The Environmental Measurement of Residential Buildings

Case Study 2:
Concrete Slab-on-ground Floored Residence

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Extensive assistance in this field of research was provided by Dr Mark Dewsbury, Dr Florence Soriano, Dr Dong Chen (CSIRO) and Dr Angelo Delsante (CSIRO retired).

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Acronyms

BCA	Building Code of Australia
HER	House Energy Rating
HVAC	Heating ventilation and air-conditioning
NCC	National Construction Code
NatHERS	Nationwide House Energy Rating Scheme

Table of Contents

List of Tables

List of Figures

1. Introduction

This case study discusses and illustrates the method and process that were undertaken by the School of Architecture, University of Tasmania, in a recent empirical validation project. This study will discuss the empirical validation of the HERS software by the use of a concrete slab-on-ground residence. The research included key aspects, namely:

- The design and construction of the test building;
- The detailed thermal measurements of the test building;
- The use of a local weather station to record site climate conditions;
- The detailed simulation of the test building using the AccuRate software;
- The graphical and statistical analysis of the measured and simulated data sets

The research was undertaken with the test house operated in an unoccupied and unconditioned mode (free running).

2. The Test Buildings

The case study house is located at 76 Auburn Rd at Kingston, 9 km South of Hobart. Six two bedroom houses were situated on the building site. The case study house is specified on the site plan as Unit 1, the 5-star slab floor house. Figure 2.1 shows the site layout plan of the houses and Figure 2.2 shows an aerial view of the housing development in Kingston, Tasmania.

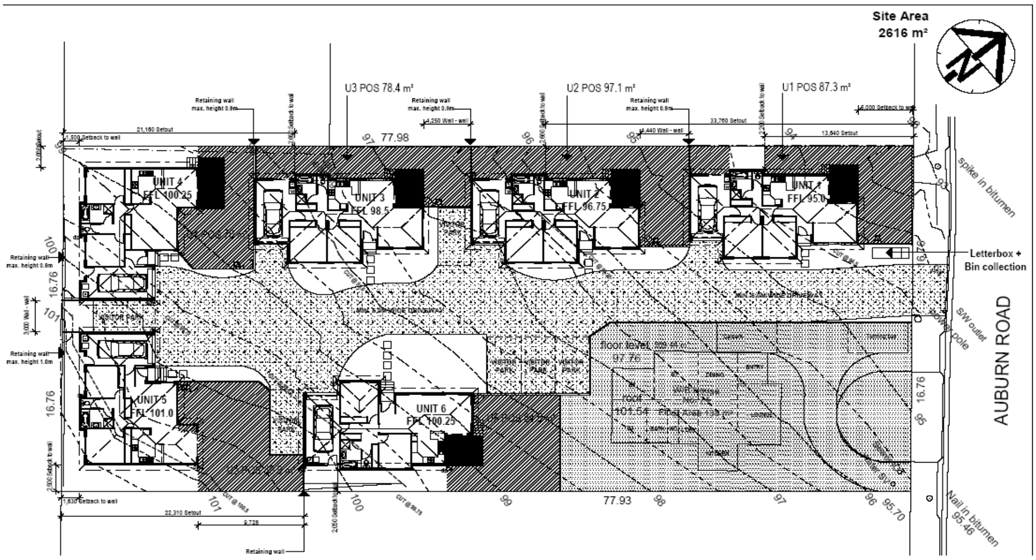

Figure 2.1 - The building layout at Auburn Road Kingston (Source: Wilson Homes)

Figure 2.2 - Aerial view of the housing development with the three test houses on the left-hand side of the driveway (Source: Google Earth)

The case study test house contains: 2 bedrooms, an open plan kitchen, dining and living area, a bathroom with separate toilet and a single garage, and an internal hallway connecting bedrooms, garage and bathroom to the common living areas. The total floor area of the house is 85.70m² with an open plan kitchen, dining and living area of 37.30m² and a single garage and laundry of 23.86m². The open plan living area is situated at the north-west side of the house and has access to a small timber deck with an area of 9.36m². There is a relatively large 13.72m² north-east facing glazed area in the kitchen/dining/living area, with a floor area of 37.30m², resulting in a window to floor area ratio of 0.36. Figure 2.3 shows the floor plan and Figure 2.4 shows the elevation drawings of the test house. Figure 2.5 and Figure 2.6 show the completed test houses in Kingston.

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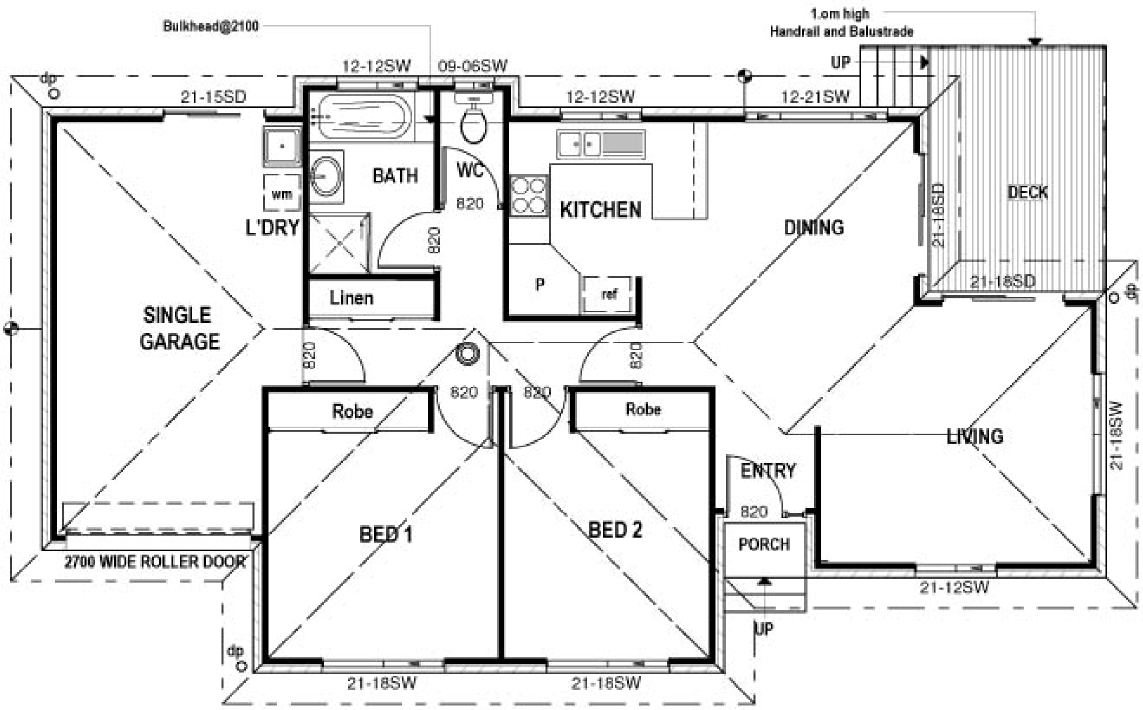

Figure 2.3 - Floor plan of the concrete slab-on-ground floored test house (Source: Wilson Houses)

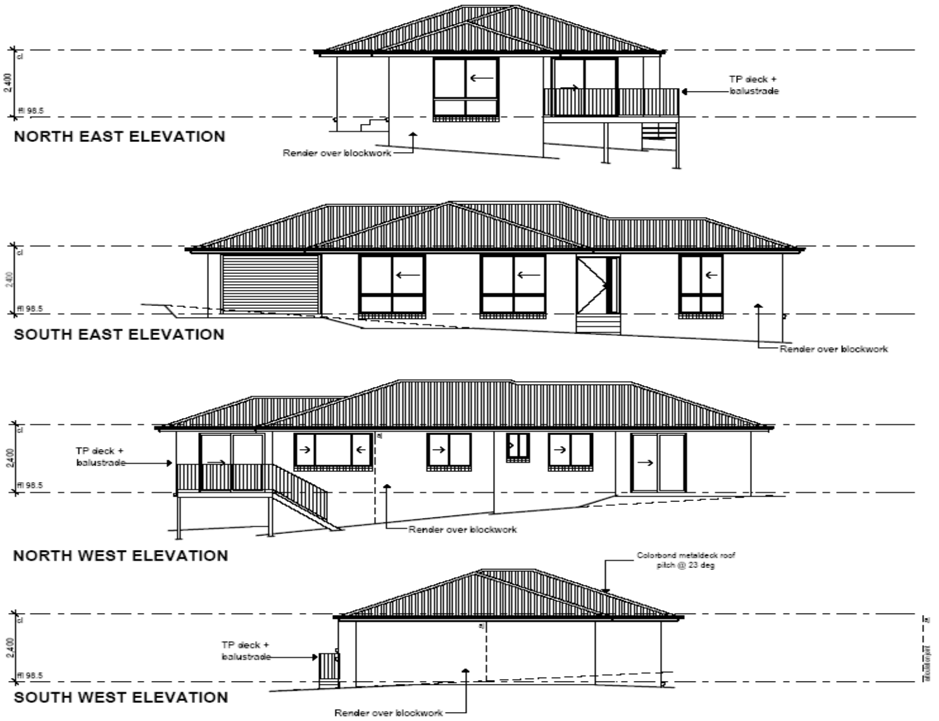

Figure 2.4 – Elevation drawings of the test house (Source: Wilson Houses)

Figure 2.5 - The test house as seen from Auburn Road, Kingston

Figure 2.6 - The housing development at Auburn Rd, Kingston, with the three test houses on the right hand side of driveway

2.1. Test Building Design Considerations

During the design and construction period the following details concerning the thermal performance of the house were considered and detailed, and construction was observed, as listed in Table 2.1.

Table 2.1: Design Considerations for the Case Study Test House

Case Study House	Design considerations
Wall cavity construction	Sealing between sarking and damp proof course specified
Wall infiltration	Sealing of sarking, taped at all sarking joints, to windows frames and top plate specified
Roof space infiltration and reflective insulation	Reflective roof sarking specified, to be installed and draped over roofing battens with the reflective side facing towards the interior of the roof space. Roof sarking was not to be taped between joints
Infiltration losses: wall, floor and ceiling penetrations	Downlight guards were specified over recessed downlights, otherwise no other infiltration guidelines were provided
Installation of insulation	Insulation for wall and ceiling space was specified to meet star rating insulation values. No subfloor insulation was specified
Framing factor	Not considered at the design and construction stage

2.2. Construction Information

The case study test house was constructed in accordance with the general Australian building standards for residential buildings. The house was designed to achieve a 5-star rating. During construction the site and house were monitored and any construction changes to the design drawings were recorded. These changes were incorporated into the standard and non-standard inputs for the AccuRate validation simulation. A general description of the construction details for the as-built condition is provided below.

2.2.1. Brick Veneer Wall Construction

The brick veneer wall of the case study house consisted of: a 90mm external rendered brick wall, a 35-40mm air cavity, a 90mm interior timber wall, framed (with studs usually at 450mm centres), with 10mm paper-faced gypsum plasterboard sheeting fixed to the inside of the stud wall. Reflective building wrap (a one-sided reflective foil wrapping) was attached to the exterior side of the stud wall with the reflective side facing the inside of wall. The building wrap acts as the water-proofing membrane of the external walls and also assists to reduce the infiltration and exfiltration from the house. Figure 2.7 (below) illustrates the typical section detail through the brick veneer wall at the test houses.

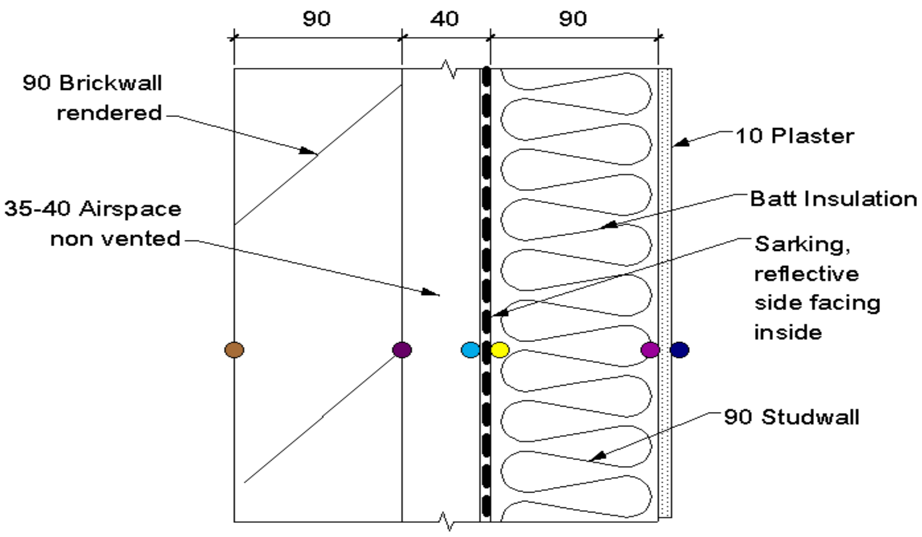

Figure 2.7 - Section detail of the brick veneer wall at the test houses

Standard building practice required a 150mm overlap of the building wrap at all joints between sheets. To reduce air infiltration and display best construction practice, the building wrap of the case study house was taped at the joints between sheets. The building wrap was also taped around window and door frames, and to the top and bottom plates of the timber wall framing. Figure 2.8 shows the taping of the wall wrapping at the junction of the building wrap.

Figure 2.8 - Taping of building wrap at the case study house

2.2.2. Concrete Slab-on-ground Floor Construction

The concrete slab-on-ground floored house had a 100mm reinforced concrete slab as the floor material. The concrete slab is positioned on a perimeter brick foundation wall, (also acting as retaining wall for the fill material) and has 400 mm deep internal concrete beams. Due to the slope of the land, the perimeter foundation wall was built to a height of about 1.2m at the front of the house and then filled and consolidated with fine crushed rock. Figure 2.9 and Figure 2.10 show the case study house before and after the pouring of the concrete slab.

Figure 2.9 – Brick wall and fill preparations for the case study house before concreting

Figure 2.10 - The case study house after the concrete floor has been poured and finished

The concrete slab-on-ground floor construction was the most widespread system in Australia and the least expensive construction method on level building sites. Figure 2.11 shows the construction detail of the perimeter foundation wall for the case study house.

