MASTERARBEIT

THERMAL IMPLICATIONS OF RADIANT ROOF BARRIERS: A FIELD STUDY IN HOT-HUMID CLIMATIC CONDITIONS

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ABSTRACT

Three 3x3 sqm test cells were made to examine the use of radiant barrier in the attics in hot and humid climate. The test cells were observed in four ventilation methods. Each ventilation method was a round of changing the vented windows, soffit boards, openings of radiant barrier at the ridges. The three test cells with natural ventilation were tested simultaneously in each round and each test cell produced its own indoor climate data. The temperature and relative humidity observations of the four ventilation methods over three test cells produce four comparative sets of room temperature and each set has 3 test cells' temperature measurements. The indoor temperatures were compared in bin and frequency distribution, psychrometric chart and PMV. The function and effectiveness of radiant barrier installed between roof tiles and rafters of two test cells were compared to the baseline case which had no radiant barrier on the roof. The roofs with purposely made holes on the radiant barrier at the ridge were compared to the tight roofs which have less amount of natural ventilation. The clay tiling and concrete tiling roofs installed with radiant barrier were discovered no significant difference in temperature measurements at the expense of different material thermal properties.

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1. INTRODUCTION

Malaysia is a tropical country situated near the equator. The climate is hot and humid throughout the year without distinctive seasonal change. In most of the days except the monsoon periods the daily ambient temperature fluctuates between 22 to 35°C and the relative humidity fluctuates between 65 to 96%. While, during monsoon the diurnal temperature frequently falls between 22 to 30°C and the relative humidity rarely drops below 75% due to frequent evening rains. The mean of monthly air temperature in any month remains constant between 25 to 27 °C and the relative humidity 75-85%. The problem of heat wave happens from 9 am to 5 pm daily when solar radiation enters the range 400 to 1000 W/m^2. The 12-month climate data of Ipoh, Malaysia, can be seen in Figure 1. The thermal performance of a building is affected by the solar absorption of the roof. During clear sky conditions up to about 1 kW/m^2 of solar radiation can be incident on a roof surface, and between 20% and 95% of this radiation is typically absorbed (Suehrcke et al. 2008).

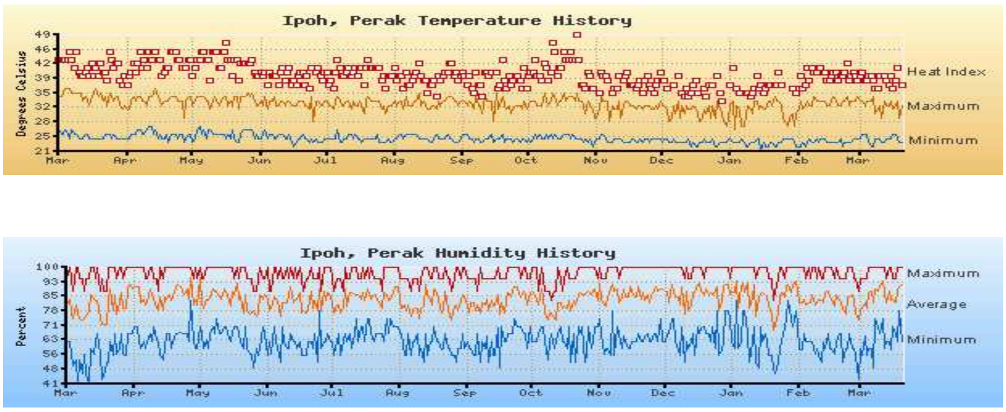


Figure 1 *top and bottom: 12-month climate data of Ipoh, Malaysia*

The warmest volume inside the building during the day is the attic which has the longest solar exposure. Heat enters into a building in two ways: solar radiation conducting through the wall and roof and hot outdoor air migrating through windows or any openings. A combination of high solar radiation and hot outdoor air often causes the attic to have elevated temperature. If the attic is a tight volume with very little natural ventilation, heat trapped inside the attic will mostly migrate downwards into the living room passing through the very thin non-insulated gypsum board ceiling and partly dissipate through small cracks and gaps of the roof. The internal wall surface temperature of the living room underneath the attic is, theoretically, parallel to the attic temperature when the living room is also not vented. Without cross ventilation or with insufficient air flow, the discomfort feeling in the living room is always relevant to heat migration. It is interesting to study heat migration in different roofing settings. Perhaps, a small and low-cost change of roofing method will give a huge thermal comfort improvement. This effect of heat migration can be seen in Figure 2 and is regarded as **Hypothesis 1** and will be elaborated by Predicted Mean Vote (PMV) method.

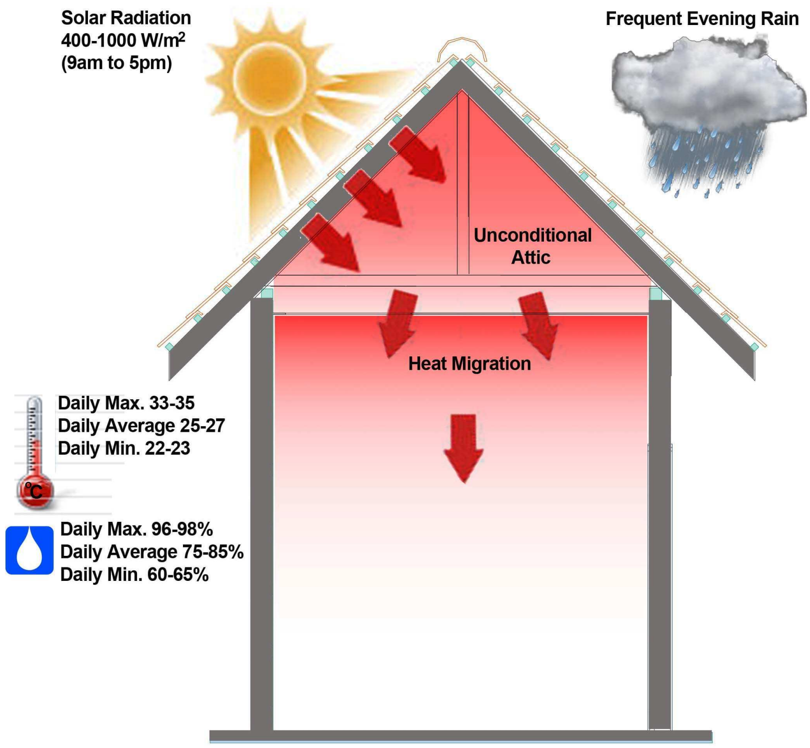


Figure 2 *Assumption of heat migration*

In absence of an active cooling mechanical system, the attic thermal pattern has the clue to explain the thermal performance of the immediate living room underneath the roof.

When a room has night ventilation by opening the windows or doors to release the indoor heat gathered during the day, the room temperature will drop to the possible minimum value just as the outdoor temperature. In contrary, when the outdoor temperature is higher, the room should not be ventilated due to the in-flow of hot air from outside. In this research project, a window operation scheme of closing and opening to have natural ventilation at a certain time line was used to further reduce the indoor temperature. The study of passive cooling technique in Malaysia can be found by "*The effects of night ventilation technique on indoor thermal environment for residential buildings in hot humid climate of Malaysia*" (T. Kubota et al. 2009).

The counter batten roof construction creates an extra air space between the roof tile exterior surface and the reflective aluminium foil. An air buoyancy effect happens when the temperatures of the non-conditioned attic and the outdoor ambient temperature are different. In addition, the airflow velocity in the inclined air space would also be exaggerated by surrounding wind. These two natural principles are tentatively thought to be practical to reduce the heat transfer from the hot tiles into the attic. Presumably, the heat dissipation in the air space is enhanced by sufficient airflows. This type of roof system is termed "cool roof system" by Monier Roofing System Snd Bhd Malaysia (see Figure 3). This cool roof system is regarded as **Hypothesis 2** and tested in Round 1.

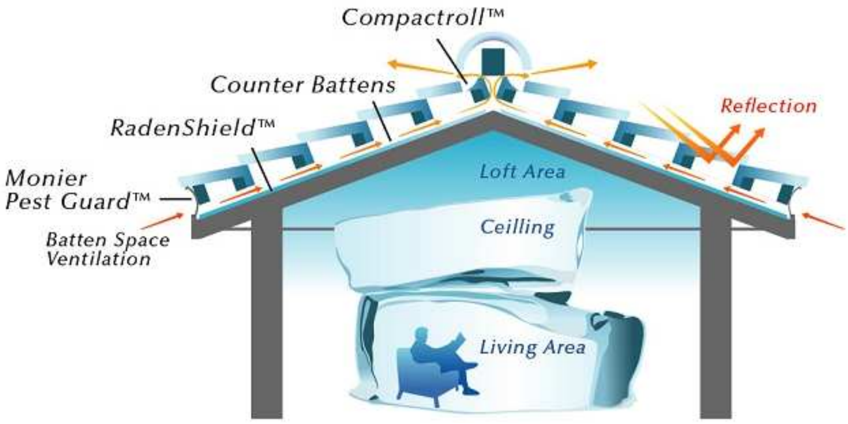


Figure 3 *Monier Roofing System's flagship COOL ROOF for hot and humid climate (Monier Brochure 2011).*

Note that the cool roof system in Malaysia is distinctively different to the above-sheathing ventilation (ASV) and a bulky insulation above rafters practiced in North America or any cold climate. Instead of using oriented strand board (OSB) underneath the counter batten and on the rafters, the cool roof system in hot and humid Malaysia has simply the very reflective aluminium foil which is a radiant barrier. Traditionally the conventional roof system, installed without insulation and radiant barrier underneath the roof tiles, is the most common practice in row houses throughout Malaysia.

The radiant barrier of the cool roof system is thought to have much heat flux reflected and diverted by airflows in the air space. Note that not every aluminium foil can be regarded as radiant barrier. The radiant barrier used in this roof research, namely RadenShield, is claimed to block 95% of heat flux in a commercial statement of the Monier Technical Center (see figure 5).

This research had four rounds of natural ventilation techniques for three different roofing systems. A field study consisting of three identical sized test cells were made, each test cell has its unique roofing method. In each tested round, these three different roofs shared an identical natural ventilation technique. The amount of roof natural ventilation was deducted from maximum to minimum in the four stages. The indoor temperature patterns of all rounds were expected to have differences when the changing the natural ventilation technique. The thermal performances of the living rooms influenced by the three roofing methods are the fundamentals of this research. Out of these 4 ventilation techniques and 3 roofing methods, the living room with the best thermal performance will be regarded as the genuine cool roof system for hot and humid Malaysia.

2. Motivation and Background

The roofing construction in hot and humid Malaysia surrounds two core factors: a) reduction of solar heat gain conducting through attic into living space; and, b) the economic and availability of building material. Many researches have been carried out outside South-east Asia in either a climate chamber or a free field regarding roofing methods under hot temperature. For example, Monier Technical Centre, UK and Oak Ridge National Laboratory (ORNL), Florida, USA are currently the best known research centers which make a range of roofing study. The study of roofing in tropics can be categorized into several areas:

1) Solar reflectance roof surface,

2) materiality and thermal property of roof tiles,

3) radiant barrier, and

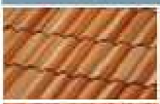
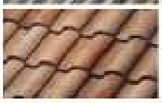
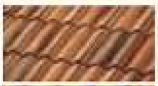
4) counter battens with air flow underneath roof tiles and vented attic.

2.1. Solar Reflectance Roof Surface

The reflectance of a roof tile is determined by its coated layer, reflectance, emittance and colour. Solar reflectance index (SRI) is a mathematic calculation numerically denoting how much solar incidence is reflected. A combination of a roof pitched angle, positional latitude and SRI determines the total solar absorption of the roof. See Table 1 for SRI Indexes of roof tile colours.

"Two popular roof tiles are made of ceramic (e.g., clay fired at high temperature) or fabricated from cement concrete. Some of the lighter types use fibres (e.g., cellulose) added for strength. The colour of a tile may be dispersed throughout, or it may be applied in the form of a coating. Perhaps the most venerable type of roof tile is the Spanish style red barrel tile made from fired clay. The modern version of this tile is sometimes a cement tile with a suitable coating. In either case, the red colour is due to the ubiquitous iron oxide material, hematite. Roofing tiles are available in a wide range of colours; more data on the solar reflectance properties is needed."(Roof Tiles 2011) From this quotation, it mentions that a modern roof tile has been developed into a variety of colour surfaces by enhanced coating techniques; while, the traditional fired clay roof tiles are always red-orange due to the iron oxide material, hematite and alumina. For the study regarding the reflective coated roof tiles, one can refer to the field study "TASK 2.5.7 FIELD EXPERIMENTS TO EVALUATE COOLCOLORED ROOFING" made by Oak Ridge National Laboratory (ORNL) and Monier Technical Centre (Miller et al. 2010).

Table 1 *SRI index table for different colours of roof tile (Suehrcke et al. 2008)*

Image	Color	Reflectance	Emittance	SRI
	Orange, Yellow, Grey, Multicolor	0.44	0.92	51
	Red	0.33	0.92	37
	Tan, Black, Multicolor	0.27	0.93	29
	Orange, Tan, Multicolor	0.25	0.93	27
	Orange, Tan, Brown, Multicolor	0.23	0.91	24
	Orange, Black, Multicolor	0.23	0.93	24

2.2. Materiality and thermal property of roof tiles

There is a doubt between using clay tiles and concrete tiles in hot and humid climate. The burnt clay tile and concrete tile have dissimilar thermal properties; therefore, these roof tiles are supposed to give a different temperature pattern in the attics.

Figure 4 and table 2 show that the reduction in daytime peak heat flow due to an increase in thermal mass is accompanied by an approximately proportionate increase in the duration of downward heat flow. This suggests that the thermal mass of the roof does not significantly affect the integrated daily heat gain through the roof. Note that the slightly negative heat flow during night-time is the result of the sky temperature being below the ambient one, i.e. the roof loses heat during night-time to the cold sky. This diagram was published in the article “Effect of roof solar reflectance on the building heat gain in a hot climate” by Harry Suehrcke, Eric L. Peterson and Neville Selby, who made a study in residential buildings in hot and humid Townsville, Australia.

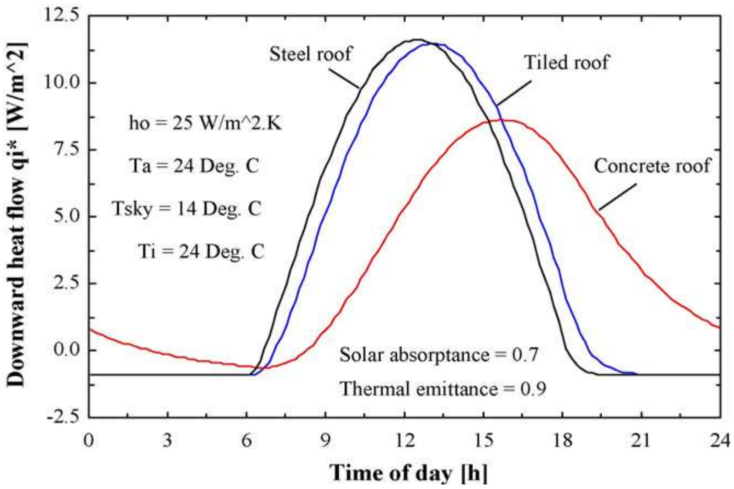


Figure 4 *Heat flux measurement of steel roof, tiled roof and concrete roof (Suehrcke et al. 2008)*

Table 2 *Thermal mass does not affect heat gain of roof (Suehrcke et al. 2008)*

Sky temperature	Daily heat gain (kJ/m^2)		
	Steel roof	Clay tiled roof	Concrete roof
$T_{sky} = T_a$	349.8	350.0	351.0
$T_{sky} = T_a - 10$ K	266.4	266.5	267.6
$T_{sky} = T_a - 20$ K	192.6	192.7	193.8

2.3. Radiant Barrier

"Solar Radiation is composed of short-wave radiation which, on arriving at the surface of the roof tiles, is absorbed and the tiles heat up. Part of this heat is lost through convection and long-wave radiation to the external environment and another part is absorbed by the roof tiles and transmitted to the space corresponding to the attic. This absorbed part transmits heat in two forms: through radiation and convection. In turn, the radiation incident on the surface of the slab (or ceiling) is absorbed and the surface heats up, transferring the heat to the internal environment of the residence." (Michels et al. 1994)

Radiant barrier, such as RadenShield by Monier Roofing (see Figure 5), is a thin and highly reflective sheet to reduce thermal transmission from the propagated side to another side. For example, it is applied on the roof either above the ceiling board or under the roof tiles sheathing board. The layer slows down solar gains entering into the attic during summer and conserves heat leaked out from the attic to outdoor during colder time (see Figure 7).

Figure 5 *Monier Roofing System's cool roof with radiant barrier*

“The reflective thermal insulators are used to reduce the heat transfer by radiation between the roof tiles and the ceiling (slab) of the building. All bodies emit or receive thermal radiation as a function of their temperatures. The amount of energy emitted is dependent on the surface temperature and on the emissivity, which is related to the good performance of the sheet. The lower the emissivity of a material, the better the radiant barrier performance.” (Michels et al. 2005) Some other samples of radiant barriers were collected for this research, the chosen product for this research was the most common at that time: double side polished and reflective without air-bound. The high-end air-bound radiant barrier is deemed to be too expensive and used for only luxurious houses.

In this research, the tested roofs were not built air-tight in Round 2, 3 and 4. The aluminium foils had holes on the ridges in that rounds. When a fraction of solar radiant heat successfully passes through the radiant barrier, the attic space is set to receive some heat gains. During night radiant cooling, the trapped heat in the attic is blocked by the radiant barrier and escapes through any roof gaps or openings. This physics mechanism is part of the goal of the research which is to find out the benefit of installing radiant barrier on the roof in hot and humid climate.

2.4. Counter Battens with Air Flow underneath Roof Tiles and Vented Attic

Oak Ridge National Laboratory (ORNL) determined that a minimum 3/4-inch air space between the tiling underside and roof deck is required to create adequate airflow to dissipate heat. In addition, ASHRAE (2005) provides empirical data for the effective thermal resistance of plane air spaces. A 3/4-in. (0.0191-m) plane air space inclined at 45° with the horizontal has a RUS-0.85 (RSI-0.15) (Kriner and Desjarlais 2011).

Therefore, the test cells in this research followed the tested preference set by ORLN. The air space underneath the roof tiles is 4 inches which is above the minimum ¾ inch and the roof pitches were set at 45° inclination.

Monier Roofing System introduces the counter batten roofing method in South-east Asia by its flagship product “Monier CoolRoof System”. The centre idea of its cool roof system relies on a) the claimed air flow underneath roof tiles to facilitate hot air removal (see Figure 6), and, b) radiant barrier layer to block solar heat gain. The cool roof system always has the layers and structure shown by the Figure 8 and 9 below.

Figure 6 *Monier Roofing System’s vented ridge and counter batten roof for hot and humid South-east Asia*

Figure 7 *left and right counter batten and vented ridge outside South-east Asia (Miller et al. 2010)*

Yet, there is no scientific study published in South-east Asia that claims that clay tiles or concrete tiles with counter battens and a radiant barrier layer would give a better indoor thermal pattern than any other type of roofing methods. The motivation of this research is mainly derived out of the extra cost consideration and its thermal performance.

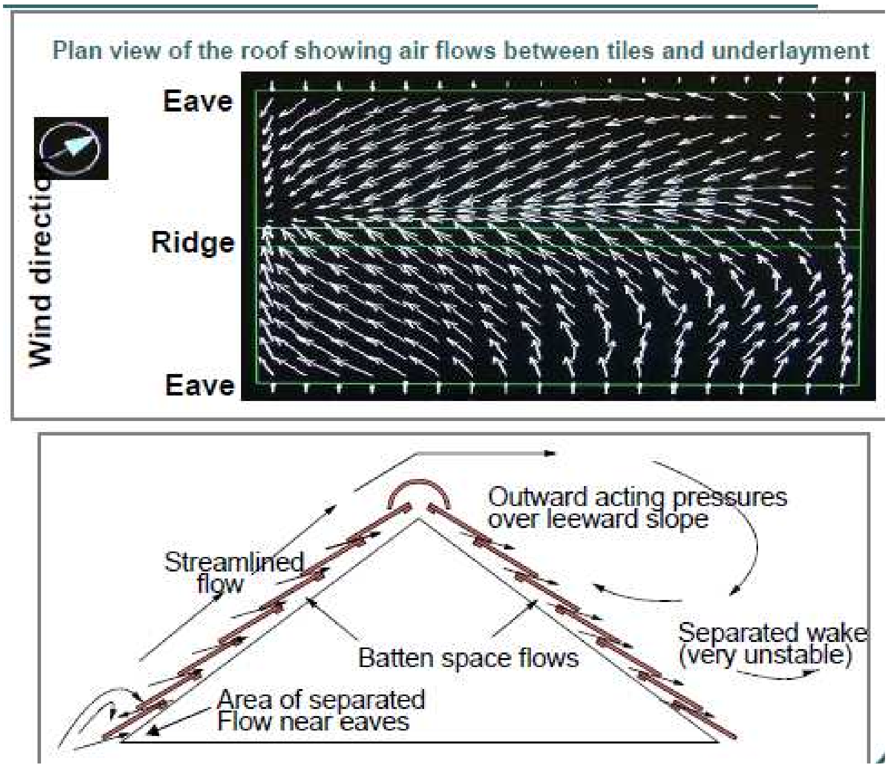


Figure 8 *top and bottom: Computational Fluid Dynamic simulation for air flow (Vandewater 2007)*

Figure 9 *Air flow roof concept (Vandewater 2007)*

Providing ventilation for the attic in a hot climate seems a necessary step to decrease the internal convection. There are many ways making the attic ventilated; these solutions include: a) the overlapping gaps between tiles, b) employing perforated soffit board, c) without soffit board at the roof eave, air flow below roof tiles and above underlayment, d) creating openings at the gabled walls; or even, e) employing a mechanical fan to suck out hot air.

Oak Ridge National Laboratory in Florida already carried out an extensive vented roof study for a range of roofing methods including shingles, metal, cement tiles, clay tiles, S-barrel tiles, flat tiles (see Figure 10).

***Figure 10** ORNL's roof study in Florida (Miller et al.)*

3. Experiment Set-Up

3.1. Description of Test Cells

The size of the test cells and indoor spaces was the foremost consideration of this research in which the test cell must be reasonably big to reflect the reality. Therefore, the volume of the test cell was determined to have a room which can accommodate 2 single beds. The three identical test cells (Figure 11) were built on a field in Ipoh, Malaysia. Each identical test cell has an 11x11 ft steel mesh reinforced concrete slab with 12 ft walls and a gable roof pitch is 45° with a ceiling to ridge height of 5 feet (1.5 meter).

Figure 11 *Test Cells on free-field.*

All the ridges of the test cells are directed from North-East to South-West, being 20° clock-wise from the East due to the site constraint. However, this azimuth orientation to the sun is still able to make both sides of roof pitches to be stroke by solar radiation at the same time. When the sun is high, solar radiation strikes fully on all the roof tiles from 10am to 4pm and strikes partially on either a side during sunrise and sunset (Figure 12). See Figures 13 to 19 construction drawings and pictures.

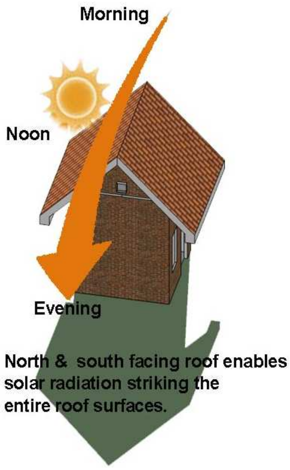


Figure 12 *The Sun strikes fully on the roof planes from sunrise to sunset.*

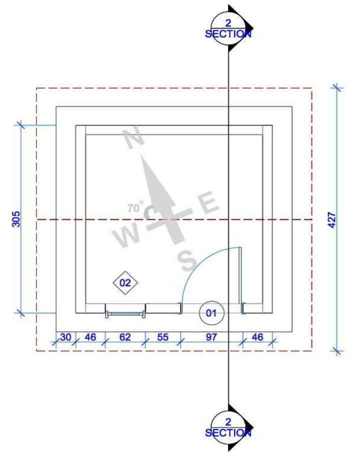


Figure 13 *Plan (3 meter x 3 meter)*

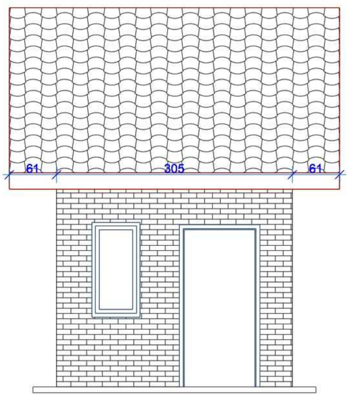


Figure 14 South Elevation

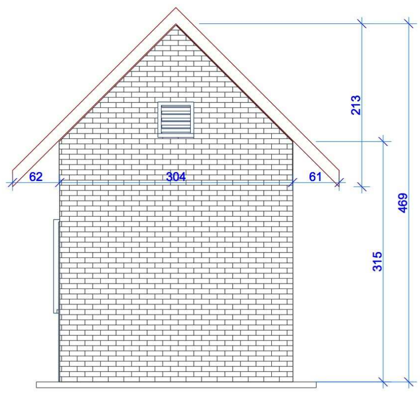


Figure 15 East and West Elevation

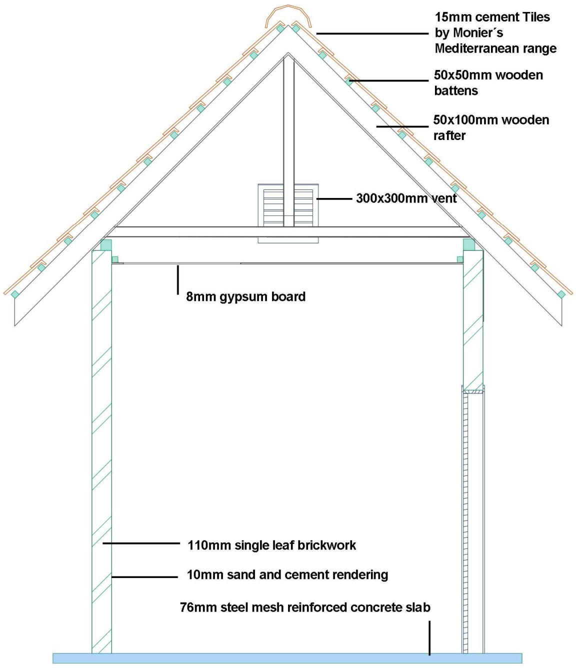


***Figure 16** Construction detail of Test Cell 1, without aluminium foil*


***Figure 17** left and right: Roof without aluminium foil*

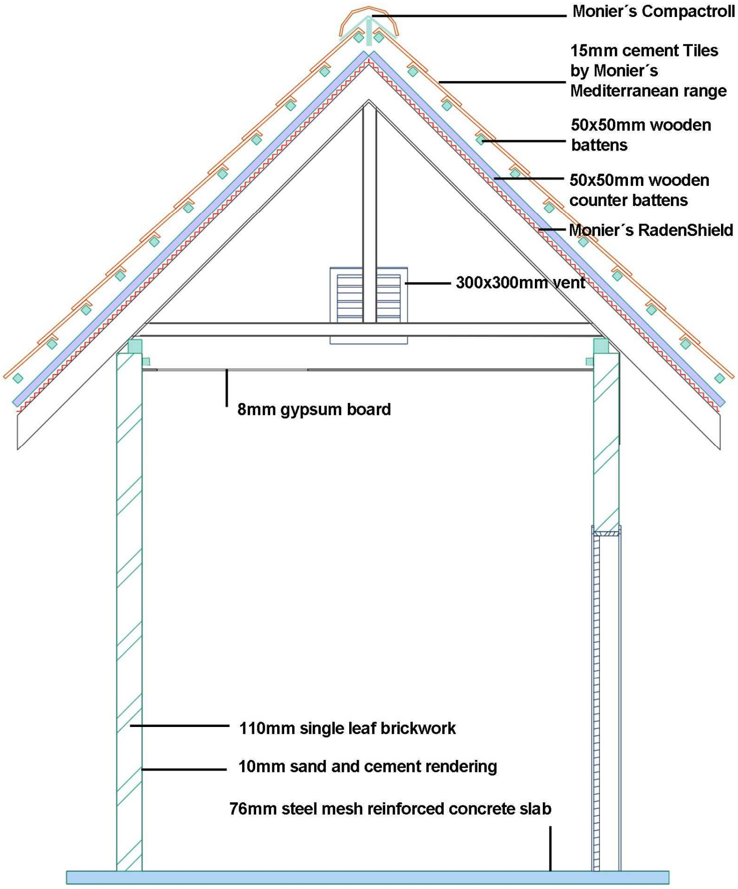


Figure 18 *Construction detail of test cell with aluminiun foil*

Figure 19 *left and right: Test cell with aluminium foil*

3.2. Data Logging

Figure 20 shows that the Hobo temperature and relative humidity data loggers were placed in the test cells for indoor thermal measurement. Figure 21 shows that the Hobo weather station was positioned on the roof to have the ambient temperature, relative humidity, solar radiation and wind speed.

