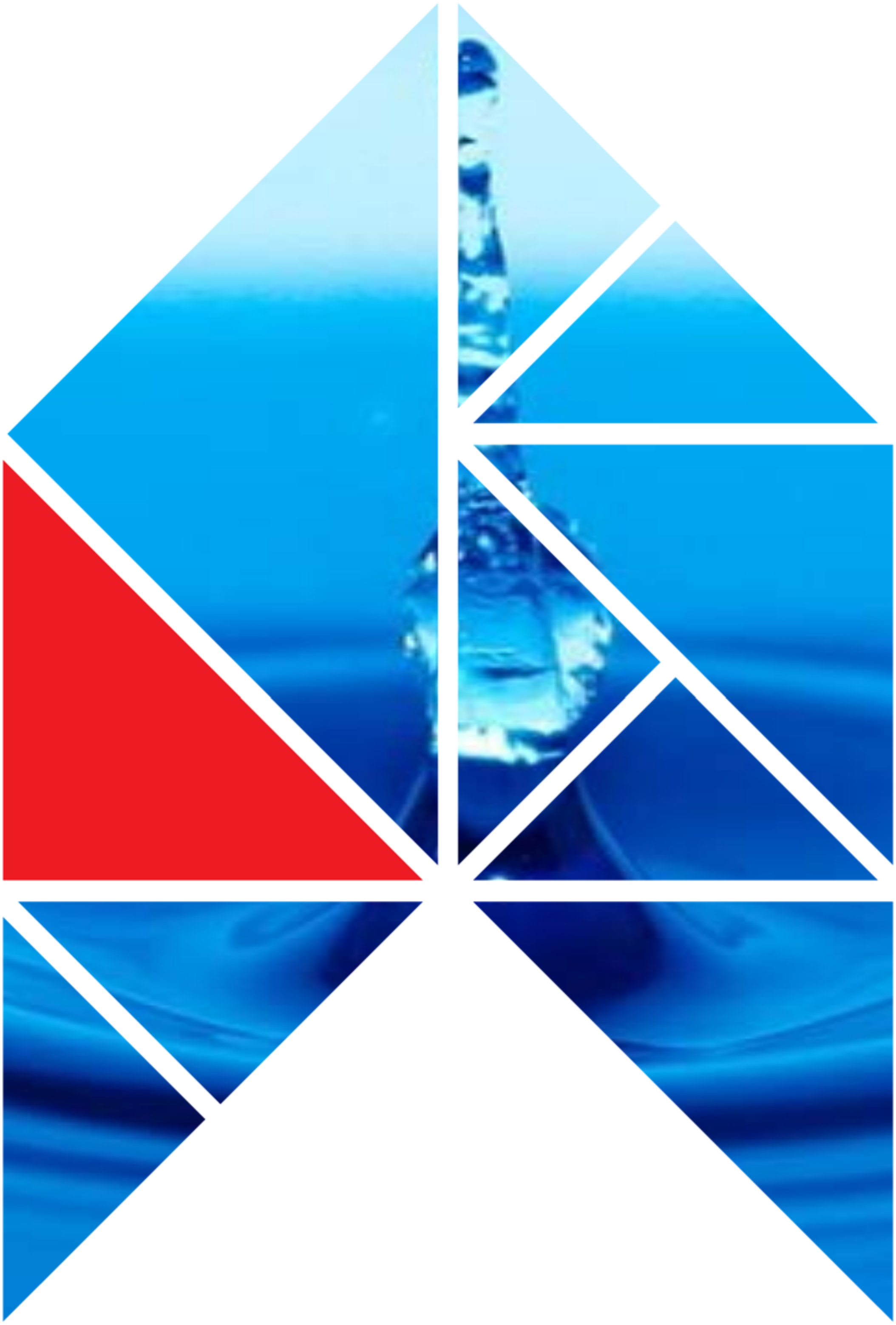
Study Report

SR344 [2016]

# Vapour control in New Zealand walls

Greg Overton



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# Preface

This is the final report from a 3-year project on vapour control in New Zealand walls. This report is intended for designers, architects and other building professionals who are considering measures to control interstitial condensation.

# Acknowledgements

This work was funded by the Building Research Levy. This project would not have been possible were it not for the assistance of BRANZ technicians, Mark Bassett and the industry members who have contributed to this project. Their input is greatly appreciated.

# Vapour control in New Zealand walls

## BRANZ Study Report SR344


## Author

Greg Overton



## Reference

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## Abstract


This study aims to provide updated guidance on the role of vapour control layers in New Zealand walls.

A series of wall specimens were installed into a BRANZ test building that was humidified periodically over a 2-year period. Measurements within the walls showed that the humidity at the sheathing/underlay reached 100% in almost all of the walls, but this only manifested itself as liquid droplets in a minority of walls. The only walls that did not reach 100% humidity were those that had a smart vapour retarder between the interior lining and the insulation in the stud space.

The hygrothermal simulation software WUFI was used to simulate the wall specimens. It was originally expected that, for the simulation and measurements to agree, airflows through/in the walls would have to be accounted for. In general, the WUFI models agreed well with the experiment without this addition, with the main exception being the moisture level in the cavity. However, it is felt the airflow processes in walls still warrant further investigation.

With the caveat that the moisture level in the drainage cavity was not simulated well, the WUFI models were then used to predict wall performance across a number of New Zealand locations. Condensation was not predicted to accumulate in any of the wall types and locations analysed. However, the models predict that most walls are likely to fail the default ASHRAE 160-2009 *Criteria for moisture-control design analysis in buildings* criteria for mould growth and corrosion. There is some debate as to how well this criteria matches with real-world failures, with overseas work suggesting the traditional brick veneer wall, which has a long track record of adequate performance, also fails the criteria.

A further sensitivity analysis was performed to ascertain when condensation accumulation could start to occur, and the dominant factor was the ventilation rate of the indoor space. When this fell to below 0.3 air changes per hour (ach) and relative humidity was uncontrolled, condensation was predicted to accumulate in the outer 5 mm of insulation, principally because the indoor humidity was so high.

The study suggests that it is not necessary to add a specific vapour control layer to prevent accumulation of liquid moisture. This is in line with previous advice from BRANZ. It is also shown that this practice is in line with current international guidance for similar climate zones, with acrylic paint systems and internal linings providing enough vapour resistance to prevent condensation damage further into the wall while still providing good drying capacity.

Further work that explains the humidity levels observed in the drainage cavity of the test walls would be valuable as would work that aims to determine adequate design indoor environments for New Zealand homes. For this study, in the absence of such data, ASHRAE 160 was used as a basis for the indoor climate in the WUFI simulations.

## Keywords

Internal moisture, condensation, vapour control

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# 1. Introduction

## 1.1 Background

The walls of New Zealand houses are typically built without any specific vapour control layer or air barrier. This is quite different to some overseas practice, where significant emphasis is placed on both an air barrier (or an air control layer) and a vapour retarder (or a vapour control layer).

This study focuses mainly on the use of vapour control layers in New Zealand. Vapour control layers limit the movement of water vapour by diffusion with the intended benefit of preventing condensation forming and accumulating within a structure. The use of vapour control layers is one of the most debated topics in building physics. Approaches vary from country to country, and this is likely because these countries (or even regions within countries) have differing climates and differing building practices.

Surface mould is a common problem in the living spaces of New Zealand homes, but genuine cases of damage from condensation within the structure, especially walls, are rare. The lack of field evidence of condensation damage is one of the contributing reasons why vapour control layers are not commonly used in New Zealand walls.

Construction styles in New Zealand have evolved for a number of different reasons, including changes to the New Zealand Building Code and trends in the use of different products. The result is that houses are being built more airtight than previously, despite there being no focus on air barriers per se, and with higher levels of insulation. There is also evidence that a significant percentage of houses are underventilated (McNeil et al., 2012). Together, these changes mean the risk of interstitial condensation may have increased. We have a higher moisture load due to reasonably airtight but poorly ventilated construction, and we have colder temperatures outboard of the insulation because of the higher level of insulation.

Despite the changes above, there is still no hard evidence of a systemic interstitial condensation problem in New Zealand. There is, however, growing anecdotal evidence that the problem exists, and it is also desirable to know at what point, in terms of insulation values, moisture loads or wall materials, that a problem might be encountered. One example of changing materials is the increasing use of steel framing. These walls often have a full thermal break on the outside of the framing, which normally takes the form of an extruded polystyrene (XPS) sheet of a certain thickness. When used in conjunction with conventional cavity insulation, this leads to a potential condensation risk where water vapour cools down as it passes through the cavity insulation and then condenses on the relatively vapour-resistant XPS. In this document, the term 'sheathing' is used for any rigid sheet product adjacent to the outside of the framing, such as an XPS sheet.

## 1.2 Previous research

Rose (2010) presents a history of condensation control in walls and highlights some of the erroneous concepts that are still in use today. In that paper, it is stated that the adoption of vapour barriers was largely on the back of work conducted by Frank Rowley (Rowley, 1939; Rowley et al., 1939), who can be considered the father of vapour barrier requirements (Straube, 2001). Using Rowley's results (perhaps incorrectly), the US Federal Housing Administration published *Minimum Property Requirements*, which contained the first numerical values for vapour barrier permeance, attic ventilation and crawl space ventilation (FHA, 1942). That publication also included the rule that a vapour barrier (resistance of 17.5 MNs/g or greater) be placed on the warm side of the thermal insulation in cold climates.

Once the use of vapour barriers became commonplace, it became very difficult to alter the status quo. Rose puts this down to the fact the prescriptive requirements were put in place prior to the science and the establishment of performance criteria. Therefore, work such as that of Hutcheon (1953) from the National Research Council of Canada, which showed that airflow explained the occurrence of condensation better than diffusion, did not have the impact it should have had in the United States.

After the initial work in the 1940s and 1950s, there have been numerous studies about the effectiveness of vapour barriers. The reader is referred to an extensive literature review conducted by the Canadian Mortgage and Housing Corporation as part of a study on the use of polyethylene vapour barriers (Wilkinson et al., 2007). This review highlights the confusion about the topic of condensation control. The summary relating to above-grade walls showed about a dozen studies where plastic sheeting vapour barriers may cause problems and about a dozen more that suggested problems would arise if this sheeting were omitted.

More recently overseas, a study by Glass et al. (2015a) compared field measurements in walls of two test structures and compared these with one-dimensional simulations using the hygrothermal modelling software WUFI (Künzel, 1995). The key parameter under investigation here was the moisture content of the oriented strand board (OSB) sheathing in walls. WUFI approximately captured the seasonal increases of OSB moisture content, but the simulated OSB moisture contents tended to be considerably lower than measured values during summer. The experimental walls with an interior kraft vapour retarder recorded lower OSB moisture contents than the walls without any vapour retarder.

There has been research on condensation in New Zealand as well. Trethowen (1972) presents a theory of condensation and mildew that has a legacy that lives on today in the form of Acceptable Solution E3/AS1 of the New Zealand Building Code. The paper has useful data about moisture emission sources and uses simple principles to illustrate that ventilation is the major process removing internal moisture rather than diffusion. Trethowen (1976) discussed adequate design values for interior humidity and used a simple mass balance equation and energy considerations to conclude that the winter vapour pressure difference between indoors and outdoors would rarely be above 4 mbar in New Zealand. This was in line with measured values from eight houses monitored in Wainuiomata. The paper called for a design method that took the moisture storage capacity of materials into account, because this could have a controlling effect on the room vapour pressure in normal structures. In a later paper, Trethowen (1979) discussed the relatively common occurrence of surface condensation in New Zealand (affecting 25–50% of homes) compared with the very low number of cases of interstitial condensation causing damage. In that paper, the Kieper diagram (a variant on the better-known Glaser method) was used to illustrate that even trace quantities of ventilation behind the cladding were enough to outweigh the effects of the diffusion properties of the materials. Trethowen (1987) again reiterated that focusing on the use of vapour barriers was unnecessary, apart from where moisture conditions really are forced (as in cold stores, swimming pool halls or cotton mills). In other cases, the structure itself would moderate vapour pressure difference between indoor and outdoor by absorbing and releasing moisture. That paper also refers to the discrepancy reported between laboratory work, which continues to forecast increasing moisture problems, and field evidence, which persistently shows this does not happen (Lieff and Trechsel, 1980). A variety of studies are referenced that show that structural condensation is not a general problem whether winter is mild or severe, vapour barriers are present or not or insulation is present or not.

BRANZ's most recent guidance on the use of vapour barriers (referring to polythene sheeting) is contained within Bulletin 439 (BRANZ, 2003). This bulletin was based on WUFI modelling and concluded that vapour barriers are not recommended for normal domestic buildings in the main population centres of New Zealand. They were however, recommended for very cold regions of the country, such as alpine regions, or where extremely high levels of moisture are generated, such as enclosed swimming pools. Figure 1 is an example output from that document showing the relative humidity at the building paper in a direct-fixed wall in Palmerston North. This was the worst case of the locations investigated in that study.

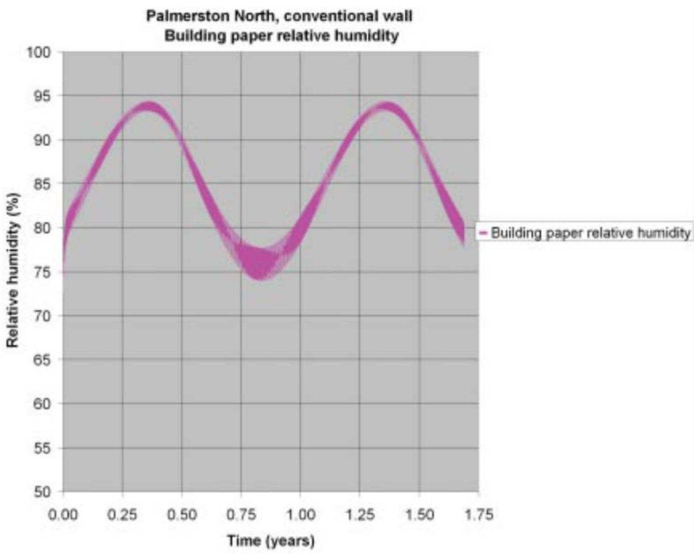



**Figure 1. Example output from BRANZ Bulletin 439 (withdrawn).**

Bulletin 439 also contained a statement saying that actual walls may be drier than those simulated because, in reality, non-designed ventilation through the walls will remove some moisture. Note that this theory is somewhat at odds with the North American approach whereby through-wall ventilation is to be minimised, using an air barrier, to stop moist air reaching cold parts of the wall by convection. It is worth reiterating that the study behind Bulletin 439 did not include airflow effects, and the effect of these airflows remains a limitation of hygrothermal models to this day. Work at BRANZ (McNeil et al., 2010) led to a simple source-sink model of airflow being adopted into WUFI. This allowed moisture removal from the back of a cladding to be modelled such that it agreed with experimental measurements at BRANZ. This source-sink model, however, does not easily lend itself to the variety of airflows that can exist in a framed wall.

The airflow processes in direct-fixed walls were recently investigated by BRANZ (Basset et al., 2015). Figure 2 shows the different airflow processes that can be active in New Zealand walls. In this study, the airflow resistances of the different flow paths were measured and were used as input to a zonal model to predict overall wall ventilation rates. The data was used to understand the drying rates that might apply to water leaks through mostly weatherboard claddings. These predicted ventilation rates agreed well with tracer measurements of ventilation behind direct-fixed claddings and explained why weatherboard claddings have a good track record of managing rainwater leaks. The measured ventilation rates for the stud space in this experiment were performed without insulation being present and therefore cannot provide the airflow rates that might allow indoor humid air to deposit moisture interstitially.

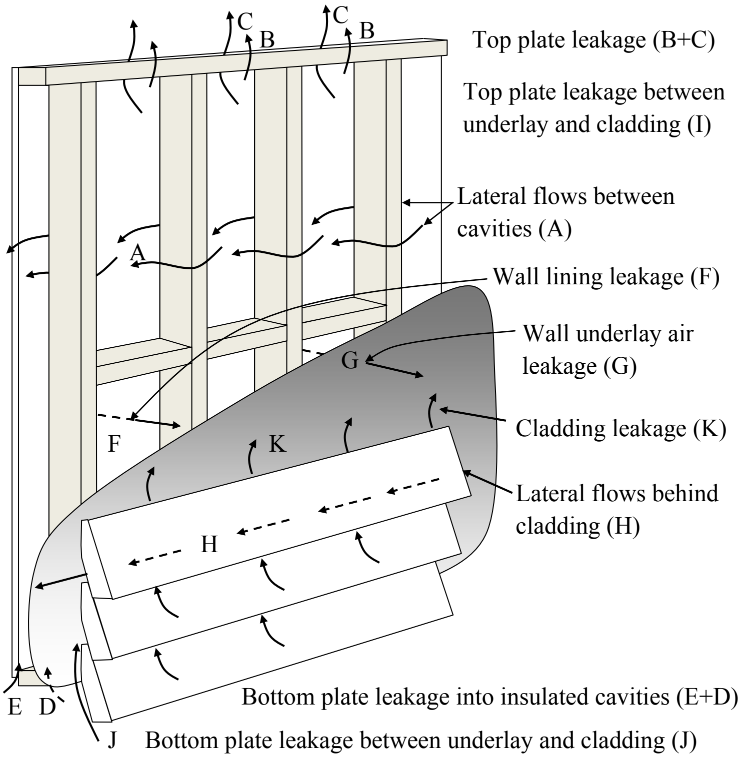



**Figure 2. Various air leakage paths in a typical New Zealand wall.**

In October 2015, Lstiburek (2015) discussed some of the challenges faced by hygrothermal modelling software and, in particular, presented a possible way of simulating wall flows using the source-sink models in WUFI by using coupled air spaces.

As it stands, the building science of interstitial moisture is unable to quantitatively bring together diffuse and air-carried moisture flows in a model that comprehensively agrees with field evidence of moisture accumulation in walls.

## 1.3 Terminology

This section briefly deals with some of the terminology around vapour control layers.

The characteristic of a material that relates to how water vapour diffuses through it, is the *vapour permeability* (SI units of kg/Pa.m.s). If this value is divided by the material thickness, the permeance of the layer is obtained (SI units of kg/Pa.$m^2$.s).

The permeance represents the mass of water vapour (in kg) that will diffuse through 1 $m^2$ of material under a vapour pressure difference of 1 Pascal in a time of 1 second.

A completely impermeable material would have an effective permeance of 0. This, technically, is a *vapour barrier*. However, the term vapour barrier, particularly in New Zealand, is taken to be synonymous with polythene sheeting. The term *vapour check* is also sometimes used interchangeably with the term vapour barrier.

A more useful term is *vapour retarder*, which reflects the fact that most materials have a measurable vapour permeance and restrict the flow of water vapour to some degree. The International Residential Code (ICC, 2015a) classifies the following:

- Class I vapour retarder: ≤0.1 perm (called impermeable)
- Class II vapour retarder: 0.1 to 1.0 perm (called semi-impermeable)
- Class III vapour retarder: 1.0 perm to 10 perms (called semi-permeable).

The units in the above list are the US perm, where 1 perm is equivalent to $5.7 \times 10^{-11}$ kg/Pa.m$^2$.s. We can see from the SI equivalent of 1 US perm that very small quantities of water vapour are involved, and it is more typical to use units that reflect this, such as ng/Pa.m$^2$.s (1 US perm equals 57 ng/Pa.m$^2$.s).

In New Zealand, it is more common to talk about vapour resistance rather than vapour permeance. Vapour resistance is the reciprocal of vapour permeance, and units of MNs/g are typically used, where the permeance (in US perms) equals 17.46 ÷ resistance (in MNs/g).

AS/NZS 4200:1994 *Pliable building membranes and underlays* has the following classification of vapour resistance:

- High: >450 MNs/g
- Medium: >7 and ≤450 MNs/g
- Low: <7 MNs/g.

Table 23 of Building Code Acceptable Solution E2/AS1 contains acceptable properties for roof underlays and wall underlays, and in general, a vapour resistance of ≤7 MNs/g is required (i.e. a low resistance) when measured in accordance with ASTM E96/E96M-15 *Standard test methods for water vapor transmission of materials* – the wet cup test. For a damp-proof course or damp-proof membrane, the resistance must be ≥90 MNs/g, which is roughly equivalent to a Class I vapour retarder.