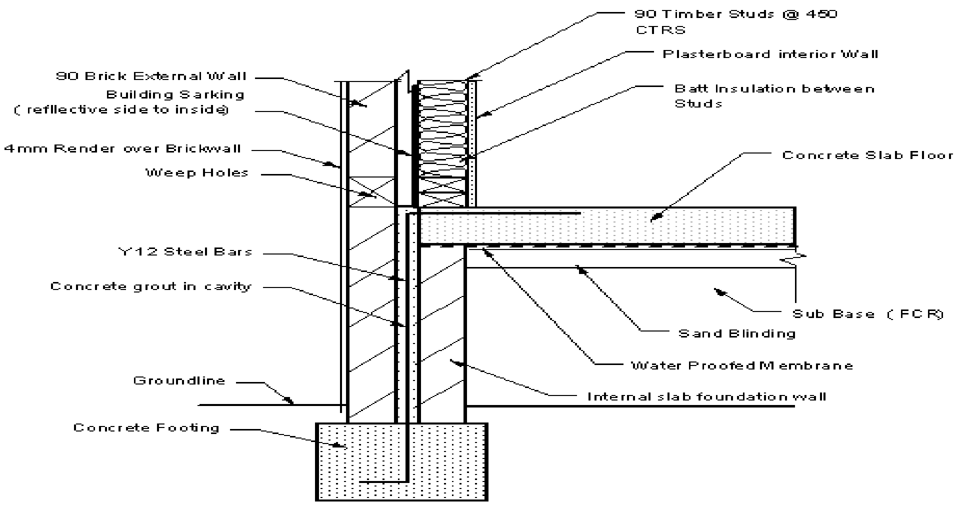

Figure 2.11 - Construction detail of the concrete slab-on-ground floored case study house depicting the perimeter wall detail

The slab floor was covered with carpet, except in the kitchen and bathrooms which were tiled.

2.2.3. Aluminium Windows and Sliding Doors

All external sliding doors and windows were manufactured by Brednams and supplied by Clark Windows, Smithton, Tasmania. Figure 2.12 shows the living room awning window and Figure 2.13 depicts the window certification of the window.

Figure 2.12 – Aluminium framed awning window from the case study house

Figure 2.13 – Aluminium framed window label showing accreditation

The case study house had double-glazed (5/12/5) aluminium framed awning windows and sliding doors in the kitchen, dining and living areas. The double-glazed aluminium frames had no internal thermal break. The remaining windows and sliding doors in this house were aluminium framed and single-glazed.

2.2.4. Ceiling and Roof Construction

The ceiling and roof construction consisted of pre-fabricated 23º pitch timber roof trusses fixed to the stud wall's top-plate, spaced at 900mm intervals. Timber roof battens were attached to the trusses, and a reflective roof sarking membrane was dished over the roof battens, with the reflective side facing downwards to the interior of the roof space. The Colorbond sheet-metal roof was fastened to the timber battens with specially designed roofing screws.

The 10mm paper-faced gypsum plasterboard ceiling lining was attached to steel furring channels, which were fixed to the underside of the roof trusses. Figure 2.14 and Figure 2.15 show the installation of the roof trusses at the case study test house. The case study house had R4.0 fibreglass batt insulation installed over the entire ceiling area.

Figure 2.14 - Installation of timber roof trusses onto the exterior stud wall

Figure 2.15 - Interior view of the roof trusses and reflective sarking

Table 2.2 details some aspects of the difference between design stage and the construction stage of the case study house.

Table 2.2: Construction Considerations of the Case Study House

Case Study House	Construction Considerations
Wall cavity construction	Constructed as specified
Wall infiltration	Building wrap and taping of all joints - installed as specified
Roof space infiltration and reflective insulation	Roof sarking installed as specified
Infiltration losses: wall, floor and ceiling penetrations	Downlight guards over recessed ceiling light fittings were installed as specified. The house was built to standard building practice, however this included no insulation or caulking between door jambs and wall frames, between window frames and wall frames, around plumbing and electrical service penetrations, between bottom plates and concrete slab floor and between ceiling and wall lining junctions,
Installation of insulation	Some shoddy installation of wall insulation Up to 200mm gaps in ceiling insulation around the recessed ceiling down-lights
Framing factors	Not considered at the construction stage

3. Empirical Data

To obtain the empirical data from the case study house required the selection, purchasing and installation of measuring and data acquisition equipment. Measurements were taken from a range of locations in the case study house and a site weather station. Once collected, the data required checking and cleaning before it was used for the empirical validation.

3.1. Data Acquisition Platform

The analogue data acquisition method, developed for the research at the test cells in Launceston, Tasmania (Dewsbury 2011), was adopted for the test house in Kingston. The were several reasons for selecting an analogue measuring platform, namely:

- Due to the low power consumed by an analogue data logger, which often included a battery power supply, the possibility of losing data during short power cuts was reduced;
- There was adequate software available to operate the data logger, minimising possible data logger failure due to software issues;
- Within the international research community this method of data acquisition had a long and proven history and as a result, there was a vast array of environmental measuring products available, which were compatible with analogue date loggers;
- Amendments to the data logger programming could be done easily when sensors were added or removed during the research;
- Although the data logger had a limited on-board memory, this could be easily expanded with the addition of a static memory card;
- Data could be downloaded via a Local Area Network;
- A local specialist consultant was available to provide professional installation and service advice for this system. This was a very important factor for choosing this system.

The Australian DT500 DataTaker series 3 data logger and a channel expansion module was used for the primary data acquisition and data storage for the case study house. The wiring for the data logger used 8 wire data cable between the data logger and individual sensors. A DT80 data logger was used to store all the data collected from the weather station and the DT500 data loggers. The DT80 data-logger was then connected to the University via an ADSL data link and was accessible from within the university's Wide Area Network. This enabled automated data downloading directly onto the research centre's server located in Launceston.

3.2. Site Climate Measurements

The minimum site-measured weather and climate data required for empirical validation includes nine key climate file inputs and is shown in Table 3.1.

Table 3.1: Minimum Site Climate Data Observation for Empirical Validation

Minimum site climate data required for empirical validation	Kingston test house climate data measured on site or calculated
Dry bulb air temperature (tenth of a degree Celsius)	Measured
Moisture content (tenth gram per kilogram)	Measured
Atmospheric (air) pressure (tenth of kilopascal)	Values taken from BOM station Ellerslie Rd, Hobart, same elevation height of 51m as case study house
Wind speed (tenth of metres per second)	Measured
Wind direction	Measured
Cloud cover in Octaves 1-8	Calculated with software program Make ACDB v9
Global solar radiation (Wh/m²)	Measured
Diffuse solar radiation (Wh/m²)	Calculated from measured global solar radiation
Normal direct solar radiation (Wh/m²)	Calculated from measured global solar radiation

The measuring equipment installed to collect the site climate data for the case study test houses is listed in Table 3.2.

Table 3.2: Measuring Equipment for the Site Weather Station

Purpose	Type of Sensor	Specification
Air temperature (ºC)	Vaisala HUMICAP HMP 45/D	-39.3ºC to +60ºC, uncertainty of ±2%@20ºC
Humidity	Vaisala HUMICAP HMP 45/D	Range 0.8 to 100% RH with an uncertainty of ±2% at 20ºC between 0 and 90%RH
Global Solar Radiation (Wh/m²)	Soldata 80 SPC Pyranometer	Pre-calibrated by the Fraunhofer Institute with an uncertainty of 3%
Vertical North Facing Solar Radiation (Wk/m²)	Soldata 80 SPC Pyranometer	Pre-calibrated by the Fraunhofer Institute with an uncertainty of 3%
Wind Speed (m/s)	Pacific Data System PDS-WD/WS-10	Element type: DC generator Sensor Output: 0 to 1 VDC (1000mV) for 0 to 100km/h (27.78m/s) linear
Wind Direction	Pacific Data System PDS-WD/WS-10	Element Type: 360 degree rotary potentiometer Electrical Deadband: 5 degrees Supply Voltage: 5 VDC standard Sensor Output< 0 to 1 VDC (1000mV) for 0 to 360 degrees of wind direction

3.3. Building Measurements

A large array of building measurement sensors was installed in the case study house to obtain reliable data for the comparison with the HERS simulation results. The location and installation methods of the sensors and the cleaning procedures of the data are described in this section.

3.3.1. Sensors Location Plan and Profile

The location of sensors in the house was designed with the expressed need to obtain data for the empirical validation. Additional sensors were installed within the house to collect additional data to support the minimum data and to allow for future studies on the thermal performance of the house.. The locations of sensors are shown in Figure 3.1.

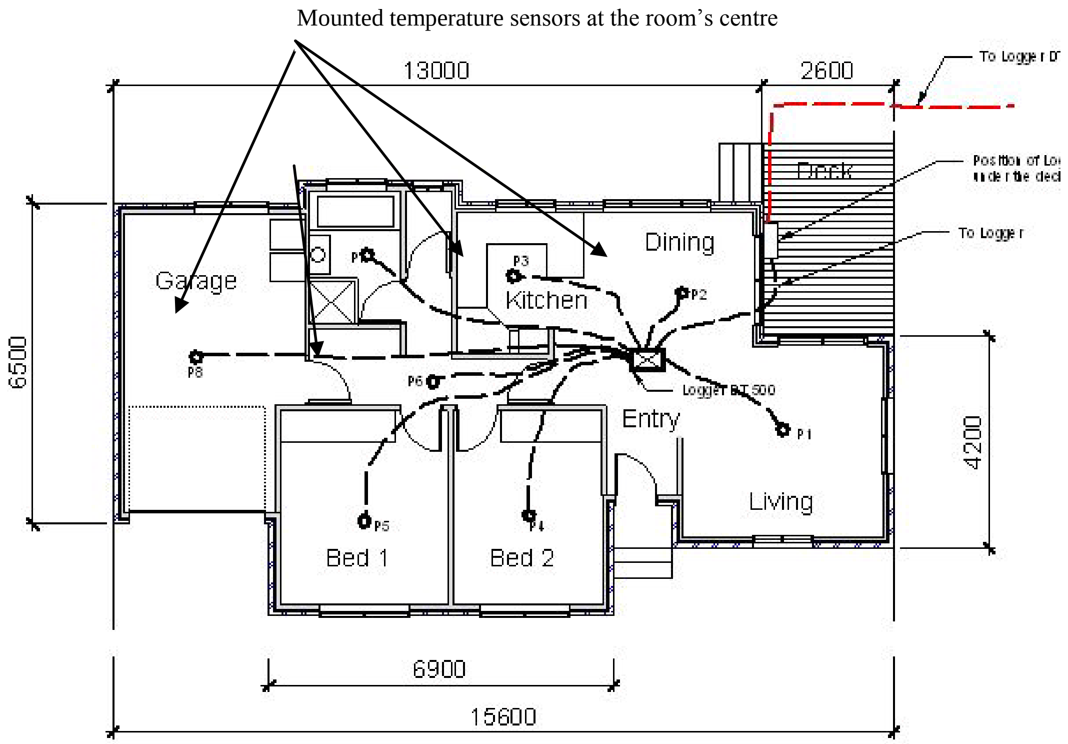

Figure 3.1 - Location of poles for sensors within the house

Dry bulb air temperature sensors were located on each pole at heights of 600mm, 1200mm and 1800mm from floor level. The poles were placed in the centre of each room, as shown in Figure 3.2 and Figure 3.3. In addition, a globe thermometer was attached to each pole at a height of 1200mm from the floor as shown in Figure 3.4.

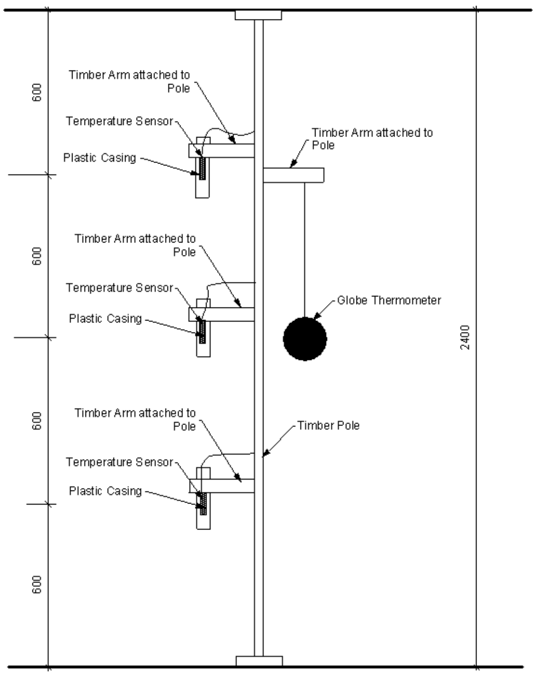

Figure 3.2 – Diagram of pole with sensors

Figure 3.3 – Photograph of pole installed in kitchen

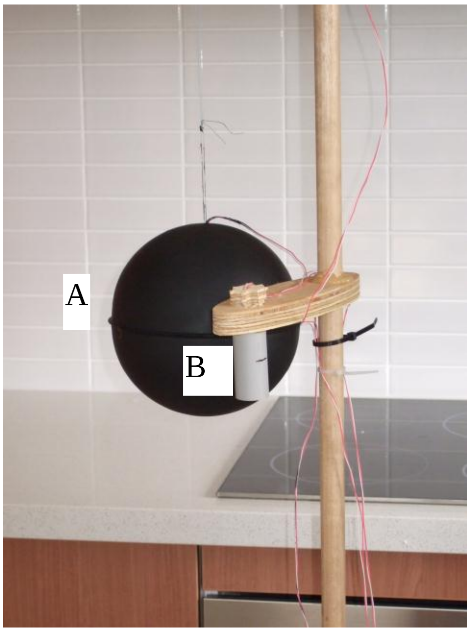

Figure 3.4 - Globe thermometer (A) and dry bulb air temperature sensor attached to the inside of the plastic casing (B)

Additional temperature sensors, which were placed within a plastic thermostat housing, were attached to the walls of each room at a height of 1200mm above floor level. The exact location of the wall mounted sensors is shown in Figure 3.5. Figure 3.6 shows the wall temperature sensor's housing, which was attached to two walls in each room of the house.