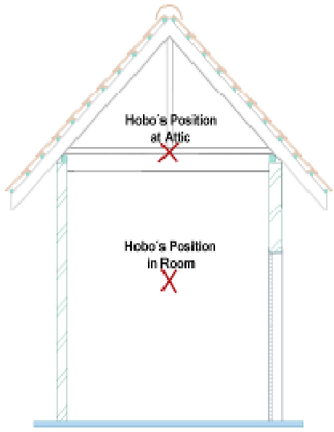


__Figure 20__ HOBO Loggers

__Figure 21__ Weather Station

The four ventilation rounds were carried out on selected days during October-December 2010. The temperature, relative humidity, solar radiation and wind speed sensors were set to have 10 minutes interval and each round had at least 7 days. The results of temperature and relative humidity logged in Test Cell 2 and 3 are compared to the Test Cell 1 which is the most common roofing in South-east Asia.

3.3. Rounds of Vented Roof Strategies and Night Ventilation

See figure 22 and table 3 below which describe that each test cell has 4 rounds of various ventilation and the night-ventilation through the opened door, which was consistently operated through all the rounds.

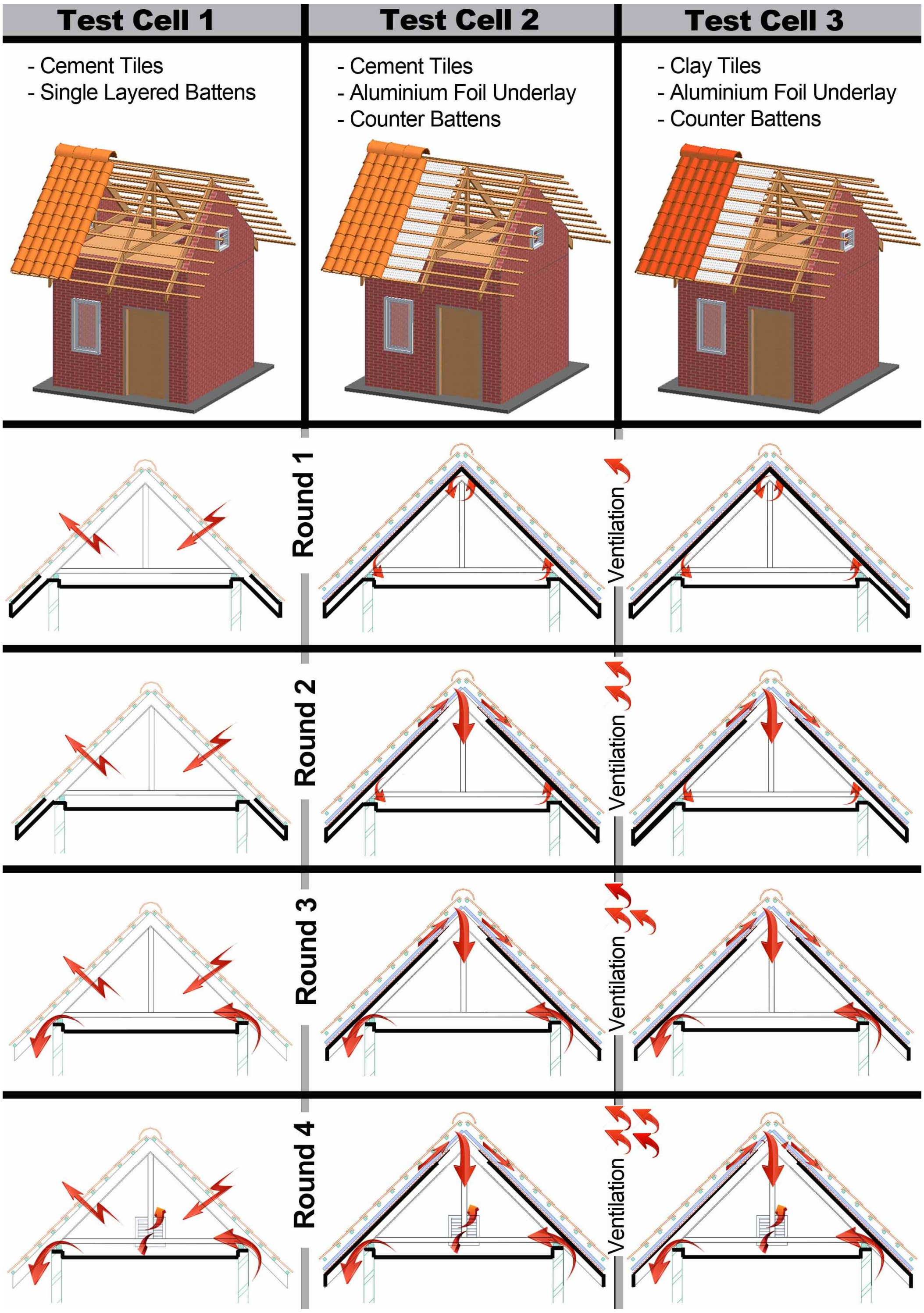


***Figure 22** Three test cells in 4 ventilation rounds*

Table 3 *Night ventilation's door timetable*

Time	Opened Door
Day (7am-7pm)	no
Night (7pm-7am)	yes

The pictures below (Figure 23 to 28) show a few key steps to define each ventilation round. Parameters that change the ventilation mode include:

a) attic windows (opened/closed)
b) soffit board (mounted/dismounted)
c) aluminium foil at the ridge (opened/sealed)

Figure 23 *Opened Attic window to allow air exchange (only in Round 4)*

Figure 24 *Closed attic window (in Round 1,2 and 3)*

Figure 25 *Maximising attic ventilation by no soffit board (in Round 3 and 4)*

Figure 26 *Minimising attic ventilation by closing the eave with soffit board (in Round 1 and 2)*

Figure 27 *Aluminium foil was cut to have ridge ventilation (Round 2, 3 and 4).*

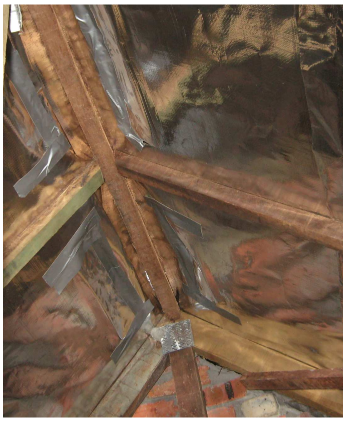


Figure 28 *Aluminium foil at ridge was sealed (Round 1).*

4. Results and Discussions

4.1. 24-hour Graphs

In each round the data collection time had at least a span of 5 days. The graphs below are the extraction of each round shortened into a 24-hour cycle to bear a closer hour by hour investigation. In each round the temperature curves show a similar pattern. Each testing round had a few particular hot days and one of these hot days was chosen for the 24-hour graph. The building envelopes are capable of retaining heat during the day, later in the evening heat inertia and dissipation to the cooler medium will happen. All test cells have a unique roofing method with a similar wall structure; it is expected to produce a various room temperature result.

4.1.1. Round 1 Room Temperatures

In Round 1, all attics had no ventilation opening and the possible infiltrations were the small cracks and gaps of the roofs. Figure 29 shows the room temperature graph of Round 1. Comparing the peaks, Room 1 is clearly the worst of all, followed by Room 2 and 3. In this round, the aluminium foils in the Roof 2 and Roof 3 apparently have an effect of radiant barrier. At the peak temperature of the day, Room 3 with clay roof tiles is obviously the best with almost 1.5°C lower to Room 1 with no aluminium foil and 1°C lower to concrete tiles.

The contrasts between peak attic temperatures are greater than room temperatures (see Figure 30). From 2 to 3 pm is the hottest period of the day. At the hottest time the Attic 3 is almost 3.5°C lower than Attic 1. Though in the attic the improvement of temperature caused by aluminium foil is quite noticeable, it has a very small effect on the temperature in the room below. In opposition to the expectations that the cumulated heat from the attic would be migrated down into the below room and make the room hotter; this migration makes very little change to the below room temperatures. **Statement A**: For Round 1, the day time attic does not affect strongly its room below. The daytime attic and room temperature patterns are similar.

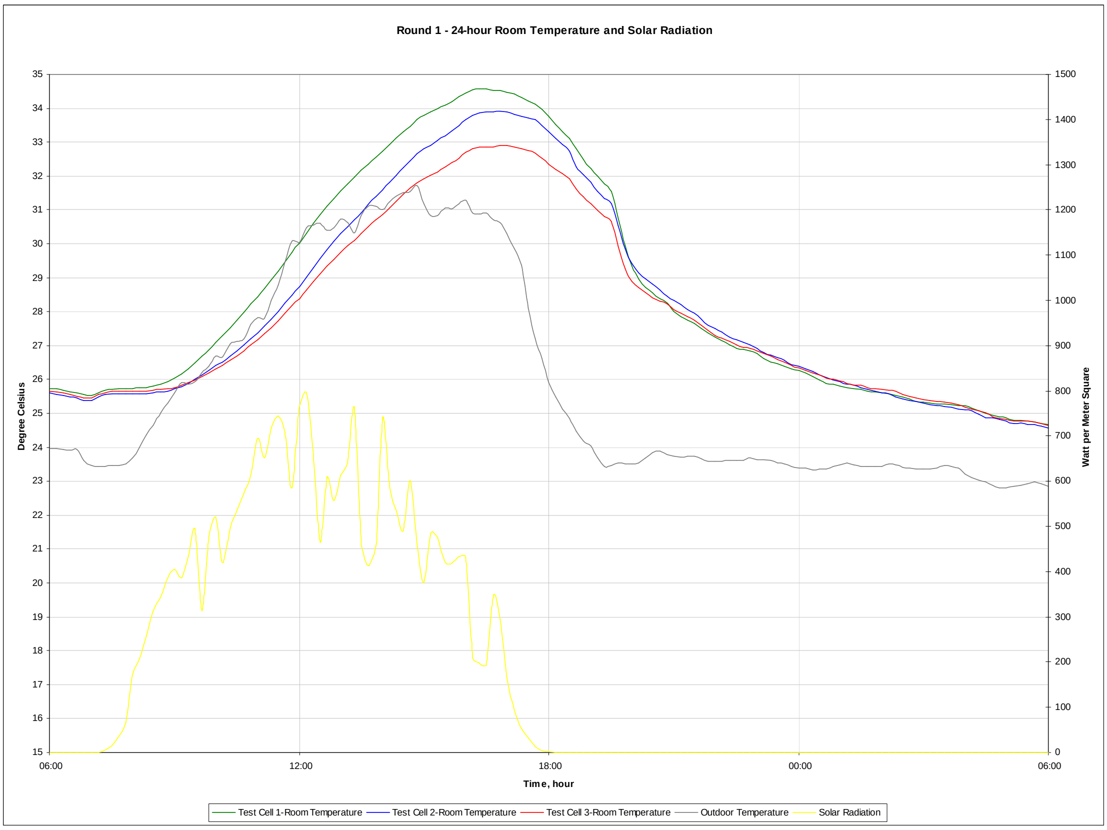


***Figure 29** Round 1 - Room Temperature Graph*

In presence of solar radiation, Room 1 is always 0.5° to 2 °C higher than Room 2 and 3. Although Room 1 has a higher room temperature range during the hottest hours, its room temperature soon after sunset drops quicker than others. But, all the rooms have a closing-up again after 8 pm and their doors at this time were already opened. This situation creates a claim that the room temperature 1 is more likely affected by opened door instead of its Attic 1. In other words, the heat in Attic 1 at night is weak to affect the below room while the door is opened. This will be re-examined again in the attic graph (Figure 30).

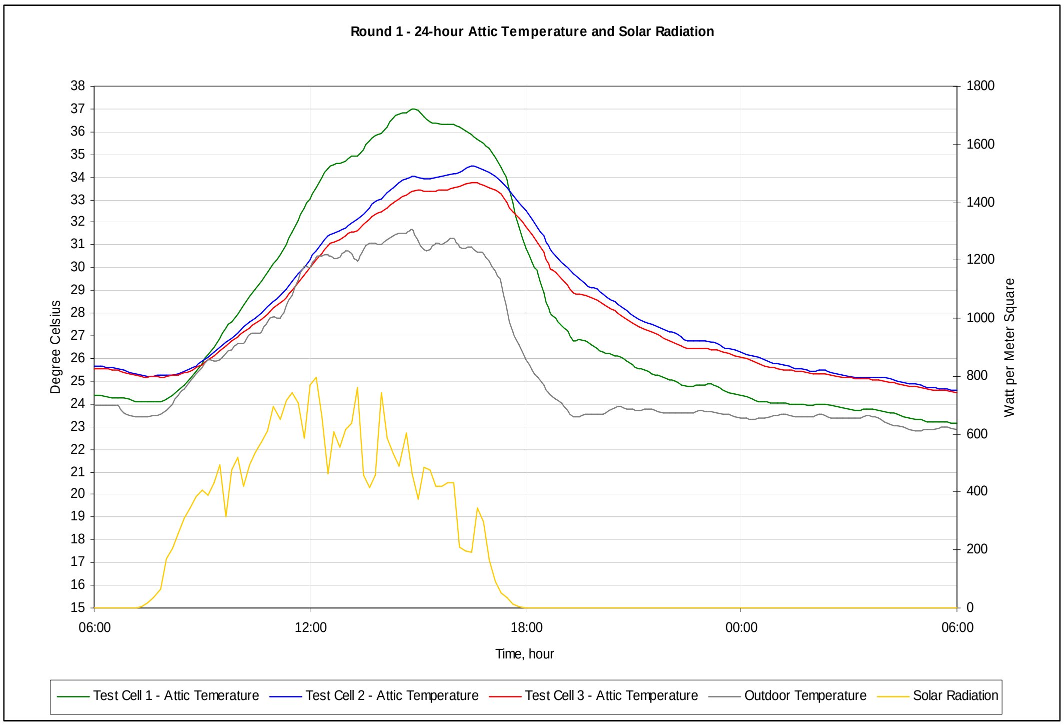


Figure 30 *Round 1 – Attic Temperature Graph*

At night the Attic 1 temperature drops faster than the other two attics which have aluminium foils. It is probably caused by faster heat dissipation in Attic 1 which has many tiling gaps and no insertion of aluminium foil. The Attic 2 and 3 are hotter than the Attic 1 at night, but all their room temperatures have a closing–up at night. **Statement B**: For Round 1, at night the opened door affects their room temperatures more than their attics. This supports the previous claim for night time Attic 1. But, whether or not the Room 2 and 3 at night were influenced by opening door more than their attics is unconfirmed. This answer lies in Round 2.

At night the Attic 2 and 3 are hotter than the Attic 1. The aluminium foil acts as a kind of insulation material that blocks air exchange between the outside and the attic volume. Therefore the heat inside the Attic 2 and 3 will be stored longer and cannot be released during the colder night hours.

Figure 31 shows the three test cells' temperatures at 14:00 and 00:00h.

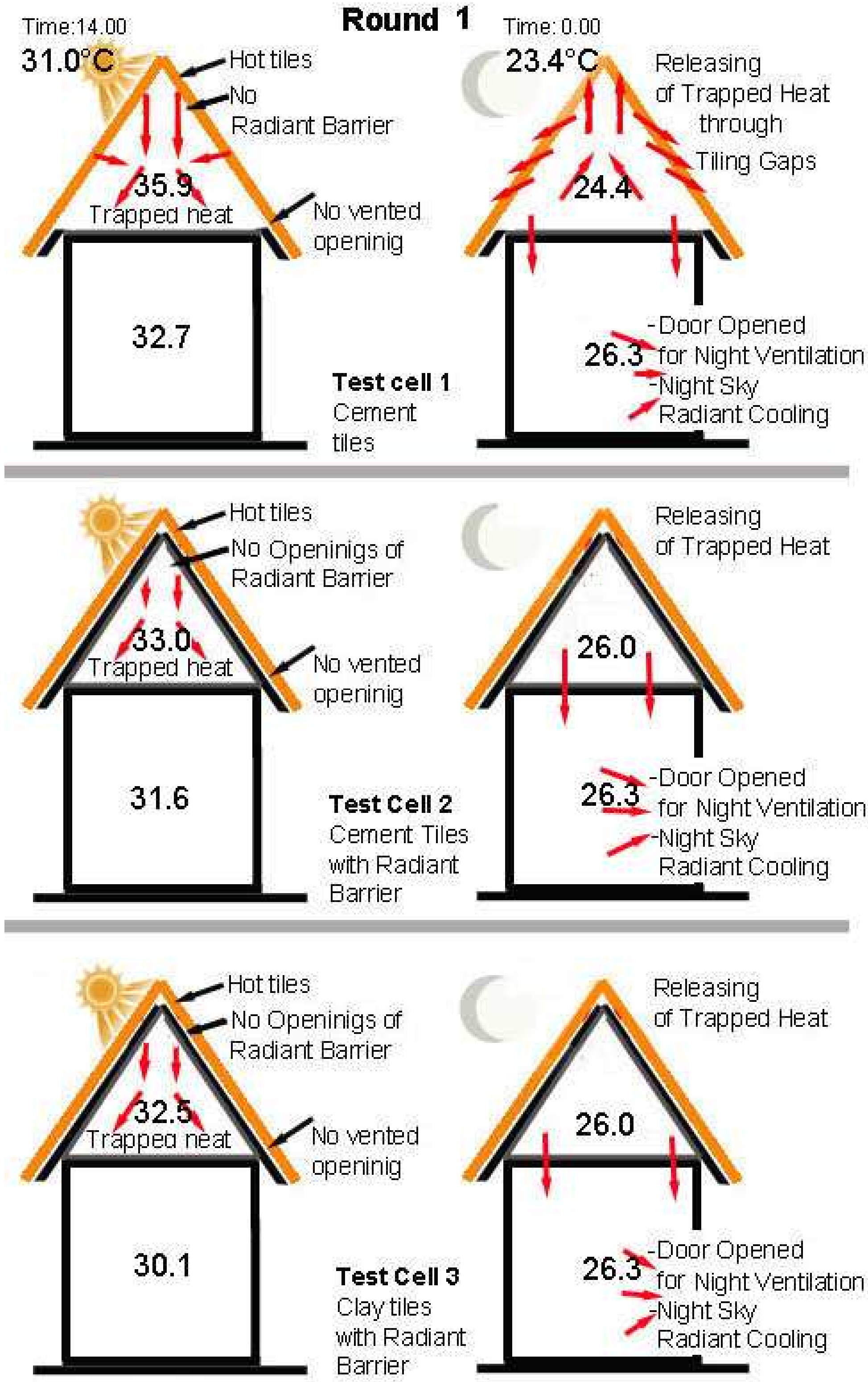


Figure 31 *Round 1: Three test cells' temperatures at 14:00 and 0:00*

4.1.2. Round 2 Room Temperatures

All roof eaves and vented windows were sealed. In Round 2, the radiant barriers of Attic 2 and Attic 3 had openings at the ridges (see Figure 27).

Interestingly, in this round the Room 2 and 3 during night time are about 1°C hotter than Room 1. All night time room temperatures have no more closing-up. The night time opened door did not affect equally all rooms just as in Round 1. Whether or not the night time Attic 2 and 3 affected Room 2 and 3 requires evidence. But, for Room 1 the case was already confirmed in Round 1 in which the Room 1 at night was not affected much by Attic 1, but by the opened door factor. In Round 2 the Roof 1 is structurally unchanged since Round 1. Roof 2 and 3 were changed, subsequently all night time room temperatures were not equalized anymore. **Statement C**: The remaining reason is that at night the too hot attic 2 and 3 did affect Room 2 and 3 more than their opened door factor. This is demonstrated by the graphs in Figure 32 & 33 that night time Room Temperature 2 and 3 are higher.

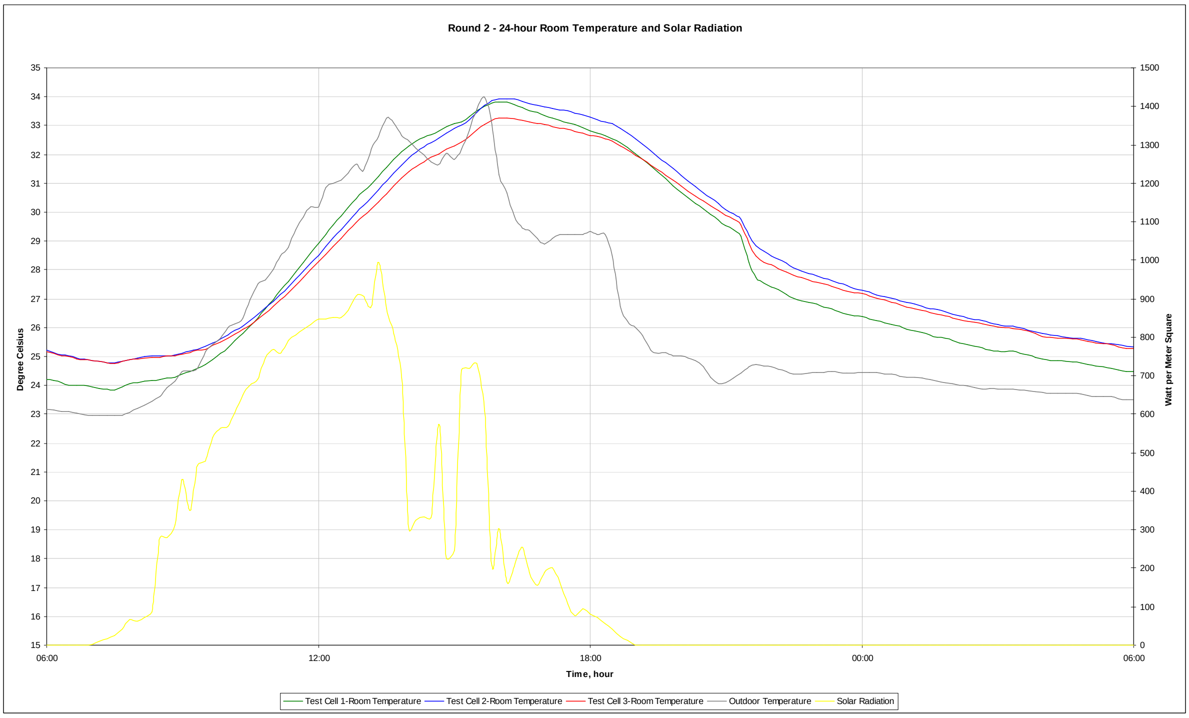


***Figure* 32** *Round 2 - Room Temperature Graph*

An assumption is made for Attic 2 and 3 of Round 2. Attic 2 and 3 were hotter because of the cut-out aluminium foils at the ridges that made the attic volumes hotter during solar radiation incidence. Subsequently, at night the heated Attic 2 and 3 eventually affected Room 2 and 3. This is unconfirmed for daytime in which Attic 2 and 3 affected Room 2 and 3. This assumption leads to two directions. Question 1: An evidence is required to show the cut-out aluminium foil leads more roof tiles' thermal mass radiant heat and the air layer's convection into the attic volume regardless day or night; the tiles acted as heat storage day and night. Eventually Attic 2 and 3 of Round 2 were hotter than that of Round 1. This Question 1 can not be answered because Round 1 and 2 were made in two different times. Round 1 and 2 had average solar radiation of 150 W/m² and 187W/m² respectively. Question 2: Did the cut-out aluminium foil lead more heat into the attic volume and the attic became hotter. Did the daytime attic eventually affect the daytime room temperature a lot? For Question 2, room temperatures graph (Figure 32) and attic temperatures graph (Figure 33) were compared to give a tentative hint.

The Attic temperature graph clearly shows that daytime Attic 1 is the hottest of all. But, according to the 24-hour Room temperature graph (Figure 32) and daytime cumulative percentage graph (Figure 34) the daytime Room 1 is not hotter than Room 2 and 3. This means that the daytime attics do not affect strongly and significantly their below rooms. This confirms again the Statement A made in Round 1.

On the rising Room 1 appears to be 0.5° to 1°C higher than the others (see Figure 32). Comparing the peaks, Room 1 and 2 share a similar temperature, while Test Cell 3 is more or less 1°C lower than the others. Hence, Room 3 is slightly better than the others. What made Room 1 be less warm than expected despite its hottest attic of all. This question can not be answered. In overall consideration of all graphs for Round 2, all room temperatures are very similar regardless day and night.

The 24-hour attic temperature patterns of Round 1 and 2 are very similar; but, their room temperature patterns are not similar. This situation is revealed in the later chapter: Bin and Frequency Analysis for Room; and in the Appendix A: daytime cumulative percentage of Room Temperature.

