

School of Architecture

Centre for Sustainable Architecture with Wood

Comparison of Test Cell Thermal Performance & The Empirical Validation of AccuRate in a Cool Temperate Climate

FWPRDC project PN04.1009

Final Report

Date: 30 June 2009

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Acknowledgments

The Centre for Sustainable Architecture with Wood (previously the Timber Research Unit) has received considerable support for this project from funding organisations, companies, industry groups and individual including:

- The Forest & Wood Products Australia;
- The Australian Greenhouse Office of the Commonwealth Department of Environment, Water, Heritage & the Arts;
- cb&m design Pty Ltd;
- Becks Hardware SPAN TRUSS SYSTEMS;
- Blue Scope Steel;
- Carter Holt Harvey Panels;
- Carter Holt Harvey: Futurebuilt;
- CSR Bradford Installation;
- CSR PGH Bricks;
- CSR Plasterboard;
- Helec Sales & Systems;
- Protec Pty Ltd;
- Readymix Concrete;
- Smorgon Steel; and
- Tasmanian Timber Promotion Board;

The authors also gratefully acknowledge:

- Dr Angelo Delsante of CSIRO Sustainable Ecosystems for his continual and generous advice;
- Dr. Des Fitzgerald, School of Mathematics & Physics, University Of Tasmania; for his guidance on statistical analysis of data;
- The staff of test cell program at the University of Newcastle, especially Dr Heber Sugo.
- Messrs Robert Lewis and Max Fang for their assistance in IT and instrumentation work; Janice Bowman, Tammie Fair, Alisa Ward and Victoria Kong, on administrative matters.

Unless otherwise noted, all photographs in this report are courtesy of Mark Dewsbury.

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Executive Summary

The general objective of this project is to better understand and quantify the thermal performance of light-frame buildings, particularly forms of construction commonly used in the Australian residential sector. Specifically, this project seeks to compare the thermal performance of three commonly used construction types used in the Australian residential sector; to empirically validate the AccuRate software in cool temperate climates such as in Tasmania; and to build research capabilities and expertise.

AccuRate is an energy rating assessment tool used during the building design phase to predict the thermal performance of a house given information on its geographical location, orientation, the type of construction materials and techniques, insulation levels, window size and orientation, shading, overshadowing, ventilation, colour of indoor surfaces, etc.

This project has two components, mainly differentiated according to the type of building purposely built for thermal performance monitoring. The components are:

- Component I: Empirical Validation of AccuRate in Three Light-frame Test Cells in a Cool Temperate Climate
- Component II: Empirical Validation of AccuRate in Three Light-frame Test Houses in a Cool Temperate Climate

This report covers only the completed activities in Component I, specifically the thermal performance monitoring of three test cells with uncarpeted floor during the free running period from January to December in 2007, and the subsequent comparisons and analysis for the empirical validation.

The test cells were built in the same location, with the same planning and orientation but using different floor construction types. Each test cell was designed to match flooring options referenced from the Building Code of Australia. To further align with the primary building types used for housing in Australia, the cells were designed with brick veneer walls with either an enclosed subfloor or no subfloor. Each cell is briefly described as follows:

- Test Cell 1 – Unenclosed perimeter platform floor with plywood cladding;
- Test Cell 2 – Enclosed perimeter platform floor with brick veneer cladding; and
- Test Cell 3 – Slab-on-ground floor with brick veneer cladding.

Prior to this project, no empirical validation studies on AccuRate were conducted on purpose-built buildings, specifically comparing platform timber-floors and slab-on-ground floors.

Each test cell was fully instrumented with a total of at least 60 sensors installed in the room, roofspace, walls and wall cavities, subfloor space, and the ground. A weather station located on the roof of Test Cell 2 provided external environment data for the AccuRate thermal performance simulation.

Comparison of the test cells' thermal performance ensued after verifying the air-tightness of the buildings. Infiltration measurements were conducted by Deakin University's Mobile Architecture and Built Environment Laboratory (MABEL) on 24-27 September 2007. The weather station on-site measured wind velocity and direction. Tracer gases namely, carbon dioxide, sulphur hexafluoride and acetone, were injected into each cell's roof space, central room, and subfloor space, respectively. It was found that the three test cells were very airtight with air change rates of up to 0.1 ACH. Under the same external wind conditions, airflows measured at the roofs were significantly higher and with a wider variation compared with the airflows in the rooms.

During both warm and cool periods, Test Cells 2 and 3 had more stable vertical temperature profiles compared with Test cell 1. The temperature swing at 600mm, 1200mm and 1800mm high measured from the floor level in Test Cell 1 (with an open subfloor) relate to the subfloor air speed. Test Cell 2 (with an enclosed perimeter subfloor with vents) had a more stable room temperature compared to Test Cell 1.

Within the whole year, the simulated room temperature was almost always lower than measured temperature. When thermal comfort bands in Launceston according to the protocol for house energy rating (2006) were considered, the simulated hourly temperatures for a warm and a cool week resulted in an underestimation of overheating degree hours during the warm week, and an overestimation of underheating degree hours during the cool week in all test cells.

When the test cells were modelled as living rooms during the cool week, average daily underheating in Test Cell 1 was overestimated by 25.09 degree hours or 11.54%; Test Cell 2 by 45.18 degree hours or 26.65%; and Test Cell 3 by 35.33 degree hours or 22.48%.

When modelled as bedrooms during the cool week, average daily underheating hours in Test Cell 1 was overestimated by 47.93 degree hours or 26.79%; Test Cell 2 by 51.36 degree hours or 45.62%; and Test Cell 3 by 38.21 degree hours or 35.82%. The calculations for under-and overheating hours also showed that the comfort temperature bands in Launceston as per the Australian Building Code are quite realistic.

Statistical analysis showed that measured and simulated temperatures in all building zones (roof, room and subfloor) have a positive linear correlation. The residual analysis showed possible interaction between room, roof and subfloor airspace. Further analysis of such interaction will be conducted given that the test cells were found to be very airtight with air change rates of up to 0.1 ACH. The airflows measured at the roofspace were significantly higher and had a wider variation compared with the airflows in the rooms. The residual time series plots show that there may be seasonal variations, so monthly residuals will be analysed in greater detail before conclusions can be made.

The on-going analysis involves several simulation re-runs (in collaboration with CSIRO), with appropriate modifications to the AccuRate scratch file, i.e., AccuRate assumed values are replaced with actual (as-built) construction parameters and material properties. These are aimed at more realistic representations of the thermal performance of light-frame houses in cool temperate climates. The planned modifications will account for:

- an increase in framing factor resulting from additional timber volume in the wall frames;
- the considerably larger quantity of timber owing to hip-type roof truss compared to the simple skillion roof truss commonly used in buildings of the same volume; and
- the measured environmental conditions in the unenclosed and enclosed subfloor, the thermal mass provided by the floor frame in the timber floored test cells, and the measured ground temperature in all three test cells.

So far, there have been many insights drawn from this empirical validation process. However, it is only when the planned simulation re-runs and analyses are completed that conclusions and possible improvements to the AccuRate model can be drawn.

This project has laid the groundwork for a broader research and development program on the thermal performance of domestic buildings in Australia. Although results so far show differences between the modelled and measured thermal performance of the test cells, the analysis is by no means complete. Conclusions leading to possible improvements in AccuRate and current building practices can not be made as of yet. It is recommended that on-going analysis and other planned activities be continually pursued and dovetailed to a broader research program designed to further understand and quantify the thermal performance of timber-framed houses.

The envisioned program will include the timely revival of the No Bills House Component, and an entirely new component which aims to provide technical assistance and documentation in support to the Australian Green Loans Program. The completion of on-going component studies that are integral to the empirical validation of AccuRate and other follow up studies on the existing test buildings will provide the much needed research continuum in support to the move to expand coverage of the Five Star standard to house renovations, as well as the impending push beyond the Five Star standard for new houses.

1 Introduction

This is the final report for the first component of the Five Star Thermal Performance project of the Centre of Sustainable Architecture with Wood (CSAW, formerly the Timber Research Unit) based at the University of Tasmania's School of Architecture in Launceston. The project commenced in January 2006 with financial support provided by the Forest & Wood Products Association, Inc. [FWPA, formerly Forest & Wood Products Research & Development Corporation (FWPRDC)] and the Australian Greenhouse Office (AGO), with the assistance of industry sponsors.

The general aim of the project is to better understand and quantify the thermal performance of lightweight timber buildings, particularly forms of construction commonly used in the Australian residential sector. The project specifically seeks to compare the thermal performance of three commonly used construction types in Australia, to validate the AccuRate software in cool temperate climates such as in Tasmania, and to build research capabilities and expertise.

AccuRate was developed by CSIRO and has been widely tested and calibrated. It is the benchmark for accrediting other software to the National House Energy Rating Scheme (NatHERS) in Australia. As an energy rating assessment tool, AccuRate predicts the thermal performance of a house during the design phase given information on geographical location, orientation, the type of construction materials and techniques, insulation levels, window size and orientation, shading, overshadowing, ventilation, colour of indoor surfaces, etc.

This project has two components mainly differentiated according to the type of building purposely built for thermal performance monitoring. The components are:

- Component I: Empirical Validation of AccuRate in Three Light-frame Test Cells in a Cool Temperate Climate

Three one-module buildings, referred to as test cells, were designed and built to match major domestic construction types, specifically for residential construction. Each test cell has a square floor plan with an internal width of 5480mm, and internal height of 2440mm. Construction details are found in Appendix A of this report.

- Component II: Empirical Validation of AccuRate in Three Light-frame Test Houses in a Cool Temperate Climate

Three 2-bedroom houses were built adjacent to each other with the same orientation, and were designed with brick veneer walls, conventional framing and insulation options. Although the houses have identical floor plans and outward appearance, these have deliberate variations in external fabric; hence have different star ratings when assessed with AccuRate.

Aside from the above components, the original project concept included a component on the construction of a high performing light-frame house, i.e., the No Bills House. While documentation was fully completed in 2005, economic constraints prohibited its construction. Nevertheless, the lessons learned specifically on the application of the AccuRate House Energy Rating (HER) software during the design stage, the implications of energy ratings in building practice and the methods of improving the thermal fabric of lightweight timber housing, proved to be invaluable in the construction and monitoring of the test cells and test houses starting 2006.

Aside from the financial support of FWPA and AGO, the construction of the three test cells were made possible through the assistance of industry collaborators such as building materials manufacturers, cb&m design Pty Ltd, and the University of Tasmania.

Previously, an interim project report presented a detailed comparison of the initial thermal performance of the test cells from August to December 2006 (Dewsbury, 2007). This report focuses on the second stage monitoring covering January to December 2007, and subsequent comparison and analysis of measured and simulated temperatures. It consists of the following sections:

- Thermal Performance Regulations – provides a review of the current state of thermal performance requirements for Australian buildings, methods of compliance to the Building Code of Australia (BCA), and an introduction to AccuRate;
- Design & construction – recapitulates background information on site planning, test cell design, documentation and construction details and the fabric matrix of the three test cells;
- Monitoring system – identifies the parameters to be measured, and updates information on instrumentation, and data acquisition and management;
- Results and Discussion – covers the thermal performance of the test cells from January to December 2007, the highlight of infiltration measurements within this period, a comparison of measured and simulated indoor temperature in the test cells, and a discussion of preliminary residual analysis.
- Conclusion and Recommendation – outlines specific areas that are currently undergoing further scrutiny as a result of preliminary residual analysis, as well as plans for a broader research program on thermal performance.

2 Thermal Performance Regulations

2.1 Brief Historical Background

In November 1998, the Australian governments endorsed the National Greenhouse Strategy (AGO, 1998), committing themselves to what then appeared to be an effective national greenhouse response. Module 1 of this strategy recognised the importance of establishing energy efficiency standards for housing and commercial buildings. Module 4.9 on Energy Efficiency Standards for Residential and Commercial Buildings puts in place the principle of developing minimum energy performance standards for the building sector. Consequently, the Commonwealth Government announced its intention to pursue a strategy that included two elements: firstly, the encouragement of voluntary measures by industry, and secondly, the introduction of minimum mandatory energy efficiency requirements in the (ABCB, 2007)

In January 2001 the AGO and the ABCB agreed to develop and include energy efficiency measures for new Australian buildings in the BCA. The BCA is the national code and all new buildings in Australia must comply with its requirements. The BCA is developed by the ABCB, which is composed of representatives from federal and state governments, researcher groups, the manufacturing sector and construction industry groups, and given regulatory functions by enabling legislation in each State. The BCA is divided into two volumes. Volume 1 is generally for larger buildings, such as residential apartment blocks, commercial, industrial and public buildings. Volume 2 applies to simpler residential buildings, such as stand-alone and attached dwellings.

In 2003, a performance objective to reduce greenhouse gas emissions by efficiently using energy was added through Amendment 12 of the BCA. This focused almost exclusively on regulating the energy use in heating and cooling buildings. The first regulation applied to Class 1 buildings (houses) required a minimum performance rating equivalent to 4 Stars. In the 2005 edition of the BCA, this performance requirement was extended to most other building classes. In 2006, the standard was raised to 5 stars for Class 1 buildings. However, several states

including Tasmania, New South Wales and Queensland, deferred the adoption of this requirement for new dwellings.

From May 2008, the coverage of the 5 star-standard was expanded to include renovations numbering about 40,000 houses annually in Victoria alone. For a 2 star house upgraded to 5 star one, it is estimated that about \$200 savings is generated annually on heating and cooling alone (Victoria Building Commission, 2008).

On 30 April 2009, the Australian Minister for Climate Change and Minister for the Environment announced through a press release, the decision made by the Council of Australian Governments (COAG), five key measures to drive growth in the number of highly energy efficient homes and commercial buildings in Australia, namely:

- Increasing the stringency of energy efficiency requirements for all classes of commercial buildings in the BCA from 2010;
- Phasing the mandatory disclosure of the energy efficiency of commercial buildings and tenancies from 2010;
- Increasing energy efficiency requirements for new residential buildings to six stars, or equivalent, nationally in the 2010 version of the BCA, as well as introducing new efficiency requirements for hot-water systems and lighting;
- Phasing in mandatory disclosure of residential building energy, greenhouse and water performance at the time of the sale of the lease, commencing with energy efficiency, from May 2011; and
- Reforming current building energy efficiency standard and assessment processes to achieve consistency across the nation.

The National Strategy on Energy Efficiency builds on the Commonwealth Government's existing commitments such as the Energy Efficient Homes package: a \$3.9 billion package to install ceiling insulation and solar hot water systems in 2.7 million Australian households (COAG, 2009).

2.2 Compliance to the BCA

The BCA provides two methods of complying with its thermal performance requirements during the building design stage, namely, the deemed-to-satisfy provisions, and performance-based alternative solutions. The deemed-to-satisfy provisions provide a relatively simple but conservative manual method of determining an external fabric matrix that will deliver the minimum required thermal performance. Developed after numerous simulations of different house types, the provisions include detailed descriptions and diagrams of satisfactory building practises and specific requirements for insulation, glazing, shading, building sealing and other factors that affect the heating and cooling of a house.

A house design that does not comply with the deemed-to-satisfy provisions (or which seeks to use a less conservative estimation method) requires a performance-based alternative solution to demonstrate compliance and be approved for construction. This means the house design has to be assessed using an approved thermal calculation method such as the use of HER software. AccuRate was developed by CSIRO as the best practise HER software for the thermal simulation of houses within Australia.

2.3 AccuRate as a House Energy Rating Tool

Continuing research to improve thermal performance of houses in various climatic conditions in Australia and consequently, further development of NatHERS have resulted in the second generation and greatly improved software version called AccuRate (Delsante, 2005b). Recent improvements include natural ventilation modelling, changes in thermostat settings and times of heating and cooling; incorporation of the effect of colour of indoor surfaces to solar absorptance; improved modelling of flow rates as a function of wind speed and direction and opening size; detailed modelling of roofspaces considering heat exchange with outside air and the building interior; improved modelling of sub-floor and roofspaces, and an increase in the number of climate zones from 4 (in NatHERS) to 69.

With AccuRate, assessment is made during the building design phase through a calculation engine that accounts for the effects of climate, orientation, construction materials, insulation levels, window size and orientation, shading, overshadowing, ventilation, etc, the rating tools predict the thermal conditions in a house on an hourly basis throughout a typical year. A star rating is assigned corresponding to the amount of energy needed to cool or heat the house to achieve thermal comfort. For example, a 10-star house is unlikely to need any artificial cooling or heating (AGO cited by Baker). Using AccuRate, assessment by an accredited energy assessor takes from 30 minutes for a simple house and longer for more complex designs.

2.3.1 Key Input Data

Developing a satisfactory alternative solution requires iterative thermal performance simulation of the house's building fabric, whereby alterations are made to that fabric until the desired star rating is achieved. AccuRate requires five key groups of input data derived from the various building plans and specifications, namely:

- **Location** – The specific location of the building is entered as a postcode reference. Once a postcode is entered, the software applies a particular climate pattern to the house. This data set is called the typical meteorological year (TMY). The TMY data is the primary thermal simulation input for the external influences of the house and includes external air temperatures, humidity, wind patterns and solar radiation.
- **Building fabric** – The building fabric of a house is made of many elements. AccuRate requires the separation of building systems into their component parts. A brick veneer wall becomes the individual elements of 10mm Plasterboard, a 90mm cavity with 88mm of insulation, a building wrap, a 50mm still air cavity with a reflective foil to one side, and a 110mm pressed clay brick. This method of house fabric assessment is applied to the sub floor walls, flooring, external walls, windows, and doors, internal walls, ceiling and roofing materials. Each material can be found in the AccuRate database and is assigned accordingly.
- **Zones** – Each room within the external fabric of a house is a thermal zone. This includes the roof space and sub floor space. Each zone is given preset values for internal heat gains based on its purpose and perceived usage patterns by human activity.
- **Elements** – Each zone is enclosed by elements of building fabric. This data informs the software of the thermal processes that affect the performance of each room. This includes the resistance value of wall system, the thermal losses and gains of windows and the rates of air change within the zone.
- **Orientation** – A descriptive orientation of the building is entered. The software uses this information to model the fluid dynamics of external air pressure on the envelope of the building. This further informs infiltration patterns of windward and leeward rooms.

2.3.2 The Simulation Program

To conduct the thermal simulation, the program:

- models the internal and external building fabric of the building;
- allows for local climatic conditions; and
- applies assumed usage patterns to produce an estimated energy usage of the house per square meter per annum.

Each material in the fabric matrix has varying conductivity, reflectance, emittance, permeability and thermal capacitance. The model combines solar heat gain, heat transfer and air infiltration through the external fabric, the thermal capacity of the building, and the climatic condition of the site to calculate energy usage. It is the sum of these qualities and the combination of materials, which affect the thermal performance of a house the most. The AccuRate library contains 69 sets of climate data. Tasmania, for example is in climate zone number 26. The external conditions are also modelled, as they have an ever changing impact on the thermal processes of the house fabric.

A typical house has various zones such as garages, bathrooms, bedrooms, kitchens, living areas. AccuRate considers the roof space and subfloor space as zones. Each of the zones has varying heat gains from human occupation and appliance heat generation. The volume of each of these zones and their interconnectivity also forms part of the required data. Given assumed values for construction practise and patterns of household use, the HER simulation uses information (or input data) on house fabric, zone and climate data to estimate the amount of total energy required to heat and cool the house to maintain human comfort.

After the complete data is encoded, a thermal simulation is run, generating an output in the form of a detailed text file on the average hourly temperature in each zone for a year. Based on this data, AccuRate calculates the energy required to heat or cool the room (or zone) to maintain human comfort. The thermostat settings to which the room is heated or cooled is specified in the ABCB's protocol for house energy rating software (2006). The calculated energy per hour to condition each zone is tallied to obtain an annual amount of heating and cooling energy for the house. This total energy is then divided by the area of the house that is conditioned, i.e., for a house of 240m² floor area, only 200m² is conditioned floor space. This results in an energy load in MJ/m² conditioned floor area per annum. As a larger house will generally create more greenhouse gas emissions than a small house, an increase or decrease in the total energy is applied based on the house's overall conditioned volume.

