



RENOVATING A PRE-1980'S WEATHERBOARD HOME; WHAT ABOUT CONDENSATION?

MARK DEWSBURY, M.AIRAH, PhD

School of Architecture & Design, University of Tasmania
Locked Bag 1323, Launceston, Tasmania, 7250
Mark.dewsbury@utas.edu.au

YUKA FOO

School of Architecture & Design, University of Tasmania
Locked Bag 1323, Launceston, Tasmania, 7250

TIM LAW, Affil.AIRAH, PhD

ABSTRACT

A significant portion of Australia's housing stock comprises weatherboard clad lightweight framed buildings, which have nil or limited envelope insulation. With the reported appearance of condensation and mould in new and old housing, this project sought to explore the condensation risk that may arise from retrofitting insulation into existing uninsulated housing. A typical house from Victoria was selected and many variations of floor, wall and ceiling insulation, glazing and building sealing were explored. A cost benefit analysis was used to establish three built fabric typologies, namely; as-is, current code-compliant with some improved glazing, and better than code insulation and improved glazing. Each of these typologies was simulated using NatHERS software to produce calculated temperatures for each room. The simulation data were used to complete a software based condensation risk analyses. The simulations results show that some walls present no condensation risk, whilst others showed a significant risk.

INTRODUCTION

In 1999, the majority of Australian homes (57%) were reported to be more than 20 years old, with Tasmanian having the oldest homes in Australia (Australian Bureau of Statistics, 2000). Many of these homes comprise of lightweight, timber framed, platform floored, timber clad and sheet-metal roofed dwellings. Many of these homes built between 1900 and 2004, have limited ceiling insulation and rarely include wall insulation and other measures to improve the thermal performance (Moreland Energy Foundation Limited, 2010). As this house typology is common to most of Australia, many research tasks have explored methods to improve these homes with support for low income families, guidelines and recommendations provided by local, state and federal governments, and low interest bank loans. Anecdotal information from Victoria and New South Wales suggests that house improvement is increasingly including the replacement of the external cladding system. Many of these renovated homes are showing a presence of condensation and mould (Katelaris, 2014; Dewsbury *et al.*, 2016a; Dewsbury *et al.*, 2016b). Aside from the accepted structural concerns associated with wet buildings (Leicester and Lhuede, 1992; Leicester *et al.*, 2003; Nguyen *et al.*, 2008; Paevere *et al.*, 2008; Paevere *et al.*, 2009), internationally, and within Australia, there is a growing body of medical evidence regarding cold buildings, wet buildings and their impact on human health (Bornehag *et al.*, 2001; The Institute of Medicine, 2004; Brandt *et al.*, 2006; Kerckmar and *et al.*, 2006; WHO, 2009; Mendell *et al.*, 2011; Johnston and Gibson, 2014;



Gasparri *et al.*, 2015; Dewsbury *et al.*, 2016b). Within the context of climate change, carbon emissions and resource depletion, the adaptive re-use of existing homes must be considered and supported. This project sought to explore the condensation risk that may arise from providing thermal performance based retrofits to existing minimally insulated weatherboard housing.

METHODOLOGY

This section discusses the methods of house selection, house improvement, cost benefit analysis, thermal simulation and condensation risk analysis that was completed as distinct components in this research task.

Selection of house plan

A review of typical plans presented several homes built between World War 1 and World War 2 that were light-weight framed buildings, with a platform floor, weatherboard cladding and sheet metal roofing. Similarly, and regardless of building orientation, many of these sample plans showed renovations which generally removed walls between some rooms and added new rooms the rear of the existing building. The selected plan, as shown in Figure 1 below, matched the general typology of many renovated 1920/30/40/50/60/70's homes. Including additions, the house has a floor area of 192m², which is still a little smaller than the average size of new Australian homes, 231m² (CommSec, 2016). The area of glazing within this renovated house is 31.1m², providing a glass to floor area of 16%. This glass to floor area ratio is quite common in older homes and in many new volume builder homes (Dewsbury *et al.*, 2006; Dewsbury and Nolan, 2015).

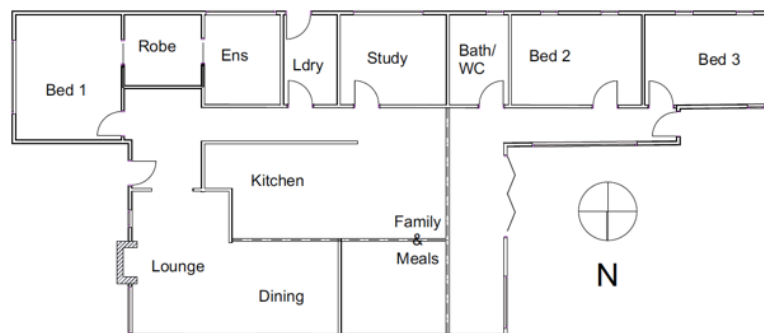


Figure 1. House plan



Selection of improvements

Previous research by the School for Sustainability Victoria explored simulation cost benefit analyses for typical Victorian houses (<http://www.sustainability.vic.gov.au/smarter-renovations-planner>), (Lee *et al.*, 2014). It was noted that many of the older uninsulated houses had a House Energy Star rating as low as 1.57 Stars, revealing the poor quality of the thermal envelope. Within this context key assumptions were established for the Base House, namely:

- Platform floor insulation – Nil
- Wall insulation – Nil
- Ceiling Insulation – R1.0
- Weather sealing actions – Minimal
- Glazing – Single glazed, timber framed
- Minimum efficiency lighting

Using the online services of the Smarter Renovations Planner, the house plan was assessed with sixteen different orientations. Aspects explored included adding ceiling insulation, wall insulation, floor insulation, draught proofing, improved glazing, improving the efficiency of lighting and the addition of photo-voltaic power. The impact of building and room orientation cannot be ignored and is best demonstrated in Figure 2 and Table 1 below, which show the pay-back results for some interventions. Figure 2 shows that improving ceiling insulation for the simulated house would have a return on investment ranging from 7 to 18 years subject to the orientation of key rooms requiring heating and cooling. Similarly, and as shown in Table 1, the inclusion of double glazing showed return on investments ranging from 41 years to 389 years subject to building orientation.

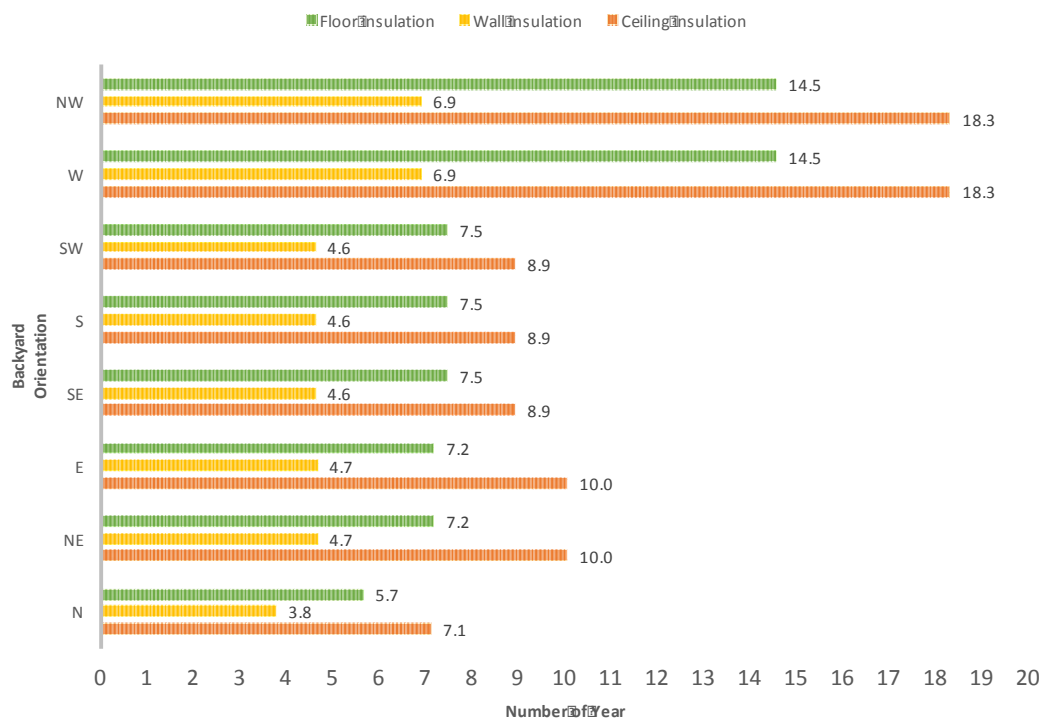


Figure 2. Comparison of payback periods for floor, wall and ceiling insulation subject to house orientation



Backyard Orientation	Ceiling insulation	Wall insulation	Floor insulation	Draught Proof	Lighting Upgrade	Window	Solar Panel	Total Payback Period
N	7.1	3.8	5.7	5.0	7.3	63.7	5.0	7.6
NE	10.0	4.7	7.2	6.9	20.3	389.2	5.9	10.3
E	10.0	4.7	7.2	6.9	20.3	389.2	5.9	10.3
SE	8.9	4.6	7.5	6.5	18.8	318.4	5.7	9.9
S	8.9	4.6	7.5	6.5	18.8	318.4	5.7	9.9
SW	8.9	4.6	7.5	6.5	18.8	318.4	5.7	9.9
W	18.3	6.9	14.5	18.7	8.9	41.2	8.3	23.8
NW	18.3	6.9	14.5	18.7	8.9	41.2	8.3	23.8
Average	11.3	5.1	8.9	9.5	10.8	214.4	6.3	13.2

Table 1. Summary of pay-back periods for all improvement options

NatHERS simulation

The NatHERS simulation was required to inform the best types of home improvements to reduce likely heating and cooling energy use and to provide input data for the condensation risk analysis. To confirm the Smart Renovation Planner recommendations and to better inform the likely ‘best’ mix of home improvements, the NatHERS AccuRate software was used to simulate all the above envelope scenarios. The AccuRate simulations were completed for several levels of intervention for ceiling, wall and floor insulation and glazing. For many climates, the National Construction Code requires additional wall insulation of R2.5 and ceiling insulation of R4.0 (ABCB, 2016). To evaluate the impact of varying levels of insulation, several values were simulated, namely:

- Walls - R2.0, R2.5, R3.0, R3.5 & R4.0
- Ceilings – R1.0, R2.0, R2.5, R3.0, R4.0, R5.0, R6.0 & R7.0
- Platform Floors – Nil & R2.5
- Draught-proofing – Nil, Medium, well-sealed
- Windows – Timber single glazed, Aluminium single glazed, Aluminium double glazed & Aluminium double glazed with Argon