A tentative answer for Question 1: The holes may destroy the function of the aluminium foil as radiant barrier. In Round 2 all the room temperatures are almost similar during the day, despite the slightly better Room 3. Previously, the Cool Roof System (Roof 2 and 3 of Round 1) with the unbroken radiant barrier layer has a better room temperature performance than the Roof 1.

Also at night, the openings in the aluminium foils at the ridge of Attic 2 and 3 do not improve the performances of Room 2 and 3. The night time Room 2 and 3 are even about 1°C higher than Room 1. As discussed, the night time attic does affect night time room temperature. The tentative reason is that there was more heat collected inside the attic during the day through the holes in the aluminium foil and it can not escape fast at night because of the aluminium foil as blockage.

A tentative assumption: heat is radiated from the hot cement/clay tiles of Roof 2 and 3 into their attics during night time through the cut-out aluminium foils near the ridges. This might be causing Attic 2 and 3 at night even hotter than in Round 1. But, the attic heat at night also escaped through the cut-outs. Eventually, night time Room 2 and 3 are affected by their hot attics. All the attic vs. room temperature differences at night are always less than 1°C (See Appendix).

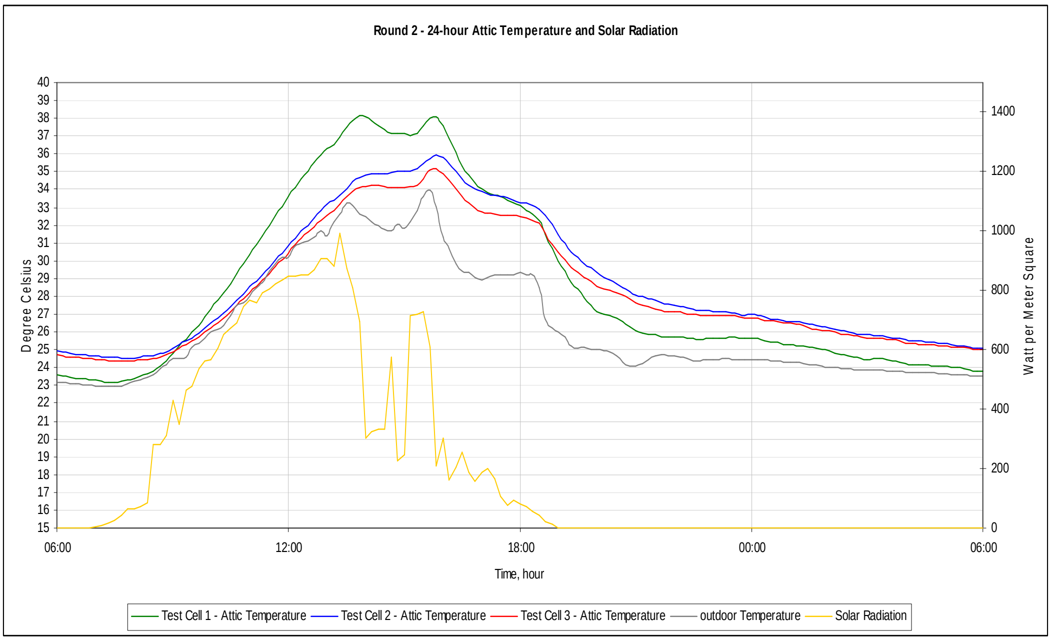


***Figure 33** Round 2 – Attic Temperature Graph*

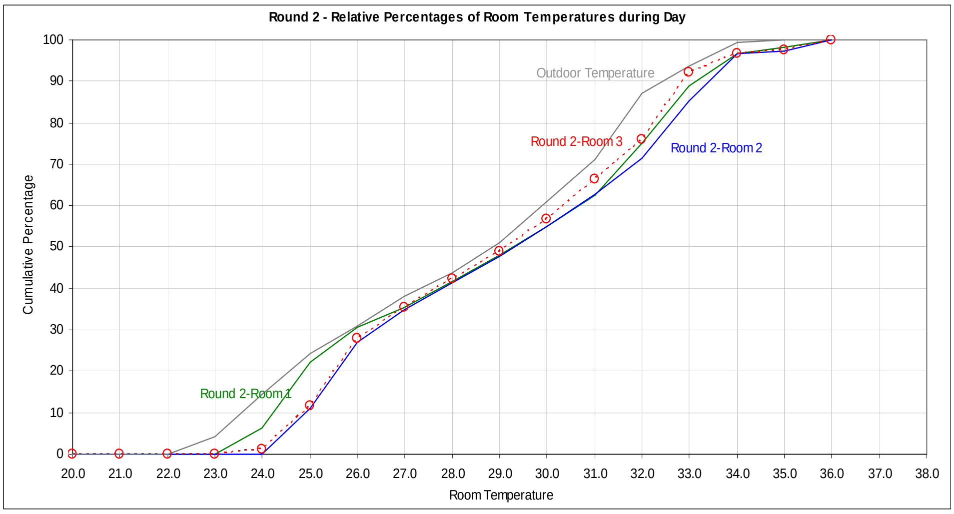


***Figure 34** Round 2 all tested days data: Cumulative percentage of room temperature for daytime only.*

The three test cells temperatures at 14:00 and 00:00 h for Round 2 can be seen in Figure 35 below.

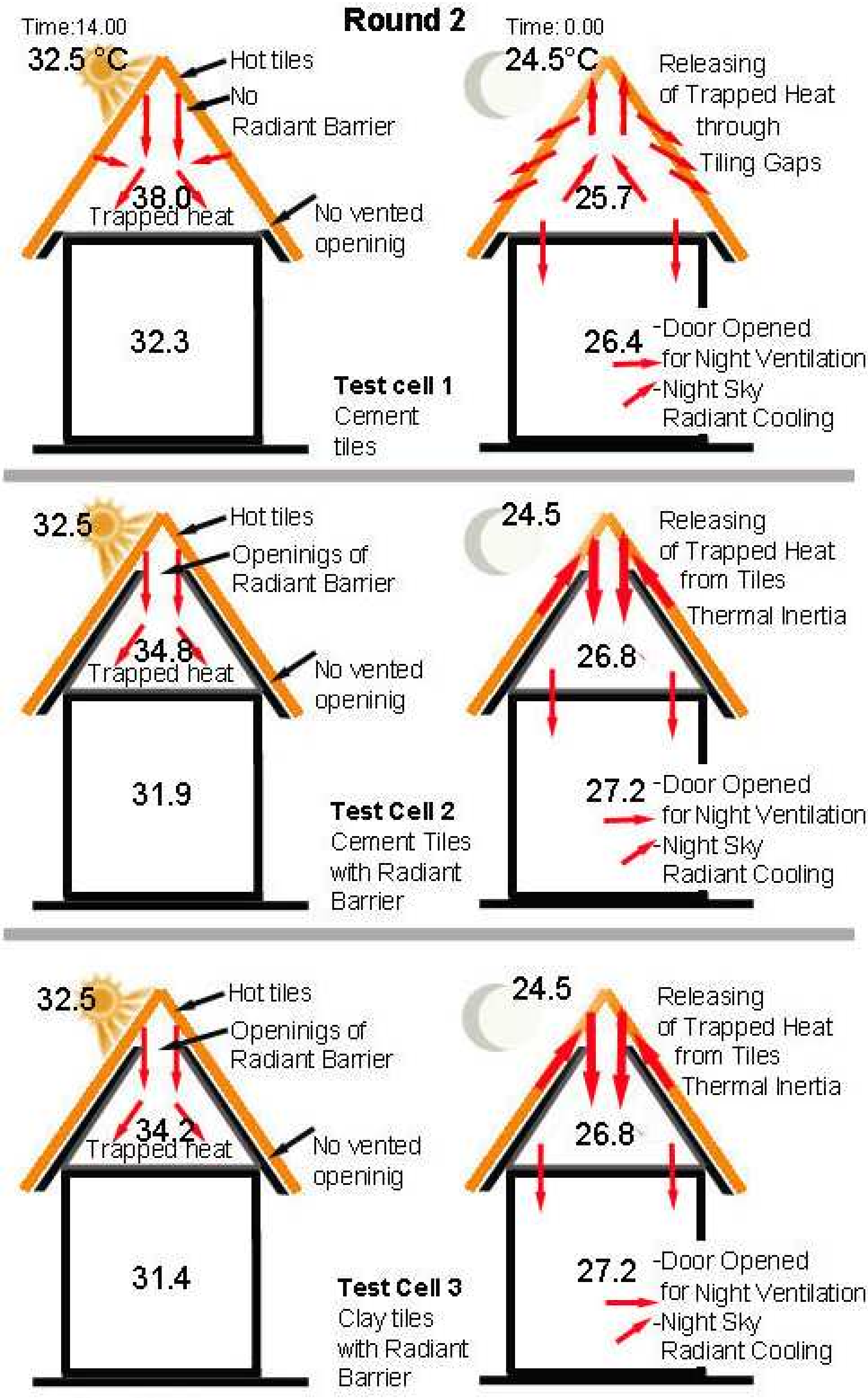


Figure 35 *Round 2: Three test cells' temperatures at 14:00 and 0:00*

4.1.3. Round 3 Room Temperatures

Round 3 has greater ventilation than Round 1 and 2. The radiant barriers at the ridge and roof eaves were cut-out and opened. An assumption is made: The concept of this ventilation setting was to create a more breathing attic for venting hot attic air. Or, creating holes on the radiant barriers at the ridge would lead more heat into the attic.

The daytime Room 1 and 3 have a close-up during the height of solar radiation (Figure 36 and 37). A question is made again similar to Round 2. Did the daytime attic strongly affect its below room? The cumulative percentage graph for daytime only in Round 3 (Figure 37) shows that Room 1 and 3 have a closing-up during daytime and Room 2 is the hottest. The daytime Attic 1 is the hottest of all, but the daytime Room 1 was not the hottest of all. This situation already happened in Round 2. Again, the daytime attics of Round 3 do not strongly affect its room below and even weaker than the situation in Round 1. Otherwise, the peaks of Room 1, 2 and 3 should be similar to the peaks of Attic 1, 2 and 3 just as happening in Round 1. A tentative explanation is that attic heat dissipated much through the opened roof eaves instead of migrating downwards to the below room. At the same time, the cut-out aluminium foils lead heat from heated roof tiles and the air layer's convection. There is no evidence to draw that Attic 1, 2 and 3 of Round 3 are less hot than that of Round 2 because of higher ventilation amount.

Attic heat will have some amount of heat migrating downwards to the below room when the roof is tight just as the cases in Round 1. For Round 3 an assumption is made. This heat migration will be even lesser because of opened roof eaves acting as ventilation openings. This claim has no way to justify. It is because daytime Room 1 and 3 are similar in Round 3, though Attic 1 is the hottest and Attic 3 is the least hot (see Figure 38). Roof 3 and 1 are structurally different.

The idea of giving higher ventilation plus radiant barrier to the attic by opened roof eaves and cut-out aluminium foils to release hot air did not succeed in this round. That was true only if Room 2 and 3 were less hot than Room 1.

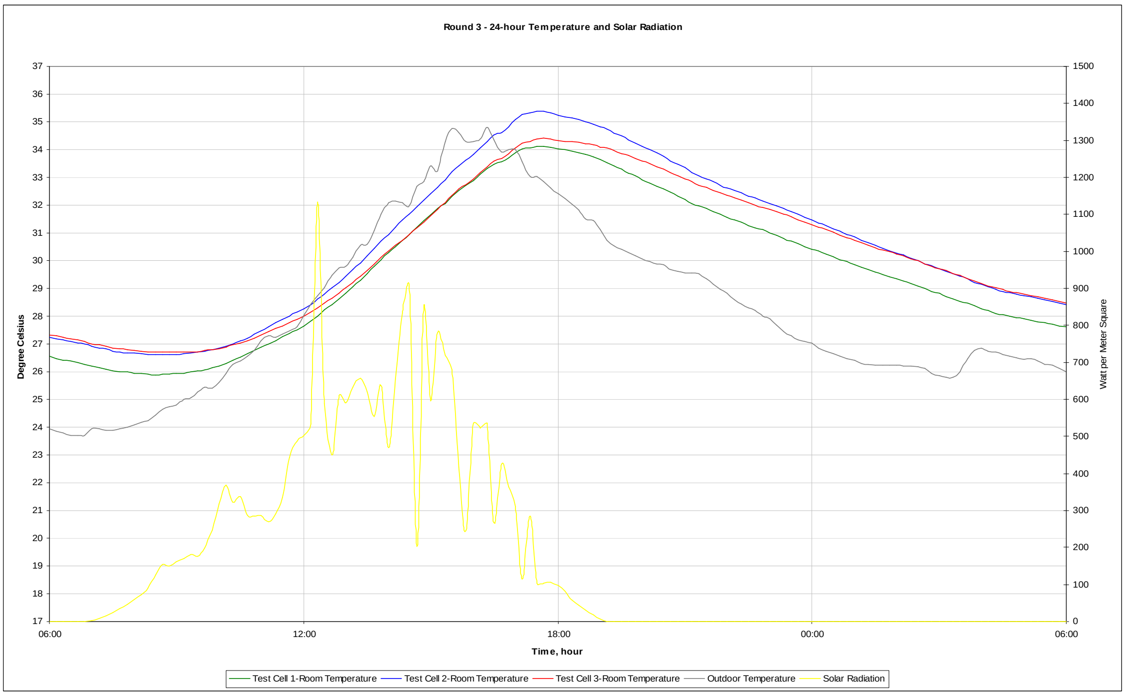


Figure 36 *Round 3 - Room Temperature Graph*

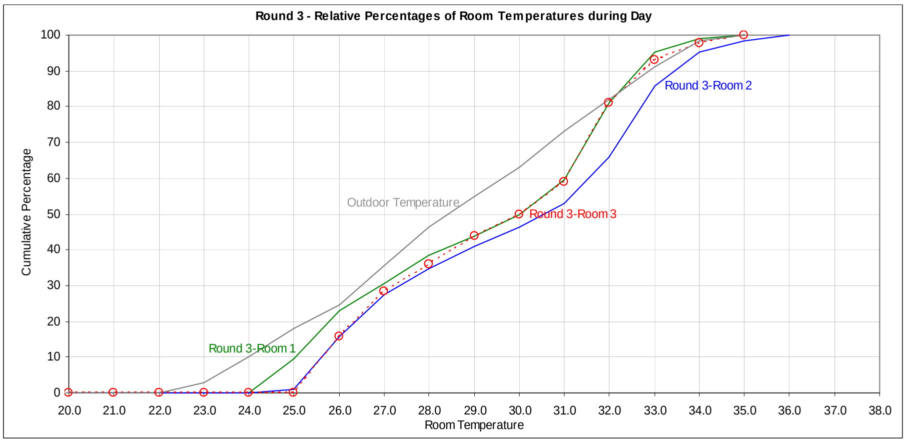


Figure 37 *Round 3 all tested days data: Cumulative percentage of room temperature for daytime only*

At night Room 1 is 0.5-1.0°C lower than the others. This is probably caused by the hotter Attic 2 and 3 which have heat dissipation slower than Attic 1 at night. For night time, Attic 1 is less hot than Attic 2 and 3 (see Figure 38). ; in the same temperature pattern, Room 1 is less hot than Room 2 and 3. Apparently, the night time opened door factor did not equalize all the room temperatures.

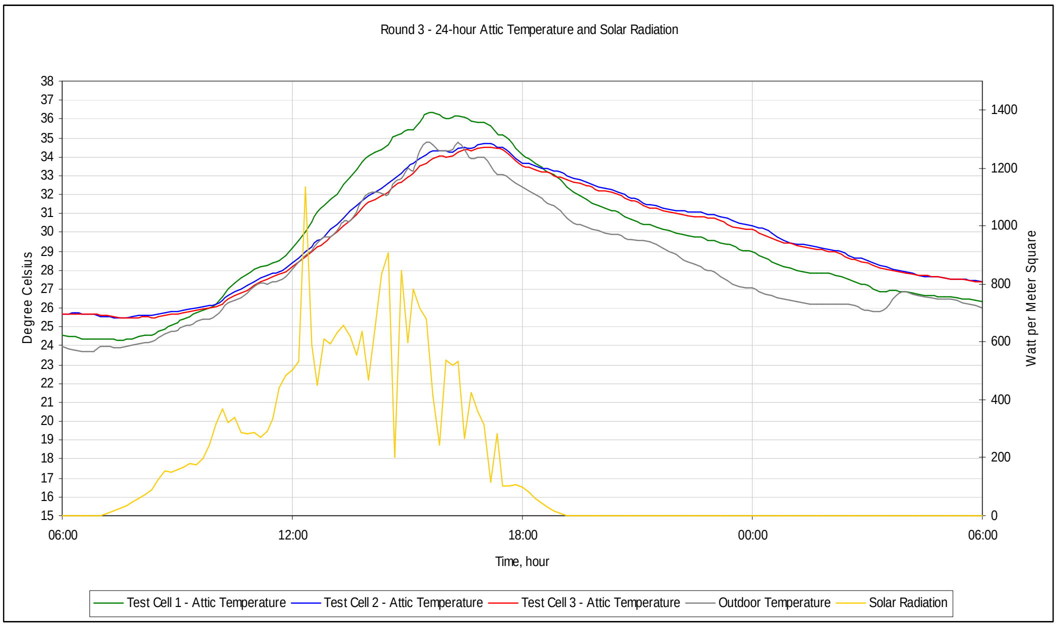


Figure 38 *Round 3 – Attic Temperature Graph*

Figure 39 shows the three test cell's temperatures at 14:00 and 00:00 h of Round 3.

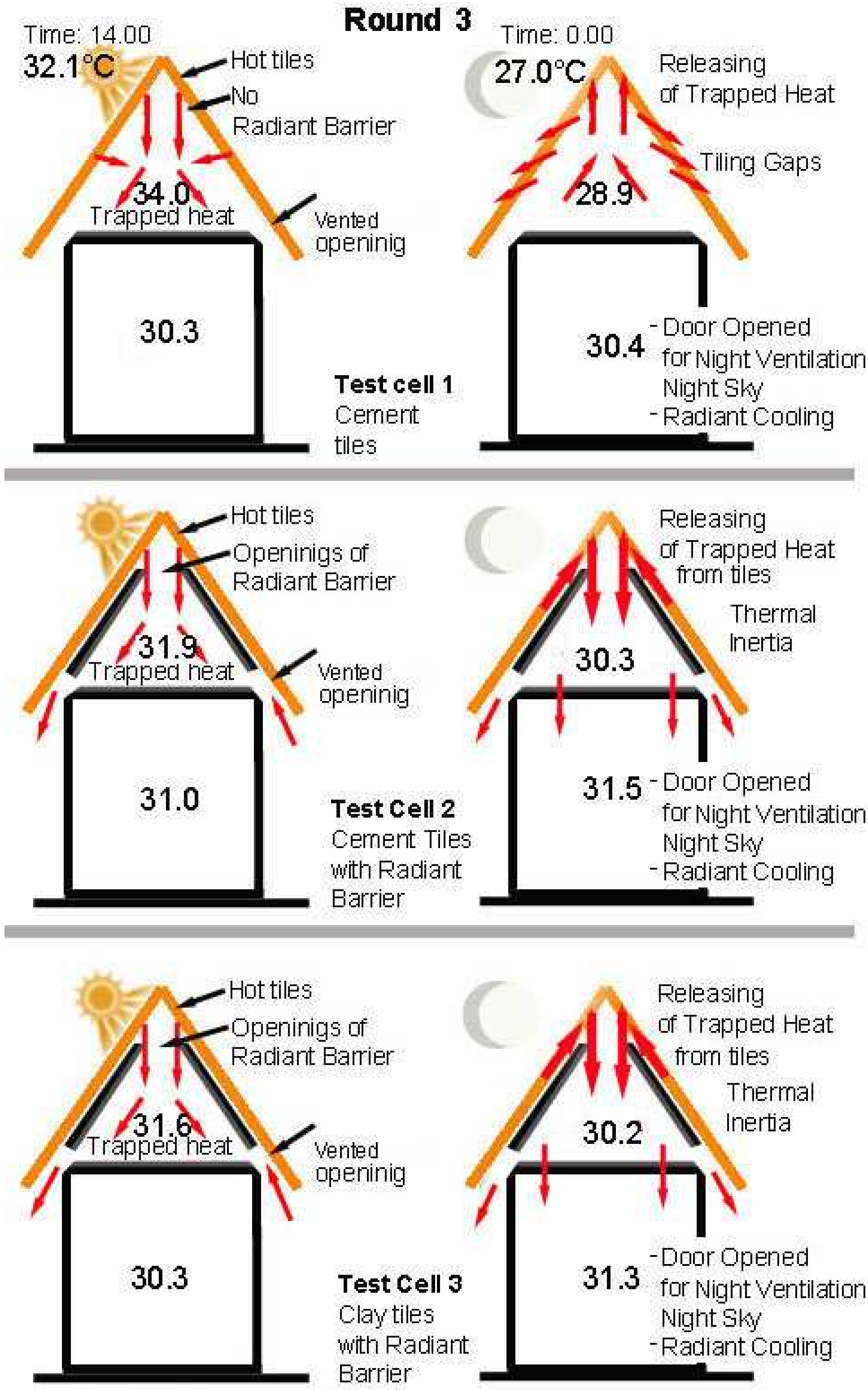


Figure 39 *Round 3: Three test cells' temperatures at 14:00 and 0:00*

4.1.4. Round 4 Room Temperatures

In addition to Round 3, Round 4 had the vented windows on the gabled walls opened. For daytime, Room 1 always performs between Room 2 and 3 on the rising (see all days Round 4 Room Temperature in Appendix A and Figure 41). Room 1 is not stable just as in Round 3. In overall, for day time Room 3 is the least hot of all. A tentative explanation is made. The greater amount of attic ventilation in Round 4 makes the Room 1 unpredictable. According to all tested days, Room 1 performs occasionally better than or sometimes leveled with Room 2 (see Appendix A). The daytime attic and room temperature patterns are not similar. Attic 1 remains the hottest of all with higher peaks of 1-2°C than Attic 2 and 3 (see Figure 42). However so, Room 2 is actually always the hottest of all, though Attic 2 is not the hottest. Very likely, the daytime attic heat affecting its below room is even weaker in Round 4 because of greater attic ventilation.

According to Figure 41 Cumulative percentage for daytime room temperatures, Room 1 and 3 are closing up in the hot region and Room 2 tends towards hotter region.

Figure 40 *Round 4 - Room Temperature Graph*

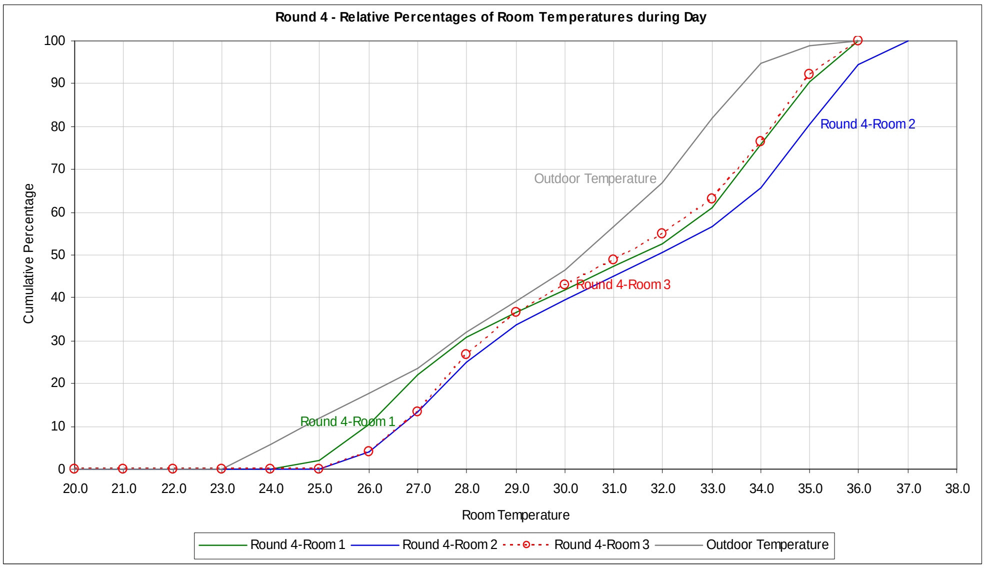


***Figure 41** Round 4 all tested days data: Cumulative percentage of room temperature for daytime only*

The night time Attic 1 is again the least hot of all and Attic 2 and 3 are similar. Also the night time Room 1 is the least hot of all and Room 2 and 3 are similar. The attics and rooms are correlated at night and the opened door factor did not affect the room temperatures much. Otherwise, all the night time room temperature should be leveled.

A short conclusion is drawn. Regarding the **Hypothesis 1**, heat migration from the attic into the room clearly happens in: I) night time Round 2, 3 and 4; II) daytime Round 1.

When the attic has greater ventilation to diffuse attic heat to outside, the daytime room temperatures receive less attic heat influence. For Round 2, 3 and 4, the daytime temperature patterns between attics and rooms are not coherent. For daytime, Attic 1 is the hottest in Round 2, 3 and 4, but Room 1 is not the hottest. Round 1's Attic 1 is much hotter than Attic 2 and 3, but Room 1 is only less than 1°C hotter than Room 2 and 3. From these two viewpoints, daytime heat migration from the attic into the below room is not expectedly notable or strong in Round 1, 2, 3 and 4.

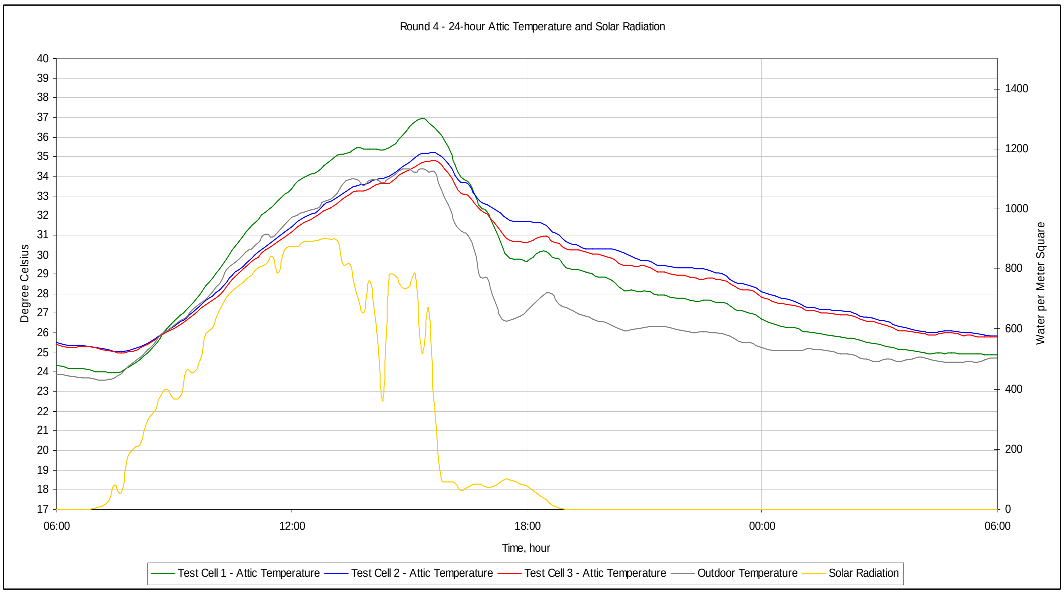


Figure 42 *Round 4 – Attic Temperature Graph*

The temperatures at 14:00 and 00:00 h can be seen in the Figure 43 below.