From the Star band table in the ABCB's Protocol for house energy rating software (2006), the star rating is determined based on the energy load and the climatic location of the house. The Star Rating is a simple way of representing the annual estimated energy use per square meter of floor area for heating and cooling a house given a range of assumptions about the behaviour of its inhabitants and their needs to remain thermally comfortable. A house that is assessed to use a lot of energy for heating and cooling each year under these assumptions has a low star rating, whereas a house estimated to use little energy for heating and cooling has a high star rating.

Figure 1 shows an assessment report generated by AccuRate.




	<p>AccuRate Regulatory Version Oct 2005 (expires 31 Dec 2005)</p> <p>Nationwide House Energy Rating Scheme</p>								
Project Details									
Project Name: 5 Star house timber floor		Postcode: 7000							
File Name: C:\AccuRate\Projects\2005-12-12 - 5 star timber.PRO		Climate Zone: 26							
Design Option: Des 8 Timb no foil									
Description: a. External Wall - Kool wall / Air Space with non reflective foil vapour barrier / R1.5 Batt / Breathable Vapour Barrier / 10 Plasterboard, (b) Windows - 3/12/3 Timb, (c) Floor 1 - Carpet & Underlay - Tile - parq/ Particle board or Cem Sheet deck / 120 air / Reflective Foil, (d)									
Client Details									
Client Name:									
Phone:	Fax:	Email:							
Postal Address:									
Site Address:									
Council submitted to (if known by assessor): Clarence									
Assessor Details									
Assessor Name: Mark Dewsbury		Assessor No. 70106							
Phone:	Fax:	Email: mark.dewsbury@utas.edu.au							
Assessment Date: 13/12/2005		Time: 1:38:							
Project Code:									
Assessor Signature:									
CALCULATED ENERGY REQUIREMENTS*									
Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units					
214.9	12.4	1.5	228.8	MJ/m ² .annum					
<small>* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.</small>									
AREA-ADJUSTED ENERGY REQUIREMENTS									
Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units					
178.2	10.3	1.2	189.7	MJ/m ² .annum					
Conditioned floor area		102.7 m ²							
Star Rating									
 5 STARS									
Area-adjusted star band score thresholds									
1 Star	2 Stars	3 Stars	4 Stars	5 Stars	6 Stars	7 Stars	8 Stars	9 Stars	10 Stars
494	394	313	250	199	157	120	84	46	2

Figure 1: An AccuRate Star Rating Report

2.4 Impact of Building Thermal Performance Regulations on Industry

The Australian domestic building sector was worth about \$38 billion in 2006 (ABS, 2007). As changes to building regulations can have a significant impact on the selection and use of particular construction options, they can also generate significant economic impact on building companies and building materials manufacturers. The introduction of more stringent energy standards for residential buildings will understandably result in increased cost due to improved construction practices. While the introduction of a 4 Star thermal performance requirement in 2003 appeared to have had relatively minor impact on construction practices and building material companies, the move to 5 Star has entailed more adjustments in some sectors of the building industry compared to others.

One construction system that has been affected by the move to the 5-Star performance requirement is timber platform floor construction in cool temperate climates. In Victoria, the use of a timber subfloor has fallen from about 20% to 15% in the construction of new housing. It appears that the preference for concrete slab on ground floors has been encouraged due to the state's thermal performance requirements (Boris Iskra 2006, pers. comm., 17 July).

In response to the upgrade from 4 to 5 stars thermal performance requirement, the timber industry raised concern on the accuracy of the HER software that underpins the BCA's regulations, and whether implementing standards and rating schemes based on the use of the model unfairly disadvantages one building material over another. The industries would also like to confirm whether proven methods that may economically improve thermal performance of particular construction systems can be accommodated in the rating tools. Due to these concerns, the adoption of 5 Star requirements has been deferred in some states including Tasmania, and in the meantime, research to validate current HER software was commissioned by various industries.

3 Empirical Validation

There are various methods of validating software. Analytical verification is particularly useful in analysing building thermal fabric. Inter-program comparison is particularly useful in diagnosing errors albeit there is no truth standard (Neymark, 2005). Empirical validation is the only technique that can assess the overall performance of the simulation engine (Delsante, 2005).

AccuRate has been tested using the International Energy Agency's Building Energy Simulation test (or BESTest) protocol, and it has been found to perform well against eight reference programs from Europe and the US (Major, 2006).

Empirical validation of AccuRate's infiltration model was conducted using four real houses in Melbourne in 1997-1998, but because the sample size was too small, changes were not incorporated into AccuRate (Delsante, 2007).

In this project, empirical validation involved monitoring the thermal performance in three test cells built in the same location, with the same planning and orientation but using different floor construction types. Specifically, two timber floored buildings were built beside a concrete slab on ground floored building. The project stages include:

- Planning and design of each test cell to meet standard building systems. The BCA was used as a guide in establishing minimum fabric requirements, from which subtle improvements in insulation levels matching that for a six-star house were made. Orientation, size, external fabric, shading, air tightness and other factors that affect the heating and cooling of a house were considered.

- Construction of three test cells. To ensure best building practise, the test cells were constructed by an established builder with impressive track record. The materials and building practises were controlled and recorded. Close supervision and strict monitoring kept variables in construction details between test cells to a minimum;
- Monitoring the thermal performance of the building extensively for a substantial period. The data collected were formatted exactly the same as in AccuRate to allow direct comparison;
- Thermal performance simulation of each test cell using AccuRate. The fabric matrix and climate data were entered into the software. For each test cell, AccuRate generated a Star Rating and a simulation report that included the calculated internal temperature, external temperature and the heat or cooling loads required to maintain human comfort;
- Comparing the monitored performance to the simulated performance. This analysis examined the hourly thermal performance data resulting from simulation using on-site weather data file (instead of the software's built-in climate data file); and
- Examination of variations and anomalies to verify improvements to the software, if any. Factors that can dramatically influence a building's actual thermal performance include the quality of building practise and variations in air infiltration rates. Depending on the methods used to insulate the building, air movement in cavities, roof and subfloor spaces will also influence the actual thermal performance; and

Figure 2 shows the schematic diagram of the thermal performance simulation specifically for empirical validation purposes in this project.

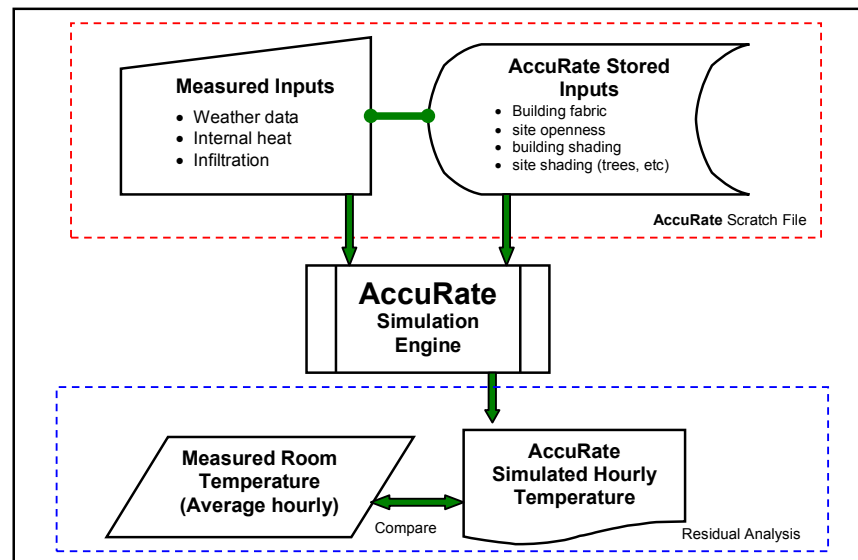


Figure 2: The Thermal Performance Simulation for the Empirical Validation of AccuRate

The following parameters were measured in all three building zones (room, roofspace, and subfloor):

- Dry bulb temperature
- Humidity
- Infiltration

The following external environmental parameters were measured:

- Dry bulb temperature

- Humidity
- Wind speed and wind direction
- Vertical north solar irradiance (NOTE: not a direct input for simulation but is recorded as reference data for future and more thorough research when examining the differences between global, diffuse and direct beam solar for lower latitudes)
- Global solar radiation
- Mean sea level air pressure

4 Design & Construction of Test Cells

The architectural plans for the three test cells are found in Appendix A. Construction started in March 2006 and finishing works were completed in August 2006.

4.1 Construction Site

The site chosen was on the northern fringes of the University of Tasmania's Newnham Campus in Launceston. Although Launceston is built at the head of a tidal river, it is approximately 50km from the open sea and is minimally influenced by maritime weather conditions. Launceston has a cool temperate climate with significant swings in temperature with cold nights and warm days in all seasons.

Figure 3 shows the layout and orientation of the test cells, whereas Figure 4 shows their location within the University campus. The site is open with the predominant weather from the northwest. The site constraints consist of:

- a car park and sports oval to the west;
- well established trees to the south;
- open grass and distant buildings, about 30m - 60m to the east; and
- open grass and distant buildings, about 13m-25m to the north.

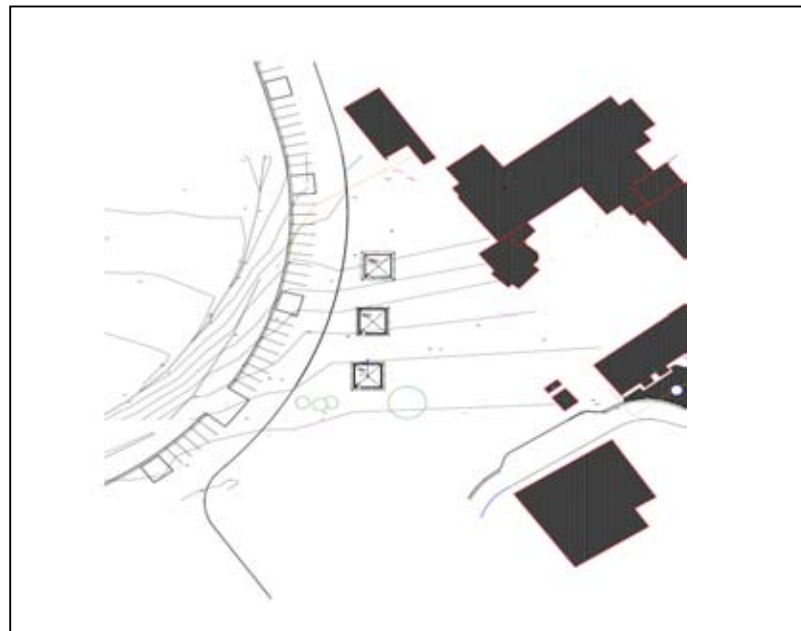


Figure 3: Site Plan of the Test Cells

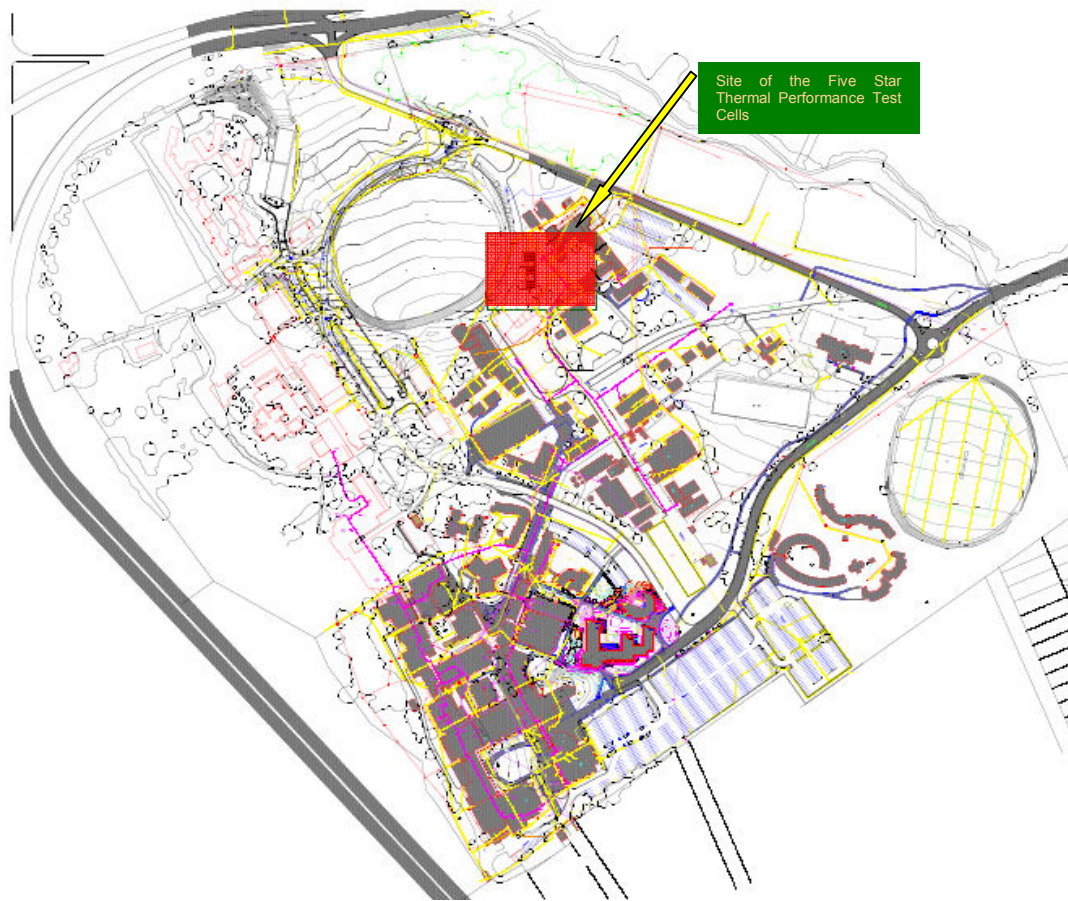


Figure 4: Location of the Test Cells at the UTas Newnham Campus

4.2. Building Types

The BCA lists three standard types of flooring options for residential construction. As shown in Figure 5, these are the unenclosed perimeter platform floor, enclosed perimeter platform floor and slab-on-ground floor.

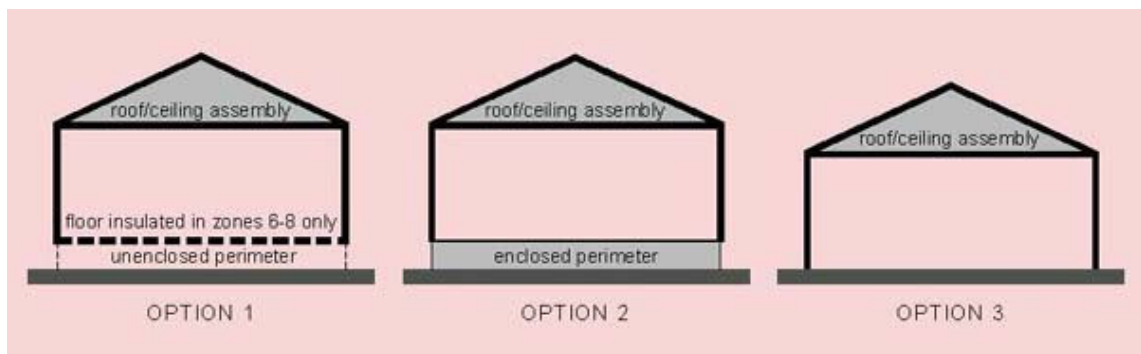


Figure 5: Standard Housing Floor Systems (ABCB., 2005)

As the BCA is a standard reference for construction practice, the test cells were matched to each of these floor options. To further align the design of the test cells with the primary building types for residential housing within Australia, brick veneer cladding was chosen for the cells with either an enclosed subfloor or no subfloor. The cells are:

- Test Cell 1 – Unenclosed Perimeter Platform Floor with plywood cladding;
- Test Cell 2 – Enclosed Perimeter Platform Floor with brick veneer cladding; and
- Test Cell 3 – Slab on Ground Floor with brick veneer cladding.

4.3 Size and orientation

International and national exemplars were examined to establish the appropriate dimensions of the test cells. However, there appear to be little similarities between various projects internationally. The major consideration was for the test cells not to be too small to allow normal room thermal fluid dynamics. Most test cells are built to standard room heights (Lomas, 1994). In Australia, test cells were recently built at the University of Newcastle. These were built using various types of brick construction to an external dimension of 6.0m x 6.0m in plan with a standard 2.4 meter internal room height (Sugo, 2004).

To allow future performance comparison, the Newcastle and Launceston test cells were matched to size and orientation as follows:

- internal length: 5480mm;
- internal width: 5480mm;
- internal height: 2440mm; and
- orientation: Solar North

4.4 External Fabric

As the three test cells have the same internal volume, the assembly of the roof and walls of each building are nearly identical. Table 1 summarises the fabric matrix of the test cells.

Table 1: Fabric Matrix of the Test Cells

Element	Test Cell 1 Unenclosed Perimeter	Test Cell 2 Enclosed Perimeter	Test Cell 3 Slab on Ground
Subfloor enclosure	Open	Single skin brick 110mm brick veneer with 2 x air vents on each wall 1 x Plywood access hatch	Not applicable
Floor	19mm Particle Board Deck on timber bearers and joists	19mm Particle Board Deck on timber bearers and joists	100mm ground keyed concrete slab
Walls (from the outside face)	12mm Ply 21mm cavity Reflective foil vapour barrier R2.5 Rockwool wall batt 10 Plasterboard	110mm Clay Brick 50mm cavity Reflective foil vapour barrier R2.5 Rockwool wall batt 10 Plasterboard	110mm Clay Brick 50mm cavity Reflective foil vapour barrier R2.5 Rockwool wall batt 10 Plasterboard
Door	Solid core	Solid core	Solid core
Ceiling (from inside face)	10mm Plasterboard R4.0 glass wool ceiling batt	10mm Plasterboard R4.0 glass wool ceiling batt	10mm Plasterboard R4.0 glass wool ceiling batt
Roof (from the inside face)	Reflective sarking with anti-glare surface towards colorbond roofing; Colorbond roofing	Reflective sarking with anti-glare surface towards colorbond roofing; Colorbond roofing	Reflective sarking with anti-glare surface towards colorbond roofing; Colorbond roofing
Other	All reflective foil vapour barriers and sarking were taped not stapled. Wall cavity sealed to maintain still air space	All reflective foil vapour barriers and sarking were taped not stapled. Wall cavity sealed between subfloor and wall to maintain still air space.	All reflective foil vapour barriers and sarking were taped not stapled.

A consistent quality of external fabric assembly was maintained to reduce variations in thermal performance. To ensure that construction practice mirrored prevailing general construction, an established quality home builder was contracted to build the cells, using their own subcontractor base. In addition, great care was taken to ensure a high standard of installation practise for all three test cells. This required close coordination with the builder and his subcontractors during the construction period.

The matrix in Table 1 lists the elements, however, further details of fabric construction practise and issues are described below for the roof, ceiling, the external walls assembly and the building wrap.

The roof construction in the three test cells is identical, i.e., the same truss design, colorbond sheet metal roofing and reflective foil sarking arrangement. After discussion with the manufacturer and industry collaborators, the sarking installation was significantly modified to standard practise in two ways, namely (See Figure 6):

- For reflective foil sarking to work effectively, it requires a no contact air gap between the roofing material and the foil sarking. This is normally achieved by draping the sarking loosely over the battens. However, it has been observed in actual practice that the foil sarking is often being pulled tight for ease of installation. This creates a thermal bridge and counters the insulating effect of the sarking. Hence, it was decided to lay the sarking over the rafters and lay the battens on top of the sarking. This guaranteed a batten depth gap between the sheet metal roofing and the sarking.
- The second difference to standard construction practise in the roof was the taping of the sarking at joints. Standard practise requires a 150mm overlap at joints in the sarking. This allows air movement in the general roof space and the cavity of the sheet metal roofing and sarking. In this project, however, the roof sarking was taped for the purpose of examining best building practise and to reduce performance variables.

