ACH@50 had a number of flow-on effects. A more airtight building allows for more considered built fabric management options for condensation mitigation. Condensation resulting from infiltration is decreased by reducing the amount of 'leaky' locations within the built fabric. Ventilation strategies that are targeted, efficient and effective can be developed for both fresh air delivery and humidity control. Also thermal control is improved. Therefore, air-tightness regulation acts as a catalyst for the more sophisticated management of condensation and requires a clear understanding of the building fabrics function in the areas of vapour, thermal and air control.

Consistency of terminology and approach

The reviewed regulations have evolved, over time, from discussing building components in isolation, to describing them as built fabric systems. ACH@50 is discussed as part of the thermal envelope. To manage the ACH@50 the regulations specify the function and properties of:

- Insulation layer - thermal regulation
- Air barrier - controlling egress of uncontrolled air
- Vapour control layer - condensation control

Any change in one component requires a consideration of the impact on the others. This approach is clear within the codes, often supported with extensive explanatory notes highlighting the need to consider impacts on other parts of the thermal envelope. This built fabric system approach is even more apparent in referenced and approved supporting documents.

The NCC has not undergone any significant reform in regard to condensation. As a result, there is inconsistency across the regulation of the built fabric and envelope system. However, the industry consultation process made clear the issue that the standardisation of terminology and general explanatory notation in all national and state guides and handbooks was important for industry professionals. Many noted, that all terminology and descriptions around condensation in associated documents should be derived from the ABCB and NCC.

Vapour control layer

All reviewed regulations provide a definition of what constitutes a VLC. However, and unfortunately, each provides a different definition of vapour retardant level. There is a significant range of terms used in these definitions, namely:

- Vapour permeable
- Vapour impermeable
- Vapour resistance
- Vapour barrier
- Vapour check

Terms like vapour resistance and vapour barrier normally do not mean vapour impermeable, rather that the material simply resits vapour migration to some degree. Each regulation reviewed provided its own definition of VCL materials and referenced their own standard.

The NCC includes terms such vapour barrier, however when compared to the international examples, there is no supporting information or referenced document which could provide a definition of what is meant by the term barrier. It could be vapour impermeable or vapour permeable or vapour resistant? The lack of any clear definitions and standards around the principles of a VCL in Australian buildings is a significant problem. If any coordinated response to condensation risk is to be undertaken, a set of standard terms must be defined. As noted during the industry consultation:

> *"I would be happy to sell a vapour resistant membrane in New Zealand, because I know what that means. But I cannot sell it here because, what I think a resistant membrane is and what a builder thinks it is could be two totally different things."*

These differences aside, there is consistency in the application and implementation of VCL's in other regulations. There is significant detail on lapping and taping, and the VCL is often supported to ensure it remains robust for many years. This level of detail is prescribed because a VCL is only effective if it is air-tight and lifetime wear and tear can significantly affect long-term, life of building, performance.

Implementation

All reviewed regulations were performance based. For most the detail on how to achieve the deemed to satisfy provisions have, over time, been removed from regulatory documents. Canada, England and New Zealand provided excellent examples of how the transitions made from regulatory performance requirements, to minimum requirements and compliant or better than code design and construction solutions. The Regulatory bodies of England and New Zealand provide comprehensive guidance and research on the latest in building practice. The United States and Canada provide equally good guidance through government and industry bodies. In all cases the Approved Documents, Referenced Standards or Technical Guides provided accredited design and construction methods that meet the requirements and standards set out in the relevant code.

In most cases the regulation has established terminology and definitions which, are consistently used between the regulatory and referenced supporting documents. Information is often provided on deem-to-satisfy and better than minimum performance options. All documents detail condensation risk, condensation mitigation strategies. The Regulation and Referenced documents adopt a building system and built fabric system approach, creating a 'kit of parts' to address condensation mitigation. All documents split the building fabric into thermal, air and vapour barrier layers.

The NCC references a number of standards and it is through these that detailed information on compliance is managed. However, the review team has found inconsistencies between the expectations expressed in the NCC and the referenced standards. These often relate to inconsistencies in terminology, definitions, and industry understandings of building science versus product sales. The ABCB *Condensation in Buildings Handbook: Second Edition 2014*, provides some insights into condensation mitigation. It does describe in detail condensation risk, the link to human health and provide detailed strategies to mitigate condensation. However, as noted in nearly all industry consultation meetings in which these documents were discussed, it was stated:

> *"Yeah, but they're not mandatory" and,*
>
> *it "differs significantly from international guidelines".*

The Industry consultation process highlighted a desire for the creation of technical guides that include construction detailing and methods of best practice for a number of cladding systems that demonstrate systems for condensation management and compliance with NCC regulation. Additionally, such guidance may also include solutions that go beyond minimum requirements, to outline potential best practise solutions, or, for example, the guide for 2019 may also show information and detailing to create a house of 2022 standards, with corresponding consideration of insulation, ventilation and vapour control layers.

Compliance testing

Building regulations require a range of components of the building be certified before they are deemed safe to occupy. Internationally, compliance for condensation risk analysis is achieved through steady state and dynamic dew point analysis and building air-tightness testing.

All regulations reviewed, except New Zealand, mandated a building pressurisation test. Between regulations there are differences around the timing and methodology of the building air-tightness test and in the maximum allowable air change rates. However, all required the 'blower door test' as part of the 'as-built' energy rating of new homes. The test was undertaken at either the completion of the house or at various stages during the build process. Leaky buildings are classed as non-compliant and require rectification. It should be noted that the very airtight houses in the CSIRO house energy efficiency research were air-tightness tested more than once during the construction process, providing some skewed data outcome (Ambrose and Syme, 2015).

The NCC does not mandate an air-tightness level. However, the market is slowly demanding blower door tests as a tool to inform house energy efficiency. At this early stage in Australia, this may lead to condensation problems where the built fabric air-tightness is not married to built fabric vapour management strategies and ventilation requirements. A very significant issue is that very 'tight' buildings could be built which will likely impact on IEQ. Air tightness alone is not a mark of success around energy efficacy and healthy internal environments. However, it does provide guidance as to the level and type of controlled ventilation that needs to be part of a building to ensure occupant health is maintained.

Social drivers

Each country examined has a system for rating the energy efficiency of new residential buildings. All linked this to their minimum performance standard in their relevant regulations. These changes in regulation are not driven by identified failures in buildings, but rather, as a result of changes in social expectations around buildings and their function. Most use a star system or a similar score card system. All used a form of the model house to compare performance and model performance against. However, it was clear that the criteria by which houses were being assessed is evolving. The criteria are being expanded, from energy use, to broader indicators of a building's internal environment. At the lower level these can be grouped under the banner of Indoor Air Quality (IAQ).

In some countries this is already evolving into the broader requirements of Internal Environmental Quality (IEQ). These quite prominently discuss condensation, moisture and mould and their potential impacts on human health. Therefore, in these countries, a house with a high star rating will not only be energy efficient, but will provide good IAQ.

As Australia moves to more energy efficient homes and in turn, the NCC prescribes higher minimum performance standards through the star rating system, there will be a need to revisit condensation mitigation regularly. Thermal insulation, air-tightness and vapour control are all linked members within condensation mitigation. A change in one requires a reconsideration of the others.