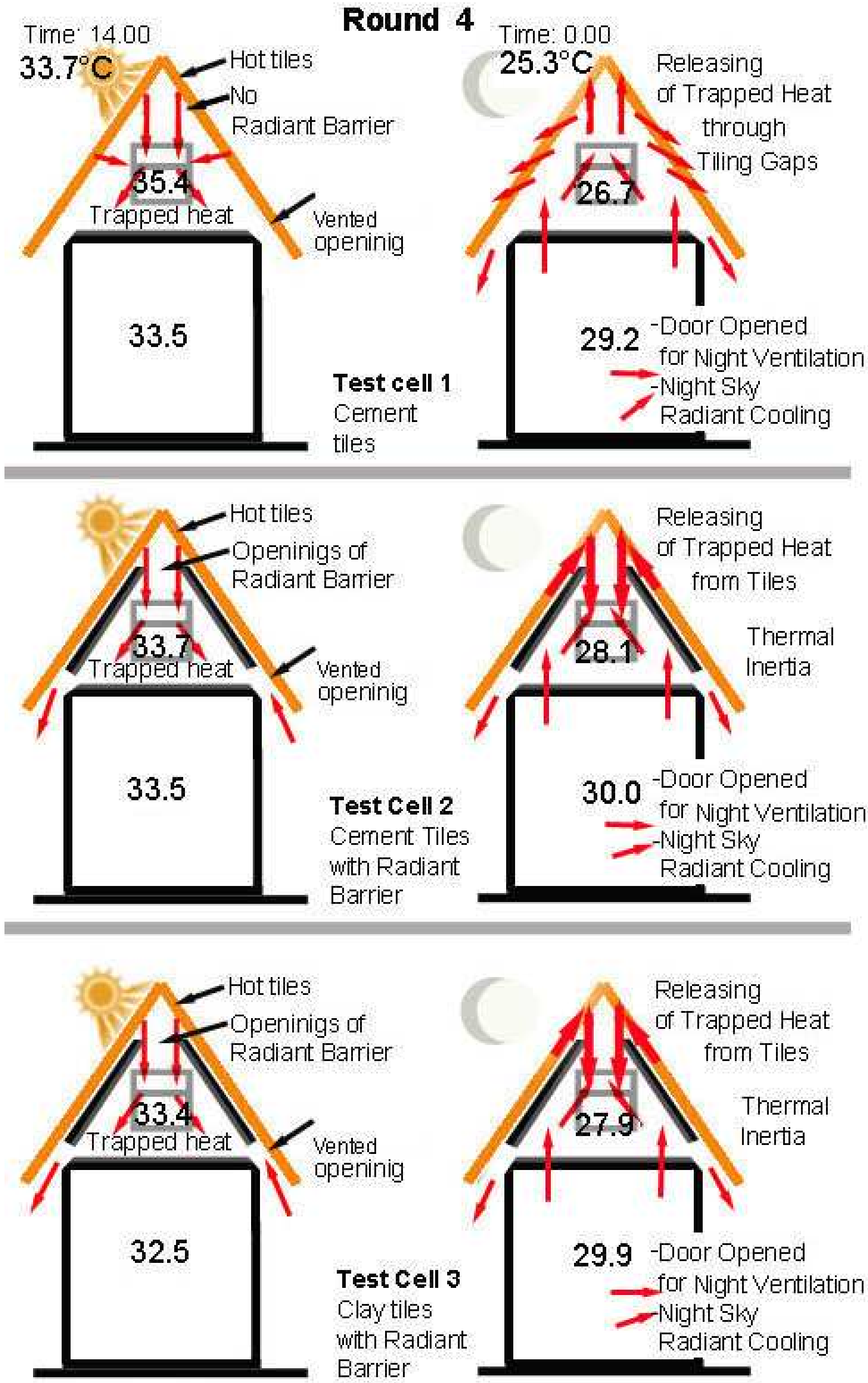


Figure 43 *Round 4: Three test cells' temperatures at 14:00 and 0:00*

4.2. Analysis Method - Bin and Frequency

4.2.1. Round 1 Bin and Frequency

Result: The temperature distributions of each room are classified into bin and frequency (Figure 44). All the room temperatures rise sharply from 24 to the peak 26°C and decrease less sharply that the way they all rose up. All these room temperatures have a similar rising and decreasing fluctuation, with strong differences between 27 and 36°C. All three room temperatures had no complicated fluctuations on the rising. It is because their night time room temperatures are leveled by the opened door factor. On the ending tails, it reflects that Room 1 is the hottest and followed by Room 2 and 3. These rising and falling patterns are coherent to the 24-hour room temperature discussion in the previous chapter.

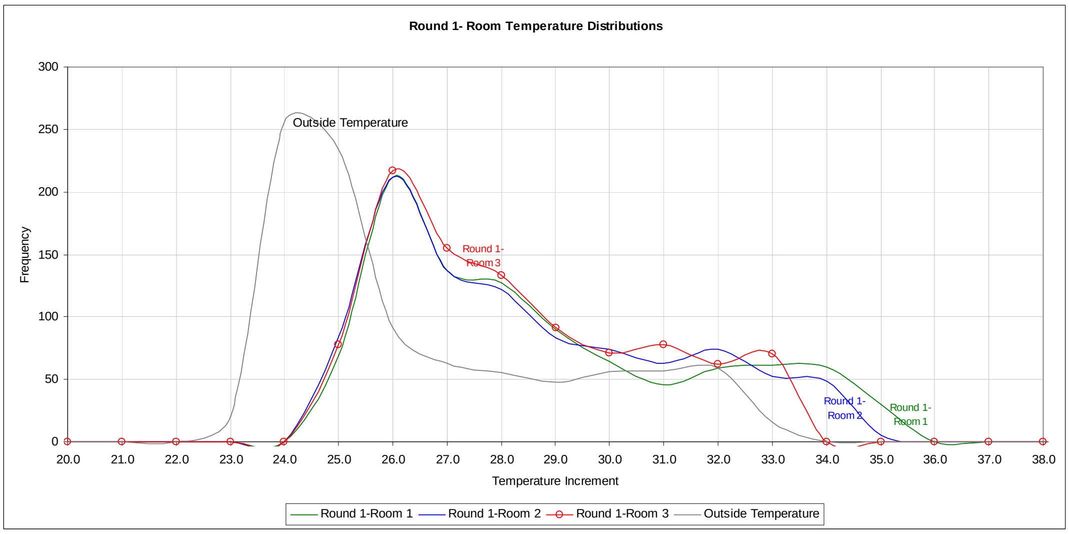


Figure 44 *Round 1 - Bin & Frequency Graph*

The cumulative percentage graph (Figure 42) is derived from the bin and frequency graph above. All the room temperatures are represented in its straight line curve.

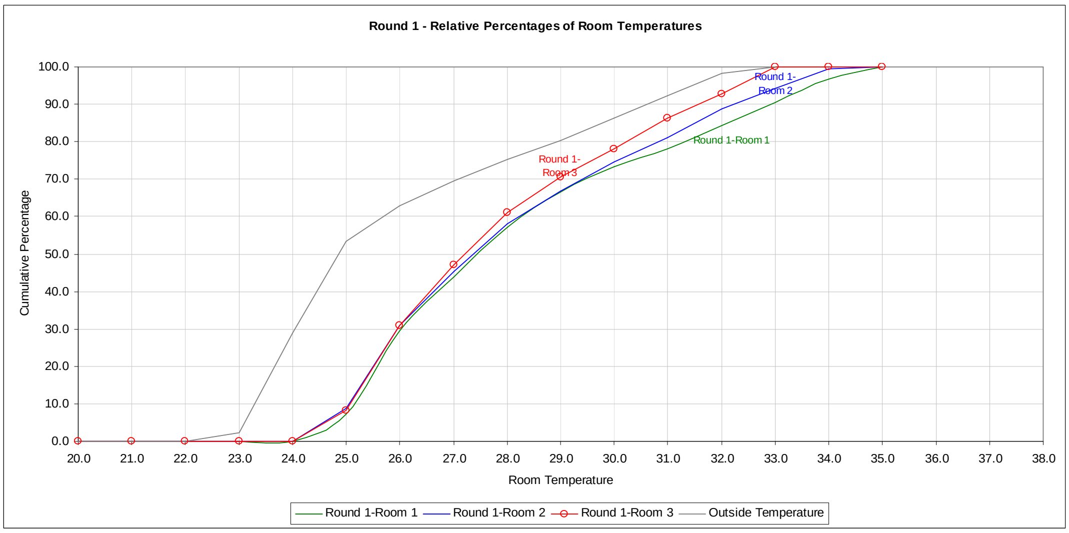


***Figure 45** Round 1 Cumulative Percentage Graph*

Rank: All rooms perform almost equally, while Room 3 is performing marginally better.

Discussion: The cool roof system with clay tiles performs slightly better than the concrete tile roofs. The aluminium foil layer under the roof tiles of Cool Roof System gives a lower peak during the outdoor hottest weather. For example, in this round 1, Room 1 has some occurrences extending to 36°C; while, Room 2 and 3 with Cool Roof System have only extending to 34°C and 33°C respectively. Thus, the advantage of Cool Roof System is not overwhelmingly better than the conventional roof which has no aluminium foil underlay. Attic 2 and Attic Cell 3 have cement and clay tile roofing respectively. There is a difference of material thermal property between them, Room 3 with clay tiles should perform better, but very small.

Figure 46 shows the cumulative graphs of room versus attic temperature distributions. Attic 1 performs the best regarding the range of temperature below 27°C. Attic 1 has almost 60% of temperature below 27°C, while Room 1, 2 and 3 and Attic 2 and 3 have only around 45% below 27°C. This can be explained by the small amount of ventilation in Attic 1 and no layer functioning as radiant barrier. Therefore Attic 1 gets very hot during the day but cools down fast during the decrease of solar radiation. And, all rooms and attics are equalized at night by the opened door factor. That might explain why all the rising curves are similar. The Attic 2 and 3 behave rather slack; they get hot slowly and also cool down slowly during the night.

Interestingly, for Test Cell 1 Attic 1 at night gets much closer to the outside temperature than the room temperature does, though the door of the room was opened during the night. This can be probably explained by the fact, that the walls have a much bigger thermal mass than the roof tiles. Therefore heat in Roof 1 can escape at large, while the room temperature is still affected by the heat stored inside the brick walls. The Attic 1 has no underlay foil, therefore the heat can escape faster than Attic 2 and 3.

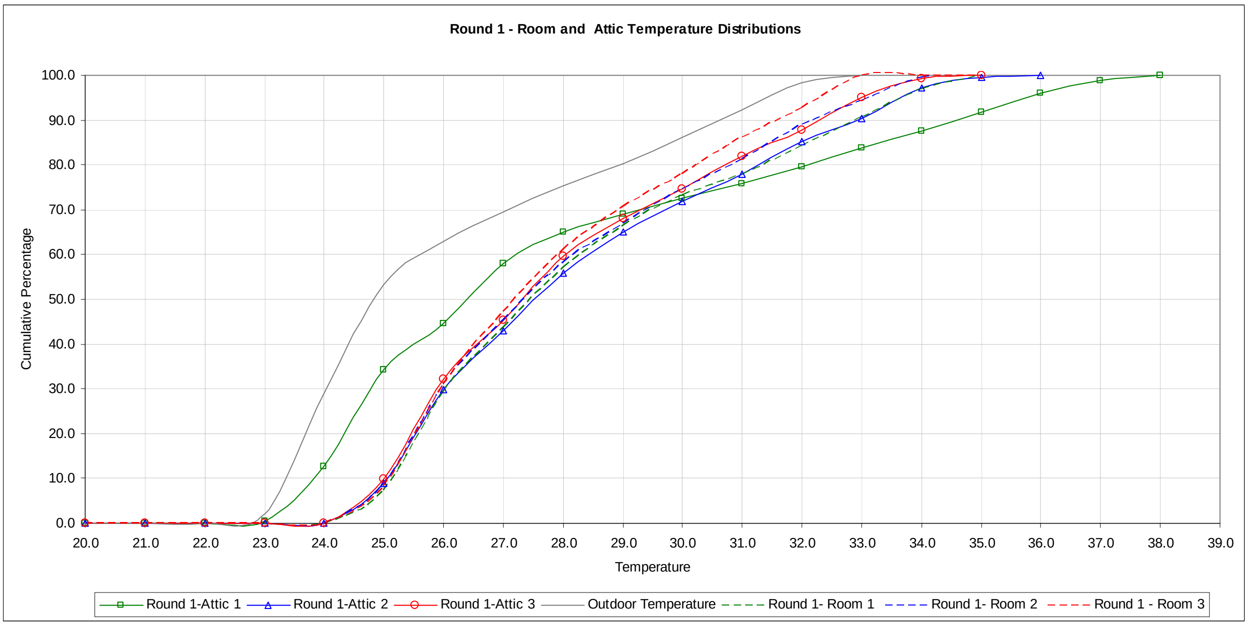


Figure 46 *Round 1 Room vs. Attic Temperatures – Cumulative Graph*

4.2.2. Round 2 Bin and Frequency

Result: The Room 1 temperature rises rapidly from 23°C to the peak 25°C and decreases gradually down to the flat line at 29°C (see Figure 47). The rising increment is 2 °C and the falling decrement is 4°C. The rises of Room Temperature 2 and 3 perform just as Room 1, but the increments and decrements are different. The rising increment of Room 2 and 3 is 2 °C which is from 24 to the peak 26°C; the falling decrement spans across only 3 °C before achieving a flat line at 29°C. All room temperatures fall again after their flat lines. The Room 1 has another decrement from 32 to 37°C; Room 2 and 3 have a decrement starting at 33°C. Room 1 performs differently from Room 2 and 3 which are of a pair performing almost coherently.

Based on the unequal rising curves, the opened door at night is proven less influential than the attic heat migration downwards as discussed in the previous chapter.

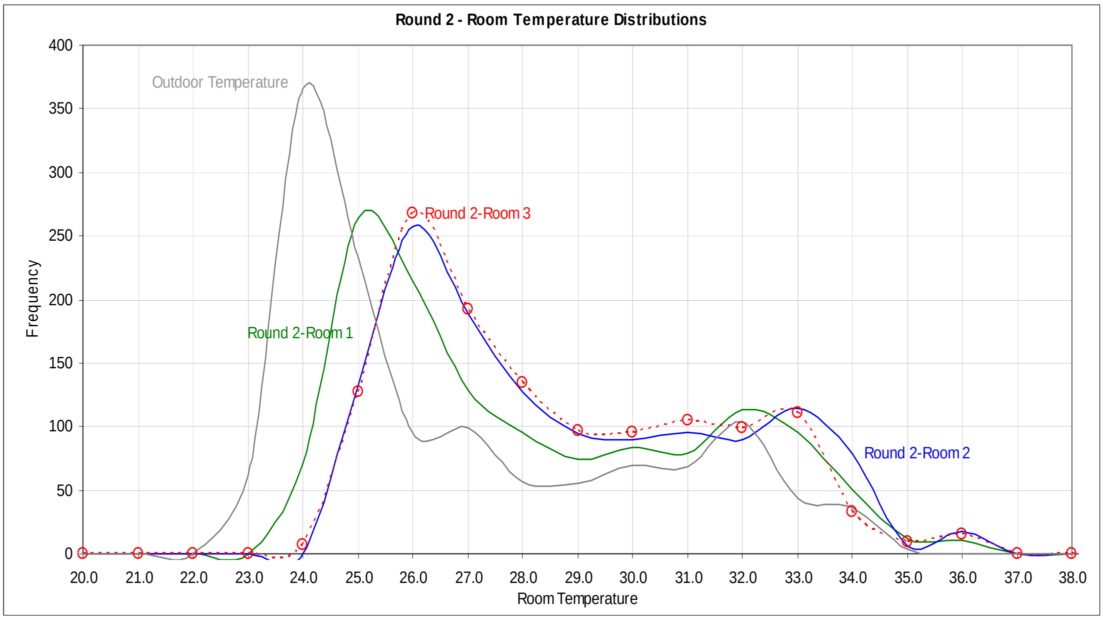


Figure 47 *Round 2 - Bin & Frequency Graph*

The entire Room 1 shifts 1 degree colder towards left hand side on the temperature classification. This shift is a uniform offset towards left hand side including its peak and minimum points. At night, Room 1 is the best.

The cumulative percentage graph (Figure 48) is derived from the bin and frequency graph above. Considering the part up to 27°C, Room 1 is clearly the best followed by Room 3 and 2. Room 3 and 2 are actually similar. This situation is probably made by the colder night time Room 1. The break down of day and night analysis is required to discuss the night time room performance. All the break down of day and night graphs are shown in Appendix A.

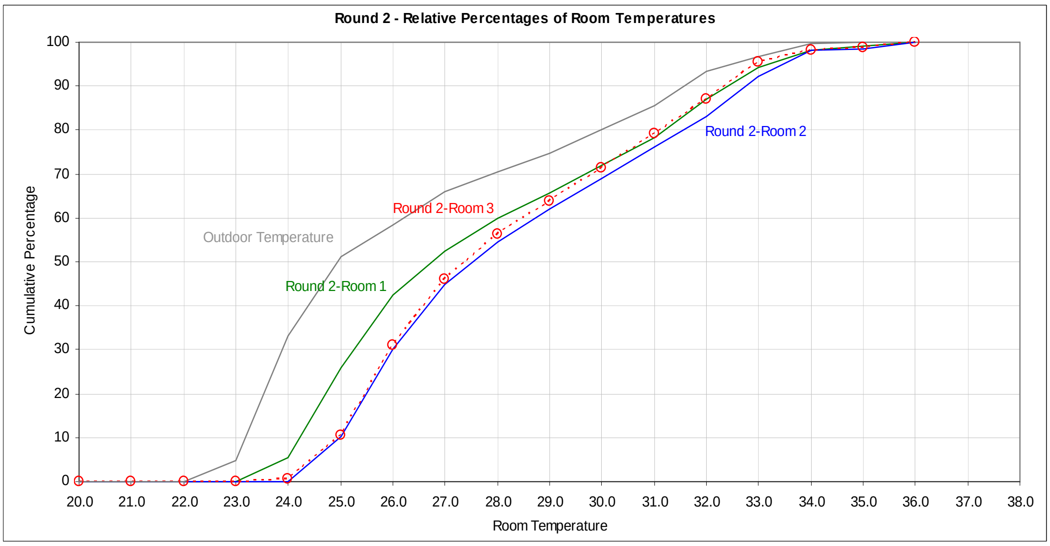


Figure 48 *Round 2 Cumulative Percentage Graph*

Rank: In Round 2, Room 1 is the best option of all on the 24-hour basis.

Discussion: The cut-out of the aluminium foil near the ridges destroyed the Cool Roof system. The openings on the top let in more hot air, which can not be released fast at night. The function of the aluminium foil as radiant barrier regardless day and night becomes ineffective once it has holes. As discussed, the night time Room 2 and 3 were influenced more by their Attic 2 and 3 than of the opened door factor. But, during daytime attic heat does not affect strongly the room below. So, the cut-out of aluminium foil makes the roof worse especially at night.

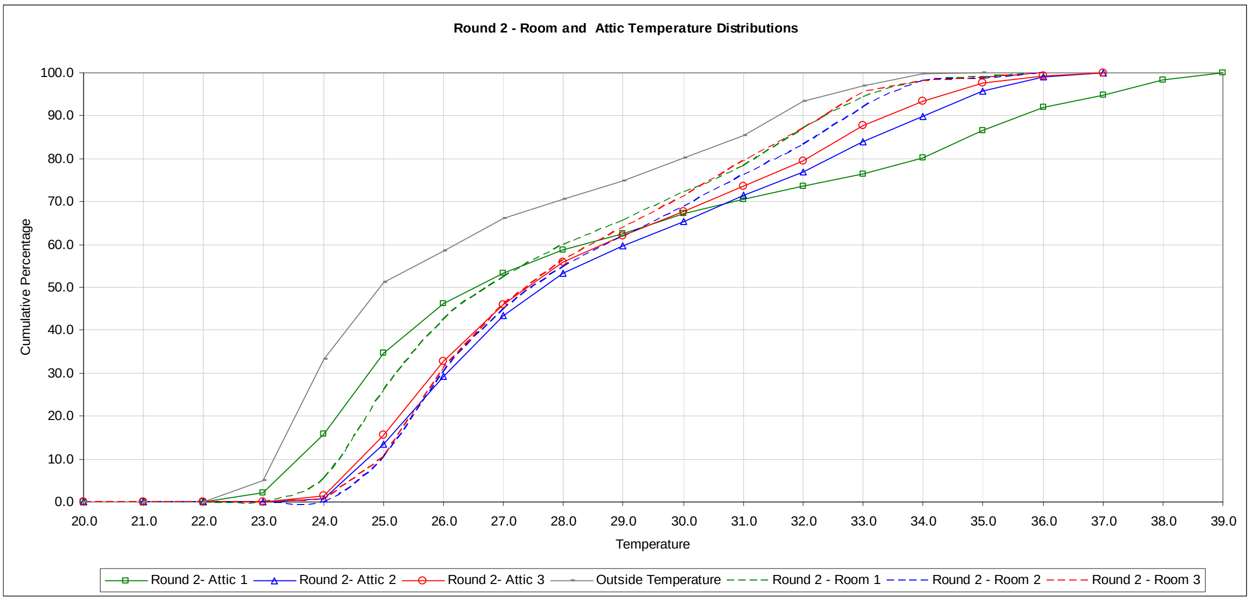


Figure 49 *Round 2 Room vs. Attic Temperatures – Cumulative Percentage Graph*

The average solar radiation incidence of Round 2 is bigger than Round 1. In Round 2 it is 187.3 W/m² and in Round 1 it is 150.7 W/m². This my explain why the percentage at 27°C of Room 1 and Attic 1 are both 55%, though in Round 1 they had a disparity result with a similar structural set up. All other rooms and attics show a similar result at 27°C.

4.2.3. Round 3 Bin and Frequency

Result: The curve of Room 1 rises at 24 °C up to its peak at 26 °C. Its curve has another peak at 28 and 32 °C. The temperatures of Room 3 and 2 rise coherently up to 26.5 °C, but fall differently with their noticeable single peaks at 32°C and 33°C respectively (see Figure 50). The double peaks of all rooms represent the night time and daytime peaks. Occasionally, during Round 2 the outdoor temperature became hot frequently standing at 27°C, this affected directly all the rooms. This is evident by the curve of outdoor temperature.

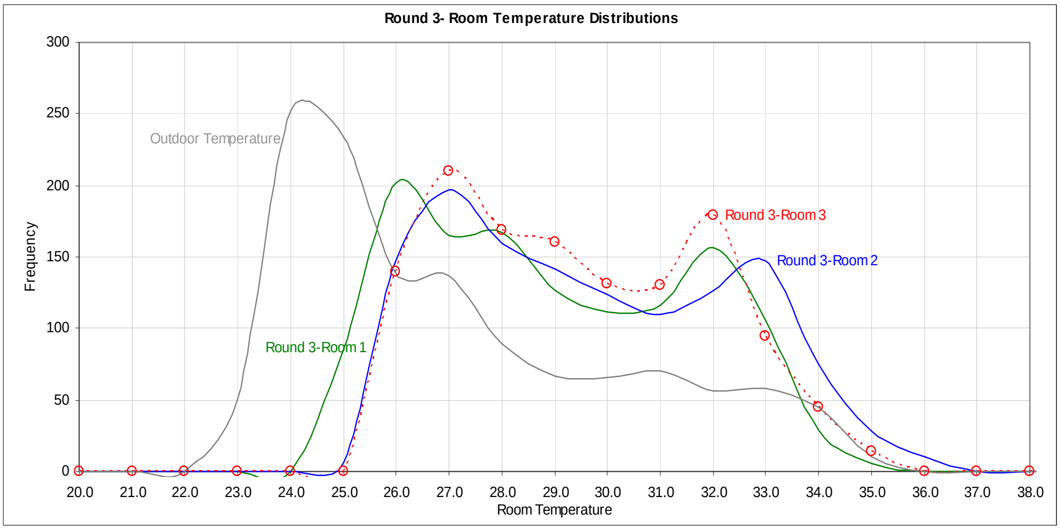


Figure 50 *Round 3 - Bin & Frequency Graph*

In this round the temperature curve of Room 1 is at the beginning shifted 1°C less warm to the left hand side comparing to Room 2 and 3. It is weak to say that Room 1 is the best of all in this round for night time and daytime.

While comparing between Room 2 and 3, their frequencies are rigourly different on the falling. There is no sufficient proof to tell which one is better and which one is worse. The cumulative percentage graph (Figure 48) may reveal evidence.

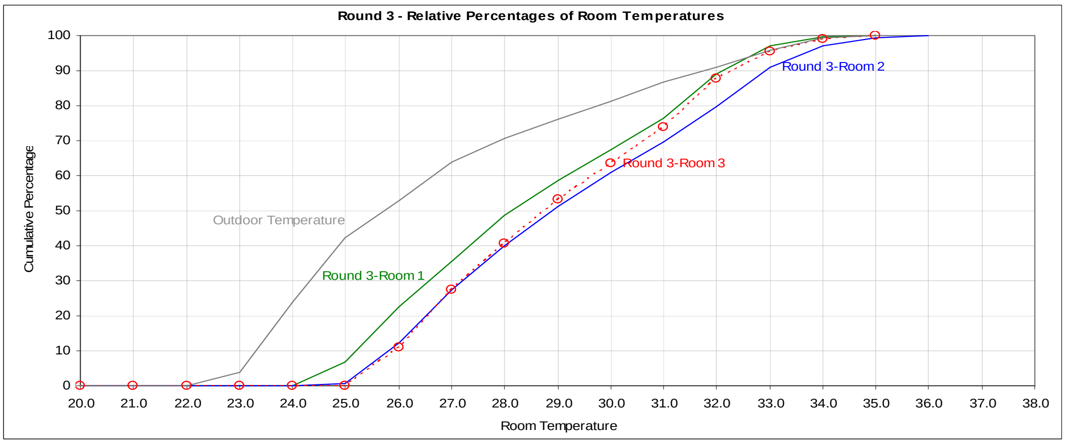


Figure 51 *Round 3 Cumulative Percentage Graph*

The cumulative percentage graph shows a similar ranking to Round 2. Room 1 is clearly the best of all for day and night. While the result of Room 2 and 3 before 27°C is almost the same. Room 3 reaches 100% by 1 degree earlier than Room 2. Room 3 is slightly better than Room 2. For example, Room 2 reaches up to 35 °C which Room 3 has not reached.