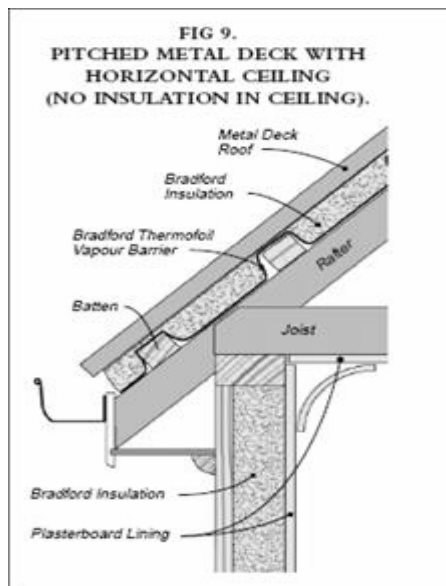


Figure 6: Typical detail of sarking based on The CSR Bradford Building Design Guide

The ceiling system for all three test cells incorporates the use of 10mm plasterboard and R4.0 glass wool ceiling batts. The current requirement for housing in Tasmania is the use of an R3.5 ceiling batt. With the current developments in building standards specifically on efficient use of energy and the concomitant need for a broader research program on thermal performance of domestic buildings, the test cells were designed and constructed to meet anticipated future requirements for testing windows, walls, doors and flooring systems. With this in mind, the use of the highest value standard ceiling batt would be a wise choice. The current off the shelf maximum product at the time of construction (in 2006) was the R4.0 ceiling batt.

The three test cells have the same internal plasterboard wall lining and wall batt insulation but the cavity size and external linings vary. The plywood cladding of Test Cell 1 has a very similar resistance (R value) to that of the clay brick veneer in Test Cells 2 and 3, but has a differing thermal capacity.

The wall insulation of the three test cells is R2.5 rockwool wall insulation batts. At the time of construction, the current requirement for housing in Tasmania is the use of an R1.5 wall batt. As the test cells will be used for some time as a platform of testing windows, doors and flooring systems, the highest value standard wall batt was used. The current off the shelf maximum product is the R2.5 rockwool wall batt.

In the roof space, the application of the building wrap to the walls was considered at length. Standard installation practice provides a 150mm overlap between sheets and this is applied to the structure with steel staples. Common faults with this form of application include the puncturing of the wrap and the provision of air movement between the cavity air space and the outside face of the plasterboard lining. To eliminate this possible variable and to display best construction practise the building wrap was taped at joints. At the same time any punctures in the building wrap were also taped (See Figure 7).



Figure 7: Taped and patched building wrap

The wall framing has an integrated provision for the eventual addition of windows on each face of the building. This required the inclusion of framing within the standard stud work of the wall panel to allow a future 1800 wide full height opening to be made without alteration to the structural frame. Figure 8 shows the framing plan for the test cells while Figure 9 shows the framing as built for Test Cell 2.

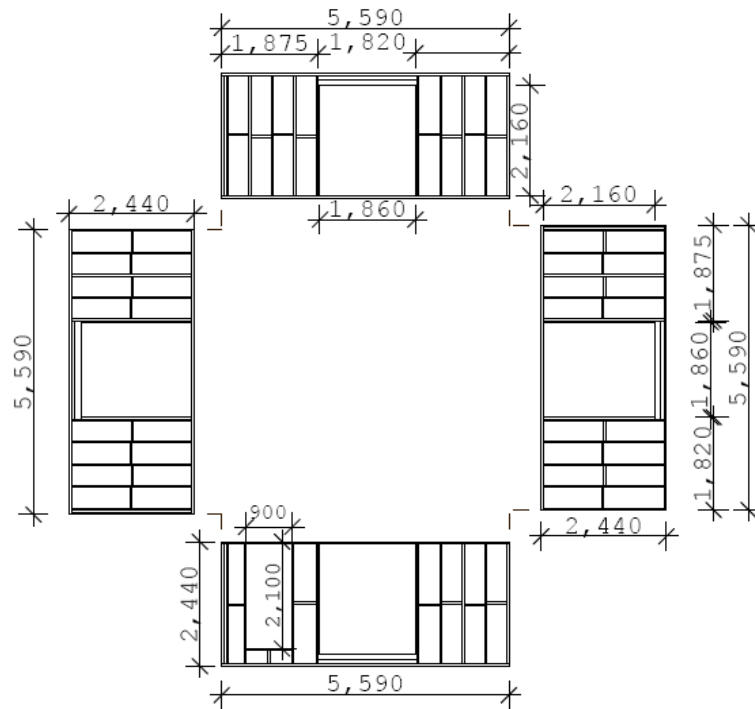


Figure 8: Test Cell Framing Plan



Figure 9: Test Cell 2 Wall and Roof Framing

The provision for future windows and current timber framing practises increased the framing factor of the wall from 12.3% to 18.3% compared to the conventional. The framing factor is the percentage of timber in the elevation of the wall. While timber is a better insulator than steel, it is not as good an insulator as bulk insulation and the greater the area of timber in a wall, the

greater the thermal conductivity of the wall as a system. A fuller description of the test cells is found in Appendix A of this report.

4.5 The Test Cells as Built

To view more detailed plans, elevations and sectional information on the three test cells, please refer to Appendix A of this report.

Test Cell 1 is an unenclosed perimeter platform floored building (See Figure 10). The building sits on timber poles, is timber framed with plywood cladding and has a sheet metal roof.



Figure 10: Test Cell 1 – Western View

Test Cell 2 is an enclosed perimeter platform floored building (See Figure 11). The building sits on poles but has a brick veneer cladding that extends to the ground plane. There are vent holes in the sub floor brick work to allow for ventilation. Test cell 2 also has a sheet metal roof.



Figure 11: Test Cell 2 – Western View

Test Cell 3 is a concrete slab on ground floored building (See Figure 12). The building sits on its concrete slab and has a brick veneer cladding that extends to the ground plane. Test cell 3 also has a sheet metal roof.



Figure 12: Test Cell 3 – Western View

4.6 Shading Issues

In choosing the best site, one of the considerations was to eliminate shading of the test cells. Various sites were extensively documented using three dimensional CAD software in modelling as many possible configurations and locations. Sun and shadow studies were generated until the best site with least shading was found. The three major shading issues that were addressed were:

- Test cells shading each other. The shadow studies defined the optimum separation between the test cells, such that no overshadowing occurred. It was found that a 7500mm north/south separation between the test cells eliminated any shading from one test cell to the other during the winter period. The winter solstice occurred near the end of construction and the actual location of the shadow path was extremely close to that predicted by the computer simulation. No overshadowing of one test cell by another occurred;
- Landscape (See Figures 13 & 14). The existing landscape included some well established trees to the south and some younger native shrubs and trees to the north of the test cell area. Due to University landscape practises, there was a desire to retain the established southern trees. The retention of these trees met our primary design criteria of full solar access during the winter cycle. The trees to the north would have provided critical shading of the test cells and were removed; and



Figure 13: Established Southern Trees



Figure 14: Clearing of Northern Trees

- Existing Buildings (see Figures 15 & 16). The site includes existing buildings to the east and north of the test cell site. The desire to eliminate winter shading was paramount in the site planning of the test cells. To reduce the impact of shading, the test cells were located as south as possible from the northern building. Extensive shadow studies showed that on the winter solstice, test cell 1 would be in full sun by 0900 hours. It was felt that this level of shading would have minimal thermal impact and could be monitored and recorded. The buildings to the east are reasonably distant with minimal shading. The shading that is created by the eastern building occurs during the sunrise period at the equinox. As with the shade from the northern building, it was felt that this level of shading would have minimal thermal impact and could be monitored and recorded. All surrounding buildings were accounted for as shading structures during the thermal performance simulation.



Figure 15: Buildings on the northern edge of the test cell site



Figure 16: Buildings and trees on the eastern edges of the test cell site

5 Test Cell Monitoring System

The long term plan is to monitor thermal performance in three distinct operating periods, namely, *(i)* unheated, *(ii)* continuously heated until the desired temperature is achieved, and *(iii)* intermittently heated. The differences between these operating modes are important.

During an unheated (or free running) period the internal temperature over time gradually forms a sine curve that responds to the external environmental conditions. The difference between the internal and external sine curves is attributed to the test cell fabric moderating the internal environment.

During a heated period, the heater in each cell is set on and off to maintain a specific temperature in the test cell. The monitored internal temperature remains generally flat, except for occasional spiking, where the external environmental conditions create a warmer internal temperature in the cell. The amount of energy for the heater to maintain the indoor temperature is important information.

When heating is intermittent, the test cell is heated and allowed to cool. The decay of the heat inside the test cell is relative to the thermal capacitance of the internal layers in the building fabric, the overall thermal performance of the test cell fabric and the external temperature.

The test cells will be monitored in each operating mode to assess building thermal performance. A log of dates and specific time when the door was opened has been kept for each test cell. This would indicate when the exterior weather condition directly influenced the test cell thermal performance.

This report covers the unheated period in 2007. During this period the heater was turned off. The resulting thermal changes inside the test cells were largely the effect of the building fabric and the external climate.

5.1 The Measured Parameters

The environmental condition for the external and internal zones are created by a mix of the air temperature, humidity, air or wind movement, solar radiation, infiltration rates and mean radiant temperature (Lomas, 1994). The infiltration rates affect the air movement between zones. In a cool climate, these can have a dramatic affect on heating requirement and conversely in a hot climate, can impact on the cooling requirement. To monitor the environmental conditions, each of these data types had to be collected.

The sensors chosen to collect data required a reasonable quality of accuracy and the ability to send or receive a signal at regular intervals for recording data. As AccuRate produces an estimated temperature for each hour to within 0.1°C, the need to establish average hourly temperature to this accuracy and precision was required. The international examples of test buildings revealed a wide range of approaches to monitoring buildings, with limited similarity of approach. In order to establish the average hourly temperature other research projects measured the environmental condition every 10 or 15 minutes. General documentation supported the notion of the ten-minute cycle over the fifteen minute cycle, if the research program had the capacity to manage the data. In this project, the average hourly temperature was calculated from the average of six readings per hour.

Using an instrumentation and data acquisition system, the ten-minute cycle of measurement was carried out in all building zones. The external zone, being outdoor weather conditions, was monitored by an on-site weather station. All three test cells have a roof space and internal room zone. Test cell 1 has an open subfloor, where as test cell 2 has an enclosed sub floor zone and the floor of test cell 3 is a concrete slab on ground.

5.1.1 External Environmental Conditions

To measure the outdoor environmental conditions, an on-site weather station and solar irradiance meter were installed above Test Cell 2 as shown in Figures 17 & 18. The weather station collects data on temperature, humidity, wind speed, wind direction, global solar irradiance, north vertical solar irradiance and diffuse solar irradiance.

For the purpose of empirical validation, a new site-specific climate file was created based on measurements taken on a 10-minute cycle. The AccuRate climate file was modified using measured values instead of the built-in climate data for zone 26. This would essentially lead to a more reliable comparison of simulated and observed thermal performance as both are based on the same climate data.



Figure 17: On-Site Weather Station



Figure 18: The diffuse solar radiation shadow ring device installed in February 2008

The climate file within AccuRate consists of 60 columns of data, of which 39 are important in the AccuRate simulation engine. A summary of the source/reference of input data for the climate file for thermal performance simulations for the test cells is given in Table 2.

Table 2 Sources of Input Data to the AccuRate Climate File for the Test Cells

Column No.	Description	Method
5-6	Month Number	On site data acquisition
7-8	Day Number	On site data acquisition
9-10	Hour Number	On site data acquisition
11-14	Dry Bulb Temperature to 0.1 degrees Celsius	On site data acquisition
15-17	Moisture Content	On site data acquisition
18-21	Atmospheric (air) Pressure	BOM - Launceston Airport. The data file includes a value for mean sea level air pressure. This has been adjusted slightly to include the slight height above sea level for the test cells.
22-24	Wind Speed	On site data acquisition; data adjusted by a factor to account for the height of measuring device
25-26	Wind direction	On site data acquisition
27	Cloud cover	Not measured. At present the simulation analysis is examining if there are any distinct variations in thermal performance for a No Cloud, 50% cloud & 100% cloud. BOM have no suitable data at present. The Satellite has information that could be interpolated into average hourly values but this would be on a fee basis as this is a non standard data request (Approx \$10K).
34-37	Global Solar Radiation	On site data acquisition
38-40	Diffuse Solar Radiation	Derived. Used methods proposed by Boland & Ridley (2008), and Ridley and Boland (2008) to estimate the diffuse fraction from measured global solar radiation. (Note: A diffuse solar radiation shadow ring device was installed on the roof of Test Cell 2 in February 2008 to provide future reference data.)
41-44	Normal Direct Solar Radiation	Derived. Used method proposed by J. W. Spencer (1982) to estimate the diffuse fraction from measured global solar radiation.
45-46	Solar Altitude	Data adopted from existing Launceston Climate file
47-49	Solar Azimuth	Data adopted from existing Launceston Climate file

5.1.2 Internal Environmental Conditions

Empirical validation requires simulating each internal zone; hence each zone was fully instrumented. Measuring equipment was positioned at mid-height at the centre of each zone. Stratification and air movement in the room were monitored using additional sensors, i.e., at 600mm and 1800mm from the floor level in the test cell room. Figures 19, 20 and 21 show the monitoring plan and section of the test cells. This method differs from ASHRAE Standard 55-2004 for interior environmental measurement (ASHRAE, 2004) but is suited for the thermal performance measurement of test buildings (Lomas, 1994).

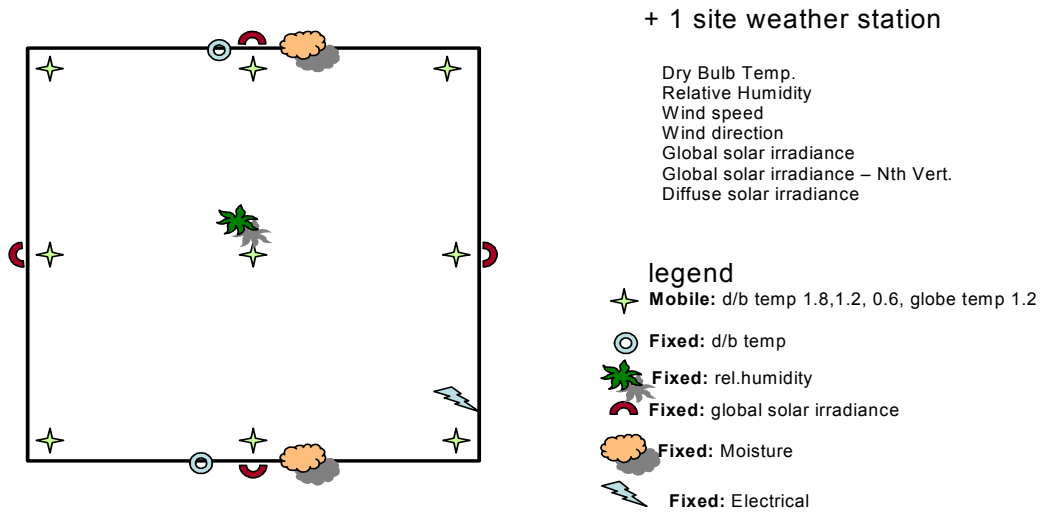


Figure 19: Monitoring Plan of the Three Test Cells

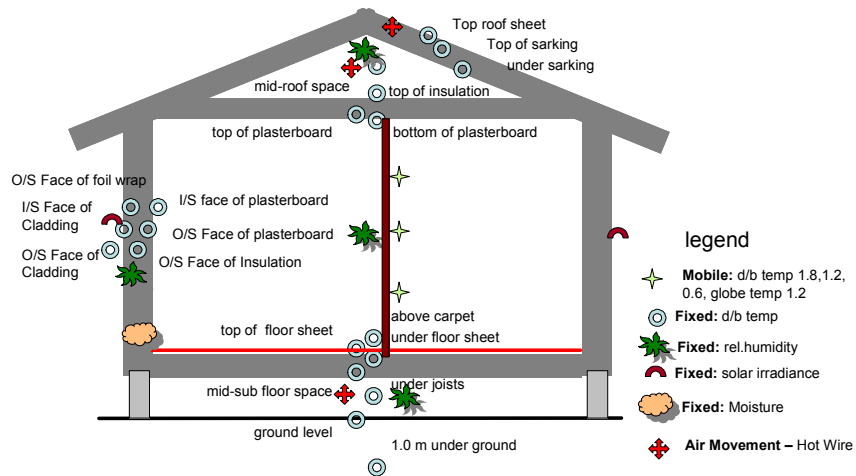


Figure 20: Monitoring Section – Platform Floor

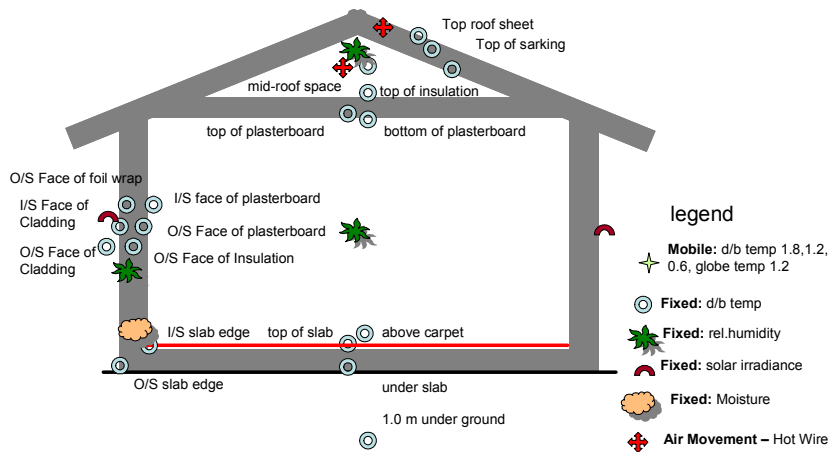


Figure 21: Monitoring Section – Slab on Ground Floor

5.1.3 The Test Cell Room

Within the test cell room, a primary pole was placed at the centre. The pole provided the knuckle for the vertical and horizontal sensor array inside the test cell. As shown in Figure 22, temperature measurements are taken from:

- Interior surface of particleboard platform floor;
- 600mm above floor (1/3 room height);
- 1200mm above floor (mid room height);
- 1800mm above floor (2/3 room height); and
- Interior surface of the plasterboard ceiling.



Figure 22: Sensors attached to the centre of room and edge of room poles

Room humidity was measured at 1200mm height. Initially, eight perimeter poles with sensors were installed in each cell, and were located 100mm from the wall surface in each of the four corners and at the centre of each wall as shown in Figure 22.

To enable a closer examination of the thermal performance of the wall fabric, sensors for measuring mean radiant temperature (MRT), as differentiated from that measuring air temperature, were fabricated. A temperature sensor was installed in the centre of a cooper globe made of two spun copper half spheres of 150 mm diameter, and coated with black paint. Each globe was placed at 1200mm height on the poles.

A horizontal profile was created by inserting sensors in each element of the wall fabric at 1200mm above floor height in both the north and south walls. These include:

- Outside surface of cladding material
- Inside surface of cladding material
- Outside surface of building wrap

- Inside surface of building wrap
- Outside surface of plasterboard lining
- Inside surface of plasterboard lining

The average solar irradiance that impacts on the outer face of the wall fabric was measured using solar irradiation sensors attached at mid height of the four external walls. This is an important factor as this heat is transferred through the external fabric through to the inner layers. The ability to measure the incidence of solar radiation on the north wall and at the same time measure the effect on material temperature will provide a better understanding of conductance, emittance, reflectance and the thermal capacitance of building materials. The walls that do not receive solar radiation will provide the base line data for the comparison.

To establish the rate of air infiltration, tracer gas tests were conducted by Deakin University's Mobile Architecture and Built Environment Laboratory (MABEL) on March and September 2007.

5.1.4 Test Cell Subfloor Space

AccuRate treats the subfloor space as a distinct zone in both the enclosed and unenclosed perimeter platform floored test cells. To measure the environmental condition in these zones, a vertical pole was installed in the centre of the space. This pole records air temperature at ground level, mid sub floor height and the outside surface of particle board flooring. A humidity sensor was also installed at mid pole height (See Figure 23).