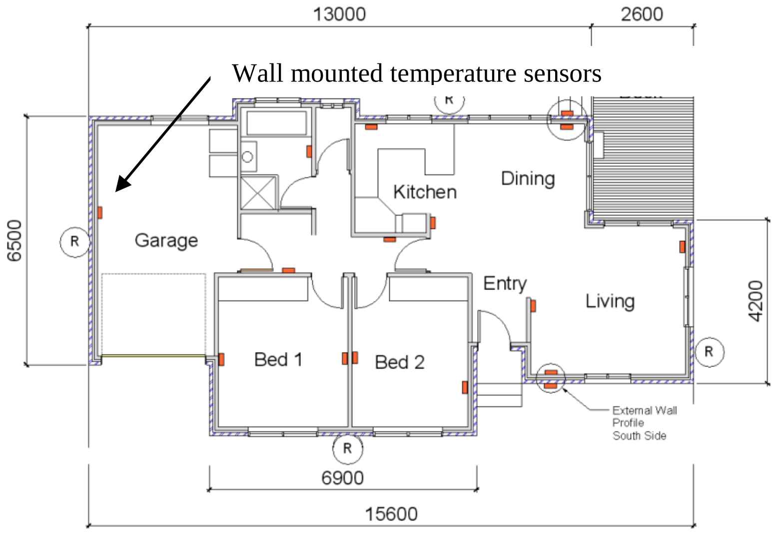

Figure 3.5 - Location of permanent temperature sensors attached to the walls at a height of 1200mm from floor level

Figure 3.6 – Wall-mounted sensor at the case study house

The location of sensors for the measurements of the full house vertical profile are shown in Figure 3.7.

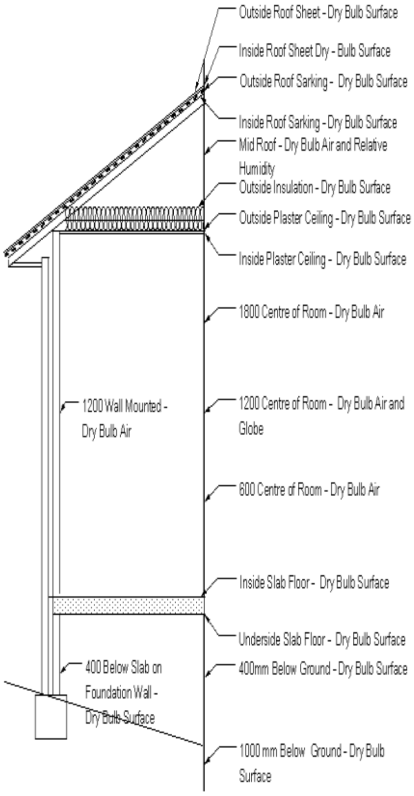

Figure 3.7 - Vertical profile of environmental measurements for the case study house

One of the many measurements taken included the temperatures of the individual brick veneer wall components, that is, from the inside surface of the plasterboard wall to the exterior surface of the brick veneer wall. Temperature sensors were installed within the north-west and the south-east wall sections to measure the heat flow through the horizontal wall section of the house as shown in Figure 3.8. In addition, vertical solar radiation was measured on all four sides of the house, at a height of 1.2m from the internal floor level as shown in Figure 3.9.

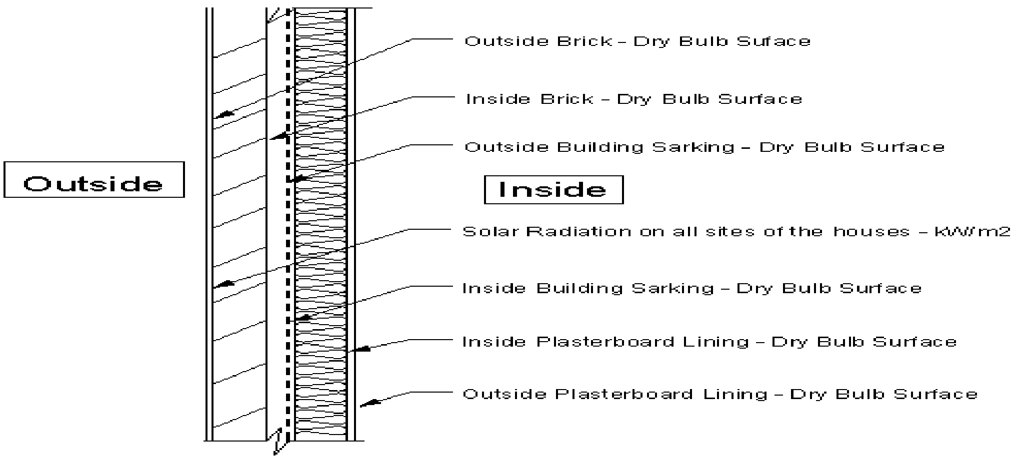

Figure 3.8 - Horizontal profile of measurements taken through a northern and southern exterior brick veneer wall

Figure 3.9 - SolData 80 SPC pyranometer fixed external walls of the case study house to measure solar radiation on the wall

3.3.2. Type and Installation Details of Sensors

Dry Bulb Air Temperature Sensor

The dry bulb temperature, (in degrees Celsius ºC), was required for measuring air and surface temperatures at various locations in the case study test house. As AccuRate produced simulated zone temperature reports to a tenth of a degree Celsius, sensors with the same degree of accuracy were selected for this project. The temperature sensor chosen was a pre-calibrated Analogue Device type AD 592 CN, as shown in Table 3.3. Nevertheless, these sensors were also calibrated on site.

Table 3.3: Air Temperature Sensor

Purpose	Type of Sensor	Specification
Air temperature (ºC)	Analog Device AD592CN	Pre-calibrated Accuracy: 0.5ºC max @ +25ºC Temperature Range -25ºC to +105ºC

Figure 3.10 and Figure 3.11 show the AD592CN temperature sensor installed at the wall of and at the centre of the rooms at three different height levels for the recording of dry bulb air temperature.

Figure 3.10 - AD 592 CN temperature sensors attached to wall plate at the wall

The dry bulb temperature sensor was the most frequent sensor used in this project, with up to 63 installed in the test house.

Dry bulb temperatures were measured at various heights in the centre of internal rooms, the roof space and the subfloor space. To support and fasten off the sensors at the centre of the different zones, an adjustable pole system was constructed, which allowed for easy adjustment to suit the height requirements of the sensor devices. This pole system comprised: a 20mm diameter timber pole, a 25 mm plastic electrical conduit and square top and bottom plates. Figure 3.11 illustrates the detail of the temperature sensor affixed to the timber poles at the centre of the zones. Three oval timber arms were fixed to each pole with hot glue at heights of 600mm, 1200mm and 1800mm from floor level (Figure 3.12). Dry bulb temperature sensors were then installed inside the electrical conduits and attached to the oval timber arm. Where the sensor conduit faced direct solar radiation, the plastic conduit was covered by reflective foil (Figure 3.13).

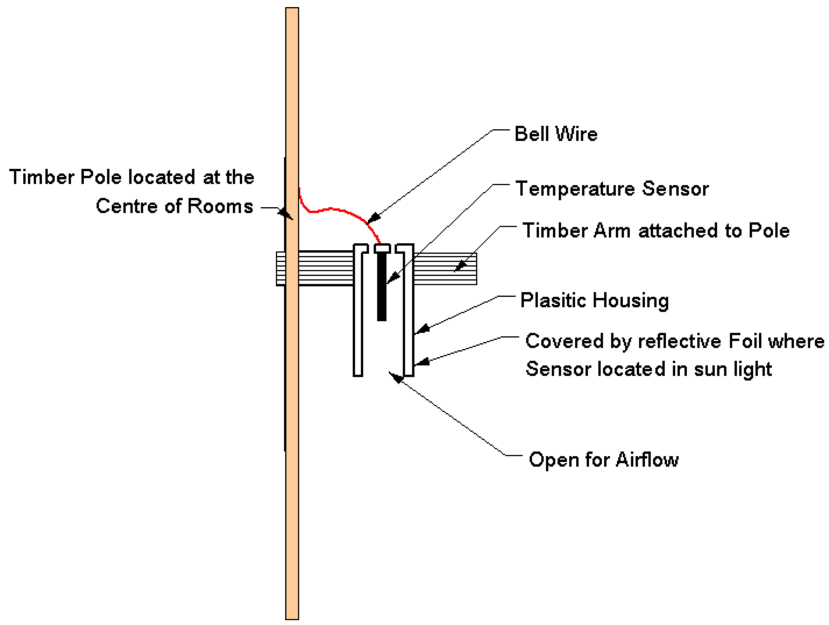

Figure 3.11 - Air temperature sensor attachment to timber pole at the centre of each zone

Figure 3.12 - Timber pole with temperature sensors located at different height levels

Figure 3.13 - Temperature sensor fixed inside a plastic pipe, covered by reflective foil

To measure the different temperature stratification and other temperature patterns in the rooms, air temperature sensors were mounted on two walls in each room, one being on the internal side of an exterior wall and the other being on the internal side of an interior wall, adjacent to another room of the house. The temperature sensors were placed inside the thermostat housing and attached to the walls at mid-wall height of the rooms. Figure 3.14 shows the detail of the wall-mounted temperature sensors. The sensors attached to the timber poles at the centre of each room were removed after the unoccupied unconditioned monitoring period, while the wall-mounted temperature sensors remained in place. Figure 3.15 shows the thermostat cover plate and Figure 3.16 shows the air temperature sensor fixed inside the thermostat housing and onto the base plate.

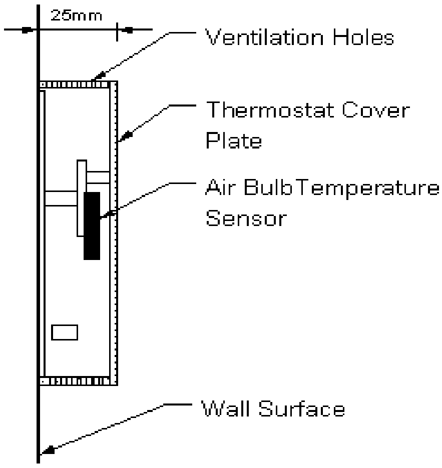

Figure 3.14 - Wall-mounted dry bulb air temperature sensor and thermostat cover plate

Figure 3.15 - Wall-mounted air temperature sensor located in a thermostat housing

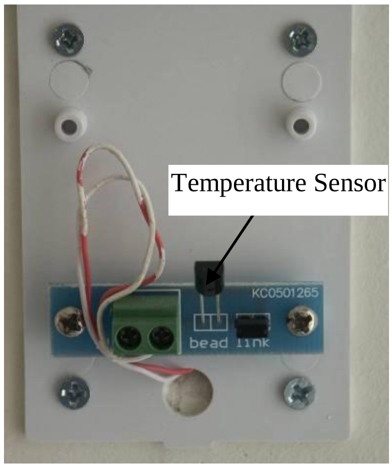

Figure 3.16 - Wall-mounted temperature sensor with bell wire connection to data-logger

When temperatures were compared between the wall-mounted and centre-mounted censor, it became apparent that the temperatures at the wall-mounted sensors were significantly higher. It was accepted that the sensor was measuring a greater proportion of wall temperature than room air temperature. Other surface temperatures in the southern bedroom of the case study house had shown wall surfaces to have a higher temperature than the measured air temperatures. This indicates that the wall-mounted sensors needed to be better insulated between the sensor and the wall as shown in Figure 3.17. In this case the thermostat housing is attached to the wall, leaving an insulated 12 mm air gap between the wall the temperature sensor.

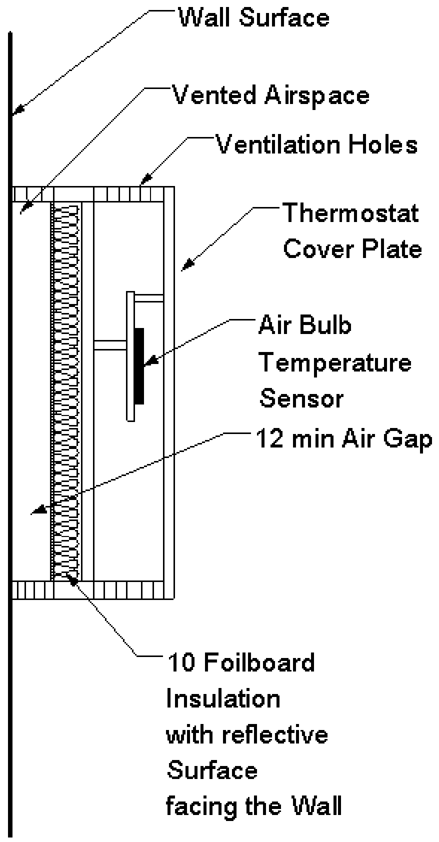

Figure 3.17 - Insulated wall-mounted dry bulb temperature sensor

Dry bulb temperature was also measured in the middle of the roof space. The temperature sensor was fixed to a timber pole using white cotton tape as shown in Figure 3.18. This figure shows the timber pole located in the roof space of the case study house with the temperature sensor attached to the pole.

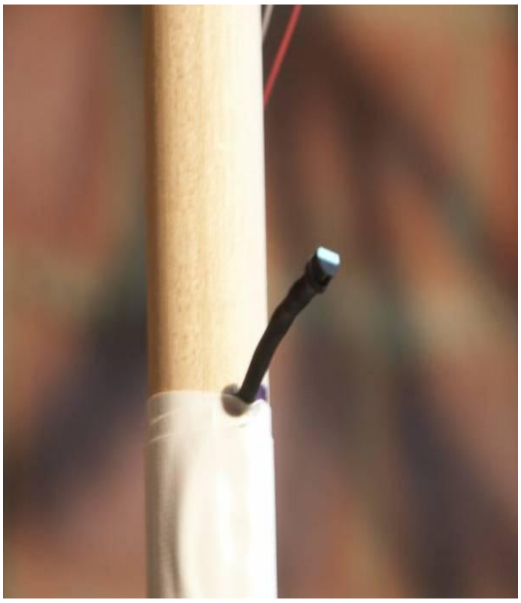

Figure 3.18 - Temperature sensor fixed to pole at mid roof space

Dry Bulb Surface Temperature

Surface temperatures of building materials were measured with the AD592CN temperature sensors. The temperature sensor's flat face, which measured the surface temperature, was affixed to the surface being measured. The sensor was then covered with an adhesive tape with similar emissivity or reflectance to the surface being measured. The adhesive tape also covered the sensor and insulated it to a certain degree from the layer of the surrounding air. The surface temperatures in the houses were measured as shown in Figure 3.19 to Figure 3.23 different surfaces were included, namely:

- Outside the metal roofing sheets,
- Inside the metal roofing sheets,
- Outside the roof sarking membrane,
- Inside the roof sarking membrane,
- Outside the insulation layer,
- Outside the plasterboard ceiling,
- Inside the plasterboard ceiling,
- Inside the floor under the carpet and carpet underlay,
- Underneath the floor,
- 400mm under the concrete slab (in ground),
- 1000mm below the concrete slab (in ground).

