Improving the thermal performance of light weight timber construction: A review of approaches and impediments relevant to six test buildings.

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ABSTRACT: The BCA's increasing residential thermal performance requirements and their methods of assessment have sparked considerable investigation into the comparative performance of light weight timber framed and high mass concrete floors. This has overshadowed the potential to improve the thermal performance of other parts of conventionally built timber framed buildings. In developing the designs for the six test building in No Bills and Best Five Star Houses project at the University of Tasmania, considerable effort has gone into modifying the detailing and construction of the timber framing to improve their thermal performance, particularly by minimising air infiltration through the floor plate and any wrapping, and preserving the integrity of the insulation layer.

This paper presents an overview of international recommendations on high thermal performance timber framed construction, their relevance to regulatory compliance in Australia, and discusses the options pursued in developing the details for a 5 Star and 8.5 Star timber-floored houses to be built and monitored in Hobart and three test cells recently built in Launceston.

Conference theme: Building and energy

Keywords: light weight timber construction

INTRODUCTION
Recent amendments to the Building Code of Australia (BCA) have included a Performance Objective for residential buildings of reducing greenhouse gas emissions by efficiently using energy. All new constructions must rate above a particular level of thermal performance when modelled in an accredited simulation program or comply with the deemed-to-satisfy provisions for the relevant climate zone. The BCA 2006 requires a 5 Star rating and the Australian Building Codes Board (ABCB) Protocol for House Energy Rating Software is shortly to establish the CSIRO's AccuRate program as a benchmark rating program. Some states have adopted the 5 Star performance requirements while others, including Tasmania and Queensland, have deferred its adoption.

By incorporating improved wall and ceiling insulation, light-weight timber framed construction systems met the 4 Star performance requirements introduced in Amendment 12 of the BCA relatively easily. However, these systems need considerable and often expensive modifications to achieve a 5 Star rating, especially when a timber framed subfloor is used in cooler climates. As it is easier to achieve a 5 Star rating in the modelling software with a concrete slab floor, timber subfloors have been loosing market share in states where this level of performance is required. Since the Victorian Government introduced 5 Star thermal performance requirements in that state in 2004 using the older FirstRate and NatHers programs to rate houses, it has been estimated that the proportion of houses built with timber subfloor has fallen from about 20% to 15% (Boris Iskra 2006, pers. comm., 17 July). Given this impact, the Australian timber industry has sought to:

• test the accuracy of the programs used to determine the thermal performance of residential building, especially in their relative treatment of light weight timber framed and high mass concrete floors;
• identify and test alterations to conventional Australian timber framed construction that can economically improve its thermal performance; and
• understand the capacity of current assessment tools to accommodate these alterations if testing found them effective in improving thermal performance.

In 2004, the Forest and Wood Products Research and Development Corporation funded research at the University of Tasmania focused around the construction of three houses with identical plans and orientation on a single site. The houses are:

• A Best Five Star Timber House – a well designed and detailed house that includes a timber framed floor and achieves a 5 Star rating when assessed using the AccuRate program;
• A Best Five Star Timber Frame and Concrete Slab House – a house whose orientation and building fabric is identical to the Best Five Star Timber House except that it has a standard concrete slab on ground floor.
• A No Bills House – a very high performance 8.5 Star timber framed house.
The houses are to be monitored in a free running state for about two months during winter, allowing the actual thermal performance of each house to be compared to the others and the predictions of the modelling program. The houses are then to be monitored while occupied for a further 18 months so the occupants' actual thermal comfort decisions and the resultant energy consumption can be compared to the assumptions and projections made in the modelling program.

The design of the three houses is complete. Following their construction being delayed past winter 2006, the construction and monitoring of three 6x6 metre thermal performance test cells were added to the research program. The cells were built on the University of Tasmania’s Launceston campus in late autumn, 2006 and initial monitoring has begun. The configurations of the test cells are:

- Test Cell 1 - Unenclosed timber framed subfloor with a light weight plywood clad wall and truss roof with sheet metal roof sheet;
- Test Cell 2 - Timber framed subfloor, with brick veneer walls, and truss roof with sheet metal roof sheet; and
- Test Cell 3 - Standard slab on ground with brick veneer walls, and truss roof with sheet metal roof sheet.