Rank: In Round 3, Room 1 is the best of all for day and night. Room 3 is slightly better than Room 2 for the day only.

Discussion: The cumulative percentage graph below in figure 52 shows the room versus attic temperatures. Attic 1 is still the best option also in this round. There is a disparity in the range of 22°-27°C degree between the other attic and room temperatures. This time all attics generally perform better than rooms in the range of 22°-27°C. A tentative explanation is that once the attics have a greater level of ventilation by the cut-out of aluminium and opened soffit board, they can cool down faster than the rooms at night. In other words, at same night time, Attic 2 and 3 might be influenced more by the cut-out of aluminium foils than that the opened soffit boards acted as alternative ventilation holes.

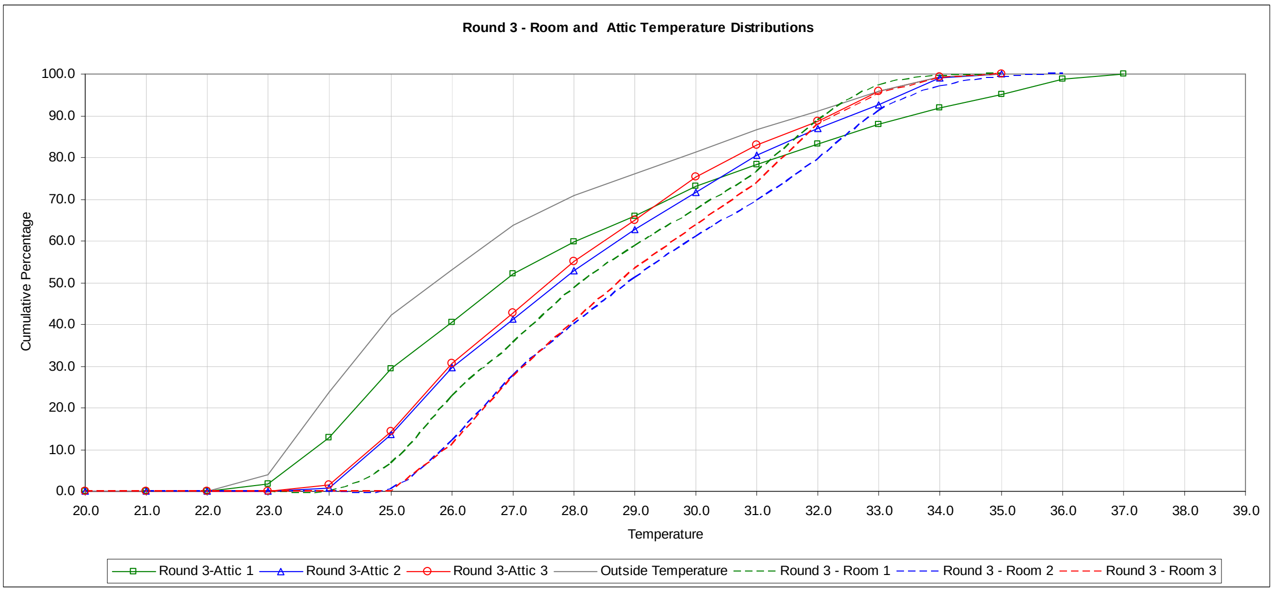


Figure 52 *Round 3 Room vs. Attic Temperatures – Cumulative Percentage Graph*

4.2.4. Round 4 Bin and Frequency

Result: In round 4, Room 1 performs just as in the previous Round 3. Room 1 has higher frequency accumulation than Room 2 and 3 on the rising. The peak of Room 1 lies at 27 and 28 °C; the peaks of Room 2 and 3 happen at 28°C. From 28 °C onwards, Room 1 has always lower frequencies than the other two rooms. This means that Room 1 is overwhelmingly better than Room 2 and 3; since, Room 1 has lower occurrences than Room 2 and 3 in the hot region of 28 and 38 °C (see Figure 53).

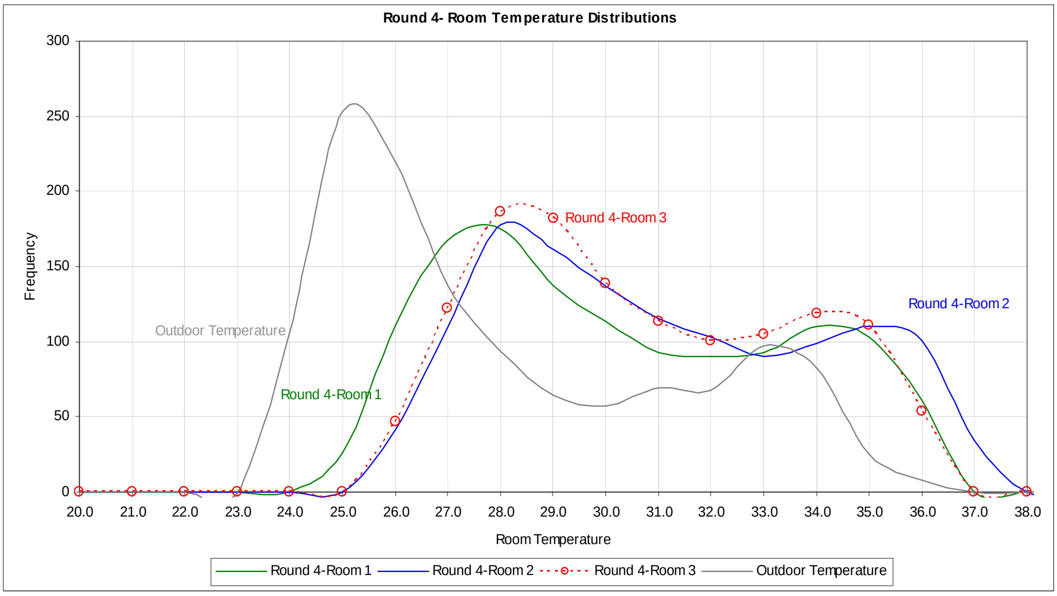


***Figure 53** Round 4 - Bin & Frequency Graph*

All rooms have second peaks in the hotter region caused by the outdoor trend. A question is made. Why and when become 27 and 28°C so frequently measured. This requires the day and night analysis that can be found in Appendix A.

Room 2 and 3 have a similar fluctuation. Their rifts appear on their two peaks and ending tails. The second peaks of Room 3 and 2 stand at 34 and 35°C respectively. The notable rift is that Room 2 is extended to 38 °C after the second peak with higher hot temperature occurrences than Room 3. There is sufficient proof showing Room 3 is better than Room 2 based on this bin and frequency graph.

The cumulative percentage graph (Figure 51) gives another proof showing that Room 3 is better than Room 2 all along; since, Room 3 closes up to 100% earlier than and maintains a rift to Room 2. Nevertheless, Room 1 is again the best choice in this round for night time and partial daytime.

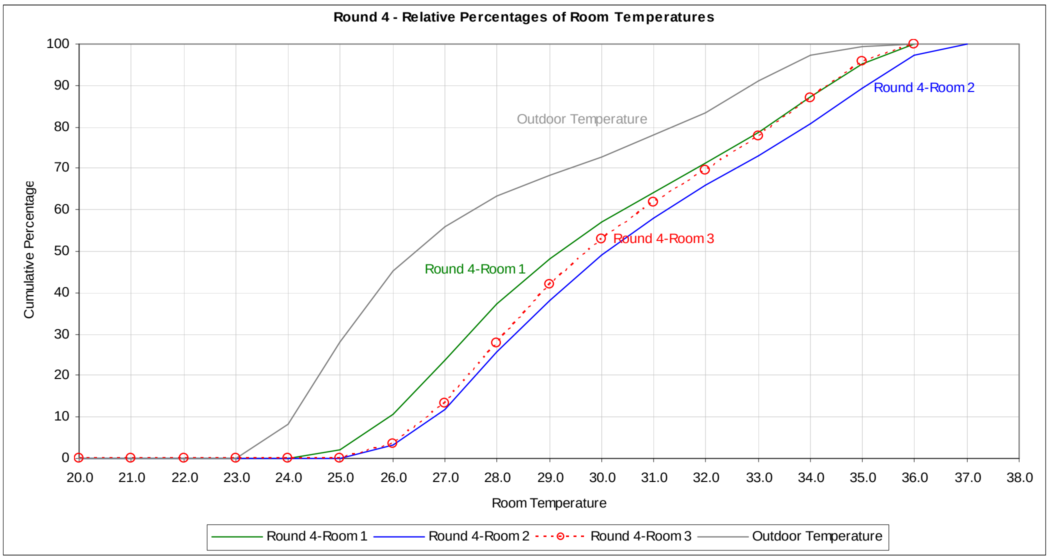


Figure 54 *Round 4 Cumulative Percentage Graph*

Rank: In round 4 Room 1 is again the best option of all and Room 3 is better than Room 2 all along.

Discussion: The result of the cumulative graph showing attic vs room temperature distribution (Figure 55) is quite similar to the previous Round 3, with the only difference of Room 3 performing better than Room 2 in the range of 22°C-27°C. The main note is that all the attics perform better than the room temperatures. This can be again explained by the higher amount of attic ventilation with the cut-out of aluminium layer near the ridges, opened soffit board and opened attic windows, which leads to faster cooling down at night.

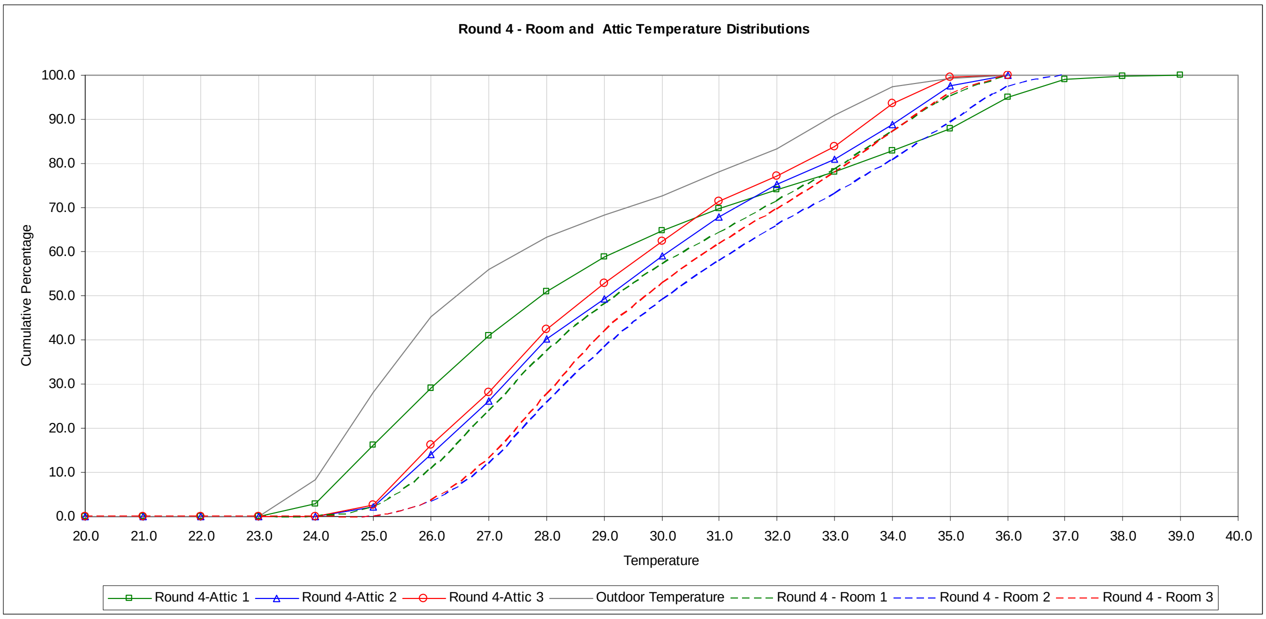


Figure 55 *Round 4 Room vs. Attic Temperatures – Cumulative Percentages Graph*

4.2.5. Test Cells in Bin and Frequency Ranking

Method: The temperature range between 22 and 27°C is set as the thermal comfort zone for 4 rounds. The bin and frequency data are re-sorted into a bar chart (Figure 56) to show the general view of all cases by grouping all the frequency points between 22 and 27 °C into a single class. The temperature occurrences fallen into 22 – 27°C are summed up into their single percentages; then, a comparison between rooms in one round can be drawn based on their percentage differences. In such a way, all the test rooms can be compared within each round and also across the four rounds.

Result: The chart below (Figure 56) clearly shows that Room 1 performs the best of all in round 2, 3 and 4. Interestingly, Room 1 is marginally worse than Room 2 and 3 in Round 1. A break down of day and night ranking is required to elaborate more insight (Figure 57 and 58). The four ventilation rounds are polarised to the two extremes in which Round 1 and 4 have minimal and maximum ventilations respectively. As discussed, attic heat during daytime does not always affect strongly the room below. Starting from Round 2, Room 1 starts to give higher percentage in the comfort zone. For example, Room 1 in round 2 is 6.5 % higher than Room 3; but, this percentage is almost double-folded to 12 % in round 4.

This chart gives evidence that aluminium foil is only useful, as long as it is completely tight without any holes and ventilation in the attic.

Therefore, in the range between 22 and 27°C, Room 1 is the best option of all whenever there is ventilation in the attic. Room 2 and 3 have no notable difference in temperature performance.

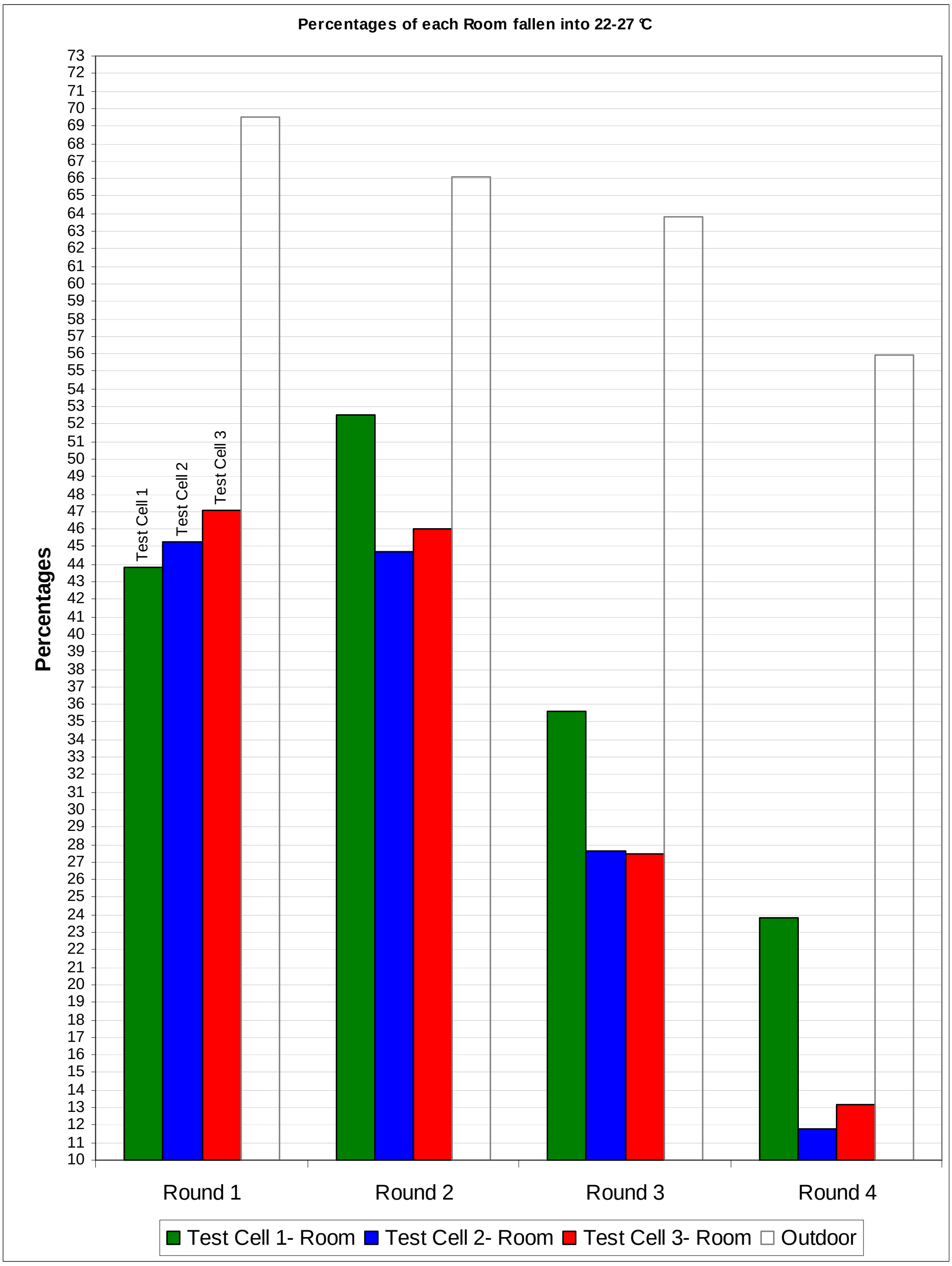


***Figure 56** 4 Rounds: Overall Ranking of three test cells in 22-27°C for 24-hour.*

For the 22-27°C thermal comfort zone on the 24-hour basis, there is an unproven direct relationship between the outdoor and Room 1, 2 and 3 (see Table 4). The Table 4 implies that when the attic is highly ventilated Round

4 and 3, the gap between the outdoor and room temperature becomes wide. In comparison to the least ventilation Round 2 and 1, the gap becomes narrow. The main structural changes are that Round 1 and 2 have soffit board closed; Round 3 and 4 have soffit boards opened.

Table 4 *Difference between Outdoor and Room in the thermal comfort zone, 22-27°C on 24-hour basis*

Difference between Outdoor and Room in the thermal comfort zone, 22-27°C on 24-hour basis

Round	1	2	3	4
Room 1	26%	14%	29%	32%
Room 2	25%	21%	36%	44%
Room 3	27%	20%	36%	43%

The chart of Figure 57 shows room temperatures fallen into 22-27°C only during night time from 19:00 to 07:00 when the doors were opened. Round 1 with non-ventilated attic shows a leveled result for all the test cells. This was already explained previously. The opened door factor is bigger than attic heat downwards migration for night time in Round 1. In Round 2, 3 and 4, more heat amounts were gathered during the daytime in the Attic 2 and 3, which affected the room below also at night.

Though clay and concrete tiles have different thermal mass, the results of Room 2 and 3 are very small.

Figure 58 shows room temperatures fallen into 22-27°C only during day from 07:00 to 19:00, when doors were closed. The result is different to the night time result. While in Room 1 of Round 1 is clearly the worst, in Round 4 with additional ventilation by the attic windows it becomes the best of all with 9% more chances fallen into 22-27°C. At the same time, Room 2 and 3 are in all 4 rounds very close to each other. Attic heat does affect the room below during daytime in Round 1. The advantage of Cool Rood System is 4 to 5% more chance fallen into 22-27°C than that Room 1 without aluminium foil.

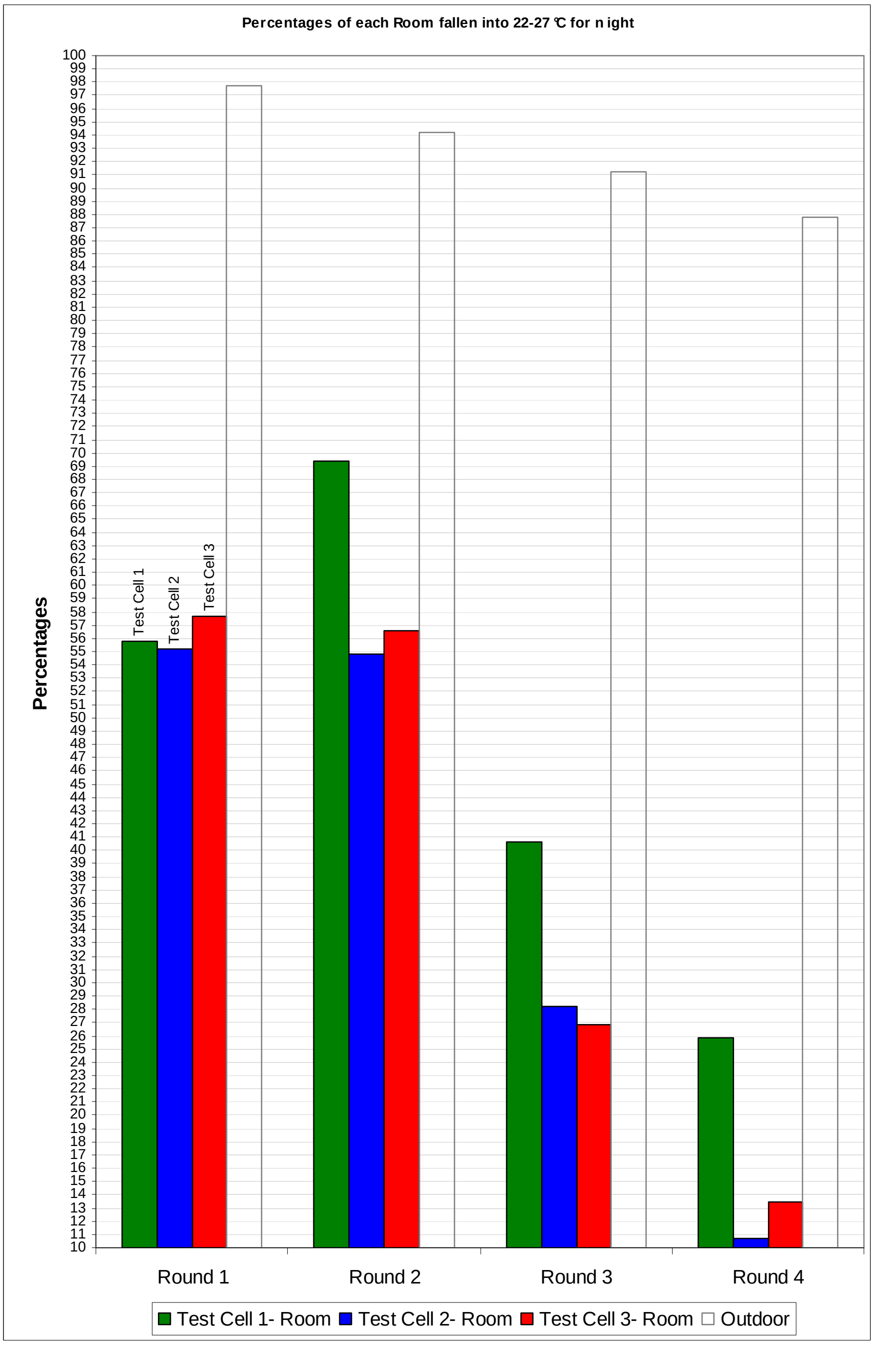


Figure 57 *Bin and Frequency Method: Room Temperatures fallen into 22-27°C for night (19:00 – 07:00) – Door Opened*

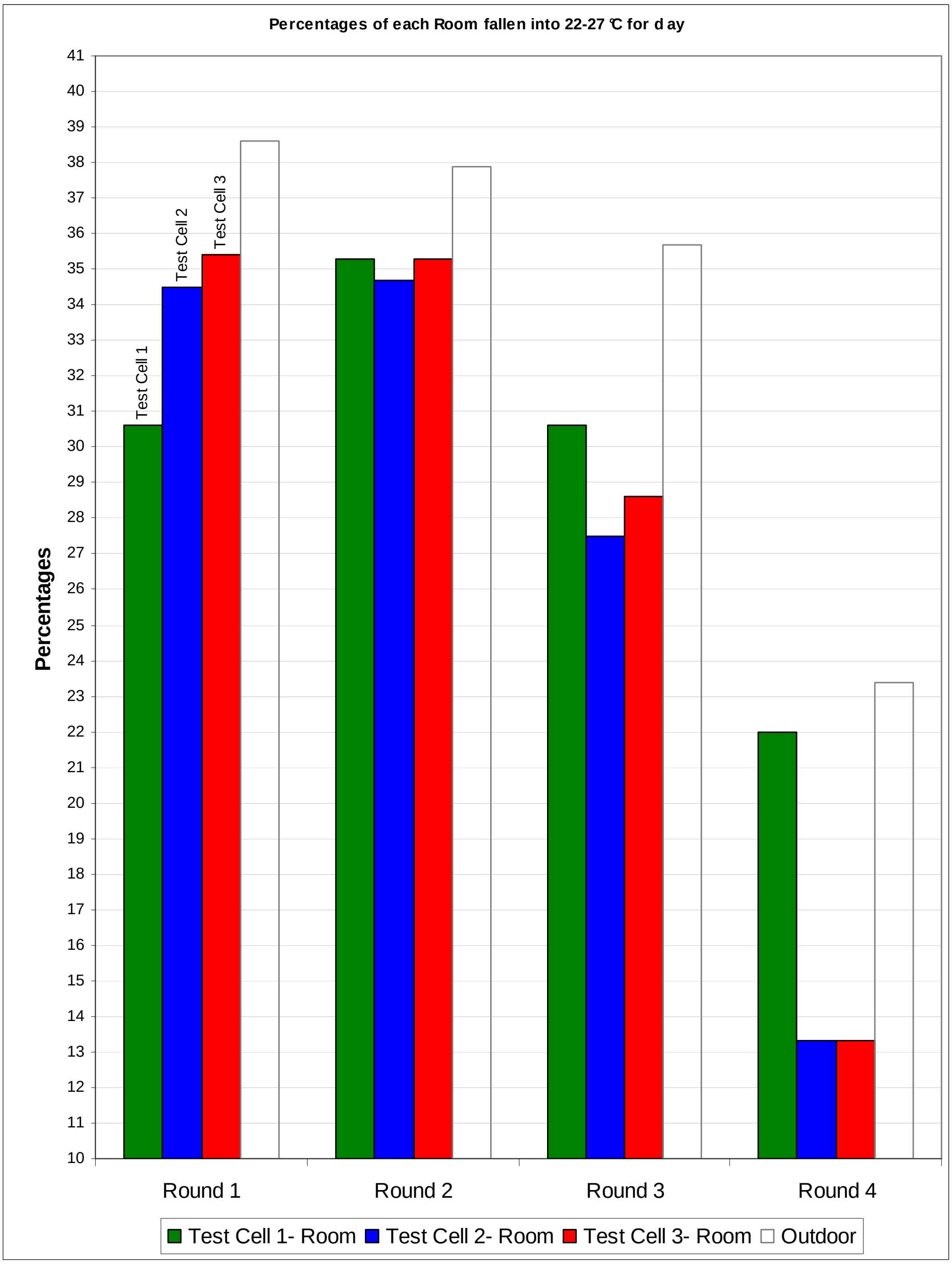


Figure 58 *Bin and Frequency Method: Room Temperature fallen into 22-27°C for day (07:00 – 19:00) - Door Closed*