The vapour resistance of a material isn’t necessarily a fixed value. Many materials become more permeable as the surrounding humidity increases. This is often a desirable property because water vapour is not trapped when the wall is wet. Natural wood products exhibit such a property and, to a lesser degree, so do manufactured wood products. This is also the principle behind smart vapour retarders. At high humidities, the vapour resistance drops to allow more water vapour through these products. This is illustrated in Figure 5.

The term *vapour control layer* is suggested here to designate a component within the wall that has been chosen to control water vapour diffusion in some way. This is to avoid confusion between multiple terms such as vapour barrier, vapour retarder and vapour check, although those terms will be used when referring to specific recommendations.

## 1.4 Existing recommendations on the use of vapour control layers

BRANZ's advice on vapour control layers refers to the use of polythene sheeting (a Class I vapour retarder in accordance with the International Residential Code classification). BRANZ's stance has been that these are generally not needed and are not recommended, because building failures due to accumulating condensation in walls are rare. More recently, it has been appreciated that vapour barriers eliminate drying paths that can help manage water leaks and should not be used. The exceptions to this guidance are for buildings with high internal moisture loads and/or in alpine regions.

The US Department of Energy's Building America programme has conducted research that has led to a clarification on the use of vapour control layers in the International Residential Code (Gatland, 2010). Largely based on the work of Joe Lstiburek (2004), the nature of the vapour control layer in a wall assembly is dependent on the climate zone the building is in, as defined in the International Energy Conservation Code (ICC, 2015b). In general, it is now permitted in the International Residential Code to only have a Class III vapour retarder (such as latex paint) in a wider number of locations than previously. A Class III vapour retarder is, broadly speaking, what is used in the majority of New Zealand construction, i.e. acrylic paint on the interior lining.

Table 1 shows how New Zealand's climate would be classified using the International Energy Conservation Code (IECC) climate zones. The climate data used was generated by NIWA (NIWA, 2008) for use in the Energy Efficiency and Conservation Authority's Home Energy Rating Scheme (HERS). The IECC employs a zone number that represents the thermal aspect of the climate (zone 1 being extremely hot and zone 8 being extremely cold) and a zone letter corresponding to the moisture classification (A = moist, B = dry, C = marine).

**Table 1. IECC climate classification based on HERS climates.**

| Location | IECC climate classification |
|---|---|
| Auckland | 3C |
| Christchurch | 4A |
| Dunedin | 4C |
| Hokitika | 4A |
| Kaitaia | 3C |
| Lauder | 5C |
| Napier | 3C |
| Nelson | 3C |
| New Plymouth | 3C |
| Queenstown | 5A |
| Tauranga | 3C |

Based on this data, all the locations in New Zealand were either moist or marine with a thermal criteria ranging from 3 to 5. It should be noted that Queenstown and Lauder only just fall into the colder zone 5.

Table 2 shows the situations where a Class III vapour retarder can be used according to the International Residential Code. Note that zones 1 to 3 are exempt from the requirement to have a Class I or Class II vapour retarder in the wall assembly as well. Also note that the R-values in Table 2 are in imperial units.

**Table 2. Use of Class III vapour retarders as defined in 2009 International Residential Code Table R601.3.1.**

| Zone 3 | Class III vapour retarders permitted for: |
|---|---|
| Marine 4 | Vented cladding over OSB<br>Vented cladding over plywood<br>Vented cladding over fibreboard<br>Vented cladding over gypsum<br>Insulated sheathing with R-value ≥R2.5 over 2 x 4 wall<br>Insulated sheathing with R-value ≥R3.75 over 2 x 6 wall |
| 5 | Vented cladding over OSB<br>Vented cladding over plywood<br>Vented cladding over fibreboard<br>Vented cladding over gypsum<br>Insulated sheathing with R-value ≥R5.0 over 2 x 4 wall<br>Insulated sheathing with R-value ≥R7.5 over 2 x 6 wall |
| 6 | Vented cladding over fibreboard<br>Vented cladding over gypsum<br>Insulated sheathing with R-value ≥R7.5 over 2 x 4 wall<br>Insulated sheathing with R-value ≥R11.25 over 2 x 6 wall |
| 7 & 8 | Insulated sheathing with R-value ≥R10.0 over 2 x 4 wall<br>Insulated sheathing with R-value ≥R15 over 2 x 6 wall |

According to the 2009 International Residential Code:

"For the purposes of this section, vented cladding shall include the following minimum clear air spaces. Other openings with the equivalent vent area shall be permitted.

1. Vinyl lap or horizontal aluminum siding applied over a weather-resistive barrier as specified in Table R703.4.
2. Brick veneer with a clear airspace as specified in section R703.7.4.2.
3. Other *approved* vented claddings."

Source: 2009 International Residential Code (ICC, 2015a).

Based on the classification of climate shown in Table 1, BRANZ's guidance on vapour control layers is in line with current overseas practice.

The National Building Code of Canada has guidance pertaining to the use of low-permeance materials, defined as having a permeance less than 60 ng/Pa.m$^2$.s (or a resistance greater than 16.65 MNs/g), whereby the ratio of outboard to inboard thermal resistance cannot exceed certain levels depending on the climate (defined by the number of heating degree days). Where the heating degree days are less than 4,999 (which effectively applies to the whole of New Zealand), the ratio of outboard to inboard thermal resistance must be a minimum of 0.2. For 30 mm XPS (approximately R1.0), the limiting inboard total R-value would therefore be R5, which is a relatively high amount of insulation in New Zealand. 10 mm XPS (approximately R0.33) only has a vapour resistance of about 5 MNs/g, so the requirements from the Canadian code do not apply. However, if the requirement on vapour resistance is ignored, the same ratio of 0.2 leads to a limiting inboard R-value of 1.65, which is lower than typically used in New Zealand in new buildings.

Table 2 also contains some information about the use of insulating sheathing such as XPS. These requirements follow the same principle as those used in the National Building Code of Canada, i.e. they are a ratio of inboard to outboard thermal resistance. For climate zone 4, the approximate ratio is 0.2, and for climate zone 5, the approximate ratio is 0.35. Assuming an inboard thermal resistance of R2.0, this means the sheathing must have a thermal resistance of value R0.4 in zone 4 and R0.7 in zone 5. By these requirements, 10 mm XPS would be unsuitable in zones 4 and 5.

# 2. Aims and objectives

The aim of this study was to generate a range of representative computer models of walls in New Zealand that were benchmarked by experiment. These models were to then be used to:

- provide an up-to-date answer regarding the role of vapour barriers in New Zealand construction
- for the range of New Zealand climates, define the various tipping points at which current construction trends will result in a moisture accumulation problem
- understand the role of airflow within the stud space in terms of moisture removal from a wall
- provide specific guidance in cases where there are multiple layers of insulation within the wall, for example, fibreglass batts in conjunction with a polystyrene sheathing.

# 3. Experimental method

The experiment consisted of constructing a number of wall specimens and installing them in a test building. The walls were instrumented with thermocouples and humidity probes, and the conditions in the walls were monitored from 1 May 2014. The interior space of the test hut was heated and occasionally humidified. In addition to the instrumentation, a borescope camera was used to inspect the inside face of the sheathing/underlay in the walls during humidification periods.

These results were then used to benchmark WUFI simulations of the walls. These simulation models were then used to investigate wall performance in areas other than the BRANZ site and subjected to different indoor conditions. This following sections describe both the experimental approach and the analysis method in more detail.

## 3.1 Wall specimens and test building

The wall specimens in this study were all 1.2 m wide x 2.4 m high to allow installation into a test building on the BRANZ site. The test building (see Figure 3) had 24 separate openings for wall specimens – 10 on each of the north and south elevations and two on the east and west elevations. For this study, five of the openings on the south elevation and one on the north elevation were used.

**Figure 3. Test building on the BRANZ site – weatherstation shown in foreground.**

A typical cross-section through a steel wall specimen is shown in Figure 4. Where a smart vapour retarder (SVR) was installed, it was placed between the insulation and the interior lining.

The framing layout was slightly different to typical New Zealand construction but was in accordance with previous studies at BRANZ, i.e. a 600 mm wide by 800 mm high central cavity was formed.

The wall specimens were all clad with fibre-cement sheet over timber cavity battens. This cladding was preprimed on the exterior face and then had two coats of acrylic paint applied to the exterior face. The interior lining of the wall specimens was 13 mm thick gypsum plasterboard.

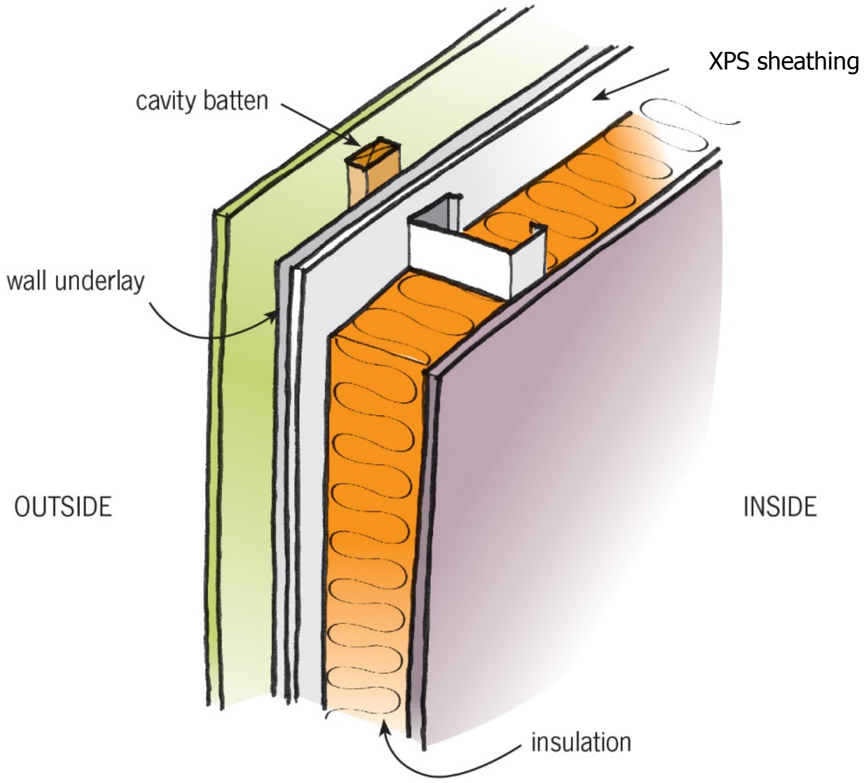



**Figure 4. Typical cross-section of a steel-framed test specimen.**

Once installed into the test building, a 10 mm hole was drilled through the interior lining to allow a borescope to be inserted through a precut slit in the insulation and view the condition of the sheathing. This hole was taped up when the borescope was not being used. In addition, two 50 mm diameter ports were installed in the interior lining, one near the top of the wall and one near the bottom. These were intended to be used to vary the air leakage through the specimen, although that aspect of the behaviour was subsequently not investigated in detail due to difficulties with the planned method for that aspect of the study. During the experiments described here, the ports were all closed off.

Table 3 contains details of the wall specimens. Where the wall specimens had a flexible underlay, it was generally a separate component in the wall. However, Wall 8 had a sheet thermal break that had a flexible wall underlay bonded to its exterior surface. This is referred to as an integrated underlay in Table 3. The original test specimens (year 1) were all steel-framed with various sheet thermal breaks. This was because the experimental design was initially focused on the use of multiple layers of insulation in walls. In year 2, it was decided to also investigate timber-framed walls and so some of the test specimens were swapped out. The worst-case wall from year 1 (Wall 8) was retained. Year 2 was split into two parts, representing where the specimens were modified. Walls 6 and 9 had insulation with a higher R-value installed to try and cause condensation. Wall 8 had the interior lining painted to see if this was enough to stop condensation forming. Where an SVR was included in a test specimen, it was located adjacent to the interior lining.

**Table 3. Details of wall specimens**

| | Wall number (position in building) | Framing (90 mm deep) | Sheathing | R-value of fibreglass insulation (W/m$^2$.°C) | Underlay | SVR | Interior lining | Orientation | Air leakage* |
|---|---|---|---|---|---|---|---|---|---|
| Year 1 (winter 2014) | 5 | Steel | 30 mm XPS | R2.8 | Separate | No | Painted | South | High |
| | 6 | Steel | 30 mm XPS | R2.8 | None | No | Painted | South | Low |
| | 7 | Steel | 10 mm XPS | R2.8 | Separate | No | Unpainted | South | Low |
| | 8 | Steel | 10 mm XPS | R2.8 | Integrated | No | Unpainted | South | High |
| | 9 | Steel | 10 mm XPS | R2.8 | Separate | No | Painted | South | High |
| | 20 | Steel | 10 mm XPS | R2.8 | Separate | No | Unpainted | North | Low |
| Year 2 (winter 2015) Part 1 | 6 | Timber | Plywood | R1.8 | Separate | No | Unpainted | South | |
| | 7 | Timber | None | R1.8 | Separate | Yes | Unpainted | South | |
| | 8 | Steel | 10 mm XPS | R2.8 | Integrated | No | Unpainted | South | |
| | 9 | Timber | None | R1.8 | Separate | No | Unpainted | South | |
| | 20 | Timber | None | R1.8 | Separate | Yes | Unpainted | North | |
| Year 2 (winter 2015) Part 2 | 6 | Timber | Plywood | R2.8 | Separate | No | Unpainted | South | |
| | 7 | Timber | None | R1.8 | Separate | Yes | Unpainted | South | |
| | 8 | Steel | 10 mm XPS | R2.8 | Integrated | No | Painted | South | |
| | 9 | Timber | None | R2.8 | Separate | No | Unpainted | South | |
| | 20 | Timber | None | R1.8 | Separate | Yes | Unpainted | North | |

*Air leakage parameter not explored experimentally.

Figure 5 shows some representative data for the vapour resistance of several materials used in the experiment. Note the plywood used in this experiment was 12 mm thick and sourced from New Zealand. The data shown in the graph is intended to be representative only, for example, not all smart vapour retarders will have the profile shown in Figure 5.

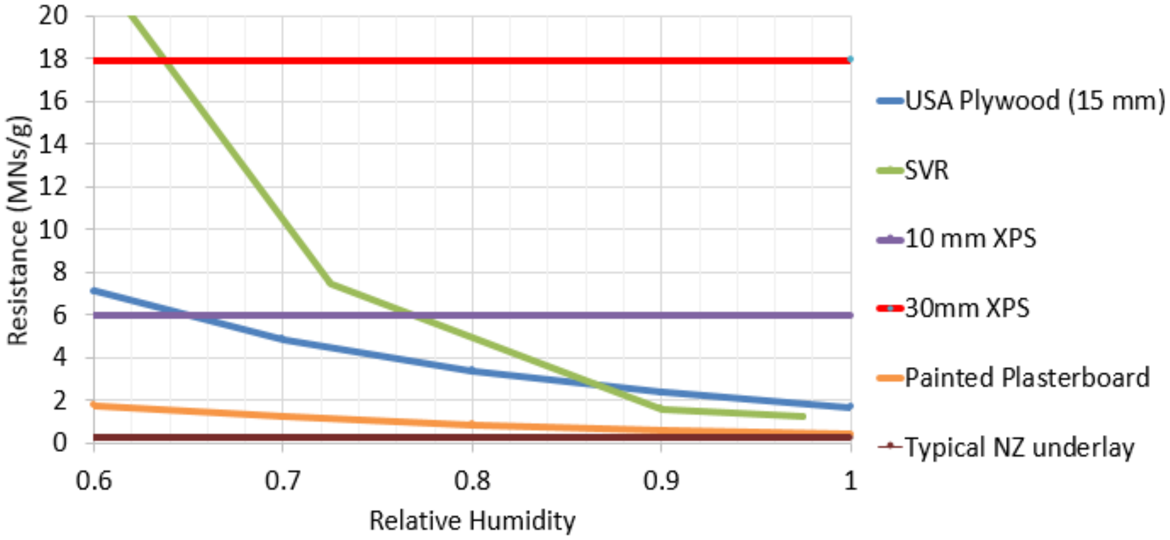



**Figure 5. Vapour resistance of various materials.**

## 3.2 Instrumentation

For each wall, the temperature and humidity were recorded at 15-minute intervals in the following locations:

- At the interface between insulation and internal lining (or SVR).
- At the interface between insulation and sheathing.
- In the drainage cavity

In addition, surface temperatures were measured on the interior and exterior of the walls.

Type-T thermocouples were used to measure the temperatures, and Honeywell HIH-4000-001 sensors were used to measure the relative humidity.

The humidity sensors were calibrated using an on-site humidity generator. A standard linear relationship between output voltage and relative humidity was used for relative humidity values up to 90%. A quadratic polynomial was used to fit the data between relative humidities of 90% and 96%. This approach was used to gain more accurate measurements when the relative humidity was in excess of 90%. The stated accuracy of the sensors is ±3.5% when using the standard linear fit from the manufacturer's data sheet. The sensors used in this study should be more accurate given each one is custom calibrated. However, extended exposure at ≥90% relative humidity causes a reversible shift of 3% relative humidity. This behaviour, and the fact that the sensors are only calibrated up to 96%, means that any readings above that could be regarded as questionable. Temperature corrections were applied in accordance with the manufacturer's data sheet using the data from the corresponding thermocouple.

The temperature and humidity inside the test building were controlled using heaters and humidifiers in conjunction with simple on/off controls. Heating was on if the indoor temperature was less than 20°C, and humidification was on if the room relative humidity was less than 70%. Two pedestal fans were used to ensure the indoor air was reasonably well mixed. Note that the humidification was not always sufficient to raise the relative humidity to 70%. The precise value of relative humidity was not considered crucial. The main intention was that it was measured and was sufficient to lead to interstitial condensation in some of the wall specimens at certain times.

The outdoor climate was measured using a weatherstation on the BRANZ site. Longwave and shortwave radiation sensors were used to enable the full radiation balance calculation to be performed in WUFI. The rain gauge of the weatherstation proved to be unreliable, and where rain effects were included in subsequent simulations, data was obtained from the NIWA Cliflo database for the experimental period (accessible at http://cliflo.niwa.co.NZ).

## 3.3 WUFI simulation and analysis method

BRANZ has access to a number of the WUFI simulation tools. The approach used in this study was to start with the most simple models possible and then refine them as necessary.

It was thought that these simple models would be significantly different to the measured results and then aspects such as wall ventilation or moving from 1D models to 2D models would be employed to hopefully improve this agreement.

The reason for using the simplest model possible was that a desired outcome of the study was to have a range of trusted working models that could be used to explore a range of climates. The reasonably simple 1D models lend themselves to this kind of parametric study more so than 2D models.

### 3.3.1 Models of the experimental walls

The models of the experimental walls relied quite heavily on the material data available in the WUFI database. Measurements of the vapour permeability and thermal conductivity of the XPS sheathing were conducted as well as vapour permeability of unpainted and painted plasterboard and the fibre-cement cladding. These measurements were in line with existing materials in the WUFI database and so these were generally used as a basis for the models in this study. One point in particular to note is that the ASHRAE 1018-RP data (Kumaran et al., 2002) for the moisture storage function of the fibreglass insulation was chosen rather than the default moisture storage function used in WUFI (which corresponds to mineral wool).

### 3.3.2 WUFI analysis for different climates

The results of hygrothermal simulations are highly dependent on the underlying assumptions. In particular, the choice of indoor and outdoor climate are critical.

#### 3.3.2.1 Exterior climate

The outdoor climates used in the analysis were those built into WUFI, which in turn, are those from the HERS scheme and discussed in section 1.4. Here, all the climate stations across the country were assessed for their suitability based on the amount and type of meteorological data collected, then a station was chosen as being representative of a particular region. The climate files for each location consist of 12 individual months of data, each selected to match the average distribution for that month over a decade or more. These climate files do not therefore represent worst-case data. A simple temperature shift could be employed to make the data more extreme.

#### 3.3.2.2 Indoor climate

There is no recognised standard indoor climate for New Zealand homes. Various standards around the world have guidance for what should be used as the indoor climate, but it is unknown how representative these are for New Zealand. The approach used in this study is to use a modified version of the intermediate method in ASHRAE 160.

In the intermediate method, the indoor humidity is a function of the 24-hour running-average outdoor vapour pressure, the moisture generation rate inside the building and ventilation rate inside the building. It is worth noting that, as implemented in WUFI, the humidity has an upper cut-off at 70%. There appears to be no physical reason why this would happen in reality other than by user intervention, i.e. ventilating more when humidity is high.