The temperature sensor attached to the inside surface of the concrete slab floor was inserted and glued into a small groove in the concrete slab and the surface was then covered with mortar. The temperature sensors located 1000mm below the ground surface were inserted into a water-proofed plastic housing, Figure 3.23.

Figure 3.19 - Temperature sensors attached to the exterior surface of the sheet-metal roof

Figure 3.20 - Temperature sensor taped onto inside surface of roof sarking

Figure 3.21 - Sensor attached to the inside of paper-faced gypsum plasterboard ceiling before being covered with a very thin layer of plaster

Figure 3.22 - Installing the sensor to the interior surface of the concrete slab-on-ground floor

Figure 3.23 - Installing the waterproofed temperature sensor housing for the temperature sensor 1000mm below ground (under concrete slab floor)

Figure 3.24 to Figure 3.29 show installation details of some of the above-mentioned sensors, which were installed to provide the horizontal wall surface temperatures profile. They were glued and taped to the individual building materials. Figure 3.24 shows the sensor was inserted into the groove of the paper-faced gypsum plaster board wall which was then covered with a very thin layer of plaster. The sensors, as shown in Figure 3.25 and Figure 3.26, were attached to the building wall wrap with a silver-faced tape. The sensors were glued and taped to the inside of the brick wall, as shown in Figure 3.27 and Figure 3.28. The sensors were inserted in a small hole in the outside of the brick wall, as shown in Figure 3.29. Finally the brick wall was rendered over, making the sensor invisible from the exterior.

Figure 3.24 – Sensor attached to the inside of the plasterboard wall

Figure 3.25 – Sensor attached to the inside of the reflective building wrap

Figure 3.26 – Sensor attached to the outside surface of the building wrap

Figure 3.27 – Sensor before being attached to the inside the of brick wall

Figure 3.28 - Sensor attached to the inside of the brick wall with red cloth tape

Figure 3.29 - Sensor attached to the outside surface of the brick wall prior to the application of a thin coat of render

Globe Thermometers

Copper globe thermometers were installed in each room, to measure a combination of dry bulb air temperature and mean radiant temperature. The globe thermometers were installed to study the relationship between dry bulb air temperature and the environmental temperature in each room. The globe thermometers were made according to the ASHRAE 2006 specification. They consisted of a 150mm diameter hollow copper ball, coated with a matt black paint and an AD592CN temperature sensor was fixed within the centre of the sphere. Figure 3.30 shows the air temperature sensor being attached within the centre of the copper ball, while Figure 3.31 shows the completed globe thermometer attached to the timber pole at a height of 1200mm from the floor level.

Figure 3.30 - Inserting the air temperature sensor into the globe half sphere

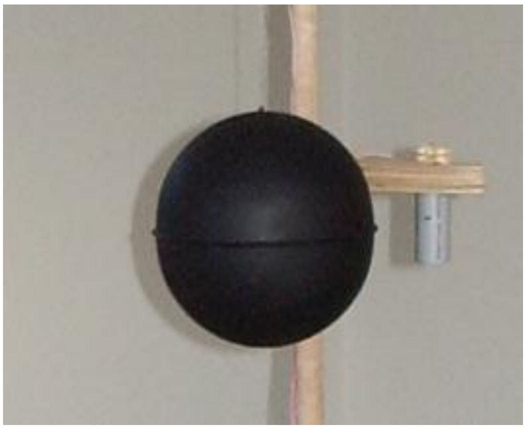

Figure 3.31 - Globe thermometer installed and measuring environmental temperature

Humidity Transmitter

The Vaisala HMW40 humidity transmitter was chosen because of input requirements and output style. The operation range is between 0 and 100% relative humidity, with a measurement of uncertainty of ±3% @ +20ºC. Figure 3.32 shows the installation of the humidity transmitter within the roof space of the case study house. The humidity transmitters were located at mid-height of the roof space in the case study house. The transmitters were attached to a timber pole with glue and a white cloth tape. The collection of the humidity data in the roof space of the case study house was not part of the validation process, but was collected for further thermal performance research analysis.

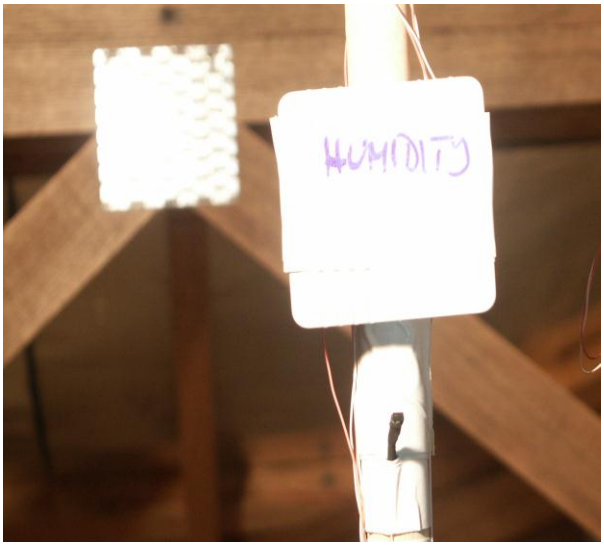

Figure 3.32 - Humidity transmitter installed in the ceiling space

Pyranometer

Solar radiation data were measured on four external walls of the case study house and as part of the site weather station. The weather station measured global horizontal and global vertical north facing solar irradiance. Based on its technical specification to measure solar irradiation in W/m² and its cost, the SolData 80SPC pyranometer was chosen for this project. The pyranometer consisted of a calibrated solar cell that generates electricity when solar radiation impacts the surface of the solar cell. All SolData SPC pyranometers were calibrated by the Fraunhofer-Institute for Solare Energiesyteme against a first class Kipp-Zoned CM21 reference pyranometer with a total uncertainty of 3%. Each pyranometer was delivered with a user guide providing a calibration factor K, expressed as mV/(kW/m²). For example, if the K is 160mV/(kW/m²) when the solar radiation was 1 kW/m², the pyranometer provided an output voltage of 160mV. Each pyranometer was then re-calibrated, with each individual K-calibration factor using the required equation (S=U/K) to achieve actual irradiation values (W/m²). Figure 3.33 shows the pyranometer attached to the external wall of the house and Figure 3.34 shows the horizontal and vertical fixed positions of the pyranometers for the site weather station.

Figure 3.33 - SolData 80SPC pyranometer fixed to an external wall

Figure 3.34 - SolData 80SPC pyranometers installed as part of the site weather station

Infiltration

The empirical validation data required input for heat losses due to infiltration. The infiltration measurements were conducted to achieve realistic data for the air change rates in the roof space and interior rooms of the case study house. The measured air change rate value was then used as part of the AccuRate simulation for empirical validation. Building air leakages were determined using the Tracer Gas Decay Method and the Simultaneous Fan Pressurization Method, (also referred to as the Blower Door Test). The measurement of infiltration was conducted by the Mobile Architecture & Built Environments Laboratory (MABEL) from Deakin University, Geelong. These tests were carried out simultaneously, to validate the blower door method by checking for a suitable similarity in results.

The tracer gas method involved the introduction of gases at a high concentration level to the measured spaces. Carbon Dioxide ($CO_{2)}$ into the roof space and Sulphur Hexafluoride (SF6) into the interior of the test house. The decay of the gases was observed and specific methods were then used to calculate the air change rate per hour (ACH). Figure 3.35 shows the MABEL comfort cart which was used in conjunction with the tracer gas and blower door tests for the case study house. Figure 3.36 shows the tracer gas decay graph from the computer during time of testing.

The blower door test was conducted twice using a pressurisation fan, which was conducted twice. In the first test the fan was attached to the front door (living room) and in the second test it was attached to the door between the garage and the hallway. In both cases, the interior of the house was pressurised in stages to 4, 8, 20 and finally, 50 Pa and the infiltration rates were accordingly measured. Figure 3.37 shows the installation of the blower door test unit and Figure 3.38 the blower door pressurisation fan.

Figure 3.35 - Comfort cart measurement equipment

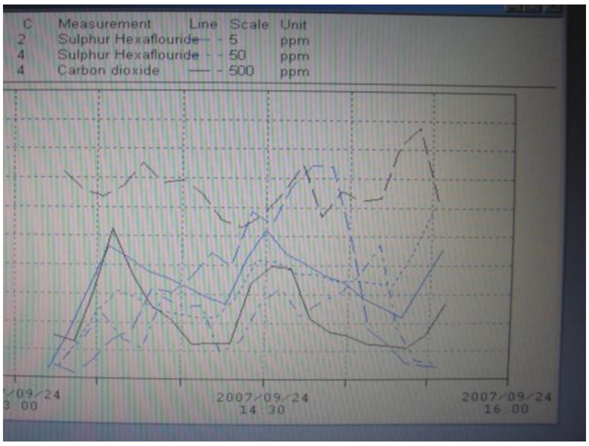

Figure 3.36 - Tracer gas computer graph

Figure 3.37 - Interior view of the blower door equipment installed in the case study house

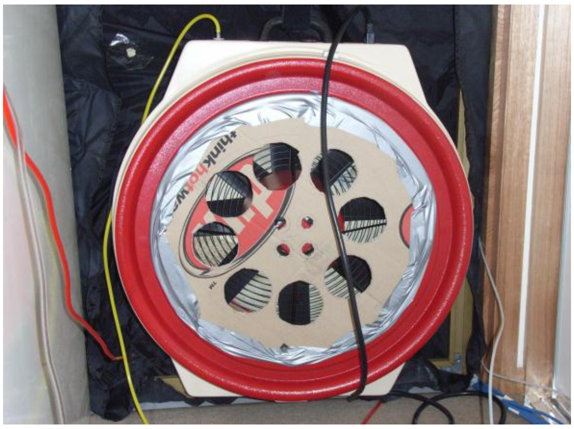

Figure 3.38 - View of the pressurisation fan of the blower door equipment

3.3.3. Cabling and Calibration of Sensors

The wiring and cabling method used for to the Launceston test cells was adapted for the case study test house. Wiring was provided to the following items:

- The Data Taker DT 500 logger and channel expansion modules for the data acquisition and storage,
- From the data logger's internal terminals to the external RJ45 terminal blocks,
- Eight wire data cable (Cat 5 cable) from the RJ 45 data logger terminal blocks to the Krone connector, which was fixed close to the particular sensors,
- Two-wire sensor feeder cables (bell wires) from the Krone connector to the individual sensors. The sensor feeder cable was soldered to the sensor's connection wires.

Figure 3.39 illustrates the wiring concept of the measuring equipment, starting from the data logger with the eight wire data cable connected to the Krone connector plate with a RJ 45 plug and continuing from the Krone's bell wire connection, leading to the individual sensors installed around the house.

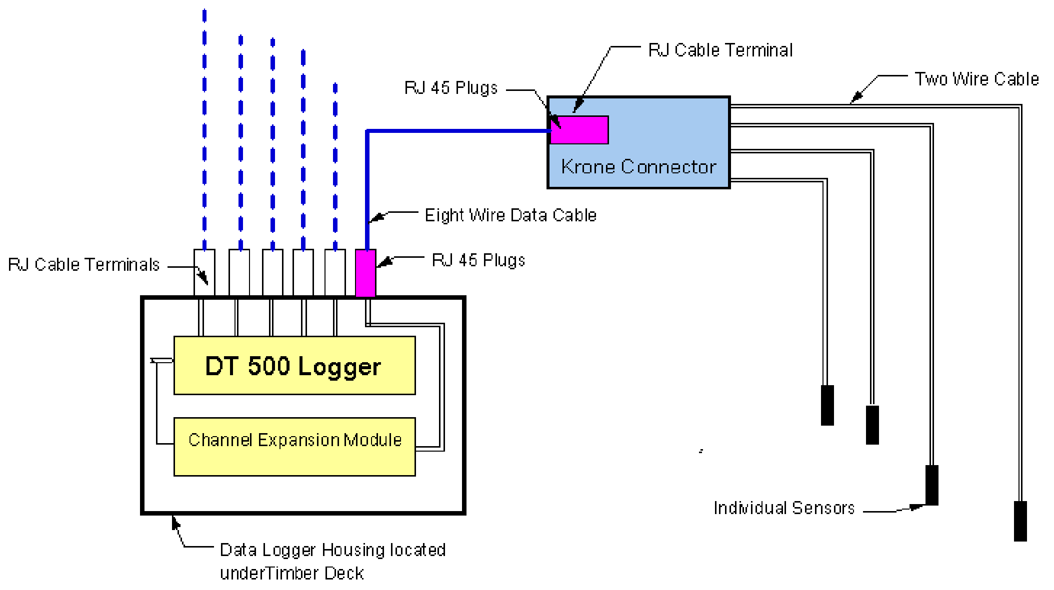

Figure 3.39 - Wiring diagram for the cabling and wiring connection between the data logger and the individual sensors

The use of an eight-wire data cable allowed each data cable to carry the signal of four individual measuring devices. Extensive planning and careful layout of sensors allowed a maximum configuration of all data logger channels

Figure 3.40 to Figure 3.45 show several key wiring and connection details. Figure 3.40 shows labelled AD592CN sensors with bell wire leads attached before installation into the brick veneer wall. Figure 3.41 depicts the data cables installed within the hallway's wall cavity, connecting the data logger to the sensors, via the Krone connectors in the roof space. Figure 3.42 shows the installation of the Krone connectors, providing the link between the data cables, from the data logger and the bell wire and individual sensors. Figure 3.43 shows the Krone connectors in the roof space fixed to the roof trusses with the data cable and bell wire connections. Figure 3.44 shows all the data cables connected to the data logger with RJ 45 plugs. Finally, Figure 3.45 shows the data logger and the interior wiring connection of the data cables to the RJ 45 cable terminals in the metal box.