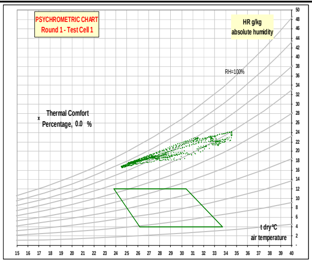
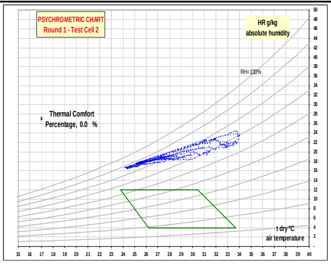
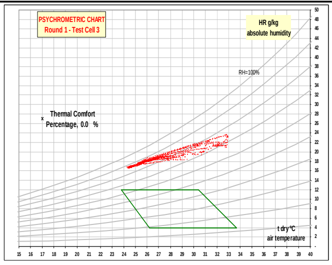
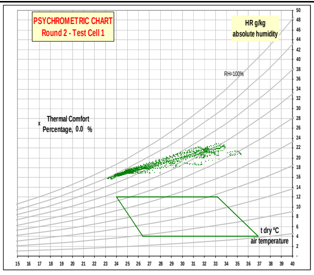
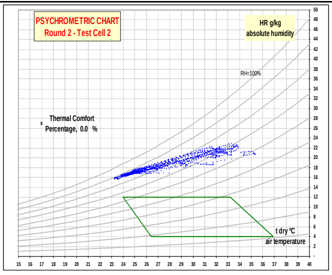
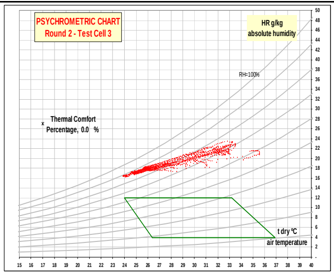
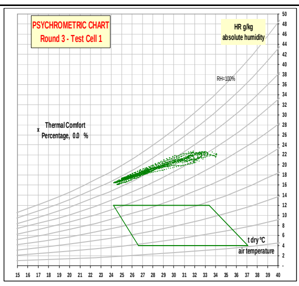
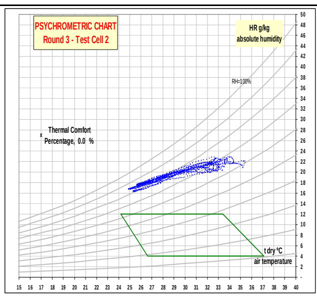
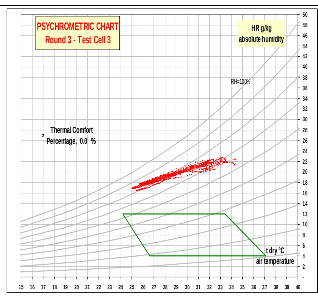
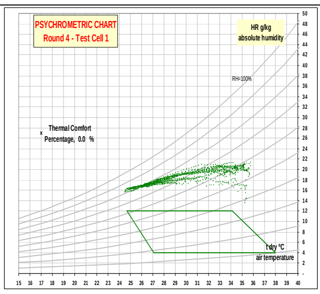
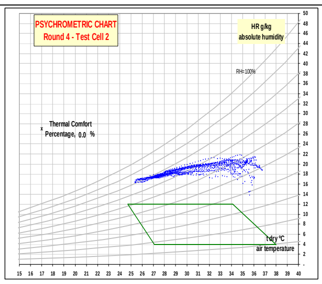
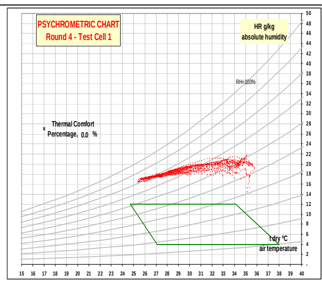
4.3. Analysis Method - Psychrometric Chart

The method of calculating comfort zone is based on Steven V. Szokolay's SET (Standard Effective Temperature). The parameters for making a psychrometric chart include indoor temperature and relative humidity, absolute humidity and monthly outdoor mean temperature. The comfort absolute humidity is set at 4 – 12 g/kg, in which the water content in the air shall not be too dense and humid to have a comfortable feeling. In hot and humid Malaysia, the rooms without mechanical ventilation are always influenced by the outdoor humid air. In this research, all the rooms were naturally ventilated; thus, all the rooms were always above the comfort absolute humidity level.

None of the rooms in all rounds falls into the comfort zone of the psychrometric chart (see Table 5). The absolute humidity levels of all rooms are always above 15 g/kg, which is 3 g higher than the maximum comfort level 12 g/kg.

There is no comparative result able to be derived from psychrometric charts.

Table 5 *Psychrometric charts of three test Cells in 4 ventilation rounds*

	Test Cell 1	Test Cell 2	Test Cell 3
Round 1			
Round 2			
Round 3			
Round 4			

4.4. Analysis Method - Predicted Mean Vote (PMV) and Heat Migration Effect

According to ASHRAE 55-2004, there are six primary factors that must be addressed when defining conditions for thermal comfort. The six primary factors are listed below (ASRHAE 55-2004).

1. Metabolic rate (human factor)

2. Clothing insulation (human factor)

3. Air temperature (environmental factor)

4. Radiant temperature (environmental factor)

5. Air speed (environmental factor)

6. Humidity (environmental factor)

Predicted Mean Vote (PMV) is a useful method to analyse the room temperatures involving more on-site climate data. Presumably, heat migrating from the attic into its room below or vice-versa direction affects the surface radiant temperatures of the internal ceiling and walls. Taking into account the factor of surface radiant temperature is arguably an alternative comparative solution to determine the best roofing method. Previously, the temperature only bin and frequency analysis may not be sufficient to reveal the entire situation. Hence, PMV which includes the 6 factors contributing to thermal comfort is seen as a more humane approach to find out the best roofing method in each round. The PMV has a thermal sensational scale ranging from the -3 (cold) to +3 (hot). In this research, the occurrences falling into: -1 (slightly cool), 0 (neutral), and +1 (slightly warm) are elaborated into four parts and grouped into a single bar chart to give an overall view. First of all, the climate data were re-sorted into spread sheets which contain the PMV and PPD (Predicted Percentage Dissatisfaction) script (Figure 59). Assumptions of clothing, air velocity, metabolism rate are made and shown in Figure 59. Secondly, the calculated PMV index data are again classified into the bin and frequency method.

PREDICTION OF THERMAL COMFORT — as per ASHRAE Standard 55-2004 and ASHRAE Fundamentals, 2005 (chapters 6 and 8)	SI		IP	
Metabolic heat production, M	1.2	met	1.2	met
Metabolic heat production in energy units, M = met x 58.15W	70	W	238	Btu/h
Work, W	0.00	met	0.00	met
Insulation of clothing assemble, clo	0.63		0.63	
Indoor air temperature, ti	22.8	°C	73.0	°F
Indoor air temperature, Ti	295.9	°K	295.9	°K
Mean radiant temperature, trad	22.7	°C	72.9	°F
Mean radiant temperature, Trad	295.7	°K	295.7	°K
Indoor air relative humidity	30%		30%	
Air velocity, V	0.10	m/s	20.0	ft/min
Velocity threshold, Vmax = 2.38 x (tcl-ti) x $^{0.25}$/12.1	0.31	m/s	60	ft/min
Saturated vapor pressure= EXP(-5.8002206 x 10^3 / Ti + 1.3914993 - 4.864023 x 10^{-2} x Ti)				
+ 4.1764768 x 10^{-5} * Ti ^ 2 - 1.4452093 x 10^{-8} x Ti ^ 3 + 6.5459673 x Log(Ti))	2,773	Pa	11.1	
Partial water vapor pressure, pa = Saturated vapor pressure x Relative humidity	832	Pa	3.3	In w.c.
Clothing insulation resistance, Rcl=0.155 x Icl	0.098	m^2 oC /W	0.017	In w.c.
Clothing factor, fcl= 1+1.29 x Rcl if Rcl<0.078, otherwise fcl= 1.05 + 0.645 Rcl	1.113		1.113	ft^2 oF h/Btu
Initial value of the convective heat transfer coefficient, hc = 12.1 x $V^{0.5}$	3.86	W/m^2 oC	0.68	
Initial value of temperature of clothing, tcla = ti + (35.5 - ti) / (6.45 * Rcl + 0.1))	27.8	°C	82.0	Btu/h ft^2°F
Computational coefficients: P1=Rcl x fcl	0.11		0.11	°F
P2=3.96 P1	0.43		0.43	
P3=100 P1	10.87		10.87	
P4=P1x ti	32.16		32.16	
P5=308.7- 0.028 (M-W)+P2 x $(tr/100)^4$	339.7		339.7	
Temperature of clothing, tcl	28.6	°C	83.6	
Temperature of clothing, Tcl	301.8	°K	301.8	°F
Final value of the convective heat transfer coefficient, hc= 2.38 $(tcl-ti)^{0.25}$	3.86	W/m^2 oC	0.68	°K
HUMAN BODY HEAT LOSS BREAKDOWN:				
Skin radiant heat loss, Hr = fcl x 3.96 x 10^{-8} (Tcl^4 - $Trad^4$)	28	W	97	Btu/h ft^2°F
Skin convective heat loss, Hc = fcl x hc x (tcl - ti)	25	W	86	Btu/h
Skin latent heat loss, Hl = 3.05 x [5.73 - 0.007 x (M-Work) - pa/1000]	13	W	46	Btu/h
Sweat heat loss, Hsw = 0.42 [(M-Work) - 58.15]	5	W	17	Btu/h
Respiratory latent heat loss, Hrl = 0.0173 M (5.87-pa/1000)	6	W	21	Btu/h
Respiratory sensible heat loss, Hrs = 0.0014 M (34 - ti)	1	W	4	Btu/h
Total heat losses, H = Hr + Hc + Hl + Hsw + Hrl + Hrs	79	W	270	Btu/h
Internal heat production = M - Work	70	W	238	Btu/h
Thermal stress L = Internal heat production - Total heat losses	-9	W	-32	Btu/h
Predicted mean vote PMV=[0.303 exp(-0.036 x 58.15 x M)+0.028] x L	-0.49		-0.49	Btu/h
Predicted percent dissatisfied PPD = 100 - 95 x exp[-(0.03353 PMV^4+0.2179 PMV^2)]	10%			
Comfort feeling	neutral			

Figure 59 *Screenshot of PMV and PPD spreadsheet script (The Academy of HVAC Ingeneering Ltd. 2006)*

4.4.1. Round 1 PMV Analysis

The PMV fluctuations of curves are very similar throughout in Round 1 due to the tight and un-ventilated attics (see Figure 60). There are no issues of various and inconsistent air flowing in and out of attics to cause an unstable heat migration that happened in Round 4. As discussed daytime cumulated heat migrating downwards from the attics to its room below is certain, but weak. When all attics have very little ventilation cumulated heat can only move downwards. Eventually, all rooms share a very similar curving tendency on the falling curves which indicate daytime. This was already mentioned in the previous chapters.

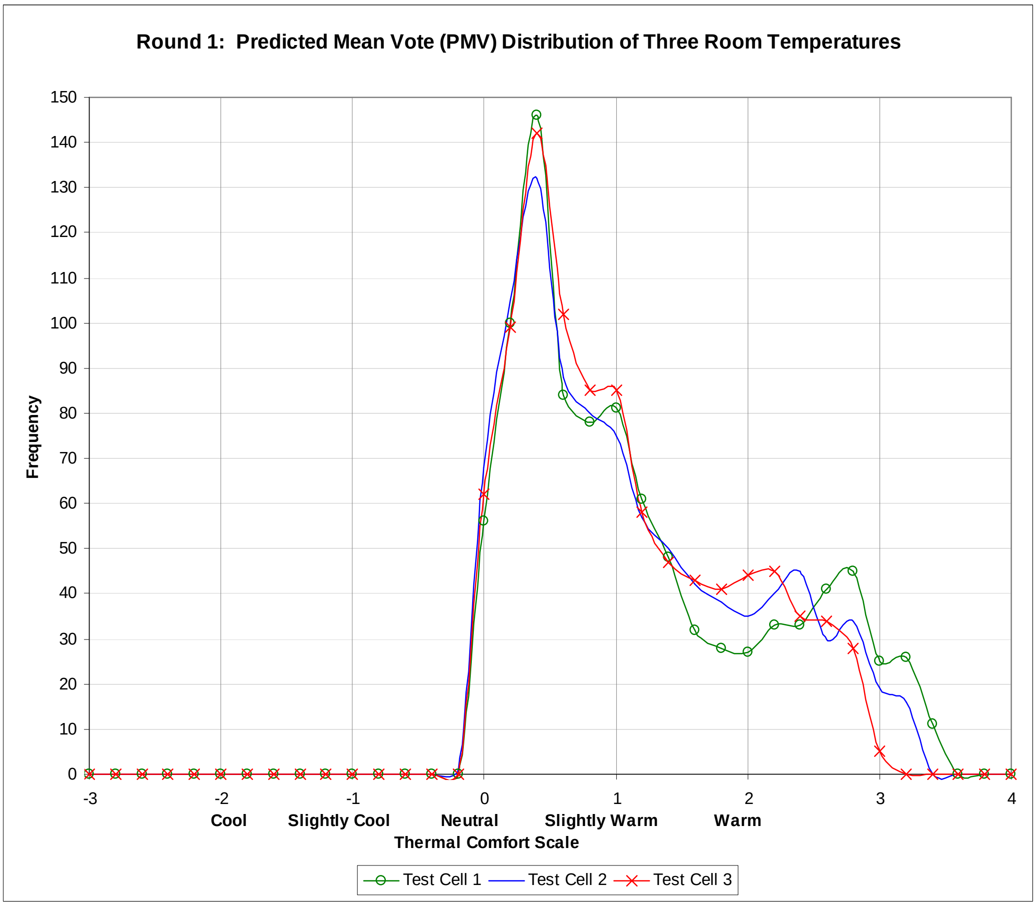


Figure 60 *Round 1 – PMV Distribution*

Result: All the rising points and peaks happen coherently at -0.8 and +0.4 respectively and the notable rifts happen from +0.2 onwards. This rising part represents that the night time opened door leveled all the room temperatures and attic heat factor is less weak to influence. The curve of Room 1 in the range +0.2 to +1 appears to be always higher than the other two rooms; this might be the night time lower Room 1 temperature. The curve of Room 3 happens to be the middle of the two rooms and Room 2 appears to be the one which has the least occurrences in the range of -1 to +1. In oppose to the curves of Room 2 and 3, Room 1 has lower occurrences in the range of +1 to +2 and tends to rise starting at +2 onwards.   It is difficult to conclude the good from the bad cases based on this PMV distribution graph.

The bin and frequency of the PMV indexes are re-sorted into cumulative percentage curves (Figure 61). This graph shows again the order that Room 3 has the highest occurrences followed by Room 2 and Room 1 in the range of -1 to +1.

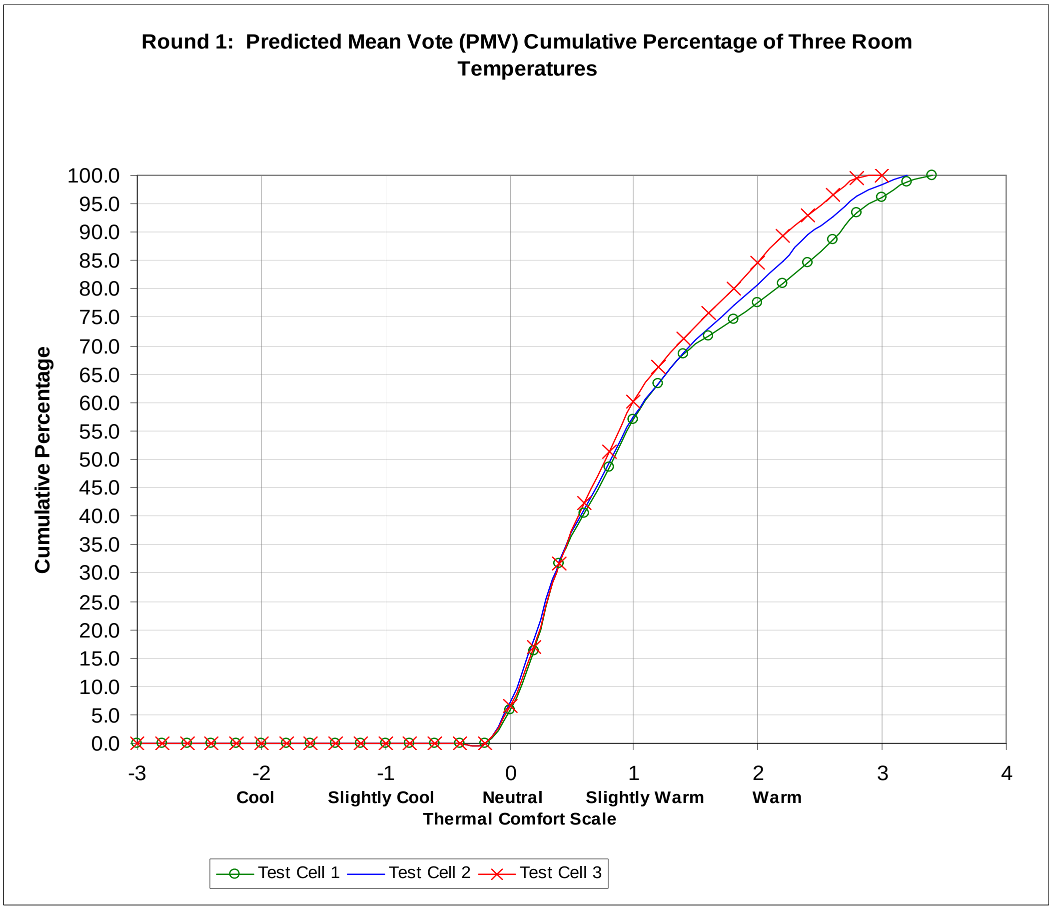


Figure 61 *Round 1 PMV cumulative percentage*

Beyond thermal comfort scale +1.5, a notable result can be drawn into attention and very likely this is the part caused by daytime. Room 3 has an earlier 100% close-up and consistent rifts to other curves.

Discussion: All the rooms perform almost equally. Narrowly speaking, Room 3 is the best option of all and marginally better than the others. Though the difference is very small, it can be said that there is no difference in using cool roof system or traditional roof structure when using concrete tiles, but clay tiles would give a marginally better result in the PMV thermal comfort zone. The ranking of Room 3 as the best one, followed by Room 2 and Room 1 is similar to the ranking of room temperatures in the previous chapter.

4.4.2. Round 2 PMV Analysis

The fluctuations of curves in the whole range are greater than in Round 1 due to some ventilation in the attics with unstable air flow. (see Figure 62).

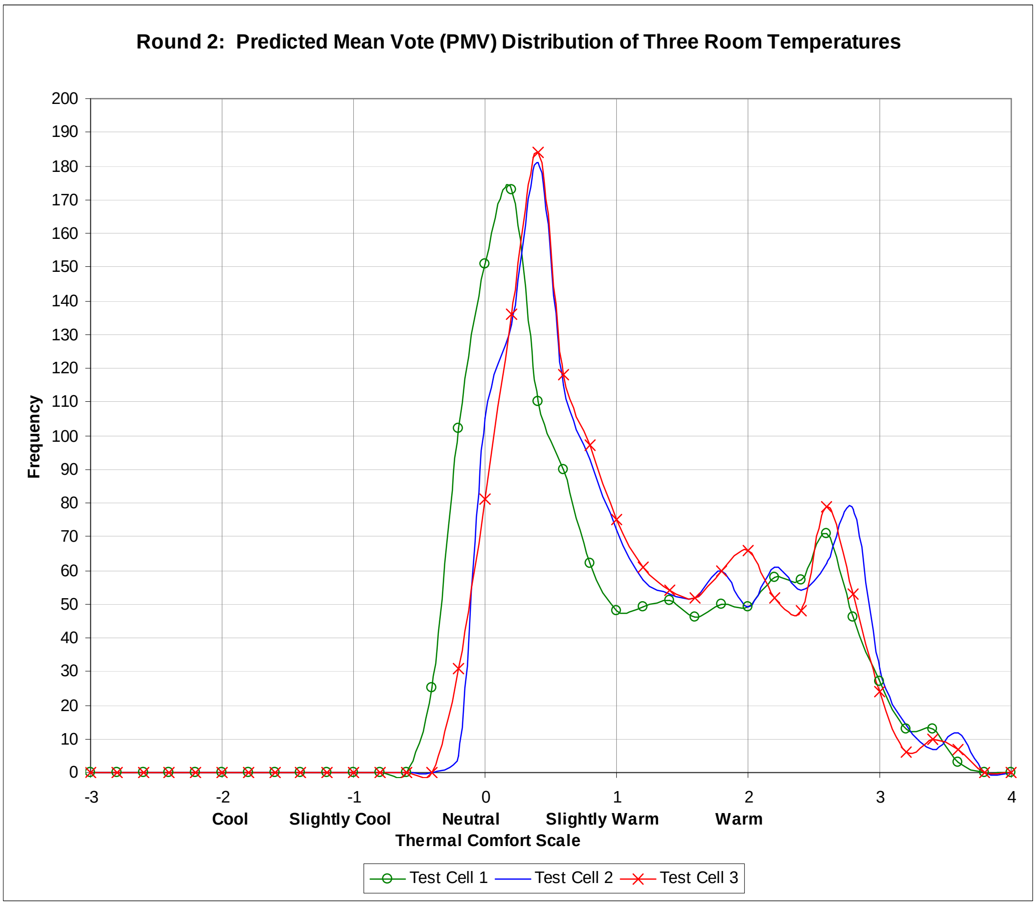


Figure 62 *Round 2 – PMV Distribution*

Result: Room 1, 2 and 3 start to rise at -0.8, -0.3 and -0.5 respectively; Room 1 and 3 have their steady ascends to their peaks. Room 1 has higher occurrences than Room 2 and 3 in the range of +1 to +2; in opposition, Room 2 and 3 have higher occurrences than Room 1 in the range beyond +2. These patterns are similar to its bin and frequency of temperature.

The cumulative percentage graph (Figure 58) reveals that Room 1 appears to be the best option of all followed by Room 2 and 3 for night time and a big part of the days.

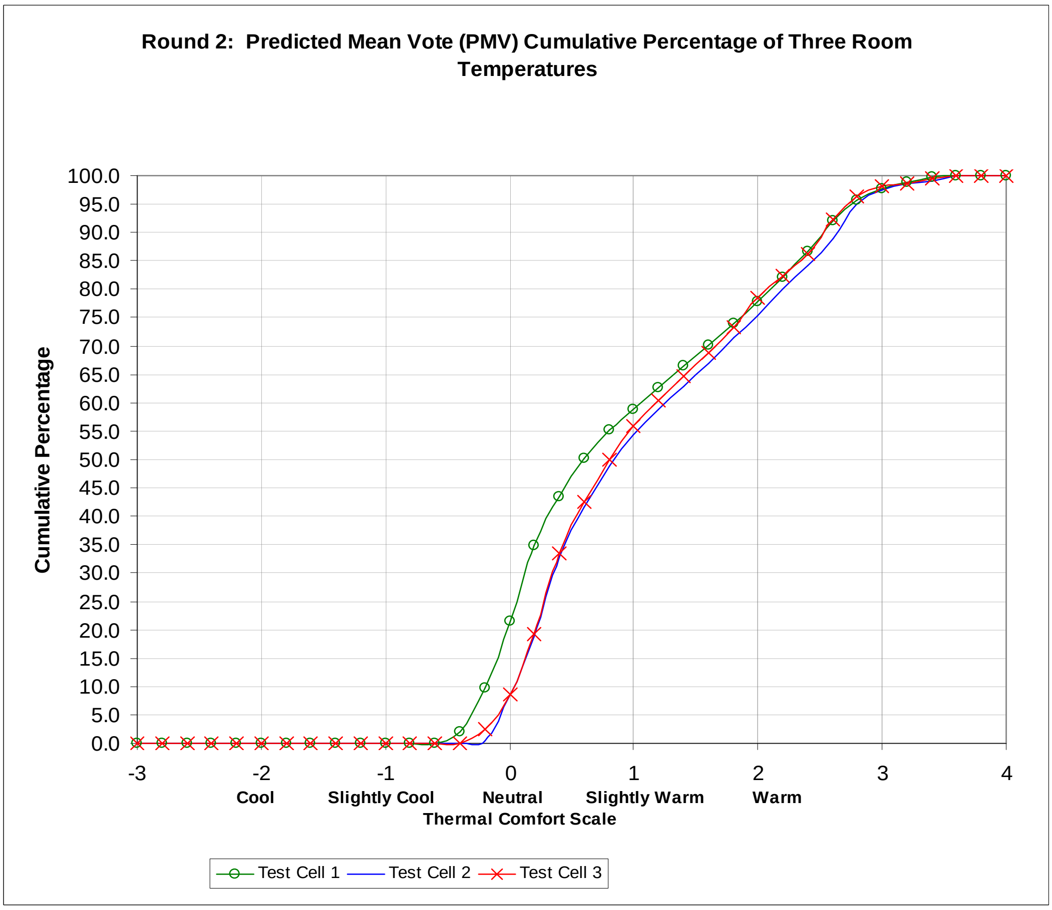


Figure 63 *Round 2 PMV cumulative percentage*

Discussion: Room 1 in the range of -1 to +1 is notably better than Room 2 and Room 3. It proves that the cut-out of aluminium layer near the ridges does not make the performance of the roof better; in opposite, it makes it worse than the performance of a traditional roofing system. Therefore, in the range of PMV thermal comfort zone, Room 1 with the traditional roofing system is the best option with this level of ventilation. Clay tiles again give a marginally better result than concrete tiles, when using aluminium foil layer. Test Cell 1 is the best option followed by Room 3 and 2. It is coherent with the ranking of the room temperatures during the day, but at night Room 1 is always colder. This is not shown in the day and night separated bin and frequency graphs for 22-27°C. This may explain why in the PMV graph is important for Room 1 which is regarded as the better one.

4.4.3. Round 3 PMV Analysis

All attics in Round 3 have higher amount of ventilation openings than Round 1 and 2. Expectedly, the fluctuations of PMV are more variously than in Round 1 and 2 due to greater amount of attic ventilation and uncertainty of heat migration (see Figure 64 for PMV Distribution).