The indoor temperature is a function of the 24-hour running-average outdoor temperature, the heating setpoint and the indoor temperature shift (the difference between indoor and outdoor temperature without any purchased heat). In ASHRAE 160, the setpoint is 18.3°C, and the temperature shift is 2.8°C. The ASHRAE 160 setpoint and floating temperature shift imply that the indoor temperature never goes below 21.1°C. This is unrealistic for New Zealand houses, which often employ very rudimentary heating schemes that vary from room to room.

In the absence of any agreed temperature and humidity profile for New Zealand, the heating setpoint was chosen to be 16°C with a temperature shift of 3°C for this analysis. Results are also shown for when the indoor humidity is allowed to exceed 70%.

The other parameters assumed for this analysis were an air change rate of 0.5 ach, a building volume of 450 $m^3$ and a moisture generation rate of $1.16 \times 10^{-4}$ kg/s, corresponding to a three-bedroom house, in ASHRAE 160.

# 4. Results

## 4.1 Photographic record of walls

Most of the walls recorded a humidity of 100% at the plane of the sheathing at some point during the experiment. However, only a limited number accumulated moisture to the point that it could be seen as droplets on the sheathing. This section shows typical images from each of the walls

### 4.1.1 Year 1

The following images are taken from the one cold snap from 2014. The period in question comprised a series of nights where the exterior temperature dropped to under 5°C, followed by a frosty morning.

#### 4.1.1.1 Walls 7 and 8

These two walls were almost identical in construction, the main features being a 10 mm XPS sheathing and an unpainted interior lining. Condensation was seen on the sheathing throughout the humidification period from 17 July to when humidification stopped on 6 August. Liquid droplets remained visible until 12 August.

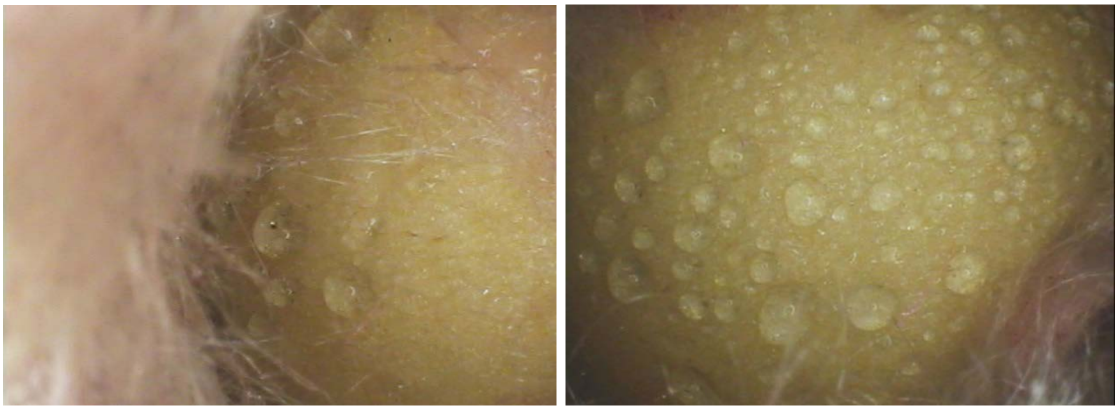


**Figure 6. Walls 7 and 8 – condensation visible for sustained periods.**

#### 4.1.1.2 Wall 20

This wall was identical in construction to Wall 8 but was on the north face of the test building. Liquid droplets were clearly identifiable on 22 July and possibly a few days afterwards. The condensation was much less widespread than on the equivalent south-facing walls.

**Figure 7. Wall 20 – condensation visible on isolated occasions (a drop is circled).**

#### 4.1.1.3 Wall 9

Wall 9 was very similar in construction to Walls 7 and 8. The only difference was the XPS sheathing used and a painted interior lining. Liquid droplets were never clearly observed in this specimen.

The photo in Figure 8 is from the same day as those from Walls 7 and 8. The sheathing always had a shimmery appearance, and while this could indicate liquid water, it was more likely to be the light from the borescope reflecting off the XPS.

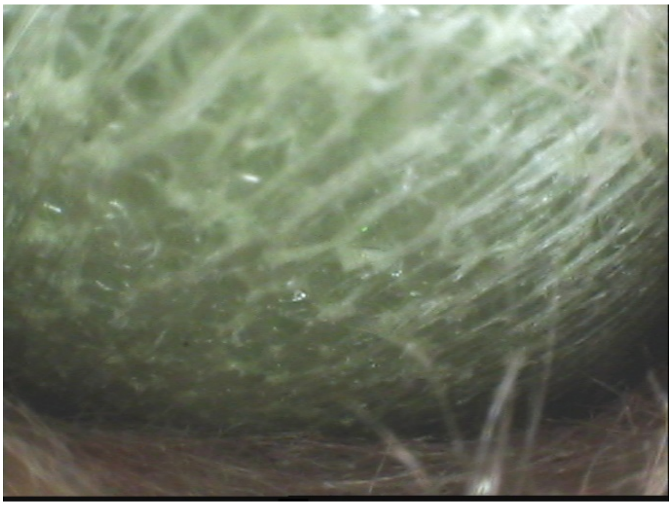


**Figure 8. Wall 9 – condensation not definitively visible.**

#### 4.1.1.4 Walls 5 and 6

These walls had the thicker 30 mm XPS installed, and no liquid water was observed

**Figure 9. Walls 5 and 6 – no condensation visible in walls with 30 mm XPS sheathing.**

### 4.1.2 Year 2 – part 1

2015 had a higher number of cold nights followed by frosty mornings than 2014. The following pictures are from a cold snap between 25 and 30 May.

#### 4.1.2.1 Wall 8

This was the worst-case wall from year 1 and, as before, liquid droplet formation was widespread over the face of the sheathing.

**Figure 10. Wall 8 – widespread condensation as in year 1.**

#### 4.1.2.2 Wall 6

This plywood-sheathed wall showed no evidence of liquid drop formation. This was unsurprising given the hygroscopic nature of the plywood. The material would have to have been near full saturation before liquid droplets would form on the surface.

**Figure 11. Wall 6 – no condensation visible on plywood.**

#### 4.1.2.3 Wall 9

Wall 9, with a flexible underlay, showed no evidence of liquid droplets during the first phase of year 2.

**Figure 12. Wall 9 – no condensation visible in part 1 of year 2.**

#### 4.1.2.4 Walls 7 and 20

These walls, with a flexible underlay and a smart vapour retarder, showed no sign of liquid water throughout the experiment. No photo is shown because it would be identical to Figure 12.

### 4.1.3 Year 2 – part 2

During this period, the R-value of the insulation was increased in Walls 6 and 9, and the interior lining of Wall 8 was painted. This was an attempt to witness liquid condensation in Walls 6 and 9 and to prevent it in Wall 8. The following pictures are from 14 July 2015, during another cold snap.

#### 4.1.3.1 Wall 6

No liquid water was seen in this wall, so the appearance of the sheathing was the same as Figure 11. A subsequent moisture content measurement using a resistance-type moisture meter suggested the water content of the plywood at that time was approximately 28%. It is feasible that, had humidification continued and the exterior conditions remained conducive, liquid droplets would have been visible once the plywood was saturated.

#### 4.1.3.2 Wall 9

Liquid droplets were visible occasionally in Wall 9, as shown in Figure 13. Note that this was with an unpainted interior lining, and it is likely that, had the lining been painted, as is usually the case in practice, these drops would not have formed under these conditions.

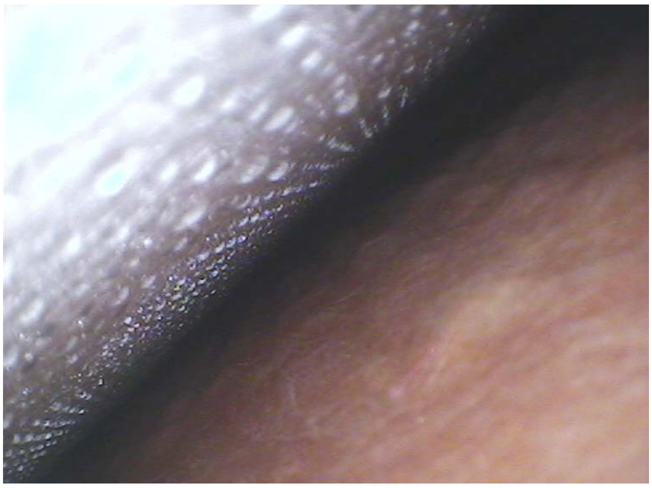


**Figure 13. Wall 9 – water visible on flexible underlay with higher level of insulation (and unpainted) lining.**

#### 4.1.3.3 Wall 8

Painting the internal lining significantly reduced the amount of liquid water observed in this wall, but water was still present here more often than in the case of Wall 9.

**Figure 14. Wall 8 – condensation still forming even with a painted interior lining.**

## 4.2 Measured conditions within the walls

This section shows the data measured in the wall specimens. Only selected results are shown due to the similarity of a number of the specimens.

### 4.2.1 Measured data – year 1

#### 4.2.1.1 Humidity at the sheathing

Figure 15 shows the 24-hour moving average humidity at the sheathing for Walls 6, 8 and 9 in year 1.

The shaded blue areas represent times when the indoor space of the test building was being humidified.

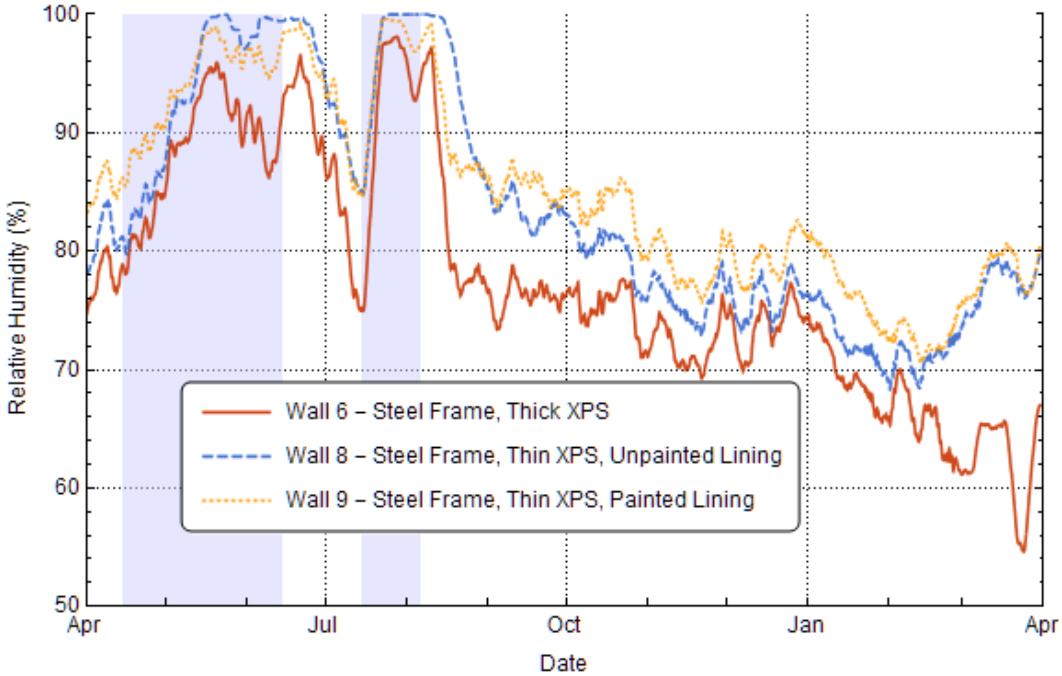



**Figure 15. 24-hour average humidity at the sheathing during year 1.**

The first humidification phase was essentially a test to see whether condensation could be seen in any of the walls at all. During the second humidification phase (which corresponded with a cold snap), the humidity at the sheathing increases rapidly in all of the walls to approximately 100%.

Figure 16 shows the hourly data during the second humidification period, showing that all of these walls reached 100% humidity for a large percentage of the humidification period.

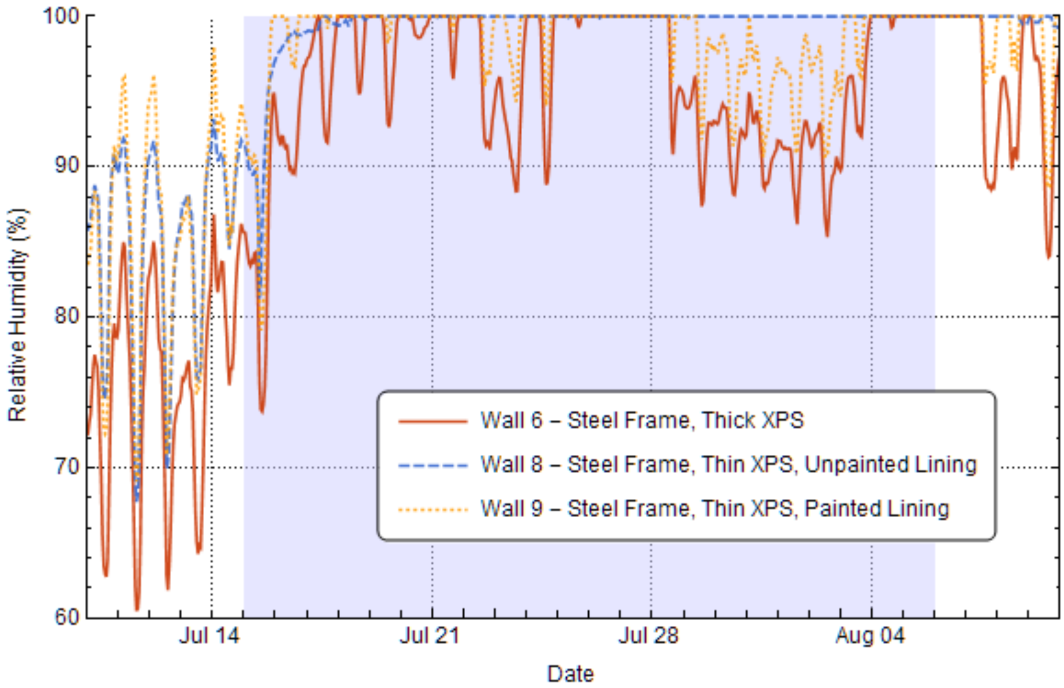



**Figure 16. Hourly humidity at the sheathing during second humidification phase of 2014.**

Figure 17 shows the difference in humidity at the sheathing between the north-facing Wall 20 and the south-facing Wall 8.

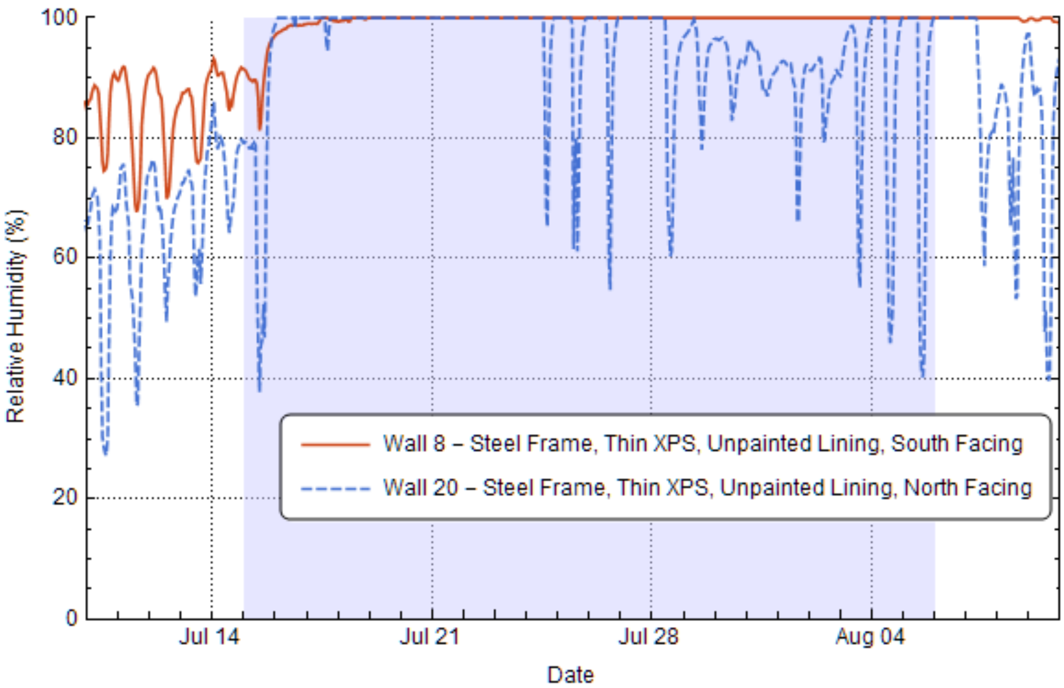



**Figure 17. Hourly humidity at the sheathing in identical north and south-facing specimens during second humidification phase of 2014.**

Again, both walls reach 100% humidity, but Wall 20, subject to more direct solar radiation, shows a clearer diurnal cycle, where the increase in temperature corresponds to a drop in relative humidity.

#### 4.2.1.2 Relative humidity in the drainage cavity

The 24-hour average relative humidity in the cavity behind the cladding is shown in Figure 18. This level of humidity was surprisingly high and as yet hasn't been adequately explained (see section 5). The relative humidity in the cavity was approximately the same in all of the south-facing walls and could be broadly approximated as a yearly sinusoid with a mean of 85% and an amplitude of 15%.

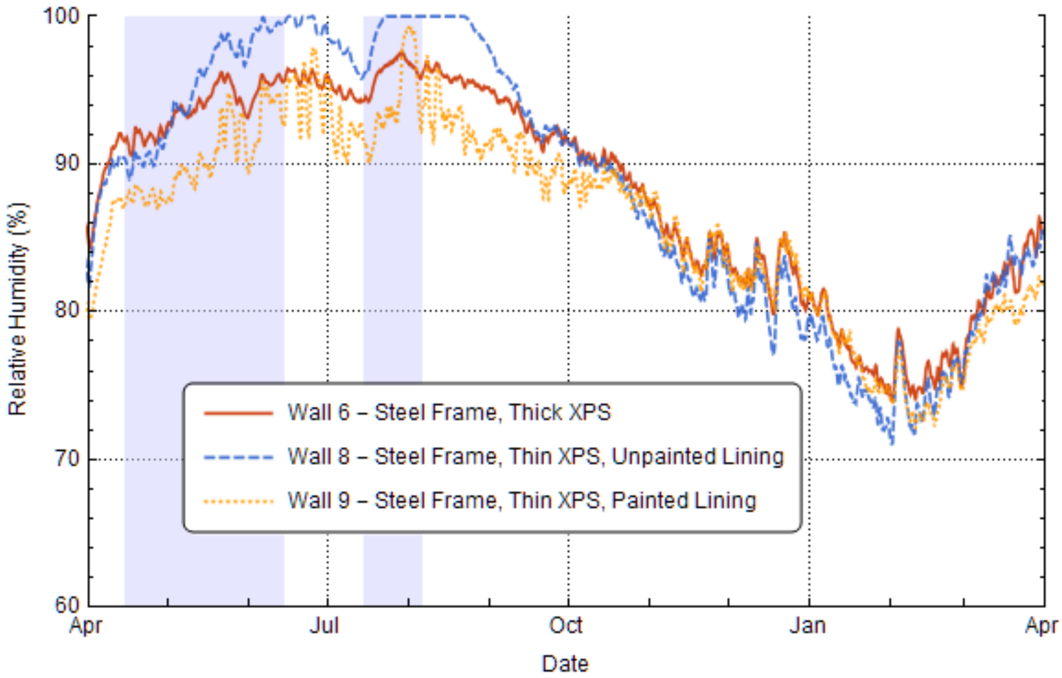



**Figure 18. 24-hour average humidity in the drainage cavity for south-facing walls.**

### 4.2.2 Measured data – year 2

#### 4.2.2.1 Relative humidity at the sheathing

Figure 19 shows the 7-day moving average humidity at the sheathing for Walls 6, 7, 8 and 9 during the first humidification period of year 2.

Wall 7, which had an SVR installed between the interior lining and the insulation, maintains a fairly constant relative humidity at about 90%, but all of the other walls had a measured humidity of 100% for significant periods of time.