The figures below show the relative changes in simulated cooling and heating energy use, in Mj/m^2 , for selected examples of floor, wall and ceiling insulation and glazing. In all cases the backyard orientation is represented by -

■ E ■ N ■ W ■ S

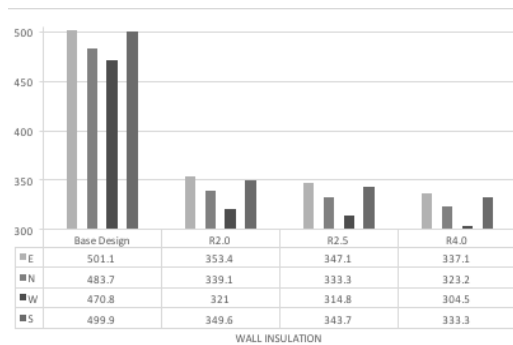


Figure 3. Comparison of heating and cooling energy consumption relative to added wall insulation

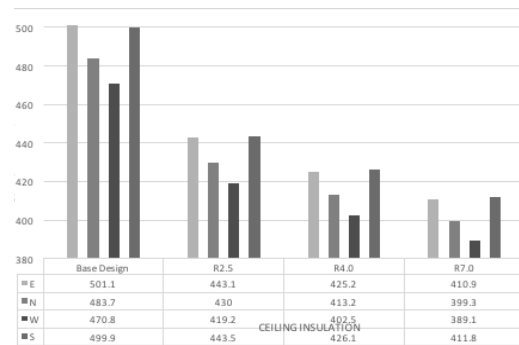


Figure 4. Comparison of heating and cooling energy consumption relative to added ceiling insulation

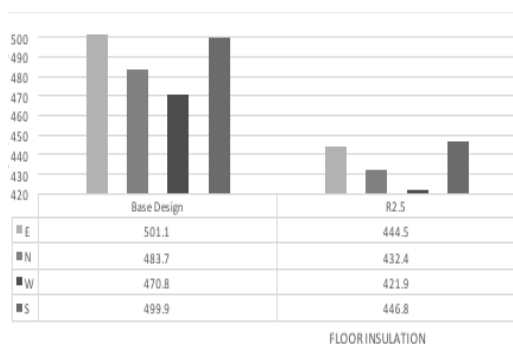


Figure 5. Comparison of heating and cooling energy consumption relative to added floor insulation

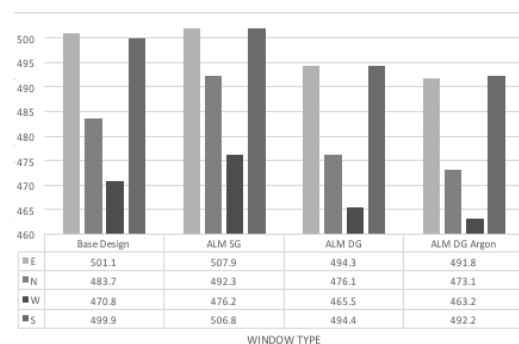


Figure 6. Comparison of heating and cooling energy consumption relative to glazing system

Results from the simulations, show that the base design with backyard facing west is likely to consume the least heating and cooling energy, whilst the east facing back yard scenario is likely to consume to most heating and cooling energy. This represents a direct relationship of passive solar gain within the living rooms, which within NatHERS are expected to be within thermal comfort bandwidths from 7:00am to midnight (ABCB, 2006). As expected, the existing single glazed timber framed windows performed better than the single glazed aluminium windows, even though many home-owners replace their timber framed windows with aluminium framed windows. Surprisingly, the adoption of double-glazed aluminium framed windows and double-glazed argon filled aluminium windows showed a relative small saving of approximately 2%. The reason for this fairly insignificant saving is the low glass to floor area ratio of 16%. The results of the AccuRate simulations for this house, demonstrated that the greatest benefit would be obtained by insulating the external walls, followed by the ceiling and floors and then finally upgrading the glazing. Table 2, below, shows the relative heating and cooling energy savings from some simulated interventions.



		Wall			Ceiling			Floor	Window		
	Base Design	R2.0	R2.5	R4.0	R2.5	R4.0	R7.0	R2.5	ALM SG	ALM DG	ALM DG Argon
E	501.1	353.4	347.1	337.1	443.1	425.2	410.9	444.5	507.9	494.3	491.8
N	483.7	339.1	333.3	323.2	430	413.2	399.3	432.4	492.3	476.1	473.1
W	470.8	321	314.8	304.5	419.2	402.5	389.1	421.9	476.2	465.5	463.2
S	499.9	349.6	343.7	333.3	443.5	426.1	411.8	446.8	506.8	494.4	492.2

Table 2. Simulated heating and cooling energy for different built fabric upgrades (Mj/m²).

The analysis of the AccuRate simulation data allowed for the establishment of the three house improvement typologies, namely:

- Base Design – No floor or wall insulation, R1.0 ceiling insulation, minimal draught proofing, timber framed single glazed windows
- Medium upgrade (similar to NCC) – Floor R2.5, Walls R2.5, Ceiling R4.0, Window unchanged, medium draught sealing practises
- Best upgrade – Floor R2.5, Walls R4.0, Ceiling R7.0, Windows unchanged, high quality draught sealing actions.