Summary of findings

The review of NCC 2003 to 2016 in Section 1 highlights that the NCC has not changed significantly in how it identifies, describes, regulates vapour management, condensation and mould. Contained within the explanatory notes of the NCC are some accurate descriptions of condensation risk. But this is not translated into regulatory requirements in a clear and consistent way. This lack of change or evolution within the NCC has the potential to significantly impact on the ability of new Class 1 and Class 2 buildings to appropriately manage condensation risk. As the built fabric of new buildings has changed to improve thermal performance, there is a lack of a clear strategy within the NCC to manage condensation. This results in significant short comings in the management of condensation in roofs and walls. The NCC has moved out of step with a range of condensation mitigation regulations that are now standard within comparable international regulatory systems

The term moisture specifically refers to liquid moisture risk. This limited definition is out of step with international regulation and has the potential to limit the scope of understanding of risk to only liquid moisture at the exclusion of condensation. There is significant support from industry for a definition of condensation to be include in the NCC, which will provide significant regulatory benefits like, but not limited to:

- its elevation to a risk that needs to be considered and addressed in modern building design and construction, and
- it drives a standardisation of terminology, and application across all regulatory and associated documentation.

The lack of clarity in the NCC around vapour control layers, restricts any strategic approach to condensation mitigation. The description of walls into a VCL or into distinct planer functions would facilitate the focus of regulation around the thermal, air barrier and vapour control layer functions. Additionally, clear definitions of the climatically appropriate VCL would assist both the design and construction industry in identifying the appropriate products to use and provide opportunities for manufacturers to provide appropriate products for increasingly conditioned Australian homes.

The NCC has no requirement for a steady state modelling of any component of the built envelope, whether floors, walls, ceiling, roof space or roofing. The lack of such modelling restricts the ability to ensure that strategies to mitigate condensation, be they mandated or not, are achieving the expected outcome.

Roof ventilation requirements within the NCC are limited, inconsistent and open to interpretation, this is in contrast to the reviewed regulations and may be contributing the lack of industry knowledge and its current practises, which often provide environments for condensation and mould.

The NCC, as with other regularity systems prescribe a minimum ventilation rate based on operable windows area per meter square of floor space. However, in regards to condensation and humidity control, whether the system is passive built fabric or a mechanical system, most regulations stipulate they must operate without the active participation of occupants, (i.e., that vapour control does not require occupant participation). The NCC is out of step with other reviewed countries in not regulating for a minimum ACH@50. It is noted prescribing an ACH@50 has a number of positive flow on effects regarding condensation mitigation.

Certification of ACH@50 provides feedback to the industry as well as certainty to consumers that the buildings condensation mitigation strategies are functioning as intended.

The current ABCB Condensation in Buildings Handbook is a good general guide, but it is not mandatory. There is a desire for technical guides such as this to provide deem-to-satisfy solutions to condensation risk.

Gap analysis - Australian Standards referenced by NCC

To complement the Gap Analysis of the NCC, a preliminary review of Australian Standards (AS) cited within the NCC (volume 2) was undertaken. Provided here is a summary of the results. The full analysis of referenced Australian Standards can be seen in Appendix 06. The gap analysis found a number of examples of conflicting information between the standards and/or the NCC which could lead to confusion or misinterpretation. Specifically, in regards to condensation risk management, there are significant differences between the NCC and referenced Australian Standards.

The gap analyses sought to identifying standards with outdated examples, diagrams, drawings or written explanations that refer to or have the potential to negatively impact the building envelope. More specifically, where inconsistencies between the NCC and AS may impact on the design and construction of the building fabric, in such a way, that it could directly or indirectly cause condensation. This inconsistency has the potential to provide confusion in the industry regarding compliance. This potential confusion is not a trivial matter. The legal ramifications of such inconsistency for compliance is significant. The gap analysis found a number of AS documents currently referred to in the NCC will likely require further review and possible revision in light of this study's recommendations. Especially, as very few made any reference to or acknowledged vapour pressure, condensation or mould.

Where condensation was identified it was usually in an informative capacity, contained in an explanatory note rather than the body of the text. Only recently revised standards provided links to sources of further information for industry education on condensation.

Standards mentioning condensation risk were primarily those relating to the construction and specification roof systems and materials. Where moisture control is discussed, it is done so only in relation to its liquid state not specifically vapour or the vapour migration needs of a roof space, including above and below the sarking plane.

Few standards mentioned specific aspects relating to condensation, such as: vapour control, vapour permeability, or infiltration in any capacity. And any discussion on external or internal vapour loads was not included in any referenced standard.

Summary

This gap analysis has identified a range of aspects that need to be regulated and included within the Australian National Construction Code – Volume One & Volume Two. Once the required performance is established, individual items may require deemed to satisfy guidance within the code, updates to appropriate Australian Standards, maybe a new Australian Standard on Condensation in Buildings, updates to other non-regulatory documents and extensive guidance and education for design and construction practitioners and manufacturers.

The general principles discussed in Parts 1 to 5 of this document have established the critical need for action within the NCC. These actions include, but are not limited to:

- The need for the ABCB to establish definitions, which relate to aspects of vapour pressure, vapour permeability, condensation and mould (somewhat like those at the start of this report).
- The need for a new and separate section on vapour pressure management and condensation and mould mitigation within volume One and Volume Two of the NCC, or
  a section within each of the current parts of Volume One and Volume Two of the NCC, which focuses on the aspects of the section that must consider vapour pressure management and condensation and mould mitigation.
- The need to regulate vapour permeability of built fabric based on climate,
- The need to regulate the leaky-ness of buildings,
- The need to regulate roof space ventilation (to continuously remove vapour),
- The need to regulate sarking zone ventilation and drainage methods (to manage the regular occurrence of condensation),
- The need to regulate built fabric systems which avoid dew point or require the use of an approved method to prove dew point will not occur within interior spaces, walls, and roof space zones.
- The need to review requirements for low pitched roof systems,
- The need to regulate ceiling insulation continuity to reduce thermal bridging at this critical location,

There are many other aspects that need to be considered at the design and construction levels but these will become manageable once regulatory performance requirements are established. This will force the design and construction sectors to provide more durable, safe and healthy buildings, which will be auditable by building surveyors, and state and local governments.

Part 6 - Cost - benefit analysis

The cost–benefit provides an evaluation of the impacts of the proposed recommendations. In the Summary of Part 5, some key items were listed as needed inclusions or additions to the NCC. Some of these are purely administrative, whereas other elements require changes to current construction practises or material choices. Within this context in this section, each suggested change in construction practise is discussed within the context of building specific, industry and Australian community potential costs and benefits that may be achieved. Where possible, cost-benefits from the proposed recommendation have been expressed in monetary terms. However, this analysis is intended only as a guide to assessing the recommendations proposed in this scoping report. Further detailed cost-benefits analyses, using the Commonwealth Office of Best Practice Regulation, Cost–Benefit Guide, would be needed to provide a more comprehensive review of suggested amendments.

It is clear that many of the potential cost-benefit effects of the proposed recommendation are not just the immediate or direct, financial effects, but there are various linkages between the proposed recommendations and other sectors of the economy, for example, increased safety, increased structural durability and the potential to reduce health care costs that would provide a significant net benefit to society.

Quantity surveyor estimated costs & benefits

Based on the list of suggested items in detailed in Part 5, standard construction processes and materials were reviewed to establish construction practise and material choice changes that may be likely. The may-be-likely is an important qualifier, as some design and construction professions that were involved in the Industry Consultation process were already applying some or all of the suggested actions. However, there is always a greater percentage of the industry that is working at the minimum requirement level. The changes established are shown below in Table 2.