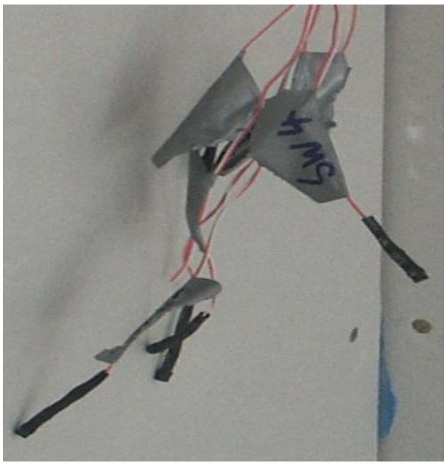

Figure 3.40 - Temperature sensors attached to bell wire

Figure 3.41 - Installation of data cables in hallway wall

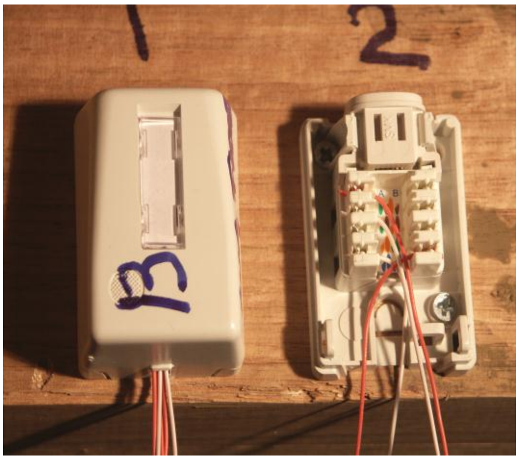

Figure 3.42 - Krone connectors connecting data

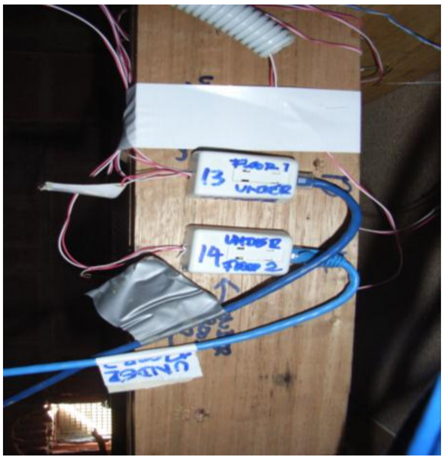

Figure 3.43 - Krone connectors fixed to truss

cables to bell wires

member connecting data cable to bell wire

Figure 3.44 - Data cable coming out of wall and connecting to data logger with RJ 45 plugs

Figure 3.45 - Data cable and RJ 45 plugs connecting the data logger's RJ 45 terminals

The installation of the wires within the case study test house took considerable time, and special care was taken that all the cables connected to the Krone connectors and individual wiring to the sensors were kept at least 600mm away from any other electrical house wiring.

Calibration of Sensors

There were two distinctive data-logger wiring stages: the internal data logger wiring and the wiring from the data logger to all the individual sensors. The wiring within the data logger was installed by the Data-logger consultant involving the following process:

- Step 1: All data from the logger was emptied, followed by data logger tests runs and checks to ensure that all channels read zero,
- Step 2: The data logging program was installed into the data logger and all channels were checked to ensure that a zero reading was still recorded,

- Step 3: Resistors and other wiring were installed to the individual channels of the data logger. The data logger was tested to ensure that a zero value was still recorded,
- Step 4: Earth reference wires were installed. The data logger was tested to ensure a zero value was still recorded,
- Step 5: The data cables were attached to the R45 terminal blocks and the data logger was tested to ensure a zero reading was still recorded.

This method for wiring the data logger, (from the data logger individual channels to the RJ terminal block) enabled removal or repair of any items which did not present a clean signal. During the beginning of the three months of data collection, occasional testing of the data loggers was performed, when all data cables were removed from the logger terminal and all wires were tested to ensure a zero reading was still recorded.

A simple step-by-step data cable testing, (RJ plug connection to the data logger and sensor feeder cable to the sensors) was introduced for the houses, based on the wiring methods at the test cells at Launceston (Figure 3.46 to Figure 3.49). The procedure for the installation of cables, wires and cable connectors is described in more detail as follows:

- Step 1: The data cable was cut to the desired length between the Logger (placed on the external wall under the deck) and the Krone connector block. The first RJ 45 plug was connected to the data cable and the cable was plugged into the terminal block of the data logger. The eight individual cables outlets were then tested at the other side to ensure a zero reading (-273.4ºC) when connected to the computer,
- Step 2: The second RJ 45 was attached to the data cable and the data logger was tested to ensure a zero value (-273.4ºC) reading,
- Step 3: The RJ 45 plug was now connected into the Krone connector block and the data logger was tested to ensure a zero value recording,
- Step 4: The sensor feeding cable (bell wires) was wired into the Krone connection block, with the sensors already wired to the feeder cables. A temperature signal was then received,
- Step 5: Output readings were then compared between data: from the data cabled sensor via the sensor feeder cable and the Krone connector block and data from direct-wired sensors at the same location. If there was a variation of more than 0.3ºC of the readings, individual sensors were replaced until similar readings were recorded. Only one cable sensor was replaced during the sensor test comparisons and the remaining

comparison between the cabled sensor and the direct wired sensors showed similar readings of not more than 0.2 ºC difference.

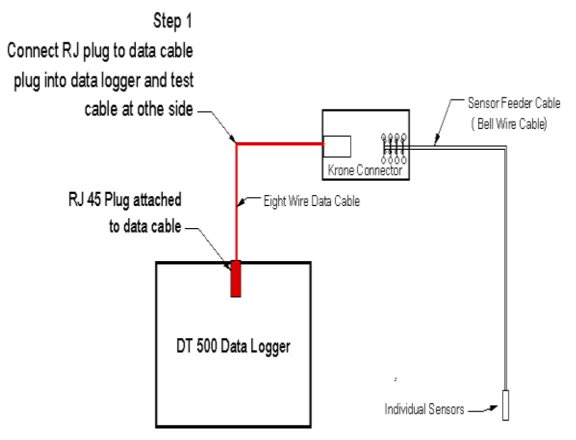

Figure 3.46 - Step 1. Installation and testing of data cable and plug connection

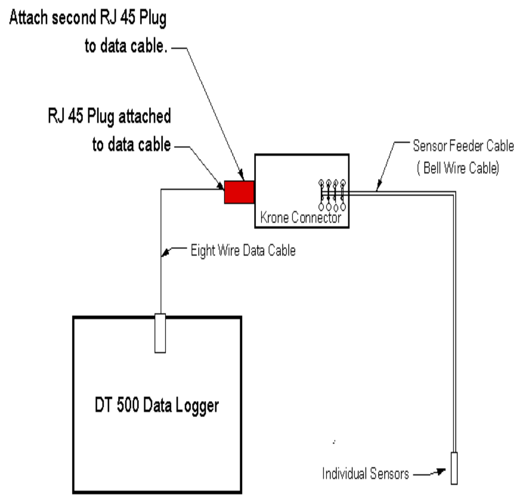

Figure 3.47 - Step 2. Attaching second RJ 45 plug to data cable

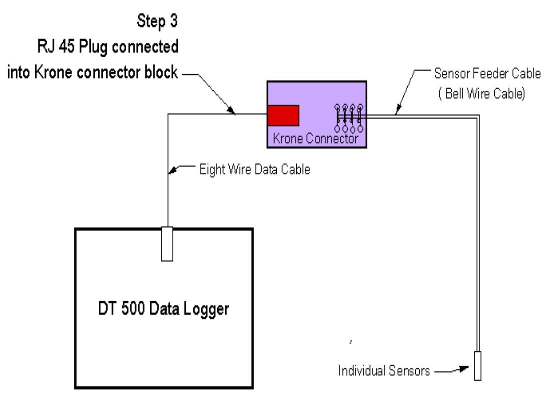

Figure 3.48 - Step 3. Connecting the RJ 45 plug into the Krone connector

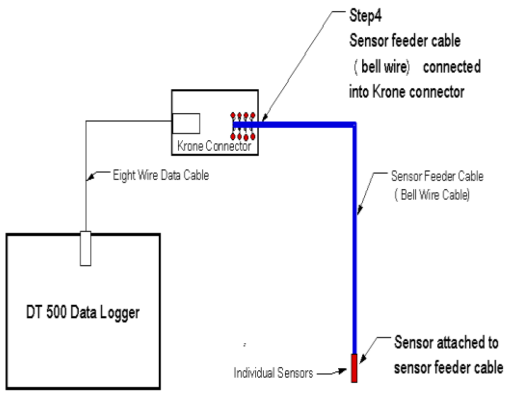

Figure 3.49 - Step 4. Connecting the sensor feeder cable into the Krone connector block

The testing of the individual cable and plug connections permitted a reliable error examination. Most of the errors were due to poorly connected RJ45 plugs to the data cables and faulty attached wires into the Krone connectors. In this case the data cable would be trimmed and a new RJ45 plug would be attached to the cable. For a faulty wire connection into the Krone connector, the wires were removed, trimmed and re-connected.

Figure 3.50 shows the installation of the sensor feeding cable and the subsequent testing of the cable and Figure 3.51 depicts the computer zero readout (-273.4ºC) for the testing of the cable and plug connections.

Figure 3.50 - Connecting and checking sensor feeder cable on site

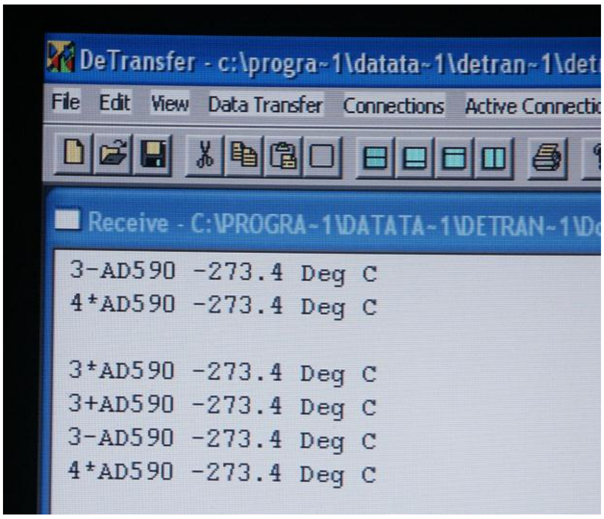

Figure 3.51 - Checking cable connection and data logger's zero value readouts

3.3.4. Operational Control of the Test Building

The test house was monitored only in an unoccupied unconditioned mode (also referred as free running operation). This included the following parameters:

- No thermostatically controlled methods were uses to condition the spaces within the buildings through either cooling or heated;
- No ventilation methods were triggered via doors, windows or any other means;
- No internal electrical loads (i.e., stove, refrigerator, television) are added to any space within the buildings;
- No internal loads, triggered by persons or animals, were added to any space within the buildings.

3.4. Data Cleaning

Up to seventy sensors were installed in the house and data was collected every 10 minutes. This resulted in a number of files and a significant quantity of data which required the time consuming activity of data cleaning. The data cleaning methods followed the same process as adopted for the test cells in Launceston, which had been developed in close consultation with CSIRO researchers (Dewsbury 2011).

The actual data checking was undertaken by employees at the School of Architecture and Design’s Centre for Sustainable Architecture with Wood (CSAW). To allow for independent and objective checking, the project researcher was not involved in the data checking process. This ensured that the data cleaning process would not be influenced by the researcher’s personal engagement and intimate knowledge of the thermal performance of the houses. All enquiries by the data checking team were attended to and their outputs were checked by the project researcher. Technical experts from the University’s School of Engineering and Architecture and Design were engaged to assist with the setting of realistic range and step measurements for all sensor locations in the house. Additionally, data checking involved cross-comparison, either with data from a nearby sensor or from additional relevant sensors in the weather station. Table 3.4 shows the step-by-step data cleaning process used for this project.

The process included some investigation and predetermining of realistic environmental measurement fluctuations for both inside and outside sensors. For example, the estimated expected inside roof temperature fluctuation was between -3ºC and 50ºC, while the actual measured temperature range was only 0ºC to 35ºC. In consultation with other experts, the project researcher had to accept or reject the measured temperature range. In general terms, the estimated environmental measurements for range and step values were within the range of actual measured values.

The graphical checking of data required a different mechanism. Here, a ten minute and an hourly interval data were checked and analysed. Unusual fluctuations, changes in patterns, or drastic spikes and sharp dips, were investigated to determine the validity of the measurements.

Table 3.4: Method of Data Cleaning of the Test Houses

Stage	Title	Description
V1	10 Minute Data Range Checks	Each sensor device was allocated an expected range of measurement. All the data were checked to ensure the measurements were within that range.
V2	10 Minute Data Step Checks	Each sensor device was allocated an expected step value within a 10 minute data reading. All data were then checked to ensure step measurements were within the pre-determined step check range.
V3	10 Minute Data Graphical Checks	Graphical software converted the data into a graphical format. This analysis checked for abnormal shifts or unusual data patterns. Large data swings were analysed and checked.
V4	Averaging 10 Minute Data into Average Hourly Format	The six individual 10 minute readings were averaged to an hourly value. The only exception was the averaging of wind speed and wind direction, which used a different method of establishing hourly values.
V5	Average Hourly Data Range Checks	Each sensor device was allocated an expected range of measurement. All data were checked to ensure the measurements were within that range.
V6	Average Hourly Step Checks	Each sensor device was allocated with an expected step value within an hourly data reading. All data were then checked
V7	Average Hourly Data Graphical Checks	The final checking process was the application of graphical software to convert the data into graphical presentation. This method highlighted abnormal shifts or unusual data patterns.
V8	Average Hourly Data	Specific selected data averaged and used for the empirical validation with AccuRate

4. Generating the Simulation Data

Prior to the input of data into the HER simulation software, a critical analysis of the as-built construction condition of the test house was completed. In addition, it was also important to obtain a critical understanding of how the construction and changes in construction, (the as-built test house), should be entered into the HER software, either via front-end or back-end inputs of the simulation program. As data entry was refined, several detailed envelope simulations were completed, in order to reduce errors in the simulation process.