The matter of glazing was discussed extensively. It may be likely that a home-owner could replace some glazing. It was significant to note, that with the traditional and relatively small windows in some rooms, the effect of glazing was not a driving force. However, when the area of glazing was increased, the payback period for glazing was significantly reduced. However, as this task was to explore a least cost renovation to improve thermal comfort, the upgrading of glazing did not demonstrate significant economic benefit.

The second key component of the AccuRate simulation process was to establish simulated internal room temperatures. The room temperature data was required as input data for the condensation risk analysis. The difference between interior and exterior temperature and relative humidity conditions will greatly affect the location of dew-point temperature within the built fabric and the vapour pressure between the interior and exterior environments (British Standards, 2011; International Organization for Standardization, 2012).

Condensation risk simulation

The condensation risk analysis required the selection of an appropriate software and the creation of external and interior thermal properties. Previous research at the School of Architecture and Design had developed strong skills in the ISO and BS5250 approved JPA software (JPA TL Ltd, 2016). Some of the key reasons for selecting the JPA software included the many commonalities between UK and Australian construction systems, the capacity to easily created and use project based climate and interior environmental data.

In addition to the input data for the external and internal environment established by the NatHERS simulations, the research had to identify typical construction methods for residential external walls. Based on previous research (CSIRO, 1962; 1970; Timi, 2015; Desjarlais, 2016; Dewsbury and Law, 2016b; a; Dewsbury *et al.*, 2016a; Dewsbury *et al.*, 2016b), and at this stage in Australian residential construction, it was identified that the most important aspect that can rarely be rectified after construction was the materials used to construct external walls. Specifically, did walls consider



vapour pressure management applicable to Australian climates. This resulted in establishing five wall systems for simulation, namely:

- Base design wall – plasterboard/no insulation/no wall membrane/weatherboard
- Medium wall 1 – plasterboard/R2.5 insulation/vapour impermeable membrane/weatherboard
- Medium wall 2 – plasterboard/R2.5 insulation/vapour permeable membrane/weatherboard
- Best wall 1 – plasterboard/R4.0 insulation/vapour impermeable membrane/weatherboard
- Best wall 2 – plasterboard/R4.0 insulation/vapour permeable membrane/weatherboard

The final input data requirements for the condensation risk analysis were the climatic values for temperature and humidity. For this task, the NatHERS climate file for Launceston was selected. Launceston was selected as it is a milder climate than central Tasmania, Hobart, many parts of central Victoria and many parts of southern and alpine New South Wales. In essence, if a condensation risk was evident in Launceston, many other locations in southern Australia would experience a similar or worse level of condensation risk. The results of the condensation risk analysis are shown and discussed in the next section

RESULTS

Each JPA condensation risk simulation provided a seven-page report, which included wall system U-Value calculations, R-Value calculations, vapour resistivity calculations, calculated moisture within the wall system and graphical condensation risk diagrams. In this research, more than 200 condensation risk simulations were completed, which included warm daytime, warm night-time, cool daytime and cool night-time variations. As expected, the greatest risk of condensation occurred when the interior conditions are warm and the exterior conditions are cool. The results and discussion below focus on the graphical condensation risk diagrams and calculated moisture within the simulated external walls. An important aspect of the simulations is the interior relative humidity. It is commonly accepted that house interiors have a relative humidity of 47% to 55% (Cheng *et al.*, 2010). However, recent data collected from occupied houses in Tasmania showed winter relative humidity values of 71%. The relative humidity value of 71% was used in this research to best simulate these high-risk winter internal conditions.

In the condensation risk diagrams below, the interior conditions are on the left and the external conditions are on the right. The red line is the calculated dry bulb temperature at each interface. The blue line is the calculated dew-point temperature at each interface. When the red and blue lines meet, the water vapour in the air will condense.

Base design

Some key examples of the results for the base design wall system are shown below in Figure 4, Fig and Table 3. Figure 4 shows the condensation risk for a bedroom that is kept overnight at 13°C, whilst Fig shows the condensation risk when a living room is kept at 20°C on a cool evening, not unlike an average winters evening in many parts of non-marine Australia. Both walls show condensation risk on the inside surface of the weatherboard cladding. Condensation risk was only removed when the interior temperatures were less than 10°C, significantly less that what is required for thermal comfort and human health. Table 3, shows the likely accumulation of moisture within the wall for different months, with different internal and external environmental conditions. In this table and following tables, GC = monthly moisture accumulation per area at an interface and Ma = annual progressive moisture accumulation per area at an interface, (representing a year on year



accumulation). This data shows significant monthly and annual moisture accumulation within this wall. This is based on the Australian principle that the air space within the wall is still. However, in real buildings, the very well vented nature of this wall allows the vapour leave the built fabric and moisture accumulation does not occur. The nature of air spaces in Australia are currently out of step with international methods (International Organization for Standardization, 2007; 2008).