The cells are simplified test houses about the size of a double garage. Besides the different construction methods used, the cells have the same orientation and size internally, have identical wall framing and insulation, are finished and painted inside and were built using current building practices. The cells as constructed have no windows, R4.0 insulation in the ceilings, R2.5 insulation in the walls, and no floor insulation. Their thermal performance was modelled using AccuRate Version V 1.1.0.0 and the results are included in Table 1. The star bands for Launceston are shown in Table 2. The assessment was performed in non-rating mode, with the test cells described as daytime use and with the heating & cooling options selected.

**Table 1: AccuRate assessment of the test cells**

<table>
<thead>
<tr>
<th>Thermal Performance</th>
<th>Test Cell 1</th>
<th>Test Cell 2</th>
<th>Test Cell 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJ/m².annum</td>
<td>Un-enclosed Platform</td>
<td>Enclosed platform</td>
<td>Slab on Ground</td>
</tr>
<tr>
<td>Total</td>
<td>374.7</td>
<td>292.8</td>
<td>286.3</td>
</tr>
<tr>
<td>Heating</td>
<td>371.3</td>
<td>292.8</td>
<td>286.3</td>
</tr>
<tr>
<td>Cooling (Sensible)</td>
<td>2.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cooling (Latent)</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2: Star bands for Launceston**

<table>
<thead>
<tr>
<th>MJ/m².annum</th>
<th>3 Star</th>
<th>4 Star</th>
<th>5 Star</th>
<th>6 Star</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>366</td>
<td>272</td>
<td>208</td>
<td>160</td>
</tr>
</tbody>
</table>

The specific research objectives of the test cells are to:

- compare the overall thermal performance of a building with a timber framed platform floor to that with a concrete slab on ground floor;
- establish the heating energy required to maintain human thermal comfort in each cells and compare it with the results predicted by modelling; and
- measure the thermal performance of a range of timber assemblies individually and as systems.

The construction on the test cells is not a direct substitute for the three full houses. The cells are more effective scientific tools but less effective tests of the capacity of the modelling program. The test cells do not have the complexity of interactions expected in a full house and they will not be occupied. However, they were considerably cheaper to build and can be modified over time. This allows iterative testing of material and fabric combinations.

As the cells are long term research tools, the first monitoring period is intended to calibrate the base configuration without solar heat gains. An extensive array of about 80 sensing devices has been installed inside each cell and through the wall, floor and ceiling systems. Each cell is fitted with an electric convection heater rigged to maintain the temperature in the centre of the room at 20°C. The heater's energy usage is being measured and recorded.

During the research conducted to support the design of the No Bills and Best Five Star Houses and the construction of the thermal performance test cells, investigation into improving the thermal performance of the building envelope sought best practice information from countries who use building systems similar to those employed in Australia, particularly light weight timber framed construction. Given the level of investment required to document and distribute best practice guidelines on the thermal performance of residential buildings, the search was effectively limited to North America and Europe. As it progressed, the investigation narrowed further to practice in the U.S.A and Canada. Those countries includes climates similar to Australia’s eastern seaboard, use light weight timber construction for a significant portion of its housing stock, and have thermal performance requirements and customer expectations in advance of those found in Australia. The U.S. Department of Energy (DOE), the Southface Energy Institute (SEI) and other groups distribute detailed best practice guidelines online. In addition to noting their relevance to regulatory compliance in Australia, the investigation supporting the No Bills and Best Five Star House project concentrated on
assessing the recommendations in these guides for economically insulating timber subfloors, improving the insulation of timber framed walls and ceilings, and reducing air infiltration through improved wrapping of the building.

1. ECONOMICALLY INSULATING TIMBER SUBFLOORS

One immediate option to improving the thermal performance of a timber subfloor is to insulate it. Guides from the U.S. DOE and SEI recommend that batts be installed flush against the floor membrane for the full length of the joists, and cut to fit around wiring and other obstructions. Installation is assumed to occur after the building is weatherproof with the insulation held in with staves or insulation hangers, as shown in Figure 1, or stapled cloth as shown in Figure 2. Unfortunately, these solutions do not translate to Australian practice easily. Without the basements and crawlspaces common under American dwellings, new Australian houses often do not have enough room under the floor to install insulation after the building is waterproof. Standard construction for a timber subfloor is to install bearers and joists close to the ground, install a continuous platform of particleboard sheet flooring and then erect the wall frames over this. Weatherproofing of this platform floor can take weeks.