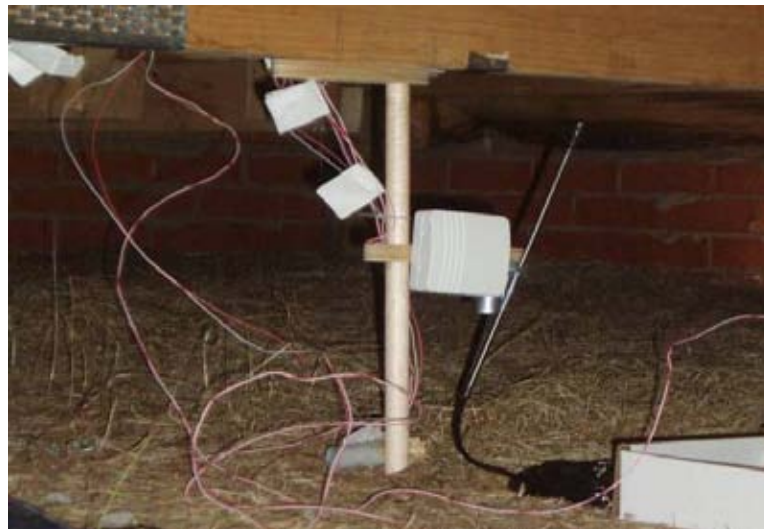


Figure 23: Sensors at the Subfloor Pole

In the case of the unenclosed perimeter platform floor, AccuRate assumes the subfloor environment to be the same as general external environmental conditions. To test this assumption, an array of temperature, air movement and humidity sensors were placed in the middle of the sub floor area. This will enable a comparison of the condition in the sub floor space and the surrounding environment as measured by the weather station.

For an enclosed perimeter subfloor, AccuRate predicts the thermal condition for the enclosed perimeter sub floor zone based on the fabric matrix, ground condition and sub floor ventilation patterns. To examine this model, temperature, air movement and humidity sensors were placed in the mid subfloor area. In addition, air movement in the subfloor space was monitored by means of sensors placed in the subfloor perimeter vents as shown in Figure 24.



Figure 24: Hot Wire Air Speed Sensor at North Sub Floor Wall Vent

Ground temperature affects various floor types in different ways; hence, in-ground temperature was also measured. For example, in a concrete slab-on-ground house, the concrete slab insulates the ground from the environmental condition. In return the concrete slab and ground insulate the floor of the house from the cool winter environmental condition. This insulation process, however, takes a few years to stabilise. In the case of an enclosed perimeter platform house, the insulation level is affected by the rate of air change in the subfloor, whereas the unenclosed perimeter platform is perceived to have little insulating effect. To measure these variables, temperature sensors were installed 1000mm below the ground surface.

One of the key issues addressed in this project is the effect of variable air change rates in the subfloor space, hence tracer gas tests were also conducted by MABEL in March and September 2007.

5.1.5 Test Cell Roof Space

AccuRate treats the roof space as a thermally interactive zone. The simulation process predicts roofspace average hourly temperature. This is a combination of the effect of the environmental conditions on the roofing fabric matrix, the effect of the test cell room below and the rate of air infiltration in the roof space. To validate the roofspace simulation model, a sensor array was installed to measure air temperature, humidity and air movement within the roof zone. A pole with sensors placed at mid-height was placed at the centre of the roof space as shown in Figure 25.



Figure 25: Roof Space Pole for Sensors

To better understand the thermal dynamics of the roof space, additional temperature sensors were installed to establish the vertical temperature profile at the following location:

- Outside surface of plasterboard ceiling
- Outside surface of ceiling batt insulation
- The mid roof space pole array
- Inside surface of sarking
- Outside surface of sarking
- Inside surface of sheet metal roofing
- Outside surface of sheet metal roofing.

An air movement sensor was placed between the sarking and sheet metal roofing in the cavity. The rate of air movement between the sarking and the sheet metal roofing affects the insulation qualities of these materials. This is treated as an air space with limited air movement in thermal modelling. Air infiltration was measured using the tracer gas method.

As in the subfloor, tracer gas tests were also conducted at the roof space by MABEL in March and September 2007.

5.2 Data Acquisition & Management

5.2.1 Sensors

The types of sensors in the test cells are listed in Table 3.

The majority of sensors were installed progressively from mid July 2006 to December 2006. During this period, minor systemic or sensor problems were recognised and rectified. This included the earth cabling between the data logger and channel expansion module, the care of cable connections or terminations, programming errors, span errors and the general testing and calibration of equipment. The rectification of these problems led to improvements in the programming and cabling systems for both the test cells and test houses.

The prolonged installation process was due to disruptions in ordering and international factors. Orders were originally placed for the majority of the equipment to monitor the three house of the Best 5 Star and No Bills project in November 2006. When this project stalled, the existing orders were cancelled. When the construction of the Test Cell project was confirmed, new orders had to be placed with international providers. Supply delays resulted. During this time, international regulations on solder changed and most entities involved in the electrical component industry experienced delays in supply. This included the manufacturer of many of the electrical components included in the test cell monitoring system. Table 4 lists the chronology of the logger installation process.

Table 3: Types of Sensors

Purpose	Sensor Type
Temperature	AD592CN
Humidity	Vaisala Humidity Transmitter, HMW40U
Air Movement	TSI Air Velocity Transducer, Model 8455
Solar Irradiation	SolData Pyranometer, 80SPC
Weather Station Temperature & Humidity	Vaisala humidity and temperature probe; HMP45A
Weather Station Wind Speed & Direction	Pacific Data Systems PDS-WD/WS-10
Current Metering Devices	VeederLine – ISA-SC-551-1

Table 4: Installation dates of data loggers in the test cells

Date	Action
14 July 2006	1 x HOB0 Installed in the centre of each test cell
20 to 26 July 2006	Preliminary data logger with 1 x unshielded AD592CN installed in the centre of each test cell
11 to 15 August 2006	Data logger A installed in test cells. Logger A records the data from the shielded temperature sensors on the room poles and electrical consumption.
24 August 2006	Data logger B installed in each test cell
25 September 2006	Data logger programming revisions for Logger A & Logger B
16 November 2006	Site Weather Station – Wind Speed & Direction
20 December 2006	Site Weather Station – Temperature & Humidity
20 December 2006	Site Weather Station – Global & North Solar Irradiance

5.2.2 Cabling System

The cabling system was suited to provide a desired level of flexibility. Figures 26-30 show the cabling practice for the integrated system developed for this project. The approach allowed the location of the logger and sensor to be changed as needed. They can be placed side by side in one project and at differing ends of a house in another. A method of cable testing was developed to ensure data accuracy, preventing data anomalies noticed in the early stages of the project.

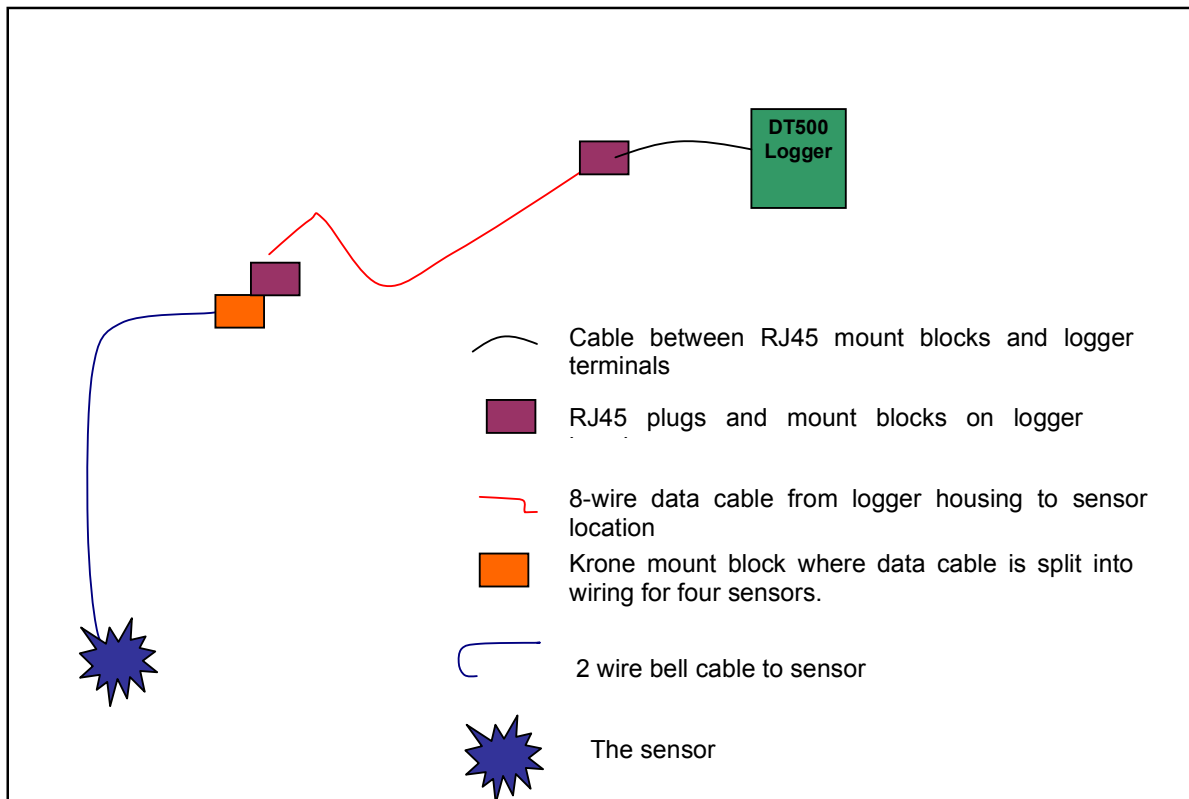


Figure 26: Diagram of Cabling System in the Test Cells

Figure 27: Cabling practice at the data logger box



Figure 28: Cabling Practice showing Category 5 data cable, connector and 2 wire sensor connection

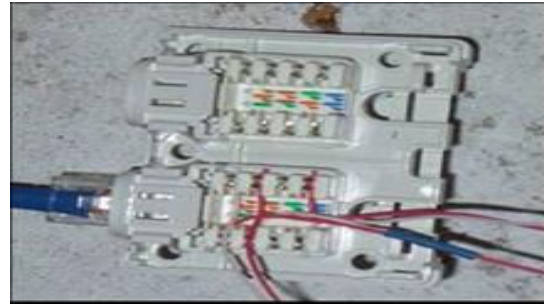


Figure 29: Cabling Practice showing RJ45 plug on outside of data logger box



Figure 30: Cabling practice showing in-wall sensors, i.e., inside brick, outside building wrap, outside insulation, outside plasterboard surface and internal plasterboard surface



5.2.3 Data Acquisition & Storage

The validation process requires the acquisition of full data sets; hence the more reliable analogue approach was adopted in this project. Internationally, projects that used digital or building management systems were prone to data losses due to power disruptions, operating system failures and general computer malfunctions (Torcellini, 2005). The Data Taker DT500 was selected based on price, operational ability, references and support services. The cost of analogue acquisition and storage devices was considerably cheaper than the digital or Building Management System options. Analogue systems rely on simplistic programming and data polling. They use minimal power, which can be upgraded to an uninterrupted power supply with a small battery housed within the data logger.

Until mid 2008, each test cell had two data loggers. One DT 500 (Logger A) primarily recorded the temperatures of the pole sensors, electricity consumption and other temperature sensors in the sub floor and roof space and the other DT 500 (Logger B) recorded data from the remaining temperature sensors, air movement, humidity and solar radiation sensors. With this system, data from each cell was manually downloaded onsite every 16 days due to the limited memory capacity of the DT500.

In 2008, the data acquisition system was upgraded. The Logger As in each test cell were linked via a parallel RS232 circuit, and were wired into another datalogger, a DT80, which was centrally located in Test Cell 2. Data from the weather data station in Test Cell 2 was also conveniently directed to the DT80. A Local Area Network (LAN) interface was added to enable automatic download of data, hence greater off site management and operational opportunities. To further safeguard against loss of data, uninterrupted power supply units were provided and static memory cards were installed in each DT500.

As a further improvement owing to the automatic data download capability, charting of raw data was also added to the system in 2008. This feature enabled immediate detection of abnormal data caused by equipment malfunction and/or disturbance to the monitored zones.

As a final step prior to data processing and statistical analysis, the data was subjected to an intensive data cleaning and checking process using a researcher-developed data checking protocol as guide. The step-wise process was a systematic method of detecting anomalies caused by abnormal occurrences in the building zones. The method includes validation of suspected outliers against reports and records of sensor malfunction, test cell doors being opened, power interruption and surges, and other disturbances to the room environment.

5.2.4 Calibration of Instruments

The sensors and data loggers were purchased new and were carefully inspected for faults prior to installation. The calibration of the data loggers were regularly checked using the manufacturer-provided in-built diagnostic procedure. Any instrument that showed an error or a questionable response was sent back to the supplier for rectification.

All sensors indicated in Table 3 were carefully chosen for their level of accuracy and ease of calibration. A diagnostic procedure was established by the researcher to ensure that wiring from the data logger to each sensor did not cause errors in measurements. On-site tests and calibration of each sensor during initial installation and subsequent replacements involved careful cross checking with a calibrated sensor. Sensors showing questionable readings were replaced.

6 Results and Discussion

The following discussions cover data collected in 2007, during the unheated operating stage without carpet cover. Firstly, the test cells' thermal performances are compared during one warm and one cold four-day period. Results of infiltration measurements taken in September 2007 are presented next, and finally, a preliminary residual analysis of the measured and simulated thermal performance of the test cells is presented.

6.1 Measured Room Temperature Stratification

Figures 33-35 show the subfloor air speed and the indoor air temperature readings at 600mm, 1200mm and 1800mm heights above the floor in the three test cells during a four-day warm period, and Figures 36-39, a cool period.

During both warm and cool periods, the airspeed in Test Cell 1 subfloor, being unenclosed, was higher than in Test Cell 2 which had an enclosed subfloor with perimeter vents. The indoor

temperature swings at the three heights in Test Cell 1 and 2 relate to the subfloor air speed, whereas the indoor air temperature in the Test Cell 3 was relatively very stable.

During the warm period, indoor temperature in all three Test Cells was warmest at mid-height (1200mm). In Test Cells 1 and 3, it was coolest near the floor level (600mm) whereas not consistently so in Test Cell 2. The temperature near the ceiling (at 1800mm) was cooler than at mid-height in all three Test Cells, suggesting an unexpected air circulation pattern.

During the cool period, Test Cells 2 and 3 show more consistent and distinct trends compared with Test Cell 1. In Test Cell 2, the temperature at a height near the ceiling was higher than at mid-height and near the floor. In Test Cell 3, the near ceiling and mid-height temperatures were higher than near the floor. In Test Cell 1, a consistent trend towards the end of the four-day period showed that the temperature near the ceiling was the highest whereas at mid-height, the lowest.

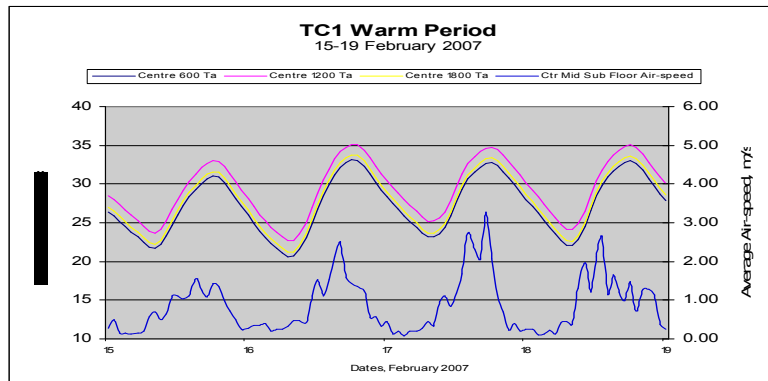


Figure 33 Test Cell 1 Room Temperature Stratification and Subfloor Airspeed during a Warm Week

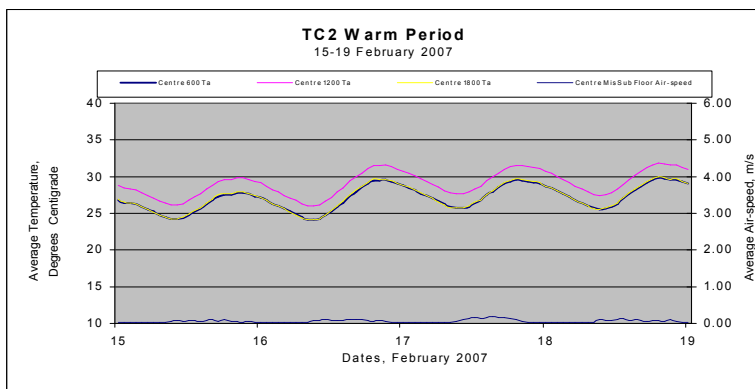


Figure 34 Test Cell 2 Room Temperature Stratification and Subfloor Airspeed during a Warm Week

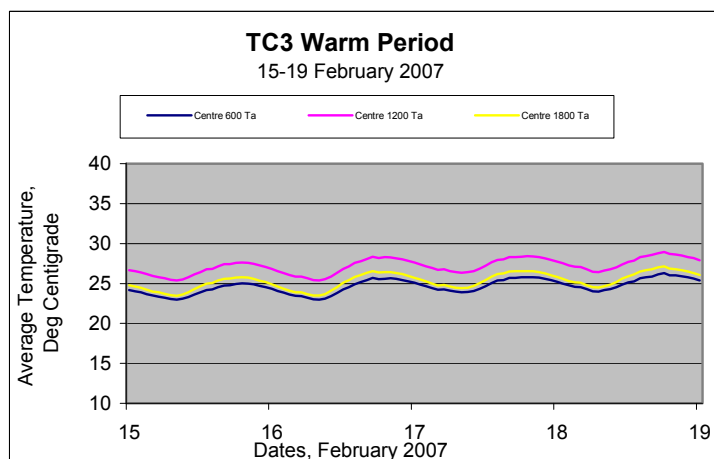


Figure 35 Test Cell 3 Room Temperature Stratification during a Warm Week

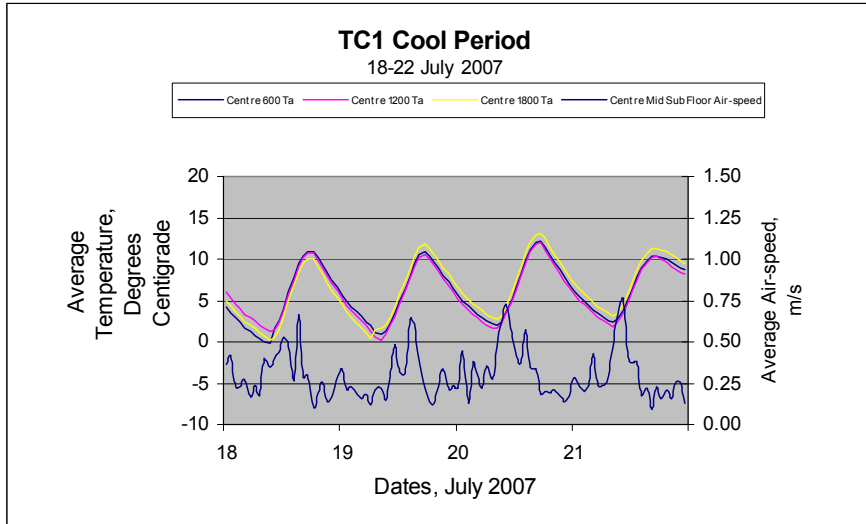


Figure 36 Test Cell 1 Room Temperature Stratification and Subfloor Airspeed during a Cool Week

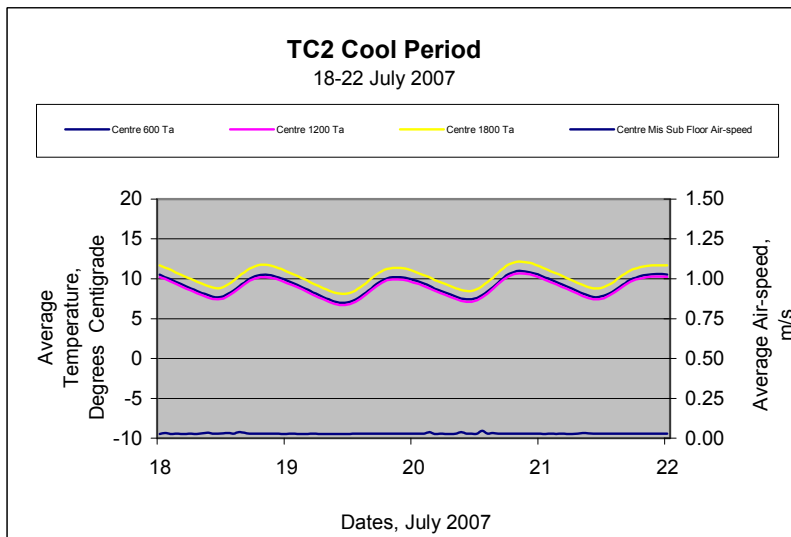


Figure 37 Test Cell 2 Room Temperature Stratification and Subfloor Airspeed during a Cool Week

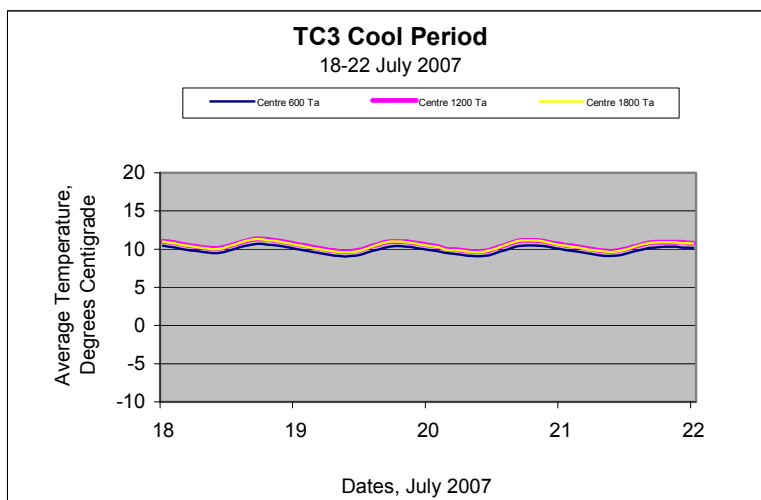


Figure 38 Test Cell 3 Room Temperature Stratification during a Cool Week

6.2 Infiltration Measurements

Air infiltration in the cells was assessed by Deakin University's Mobile Architecture and Built Environment Laboratory (MABEL) on 24-27 September 2007. The weather station on-site measured wind velocity and direction. Tracer gases namely, carbon dioxide, sulphur hexafluoride and acetone, were injected into each cell's roof space, central room, and subfloor space, respectively. Two test cells were tested simultaneously, with Test Cell 2 serving as the reference point for the other two cells. Air change rate was calculated in terms of air change per hour (ACH), i.e., one ACH means that the air in the house is replaced in a one-hour period. To determine potential air leakage pathways, thermal images of the interior and exterior fabric of the test cells were taken while heaters were switched on.