In preparation for the thermal simulation of the test house, a range of modifications to the HER's software inputs were required, namely:

- Determine the 'as-built' values for the roof, ceiling and wall fabrics for the modification of the fabric's thermal properties,
- Determine the 'as-built' values for shading objects near to the test house that would affect the building's thermal performance,
- Use of measured infiltration values for the house interior, and the roof space,
- Modification of the thermostat settings within the software to recognise the unoccupied unconditioned state (free running operation) within the internal zones of the house,
- Modification of the window input settings to a closed window position for all internal zones to simulate a non-vented, free running mode of the test house,
- Modification of the window framing ratio based on the windows installed in the test houses,
- Using site-measured climatic data instead of the HER software's in-built default climate file.

These modifications required a significant number of front-end and back-end input changes for the purpose of providing and empirical validation envelope simulation of the test house.

4.1. Site-measured Weather File for Empirical Validation

The site climate data input requirements, as shown in Table 4.1, were collated from either the existing HER's TMY file, BOM data, site-measured data or calculated values based on site measured data. Site measured climate data were measured at 10 minute intervals. The climate data were checked and cleaned using the same data cleaning process as the measured house data. Table 4.2 presents a sample of the on-site climate file, as acquisitioned from the DT 80 data logger.

Table 4.1: Site Climate Data Input for the Test House

Type of Input	Reference
Month number	From HER TMY file
Day number	From HER TMY file
Dry bulb air temperature (tenth of degree Celsius)	Site measured
Moisture content (tenth gram per kilogram)	Site measured
Atmospheric air pressure (tenth of kilopascal)	The BOM data came from a location with a very similar altitude to the test house.
Wind speed (tenth of metres per second)	Site measured
Wind direction (0 to 16)	Site measured
Cloud cover (0 to 8)	Calculated data with the program (Make ACDB v9)
Global solar radiation (Wh/m²)	Site measured
Diffuse solar radiation (Wh/m²)	Calculated from site measured data
Normal direct solar radiation (Wh/m²)	Calculated from site measured data
Solar altitude (0 to 90 degrees)	From HER TMY file
Solar azimuth (degrees)	From HER TMY file

Table 4.2: Sample of the Site Climate Data (EXCEL format)

DATA AVERAGING STARTS HERE. ALL SCALES AND WIND DIRECTION/SPEED DATA CONSIDERED CORRECT.

		m/s	Deg. from Nth	Deg. Centgrd.	% RH	kw/sq_m	kw/sq_m
6/9/2007	1:00:00 PM	7.74563	205.18355	19.47771	35.49002	0.32661	0.44173
6/9/2007	1:05:00 PM	10.82517	351.76074	19.05207	39.24554	0.60724	0.85305
6/9/2007	1:10:00 PM	6.65398	192.37823	19.78958	35.07518	0.49924	0.69213
6/9/2007	1:15:00 PM	8.25591	177.0159	19.30822	38.11343	0.52521	0.7319
6/9/2007	1:20:00 PM	7.272	184.9097	19.48072	36.12559	0.61459	0.8519
6/9/2007	1:25:00 PM	7.89808	184.30019	19.47902	37.94512	0.18584	0.24244
6/9/2007	1:30:00 PM	10.25002	169.91263	17.91193	40.91792	0.25954	0.35377
6/9/2007	1:35:00 PM	10.77329	172.97968	17.12326	42.03335	0.61079	0.85332
6/9/2007	1:40:00 PM	9.19717	172.05998	17.50165	41.58142	0.59754	0.82651
6/9/2007	1:45:00 PM	8.15682	208.27592	18.96708	39.03234	0.61018	0.84664
6/9/2007	1:50:00 PM	7.29314	181.35695	19.18412	38.21769	0.52228	0.67188
6/9/2007	1:55:00 PM	9.71505	192.82501	18.59184	39.234	0.58799	0.80925
6/9/2007	2:00:00 PM	8.08082	210.63979	18.41893	40.68654	0.24062	0.33318
6/9/2007	2:05:00 PM	6.69032	174.07941	18.47278	38.96243	0.58834	0.82003
6/9/2007	2:10:00 PM	8.81508	213.80502	18.77082	39.27591	0.17585	0.23377
6/9/2007	2:15:00 PM	9.2485	194.3858	17.77205	40.12176	0.17117	0.21663
6/9/2007	2:20:00 PM	8.69248	188.50137	17.35881	41.66214	0.16403	0.21803
6/9/2007	2:25:00 PM	9.80251	210.70758	17.14646	41.80394	0.27176	0.37295
6/9/2007	2:30:00 PM	4.57043	188.0186	18.29817	38.90648	0.45522	0.64341
6/9/2007	2:35:00 PM	8.44203	172.75661	19.01917	35.70838	0.51618	0.72826
6/9/2007	2:40:00 PM	7.84162	184.799	19.31995	35.87874	0.51236	0.719
6/9/2007	2:45:00 PM	7.62718	195.5818	19.29534	35.95545	0.14781	0.18214
6/9/2007	2:50:00 PM	7.88956	196.34543	18.97644	36.55281	0.19705	0.19448
6/9/2007	2:55:00 PM	8.92915	177.6087	18.23884	38.85389	0.35333	0.43114
6/9/2007	3:00:00 PM	8.70583	182.04565	18.29216	38.90921	0.1915	0.20546
6/9/2007	3:05:00 PM	7.94345	216.47163	17.94094	40.62796	0.15044	0.18419
6/9/2007	3:10:00 PM	7.31784	180.93343	17.37962	40.67196	0.12184	0.13835
6/9/2007	3:15:00 PM	8.35964	171.29547	17.01033	41.46204	0.1878	0.1826

4.2. HER Software Front-end Standard Inputs

4.2.1. Postcode

The postcode enables the software to assign the appropriate site-measured climate file. The site measured climate file was given the same name as the normal default file for postcode 7000 (Climate zone 26, Hobart).

4.2.2. Exposure and Ground Reflectance

The properties for these inputs were:

- Exposure - Suburban: The location of the test house can be classified as suburban, as the test house is surrounded by low-rise built-up areas of the suburb of Kingston.
- Ground Reflectance - 0.5: The rear of the house is close to a white grey driveway. The default ground reflectance setting on 0.2 assumes that the building is surrounded by grass. As the driveway at the rear would reflect some solar radiation towards the test house the default value of 0.2 has been re-set to 0.5.

4.2.3. Construction Information

Table 4.3: Construction Information for the Case Study Test House

Constructions	Details	
External Walls, North, East, West , South.	Brick Veneer Wall, 90mm Generic concrete blocks 4mm rendered, Air gap vertical 31-65mm (40mm nominal) unventilated reflective (0.4/0.9; E=0.38) Rockwool bat (K= 0.033) 46mm, Plasterboard 10mm	
	External Surface	Colour: light, Solar Absorptance 30%
	Internal Surface	Colour: Paint, light cream, Solar Absorptance 30%
Windows	Bradnam’s generic aluminium sliding door, single glazed 3mm	U-Value (NFRC) 7.14 Frame fraction 15% SHGF (NFRC) 0.75 Frame absorption 96%
	Bradnam’s generic aluminium sliding window single glazed 3mm	U-Value (NFRC) 6.51 Frame fraction 14% SHGF (NFRC) 0.75 Frame absorption 96%
	Bradnam’s generic aluminium sliding doors, double glazed, 3/18/4mm	U-Value (NFRC) 4.51 Frame fraction 17% SHGF (NFRC) 0.62 Frame absorption 96%
	Bradnam’s generic	U-Value (NFRC) 4.00

	aluminium sliding window 3/11/4mm	Frame fraction 17% SHGF (NFRC) 0.63 Frame absorption 96%
Doors	Timber Mountain Ash 40mm	
	External Surface	Colour: Medium, Solar Absorptance 50%
	Internal Surface	Colour: Medium, Solar Absorptance 50%
Ceiling	Plasterboard ceiling: glass wool bat (k=0.044) 96mm, Plasterboard 10mm	
	Top Surface	Colour: light, Solar Absorptance 30%
	Bottom Surface	Colour: light cream, Solar Absorptance 30%
Floor (Garage)	Garage Floor, Concrete Standard (2400kg/m³)	
	Top Surface	Colour: light grey, Solar Absorptance 75%
	Bottom Surface	Colour: Concrete Dry, Solar Absorptance 62%
Floor (Tiles and Slab)	Kitchen floor, Entry floor, Concrete Standard (2400kg/m³) Ceramic tiles 8mm	
	Top Surface	Colour: Dark, Solar Absorptance 85%
	Bottom Surface	
Floor (Carpet and Slab)	Living and Dining Area, Bedrooms and Hallway, Concrete Standard (2400kg/m³) Carpet 10mm, Underlay 8mm	
	Top Surface	Colour: Light grey, Solar Absorptance 75%
	Bottom Surface	
Interior Walls, uninsulated	Plasterboard on 90mm Studwork, 10mm Plasterboard, air gap vertical (90mm nominal) 10mm Plasterboard	
	First Surface	Colour: Light cream, Solar Absorptance 30%
	Last Surface	Colour: Light cream, Solar Absorptance 30%
Interior Wall, insulated	Plasterboard on 90mm Studwork, 10mm Plasterboard, R 2.5 Rockwool bat, 10mm Plasterboard	
	First Surface	Colour: Light cream, Solar Absorptance 30%
	Last Surface	Colour: Light cream, Solar Absorptance 30%
Roof	Metal Deck: Steel 1mm, Air gap 22.5 º, 31-65mm (40mm nominal) ventilated reflective (0.4/0.9, E=0.38)	
	External Surface	Colour Dark, Solar Absorptance 85%
	Internal Surface	Colour Light, Solar Absorptance 27%
Skylight	Nil	
Roof Window	Nil	

4.2.4. Zone Information

Table 4.4: Zone Information for the Case Study Test House

Habitable Zones						
Name of Zone	**Type of Zone**	**Volume (m^3)**	**Floor Height (m)**	**Ceiling Height above floor (m)**	**Heated**	**Cooled**
Garage/Laundry	Garage	50	0.0	2.4	N	N
Bath	Other (daytime usage)	11.8	0.6	2.4	N	N
WC	Other (daytime usage)	3.6	0.6	2.4	N	N
Kitchen/Dining/Living		88.8	0.8	2.4	N	N
Bed 2	Other (daytime usage)	28.1	0.6	2.4	N	N
Bed 1	Other (daytime usage)	31.5	0.6	2.4	N	N
Hall	Other (daytime usage)	17.2	0.6	2.4	N	N

Roof Space Zone					
Name	**Volume (m^3)**	**Reflective**	**Sarking**	**Roof Surface**	**Openness**
Roof Space	77.0	N	Sarked	Continuos	Standard

4.3. HER Software Non-standard Inputs

4.3.1. Framing Factor

Wall Framing Factor & Insulation Amendments

Determining the framing factor for the case study test house required the calculation of the area of wall framing. A scale drawing of the floor plan and 16 individual wall-elevations (showing the exact framing layout) were produced with the assistance of site photographs taken at the construction stages. Figure 4.1 to Figure 4.4 show sample photographs that were used to establish the wall elevation drawings.

Figure 4.1 - Corner detail at the framing stage of one of the platform floored houses

Figure 4.2 - Framing stage of the test house of one of the platform floored houses

Figure 4.3 - Completed wall-framing stage of one of the platform floored houses

Figure 4.4 - Framing stage of the concrete slab test house

Figure 4.5 depicts the elevation drawings that were produced for the wall-framing of the house, which was used for calculating the wall-framing factor.

The exact wall-framing ratios for the test houses were calculated as shown on Table 4.5.

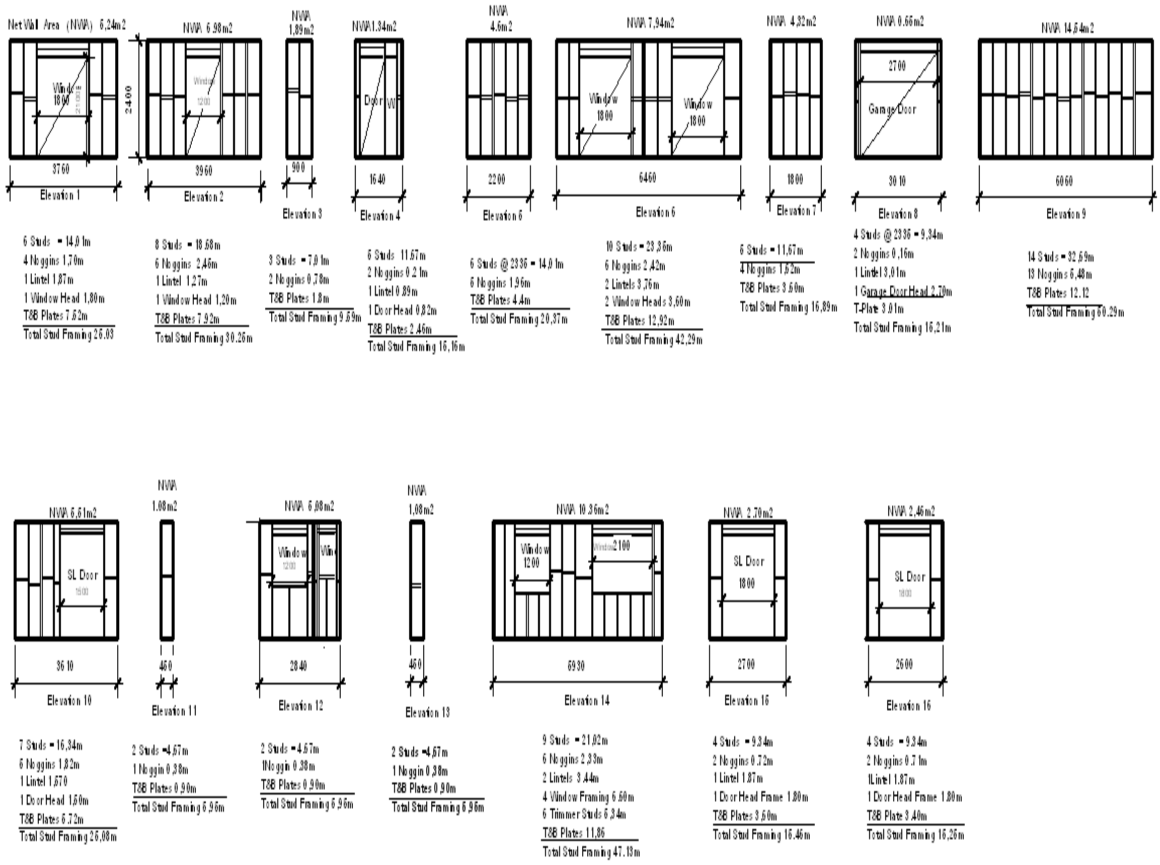

Figure 4.5 - Elevation of external views of wall framing of the test house

Table 4.5: Calculating the Wall Framing Factor for Twelve Individual Wall Elevations