![Figure 1: Sub floor insulation (Source: SEI 2002)](image)

![Figure 2: Sub floor insulation (Source: SEI 2002)](image)

As Williamson and Beauchamp (2005) report, installing insulation as the floor platform is assembled is problematic. Draping foil over the joists and under the sheet flooring (with or without bulk insulation) conflicts with the requirements of AS 1860.2-2006: Particleboard flooring - Installation to glue sheet flooring to the joist. While practice in New Zealand permits nailing or screwing the sheet flooring, gluing appears to have been built into the standard because it significantly reduces the number of builder call-backs for squeaky floors. Even if the insulation is installed before the sheet flooring, water can accumulate in the foil or bulk insulation after installation and before weatherproofing. This reduces the insulation’s effectiveness and potentially encourages rot or mould in the timber. Some builders are stretching foil, air-cell or similar products over the bearers before the joists are positioned and then building the floor platform above this. However, this positions the foil well away from the sheet flooring, reducing its effectiveness due to convection effects. It also leaves the foil susceptible to considerable damage as the building process continues, especially from services trades (Jono Buist, 2005, pers. comm. 18 November). Industry has initiated changes to AS 1860 and commissioned research on the need to glue the floor sheeting and the effects of wet insulation on timber substrates (Angelo Guerrera 2006, pers. comm. 9 June). These projects are currently incomplete. With builders and material suppliers reticent to guarantee arrangement with which they have little experience, there currently does not seem to be an acceptable and economic way of insulating a timber subfloor that has less than 600 mm clearance off the ground.

1.1 Incorporation in the test buildings

For the Best Five Star Timber House, the developer chose to avoid underfloor insulation, opting to reach 5 Star performance instead by fully double glazing the house. For the No Bills House, the floor has been designed to accept R6.0 bulk insulation fitted between I-beam joists and installed after the building is weatherproof. It is to be held in place with a plywood soffit fit ted between the joists. Neither of the timber floored test cells had insulation installed initially. Both were constructed so that bulk and foil insulation can be installed later.

2. IMPROVED INSULATION OF WALLS AND CEILINGS

In addition to the performance of any fenestration, the quality of insulation installation and the detailed assembly of the timber frame can influence the thermal performance of a house’s external envelope. The Californian Energy Commission (CEC) (2005), which appears to establish and manage building performance requirements in that state, identifies three problems created by improper insulation installation: when insulation is not in contact with the air barrier or housewrap, an air space can be created that in effect “short circuits” the effectiveness of the insulation; gaps or voids in the insulation can lead to significant portions of the wall, roof or floor being essentially not insulated; and compression of the insulation, usually around pipes or other building services embedded in wall, ceiling, or floor cavities, can degrade insulation performance. To encourage high quality installation, the CEC offers a credit in their performance assessment of housing if the insulation installation has third-party verification.

Part 3.12.1 of the Building Code of Australia (BCA) requires that insulation must abut other insulation and form a continuous barrier. It requires reflective insulation to be installed with required air spaces, be closely fitted against penetrations and be adequately supported. However, the BCA does not require inspection of the insulation’s...
installation or any feature of the design used to comply with its thermal performance requirements. In Tasmania at least, building surveyors are satisfied with a declaration from the builder that the insulation and other features are installed (Greg Green 2006, pers. comm. 13 July). These features are not inspected.

It is intended that the installation of the insulation in the No Bills and Best Five Star houses will be as good as currently available off-the-shelf products and industry skill can allow. During the construction of the three test cells, particular care was taken in this phase of construction. Though the installer was chosen by the insulation supplier, considerable additional instruction was required to ensure that the insulation was packed snug between the studs and plates.

2.1. Assembly of the framework

The detailed assembly of the timber frame can influence the thermal performance of a fully insulated wall or ceiling and the potential to fully insulate those surfaces. While a reasonable insulator in its own right, timber has a lower thermal performance than insulation. Consequently, the thermal performance of the completed wall will be influenced by the fraction of the wall or ceiling area that is timber.