Table 2: Regulatory changes and likely construction implications

Suggested Change	Method
Regulate vapour permeability	A change in building wrap system selection Include vapour cavity in wall construction
Regulate building leaky-ness	Additional inspection, or A building pressurisation and depressurisation test
Regulate sarking ventilation	This is currently shown in most manufacturer details. Once regulated, this becomes a compliance issue
Regulate roof space ventilation	Attic Roof's - Add vent systems to eaves, gables and ridges Cathedral Roof's - Add vent systems
Regulate dew point analysis	Steady state dew point analysis With the view to migrate to Dynamic dew point analysis within 3 years
Remove roof space thermal and condensation bridging	The increase in depth of truss, or roof framing, at the junction of roof and top plate to ensure continuity of insulation and roof space ventilation
Regulate additional requirements for low pitched roof systems	For climates where sarking and roofing often reach dewpoint temperature, an additional insulation layer will be required and anti-ponding measures should be applied

The proposed recommendations were submitted to a quantity surveyor to establish likely compliance related construction costs. The quantity surveyor was provided with four volume builder style plans, namely:

- An average sized single storey Class 1 house ($247m^2$),
- An average sized two storey Class 1 house ($276m^2$),
- A larger single storey Class 1 house ($357m^2$), and
- A double storey Class 2 unit ($110m^2$).

The costs, were developed based on nationally standard volume builder pricing for Australian construction, September 2016. A summary of the likely costs is shown below Table 3. A more comprehensive listing of the costings is provided in Appendix 08. Each of the measures above include many variables and a few of these are discussed below.

Table 3: Summary of Quantity Surveyor estimates

Alteration\Cladding Type	**Single storey ($247m^2$)**	**Two storey ($276m^2$)**	**Two storey large ($357m^2$)**	**Double storey Class 2 unit ($110m^2$)**
Vapour permeability Building Wrap Wall Cavities	 $280 $3,095	 $480 $5,175	 $510 $5,530	 $150 $850
Building Leaky-ness Ceiling air barrier Inspection, or Blower door test	 $125 $500, or $500	 $125 $800, or $800	 $125 $800, or $800	 $125 $500, or $500
Sarking Ventilation	$0	$0	$0	$0
Roof Space Ventilation Attic Roof Cathedral Roof	 $1,840 $3,600	 $3,055 $4,815	 $3,250 $5,209	 $450 $1,100
Steady state dew point analysis	$250	$250	$250	$250
Remove roof space thermal and condensation bridging Trusses to have upstands Cardboard baffle	 $2,550 - $4,600 $1,000	 $2,500 - $4,200 $1,550	 $2,700 - $4,500 $1,400	 $980 $250
Low pitched roof actions Added insulation Anti-ponding measures	 $3,300 $1,500	 $2,700 $2,300	 $2,700 $2,140	 $650 $420
Non Regulatory Cloth dryer externally vented	$195	$195	$195	$195

Costing discussion

The cost of providing a better quality and climatically appropriate building wrap system will provide long-term condensation, mould, and air barrier benefits for this very minor cost. The addition of a vapour cavity for all cladding types shows a much higher cost. However, there are a few points to note, namely; all brick construction already includes a vapour cavity, and many manufacturers of sheet cladding systems show a vapour cavity within their specified construction documentation. Within this context many builders are not building to the manufacturers specification. Regulation will remediate this issue.

The removal of items that compromise the air barrier of the ceiling is a critical component to both vapour pressure management and thermal performance. This minor cost is associated with the shift from vented downlights to sealed LED type lamp systems. The new generation of lamps also allow continuous insulation removing thermal bridging issues. The 'checking' of air barrier performance requires that the NCC specify an acceptable level of passive, (or pressurised) air change rate per hour. To ensure compliance the international examples have shown that either a building inspection or a certified blower door test is suitable.

The sarking insulation and ventilation issue is perplexing. Current regulation does not provide clear guidance on this matter. However, literature from reputable manufacturers specify the need for a ventilated cavity between the roofing material and the sarking system. Regulation will promote minimum adequate practice.

Roof space ventilation and roof space thermal bridging are very much co-related. The ventilation includes the current cost to retrofit vents to gables and eaves. It should be noted that the installation of vents to eaves provides the greatest portion of the cost. Already, some manufacturers are exploring importing, or modifying current production lines, to provide vented eave lining systems within the Australian market. This will significantly reduce the estimate shown here. However, the top plate and roof system junction has been problematic and unregulated thermal and condensation bridge in some climate types since 2004, when ceiling insulation became mandatory. In most cases there has been no change in construction detailing since the pre-ceiling insulation days. This is a significant industry based shortcoming. If industry had adopted change in 2004 with subtle increases in the space of this connection in 2005, 2007 and 2010, there would be a minimal cost associated with any recommended changes. The development and implementation of deem-to-satisfy roof ventilation requirements will need to be considered in-depth and may require the adaptation of current practises.

The cost attributed to the steady state dew point analysis is based on costs for these services in Canada, USA and the UK. This is a minimum required action for all climates where heating or cooling is used. In the first instance it might only be applied for climates where heating is used. However, recent industry advice on condensation problems in south east Queensland indicates that dew point analysis may be required for most NCC climate types. The comment with regard to the adoption of a dynamic dew point analysis relates the significant short comings associated with steady state modelling. As discussed in the analysis of international trends, many countries are about to adopt dynamic modelling. This is because dynamic modelling allows for variations in internal and external building conditions to be tracked in more detail. This targets areas of risk with more precision and allows the most economical responses to be developed to address specific and identified risk.

Internationally, and in the Tasmanian & New Zealand experiences, low pitched roofs are a dilemma. Some countries have extensive regulation and guidance for any roof pitch that is lower than 15°C. For a mix of reasons many new houses have roofs with a pitch lower than 15°C. Condensation will form in most roof spaces at some time, whether it is Darwin on a clear skied night in the wet season and a house on southern Queensland in winter. On a pitched roof the condensate can run freely from where it forms on the sarking to the eaves and gutters of the house. However, on a low pitched roof, the condensate forms and drips into the ceiling roof space (timber or steel), insulation and plasterboard, leading to significant durability and structural issues.

The clothes dryer issue is outside the remit of the NCC. However, the NCC could include a cautionary note. This would then promote the use of external ducting systems by appliance regulators and state or local government agencies.

Industry education and upskilling

The Tasmanian and New Zealand experiences have demonstrated that there is a significant knowledge gap within both the design and construction sectors. This was further reinforced by many of the text responses provided in the nationwide condensation survey. However, in both the Tasmania and New Zealand experiences, education was found to be a critical component to address both the theory and construction practise components of the vapour pressure management, condensation and mould problem.

The ABCB often provides update training for annual and triannual NCC updates. It would be advantageous for this training be extended to a full day event if the recommendations are adopted. This will allow adequate time to present the regulatory reasoning and processes involved to manage vapour pressure, and mitigate condensation and mould. Within the broader community some manufacturers are already providing ‘road-shows’ in all states, where these issues are often discussed to full houses.

Additionally, by establishing these new regulatory requirements, the technical and tertiary training sector will need to include these components within teaching and learning outcomes for the next and following generations of designers and builders.