Elevation	Tot Length of all Studs (m)	Stud Width (m)	Stud Area (m2)	Lintel Length (m)	Lintel Width (m)	Lintel Area (m2)	Timber Area (m2)	Wall Area (m2)	Framing Ratio
1	25.03	0.035	0.876	1.876	0.19	0.35	1.23	5.24	0.23
2	30.25	0.035	1,059	1.27	0.15	0.19	1.25	6.98	0.18
3	9.59	0.035	0.336				0.336	1.89	0.17
4	15.16	0.035	0.531	0.890	0.15	0.134	0.665	1.34	0.49
5	20.37	0.035	0.713				0.713	4.60	0.16
6	42.29	0.035	1.480	3.76	0.19	0.714	2.194	7.94	0.28
7	16.89	0.035	0.591				0.591	4.32	0.14
8	15.21	0.035	0.532	3.01	0.25	0.753	1.285	0.65	1.98
9	50.29	0.035	1.760				1.760	14.54	0.12
10	25.08	0.035	0.878		0.15	0.236	1.114	5.51	0.20
11	5.95	0.035	0.208				0.208	1.08	0.18
12	30.88	0.035	1.081	1.94	0.15	0.291	1.372	5.08	0.27
13	5.95	0.035	0.208				0.208	1.08	0.18
14	47.13	0.035	1.650	3.44	0.19	0.653	2.303	10.36	0.22
15	15.46	0.035	0.541	1.87	0.19	0.355	0.896	2.70	0.33
16	15.25	0.035	0.534	1.87	0.19	0.355	0.889	2.46	0.36
						Total	17.01	75.47	0.23

Now that the framing factor had been calculated, the isotherm planes method was used to establish the average R-value for the timber studs and wall insulation for the test house, as shown below:

$$U_{av} = 0.77 \times (1/2.5) + 0.23 \times (1/0.53)$$

$$U_{av} = 0.742 W/m^2K$$

$$R_{av} = 1/0.742 m^2K/W$$

$$R_{av} = 1.347 m^2K/W$$

This established the final R-value for the external walls, as shown in Table 4.6. This resulted in a revised insulation thickness of 45mm (i.e., insulation = Conductivity x revised value for wall insulation - 0.033 x 1.35 = 45mm)

Table 4.6: Isothermal Method to Establish Revised Wall Insulation

Element	R-Value test house (m^2K/W)
OS Surface (24km/h wind)	0.030
Brick wall	0.180
Reflective cavity	0.280
Rav for studs and insulation based on 0.23/0.77 ratio	1.35 revised R-value for AccuRate input
10 Plaster board	0.06
IS surface (still air)	0.12
Rt(av)	2.016

Ceiling Framing Factor & Insulation Amendments

The area of the ceiling framing was calculated to establish the ceiling framing factor, in the same manner as that used for the external walls. In order to calculate the area of ceiling framing, a scaled ceiling framing diagram was drawn indicating all ceiling timber members, as shown in Figure 4.6.

All the ceiling members, including the individual lengths and areas, were calculated, as shown in Table 4.7.

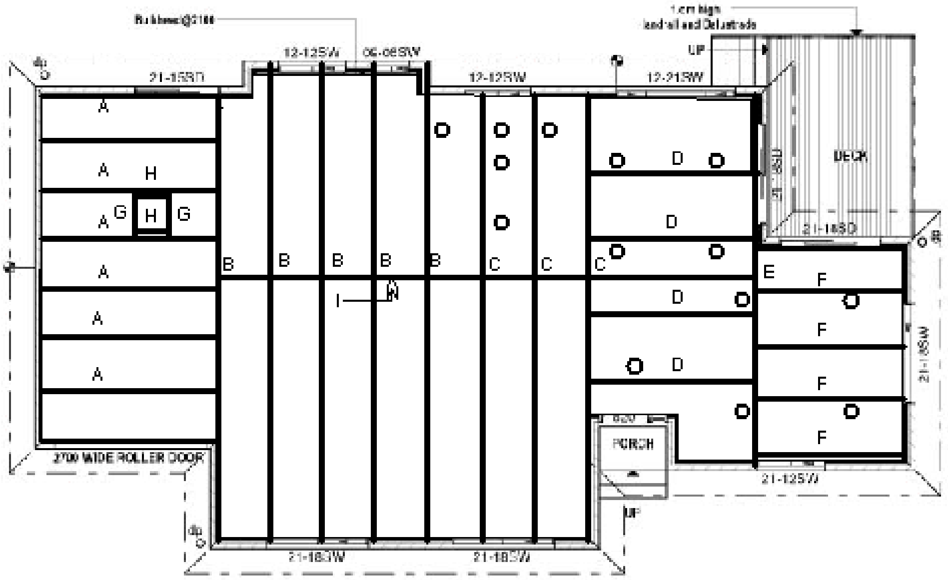

Figure 4.6 - Diagram of the ceiling framing layout

Table 4.7: Calculating the Area and Framing Ratio of Ceiling Framing

Member	Quantity	Individual Length (m)	Total Length (m)	Width (m)	Area (m^2)
A	8	3.05	24.40	0.035	0.85
B	5	8.56	42.80	0.035	1.50
C	3	8.00	24.00	0.035	0.84
D	4	2.95	11.80	0.035	041
E	1	4.10	4.10	0.035	0.14
F	4	2.75	11.00	0.035	0.39
G	2	0.86	1.72	0.035	0.06
H	2	0.60	1.20	0.035	0.04
I	1	9.50	9.50	0.035	0.33
			Total Ceiling Area 98.2m²	Total Timber Area	4.56
				Framing Ratio	0.046

Now that the framing factor had been calculated, the isotherm planes method was used to establish the average R-value for the ceiling for the test house, as shown below

:

$$U_{av} = 0.954 \times (1/4.0) + 0.046 \times (1/0.53)$$

$$U_{av} = 0.326 W/m^2K$$

$$R_{av} = 1/0.326 m^2K/W$$

$$R_{av} = 3.07 m^2K/W$$

Table 4.8: Isothermal Method to Establish Revised Ceiling Insulation

Element	R-Value test house (m^2K/W)
OS Surface	0.030
Rav for ceiling joists and insulation (based on 0.954/0.046 ratio)	3.07
10 Plasterboard	0.06
IS surface (still air)	0.12
Rt(av)	3.28

The revised R-value for the ceiling of the test house was 23% less than the software's default input setting of 4.31m^2K/W. The insulation thickness was revised to account for this factor (i.e., Conductivity value revised for ceiling insulation - 3.07 x 0.044 = 135mm)

4.3.2. Unoccupied & Unconditioned Mode of Operation

This method is also referred to as free-running or free-floating and required the following modifications to be undertaken.

Ventilation – Door & Window Opening

During the unoccupied and unconditioned measurement stage, all windows and doors remained in the closed position. The AccuRate program input requested the percentage of window and door openings to be selected during the window data entry. The openable area for the windows and doors is used by the software to calculate cooling from natural ventilation. All the window and door data entries listed the openable area as zero, which replicated the unoccupied and unconditioned mode of operation. In addition, during the unoccupied and unconditioned operation no indoor window coverings were drawn and this was reflected in the AccuRate data entry by selecting 'no window coverings'.

Thermostat Settings

During the unoccupied and unconditioned mode of operation no auxiliary heating or cooling requirement was used and there were no internal energy loads. Simulating these conditions within the AccuRate software was achieved by setting the simulation to a 'Non-Rating' mode in the AccuRate's manager screen and de-selecting the heating and cooling requirement for each zone. In addition, this action also automatically eliminated all internal sensible and latent heat gains.

Infiltration Rates

The measurement of infiltration in the case study test house was conducted by the Mobile Architecture & Built Environments Laboratory (MABEL). The new infiltration values obtained from these tests were used to provide amended values to the AccuRate scratch file. In AccuRate the infiltration rate, in air changes per hour, is specified as (Delsante 2005):

$A + B \times v < 1\text{m/s}$ or $A + B \times \sqrt{v} > 1\text{m/s}$

where A = Air change per hour

B = Wind reduction factor

v = wind speed per hour, multiplied by the terrain factor

The values for A and B were calculated based on MABEL's measured infiltration data (Luther 2008) and are shown in Table 4.9. For comparison, AccuRate's default values are shown in the same table.

Table 4.9: AccuRate's Default Infiltration Values and Measured Infiltration Values

House Type	AccuRate Default Value A	AccuRate Default Value B	Measured Value A	Measured Value B
Test House Roof Zone	2.00	1.00	1.60	0.07
Test House Internal Area	1.07	0.09	0.55	0.00

Window Framing Ratio

AccuRate's scratch file also contained the construction data for windows, which included specified values for the window framing factor. The actual values were calculated based on measured data. The values were then modified in AccuRate scratch file. Figure 4.7 and Figure 4.8 show the window framing details at the case study test house.

Table 4.10 shows the comparison of AccuRate's in-built window framing factor and the measured window framing factors, demonstrating a significant difference for the sliding doors located in the kitchen, dining and living areas. As a result of this finding, AccuRate's in-built value of 0.23 was modified to the measured value of 0.17.

Figure 4.7 - Window frame detail for the bedroom window

Figure 4.8 - Close up image of window framing

Table 4.10: Comparison of AccuRate's In-built and Measured Window Framing Factors

Window Location	In-built Window Framing Ratio	Measured Window Framing Ratio
Laundry Sliding Door (Single Glazed)	0.17	0.15
Bedrooms, Bath and WC Windows (Single Glazed)	0.15	0.14
Kitchen/Dining/Living, Sliding Doors (Double Glazed)	0.23	0.17
Kitchen/Dining/Living Windows (Double-Glazed)	0.20	0.17

The window framing ratios were modified in AccuRate's scratch file from the default settings to the measured values.

4.4. The HERS Simulation

For the purpose of determining the incremental effects caused by as-built fabric and measured climate file inputs, four simulation types were completed, as described below.

4.4.1. Default Fabric / Default Climate File

This was a standard AccuRate simulation, based on the in-built values of the building fabric and the climate. The term Default Fabric / Default Climate File refers to the standard and default view of the building fabric and the unquestioning acceptance of a default climate file. This is the standard type of simulation used by house energy assessors completing House Energy Star Rating reports.

4.4.2. Default Fabric / Measured Climate File

This was an AccuRate simulation, where the original default values for the building fabric were used, but the site-measured climate data was substituted in place of the default climate file. This simulation was carried out to identify the difference in thermal performance based on the in-built climate versus the site-measured climate data.

4.4.3. As-built Fabric / Default Climate File

With this type of simulation the front-end and back-end data input values of the building fabric were based on the ‘as-built’ values discussed above. However, the in-built climate file was still used in this simulation type. In this type of simulation, the difference between ‘as-designed’ (building fabric information based only on building plans) and ‘as-built’ (building fabric information based on the observed condition) were clearly identified. This type of simulation has been used for some past validation projects of thermal simulation programs.

4.4.4. As-built Fabric / Measured Climate File

This AccuRate simulation used the ‘as-built’ values for the building fabric and the site-measured climate data. This type of simulation was used to create the AccuRate empirical validation data set for comparison with the measured zone temperatures.

4.4.5. AccuRate Energy Report

This report was used as a checking mechanism to ensure the house was simulated in the unoccupied and unconditioned state. The values in the report should all be zero, as shown in Figure 4.9.

```
 Total number of conditioned zones =   1

Month Day Hour     ----Open space stud---
           Heat    CoolS    CoolL
  1    1    0       0.0      0.0      0.0
  1    1    1       0.0      0.0      0.0
  1    1    2       0.0      0.0      0.0
  1    1    3       0.0      0.0      0.0
  1    1    4       0.0      0.0      0.0
  1    1    5       0.0      0.0      0.0
```

Figure 4.9 - Energy txt AccuRate Output File

5. Comparing Simulated and Measured Data

Graphical and statistical methods were used to compare the simulated data with the measured data and they included the following approaches:

- Graphical comparison of site-measured external temperatures and AccuRate's in-built TMY external temperatures;
- Graphical comparison of temperature profiles in the living room of the test house resulting from AccuRate's in-built TMY file and the site-measured climate file;
- Graphical comparison measured and simulated hourly temperature profiles for all zones of the test house including the roof zone;
- Graphical comparison of measured and simulated maximum and minimum daily temperatures for all zones of the house, including the roof zone;
- Statistical scatter-plot comparison between simulated and measured temperatures for all zones of the house, including the roof zone;
- Statistical distribution of temperature residuals for all zones, including the roof zone;
- Statistical scatter-plot comparison between the temperature residuals of adjoining zones in the house;
- Statistical scatter-plot comparison between room residuals and climate parameters such as: air temperatures, global solar radiation, wind speed and wind direction.

Examples of these forms of analysis are shown below.

5.1. Graphical Comparison of Site-measured and TMY Air Temperatures

This form of analysis showed the significant difference between the site-measured climate data and the default TMY climate file, as shown in Figure 5.1.