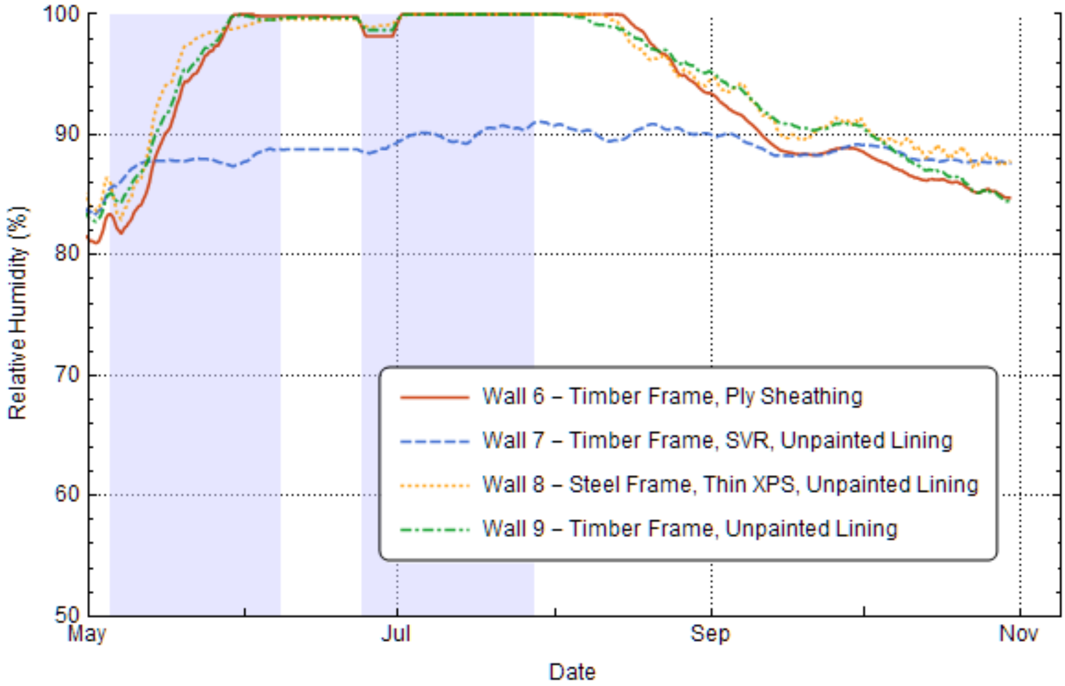



**Figure 19. 7-day average humidity at the sheathing during year 2.**

Figure 20 shows the 24-hour average relative humidity in Walls 7 and 20, which contained an SVR and were constructed to be identical, but are on opposite faces of the building.

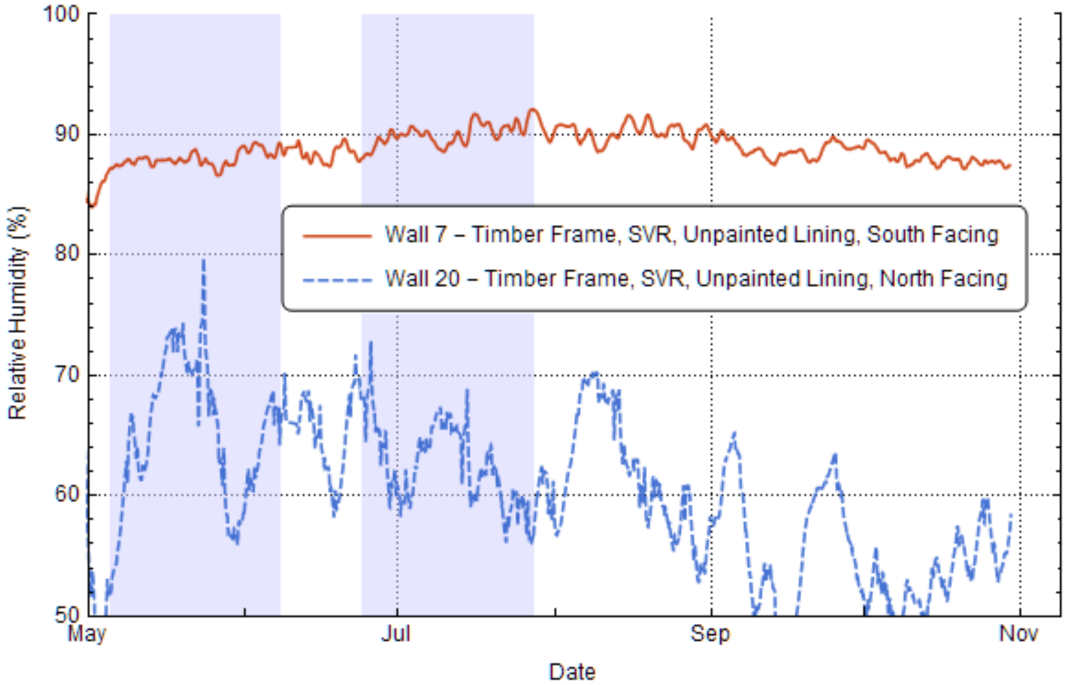



**Figure 20. 24-hour average humidity at the sheathing of Walls 7 and 20 – year 2.**

As in year 1, the north-facing wall has a lower humidity at the sheathing than an equivalent south-facing wall.

These two walls were the only ones to not experience 100% humidity at the sheathing at any time during the experiment, albeit they only had R1.8 insulation installed in them.

#### 4.2.2.2 Relative humidity in the cavity

The 7-day average relative humidity in the cavity behind the cladding is shown in Figure 21. As in year 1, this level of humidity was surprisingly high and as yet hasn't been adequately explained.

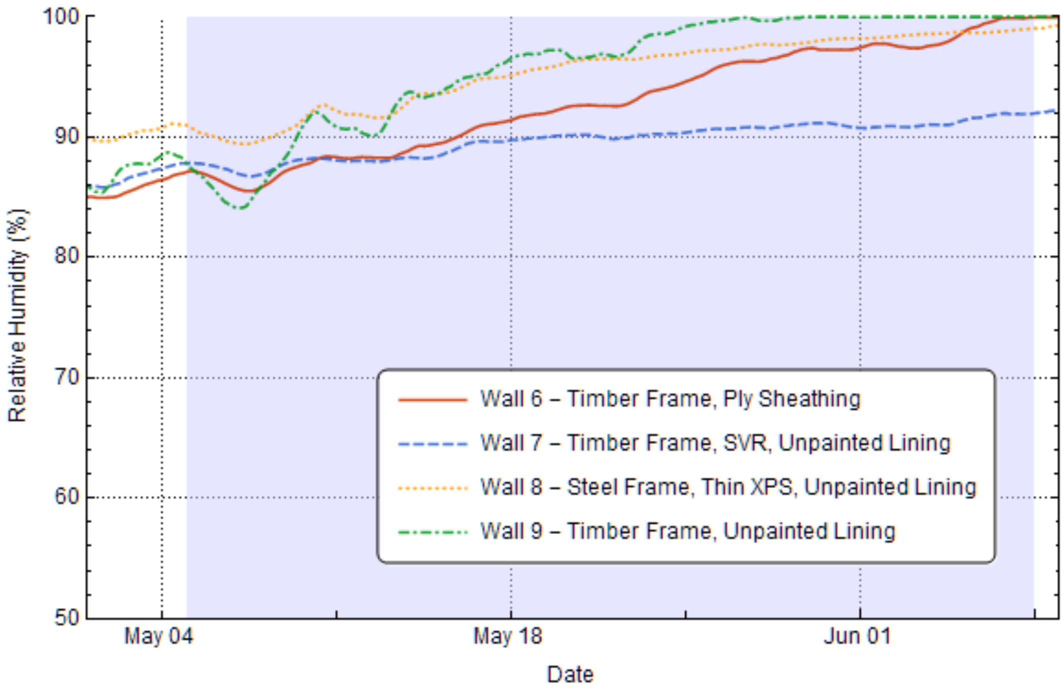



**Figure 21. 7-day average humidity in the cavity during year 2.**

Note that the humidity associated with Wall 7 (with an SVR), whilst still high, is slightly lower than the other walls.

#### 4.2.2.3 Relative humidity at the plane of the SVR

Adding a vapour control layer, such as an SVR, can potentially increase the risk of condensation occurring at that position. Figure 22 shows the 24-hour average data humidity between the SVR and the insulation.

Based on the 24-hour averaged data, the humidity is similar in both north and south-facing walls.

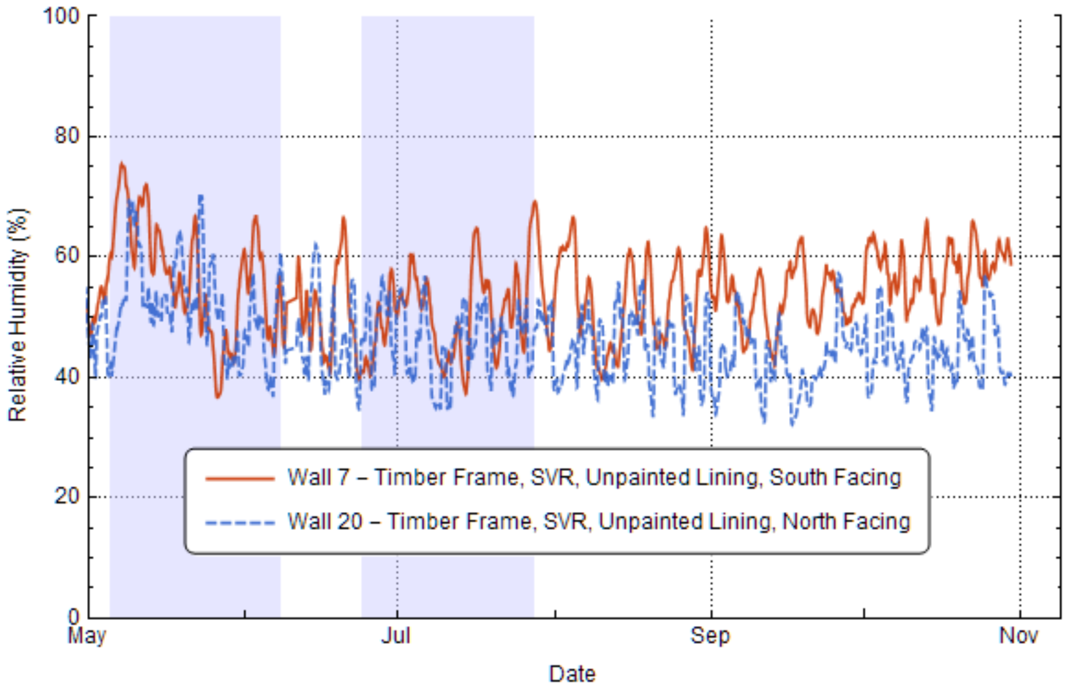



**Figure 22. 24-hour average humidity between the insulation and SVR of Walls 7 and 20 – year 2.**

Figure 23 shows the humidity at the same position for year 1 and year 2, but hourly data is shown rather than a 24-hour average. The change associated with a different wall construction in year 2 is clear. It is also evident that the humidity at the SVR itself occasionally reached 100% on the north-facing wall but only for short time periods.

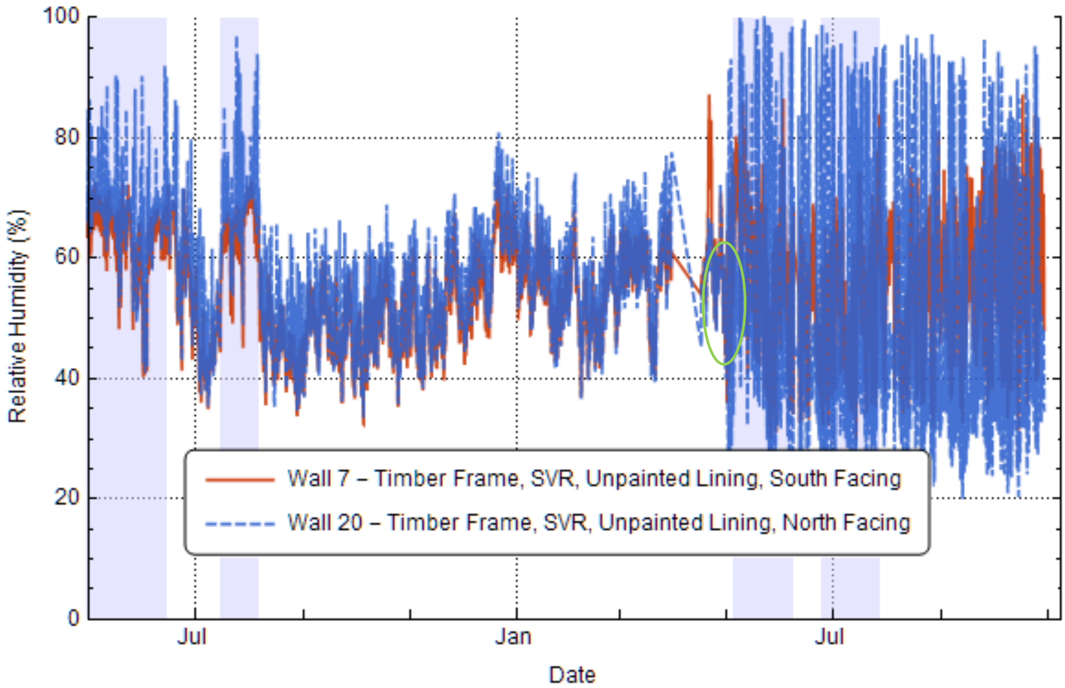



**Figure 23. Hourly humidity at the interface between the insulation and the SVR/internal lining (green circle shows when the SVR was installed).**

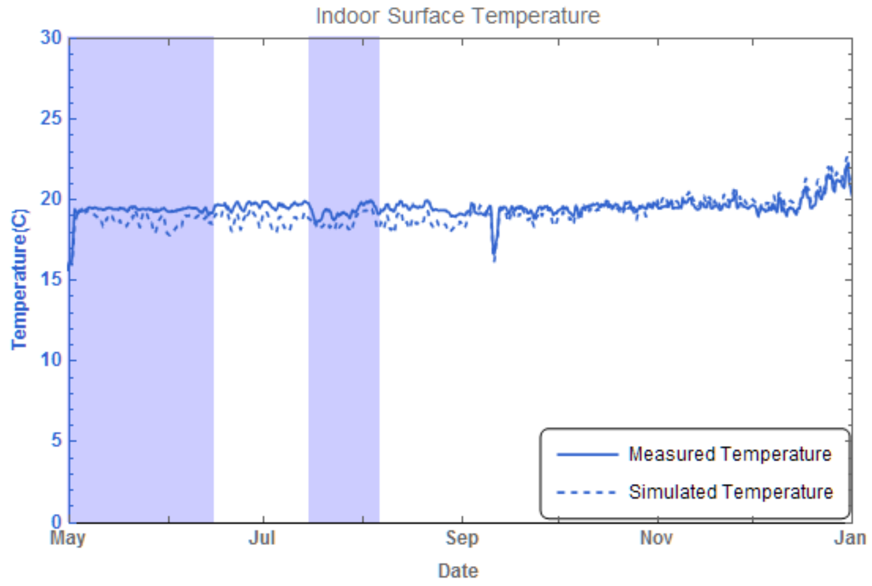
## 4.3 WUFI modelling of experimental walls

The results in this section show a comparison between the measured data and a numerical simulation of the walls using WUFI Pro V5.3. For clarity, data from only a few walls is shown, though the agreement in these cases is representative of all the walls.

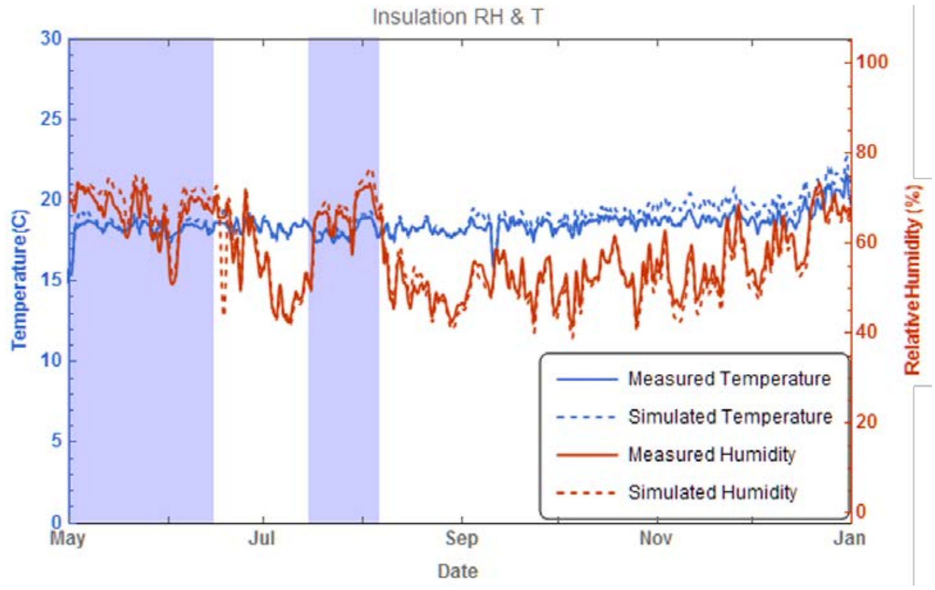
All of the results in this section relate to one-dimensional models, so the effect from any framing is not included. No ventilation or driving rain are included in these models. These aspects and the use of two-dimensional models are discussed later.

Figure 24 a) to e) shows the 24-hour averaged measured and simulated results for Wall 8 in year 1. These graphs show that the temperatures are predicted reasonably well throughout the wall. The relative humidity is significantly different at the sheathing during non-humidification periods and is significantly different in the cavity throughout the experiment

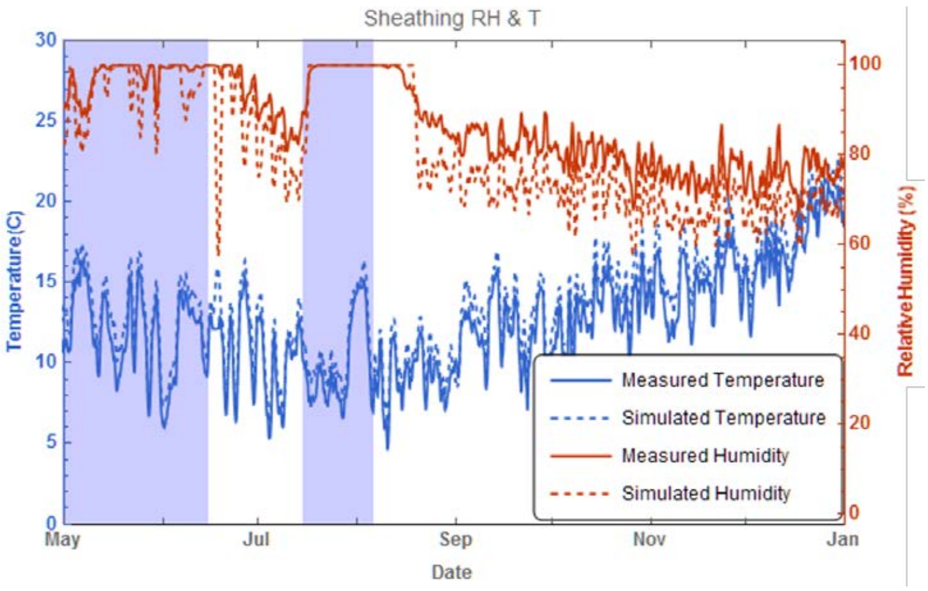
a)



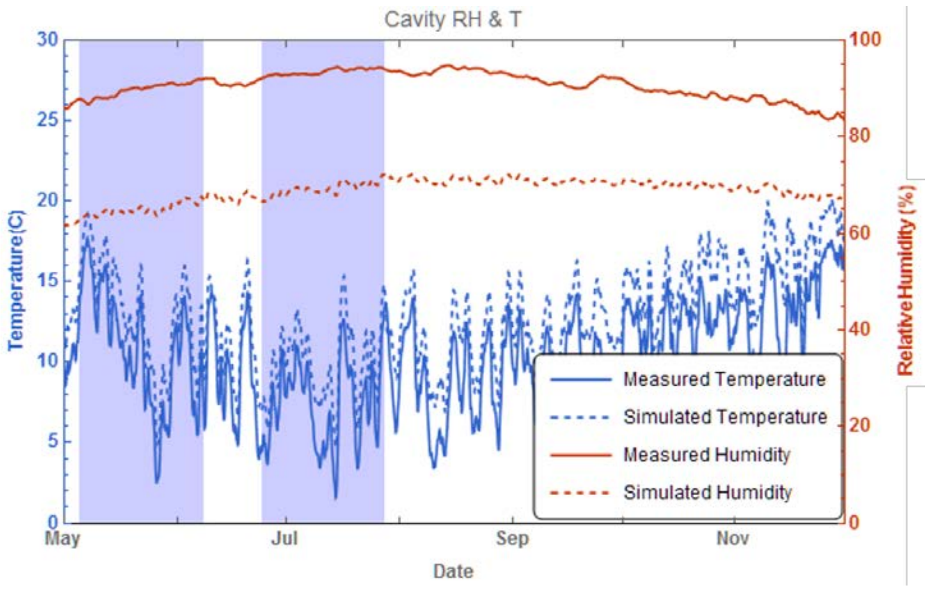

b)



c)




d)




e)