Community benefit

The Tasmanian experience and that of some industry representatives in Victoria, ACT and NSW have seen first-hand the human and life affecting impact condensation and mould has caused for owners of new homes, units and apartments. The financial stress, family breakdown and significant impact on family short and long-term health is well known. Regulation to address these issues will provide significant community and human health benefits. Aside from the built fabric remediation costs described within the New Zealand and Tasmanian experiences, the section in Part 1, which described health issues also estimated the likely health cost that is currently born by the entire Australian community. Not to mention how chronic disease affect the lifetime opportunities for those that suffer from built fabric caused asthma and associated immunology and allergy conditions.

In Australia, a common thread of economic discussion includes the value of the family home as a family and national asset. However, many of these homes suffer from condensation and mould problems. As Australian society becomes more educated, like the populations of the USA, Canada, UK and Europe, there will be a desire to NOT be in buildings that show condensation and mould. This may cause a reduced rate of return on a significant number of existing Class 1 and Class 2 buildings that experience condensation and mould, compared to buildings in a similar asset class that have been built with appropriate and effective condensation mitigation measures. Within tenant representative bodies, education is already underway, warning would be tenants of the long-term health impacts from living in mould affected buildings.

By providing the appropriate regulatory framework to ensure Australian homes are condensation and mould free, we will be seen as coming into ‘step’ with minimum interior environmental expectations of other developed nations. Additionally, this will provide more durable and more thermally comfortable buildings.

The National Energy Productivity Plan for 2019 to 2028 aims to improve the energy productivity of Australian buildings. The measures discussed in this report will provide beneficial outcomes for items 2, 29, 31 and 32 of the NEPP.

Finally, the recommendations listed above also support the Australian Government's research priority areas of Health, Environmental Change and Energy.

Part 7 – Unintended consequences and further research

Overview

This Part provides an analysis of potential unintended consequences stemming from the proposed recommendations. As this is a scoping report, the unintended consequences have been clustered around key themes that have emerged from the research. The aim is to identify broad potential problems, further research would be needed to ascertain the extent of any issue and their impact on any implementation strategy.

Compliance

The proposed recommendations outline a number of changes to the NCC. To ensure these proposed regulations are implemented correctly will require the development of industry compliance mechanisms. Historically, when new compliance requirements have been mandated there has been a drop of in the number of 'certified' suppliers. This has occurred when builders were required to be certified in most jurisdictions in the early 2000's, and more recently for the Residential Energy Assessors. In both cases there was a slight jump in the average cost of services, however in both cases a better outcome has been achieved for the industry and the broader community.

Industry up-skilling

The problem with damp from condensation is significantly different from water damage from incidents of flood, leaking appliance or plumbing leaks. With incident-based water damage once the cause is rectified, restoration works can be implemented to make the dwelling habitable again. Unlike a flood event, condensation is not a short term problem which can be resolved simply. Rather, it is a persistent and recurring part of a building if it is not designed and constructed to appropriately mitigate its causes. In this report it is clear that condensation does not have an easy fix, and thus any remediation is bound to be temporary. This is a point that bears emphasis if the industry expresses resistance to further education and training: a building that repeatedly and persistently has condensation is a problem with either design or construction that should have been avoided in the first place.

Of particular importance is that architects and building designers are key to solving this problem. There is no one correct way of building and there are many ways to compensate for one aspect with another, for example to locate a wet area in a sunny aspect. As condensation is a system-based problem, the whole dwelling needs to be understood as systems of envelope, ventilation and vapour management. Architects and building designers are thus in a unique position to understand and solve condensation holistically, using system-based thinking.

A possible unintended consequence is that by placing the responsibility of condensation risk management on the design and construction professions, that they have the skills to undertake the task or engage specialised aid. Just as energy assessors became a new industry with the performance-based approach to energy efficiency standards, it is likely that a new set of professionals will also emerge to evaluate and assist designers in condensation risk analysis and risk management. The increased level of professionalism around condensation mitigation will also cascade down to builders. Targeted and detailed training will be needed to ensure all builders understand and have the skills to meet the designer's mitigation strategy.

It is possible that some designers may decide that the new requirements are too onerous and may not seek to become professionally competent in condensation risk mitigation. This is a potential issue whenever there is any regulatory change. Previous regulatory changes have seen designers adopt a range of solutions to manage compliance. It is anticipated the same will apply here, as the public has an expectation that the industry will have minimal competence in condensation matters.

Effects on IEQ

A number of the proposed recommendations will over time increase the complexity of design and construction of new Class 1 and Class 2 buildings. The aim is to improve building systems to manage condensation and associated risks to building integrity and human health.

Through the industry consultation process, a number of designers and builders expressed their satisfaction at achieving very low ACH@50 within their buildings. The link being made between thermal efficacy and air-tightness. However, it is internationally accepted practice that any building below 5 ACH@50 requires some form of permanent and automated mechanical ventilation to ensure appropriate IEQ and human health.

There is a risk that the impropriate application of the proposed recommendations may lead to buildings that manage condensation, but may not provide appropriate IEQ for human health. This risk should be addressed through appropriate additional comments in the NCC and education that discusses the integrated nature of design and construction, in which condensation risk management is a part of a holistic strategy to achieve IEQ.

Further research

Further nation and climate based research is required as regulations are applied and developed, in many areas, some of which are traditional ABCB fields and others are new, namely:

- Further research on the extent and types of condensation problems. This can be achieved through a deeper analysis of text based responses from the nationwide condensation survey and from new and more targeted surveys in in next year and in three years' time.
- Further research into the process and mechanisms needed for all relevant building materials to be provided with a vapour permeability value. At present most Australian building materials do not include values for vapour permeability. As the design and construction sectors grapple with understanding vapour permeability, all built fabric components will need to include a nationally consistent vapour permeability value.
- A hygrothermal study will need to be undertaken to assess the condensation risk of current standard subfloor, floor, external wall, internal wall, ceiling and roofing systems in all NatHERS climate types. This study will need to adopt a dynamic modelling method. This is a key area of knowledge that is required to advise construction standard systems within the NCC, referenced standards and manufacturers technical documentation.
- The roof space discussion and recommendation in this scoping report have relied heavily on data from the international literature review. This data

should be empirically validated within Australian roof construction typologies.

- Adequate subfloor ventilation is a key component for managing ground moisture. However, many new homes in increasing dense subdivisions receive limited air flow. This limited subfloor airflow situation requires research to establish if the current mm^2/lm ratios are still appropriate, if a larger ratio requires development or if a permanent active ventilation system is required.
- The CSIRO completed some limited research in 2015 which included the measurement of house leaky-ness. This research needs to be expanded and extended to carefully assess built fabric system and how they affect building air-tightness. This data is also required to inform a starting value of ACH@50 in current code compliant housing for inclusion in the NCC.
- As Class 1 and Class 2 buildings become more air-tight, research needs to explore the point (xx ACH@50) at which passive ventilation provides enough fresh air and allows pollutants to leave, and at which point (yy ACH@50) automated mechanical ventilation is required to ensure occupant health.
- The economic cost of building remediation is a hidden cost. This report has documented the confidentiality and out of court settlement methods that have been adopted to remediate condensation and mould affected Class 1 and Class 2 buildings. Even the insurance industry will not provide data and increasing insurance policies are including clauses that exclude damage resulting from condensation and mould. A study needs to occur to establish a more accurate value of the home owner, builder, building designer and wider community cost associated with condensation and mould affected buildings.
- The economic cost of unhealthy environments is of significant concern to many health professionals. As mentioned in the report, several states have allergy and immunology researchers who are grappling with a growing case load of patients suffering from chronic disease caused by the building they either live in, work in or both live in and work in. New research needs to occur to better quantify the community cost associated with WET buildings.