The detailing of corners, lintels and eaves limits the capacity to fully insulate those locations. The tradition three stud arrangement used to make up a corner or return usually creates a void that can only be filled with insulation from the outside, before the building is wrapped. As the insulation is usually installed after wrapping and by a different trade, these voids are often left empty and form a thermal break in the wall. The detailing of lintels has a similar effect. The roof to wall frame joint creates another problem. Common practice in truss construction is for the top and bottom truss chord to meet at the top plate of the wall and for the top chord to then extend to form part of the eave. This detail restricts the space at the top of the wall plate to the depth of the top chord and limits bringing the full depth of the ceiling insulation fully over the wall insulation. To reduce these insulation constraints, the U.S. DOE (2000) promotes advanced wall framing techniques that it claims can provide up to a 30% improvement in effective R value. The features of advanced wall framing are shown in Figures 3 to 6. The system optimises the use of timber in the frame to reduce the timber fraction and eliminate voids in the insulation. In the system, structural elements are aligned directly over each other from the roof frame to the bearer. Studs are spaced at 600 mm centres, with trusses positioned over studs, and the studs then located directly over the joists. Where possible, windows and doors align with the stud openings. As shown in Figure 4, corners are substantially different to current Australian practice. Special plastering clips remove the need for a nailing stud blocking the corner on the inside face, allowing the insulation to run through to the corner stud. For a brick veneered building, only two studs are needed instead of three and the space between can be insulated.

Unlike Australian practice, the trusses in the advance wall framing model carry through well above the top plate line, allowing the siding or soffit dam to be fitted to retain the ceiling insulation at its full depth through to the external wall. This is shown in Figure 5. Figure 6 shows the suggested arrangement for insulated headers with the load-bearing timber element positioned on the outside face of the wall, and insulated with other fibreglass batts or polystyrene insulation as space allows on the inside face.Lintels are also supported on sheet metal hangers to reduce the need for jack studs.

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**Figure 3:** Advance wall framing (Source: DOE 2000)

**Figure 4:** Juncture of roof to wall (Source: DOE 2000)
2.1 Incorporation in the test buildings

Testing for improved insulation performance is an essential component of building the No Bills and Best Five Star houses and the test cells. Each type of house provides different problems. With the No Bills house, the design insulation levels are well outside conventional practice: R10 in the roof and R6 in the walls. The R6 insulation in the floor is discussed above. To accommodate the R10 insulation fully up to the outside face of the external wall, an upstand has been included in the design of the trusses. This allows the building wrap and the wall lining to run through to the line of the top of the ceiling insulation. As shown in Figure 7, a similar approach was taken with the truss upstands in the test cells. Fitting enough insulation in the walls of the No Bills House to achieve a R6 rating was more difficult. It requires at least 230 mm between the inside and outside faces of the wall. Several framing options were considered. One option was framing the walls with off-the-shelf I-beams as studs and plywood or LVL as plates. Another was to assemble a wide frame using conventional framing. Eventually, it was decided that the walls would be two separate 70 mm wall frames, spaced to the required distance. The external wall would be load bearing while the internal wall is really a support for internal lining. This option had several advantages. The walls were standard 70 mm units that could be assembled by any prefabricator, light and easy to stand and adjust, and the space between the wall frames could be full insulated. The only disadvantage envisaged is aligning the two frames accurately and blocking around openings.

Figure 5: Juncture of roof to wall (Source: DOE 2000a)  
Figure 6: Insulated lintels (Source: DOE 2000)

The Best Five Star Houses are designed to use standard construction as much as possible, except that plastering clips will be used in the corners if they can be secured from material suppliers. Allowance has also been made for the trusses to accommodate the required depth of insulation.

Figure 7: Test cell 3 wall and roof frame  
Figure 8: Test cell 1 insulated corner voids
The test cells presented different challenges that resulted in different detailing decisions. The wall frames were assembled by a commercial fabricator using standard domestic detailing. As shown in Figure 8, voids in the corners of the frame were insulation filled as part of wrapping. To accommodate future increases in ceiling insulation, the trusses were built with upstands, as shown in Figure 7. To add openings to the walls easily in the future, lintels and supports to accommodate a standard 1800 wide window or door unit were built into the frames. This increased the timber fraction (or framing factor) in the wall frame from 12.25% if the frame had been built with a standard 450 mm stud spacing to 18.3% as built. The extent that this affects the walls' thermal performance is yet to be determined. The assumptions in AccuRate for the thermal bridging of the frame material are yet to be confirmed.