6.2.1 External Wind Speed and Air Change Rates

Figures 39, 40 and 41 show the wind speed and its effect on the air change rates per hour (ACH) in the roof and rooms over a two-day period. With ACH generally not exceeding 0.1, it can be said that the rooms were very airtight when the doors were shut. It was noted that measurements greater than 0.1 were instances when doors were opened such as when staff entered the room to monitor the tests. In the roof spaces, however, higher airflow was observed compared with the airflow in the rooms, with Test Cell 1 and Test Cell 3 roof spaces experiencing relatively higher airflows compared with Test Cell 2.

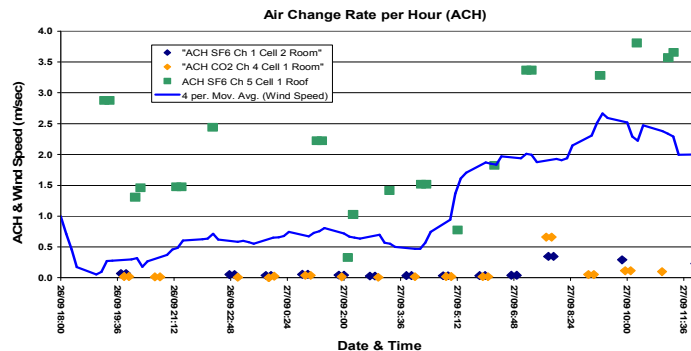


Figure 39: Wind velocity and air change rates in the rooms and roofs of Test Cell 1 and Test Cell 2

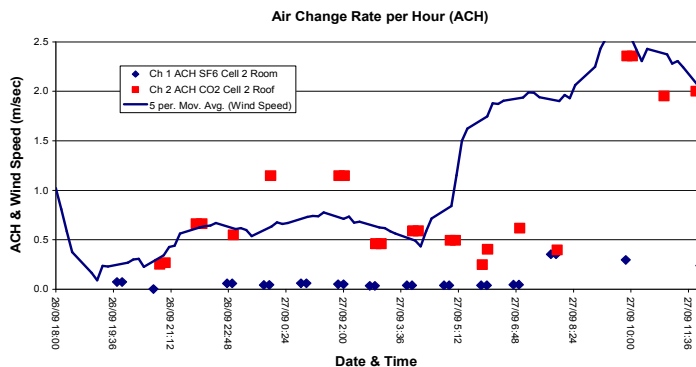


Figure 40: Wind velocity and air change rates in the rooms and roofs of Test Cell 2

Figure 42 shows that in Test Cell 2, acetone tracer gas released in the subfloor space (Ch 3) was detected in the room (Ch 1), possibly due to leakage at the bottom plate-particleboard joint. Furthermore, the decay rate of the acetone tracer gas was significantly slower compared to its migration into the room. This could be attributed to the quality of building wrap installed in the wall cavity, which appears to have prevented the tracer gas from leaking out through the walls.

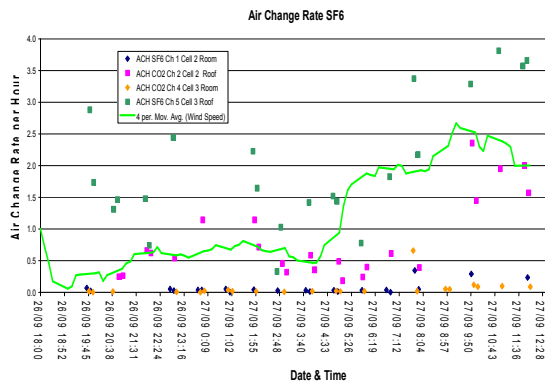


Figure 41: Wind velocity and air change rates in the rooms and roofs of Test Cell 2 and Test Cell 3

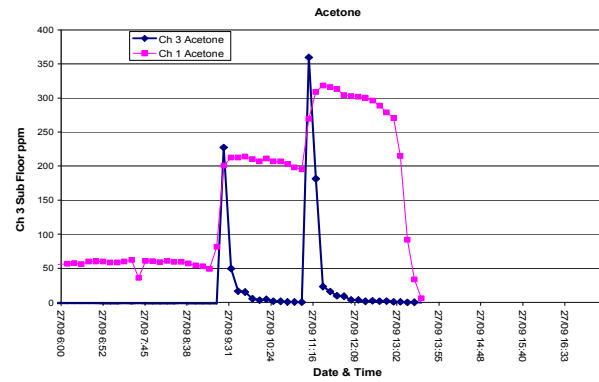


Figure 42: Volume of acetone gas migrating from the subfloor into the room in Test Cell 2

6.2.2 Thermal Imaging

Figures 43 and 44 are thermal images of the Test Cells 1 and 2 facades taken when the heaters inside the test cells were switched on. Figure 40 shows that the temperature of Test Cell 2's east façade (brick wall) was around 25°C, which is significantly warmer than its surroundings, whereas that of Test Cell 1 (plywood wall) was around 40°C. In both cases, the cavity air space reduced heat flow to the next layer of building wrap and wall insulation.

Figure 44 shows the north facade of Test Cell 1 around noon. The wall surfaces that were not shaded i.e., not covered by the shadow cast by the eaves at that particular time of the day, had temperatures ranging from about 20°–30°C, whereas under the eaves and the surroundings areas were cooler with temperatures ranging from around 18°C down to less than 10°C. The image also shows that the temperature at the open subfloor space was cooler at around 12.9°C maximum compared with its surroundings.

Figures 45 and 46 are thermal images of the interior walls and the adjoining floors in Test Cell 2 (timber floor with enclosed subfloor) and Test Cell 3 (with concrete slab-on-ground floor), respectively. The images show that, with the heaters inside the test cells switched on, the surface temperature of the concrete slab was higher compared with that of the timber floor. The cooler temperature at the wall-to-wall and wall-to-floor joints compared with the adjacent surfaces are evident, indicating potential air or thermal leakage pathways. This can explain the migration of the acetone tracer gas from the subfloor of Test Cell 2 as shown in Figure 42.

Wall and wall-to-floor joints are potential leakage pathways in both timber floor and concrete slab floor houses.

6.2.3 Infiltration rates in the test cells

The three test cells were very airtight with air change rates of up to 0.1 ACH. Under the same external wind conditions, airflows measured at the roofs were significantly higher and with a wider variation compared with the airflows in the rooms. Such variation indicates that construction practice is important to the thermal performance of the houses, as the three roofs had identical design and construction details, and were built in a standard work sequence by the same tradesmen. Furthermore, thermal images showed that unintentional openings in wall-to-wall and wall-to-floor joints are potential air leakage pathways in both timber floor and concrete slab floor houses.

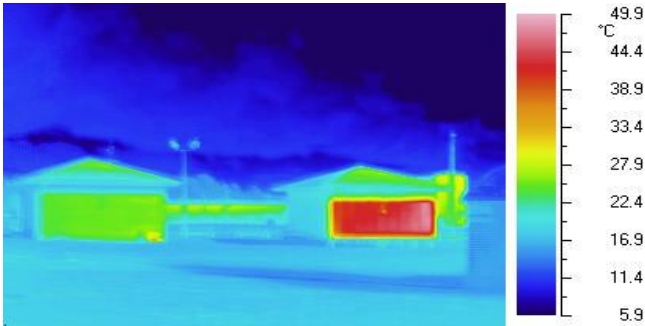


Figure 43: East walls of Test Cell 2 and Test Cell 1 at 11:50 AM 28/09/07

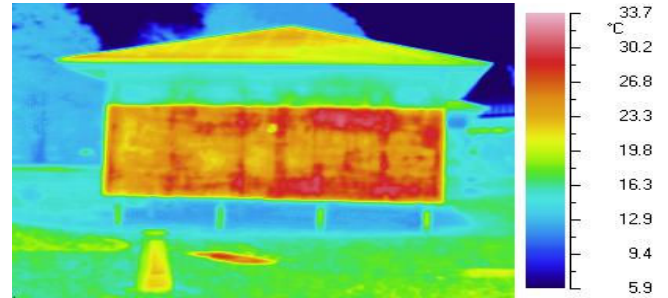


Figure 44: North wall of Test Cell 1 with heater ON 12:05 PM 28/9/07

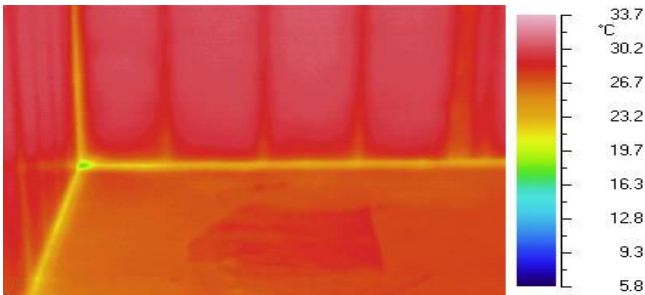


Figure 45: Inside Test Cell 2 with heater ON 2:55 PM 28/09/07

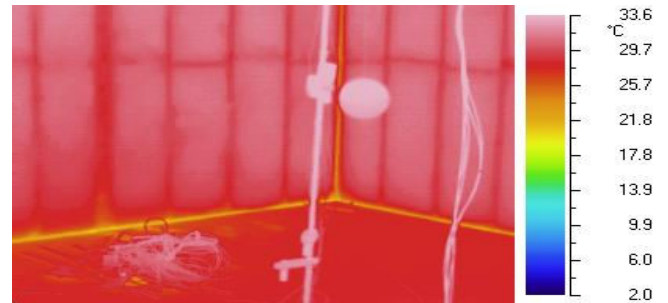


Figure 46: Inside Test Cell 3 with heater ON 2:58 PM 28/9/07

6.3 Comparison of Simulated vs. Measured Room Temperature

The measured data is the average of the average of temperature readings taken every ten minutes at 600mm, 1200mm & 1800mm heights measured from the floor of the room.

On the other hand, the scratch file for AccuRate simulation reflected site-measured weather data, instead of the AccuRate's built-in TMY, and with no room heating or cooling for the entire 24 hours of each day.

6.3.1 Comparison on a Warm Week

In all three test cells, the measured temperature is higher than simulated temperature (See Figures 47-49). In Test Cell 3, the wave patterns of measured temperature appear almost like an elevated version of the simulated one, i.e., their time lags are almost identical, and their peaks and swings occur at the same time. In Test Cell 2, this observation is also true but to a lesser extent. A completely different behaviour is observed in Test Cell 1, i.e., the time lag for measured temperature is greater than simulated, and the occurrence of their peaks and swings do not coincide. Furthermore, the range for measured temperature is smaller than simulated.

Figure 47: Outdoor, simulated and measured temperature in Test Cell 1 on a warm week

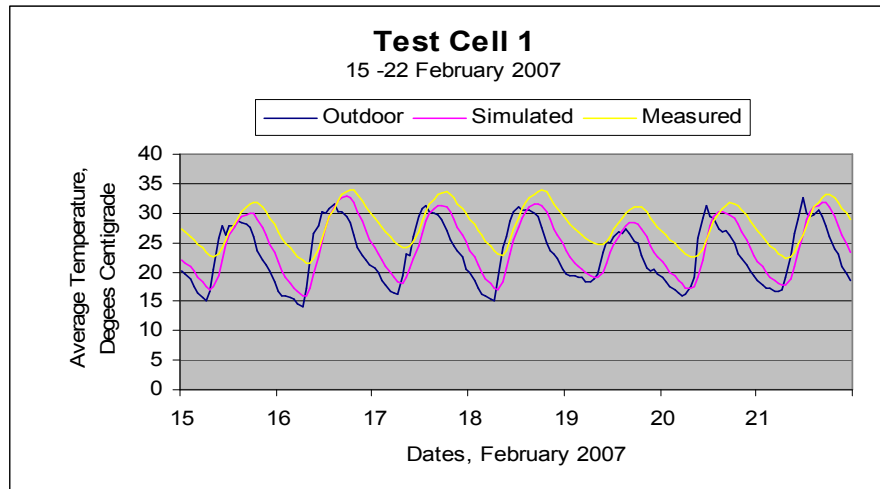


Figure 48: Outdoor, simulated and measured temperature in Test Cell 2 on a warm week

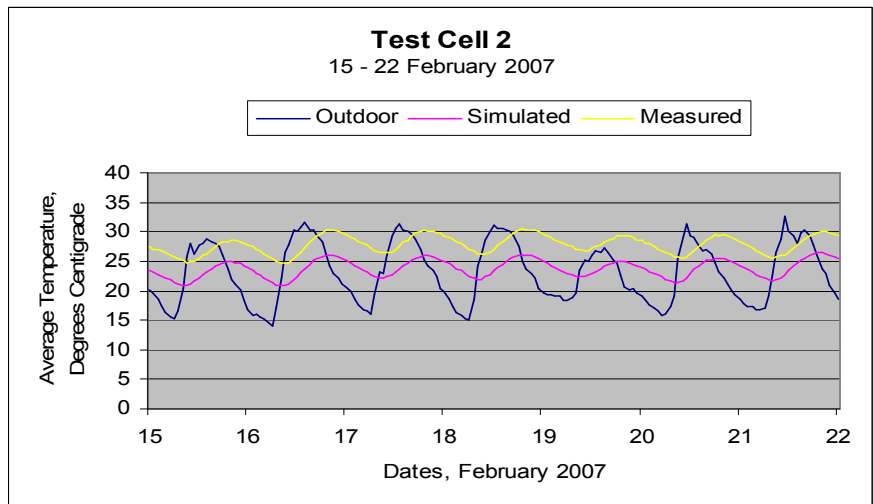
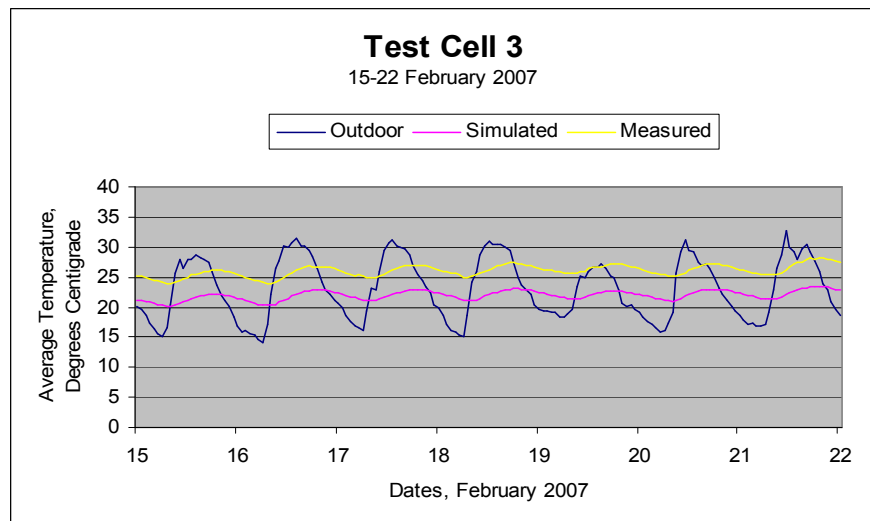


Figure 49: Outdoor, simulated and measured temperature in Test Cell 3 on a warm week



6.3.2 Comparison on a Cold Week

Measured temperature was always higher than simulated temperature in Test Cells 2 and 3, but not in Test Cell 1 (See Figures 50-52). Although the maximum values for both measured and simulated were very close in Test Cell 1, the minimum values for simulated temperature were significantly lower. Similar to the observation on peaks and time lags during the warm period, the simulated temperature wave in Test Cell 3 conforms closely with the measured one. This was also observed in Test Cell 2 but to a lesser extent. As in the warm week, the peaks, swings and ranges in measured and simulated temperatures in Test Cell 1 do not conform.

Figure 50: Outdoor, simulated and measured temperature in Test Cell 1 on a cold week

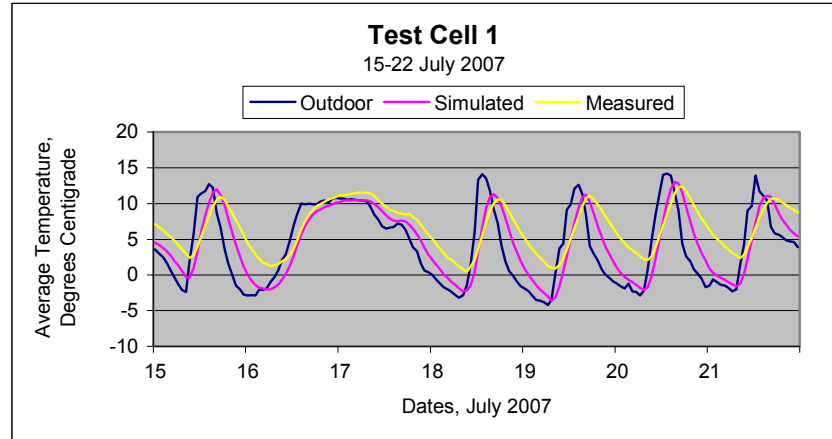


Figure 51: Outdoor, simulated and measured temperature in Test Cell 2 on a cold week

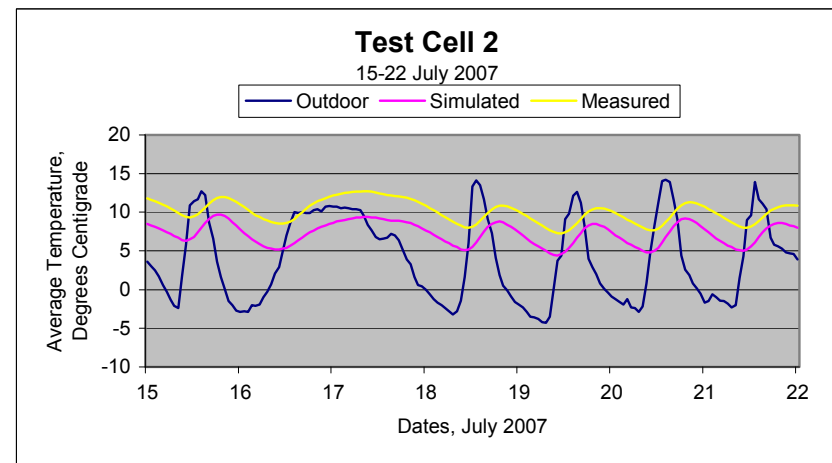
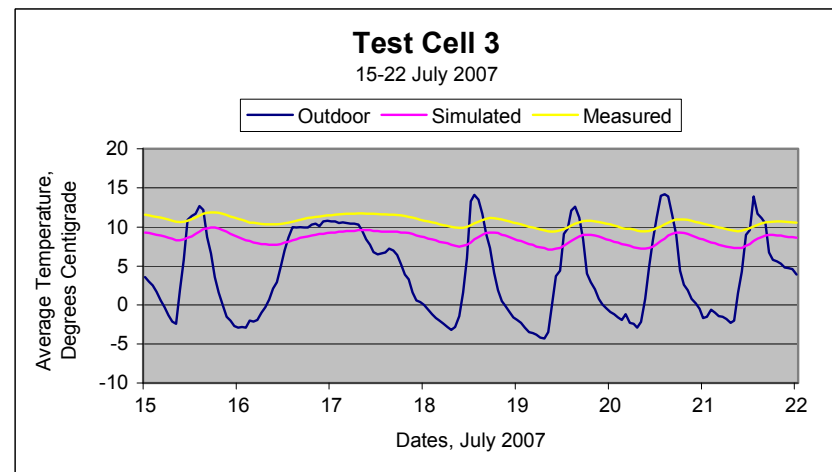


Figure 52: Outdoor, simulated and measured temperature in Test Cell 3 on a cold week



6.3.3 Comparison of the Overheating and Underheating Degree Hours

Degree underheating and degree overheating hours are measures of the difference between the actual room temperature and a designated comfort temperature band over time. For example, if the actual room temperature in a room is 12°C for 3 hours and the thermostat setting is 20°C, the degree under-heating hours are 3 x (20 - 12) or 24 degree under-heating hours.