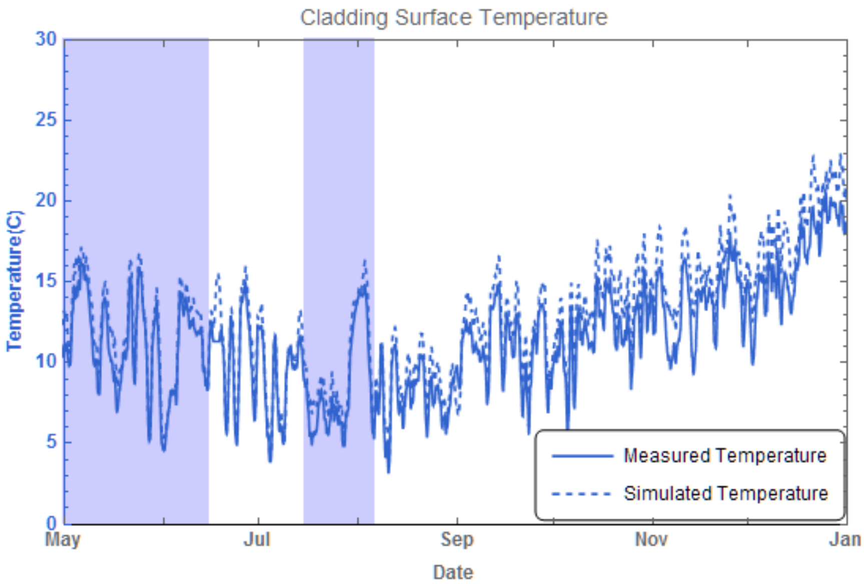
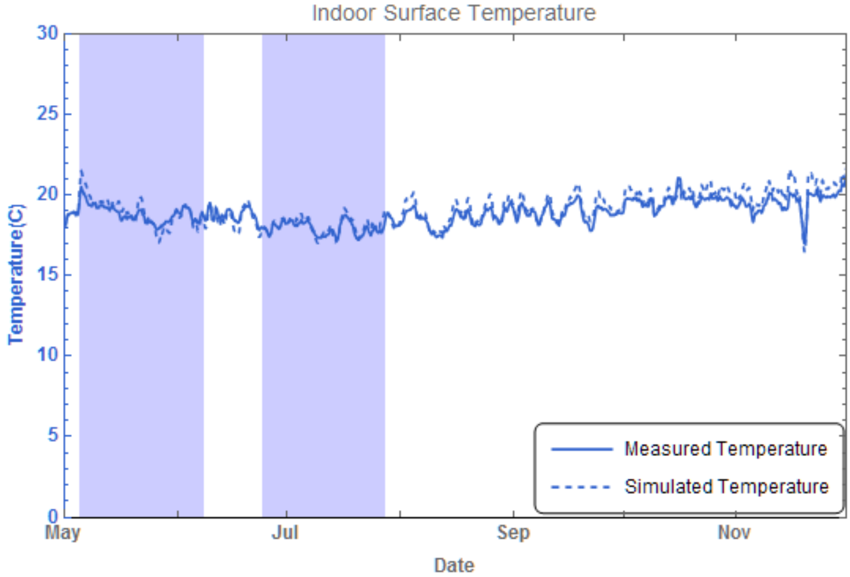


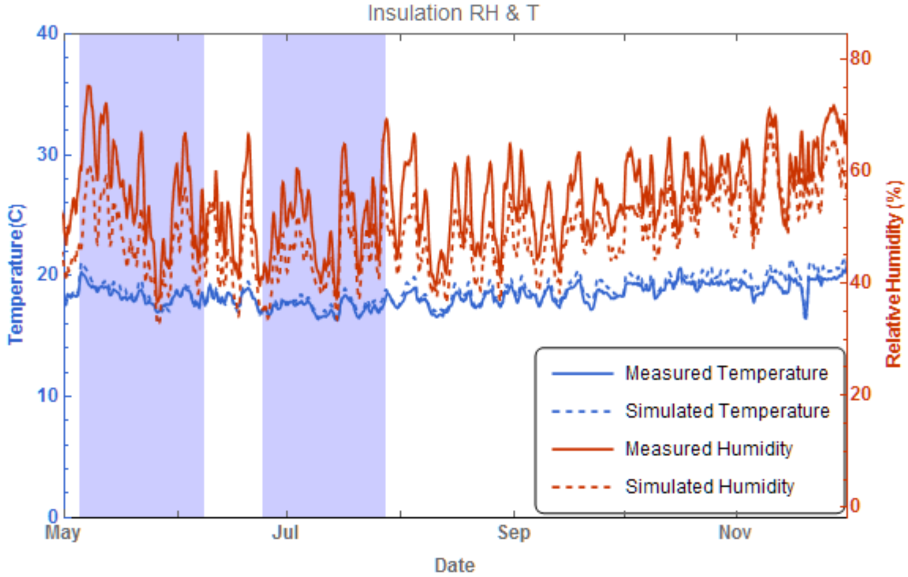

**Figure 24. Measured and simulated data for Wall 8 in year 1.**

Figure 25 a) to e) shows the measured and simulated results for Wall 7 in year 2. Again, the temperatures are predicted reasonably well throughout the wall. The relative humidity is significantly different at the sheathing and the cavity throughout the experiment.

a)




b)



c) d) e)

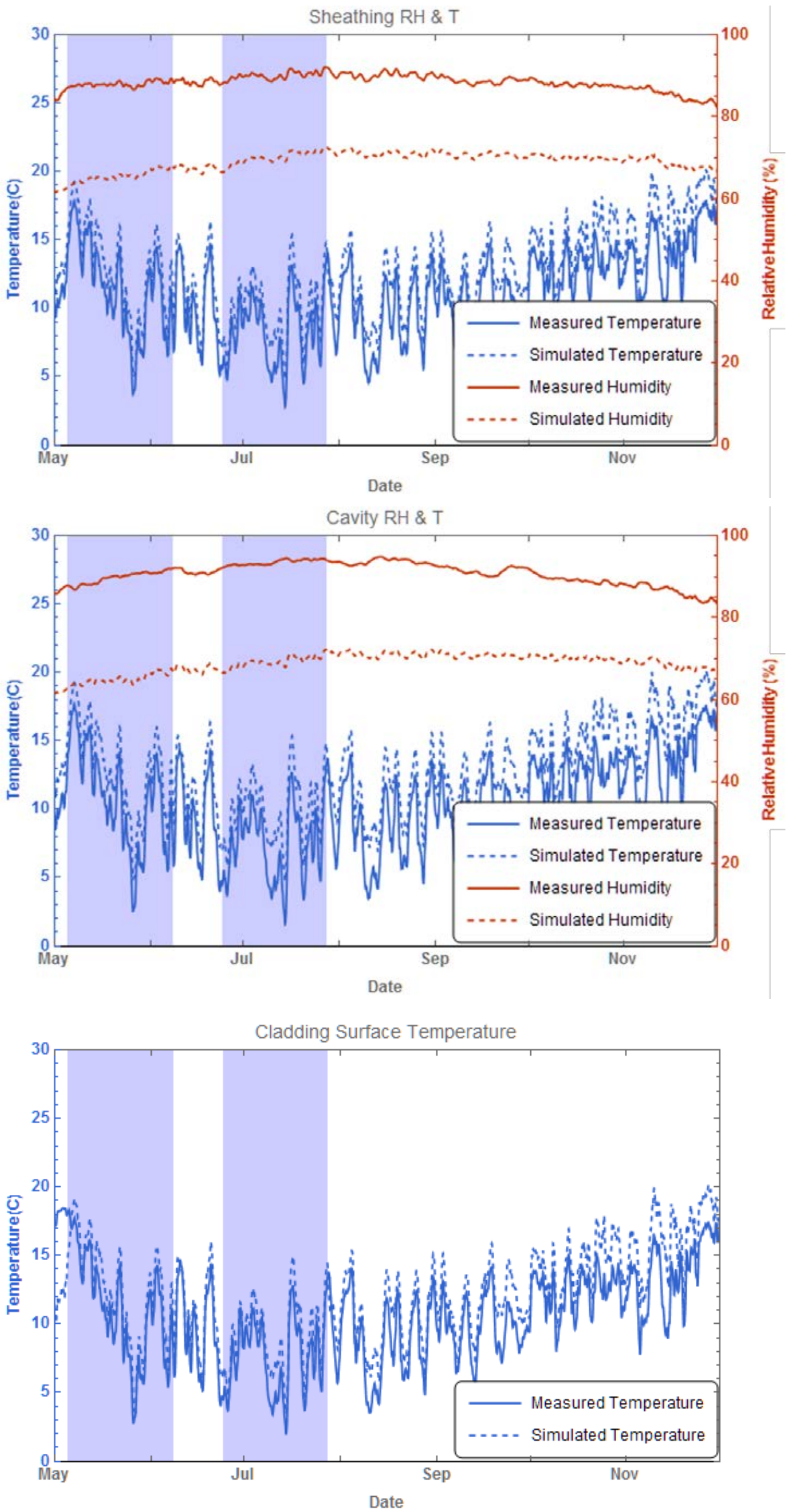



**Figure 25. Measured and simulated data for Wall 7 in year 2.**

## 4.4 WUFI models of different climates

The indoor temperature and humidity profiles described in section 3.3 were used in conjunction with the WUFI models used to simulate the experimental walls. The following results relate to wall constructions similar to those tested in the experiment. A wall with 50 mm XPS sheathing is included, but this type of wall was not part of the experimental set-up.

The following figures show predicted performance for a range of south-facing walls in Queenstown, Auckland and New Plymouth when subjected to the HERS exterior climate in conjunction with the ASHRAE indoor climate with a heating setpoint of 16°C. The results from New Plymouth are presented because it has the highest condensation risk according the criteria used here.

For each location the following figures are presented.

- The humidity at the underlay/sheathing compared with ASHRAE 160 failure criteria (indoor humidity limited to 70%).
- The humidity at the underlay/sheathing compared with ASHRAE 160 failure criteria (indoor humidity allowed to exceed 70%).
- The amount of moisture above free saturation of the outer 5 mm of the insulation with:
  - indoor humidity limited to 70%
  - indoor humidity allowed to exceed 70%.
- The moisture content of plywood sheathing with R1.8 and R2.8 insulation and with:
  - indoor humidity limited to 70%
  - indoor humidity allowed to exceed 70%.

Figure 26 to Figure 29 show a selection of results for Queenstown. Figure 26 and Figure 27 show how the humidity at the plane of the underlay/sheathing compares with the respective ASHRAE criteria (the red line in each graph). Figure 26 shows the cases when the interior humidity is limited to 70%, and Figure 27 shows the results when it is allowed to exceed 70%.

Figure 28a and 28b show the moisture content above free saturation in the outer 5 mm of the cavity insulation. (This is an approximation of the amount of liquid condensate at any time.)

Figure 29a and 29b show the difference in the moisture content of plywood sheathing when R1.8 or R2.8 insulation is installed.

Figure 30 to Figure 33 shows similar information for Auckland, and Figure 34 to Figure 37 shows results for New Plymouth.