Part 8 – Discussion and conclusion

Condensation in Class 1 and Class 2 buildings

Condensation is a physical phenomenon, which occurs naturally where-ever and when-ever the physical conditions are conducive. And as a side benefit, mould often grows where condensation forms within the built environment. The principle physical drivers are: air pressure, temperature and humidity. These same physical conditions occur within all built structures, in all climate types. Within the building (its internal environment), within its intermediate zones (subfloor and roof space zones) and within the building structure (floor, walls, ceilings and roofing materials). These natural process cannot be stopped from occurring. However, buildings can be designed and constructed in a way that manage vapour pressure, condensation risk and subsequent mould growth. The design and construction of a building can avoid creating conditions that lead to a building experiencing prolonged periods of damp, which leads to poor indoor environmental qualities, (affecting occupant health), mould, and building degradation.

Is there a condensation problem?

The nationwide condensation survey presented patterns of prevalence in Class 1 (houses) and Class 2 (apartments) were broadly similar. Likewise, response about comparison with 10–15 years ago, and with 2–5 years ago, were broadly similar. This suggests a lack of effect of different versions of the Code, since both time periods had similar responses. The survey does not provide evidence that the code amendments or particularly climates are directly responsible (or not) for condensation. Whilst some states have higher average responses for observed condensation problems, the general consensus was that the overall magnitude of problems (as assessed by respondents) was extensive enough to be of concern. The extent of problems was generally assessed as high.

Does Australian regulation allow condensation in buildings

At present there is no regulation that requires building designers and builders to consider climate appropriate vapour pressure management and material choices to mitigate condensation and mould in new buildings. This is further exemplified by the Australian NCC which includes no definition or adequate discussion on matters pertaining to vapour control, condensation or mould.

This is in significant contrast to the building regulations of New Zealand, U.S.A., Canada, U.K., and European nations. The regulations from these peer level nations provide extensive definition, regulation and guidance to manage vapour pressure, provide air-tightness, reduce thermal bridging, with mandatory ventilation requirements, minimum indoor air temperatures (and at times maximum indoor air temperatures), to mitigate the occurrence of condensation and mould, and to provide healthy interior environments, that also ensure structural and built fabric durability.

Learning from work already undertaken by TAS and NZ

Work in Tasmania and New Zealand revealed that interstitial condensation was the most significant factor to the proliferation of mould in buildings, which in turn undermined the health of the occupants, a central issue in ABCB's mission. Of particular concern were the use of vapour impermeable building wrap, hard-fixing of sheet metal to sarking (no cavity) and low-pitched roofs that lacked structured ventilation. In New Zealand a vapour cavity is mandatory and foil products are prohibited. This is largely attributable to organisations like BRANZ which offer definitive advice on building science matters, and an official Australian entity like this is needful.

In both these cool climates, interstitial condensation is worst in winter but can go undetected for years. The Tasmanian experience reveals that there is a lack of knowledge in both building science and microbiology by EHOs to make the all-important determination of when a building is unfit for habitation and this has left home owners without recourse for a mouldy building that have been 'built to code'. Importantly, if EHOs do not explore the interstitial spaces in walls, ceilings and floors, they can be missing the bulk of where condensation and mould actually happens.

Costs and benefits of new regulation

The part of this report that discussed the costs and benefits of identified areas of focus for new regulations. The new regulations would require varying changes to contemporary design and construction practises and material specification. Subject to the type of construction considered, the cost will vary significantly. For houses with a brick veneer wall, a vapour cavity already exists but for many sheet and board construction systems which apply the current minimum requirements of the NCC, there is no vapour cavity and significant thermal bridging can occur. Both of these variables can cause condensation to form within the wall in many Australian climates. Similarly, roof space design and construction practices have not evolved since before ceiling insulation was required. This has established in many buildings a lack of roof space ventilation, thermal bridging on the external perimeter of rooms and condensation bridging between elements of the roof and sarking system, ceiling insulation and wall fabric. To modify roof design and construction practises will incur a cost.

However, the benefits cannot be ignored. Based on the nationwide condensation survey, more than 40% of new buildings have condensation and mould. The Tasmanian experience detailed the extensive and costly remediation process that was required for new homes with concerning amounts of condensation and mould. The amount of moisture trapped within the building was compromising structural systems, significantly affecting built fabric durability, causing significant financial hardship to the house occupants, often led to family breakdown and was linked to significant chronic disease that the house occupants developed, (like asthma and other allergy and immunology conditions). These are significant costs which are being borne by individuals, organisations, communities and social services organisations and medical services which are far removed from the building regulatory framework. The costs associated with the long term human health implications from condensation and mould within buildings, far outweighs costs to implement regulatory, design, construction practise and material choice changes.

Australian building industry

The industry consultation completed as a component of this report, combined with previous industry collaboration from the Tasmanian experience, has established invaluable feedback on the issue of condensation in buildings. The consultation clearly stated that condensation is increasingly recognised as a problem in all Australian jurisdictions, with some presenting more problems than others, or different types of problems. Within the building regulator, building design, engineering, building surveying, builder and sub trades sectors, there is an awareness of condensation but the level of knowledge about what causes condensation and mould varies significantly. And when condensation issues are identified there is a lack of awareness of solutions that address the physical problem, or where to find relevant and impartial guidance that is not linked to commercial interests.

All industry sectors raised concern about the lack of regulation, standardised terminology and quality explanatory documentation from the NCC, Australian Standards, State and Local government guides and manufacturer based literature. All noted that this level of guidance must be coordinated by the national building regulator. Many informed individuals referred to high quality standards, codes and technical documents available from other nations. Many of these individuals were aware that it was not the occupant's role to manage vapour pressure, condensation and mould but that of the built fabric.

Everyone agreed that education is required now and will be further required when new regulations are developed and implemented. This was on concern to many who were managing in excess of 10 years of condensation problems and a few more years of new construction before and regulatory change occurs.

Informed individuals further asked for guidance 'now' on air barriers, vapour control layers, air-tightness, thermal bridging and other aspects which affect the problem that is occurring now.

Conclusion

Has NCC led to or contributed to condensation risk? The scoping report has been asked to answer this question. However, in doing so it is not the intention to allocate any blame. The NCC has been amended over time to reflect changes in building science, building practices and social expectations around building function, service and safety. However, the national building regulations has not provided performance requirements to manage vapour pressure, to manage condensation risk or to class mould or condensation as significant risks to building durability and human health. This is in contrast to the evolution of building regulations of New Zealand, U.S.A, Canada, U.K. and the European Union. These other nations had no or minimal regulation before the 1990's, but since that time have increased regulatory requirements significantly to manage vapour pressure, manage condensation and mould risk and to provide healthy internal environments.

The nationwide condensation survey, experiences in Tasmania and a growing chorus of concern being raised in all Australian jurisdictions has clearly made building regulators aware that there is a national condensation problem. The impact this is having on individuals, business and communities is significant from both an economic and human health perspective. Additionally, thermal performance and building efficiency enhancements within the NCC since 2004, combined with occupant expectations for thermal comfort has created significant vapour pressure differentials within the built fabric leading to condensation and mould in many buildings. This new problem will only increase as buildings further improve the thermal comfort of interior spaces. The need for clear regulation and technical guidance is paramount to manage these significant risks in all buildings.