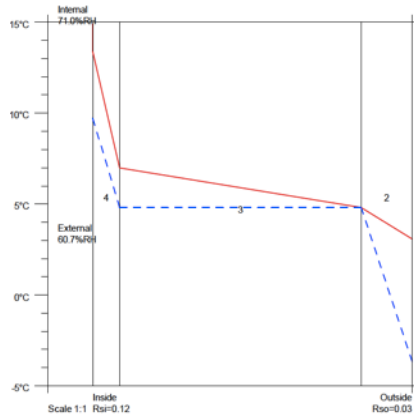


Figure 4. Condensation risk from a conditioned bedroom

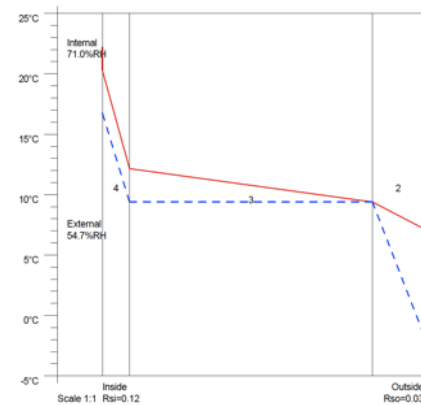


Figure 8. Condensation risk from a conditioned living room

MONTH	INT T (C)	INT RH (%)	EXT T (C)	EXT RH (%)	GC (KG/M ²)	MA (KG/M ²)
JAN	31.1	71.0	15.7	47.4	5.1	49.7
FEB	30.5	71.0	16.2	46.8	3.9	3.9
MAR	31.0	71.0	14.7	47.8	5.7	9.6
APR	29.9	71.0	11.8	53.5	6.2	15.8
MAY	22.4	71.0	9.0	52.7	2.7	18.5
JUN	21.0	71.0	7.1	51.2	2.6	21.1
JUL	22.2	71.0	6.7	54.7	3.5	24.6
AUG	24.6	71.0	7.3	49.5	4.6	29.2
SEP	24.7	71.0	9.2	50.2	3.8	33.0
OCT	25.1	71.0	10.6	48.5	36.5	36.5
NOV	26.5	71.0	12.8	39.0	3.2	39.7
DEC	30.6	71.0	15.4	42.8	4.9	44.6

Table 3. Moisture accumulation in base design wall

Medium upgrade

Some key examples of the results for the medium upgrade wall system are shown below in Fig 9 to Fig 12 and Table 4. The first two figures, Fig 9 and Fig 10, show the results for the wall system with the commonly used vapour impermeable wall membrane. Like the base design house above, the figures show a conditioned bedroom and a conditioned living room. In both cases, dew-point is occurring on the inside surface of the vapour impermeable membrane. That is, the moisture is being trapped within the wall. Table 4 shows the moisture accumulation within this wall system. The accumulation of moisture within these simulations reflects observations of condensation and mould in many new homes constructed with vapour impermeable wall membranes.

Fig 11 and 12 below, show the condensation risk in the medium upgrade wall system which included a vapour permeable membrane. In both these scenarios, condensation risk still exists, and at times moisture will form on the inside surface of the membrane. However, the nature of the permeable membrane allows the vapour to leave the wall fabric whenever the temperature is above dew-point. However, and as a result of thermal bridging, whenever dewpoint occurs within the vapour cavity, all vapour on the inside and outside surfaces of the wall membrane will condense.



This is best exemplified in Fig 12, which shows the temperature and dew-point temperatures in parallel between the vapour permeable membrane and the inside surface of the wooden cladding. This would lead to regular wetting and drying within all these materials. This is a matter that requires further investigation, as any moisture in the wall may reduce long-term structural integrity and reduce the insulation properties of the wall batt insulation.

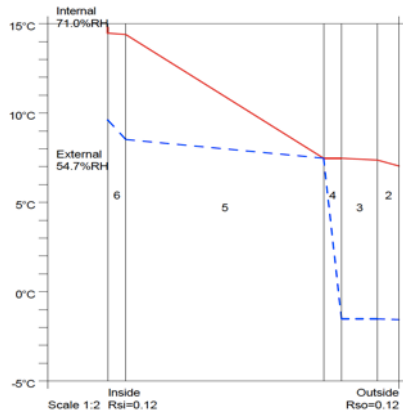


Figure 9. Condensation risk from a conditioned bedroom with vapour impermeable membrane

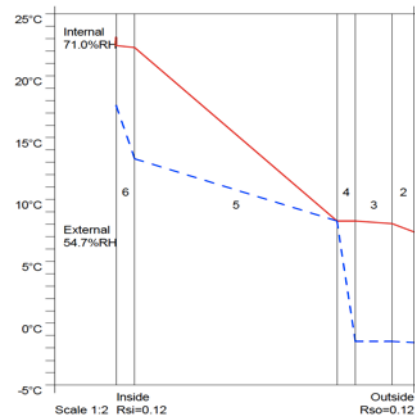


Figure 10. Condensation risk from a conditioned living room with vapour impermeable membrane

Month	Int _i (C°)	Int _i (%RH)	Ext _e (C°)	Ext _e (%RH)	Gc _i (Kg/m ²)	Ma _i (Kg/m ²)
Jan	26.4	71.0	15.7	47.4	1.5	23.2
Feb	25.9	71.0	16.2	46.8	1.1	1.1
Mar	26	71.0	14.7	47.8	1.0	2.0
Apr	24.8	71.0	11.8	53.5	2.0	4.0
May	23.7	71.0	9.0	52.7	2.3	6.3
Jun	22.7	71.0	7.1	51.2	2.3	8.6
Jul	23.1	71.0	6.7	54.7	2.6	11.2
Aug	23.9	71.0	7.3	49.5	2.7	13.9
Sep	25.4	71.0	9.2	50.2	2.8	16.7
Oct	24.5	71.0	10.6	48.5	2.2	18.9
Nov	24.3	71.0	12.8	39.0	1.6	20.4
Dec	25.3	71.0	15.4	42.8	1.2	21.7