3. REDUCING AIR INFILTRATION THROUGH IMPROVED WRAPPING

The movement of air through leaks, cracks, or other openings of a building’s external envelope significantly affect its thermal performance. Franklin Associates (2000) report that the U.S. DOE has determined that about one-half of all energy used in heating and cooling homes results from air infiltration from the outside of a house to the inside. The Australian Greenhouse Office’s (AGO) Passive Design 1.4 brochure (2005), states that air leakage accounts for 15 to 25 percent of winter heat loss in Australian buildings. It recommends a range of actions to reduce this leakage including weather stripping doors and windows and sealing gaps between the window/door frame and the wall prior to fitting architraves. With the increasing adoption of performance testing for doors and windows, the performance of these openings is likely to be improving. However, there is probably considerable scope to improve the thermal performance of Australian light weight timber framed buildings by wrapping the building more effectively and sealing around any openings. Either double sided foil or plastic wrapping systems can be used.

![Figure 9: General sealing (Source: DOE 1999)](image)

There is considerable amount of North American literature in this area. In a major review of the field, Sherman and Chan (2004) report that a study by Wilcox and Weston (2001) measured the air tightness of four pairs of new California homes built with and without spun-bonded polyolefin housewrap. They found that houses with housewrap are on average 13% tighter than their counterparts. Sherman and Matson (2001) compared the air leakage of new energy-efficient houses against other new conventional houses. They found that energy-efficient houses are tighter built in general. Also, they found that there was less variation in the air tightness of houses built under energy-efficiency programs compared to the others. They concluded that a key benefit of these programs is the promotion of consistency in construction practice. Sherman and Chan (2004) also reported that in Canada, Hamlin and Gusdorf (1997) found that energy efficient R-2000 houses are at least twice as airtight as new conventional houses in most regions of the country. Sherman and Chan (2004) also report that in countries where there is a demand for tighter envelopes driven by building codes or energy saving requirements, new construction has been shown to be more air tight than older ones. They found that some air leakage pathways are common among many dwellings, such as the connections between building materials and components. Leakage to attics, basements, crawl spaces, and garages

![Figure 10: Wrapping details (Source: DOE 2000b)](image)
is significant. They summarized the position by stating that many studies have addressed the effectiveness of air barriers and building materials to minimize leakage, but it is often the quality of workmanship and careful design that are the determining factors in achieving desirable air tightness.

Current window testing standards do not include air leakage from the joint between the window and wall assemblies. Presenting a test methodology for quantifying this leakage, Louis and Nelson (1995) reported case studies that show that the extraneous air leakage from window perimeters is often higher than the air leakage through the window unit. Sherman and Chan (2004) report that Proskiw (1995) found that the conventional U.S. rough-opening sealing method for windows of this time can contribute up to 14% of the total leakage of a single-family detached dwelling. The space between the window and the frame was packed with fiber glass. They state that this source of air leakage can be reduced greatly by using alternative sealing method, such as casing tape, and closed cell foam. The DOE (1999, 2000a, 2000b) and the SEI provide detailed guidance on reducing air infiltration by effective wrapping and sealing.

As shown in Figures 9 and 10, they promote sealing of the wall plates to the particle board or plywood sheet flooring, sealing of the plasterboard (drywall) to the wall frames, and sealing all penetrations through the floor, wall and ceiling plates. The recommendations on effective housewrapping are extensive and include taping all joints and tears, caulking around services opening, sealing around window opening, plumbing openings, and baths. Their recommendations cover both foil and plastic wraps.

3.1 Regulation regarding wrapping
Under California’s regulatory regime, approved computer programs use a default specific leakage area (SLA) of 4.9 for designs that do not qualify for a compliance credit for sealing the building envelope. To qualify for the “default” compliance credit of a 0.50 reduction in the SLA, an air-retarding wrap must comply with the relevant ASTM standard and be installed to the manufacturer’s specifications. The minimum installation requirements include:

- The air-retarding wrap must be applied continuously,
- All tears or breaks must be repaired with manufacturer approved tape,
- All horizontal seams must be lapped in a shingle-like manner and taped,
- All vertical seams must be lapped,
- All windows and penetrations must be taped or caulked, and
- The air-retarding wrap must be taped or otherwise sealed at the slab junction.