However, the level of condensation risk and the type of risk does vary from climate to climate. The current eight climate types within the NCC may be inadequate in providing a sophisticated, detailed and appropriate level of risk mitigation across Australia. In the first instance, the NatHERS climate zones may provide a more informative climate typology when considering the matrix of climate specific built fabric actions that may be required. The international examples analysed showed successful regulatory strategies to minimise condensation risk. Like the NCC, many of these are performance based, but their approach to condensation and mould mitigation is holistic and integrated.

Although the management of condensation risk in the NCC is currently inadequate, options, both regulatory and non-regulatory, already exist in other nations, that could be modified to meet the need of Australian buildings, and uphold the principles of occupant safety and occupant health as the principle functions of the NCC.

To achieve these high level goals, the NCC must consider the inclusion of several short and long-term strategies. The long-term goal is clear – to have no condensation or mould occur within buildings in Australia. The short term is much more challenging but must at the earliest possible time include actions to address problems that are occurring now and should include:

- Addressing the need for vapour permeability in all Australian buildings
- The need to establish vapour cavities in all external envelopes
- To establish a benchmark building leaky-ness value – i.e., 8 to 10 ACH@50
- To require the ventilation of the sarking zone, unless and engineered solution is provided
- To regulate minimum supply and exhaust ventilation for attic and cathedral roof spaces.
- To develop regulation that supports the establishment of a dew point analysis for the built fabric (subfloors, floors, walls, ceiling, roof spaces and roofing systems) to provide technical evidence that vapour pressure and condensation risk is being managed.
- To require adequate roof space design and construction practises to remove current, and out of date, thermal bridging and condensation bridging practises.
- To require a true condensation risk analysis of low pitch roof systems, which may require the use of blanket insulation systems against the roofing material to eliminate uncontrolled condensation.
- And a non-regulatory action to explore methods to encourage the external ducting of exhaust air from clothes dryers.

Finally, to use the words of other regulations reviewed for this report,

> *The occurrence of condensation is governed by complex interrelationships of factors… Designers and builders need to integrate a range of principles to resolve condensation risk … Buildings are often not used as intended by occupants and so a designers and builders need to err on the side of caution and adopt robust fail-safe built fabric solutions.*

Part 9 – Scoping report recommendations

This part outlines the proposed recommendations that are likely to address the condensation risk in the Australian Class 1 and Class 2 buildings, (and by default other classes of buildings). The recommendations are outcomes of the analysis of current condensation and mould problems occurring in new Class 1 and Class 2 buildings, and international literature review on condensation and mould in buildings, a review of building regulations from other developed nations, and industry consultation. This process has enabled the identification of gaps within current regulation for Class 1 and Class 2 buildings that is likely to not mitigate condensation and mould in new buildings.

Key recommendations

The key recommendations are established in a staged manner. In essence stage one includes actions that provide a framework for future improvements and some actions to address current condensation and mould problems being experienced by building occupants throughout many parts of Australia. In some respects, odd locations could be exempted from some requirements but this might make the management of compliance more difficult.

Stage 1 - for 2019

1.1. New Defined Terms: The ABCB develop new definitions and commentary for physical properties that relate to vapour pressure, vapour control, condensation and mould. These are to be included within the Defined Terms sections with Volume One and Volume Two of the NCC.

1.2. ABCB Guidance to Australian Standards: The ABCB should instigate a discussion with regard to either a new Australian Standard be developed which addresses issues discussed in this report (like BS5250) or that an existing standard be reconfigured such that these issues are addressed appropriately.

1.3. New Regulation: Either a new section or new subsections are developed and included within Volume One and Volume Two of the NCC, which focus on the issue of vapour pressure management, condensation risk and mould mitigation. If the new subsection route is selected, regulation and commentary would need to be included in sections pertaining to subfloors, floors, walls, ceilings, roof spaces, roofing, energy efficiency, thermal bridging and building sealing.

1.4. ABCB Guidance to Australian Standards: The ABCB requirement for AS4200 Pliable Membranes in both Volume One and Volume Two of the NCC, and also adopt the definitions, regulations, performance requirements and principles established. This would include the establishment of climatically appropriate and scientifically proven vapour permeability measures for all membranes that may be used as moisture barrier, air barrier or vapour control layer. As an example Canada and the U.S.A have 3 classes of permeability to suit different climate types).

1.5. New Regulation: New performance requirements stipulating the use of a vapour permeability based climate appropriate vapour control layer for all Class 1 and Class 2 buildings.

1.6. Amended Performance Requirement: Stipulations that no actions, included services installations, is to compromise the air barrier system (linings and membranes) of the Class 1 or Class 2 building.

1.7. New Commentary: Within Building Sealing include a new commentary which quantifies building leakage as 8 to 10 ACH for the current energy efficiency regulation. It would be expected that if a new Class 1 or Class 2 building was constructed as per the Deemed to Satisfy requirements, it would have a building leaky-ness in the range of 8 to 10 ACH. This will enable market leaders and consumers to start making informed choices on methods to show compliance. This could include the non-regulatory or regulatory use of blower door testing. This commentary should also include a cautionary note, that any Class 1 or Class 2 building with a measured ACH of <5 should include an automated mechanical ventilation system for fresh air supply within the building.

1.8. New Regulation: A new performance requirement stipulating proof of condensation risk management. In climates where condensation problems appear to be more prevalent, (i.e., climate zones 4, 5, 6,7 & 8), require a NatHERS approved climate file for location specific steady state dew point analysis for floors, external walls and roof spaces (ceiling, roof space and roofing system). This methodology would also identify issues with regard to low pitch roof systems and their common problematic incapacity to appropriately manage condensation. It should be noted that instances of condensation and mould are increasing in Australia's top-end and condensation risk analysis may also be required for these hot and humid climates.

1.9. Regulation Amendment: Within the Energy Efficiency sections of Volume One and Volume Two, the separation of the roof space as a single element into its components of ceiling with insulation, ventilated roof space, sarking system, ventilated cavity between sarking and roofing system. Internationally unconditioned roof spaces are required to be significantly ventilated zones. This will also provide additional regulatory power to address the current problem of sarking systems which are often not installed as per reputable manufacturer specifications.

1.10. New Regulation: A performance requirement for roof space supply and exhaust ventilation in all climate types. This is to include Attic and Cathedral style roof systems. This may be achieved by establishing a mm2 requirement per lineal metre of wall or per m2 of roof space.

1.11. New Regulation: A performance requirement that establishes the inclusion of a vapour cavity between the cladding system and the vapour control layer on all Class 1 and Class 2 buildings. This will address significant issues of condensation forming on the inside surface of wall wrap systems currently being experienced in Qld, NSW, ACT, Vic, SA, & Tas..

1.12. New Regulation: A performance requirement that any room with a mechanical exhaust system (i.e., range-hood, bathroom extraction, internal toilets) must provide either a passive method for supply air or an automated mechanical fresh supply air system – for clean and unpolluted make-up air. Additionally, no mechanical exhaust system is to be vented into an unconditioned roof space.