In Launceston, the thermostat settings to achieve a comfortable temperature during particular hours of the day and night in the living rooms and bedrooms are shown in Table 5. It is assumed that no activity occurs from 12 midnight until 6AM in the living room, and similarly, from 10AM-3PM in the bedrooms.

Table 5: The thermostat settings in Launceston for the Living Room and Bedroom (ABCB, 2006)

	Time	Temperature, °C	
		Minimum	Maximum
Living Room	0700 to 2400	20.0	22.5
	0000 to 0600	nil	nil
Bedroom	0000 to 0700	15.0	22.5
	0800 to 0900	18.0	22.5
	1000 to 1500	nil	nil
	1600 to 2400	18.0	22.5

In order to further compare the thermal performance of the Test Cells relative to each other, overheating and underheating degree hours were calculated for the warm and cold weeks that were earlier discussed in Section 6.3.2, the temperature charts of which are shown in Figures 47-49, and 50-52, respectively.

Tables 6 and 7 summarize the daily average simulated and as measured under-heating hours and over-heating degree hours for the three cells. In Table 6, the cells were assumed to be living rooms, whereas in Table 7, bedrooms. The thermostat settings used in the calculations are found in Table 5.

In Table 6, “Difference” was calculated as the simulated value less the measured value. Ideally, we would like the absolute values of the differences between simulated and measured to be as small as possible. The negative values of “Difference” indicate that, for all test cells, lower values of overheating degree hours were obtained from the AccuRate predicted hourly temperatures within the 7 days, compared to measured values. Table 6 also shows that based on AccuRate hourly temperatures, overheating degree hours are underestimated (relative to the measured values) by as much 33.61 degree hours for Test Cell 1, 28.06 degree hours for Test Cell 2, and 60.18 degree hours for Test Cell 3.

In Table 6, the percentage ratio of simulated to the measured overheating degree hours for each test cell is shown. The closer this percentage value to 100%, the closer is the simulated daily overheating degree-hours value to the measured. A value less than 100% indicates an underestimation by AccuRate relative to measured values, and a value over 100% indicates an overestimation. With the assumed thermostat settings as in Table 5, the AccuRate simulation more closely predicted overheating degree hours for Test Cell 1 (68.48%), compared to Test Cell 2(10.56%), and Test Cell 3 (4.29%). The daily average overheating degree hours during the warm week for Test Cell 2 and 3 are considerably underestimated by AccuRate.

It is interesting to note that, with assumed thermostat settings as in Table 5, AccuRate-predicted hourly temperatures resulted in some underheating degree hours for Test Cell 1 (4.71 degree

hours) and Test Cell 2 (4.07 degree hours) during the warm week, whereas the measured temperatures resulted in very little to none at all.

For the cool week, the positive values of daily average underheating degree hours in Table 6 indicate that underheating degree hours resulting from AccuRate hourly temperatures are higher compared to measured ones. Test Cell 1 daily average underheating hours based on simulated hourly temperature values was overestimated by 25.09 degree hours relative to measured values, 45.18 degree hours for Test Cell 2, and 35.33 degree hours for Test Cell 3. In terms of absolute value, Test Cell 2 daily average underheating degree hours appears to be overestimated significantly, compared to Test Cell 1 and 3.

Table 7 shows a comparison of daily average under- and overheating degree hours in the test cells modelled as bedrooms. The results are very similar to Table 6, i.e., an observed underestimation of daily overheating degree hours by AccuRate especially in Test Cells 2 and 3 during the warm week, and the overestimation of underheating degree hours especially in Test Cell 2 during the cold week is accentuated. Similarly, AccuRate-predicted hourly temperatures resulted in some unexpected underheating degree hours for Test Cell 1 and Test Cell 2 during the warm week although the values are almost negligible. Notably, the measured temperatures resulted in no underheating degree hours during the warm week, and no overheating degree hours during the cool week.

These results also show that based on the thermostat settings in Launceston as per ABCB protocol for HER software (2006), similar trends in overheating and underheating degree hours are obtained for the living room and bedroom during the warm and cold weeks.

Table 6: Daily Average Under/Overheating Degree Hours in the Test Cells assumed as Living Rooms

	Test Cell 1				Test Cell 2				Test Cell 3			
	Simulated	Measured	Difference	Simulated Measured %	Simulated	Measured	Difference	Simulated Measured %	Simulated	Measured	Difference	Simulated Measured %
Warm Week												
Overheating	73.00	106.61	-33.61	68.48	3.31	31.38	-28.06	10.56	2.70	62.88	-60.18	4.29
Underheating	4.71	0.00	4.71	-	4.07	0.13	3.94	31.30	0.00	0.00	0.00	-
Cold Week												
Underheating	242.40	217.31	25.09	111.54	214.69	169.51	45.18	126.65	192.47	157.14	35.33	122.48
Overheating	0.00	0.00	0.00	-	0.00	0.00	0.00	-	0.00	0.00	0.00	-

Table 7: Daily Average Under/Overheating Degree Hours in the Test Cells assumed as Bedrooms

	Test Cell 1				Test Cell 2				Test Cell 3			
	Simulated	Measured	Difference	Simulated Measured %	Simulated	Measured	Difference	Simulated Measured %	Simulated	Measured	Difference	Simulated Measured %
Warm Week												
Overheating	57.64	96.64	-39.00	59.65	3.43	33.22	-29.80	10.32	2.70	56.01	-53.31	4.82
Underheating	0.29	0.00	0.29	-	0.11	0.00	0.11	-	0.00	0.00	0.00	-
Cold Week												
Underheating	226.83	178.90	47.93	126.79	163.93	112.57	51.36	145.62	144.91	106.70	38.21	135.82
Overheating	0.00	0.00	0.00	-	0.00	0.00	0.00	-	0.00	0.00	0.00	-

6.3.4 Implications of the Measured and Simulated Thermal Performance Comparison

In general, AccuRate simulated hourly temperatures in the test cells were lower than the measured values in all test cell zones. It has been shown that this resulted in an underestimation of overheating degree hours in the bedroom and living room during the warm weather; and an overestimation of underheating degree hours in all test cells during cool weather, but most especially Test Cells 2 and to a lesser extent, Test Cell 3.

Assuming that the comparison of over- and underheating degree hours presented in Section 6.3.3 generally applies throughout the whole year, it is possible that the thermal performance representation of features common to all test cells are under-rated in AccuRate. A closer examination of the roof and wall models, specifically the contribution of timber frame elements such as the trusses, walls and floor frames, will be looked into in an attempt to account for the discrepancies.

AccuRate assigns a default wall framing ratio based on conventional construction methods. In hot-box tests, the framing factor is often between 11 and 14%. In reality, however, the construction methods that have emerged, including those used in the test cells, have larger framing factors. A study performed by ASHRAE in 2003 found an average 25% framing factor for US homes (Kośny, 2006). The construction details that contributed to an increased wall framing factor include the following:

- (i) Provision for future windows. The basic wall framing in the test cells consists of a bottom plate, studs, noggings and a double top plate. As a provision for the eventual installation of a window of 1800mm wide-full height opening without altering the structural frame, additional lintel and jamb studs were installed. This resulted in an increase in framing factor from 12.3% to 18.3%.
- (ii) Stud spacing. The frames were prefabricated with stud spacing of less than 450mm centres at an average. This added at least one stud to the wall frame.
- (iii) Double top plate. This has become a standard practice so that the builder does not need to consider the vertical structural line to support roof trusses. This added an extra 35mm of framing around the entire building.
- (iv) Jamb studs: In the test cells the double jamb stud system was used, resulting in an increase in the framing ratio. This created a section of 105mm (3x35) timber bridging in the wall. Houses built in the 1990s would only have the standard 50mm stud with a notched lintel.

The test cells have R2.5 wall insulation installed within the timber framing. A careful analysis of the test cells wall framing undertaken jointly with CSIRO resulted in a revised R value for each wall. The current analysis of the wall timber framing ratio reduced the wall system R value by 25%.

In roofspaces, the low thermal conductivity of timber minimises the occurrence of thermal bridging resulting in a reduction of the overall R-value of a structure. The test cells have a unique residential hip-type roof truss made of considerably larger quantity of timber compared to the simple skillion roof truss commonly used in buildings of the same volume. A more realistic value of thermal mass in the roofspace will be determined and used in future simulations.

Furthermore, the roof construction of the test cells was such that the sarking was laid over the rafters and the battens, on the sarking. In addition, the sarking was taped instead of overlapped as a means of minimising air movement from the cavity between the sarking and metal roofing to the general roof space.

The differences in time lags of the peaks and swings of measured and simulated room temperatures relative to outdoor temperature, which was particularly observed in Test Cell 1 and to a lesser extent in Test Cell 2, suggest a careful examination of the subfloor and ground

models. AccuRate assumes that the subfloor space environmental conditions and the external environment are the same. The actual measurements of the subfloor conditions, as well as the ground conditions in this project provide an opportunity to validate this assumption.

6.4 Residual Analysis

Residual values were calculated for all building zones (room, roof and subfloor) in all three test cells within a 12 month period in 2007. A residual is the difference of measured temperature and that resulting from the AccuRate simulation (referred to as simulated or predicted temperature). A positive residual results when the measured is higher than the simulated temperature.

Residuals can be used to detect or track any factors which contribute to systematic errors (bias) in the models. Ultimately one might search for relationships between the residuals and various inputs to the model, especially where the residuals appear to be relatively large, and thus contribute to improvements in the model.

6.4.1 Residual Histograms and Time Series

The residual histograms give a detailed description of the overall size and distribution of the residuals. The time series of residuals displays their behaviour through time, including any drift, burst errors, or possible seasonal effects not included in the models.

The residual histograms in the three building zones in each test Cell are shown in Figure 53, and the time series in Figures 54A and 54B. Note that in Test Cell 3, measurements in October to December were tentatively not included at this point pending further examination of suspected anomalies. Also, possible causes for unexpected elevated residuals such as those between the 5000th and 6000th observations in Test Cell 1 (Figure 54A) will be examined and discussed in future technical reports.

In general, the room temperature residuals are mostly positive except for a small number of negative residuals in Test Cell 1, i.e., in general, measured temperature in the test cell rooms are almost always higher than those predicted by AccuRate. In Test Cell 1, residuals fall within the range of -4°C to 8°C, but largely within 0°C to 6°C; in test Cell 2, range is from 1°C to 6.5°C but largely between 2.5°C to 5°C; and in test cell 3, range is from 1 to 5.5 but largely within 1.5 to 4.5°C.

The bulk of roof temperature residuals in all three test cells are positive, but are relatively larger than the room and subfloor residuals. The residuals in Test Cell 1 roof fall within -25°C to 15°C, with the bulk falling within -5°C to 10°C; in test cell 2 the range is -8 to 14, but mostly within -2°C to 8°C; and in test cell 3, residuals range from -15°C to 12°C, and mostly within 3°C to 9°C. In general, we want the residuals to be small. The large roof residuals firm up suggestions to further examine AccuRate's representation of the roof zone thermal performance.

In the roof residual time series shown in Figure 54A, the residuals in the extreme portions of the time series, i.e. during the warm months, appear to be larger than the cold months. This suggests examination of seasonal variations in the roof model.

In the timber floored test cells, the subfloor temperature residuals are mostly positive, the range of which are very close to the range of room residuals. The subfloor temperature residual time series shows that AccuRate's predicted temperatures in the enclosed subfloor are generally closer to the measured temperature throughout the year, compared to the unenclosed subfloor. This further suggests validation of AccuRate's assumptions on the subfloor environmental conditions.

6.4.2 Correlation of Measured and Simulated Temperature

For all test cells, scatterplots of measured vs. simulated temperatures in the room, roof and subfloor (see Figures 55A and 55B) show positive linear correlation, i.e., the simulated temperature increases linearly as the measured temperature increases. In each plot, the linear relation of measured and simulated temperatures is expressed by the equation indicated in each chart. The steeper the slope of the fitted line, the bigger is the increment in measured temperature corresponding to a 1°C increase in the simulated temperature. For example, a simulated temperature of 0°C in Test Cell 1 corresponds to a measured temperature of 2.40°C and every 1°C increment in simulated room temperature corresponds to a measured temperature increment of 0.89°C. In Test Cell 2, a simulated temperature of 0°C corresponds to a measured temperature of 2.79°C and every 1°C increment in simulated room temperature corresponds to a measured temperature increment of 1.06°C.

6.4.3 Heat Transfers between Adjacent Zones

Plots of residuals against various inputs may also be a useful diagnostic tool. Plots of residuals in the test rooms vs. residuals in adjacent spaces may help to confirm whether heat transfers between adjacent spaces are correctly modelled.

In Figure 56, the room and roof residuals in Test Cells 1 and 3 are positively correlated, unlike in Test Cell 2. In Test Cell 1, a 0°C residual (i.e., measured and simulated are equal) in the roof temperature corresponds to a room temperature residual of 2.40°C, and every 1°C increase (or decrease) in roof residual corresponds to 0.22°C increase (or decrease) in room residual. In Test Cell 2, a 0°C roof temperature residual corresponds to a room temperature residual of 4.18°C, and every 1°C increase (or decrease) in roof residual corresponds to 0.06°C decrease (or increase) in room residual. In Test Cell 3, a 0°C residual in the roof temperature corresponds to a room temperature residual of 3.39°C, and every 1°C increase (or decrease) in roof residual corresponds to 0.01°C increase (or decrease) in room residual.

On the other hand, the room and subfloor residuals for both test cells are positively correlated, i.e. as the subfloor residual increases, the room residual also increases. When measured and simulated subfloor temperatures are equal in Test Cell 1, the measured room temperature is higher than the simulated temperature by 1.78°C. In Test Cell 2, when measured and simulated subfloor temperatures are equal, the measured room temperature is higher than the simulated temperature by 2.89°C.

These plots have been useful in detecting instrumental etc. errors. Ultimately we hope to examine the groups of residuals of largest magnitudes, in order to understand the reasons behind apparent failures in the model to deal with certain kinds of conditions. The plots of the kind “room vs. roof” and room vs. subfloor in Figure 56 suggest that some joint time series exploration may be helpful in understanding the model responses. In Figure 57, the positive correlation of the measured subfloor vs. room residual in Test Cell 1 in contrast to the negative correlation in Test Cell 2 suggests further examination of the subfloor and ground models as follows:

- (i) Unenclosed platform floor. At present AccuRate treats the subfloor temperature for this type of building as the same as the environmental air temperature. In this project, it was observed that the measured temperature for the subfloor zone of the unenclosed platform floored test cell was not the same as the environmental air temperature. The effect of the thermal mass of the timber poles, bearers & joists to the subfloor environment will be examined in future simulations.
- (ii) Enclosed platform floor. The current simulated subfloor model is showing a distinct difference to the site measured data in the enclosed subfloored test cell. A careful analysis of the subfloor ventilation and thermal mass is being undertaken and will be included in future simulations.

(iii) Ground Model. Although this applies directly to the slab on-ground test cell, the ground model in all three test cells has been called into question. The ground and subfloor models require further development before too many conclusions are made. Future analysis will be undertaken to examine the site measured ground temperatures compared with the ground temperature used in AccuRate. Comparison shall be made with the ground models in Energy Plus and one other international reference software.