## Queenstown

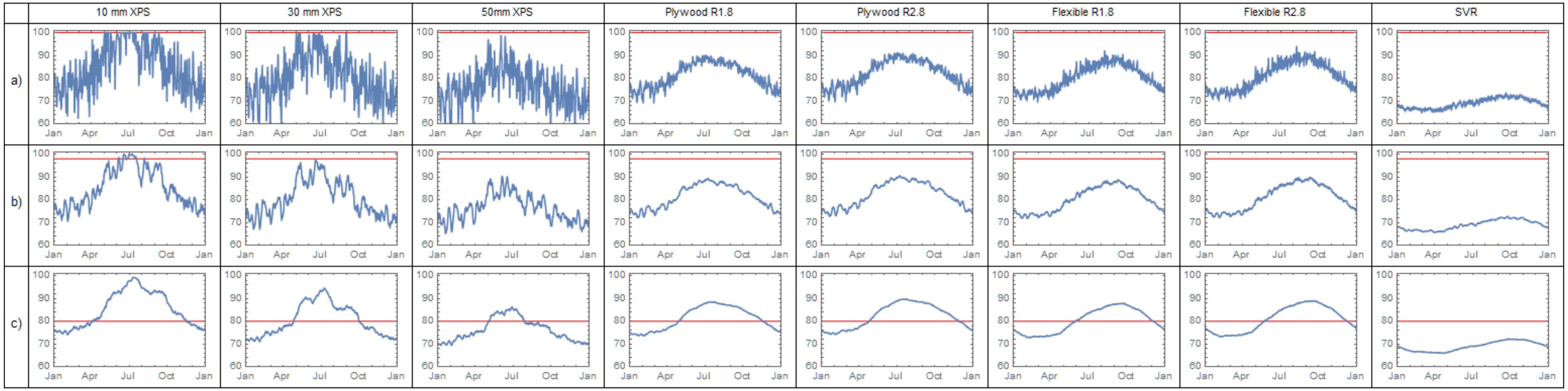



**Figure 26. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity cannot exceed 70%.**

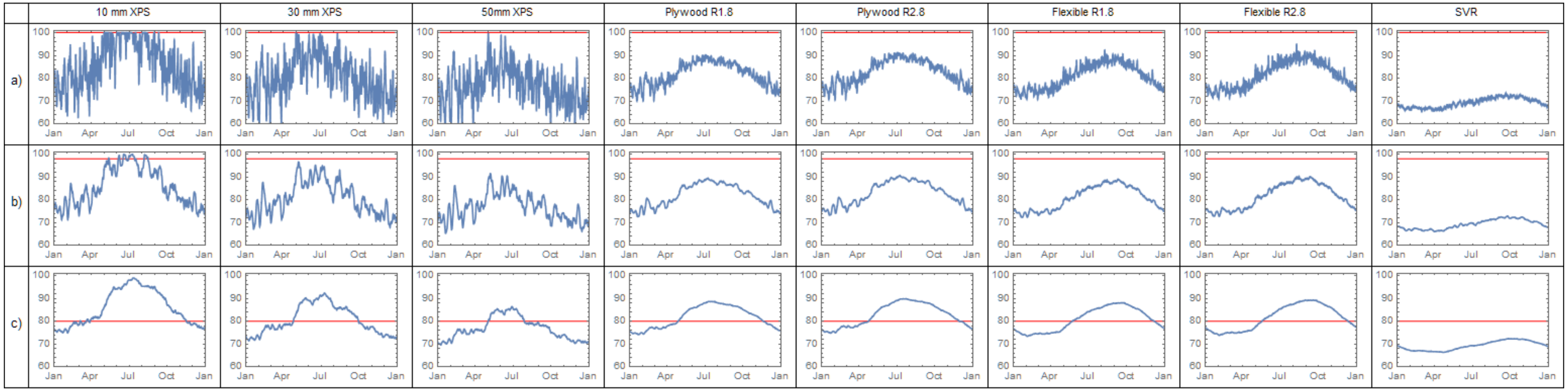



**Figure 27. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity can exceed 70%.**

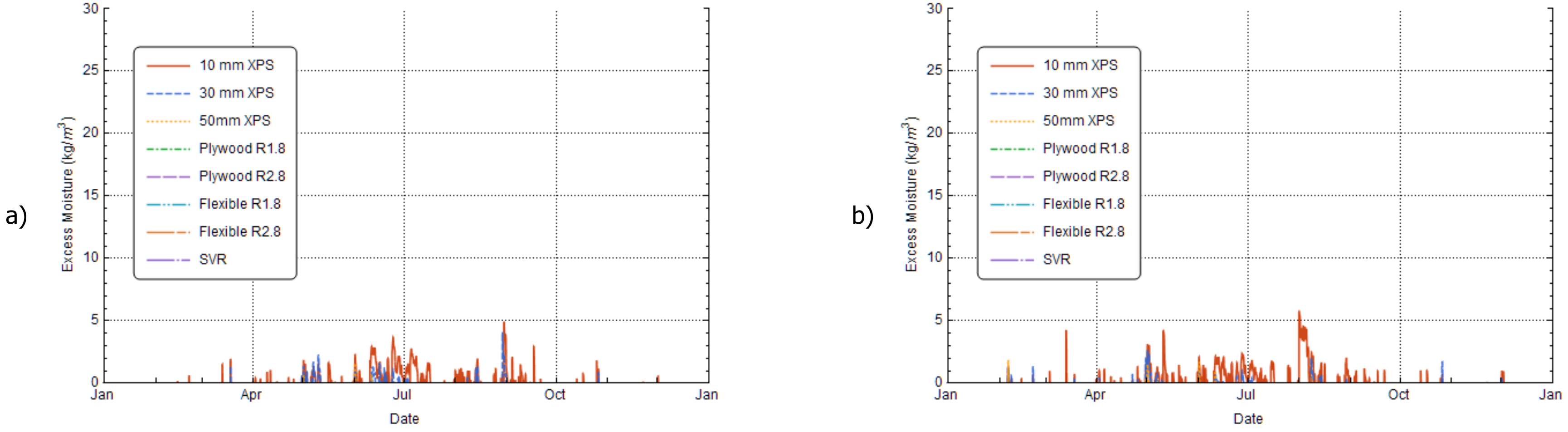



**Figure 28. Excess moisture in outer 5 mm of cavity insulation – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

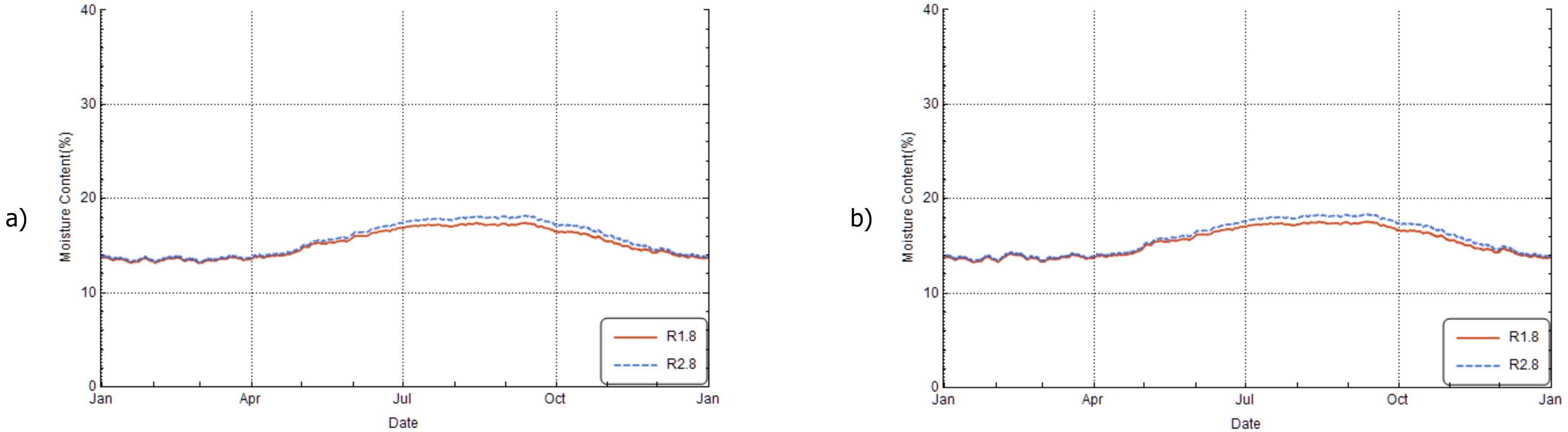



**Figure 29. Moisture content of plywood sheathing – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

## Auckland

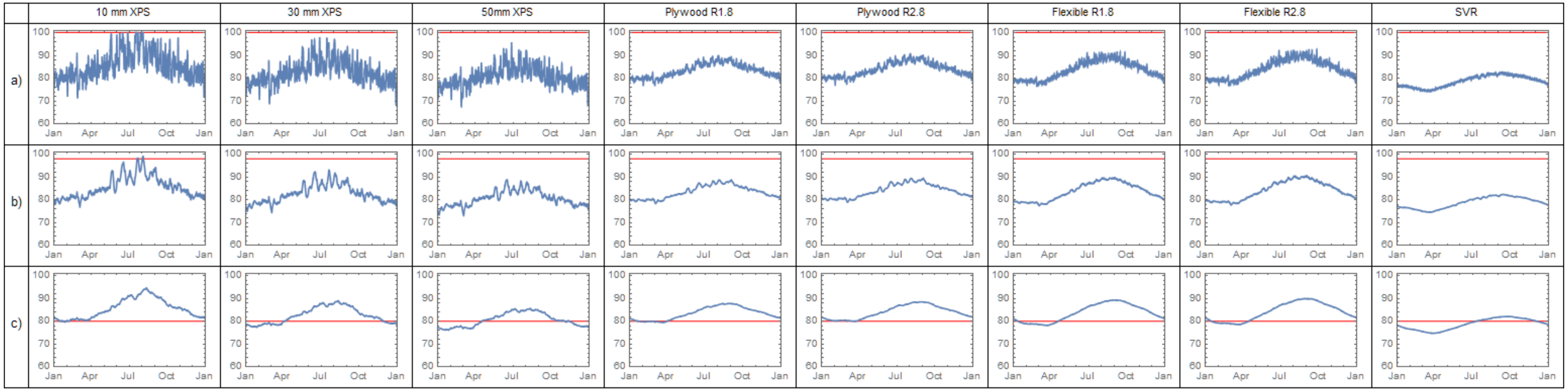



**Figure 30. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity cannot exceed 70%.**

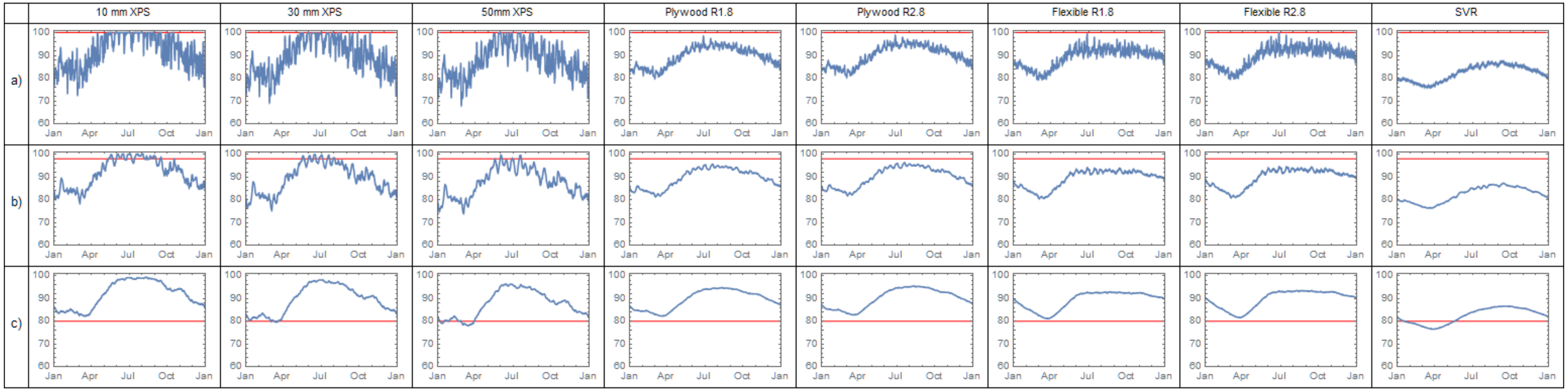



**Figure 31. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity can exceed 70%.**

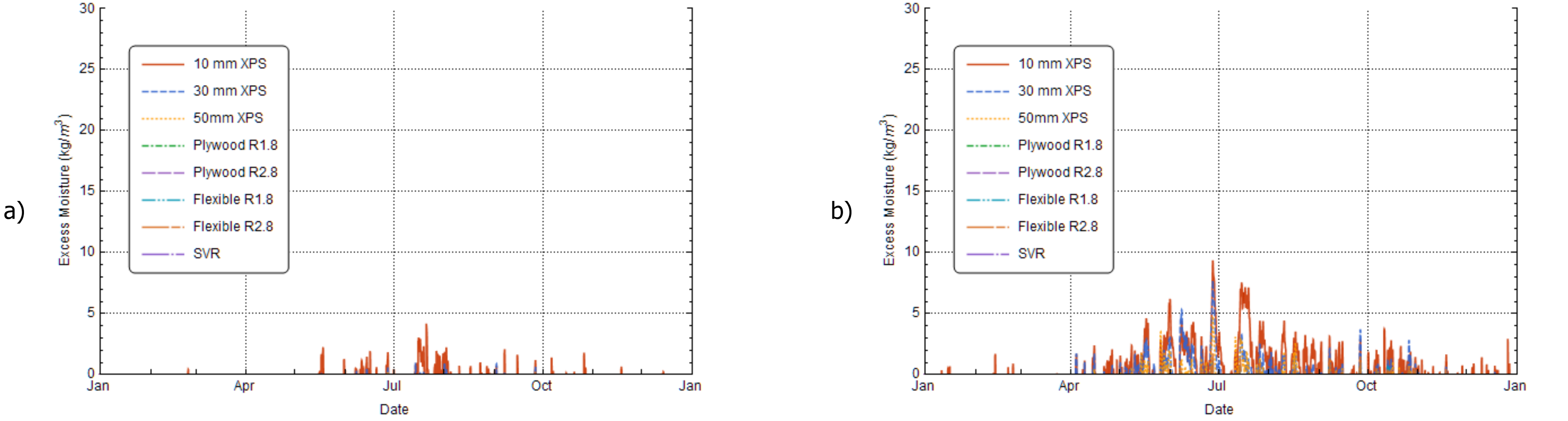



**Figure 32. Excess moisture in outer 5 mm of cavity insulation – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

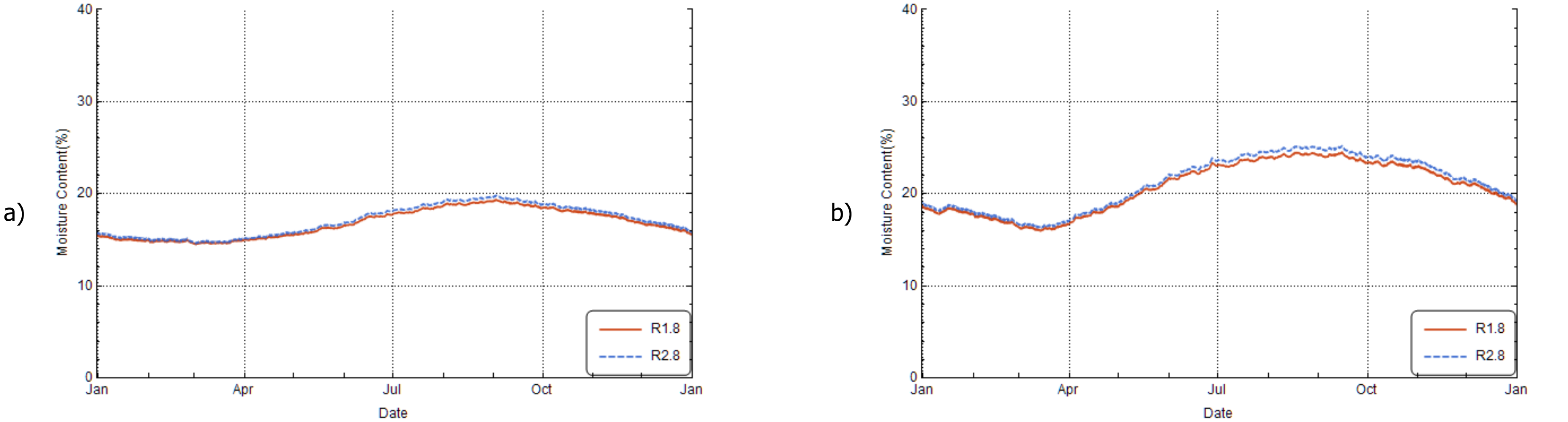



**Figure 33. Moisture content of plywood sheathing – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

## New Plymouth

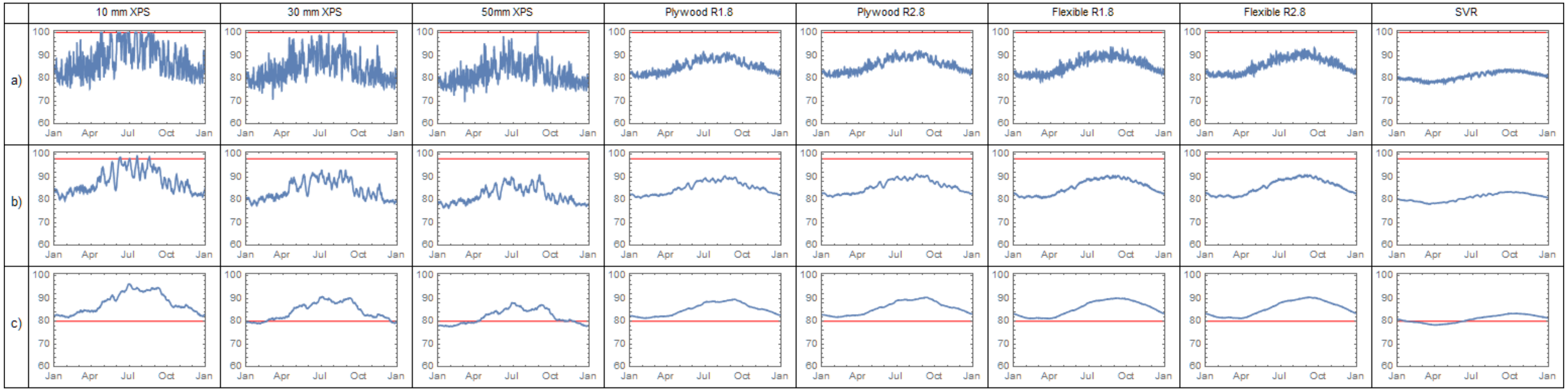
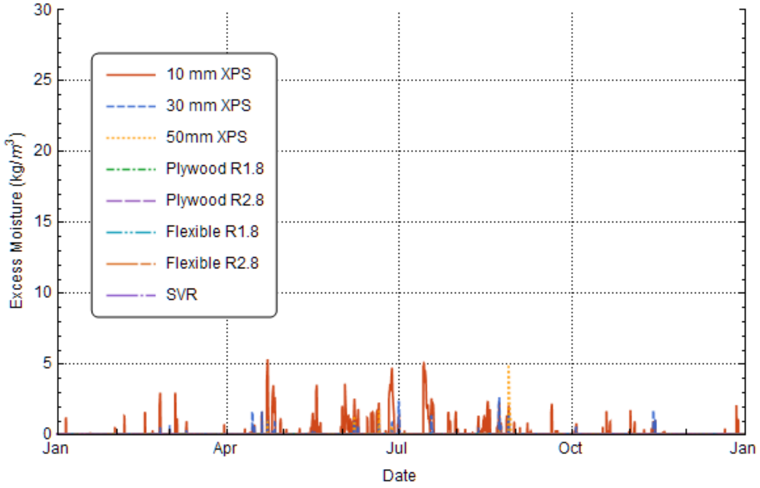



**Figure 34. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity cannot exceed 70%.**


**Figure 35. Humidity at the sheathing/underlay compared with ASHRAE 160P criteria – a) 24-hour average, b) 7-day average, c) 30-day average. Indoor relative humidity can exceed 70%.**

a)




b)

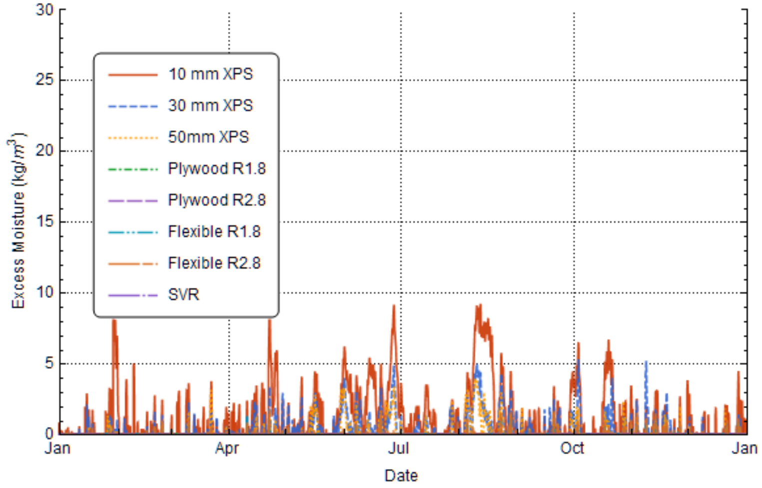
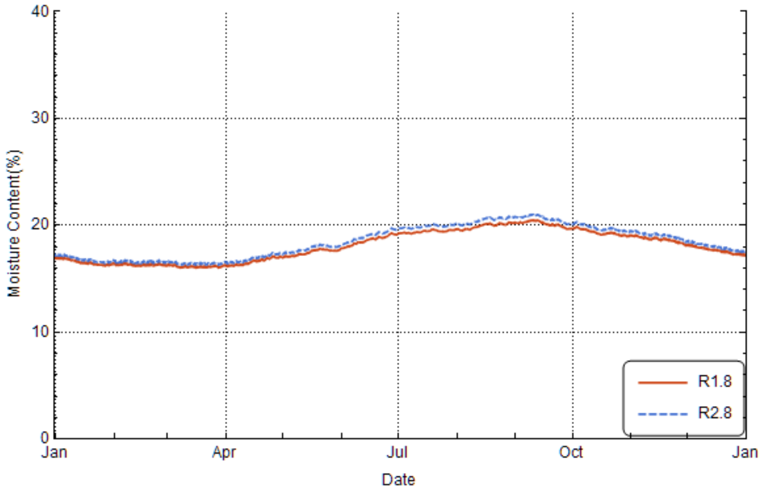



**Figure 36. Excess moisture in outer 5 mm of cavity insulation – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

a)




b)

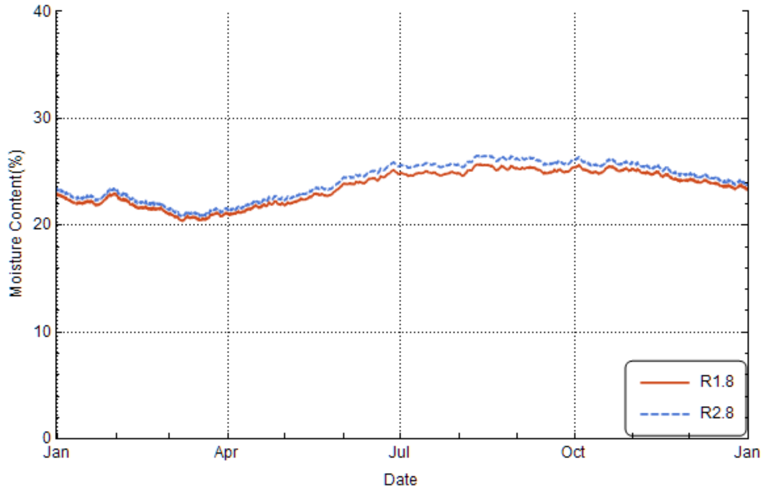



**Figure 37. Moisture content of plywood sheathing – a) indoor RH limited to 70%, b) indoor RH allowed above 70%.**

# 5. Discussion

## 5.1 General agreement of models with measured data

Agreement between the experimental data and the WUFI simulation is not as good as it was hoped to be prior to the experiment. The reason for this appears to be related to the moisture levels in the cavities of the walls, with the measured relative humidity in each cavity being higher than expected. To illustrate this further, Figure 38 shows the 24-hour averaged vapour pressure calculated from the measured temperatures and humidities for the indoors, outdoors and cavity from year 1 in Wall 8.

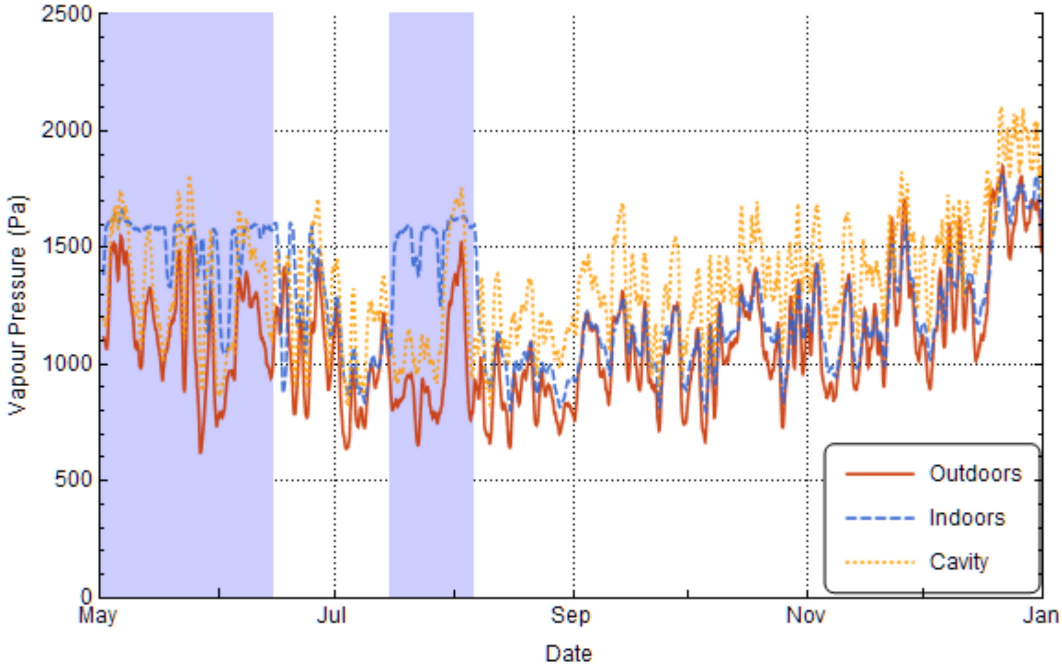
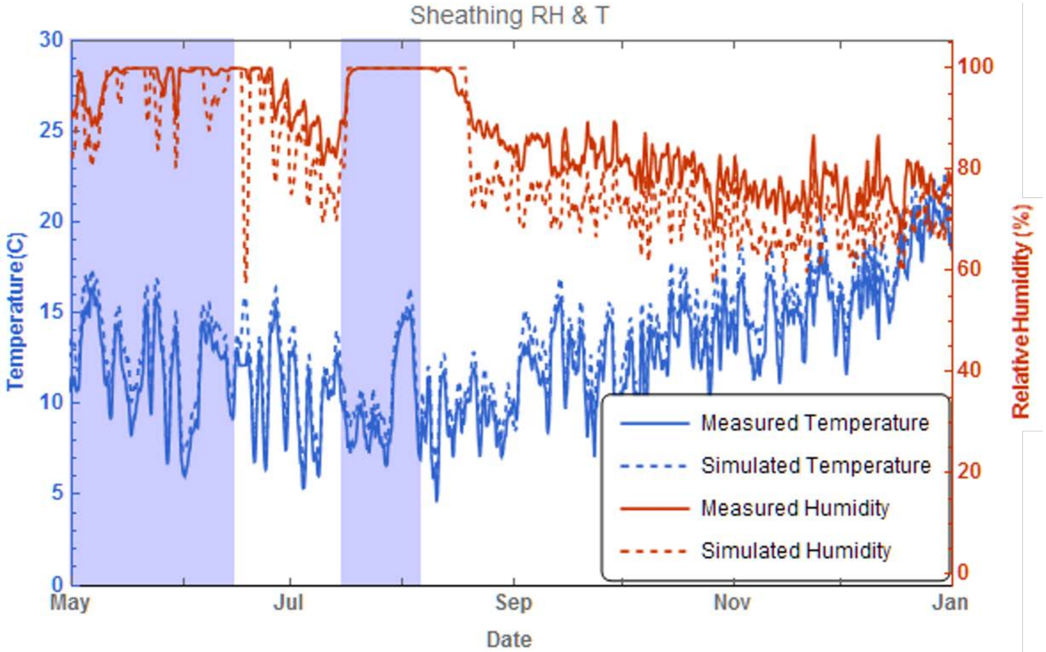



**Figure 38. Vapour pressure from temperature and humidity measurements in Wall 8.**

During the humidification period (the shaded region), the indoor vapour pressure is higher than the outdoor vapour pressure due to humidification. Once humidification is finished, the indoor and outdoor vapour pressures are approximately equal, as expected. However, particularly after the humidification period, the vapour pressure in the cavity is higher than both indoors and outdoors, suggesting moisture is somehow being added to the space. This moisture source has still not be satisfactorily explained. Rain penetration through the field of the cladding was a possible explanation, and WUFI was used to add a fraction of driving rain to the inside of the cladding. Whilst this understandably increased the humidity in the cavity, it did not explain the results completely. If the fraction of rain was chosen to approximately match the humidity in the cavity of the south-facing walls, it would lead to humidities in the north-facing walls that were significantly higher than were actually measured. It was also suggested that the cladding had degraded over time and hygroscopically absorbed more moisture than expected, but subsequent measured moisture contents suggested the moisture level was in line with new unused cladding. Another potential moisture buffer in the walls were the timber battens forming the cavity. WUFI 2D and an in-house nodal model were used to simulate the presence of this buffer but again did not satisfactorily explain the higher moisture level in the cavity. Another theory was that the humidity probes had drifted since their calibration, but an in-situ comparison with a reference gauge suggested this was not the case. Alternatively, the source could be internal moisture. Figure 21 shows the cavity humidity was lower (but still higher than predicted) when an SVR was used, which would restrict the flow of water vapour through the wall. Regardless of what was causing the higher moisture levels in the cavity, if the measured cavity conditions are applied to the WUFI models, the agreement between simulation and measured data is significantly improved.