1.13. New commentary: Volume One and Volume Two include new commentary describing the significant moisture load a clothes dryer can place on the internal and external envelope which can lead to significant condensation and mould problems, which can be alleviated by the installation of exhaust air ducting to the external environment.

1.14. ABCB Guidance to Australian Standards: The ABCB require that all referenced standards be reviewed for terminology, diagrams and descriptions of practise to ensure all comply with the expectations of vapour pressure management and condensation and mould risk management defined and required within the NCC.

1.15. Education: The ABCB should be the provider and organiser of high quality literature and guidance to regulators, designers and builders. The current Condensation Handbook, even though amendments are required, is a good example of an educative document. Additionally, the ABCB should consider providing 'road-show' for NCC update training each time a new edition of the regulation is due for release. This training period must be expanded to include a deep discussion on vapour pressure and condensation and how the built fabric should be designed and constructed to manage these matters. The ABCB should actively inform all construction industry professional bodies and training providers of this new knowledge and impending regulation. This will allow adequate time for the design and construction sectors to upskill before new regulations are applied.

Figure 17 below, ranks each of the Stage 1 recommendations within the context of the likely impact to reduce condensation and mould in Class 1 and Class 2 buildings relative to the estimated and/or complexity of implementation.

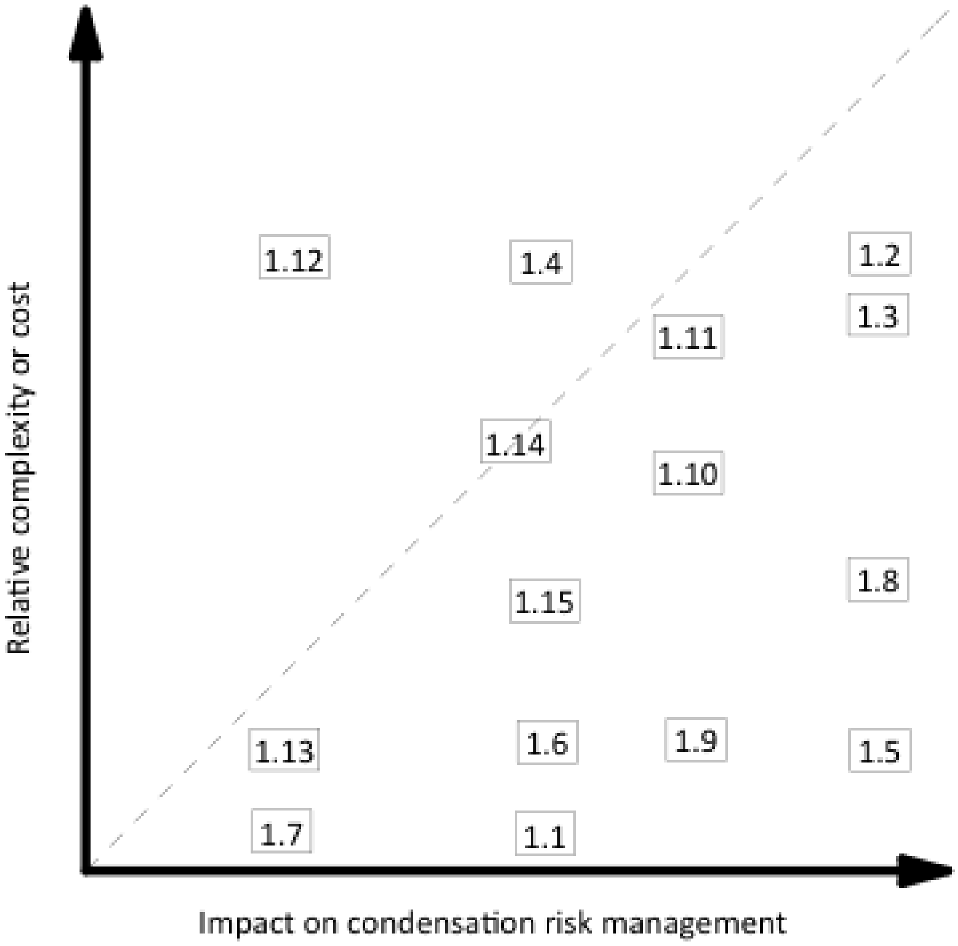

Figure 17 - Impact and complexity rankings for Stage 1 recommendations

Stage 2

Subject to the industry's capacity to adequately comply with the items described above in Stage 1, the Stage 2 recommendations would ideally be applied in the NCC revisions for 2022.

2.1. New Regulation: A new performance requirement stipulating that all Class 1 and Class 2 buildings to have an appropriate Vapour Control Layer.

2.2. Amended Regulation (new in Stage 1): The amendment of the requirement for proof of condensation risk management to include the use of an approved software tool to prove condensation risk management has been applied to subfloors, floors, walls, ceiling and roof systems. This would apply to all jurisdictions.

2.3. New Regulation: A new performance requirement stipulating that all Class 1 and Class 2 buildings to have an air-tightness such as 8 ACH@50 (i.e., building pressurisation and depressurisation test).

2.4. Enhanced Regulation: For all climate types, include the requirement for ceiling insulation baffles to protect ceiling insulation from moisture wicking and movement away from the perimeter of the building.

2.5. New Regulation: The include a new Performance Requirement within the sections of the NCC which include vapour pressure management and condensation risk analysis stipulating that architectural documentation clearly show continuity of air barrier systems, insulation, vapour control layers and the inclusion vapour cavities.

2.6. New Commentary: Within the Energy Efficiency sections of Volume One and Volume Two include a detailed commentary on thermal bridging its' known contribution to condensation and mould in buildings.

2.7. ABCB Guidance to Australian Standards: The ABCB advise relevant Standards committees of expected amendments in the 2022 NCC and require amendments, as required, within referenced Standards to ensure all comply with the expectations of vapour pressure management and condensation and mould risk management defined and required within the NCC.

Figure 18 below, ranks each of the Stage 2 recommendations within the context of the likely impact to reduce condensation and mould in Class 1 and Class 2 buildings relative to the estimated cost and/or complexity of implementation. These condensation risk and complexity values are estimated based on the assumed adoption of the stage 1 recommendations.