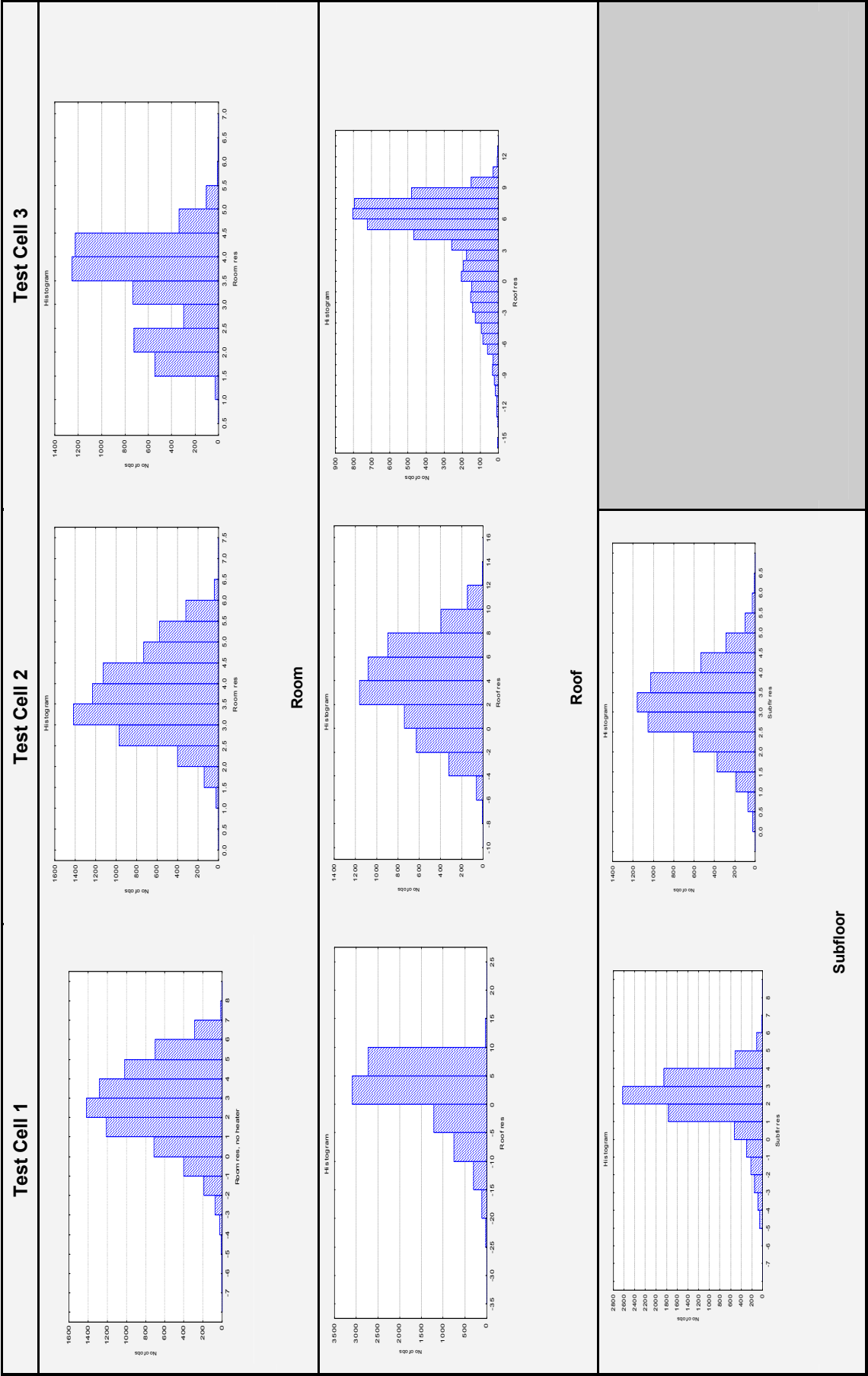


Figure 53 Test Cell Zones Residual Histograms

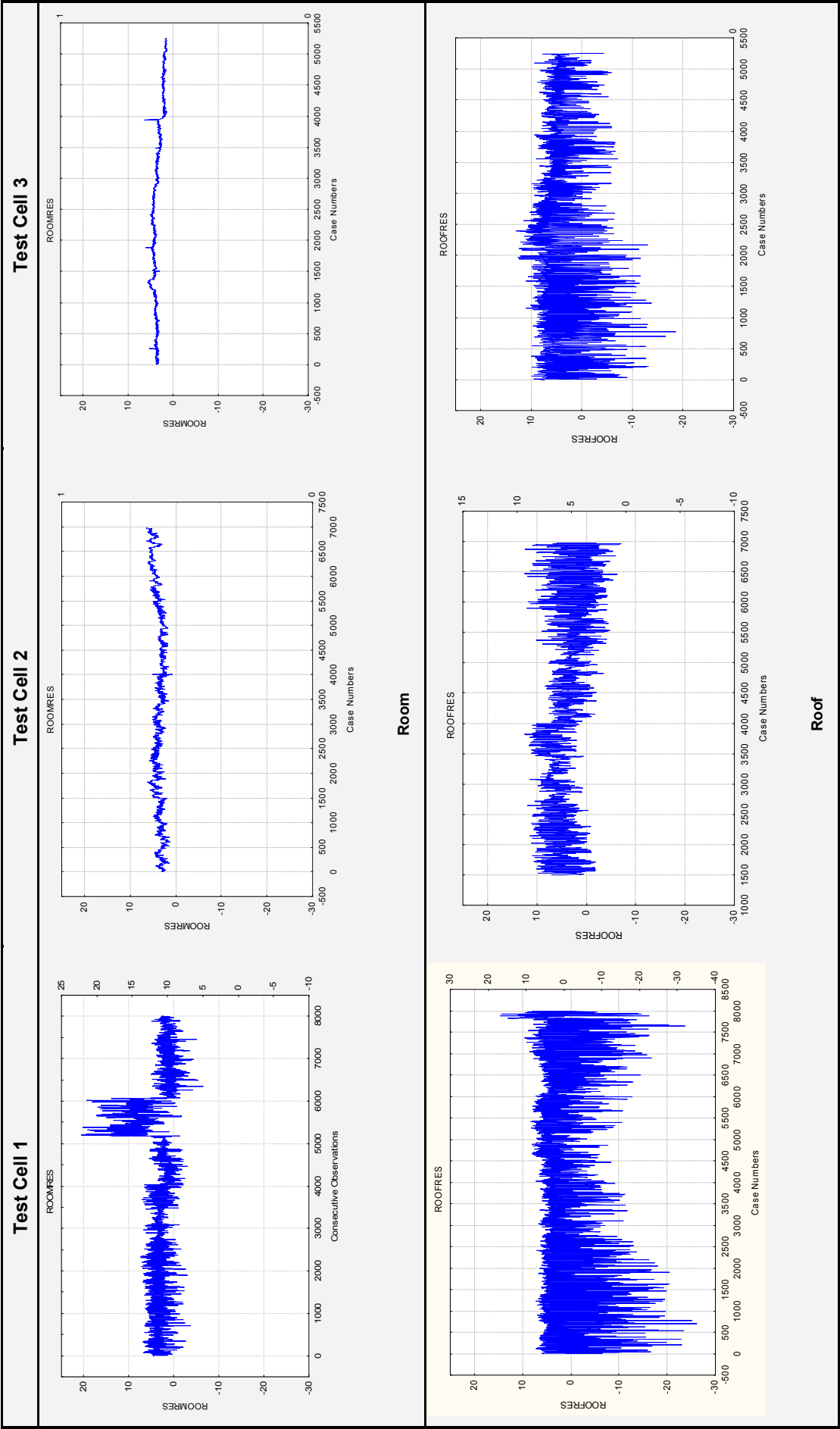
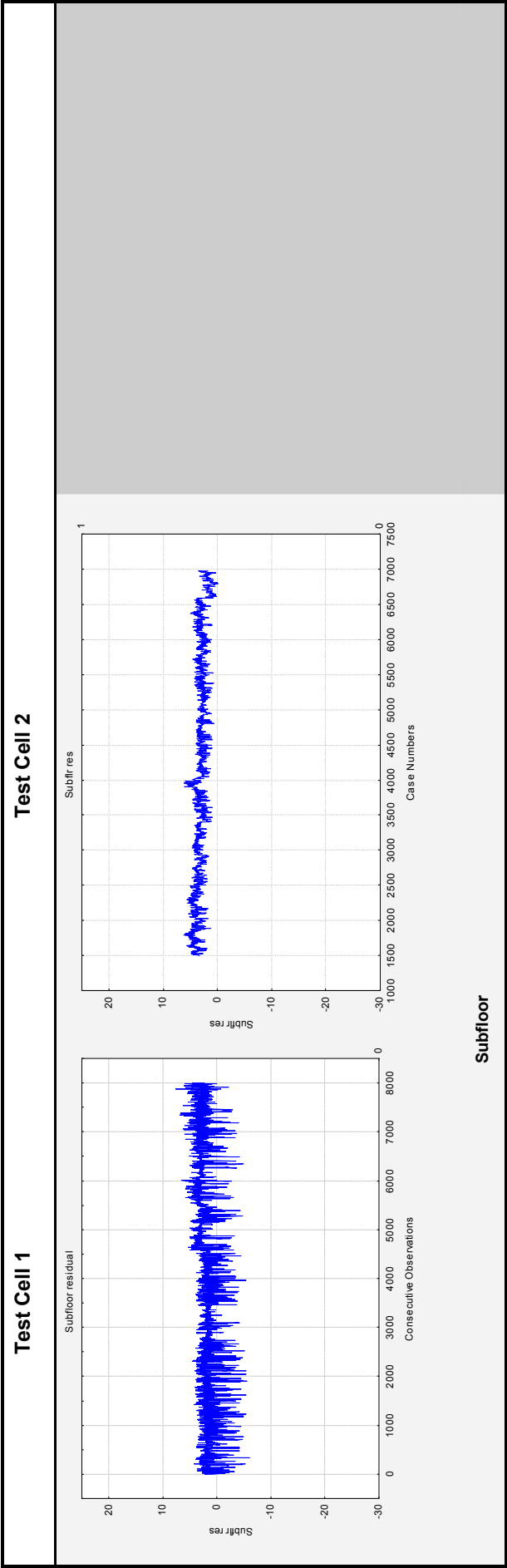


Figure 54A Room and Roof Temperature Residual Time Series



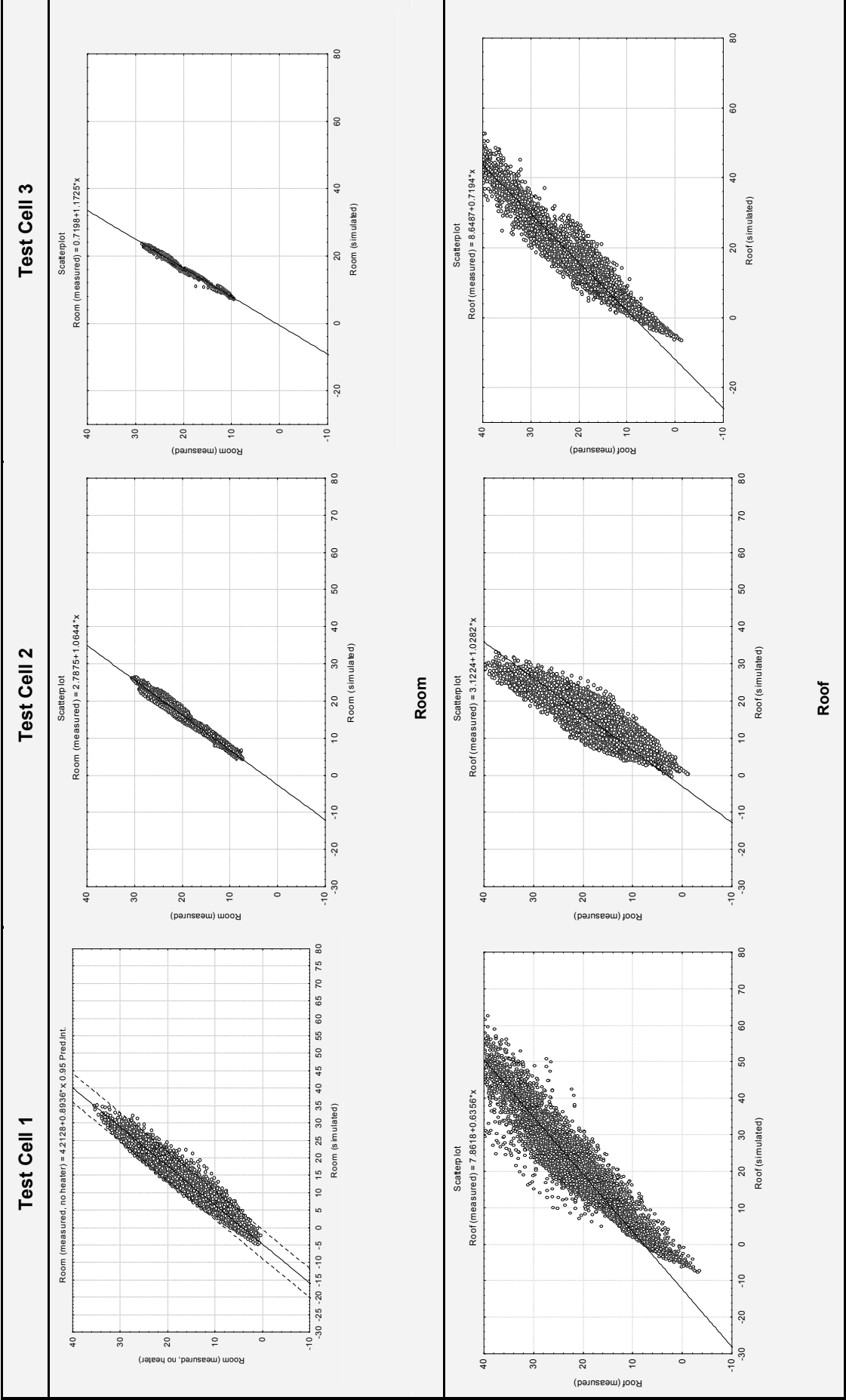


Figure 55A Temperature in Rooms & Roofs: Measured vs. Simulated

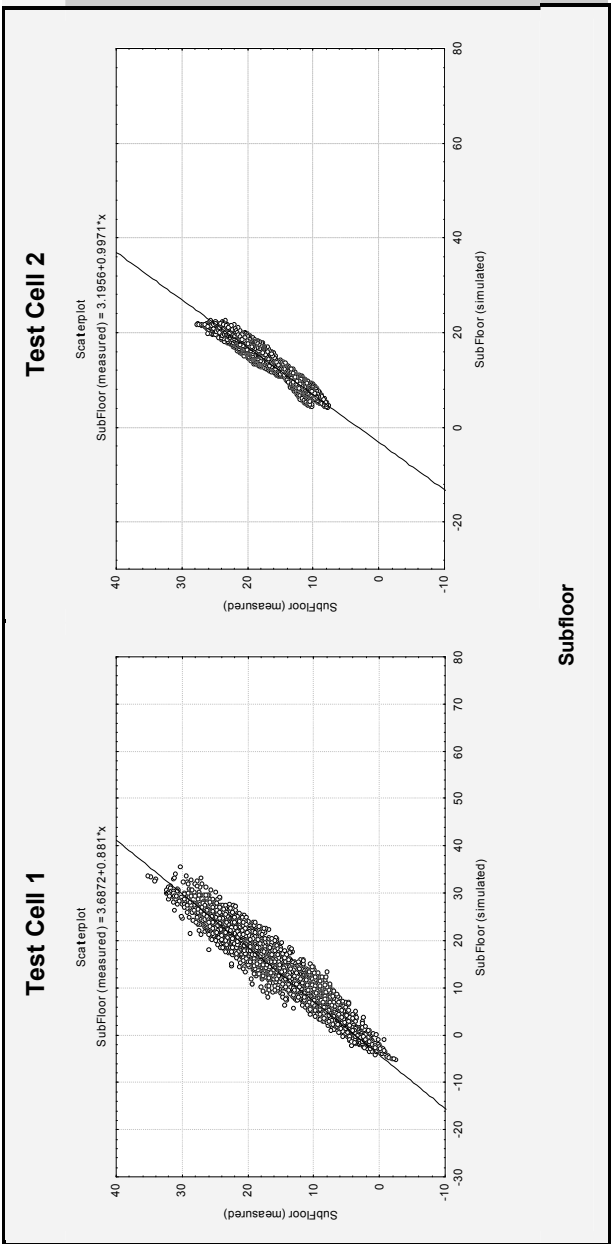


Figure 55B Temperature in Subfloors: Measured vs. Simulated

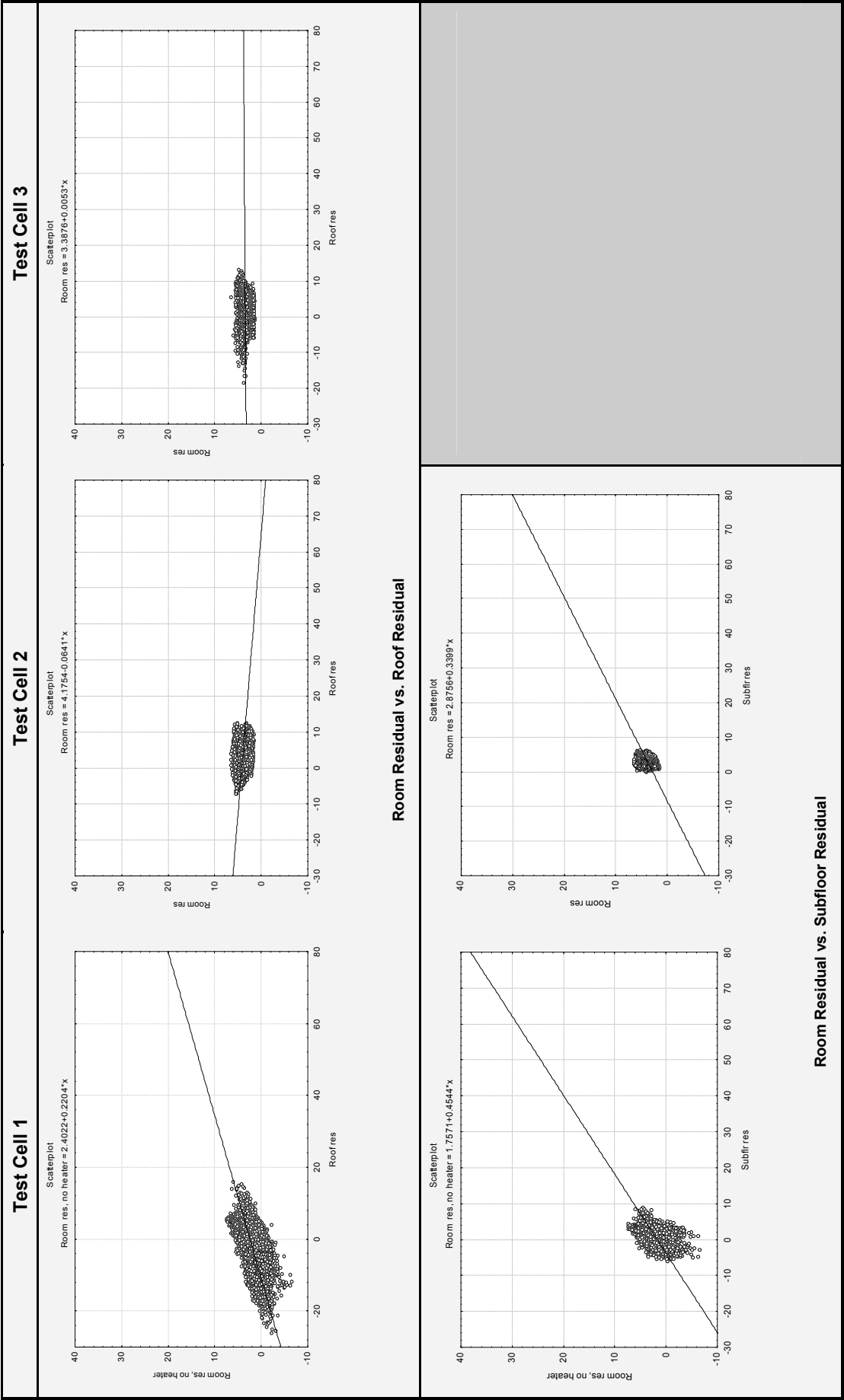


Figure 56 Scatterplot of Temperature Residuals: Room vs Adjacent Zone

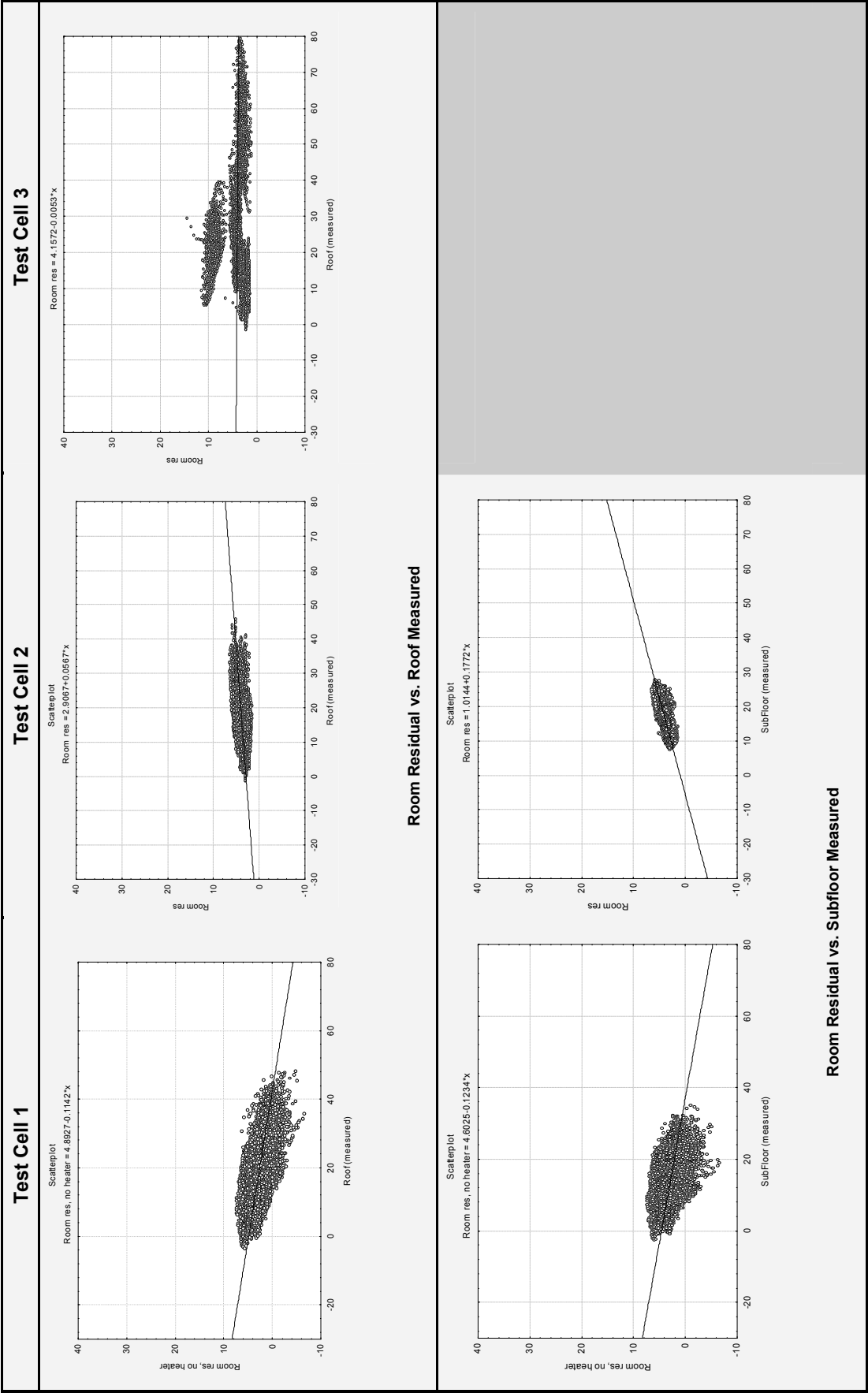


Figure 57 Scatterplot of Room Temperature Residual vs. Adjacent Zone Measured Temperature

7 Conclusions and Recommendations

7.1 Further Critical Analysis

The comparison of measured and simulated temperature, and the subsequent preliminary residual analysis presented in this report point out the need for further critical analysis of simulated and measured thermal performance data.