Table 4. Moisture accumulation in medium upgrade, vapour impermeable wall

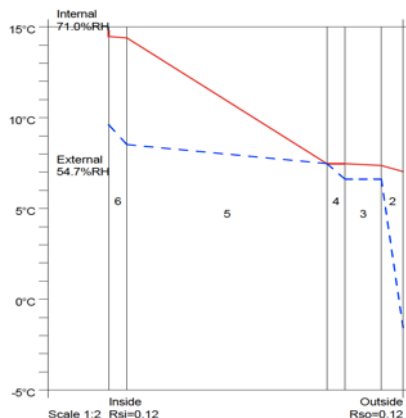


Figure 11. Condensation risk from a conditioned bedroom with vapour permeable membrane

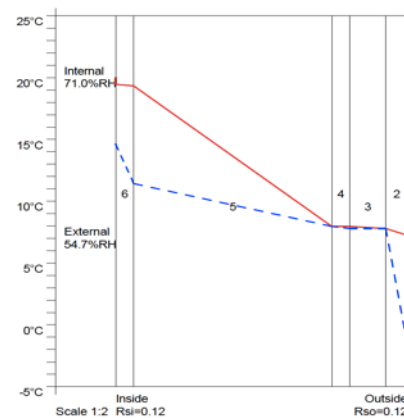


Figure 12. Condensation risk from a conditioned living room with vapour permeable membrane



Best upgrade

The best external wall upgrade maintained a much greater difference between internal and external air temperatures. Like the medium upgrade scenario, the best upgrade wall system simulations included vapour impermeable and vapour impermeable membranes. The results for these wall systems are very similar to the medium upgrade analysis discussed above. Fig 13 and Fig 14 below show examples of the graphical condensation risk analysis for the vapour impermeable membrane wall system. In both figures, and until the room temperature is less than 10°C, condensation forms on the inside surface of the membrane and is trapped within the wall. Table 5 below shows the calculated moisture accumulation within the vapour impermeable wall system. It is marginally less than what is shown in Table 4, for the medium upgrade wall system. This requires further investigation but may be caused by the moisture buffering properties of the wall insulation.

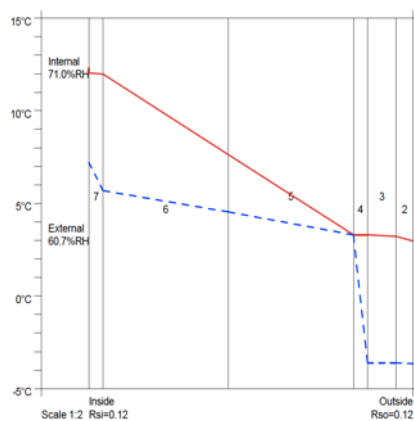


Figure 13. Condensation risk from a conditioned bedroom with vapour impermeable membrane in the best upgrade wall

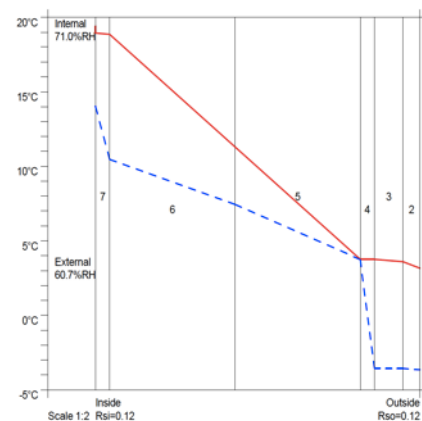


Figure 14. Condensation risk from a conditioned living room with vapour impermeable membrane in the best upgrade wall

Month	Int (°C)	Int (%RH)	Ext (°C)	Ext (%RH)	Gc (Kg/m ²)	Ma (Kg/m ²)
Jan	26.4	71.0	15.7	47.4	1.1	19.7
Feb	25.9	71.0	16.2	46.8	0.9	0.9
Mar	26	71.0	14.7	47.8	1.4	2.2
Apr	24.8	71.0	11.8	53.5	1.6	3.9
May	23.7	71.0	9.0	52.7	1.9	5.8
Jun	22.7	71.0	7.1	51.2	2.0	7.8
Jul	23.1	71.0	6.7	54.7	2.2	9.9
Aug	23.9	71.0	7.3	49.5	2.2	12.1
Sep	25.4	71.0	9.2	50.2	2.1	14.3
Oct	24.5	71.0	10.6	48.5	1.8	16.1
Nov	24.3	71.0	12.8	39.0	1.4	17.5
Dec	25.3	71.0	15.4	42.8	1.1	18.6

Table 5. Moisture accumulation in best upgrade, vapour impermeable wall

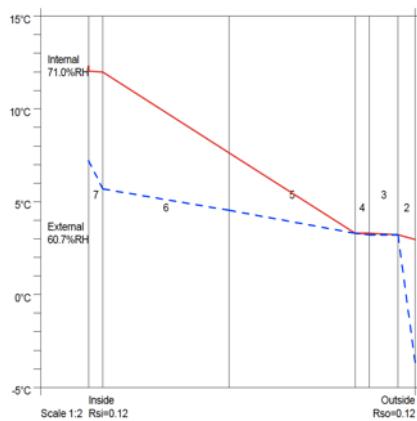


Figure 15. *Condensation risk from a conditioned bedroom with vapour permeable membrane in the best upgrade wall*