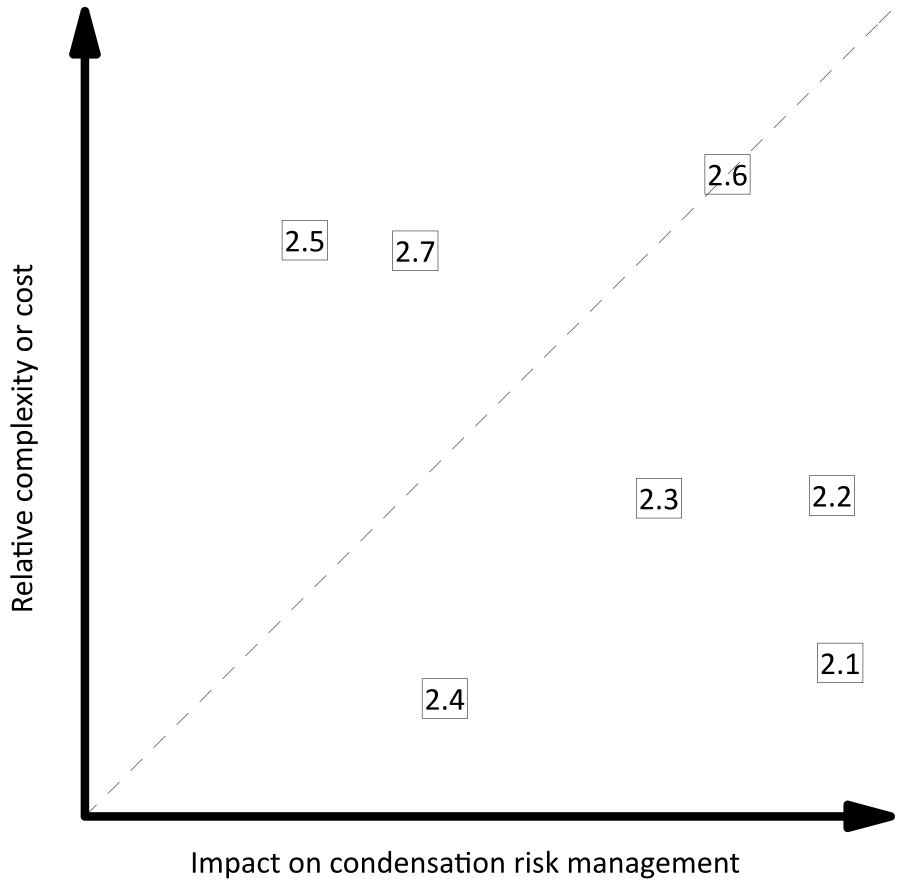

Figure 18 - Impact and complexity ranking for Stage 2 recommendations

Stage 3

Subject to the industry's capacity to adequately comply with the items above, in Stage 1 and Stage 2, the items listed below would ideally be applied in NCC revisions for 2025 or earlier.

3.1. Enhanced Regulation: Within the Building Sealing section require a maximum ACH@50 for new Class 1 and Class 2 buildings of 8 ACH@50.

3.2. Enhanced Regulation: Dew point analysis
– Require the use of an approved dynamic hygrothermal modelling software to prove compliance of vapour pressure management of floors, walls, ceilings, roof spaces and roof systems. (This methodology is soon to be required in other developed nations.)
– Require the use of an approved dynamic hygrothermal modelling software to prove thermal bridging has been appropriately addressed for floors, walls, ceilings, roof spaces and roof systems. (This methodology is soon to be required in other developed nations.)

3.3. New Regulation: This would apply equally to both the Vapour Pressure/Condensation and Energy Efficiency sections of regulations for Class 1 and Class 2 buildings
– A new performance requirement that no interior room should exceed 28°C when modelled with an approved building simulation software,
– A new performance requirement that no interior room should have a minimum

temperature of 14°C when modelled with an approved building simulation software.

3.4. ABCB Guidance to Australian Standards: The ABCB advise relevant Standards committees of expected amendments in the 2025 NCC and require amendments, as required, within referenced Standards to ensure all comply with the expectations of vapour pressure management and condensation and mould risk management defined and required within the NCC.

Figure 19 below, ranks each of the Stage 3 recommendations within the context of the likely impact to reduce condensation and mould in Class 1 and Class 2 buildings relative to the cost and/or complexity of implementation. These condensation risk and complexity values are estimated based on the assumed adoption of the Stage 1 and Stage 2 recommendations.

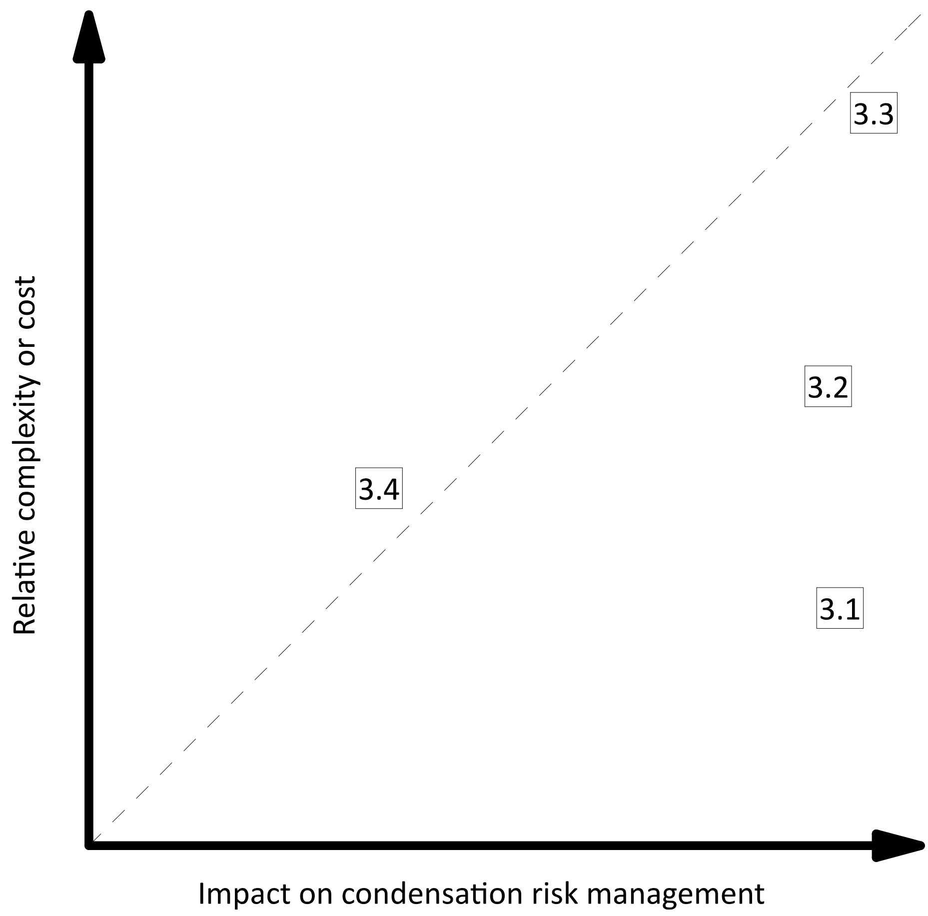

Figure 19 - Impact and complexity ranking for Stage 3 recommendations

Benefits from recommendations

This report has included a review of the causes of condensation and mould within new buildings. This included how condensation and mould significantly impact building (including structural), durability and their equally significant impact on occupant health. The review of experiences in New Zealand and Tasmania further exemplifies these issues. The nationwide condensation survey has identified that condensation and mould is of concern in all Australian jurisdictions. The literature review of building regulations from U.S., New Zealand, Canada, U.K. and Europe has shown significant regulations that have been developed to address vapour pressure, condensation and mould. At present the Australian regulations include no performance requirements to manage vapour pressure and to mitigate the occurrence of condensation and mould.

All the recommendations listed above have been developed with a staged implementation in mind to allow for industry wide up skilling and appropriate technical guidance development. Each recommendation will have a significant benefit to building occupants, building owners and the broader community through:

- Significant improvements to the durability of the built fabric
- Significant improvements to the indoor air quality, and related human health impacts, within Australian Class 1 and Class 2 buildings
- An increase in workforce productivity which results from healthier buildings
- The National Energy Productivity Plan for 2019 to 2022 provides significant guidance for building and health improvements. The recommendation mentioned above address items 2, 29, 31, 32 of the NEPP.
- The adoption of these recommendations can result in benefits to human health with flow on positive social and economic effects and are in line with the stated objectives of the NCC.
- The recommendations listed above also support the Australian Government's research priority areas of Health, Environmental Change and Energy.

List of appendices

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