Figure 39 shows a comparison for Wall 8 during year 1 for the conditions at the sheathing. In case b) of Figure 39, the cladding and cavity have been removed from the model and the measured cavity conditions have been applied as the external climate. The good agreement shown in case b) of Figure 39 suggests that, in general, the parameters used in the WUFI models are sufficiently representative.

a)




b)

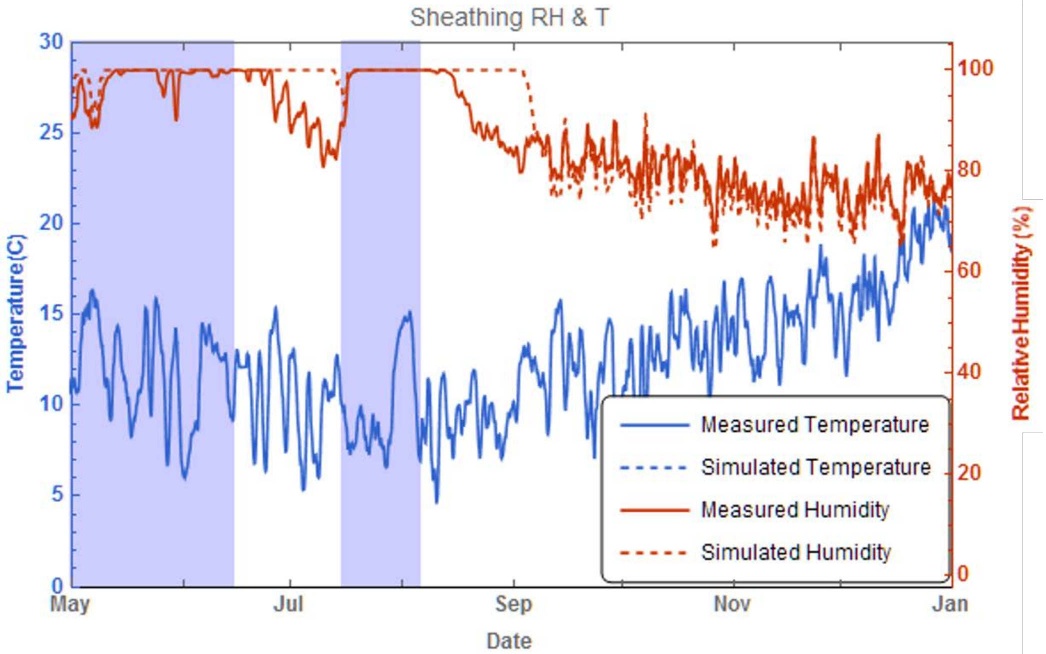



**Figure 39. 24-hour averaged measured and simulated data from Wall 8 in year 1 with a) uncorrected and b) corrected cavity conditions.**

Given that we have not been able to satisfactorily explain the moisture levels in the cavity, this will be explored further in future work. This difference between experiment and simulation should not be forgotten when considering the following analyses.

In addition, based on BRANZ's previous experience, ventilation was expected to deal with any moisture in the cavity. The fact that the humidity was relatively high could mean that the infiltration paths that permit significant ventilation to occur may not have been present in the test walls. This was not intentional during construction, but if infiltration was removed, the cavity would have been ventilated only by the bottom vent. The WUFI models used in the analysis did not include cavity ventilation, so this cannot explain the difference between measurement and simulation. Air exchange in the cavity would typically act to remove moisture. If cavity ventilation is included in the models, it would actually increase the disagreement between simulated and measured data. It should be noted, however, that including a representative amount of cavity ventilation in the models does not significantly alter results shown in section 4.4. The vast majority of walls fail to meet the ASHRAE 160 criteria.

It would be useful to assess whether infiltration paths are being reduced in 'real' buildings since, without them, it may well be necessary to add dedicated top vents to maintain drying capacity.

## 5.2 Airflows in walls

One of the hypotheses prior to the experiment in this study was that the WUFI models would overpredict the condensation risk and that airflow mechanisms would have to be included to bring the simulations into alignment with the experimental results. In particular, it was thought it would be necessary to include those airflows that occur in the insulated space of the wall.

Little progress was made in this endeavour because of difficulties experienced in measuring the airflow resistances of the different flow paths in the wall. In addition, the airflow effects may have been masked by the cavity moisture level. In previous work at BRANZ, tracer gas measurements were used to quantify ventilation rates, and these were found to agree well with a numerical model based on airflow resistances and the wind and stack pressures driving the flow. In this study, it was decided to forgo the tracer gas studies and just use the models based on the airflow resistances. However, when the measurements were performed, it was difficult to isolate the individual flow paths, principally because the insulation had a significant flow resistance itself. This also meant that opening the port in the internal lining would have had little effect on the overall airflow going through the wall. These aspects, combined with the fact that there was only one real cold snap in year 1 and hence only one wetting/drying cycle, meant that airflow effects have not been investigated properly.

As discussed in the introduction, real walls have a number of potential airflow paths. Research also suggests that our homes are being built more airtight than previously, and so the magnitude of these flows is likely to decrease, bringing them closer to the experimental walls in this study. In-service wall ventilation levels would be extremely valuable in determining the importance of airflows on the moisture management capability of New Zealand walls.

## 5.3 2D models

The WUFI models that were used for the analysis are one dimensional. A two-dimensional model would be more representative, because the framing can be included. A limited amount of two-dimensional modelling was performed in this project. For the areas of interest, particularly the humidity at the plane of the underlay and sheathing, there appeared to be little difference between the one-dimensional and two-dimensional simulations. Figure 40 shows the humidity at the underlay for a timber-framed wall with a flexible underlay. Figure 41 shows the humidity at the sheathing for a steel-framed wall with a 10 mm XPS sheathing. In both cases, the interior and exterior conditions correspond to the BRANZ test building. Note the lower humidity at the steel framing because of the increased heat flow through the steel.

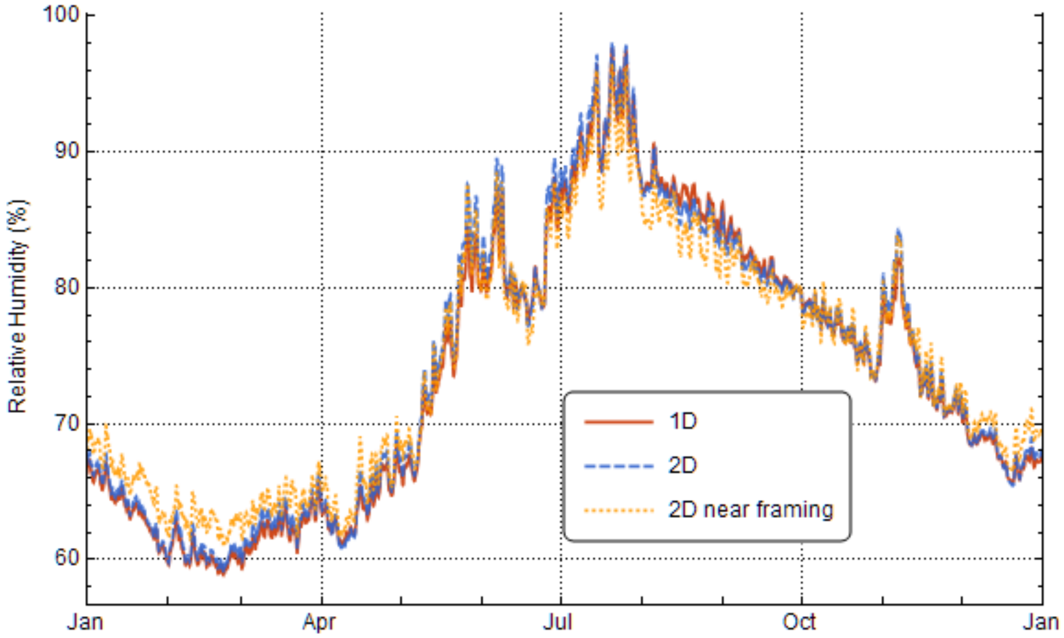



**Figure 40. Simulated humidity at the underlay for a timber-framed wall.**

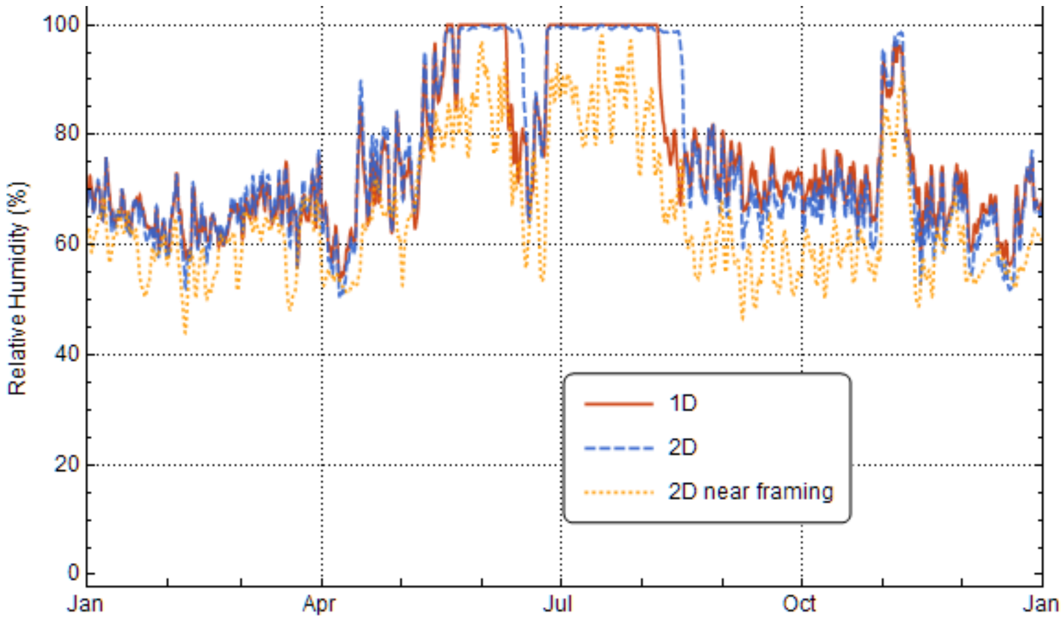



**Figure 41. Simulated humidity at the sheathing for a steel-framed wall.**

## 5.4 Using the WUFI models to explore different climates

With the caveat that the cavity moisture levels measured in this experiment were higher than those simulated in WUFI, the WUFI models can be used to investigate the behaviour of the walls under different climatic conditions. However, two difficulties arise straight away:

- What is a typical indoor climate for New Zealand homes?
- What is a suitable failure criteria for assessing condensation?

The indoor climate is discussed in section 2.3, but this remains a key assumption in an analysis. A current BRANZ project is aiming to understand the New Zealand indoor climate in more detail, and the results of that study could be used to refine the analysis here.

Failure criteria are also an important consideration. Various standards, such as BS 5250:2011 *Code of practice for control of condensation in buildings* in conjunction with BS EN 1SO 13788:2012 *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods*, look for a situation where there is no net accumulation of condensation over a year. In New Zealand, it has been suggested that condensation probably does occur occasionally in walls but that it is only transient and probably evaporates within a few hours, and this is why we haven't seen large numbers of cases where this has caused damage. This accumulation criteria relates to liquid moisture, but high humidity within structures can support mould growth and corrosion/decay without condensation occurring. For this reason, ASHRAE 160 has a series of failure criteria relating to different averaging periods for the relative humidity on any surface, specifically that:

- 24-hour average should not reach 100%
- 7-day average should not exceed 98%
- 30-day average should not exceed 80%.

The third criterion is specifically aimed at preventing mould growth and corrosion. It is stated in ASHRAE 160 that mould-resistant materials may be able to resist higher surface relative humidities and that other criteria as specified by the manufacturer may be used.

In the results shown in section 4.3, the ASHRAE criteria have been plotted against the humidity at the sheathing/underlay. In addition, the excess moisture (condensation) in the outer 5 mm of fibreglass insulation is shown, and the moisture content of plywood sheathing is shown.

### 5.4.1 Key results from analysis

The following points from the analysis can be made, but it must be remembered that they are underpinned by assumptions about the indoor climate and do not include the fact that the cavity moisture levels in the BRANZ experiment were significantly higher than was expected and modelled.

### Otago is not the worst location for condensation

It is often perceived that Central Otago represents the area of New Zealand where condensation is most likely to accumulate in walls. According to this analysis, that is not necessarily the case. Based on the climate data used, New Plymouth turns out to be the location where moisture accumulation in the insulation is highest and moisture content of plywood sheathing is the highest and also the location where the ASHRAE criteria are hardest to meet. Note, however, that the climate files are based on particular weatherstations, and if the local climate is different to that at the weatherstation, the result would, of course, also be different. In the earlier study behind Bulletin 439, Palmerston North was the worst location, so perhaps this result is not that surprising. Overall, there is not a vast difference in the results for any of the New Zealand locations analysed, and this is broadly in line with the climate analysis mentioned in section 1.

### Ongoing accumulation of condensation is not predicted

In all locations, there are occasions when condensation would occur at the sheathing in a few of the wall specimens. This is shown by the fact the excess moisture in the outer 5 mm of cavity insulation is sometimes greater than 0. The highest amounts of excess moisture are in the 10 mm and 30 mm XPS walls, but none of the walls show this moisture accumulating over the year. This result is in line with the fact there has been little evidence of condensation accumulating in New Zealand walls to date.

Of all the walls examined in this analysis, the 10 mm XPS walls were the only ones to fail all of the ASHRAE criteria under all climate assumptions. It is still unlikely that moisture will accumulate in such walls in the long term, but a more sensible option may be to use a minimum thickness of 30 mm when using XPS sheathing. This wall still fails the ASHRAE criteria, but its performance is more in line with 'traditional' walls employing a flexible underlay and would be also be in line with the requirements in the International Residential Code, discussed in section 1.

### Plywood sheathing moisture contents may be elevated in practice

In general, it is desirable to keep timber moisture content levels below 20%. In this analysis, the moisture content of the plywood sheathing exceeded 20% in both New Plymouth and Auckland, especially when the indoor humidity was permitted to go above 70%.

### Moderate R-value increase unlikely to cause further issues

The results of this analysis show that the difference between a wall with R1.8 insulation and a wall with R2.8 insulation, in conjunction with a plywood or flexible underlay, is very small. Moisture is not predicted to accumulate in either case, and the humidity at the sheathing/underlay is only marginally higher in the R2.8 case. Section 5.2 briefly looks at 140 mm framing as well.

### The humidity in New Zealand walls typically exceeds ASHRAE criteria and is at risk of supporting mould growth

Going by the ASHRAE failure criteria, in particular, the 30-day average criterion, very few of the wall constructions in this analysis would be deemed acceptable. In Queenstown, only a wall with an SVR leads to a humidity under all of the ASHRAE limits (Figures 26 and 27). In Auckland and New Plymouth, even the SVR wall fails. In the case where the indoor humidity is allowed to exceed 70%, none of the walls in

New Plymouth fall under the 80% criteria at any point during the year (Figure 36). Figure 1 shows a previous analysis for Palmerston North, and it is clear that wall also fails the ASHRAE criteria, with the humidity only dropping below 80% for a small portion of the year.

The simulation made some assumptions about heating in New Zealand indoor climates, but even the indoor climate can only help to a certain degree here. Figure 42 shows the 10 mm XPS and SVR walls from the New Plymouth analysis and adds the case when the indoor climate is set to the ASHRAE default design value (21.1°C heating setpoint). Both walls still fail to meet all the criteria.

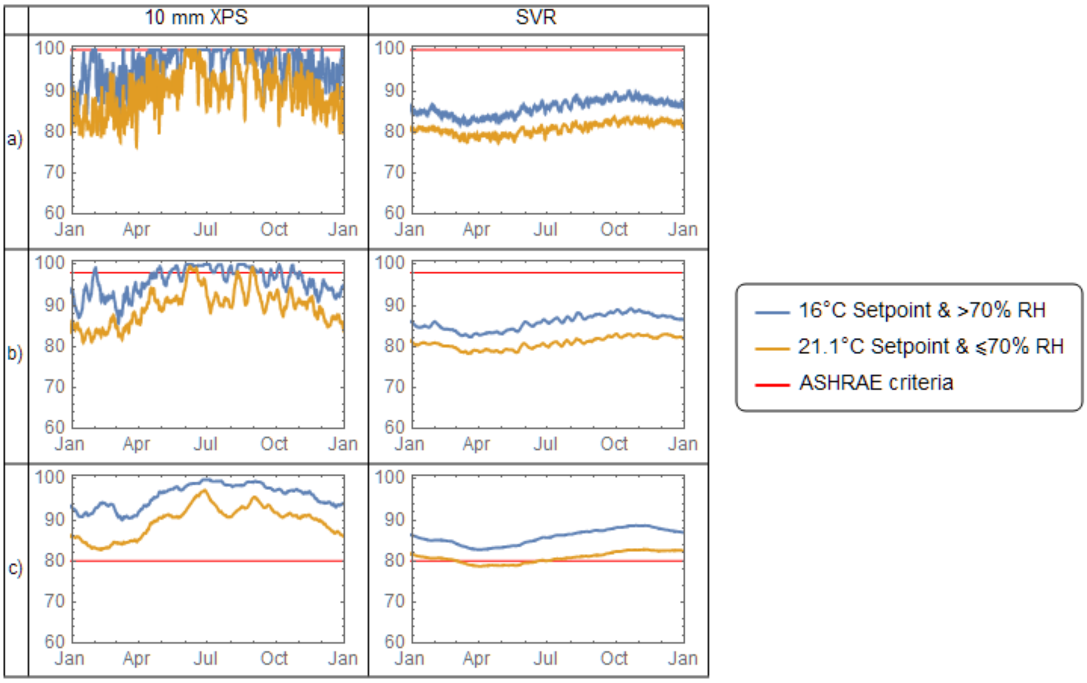



**Figure 42. Best and worst case walls from New Plymouth analysis showing effect of modifying the indoor heating setpoint.**

There has been some recent discussion (Ueno, 2015; Glass et al., 2015b) about the 30-day 80% RH criteria. That work found the predicted performance of traditional brick veneer walls, which have a long track record of success, also failed to meet this requirement and that real walls where the humidity exceeded this criteria often had little sign of damage. It is now proposed to modify the criteria to utilise a mould index based on Ojanen et al. (2010) so that the criteria better aligns with experimental observations of mould growth. This will be investigated in the follow-up work to this study. Other amendments to ASHRAE 160 are also planned (TenWolde, 2011).

### Smart vapour retarders can increase the margin of safety

Using an SVR increases the margin of safety in the wall in terms of condensation risk. It is still not enough to meet the ASHRAE 80% criteria, but of all the walls examined in the analysis, the walls with an SVR had the lowest humidity at the sheathing/underlay. The SVR walls were also the only walls that didn't register 100% humidity at the underlay/sheathing during the experiment at BRANZ.

## 5.5 Moisture accumulation threshold

The analysis above predicts that moisture is unlikely to accumulate in any of the wall configurations. This section shows a follow-on analysis that illustrates the effects of different parameters on moisture accumulation. The base case is a wall with a typical flexible underlay in Queenstown.