Measured and simulated temperatures had a positive linear correlation, and simulated temperature was almost always lower than measured temperature in the room, roof and subfloor zones in the three test cells. It has been shown that this can result in an underestimation of overheating degree hours in the bedroom and living room during the warm weather, and an overestimation of underheating degree hours in all test cells during cool weather. The results also underscore the importance of realistic comfort temperature bands over time in specific building and climate zones.

Further analysis of the interaction of airspace temperatures in the building zones will be conducted given that the test cells were found to be very airtight with air change rates of up to 0.1 ACH. Furthermore, under the same external wind conditions, airflows measured at the roofspace were significantly higher and with a wider variation compared with the airflows in the rooms. The time series plots of residuals show that there may be seasonal variations, so monthly residuals shall be analysed in greater detail.

Several simulations will be run with appropriate modifications to the AccuRate scratch file, i.e., AccuRate assumed values will be replaced with actual (as-built) construction parameters and material properties. These are aimed at more realistic representations of the thermal performance of light-frame houses in cool temperate climates, drawing insights from the validation process, and deriving possible improvements to the AccuRate model. The planned modifications will account for:

- an increase in framing factor resulting from the provisions for the eventual installation of windows such as an additional lintel and jamb studs, additional studs to accommodate prefabricated walls,, an additional 35mm of framing around the entire building due to the top plate, and the installation of double jamb studs.
- the considerably larger quantity of timber owing to hip-type roof truss compared to the simple skillion roof truss commonly used in buildings of the same volume. The considerable thermal mass provided by the timber in the roof space may be serving as thermal bridge to the test cell room, resulting in a reduction of the overall R-value of the roof space.
- the measured environmental conditions in the unenclosed and enclosed subfloor, the thermal mass provided by the floor frame in the timber floored test cells, and the measured ground temperature in all three test cells.

7.2 Further Research Beyond Five Stars

This report has presented the significant project accomplishments and insights drawn from the empirical validation using purposely built test cells. The results of the statistical analysis will be discussed more exhaustively in future technical reports and publications. Only when the planned simulation re-runs and analyses are completed that conclusions and possible improvements to the AccuRate model can be drawn.

This project has laid the groundwork for a broader research and development program on the thermal performance of domestic buildings in Australia. Although results have so far showed differences between the modelled and measured thermal performance of the test cells, the analysis is by no means complete, and conclusions can not be made as of yet in order to propose improvements to AccuRate and current building practices. It is recommended that on-

going analysis and other planned activities be continually pursued and dovetailed to a broader program designed to further understand and quantify the thermal performance of timber-framed houses.

The envisioned program will include the timely revival of the No Bills House Component, and an entirely new component which aims to provide technical assistance and documentation in support to the Australian Green Loans Program. The program will enable the completion of on-going component studies that are integral to the empirical validation of AccuRate, and provide the much needed research continuum in support to the move to expand coverage of the Five Star standard to house renovations, as well as the impending push beyond the Five Star standard for new houses.

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Appendix A Test Cell Construction Information

Test Cell 1: Plans, Elevations and Section

The fabric of Test Cell 1 is detailed below;

Table 7: Test Cell 1 Fabric Matrix

Item	Specification
Footings	Treated poles set in a concrete pier
Floor	19mm Particle board deck on timber bearer and joists
Walls	10mm Plasterboard, 90mm softwood stud framing, R2.5 rockwool wall batt insulation, reflective foil wrap, 21mm cavity, 12mm plywood lining
Ceiling	10mm Plasterboard, R4.0 Glass wool ceiling batt
Roof	Softwood truss, battens, reflective foil sarking, Colorbond sheet metal roofing

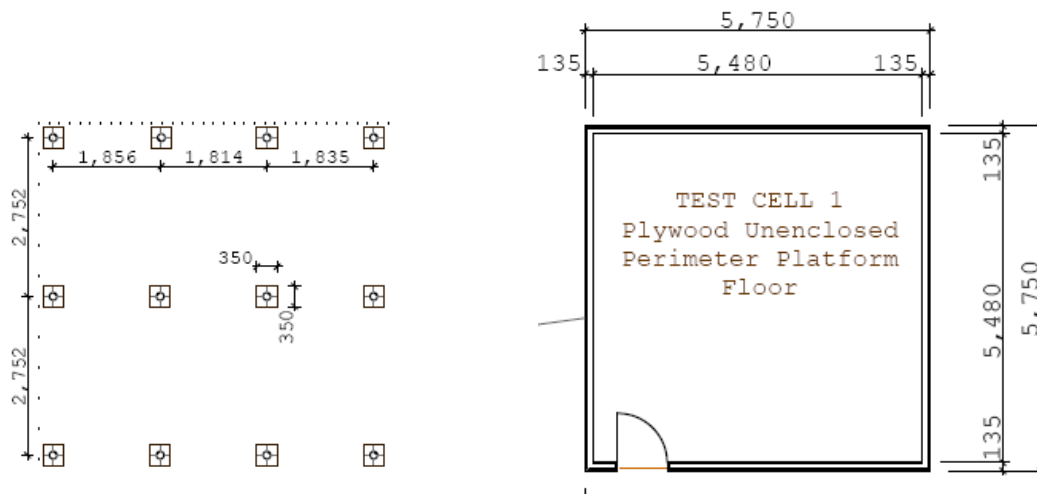


Figure 41: Test Cell 1 Footing Plan & Floor Plan

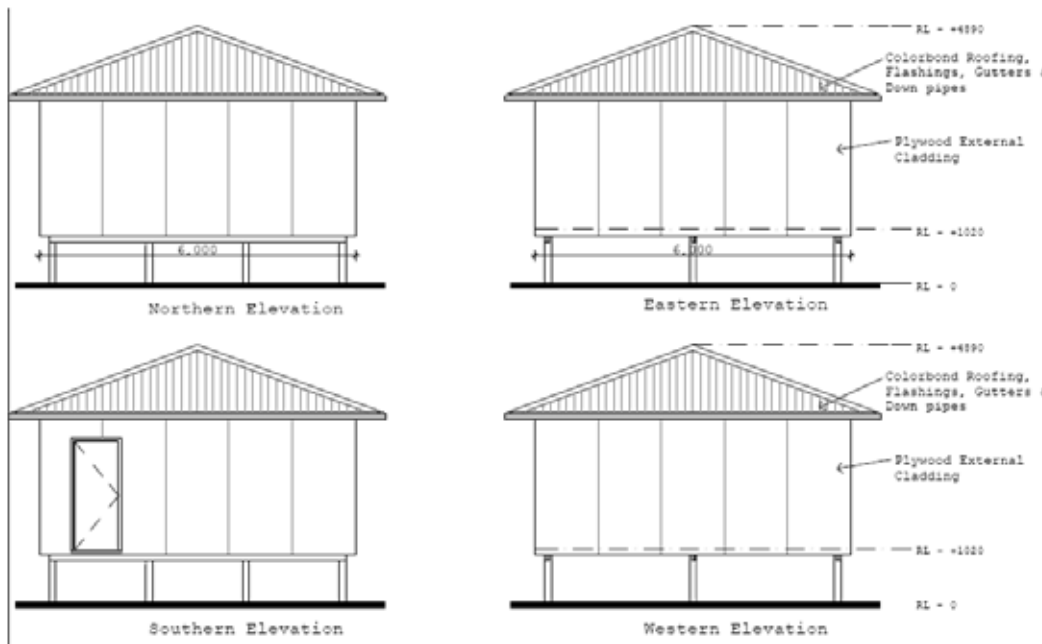


Figure 42: Test Cell 1 Elevations

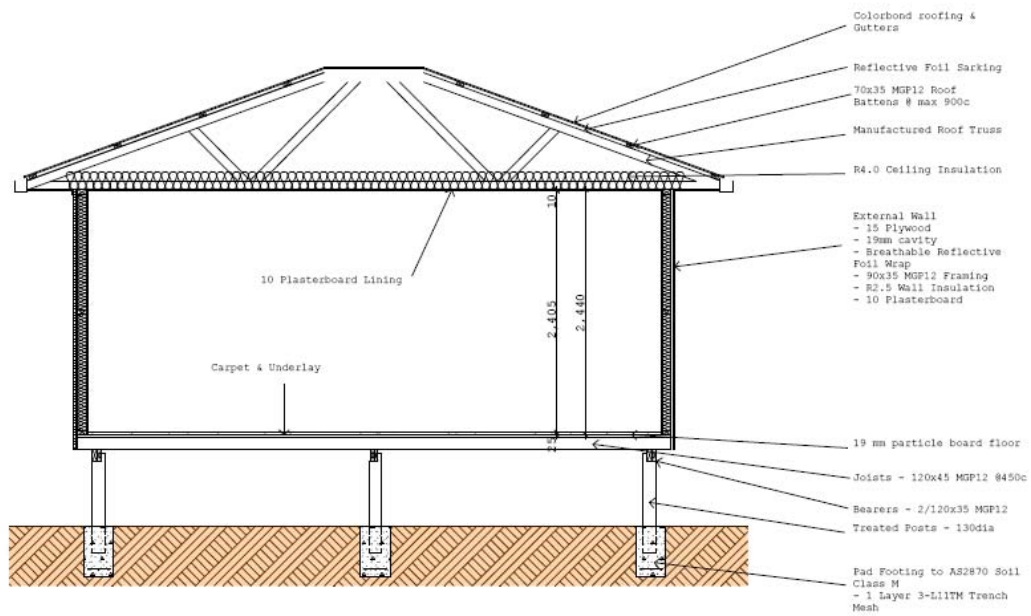


Figure 43: Test Cell 1 Section

Test Cell 2: Plans Elevations and Section

The fabric of test cell is detailed below;

Table 8: Test Cell 2 Fabric Matrix

Item	Specification
Footings	Treated poles set in a concrete pier
Floor	19mm Particle board deck on timber bearer and joists
Walls	10mm Plasterboard, 90mm softwood stud framing, R2.5 rockwool wall batt insulation, reflective foil wrap, 50mm cavity, 110 clay brick
Ceiling	10mm Plasterboard, R4.0 Glass wool ceiling batt
Roof	Softwood truss, battens, reflective foil sarking, Colorbond sheet metal roofing

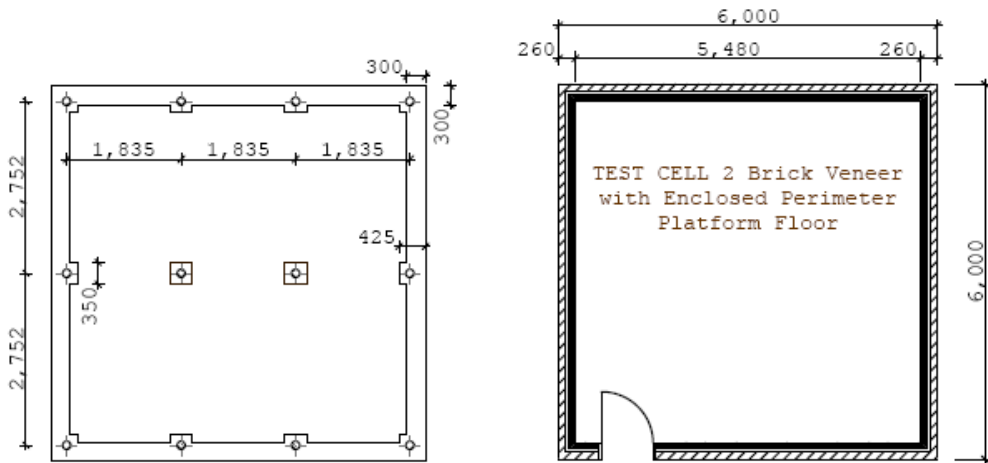


Figure 44: Test Cell 2 Footing Plan & Floor Plan



Figure 45: Test Cell 2 Elevations

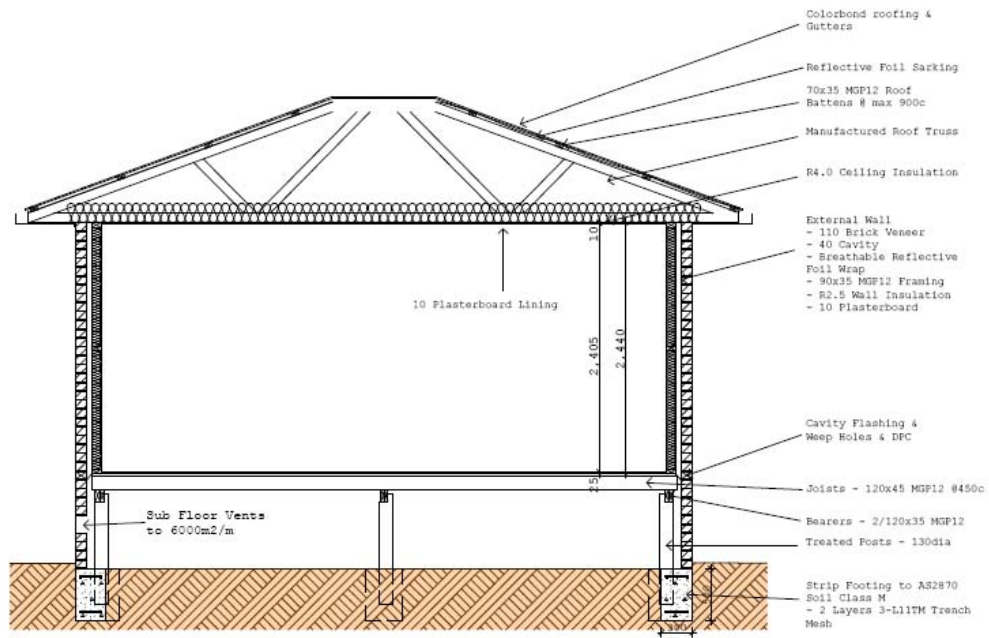


Figure 46: Test Cell 2 Section

Test Cell 3: Plans Elevations and Section

The fabric of test cell is detailed below;

Table 9: Test Cell 3 Fabric Matrix

Item	Specification
Floor	100mm Concrete slab on ground
Walls	10mm Plasterboard, 90mm softwood stud framing, R2.5 rockwool wall batt insulation, reflective foil wrap, 50mm cavity, 110 clay brick
Ceiling	10mm Plasterboard, R4.0 Glass wool ceiling batt
Roof	Softwood truss, battens, reflective foil sarking, Colorbond sheet metal roofing

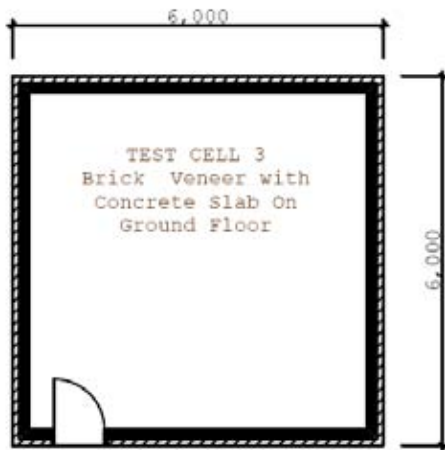


Figure 47: Test Cell 3 Floor Plan

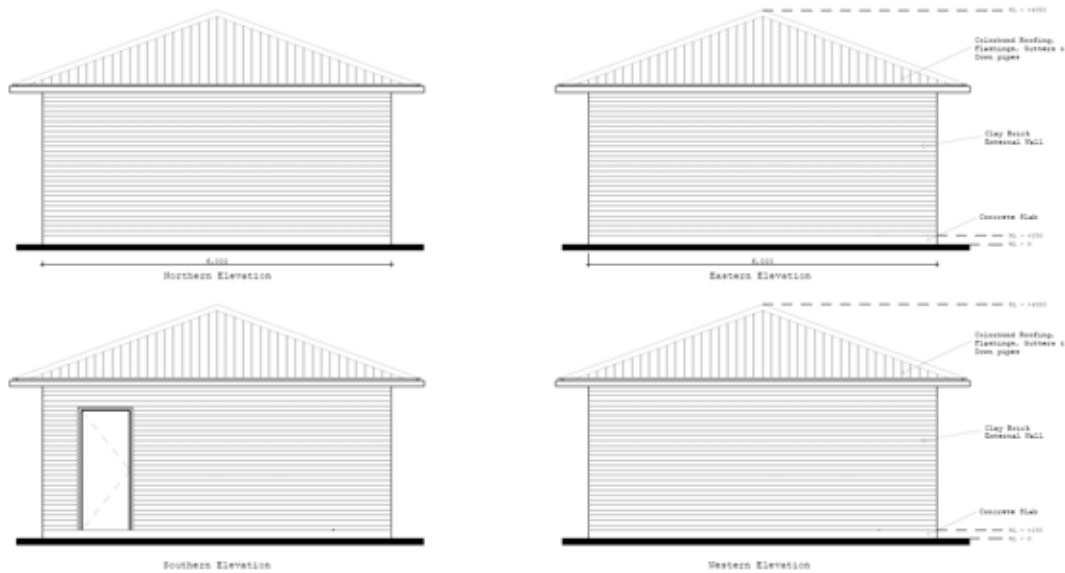


Figure 48: Test Cell 3 Elevations

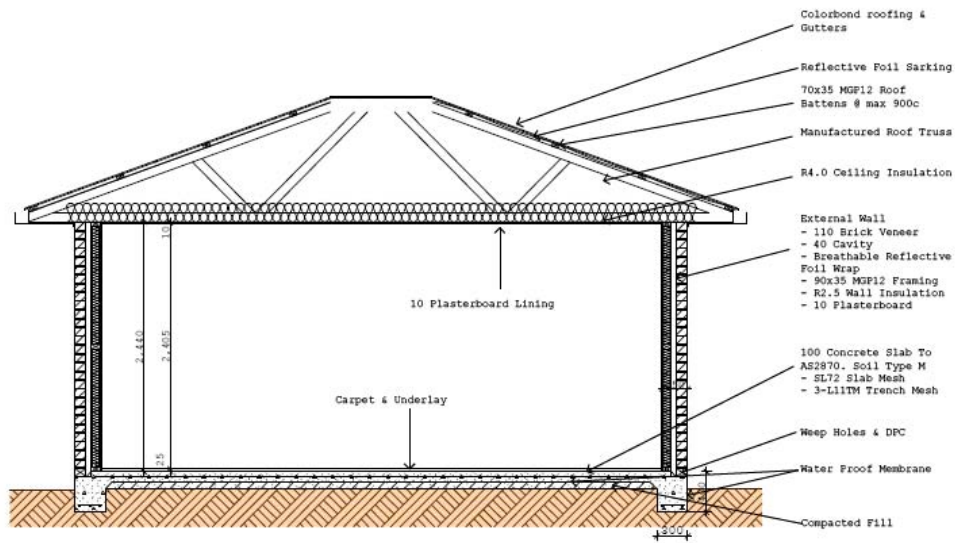


Figure 49: Test Cell 3 Section