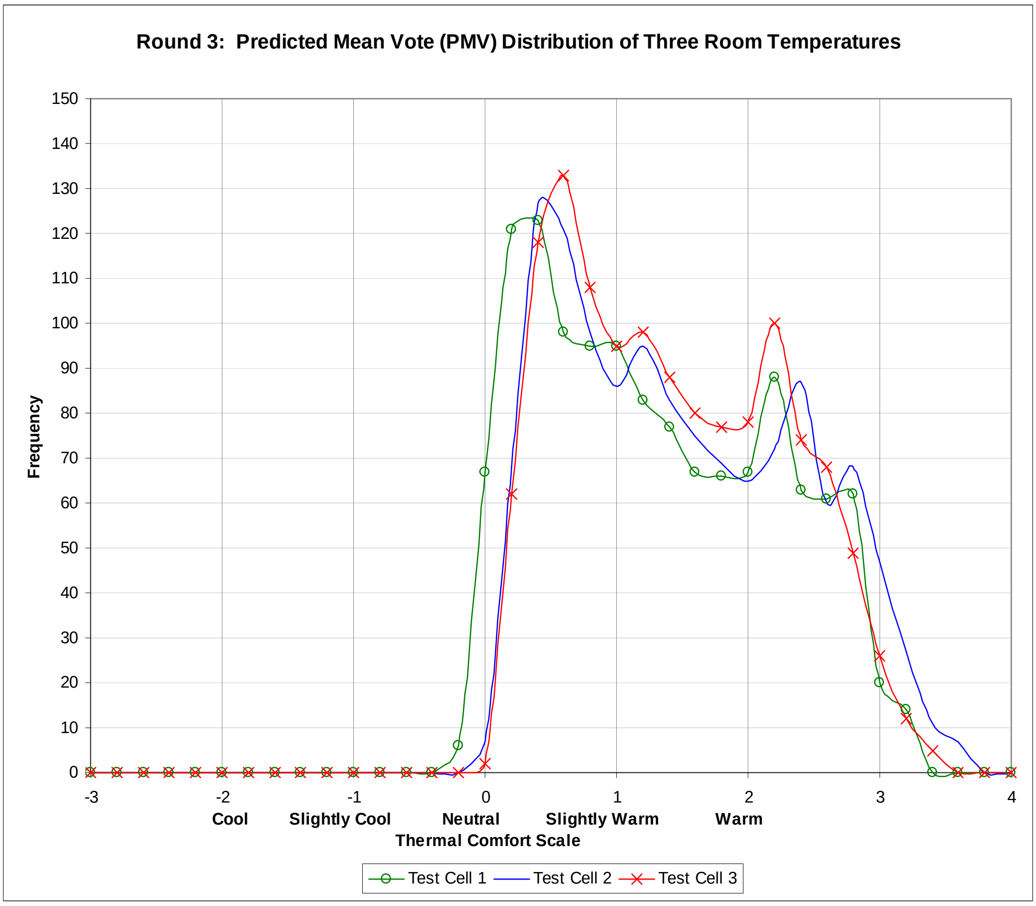


Figure 64 *Round 3 – PMV Distribution*

Result: Room 1 has greater occurrences than Room 2 and 3 in the range before neutral-0. Room 3 has more occurrences than the others from +0.5 to +3.0. This might be coming from the daytime Room 3. This Figure 64 can not give a ranking because of their strong and various fluctuations.

Figure 65 shows the cumulative percentage graph. Room 1 is then claimed to be the best of all throughout the entire thermal comfort.

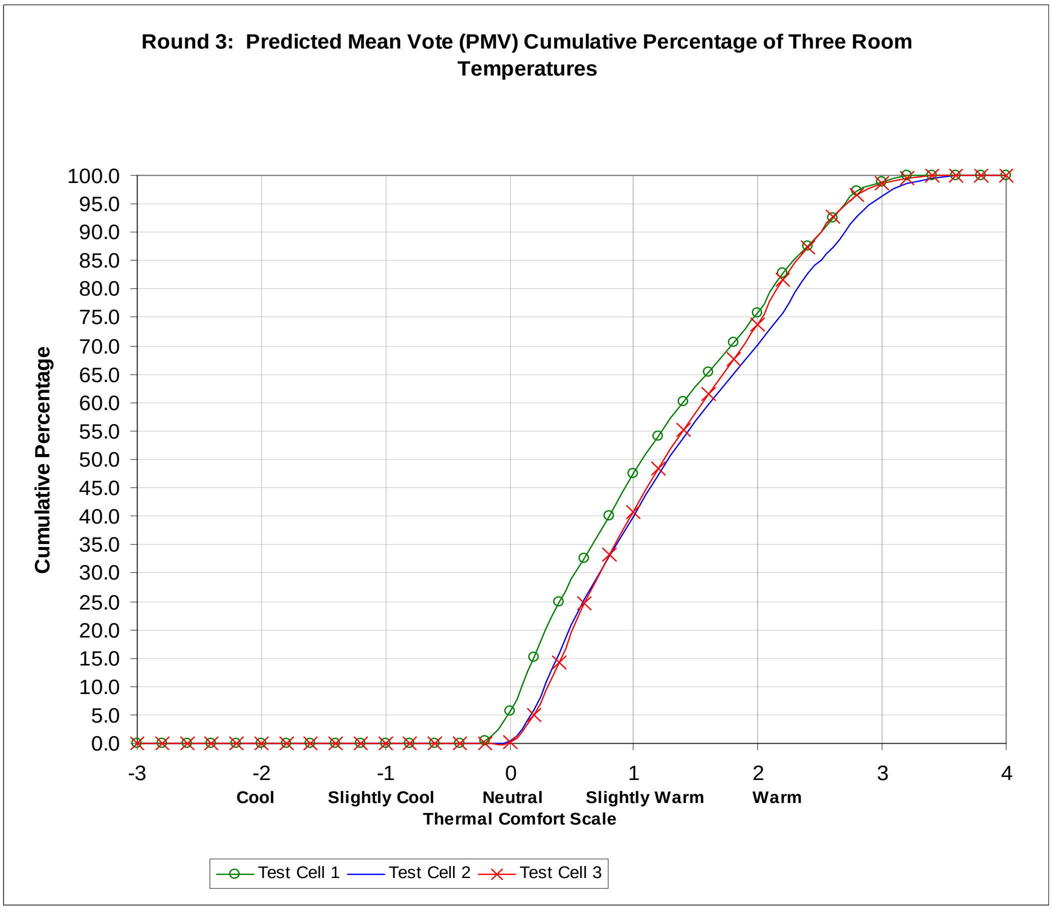


Figure 65 *Round 3 PMV cumulative percentage*

Discussion: Similar to the previous Round 2, Test Cell 1 is better than 2 and 3 for the night time and a bigger part of daytime. This is coherent with the room temperatures ranking in the previous chapter, in which Room 1 is also the best option. Room 2 and 3 have no difference in the range of -1 to +1 which is regarded as the thermal comfort zone.

4.4.4. Round 4 PMV Analysis

Round 4 was made during the hottest period that caused all rooms to have higher occurrences in the range beyond +1 (see Figure 66).

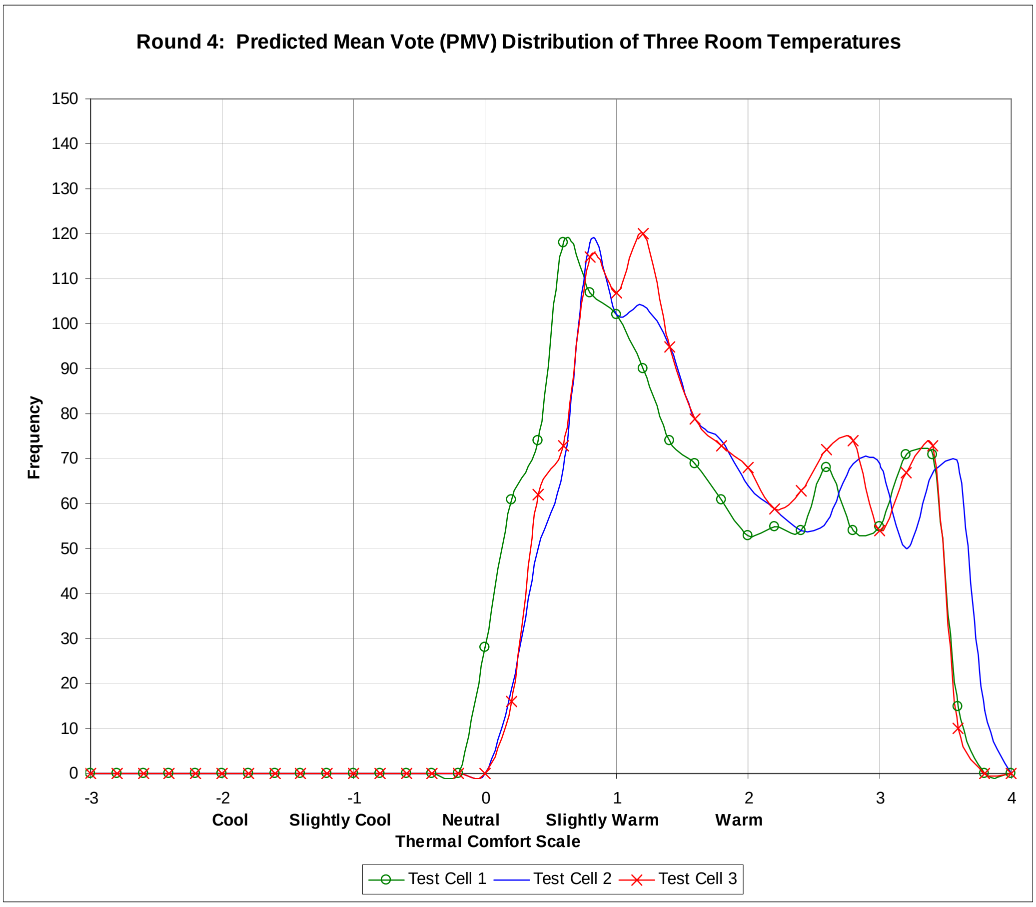


Figure 66 *Round 4 – PMV Distribution*

Result: Room 3 and 2 basically share a similar fluctuation with some slacks and disparity beyond +2. Apart from that Room 1 has the highest occurrences before neutral-0 and is the least from 0 to +3; the entire curve movement of Room 2 is always a step hotter than Room 1. It is evident at their rising point, peaks and declination. For night time and bigger part of daytime, Room 1 without radiant barrier performs better than Room 2 and 3 with radiant barrier.

The cumulative percentage graph shows a similar ranking to the previous Round 3 (see Figure 67).

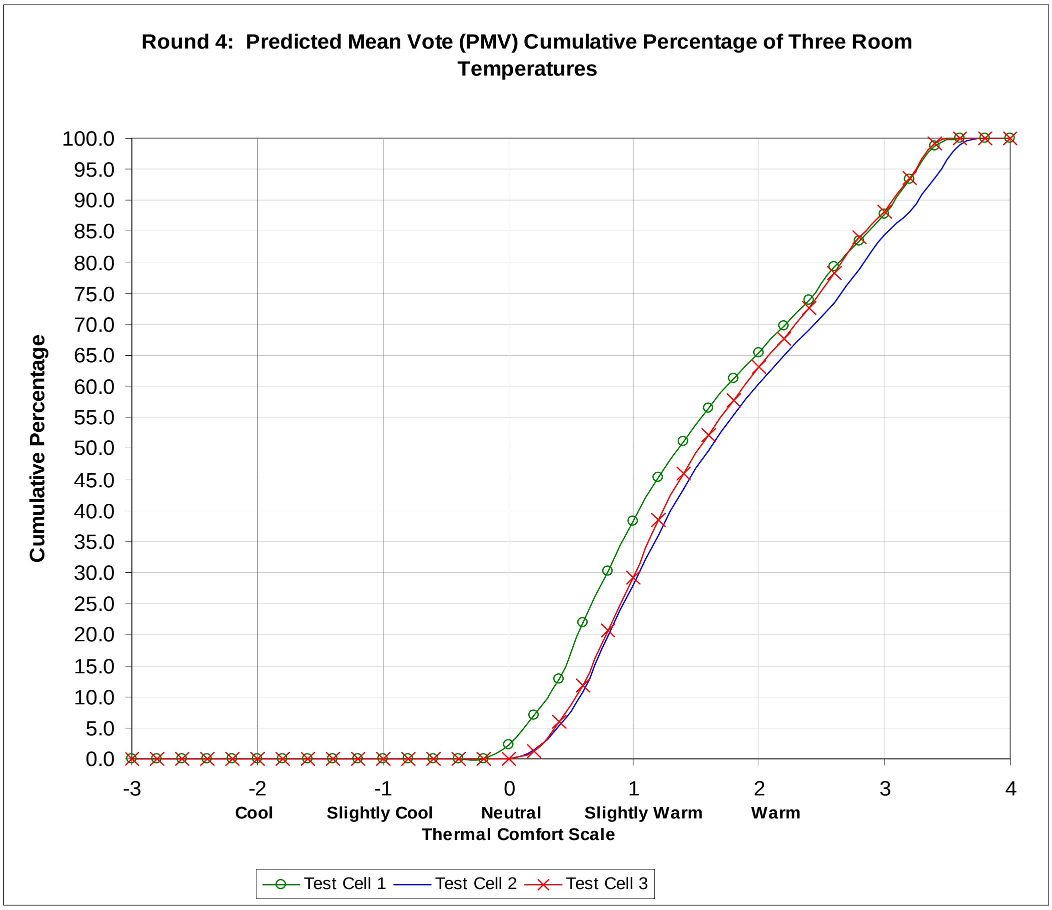


Figure 67 *Round 4 PMV cumulative percentage*

Discussion: As already noticed in the bin and frequency graphs, opening small windows for ventilation in the attic gives little difference to all of the roof performances.

4.4.5. Rooms in PMV Ranking

The bar chart in Figure 68 summarises all rooms in each round by summing up the cumulative occurrences of PMV index falling into the range of -1 to +1.

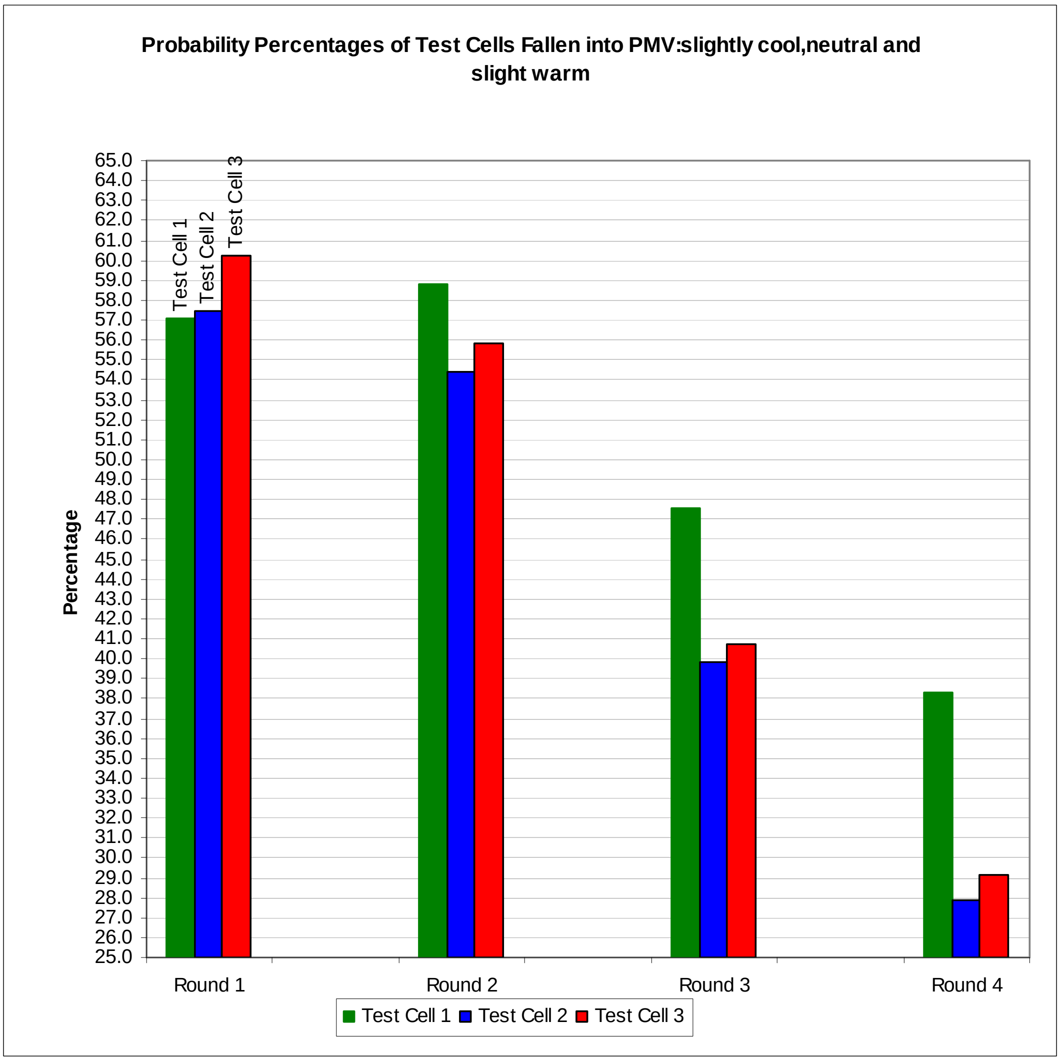


Figure 68 *Relative Comparison of Three Test Cells in All 4 Rounds by Predicted Mean Vote (PMV)*

All the rounds were tested in four various periods with different means of outdoor temperature and solar radiation, it was not appropriate to compare the cases across the rounds based on their occurrences of thermal comfort percentage. For example, Round 1 had a lower mean of outdoor temperature than Round 4. All the rooms in Round 1 have cumulative occurrences of thermal comfort over 50%; while, all the rooms in Round 4 had less than 40%. It did not mean that any room from Round 1 works better than any room from Round 4.

Result: In Round 1, Room 3 performs better than the other two rooms; in opposite, Room 1 performs notably better than the other two rooms in Round 2, 3 and 4. Room 1 is always 3 to 10% better than Room 2 and Room 3 in Round 2, 3 and 4.

Discussion: Room 3 with clay tiles and radiant barrier is the best option of all rooms in Round 1. Interestingly, for 3 rounds Room 1 which has no radiant barrier below cement tiles performs better than Room 2 and 3 with radiant barrier. The overview proves that aluminium foil layer is only effective, as long as it has no holes or openings. Once the aluminium foil is destroyed, the function of radiant barrier gets ineffective because of storing of heat by roof tiles direct radiation and the air layer's convection. Using aluminium layer as a radiant barrier should not have ventilation.

5. Conclusion

The two different comparative methods bin & frequency and PMV analysis (Figure 69) produce a coherent pair of result. The charts clearly show that the aluminium foil as radiant barrier and roof tile underflow in Attic 2 and 3 only work when it has no holes or ventilation openings in the attic. In Round 1, the attics are tight; the Cool Roof System can have some advantages. For the Cool Roof System, Roof 3 with clay tiles is slightly better than Roof 2 with concrete tiles. Round 2, 3 and 4 show that any openings in the aluminium foil layered roof will destroy the function of radiant barrier.

Therefore, in the other 3 rounds Room 1 always remains the best solution.

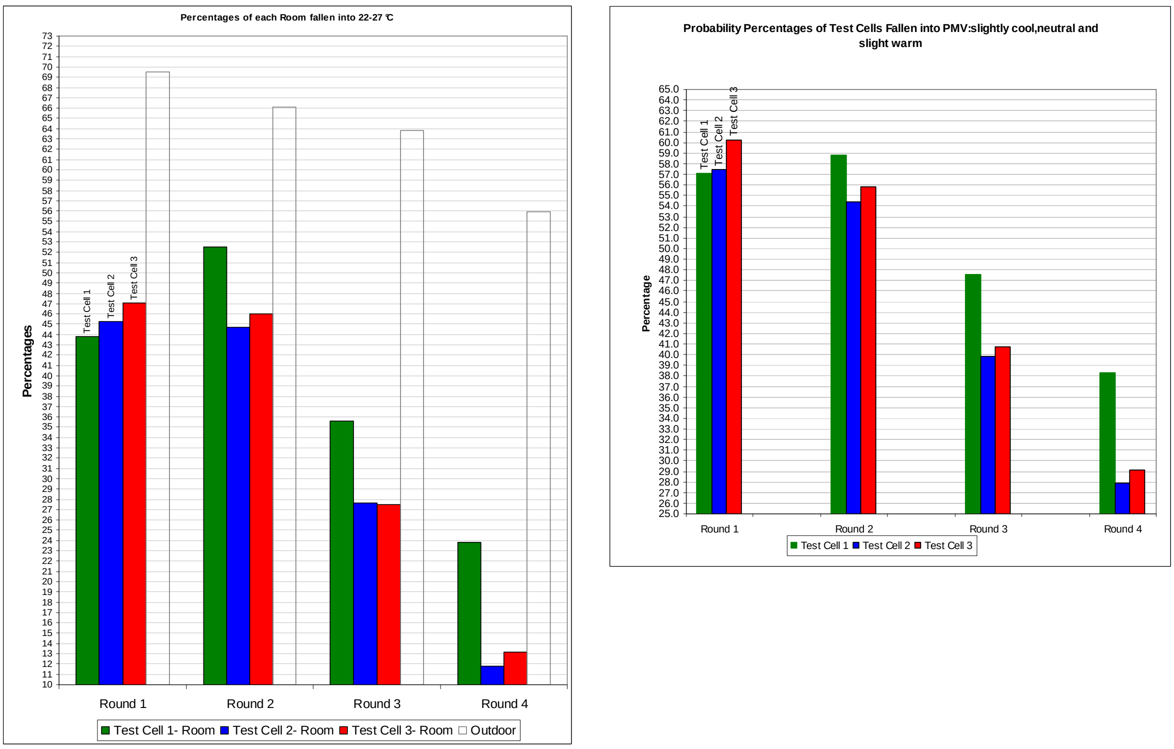


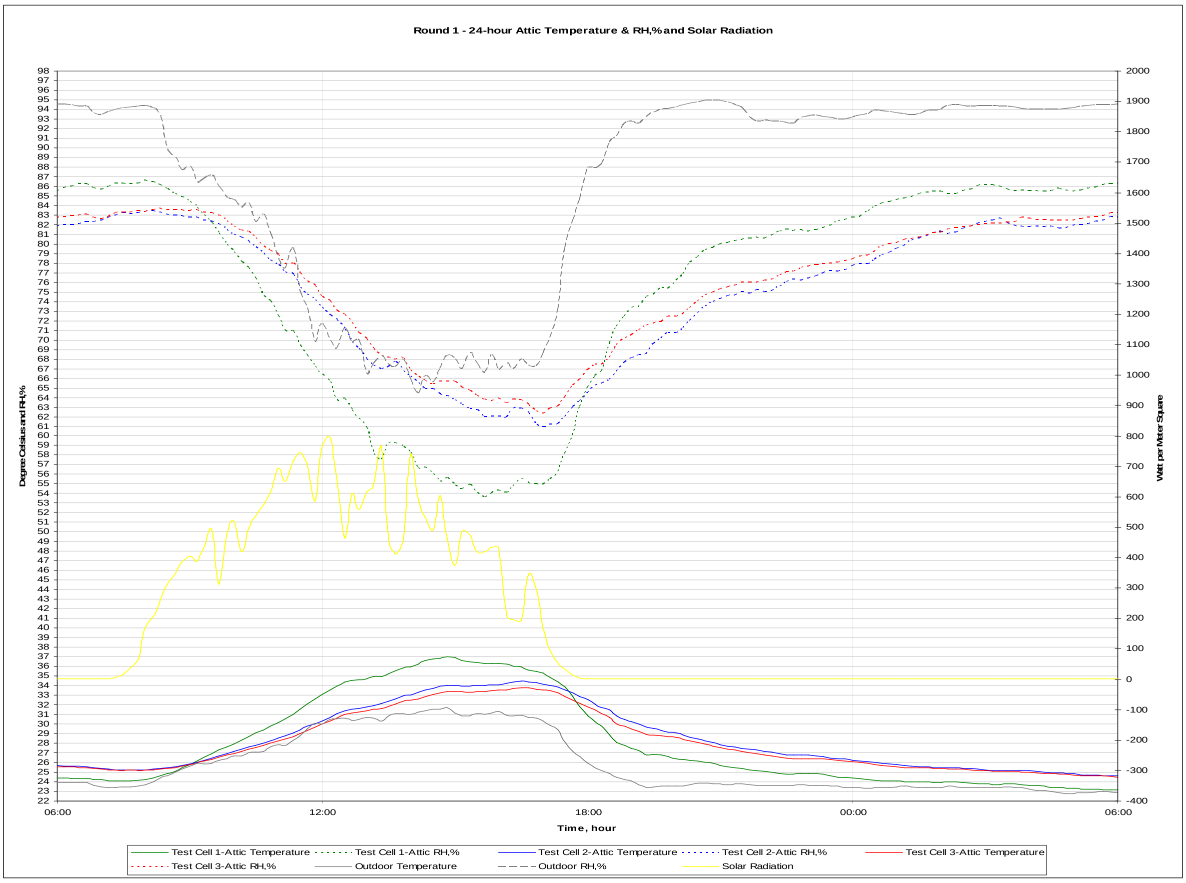
Figure 69 *Comparative Result of Two Analysis Methods.*

By the bin & frequency method, cement or clay roof tiles suggest very small difference when radiant barrier is used underneath the tiling regardless the rounds and roofs. It is because daytime attic heat does not overwhelmingly influence the room below as discussed in the chapters.

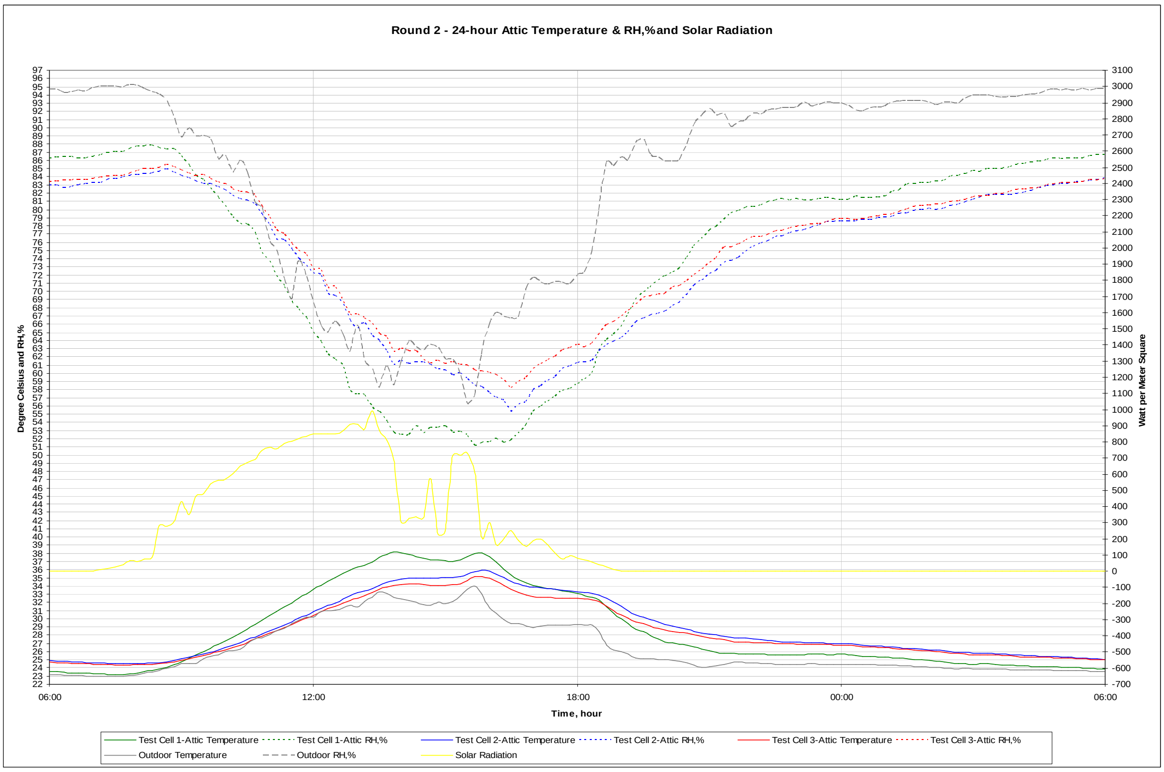
If the Cool Roof System is used, the attic must be tight and shall not have any openings. Otherwise, heat will be gathered during the day inside the attic, which cannot be released quickly during the night.