This credit for air-retarding wrapping does not require house energy rating scheme rater verification. The assumed SLA can be reduced further by blower door test. The regulation also states that for the building envelope, field verification and diagnostic testing procedures exist for insulation quality and for reduced infiltration, and both are compliance options. Field verification and diagnostic testing is a way to ensure that the energy efficiency that shows up in the calculations and on the plans makes its way to the homeowner.

In Australia, Part 3.12.3.5 of the BCA does not address wrapping or sealing of the building in its deemed-to-satisfy provision except in the most general manner and there appears to be no verification procedures in use on Australian building sites. AccuRate Version V 1.1.0.0 appears to only have a simple checkbox to mark the house as well sealed or not well sealed.
3.2. Incorporation in the test buildings

Testing for and developing practical skill in reducing air-infiltration is also an essential component of building the No Bills and Best Five Star houses project. To ensure compliance with DOE recommendations, a building design and detailing checklist has been distilled from the various best practice guides and used during the design phase. A site assessment checklist is to be prepared.

Considerable experience was gained during the construction of the thermal performance test cells. While heavy duty foil was recommended by CSR, the material sponsors, none was available in the state when it was due to be installed. As the construction schedule could not sustain a further delay, light duty foil was used. The foil producers recommended that the foil be positioned underneath the roofing battens and only drape over the batten closest to the gutter. This confounded the carpenters initially as their normal practice is to fit the foil directly over the battens immediately before the roof sheet is fixed. The tradesmen eventually worked out the correct installation process but they found the change a challenge to understand and accept.

As each building was wrapped, all edges were taped. As seen in Figure 11, a large number of holes and tears resulting from misplaced foil tacks and other damage were repaired. Once the buildings were roofed, a team worked with one inside and one outside to spot daylight through holes in the wrap and patch it. The bricklayers' occasional slips with trowels resulted in punctures that were repaired as the work progressed. As seen in Figure 12, the wrap overlapped flashing and any overlaps taped. This whole experience supported Sherman and Chan's view that careful design and the quality of workmanship are the determining factors in achieving desirable air tightness. It also shows that the understandings of the designer, material supplier and tradesperson, and the links between them, need considerable development if airtight construction is to become standard practice in Australia.

CONCLUSIONS

Australia has recently included thermal performance requirement into its regulatory regime with the stated objective of reducing greenhouse gas emissions. As the level of required thermal performance has increased from 4 to 5 Stars, sometimes significant modifications have had to be made to building designs to achieve compliance. Consequently, demand for building materials and systems have changed. Understandably, the effected industries have sought to test the accuracy of the tools being used to assess compliance and examine if the tools and the regulations combined actually achieve the initial policy objective. For the wood products industry, the major effects have been on the use of timber framed flooring systems, especially in cooler climate. The research the industry has commissioned at the University of Tasmania is designed to test these regulatory changes by attempting to match the performance predicted by the rating software with the measured performance of test cells and full sized houses. The research also includes investigation of more energy-efficient ways of building economic timber framed systems. This includes measures that international practice suggests are important features but which do not appear to carry much weight in assessing residential buildings in Australia. These measures include improving the insulation of timber framed walls and ceilings and reducing air infiltration through improved wrapping and sealing.

Of the six buildings to be constructed, the three test cells were completed recently and detailed monitoring began in August, 2006. Over the next three years, the cells and the full houses should provide:

- detailed comparisons of the thermal performance of a building with a timber framed platform floor to that with a concrete slab on ground floor;
- assessment of the capacity of the AccuRate modelling software to predict the actual thermal performance and energy requirements of the test buildings;
- indications of the importance of factors such as wrapping, insulation quality and air infiltration to actual thermal performance under Australian conditions; and
- measurement of the thermal performance of a range of timber assemblies individually and as systems, and of key factors that influence this performance, such as the air movement in subfloor, cavity and roof spaces.

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