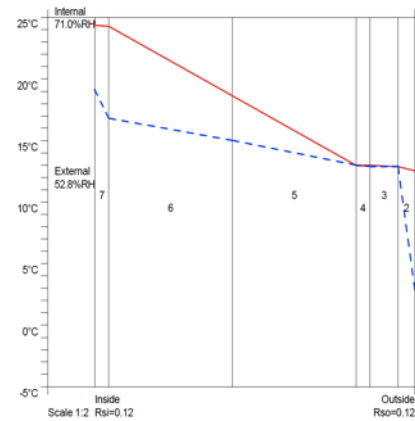


Figure 5. *Condensation risk from a conditioned living room with vapour permeable membrane in the best upgrade wall*

Fig and Figure 5 above, show the vapour permeable graphical analysis of the best upgrade wall, and in a similar fashion to the medium upgrade wall discussed above, the vapour is allowed to leave the built fabric and condense within the cavity space. The monthly data for this wall system does show occasional moisture accumulation in the wall which is readily allowed to leave the built fabric when the wall temperature increases.

CONCLUSION

On a daily basis, many existing homes in Australia's temperate climates are being improved or upgraded. However, very few consider vapour pressure management. Within the natural environment, the vapour pressure system is always striving for equilibrium. However, within the built environment significant differences in external and internal air moisture content, air temperature and vapour pressure is established. This drives the natural system to find equilibrium within the skins of the building. In temperate and cool temperate climates, the vapour pressure is often outward, for significant portions of the year.

In this research, the condensation risk analyses for the as-is (base design), medium upgrade and best upgrade houses all demonstrated dewpoint occurring somewhere within the external envelope. In the wall systems which included a vapour impermeable membrane, (or building wrap), the vapour and moisture was shown to form on the inside surface of the membrane, leading to an accumulation of moisture. The long-term accumulation of moisture, from less than 1kg/m^2 to more than 20kg/m^2 , is significant and is likely to promote structural degradation, a reduction in the insulation properties and mould growth.

The medium upgrade and best upgrade walls which included a vapour permeable membrane did show a much lower, or nil, moisture accumulation within the wall. The vapour permeability properties of the wall membrane allowed the water vapour to leave the built fabric whenever dew-point is occurring outside the membrane. This research highlights a significant long-term, and built fabric affecting, condensation risk that is occurring in many renovations and house upgrades in temperate Australia, where a vapour impermeable membrane building wrap system is being installed. Additionally, most housing, (not including brick veneer), does not include a vapour or drainage cavity. The thermal bridging between cladding system and wall membrane would significantly compromise the capability of vapour to leave the internally conditioned wall.



However, this research did identify that the most robust wall system, to reduce the occurrence of condensation and moisture accumulation, for the medium upgrade and best upgrade walls, included a vapour permeable wall membrane and a vapour cavity between the membrane and the cladding. Within the Australian design and construction industry, this focus on condensation risk is in its infancy. Extensive simulation, analysis and observation of built fabric systems needs to occur.

ACKNOWLEDGEMENTS

The study was completed in the summer of 2017 with support from the Dean's Summer Research Scholarship Program, Faculty of Science, Engineering and Technology, University of Tasmania.

REFERENCES

1. ABCB (2006) *Protocol For House Energy Rating Software V2006.1* Australian Building Codes Board.
2. ABCB (2016) *The National Construction Code: Volume 2, Building Code of Australia Class 1 to Class 10 Buildings*, ed., The Australian Building Codes Board, Canberra ACT.
3. Australian Bureau of Statistics (2000) *4182.0 - Australian housing survey -- housing characteristics, costs and conditions, 1999*, Canberra.
4. Bornehag, C. G., Blomquist, G., Gyntelberg, F., Jarvholm, B., Malmberg, P., Nordvall, L., Nielsen, A., Pershagen, G. and Sundell, J. (2001) Dampness in buildings and health - Nordic interdisciplinary review of the scientific evidence on associations between exposure to "dampness" in buildings and health effects (NORDDAMP), *Indoor Air-International Journal of Indoor Air Quality and Climate*, 11(2), 72-86.
5. Brandt, E., Bunch-Nielsen, T. and Thomson, P. (2006) *Mould problems in buildings in the nordic countries-with an emphasis on roofing*, HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People, Proceedings, 359-364.
6. British Standards (2011) *BS 5250:2011 Code of practice for control of condensation in buildings*, BSI, London.
7. Cheng, M., Galbally, I., Gillett, R., Keywood, M., Lawson, S., Molloy, S. and Powell, J. (2010) *Indoor air project - part 1: main report - indoor air in typical Australian dwellings*, The Centre for Australian Weather and Climate Research (a partnership between CSIRO and the Bureau of Meteorology).
8. CommSec (2016) *CommSec Home Size Trends Report: US overtakes Australia to build biggest homes*, Economic insights.
9. CSIRO (1962) Some common oversights in building, in, *Notes on the science of building*, Experimental Building Station: Department of Housing and Construction Marrickville.
10. CSIRO (1970) Note 61: Condensation in Dwellings in, *Notes on the science of building*, CSIRO, Rydalmere.
11. Desjarlais, A. (2016) *Condensation In hot and humid and mixed humid climates*, in M. Dewsbury (ed.), email discussion - Oak Ridge National Research Laboratory.