The following parameters were explored:

- Climate change – the HERS climate file for Queenstown had the following temperature shifts applied over the year:
  - Minus 2.5°C
  - Minus 5°C
  - Minus 7°C

Figure 43 through Figure 45 show the excess moisture in the outer 5 mm of insulation for the following configurations:

- R1.8 insulation
- R2.8 insulation
- Framing depth increased to 140 mm (R4.4).

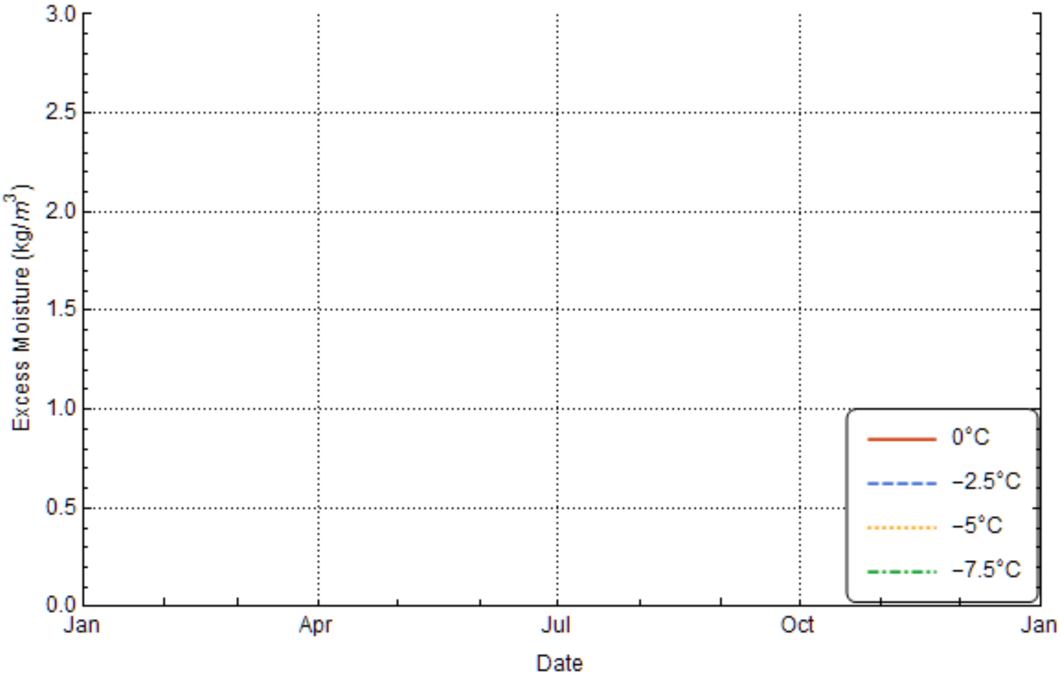



**Figure 43. Excess moisture in outer 5 mm of insulation – effect of temperature shift on a 90 mm framed wall with R1.8 insulation.**

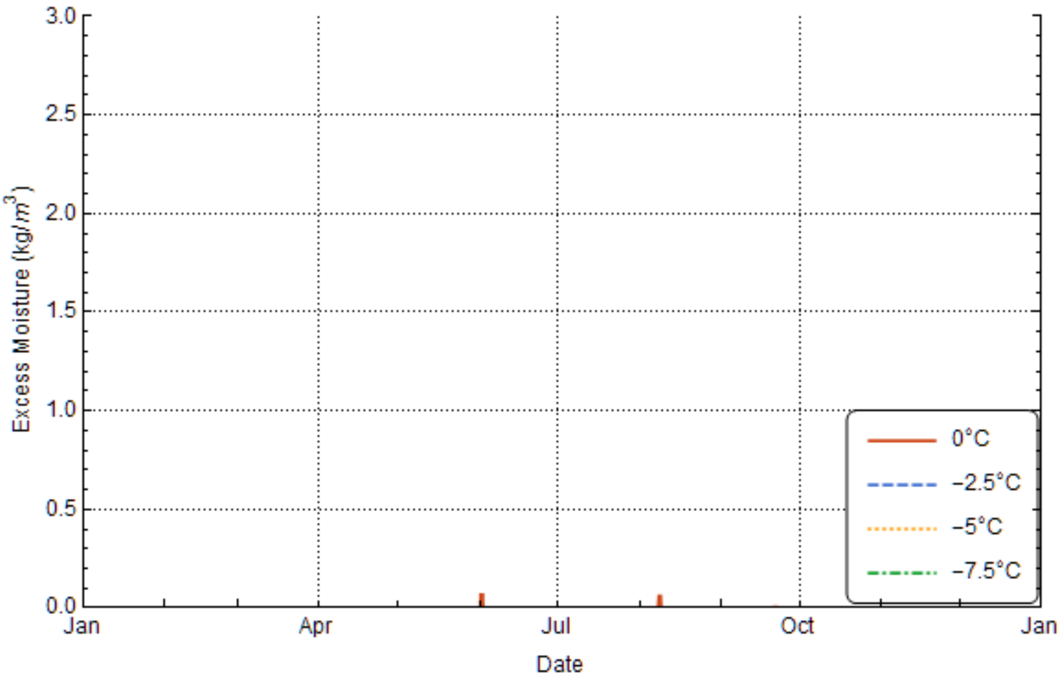



**Figure 44. Excess moisture in outer 5 mm of insulation – effect of temperature shift on a 90 mm framed wall with R2.8 insulation.**

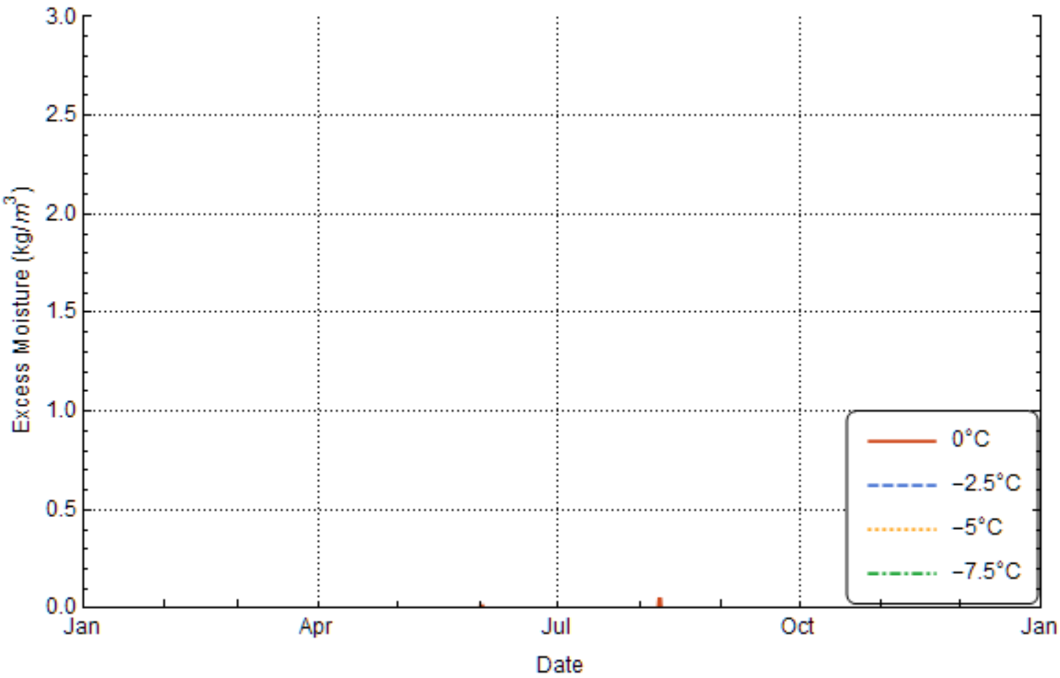



**Figure 45. Excess moisture in outer 5 mm of insulation – effect of temperature shift on a 140 mm framed wall with R4.4 insulation.**

In all cases, no moisture is predicted to accumulate over time. A tiny amount of transient moisture is predicted in the cases with the default climate for the R2.8 and R4.4 walls.

## Vapour resistance of underlay

The wall with R2.8 insulation had its underlay altered so that the vapour resistance was at the maximum level stated in Table 23 of E2/AS1 (7 MNs/g). All other parameters were identical. Note that the underlay in the BRANZ experiments and the earlier analysis had a vapour resistance of approximately 0.25 MNs/g.

Figure 46 shows that some moisture accumulates over the winter for all of the climate files, with the amount increasing as the exterior temperature becomes colder.

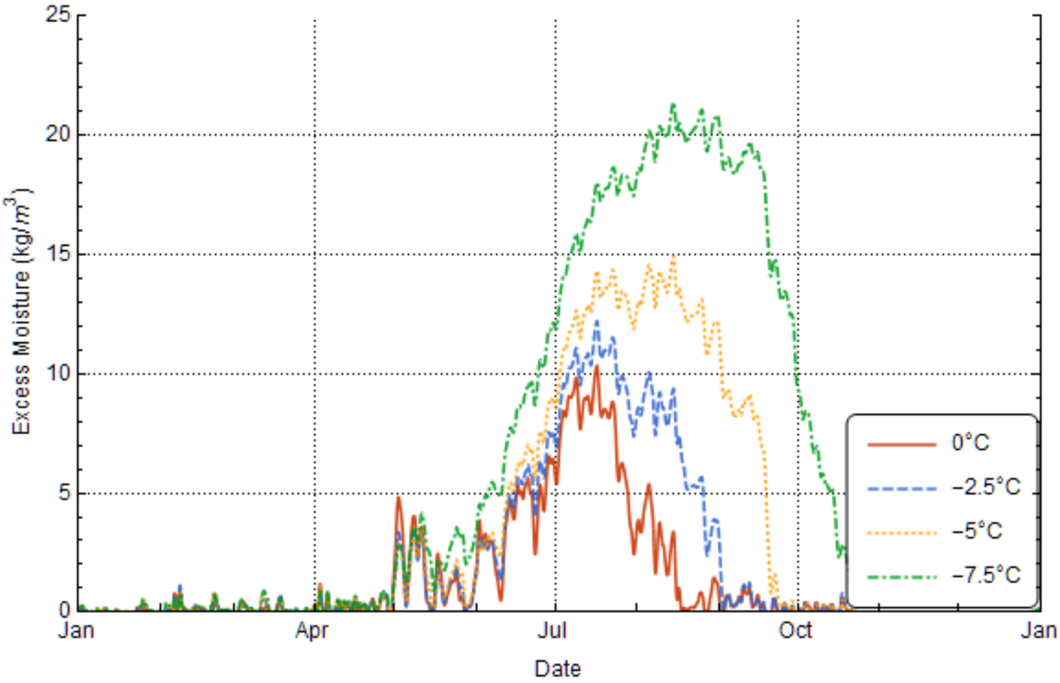



**Figure 46. Excess moisture in outer 5 mm of insulation – effect of temperature shift on a 90 mm framed wall with R2.8 insulation and an underlay with a vapour resistance of 7 MNs/g.**

## Ventilation

The 90 mm framed wall with R2.8 insulation was subjected to ASHRAE-style indoor climates with a range of ventilation rates. The heating setpoint was 16°C, and the moisture generation rate corresponded to a 3-bedroom house (1.16 × $10^{-4}$ kg/s). The relative humidity was allowed to exceed 70%. A minus 2.5°C temperature shift was applied to the exterior climate.

Figure 47 shows the effect of varying the ventilation rate from 0.5 ach down to 0.1 ach. Once the ventilation rate goes below 0.3 ach, the indoor relative humidity increases rapidly to the point that, at 0.1 ach, it rarely drops below 90%. This leads to significant moisture accumulation in the 0.2 ach and 0.1 ach cases.

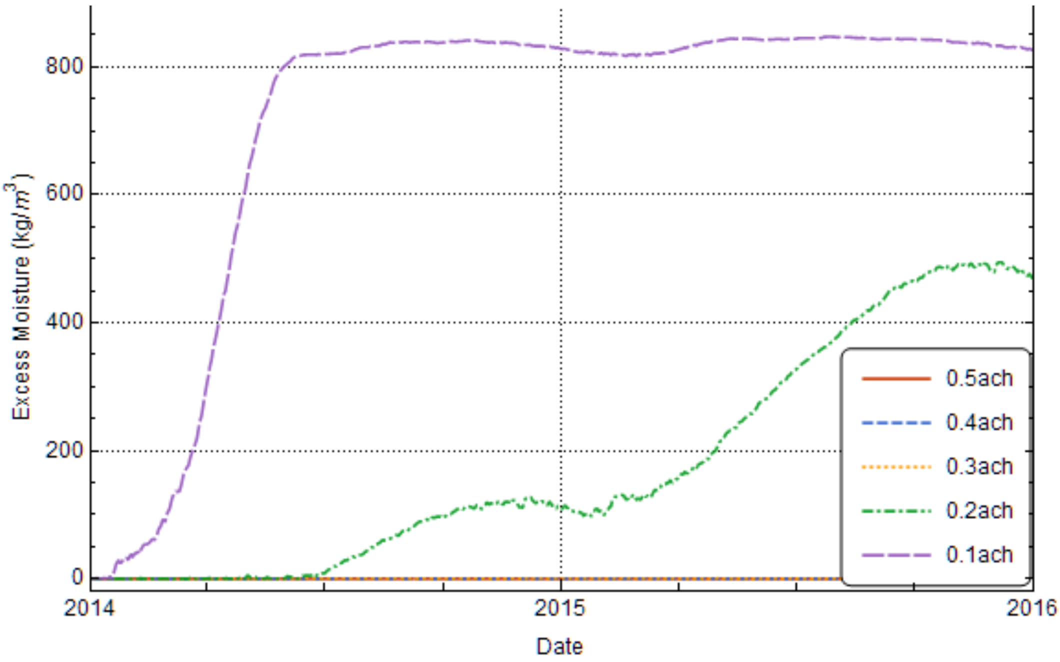



**Figure 47. Excess moisture in outer 5 mm of insulation – effect of room ventilation rate on 90 mm framed wall with R2.8 insulation.**

## Moisture generation rate

The base indoor climate used in this analysis had a moisture generation rate that corresponded to a 3-bedroom house. In conjunction with an exterior climate with a minus 2.5°C temperature shift, the following moisture generation rates were also examined:

- 3 bedrooms ($1.16 \times 10^{-4}$ kg/s)
- 5 bedrooms ($1.39 \times 10^{-4}$ kg/s)
- 5 bedrooms with jetted tub without exhaust fan ($1.54 \times 10^{-4}$ kg/s)
- $2 \times 10^{-4}$ kg/s

Figure 48 shows that excess moisture is only commonly predicted in the case where the moisture generation rate was $2 \times 10^{-4}$ kg/s, which is far in excess of the design value for a 5-bedroom house with a jetted tub without exhaust fan.

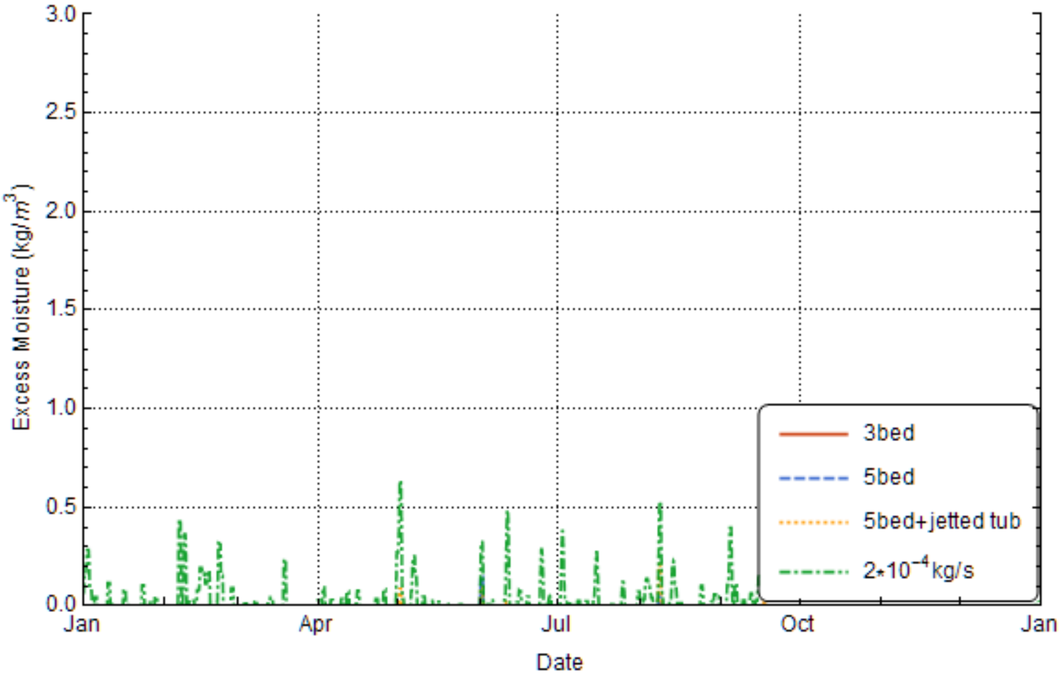



**Figure 48. Excess moisture in outer 5 mm of insulation – effect of moisture generation rate on 90 mm framed wall with R2.8 insulation.**

### 5.5.1 Key points from follow-on analysis

Moisture accumulation is the criterion that has been traditionally used to assess condensation risk in New Zealand. Section 5.1 shows that, although many styles of walls are likely to fail mould growth criteria, none are likely to experience significant moisture accumulation.

The follow-on analysis in section 5.2 suggests that the biggest factor in creating a moisture accumulation problem is a lack of room ventilation, followed by having a high resistance underlay. Note that, in this analysis, the increase in vapour resistance of the underlay was done in isolation, i.e. thermal properties were unaltered. Other factors including increased insulation, climate change and moisture generation had little effect on moisture accumulation over the range of parameters explored here.

# 6. Conclusions

A series of wall specimens were installed into a BRANZ test building, which was humidified periodically over a 2-year period. Measurements within the walls showed that the humidity at the sheathing/underlay reached 100% in almost all of the walls, but this only manifested itself as liquid droplets in a minority of walls. The only walls that did not reach 100% humidity were those that had a smart vapour retarder between the interior lining and the insulation in the stud space.

The hygrothermal simulation software WUFI was used to simulate the walls. It was originally expected that, for the simulation and measurements to agree, airflows through/in the walls would have to be accounted for. In general, the WUFI models agreed well with the experiment without this addition, with the main exception being the moisture level in the cavity. Further, the original plan of using a network of airflow resistances to calculate ventilation rates was unsuccessful. This was primarily due to the high airflow resistance of the R2.8 insulation used in the majority of the walls. If the trend towards more airtight houses continues, there is likely to be less of an effect from airflows on the hygrothermal behaviour of the wall. This means the simulation models may begin to agree with real walls better in this regard.

In the experiment in this study, relative humidity in the water-management cavity was much higher than expected. Vapour pressure in the cavity suggests a water source is active, but this has not been adequately explained and warrants further investigation.

If the cavity moisture levels indicated by WUFI are accurate, the models suggest that current typical New Zealand walls are at a high risk of damage due to mould growth. However, there is debate about the suitability of that criteria among the international building physics community. To change current practice on the basis of this criteria but with a lack of real field evidence would be controversial. Despite the apparent mould risk, New Zealand's approach to vapour control has been in line with current international recommendations on the use of vapour control layers, based on climate. One possible exception to this is the use of 10 mm XPS sheathing as a thermal break in conjunction with bulk insulation in the stud cavity. According to the International Residential Code, 10 mm XPS sheathing would not have a high enough R-value for IECC climate zones 4 and 5, whereas 30 mm XPS would satisfy that requirement.

If the cavity moisture levels indicated by WUFI are accurate, the models suggest that current typical New Zealand walls are at a low risk of accumulating liquid water. A range of parameters were explored to assess the onset of moisture accumulation in the outer 5 mm of insulation in the stud space. For typical New Zealand walls with a flexible underlay, moisture accumulation becomes a problem only when the indoor relative humidity becomes excessively high due to a low room ventilation rate.

Further work should investigate cavity humidity levels for a range of claddings and non-standard construction. It would also be desirable to analyse typical indoor climates with the aim of setting suitable design parameters for future analysis. Field measurements of wall humidity and/or wall ventilation in real buildings, where the walls are not discrete opaque test specimens, would also be invaluable.

If real-world cases of interstitial moisture accumulation or mould growth are encountered, they should be brought to the attention of BRANZ as soon as possible so the underlying causes can be established.

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