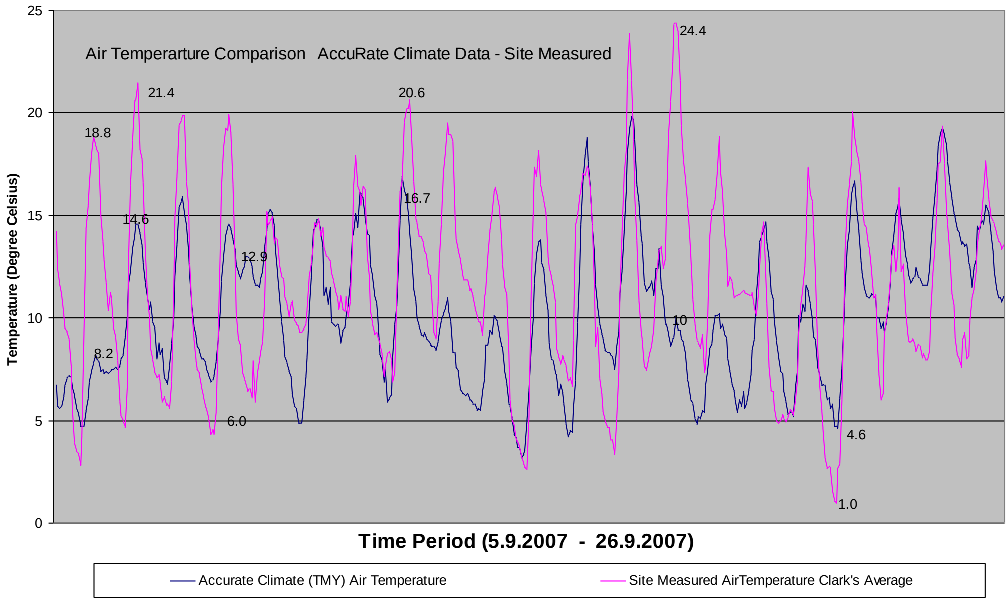

Figure 5.1 - Temperature comparison between site-measured and TMY air temperature values

Figure 78 shows AccuRate's predicted thermal performance comparison for the living room of the slab floor house, using the in-built AccuRate climate data and the site-measured climate data. The comparison of thermal performance shows a significant temperature difference between AccuRate's simulation, using original inbuilt TMY climate data, and AccuRate's simulation, using site-measured climate data.

5.1.1. Graphical Comparison of Zone Simulated and Measured Temperatures

Figure 5.2 shows a graphical time series analysis of the simulated and measured temperatures for a zone within the case study house.

Figure 5.3 shows a graphical time series analysis of the simulated and measured maximum and minimum temperatures for a zone within the case study house.

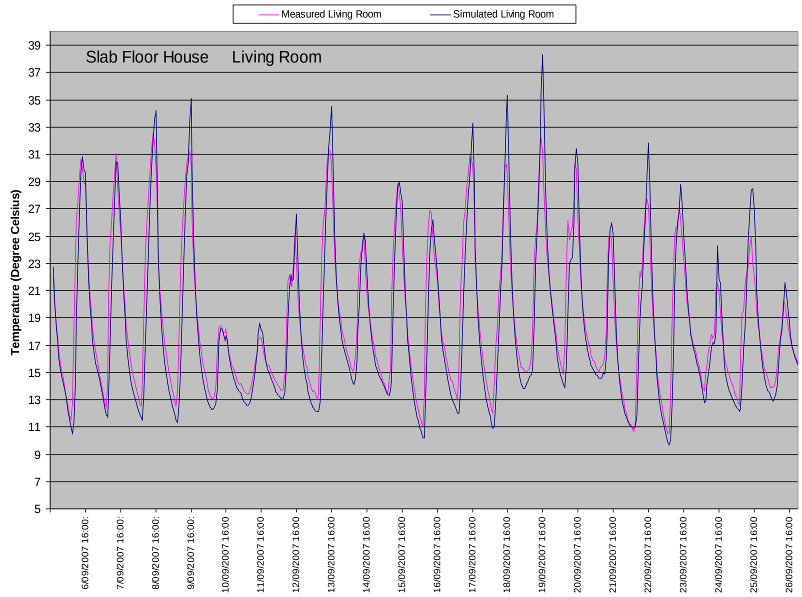

Figure 5.2 – Graphical time series comparison of simulated and measured zone temperatures

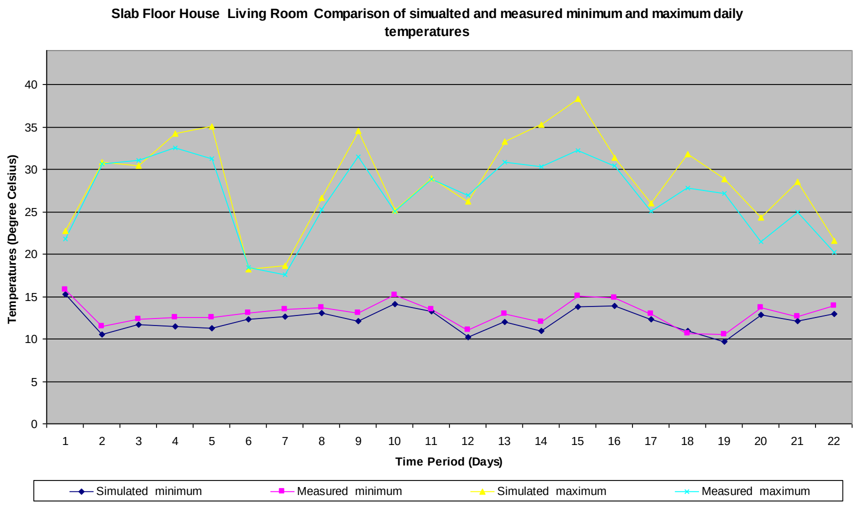

Figure 5.3 - Graphical time series comparison of simulated and measured maximum and minimum zone temperatures

5.2. Statistical Analysis

5.2.1. Measured and Simulated Correlation Diagrams

The scatter-plot of simulated and measured temperatures for each zone was completed, as shown in Figure 5.4. The best fit and perfect fit lines are drawn for comparison, and the coefficient of determination (r^2) is indicated at the bottom left hand corner.

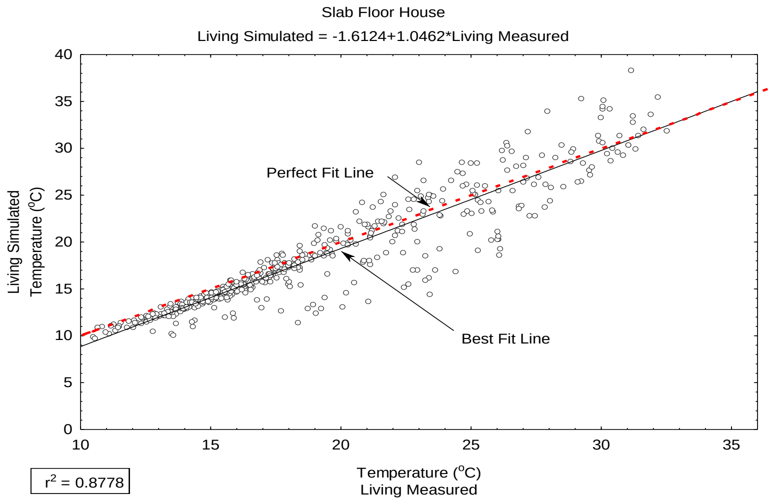

Figure 5.4 – Scatter-plot of simulated and measured zone temperatures

5.2.2. Residual Histogram Analysis

Residual histograms were created for each zone to allow for and exploration of the residual value distribution, as shown in Figure 5.5.

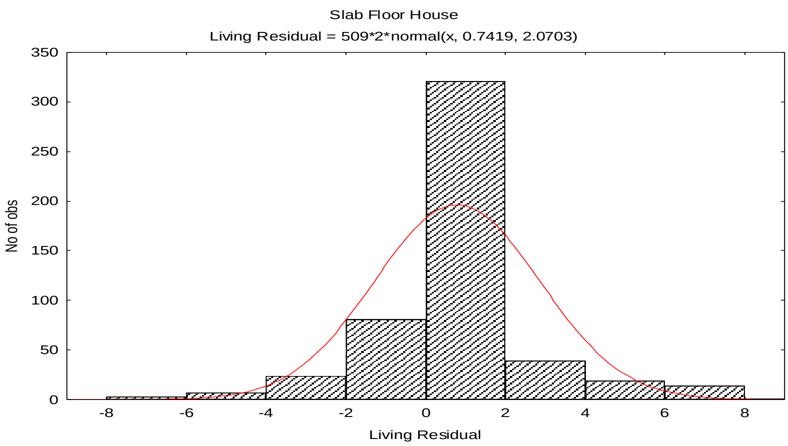

Figure 5.5 – Histogram showing distribution of zone residual values

5.2.3. Correlation Analysis of Residual Values Between Adjoining Zones

Figure 5.6 and Figure 5.7 show the scatter-plot diagrams analysing the residuals of two adjoining zones. This form of analysis is used to explore any possible correlation between the residual values in adjoining zones.

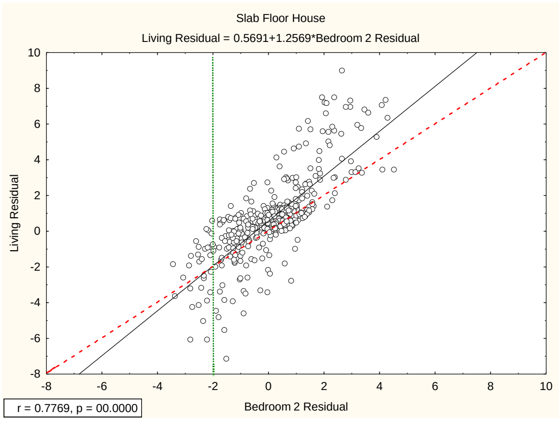

Figure 5.6 – Scatter-plot 1 of adjoining zones

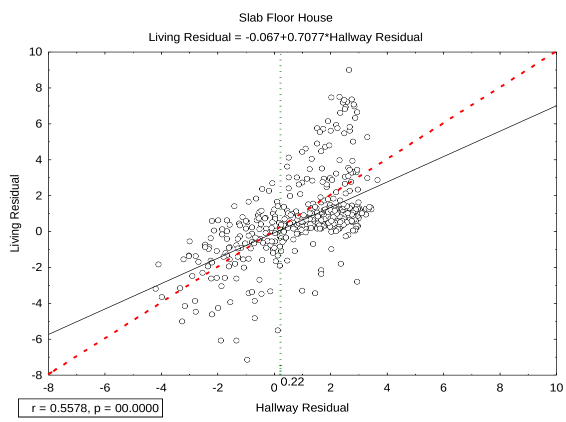

Figure 5.7 - Scatter-plot 2 of adjoining zones

5.2.4. Correlation Between Zone Residual Values and Climate Parameters

Figure 5.8 to Figure 5.11 show scatter-plots used to explore any correlation between: the zone residual values and site air temperature (Figure 5.8); global solar radiation (Figure 5.9); wind speed (Figure 5.10) and wind direction (Figure 5.11).

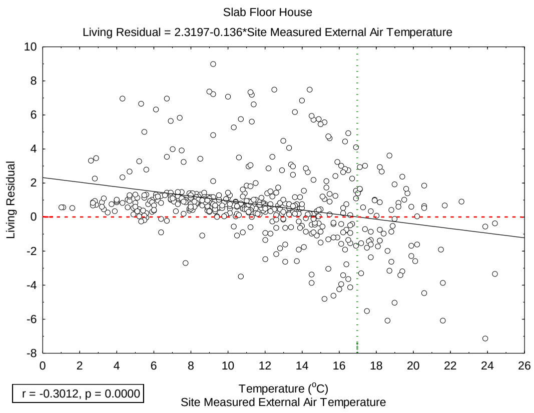

Figure 5.8 – Scatter-plot of zone residual values and external air temperature

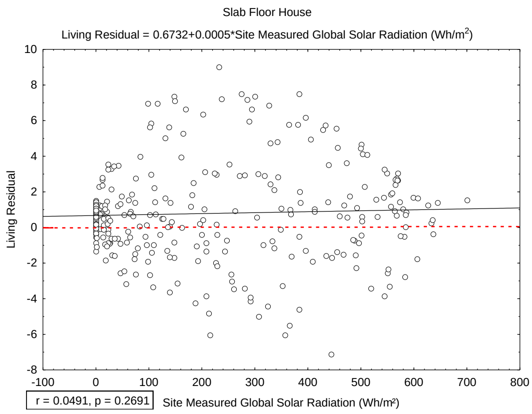

Figure 5.9 – Scatter-plot of zone residual values and global solar radiation

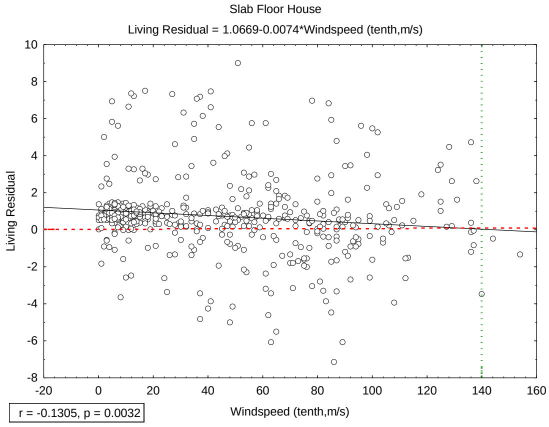

Figure 5.10 – Scatter-plot of zone residual values and site wind speed

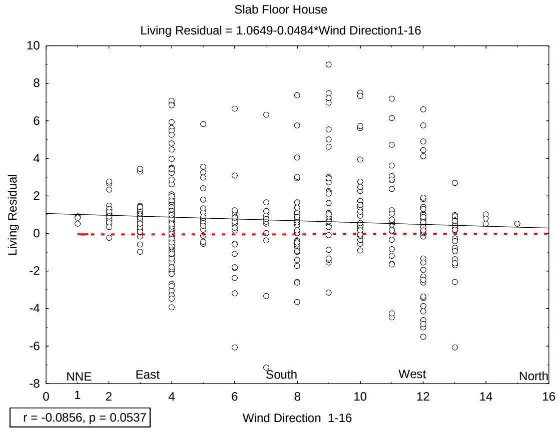

Figure 5.11 – Scatter-plot of zone residual values and site wind direction

6. Conclusion

The aim of this research was to empirically validate the AccuRate house energy rating software for a concrete slab-on-ground floored house in southern Tasmania. This case study illustrates that this involved the establishment of several key components and methods, namely:

- The construction of a test house in Kingston, Tasmania. The building type was a concrete slab-on-ground floored, two bedroom residence, built to Australian standards and regulations.

- The installation of data acquisition, data storage systems and equipment to measure the internal and site environmental conditions

- The completion of a detailed building envelope simulation using the AccuRate HER software

- The collation and cleaning of a measured and simulated data sets

- The graphical and statistical analysis of the measured and simulated data sets

All the stages of the research were completed in a rigorous manner to enable the aim of the research activity to be achieved.

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