12. Dewsbury, M. and Law, T. (2016a) *Recent increases in the occurrence of condensation and mould within new Tasmanian housing*, 50th International Conference of the Architectural Science Association 2016, Adelaide, 715-724.
13. Dewsbury, M. and Law, T. (2016b) *Temperate climates, warmer houses and built fabric challenges*, International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016, Procedia Engineering, Sydney.
14. Dewsbury, M., Law, T., Fitz-Gerald, D., McComish, B., Potgieter, J., Chandler, T. and Soudan, A. (2016a) *Scoping study of condensation in residential buildings: final report*, Australian Building Codes Board, Launceston.
15. Dewsbury, M., Law, T. and Henderson, A. (2016b) *Investigation of destructive condensation in Australian cool-temperate buildings*, in D. o. J. Building Standards and Occupational Licensing (ed.), University of Tasmania, Launceston.
16. Dewsbury, M. and Nolan, G. (2015) *Thermal performance for timber-framed residential construction: building comfortable and energy-efficient timber houses*, Wood Solutions Technical Guides, ed., Wood Solutions, Melbourne.
17. Dewsbury, M., Nolan, G., Fay, M. R. and Vale, R. J. D. (2006) The use of AccuRate, in the design process of Two Developer Type Timber Platform Houses, to achieve a 5 Star & an 8 Star House Energy Rating, *Australian and New Zealand Architectural Science Association (ANZAScA), Annual Conference*, edited by V. S. T. W. Susan Shannon, Adelaide, 2006, 26-33.
18. Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., Leone, M., De Sario, M., Bell, M., Guo, Y., Wu, C., Kan, H., Yi, S., Coelho, M., Saldiva, P., Honda, Y., Kim, H. and Armstrong, B. (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study, *The Lancet*, 386(9991), 25-31.
19. International Organization for Standardization (2007) *ISO 6946: Building components and building elements - thermal resistance and thermal transmittance - calculation method*, Geneva.
20. International Organization for Standardization (2008) *ISO 13789: Thermal performance of buildings - transmission and ventilation heat transfer coefficients - calculation method*, Geneva.
21. International Organization for Standardization (2012) *ISO 13788:2012 - Hygrothermal performance of building components and building elements -- Internal surface temperature to avoid critical surface humidity and interstitial condensation -- Calculation methods*, Geneva.
22. Johnston, J. E. and Gibson, J. M. (2014) Spatiotemporal variability of tetrachloroethylene in residential indoor air due to vapor intrusion: a longitudinal, community-based study, *Journal of Exposure Science and Environmental Epidemiology*, 24(6), 564-571.
23. JPA TL Ltd (2016) *JPA Designer: SAP 9.92 module • U-value modules & Condensation Risk (Version 6.03a1 and above)*, JPA TL Ltd., Newcastle upon Tyne.
24. Katelaris, C. (2014) *Behind the scenes discussions - mould and human health - at 10th International Congress of Aerobiology* in M. D. T. Law (ed.), Telephone discussion.
25. Kerckmar, C. M. and et al (2006) Reduction in asthma morbidity in children as a result of home remediation aimed at moisture sources, *Environmental Health Perspectives*, 114(10).
26. Lee, T., Wu, C., Guthrie, K. and Dewsbury, M. (2014) *Renovation cost-benefit analysis*, Energy Partners.



27. Leicester, R., Goldfinch, J., Paevere, P. and Foliente, G. (2003) *Truss Trouble*, CIB-W18 Meeting 36, Colorado, USA.
28. Leicester, R. and Lhuede, E. (1992) *Mechano-sorptive effects on toothed plate connectors* Proceedings of IUFRO 5.502 Meeting, Bordeaux, France.
29. Mendell, M. J., Mirer, A. G. and Cheung, K. (2011) Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence *Environ Health Perspective*, 119:748-756.
30. Moreland Energy Foundation Limited (2010) *On-ground assessment of the energy efficiency potential of Victorian homes: report on pilot study*, Sustainability Victoria.
31. Nguyen, M., Paevere, P., Leicester, R. and Syme, M. (2008) *Models for Prediction of Microclimate and Timber Moisture Content within the Building Envelope*, Proceedings of the 10th World Conference on Timber Engineering, Miyazaki, Japan.
32. Paevere, P., Nguyen, M., Syme, M. and Leicester, R. (2008) *Nailplate Backout – is it a Problem in Plated Timber Trusses?*, Proceedings of the 10th World Conference on Timber Engineering, Miyazaki, Japan.
33. Paevere, P., Nguyen, M., Syme, M., Leicester, R. and Ho, K. (2009) *Mechano-sorptive nailplate backout in nailplated timber trusses*, Forest and Wood Products Australia, Melbourne.
34. The Institute of Medicine (2004) *Damp indoor spaces and health*, The Institute of Medicine, Washington DC.
35. Timi, J. (2015) *Condensation problems in new buildings in Victoria* in M. Dewsbury (ed.), CSR Bradford Insulation.
36. WHO (2009) *Damp and mould: health risks, prevention and remedial actions*, WHO Regional Office for Europe.