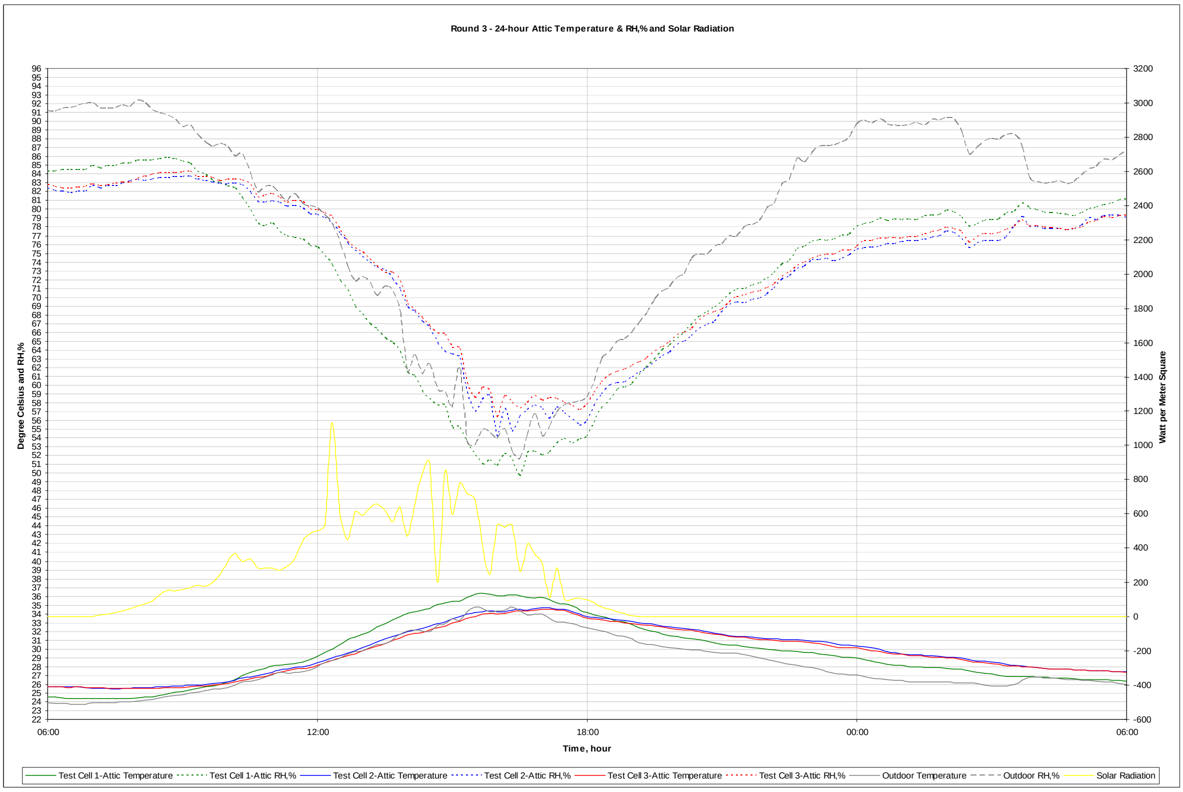
Regarding Hypothesis 2, Cool Roof System with the concept of aluminium foil and airflows has some degree of advantage, but not convincing, from 7 a.m. to 7 p.m. which is the most important period for demanding thermal comfort for people who stay inside the house. While, considering the 24-hour cycle the Cool Roof System does not show a significant advantage over the conventional roof which has no aluminium foil based on the quantitative analysis.

6. Appendix

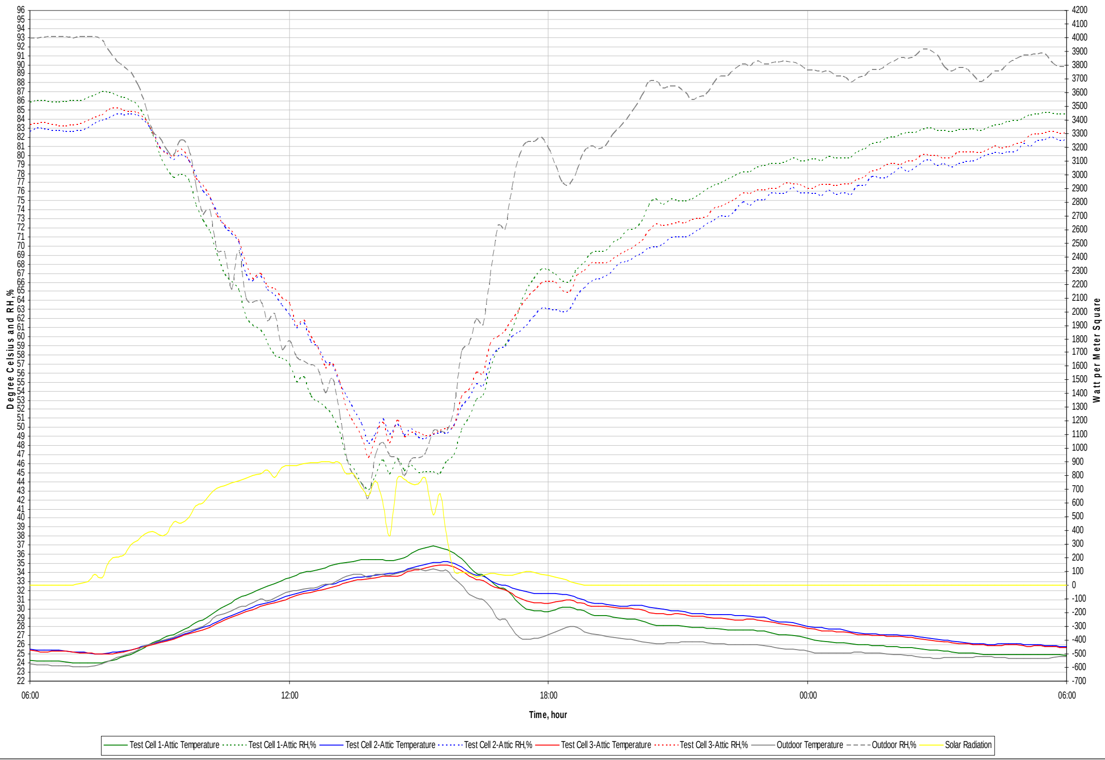


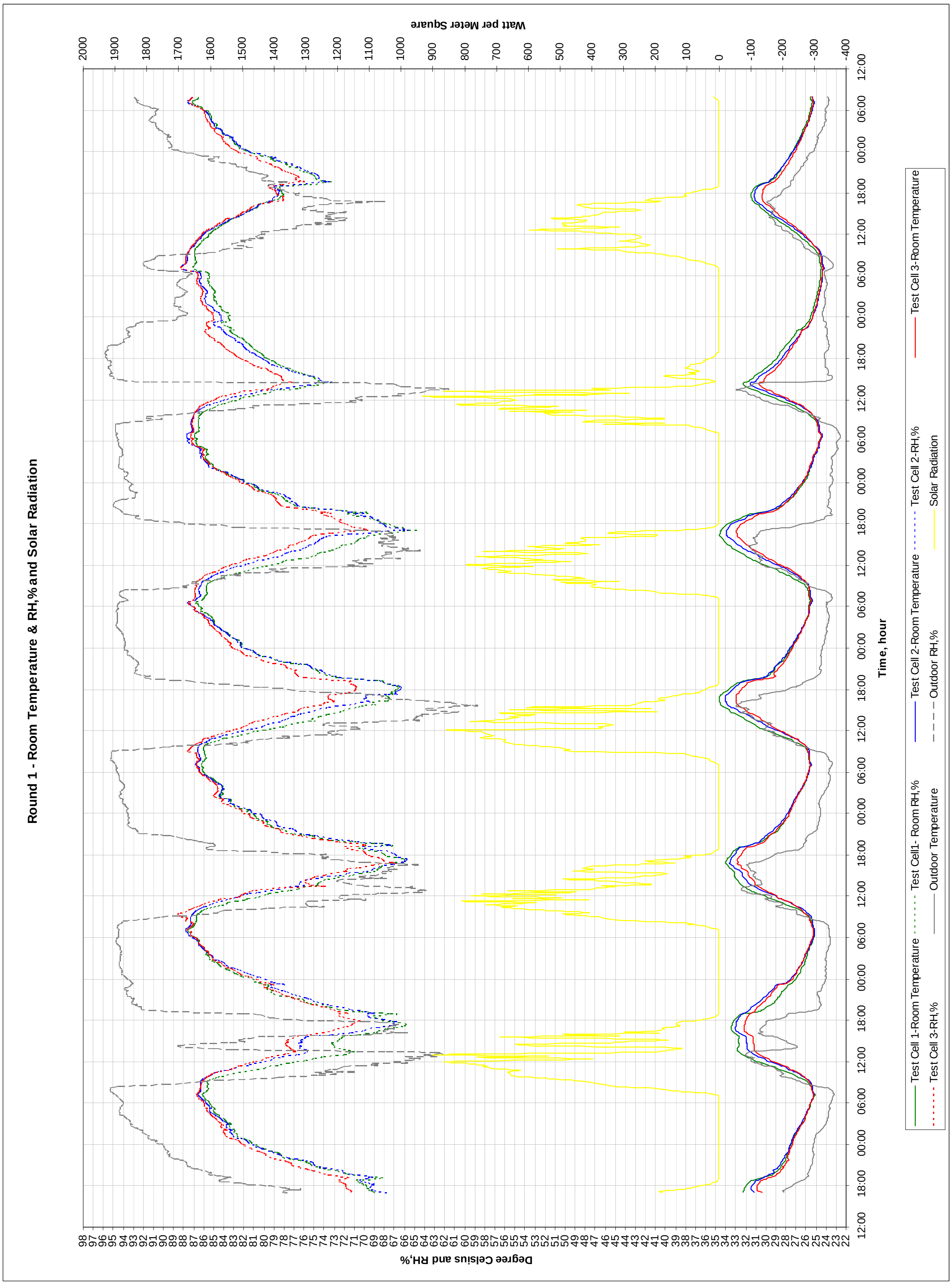
Round 1 - 24-hour Attic Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
06:00
12:00
18:00
00:00
06:00
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

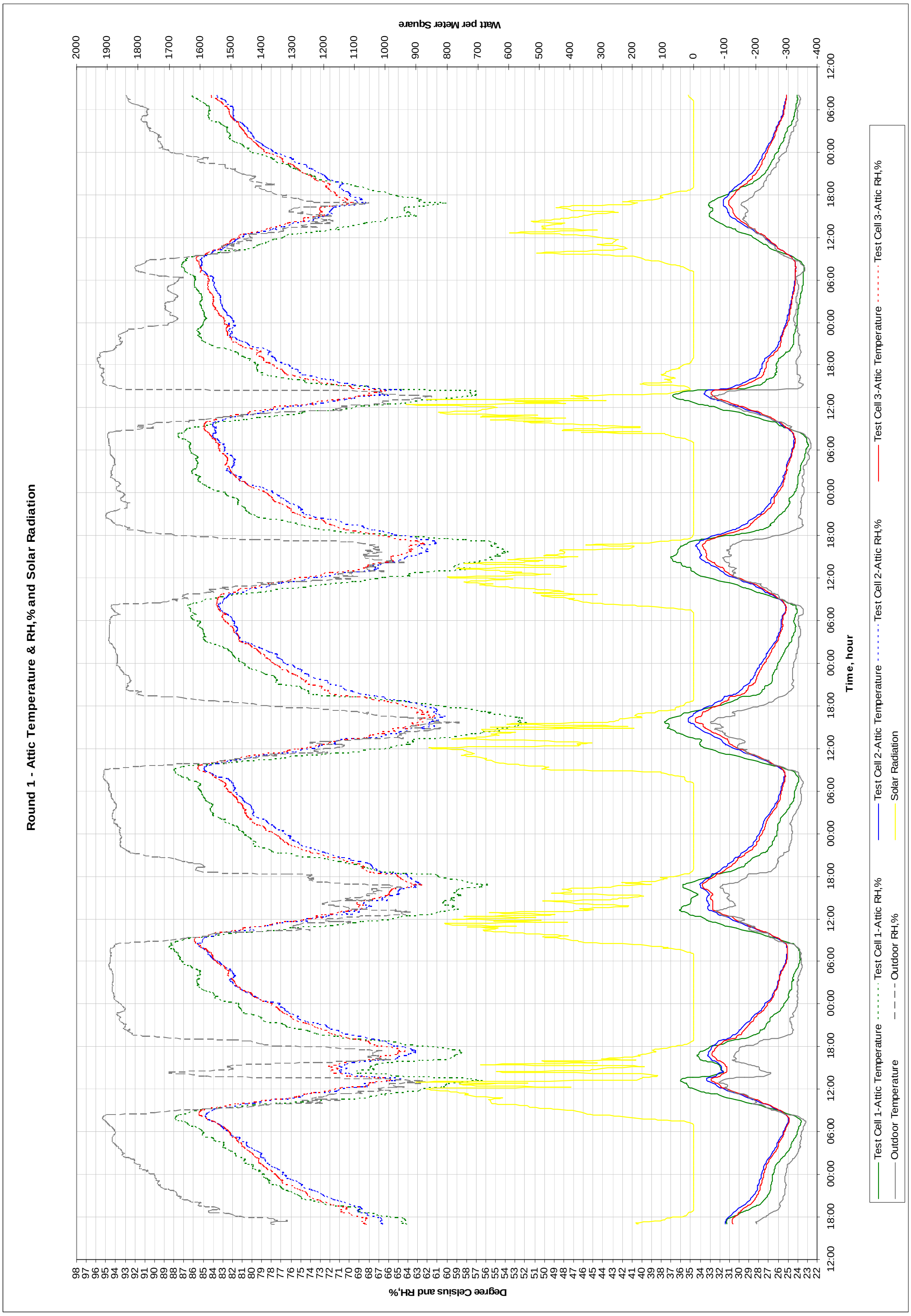

Round 2 - 24-hour Attic Temperature & RH,%and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
06:00
12:00
18:00
00:00
06:00
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

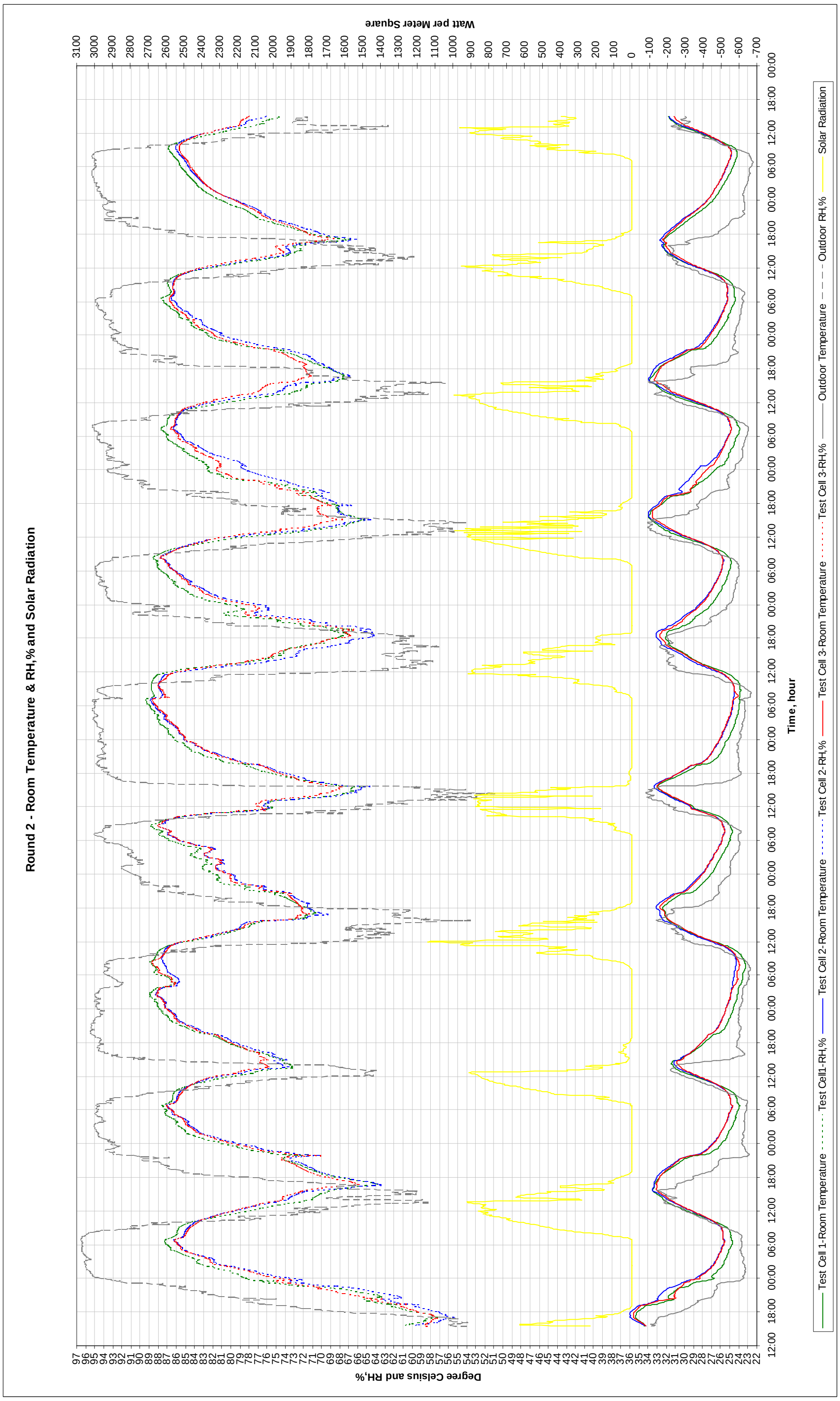

Round 3 - 24-hour Attic Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
06:00
12:00
18:00
00:00
06:00
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

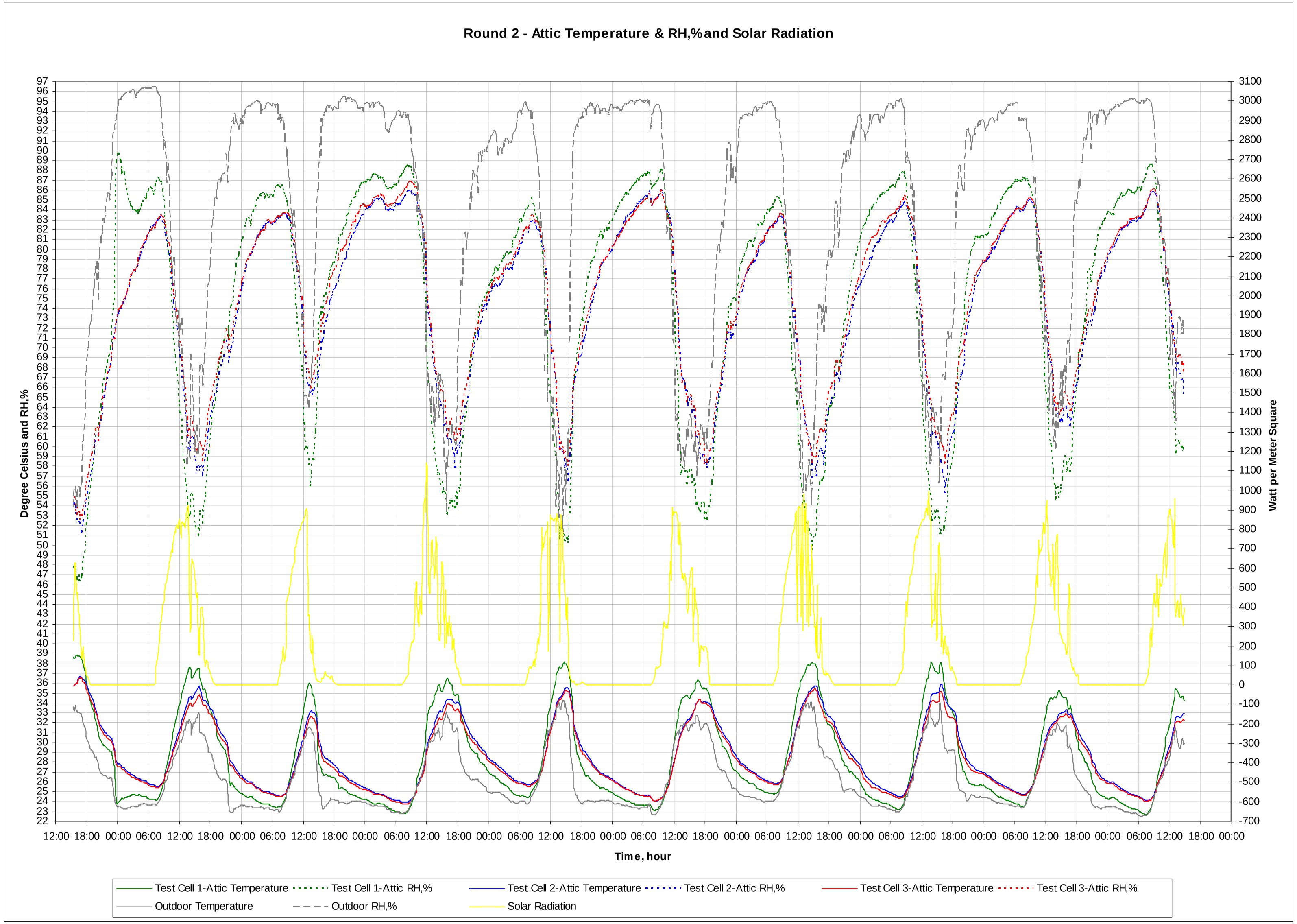
Round 4 - 24-hour Attic Temperature & RH,% and Solar Radiation

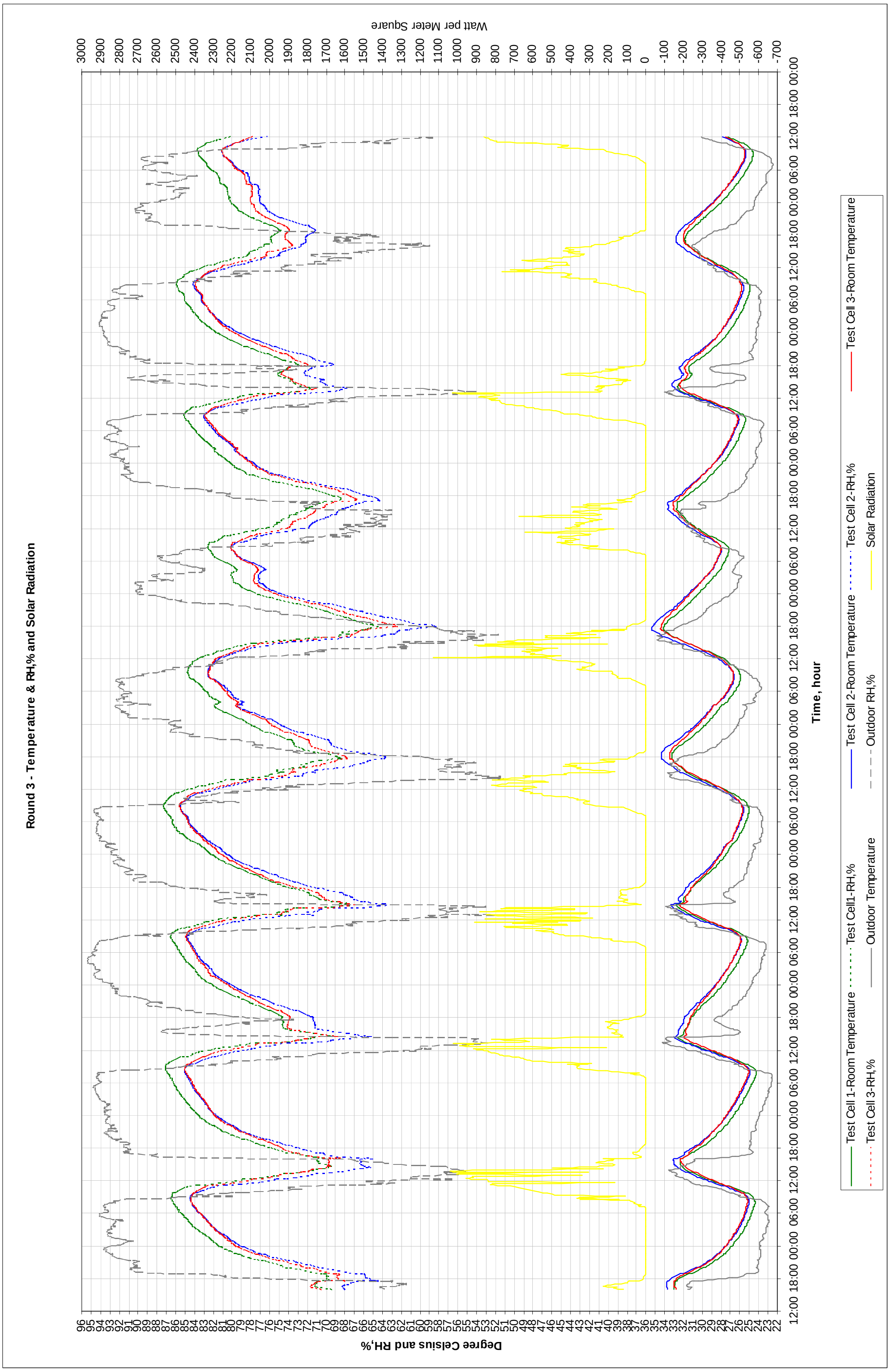


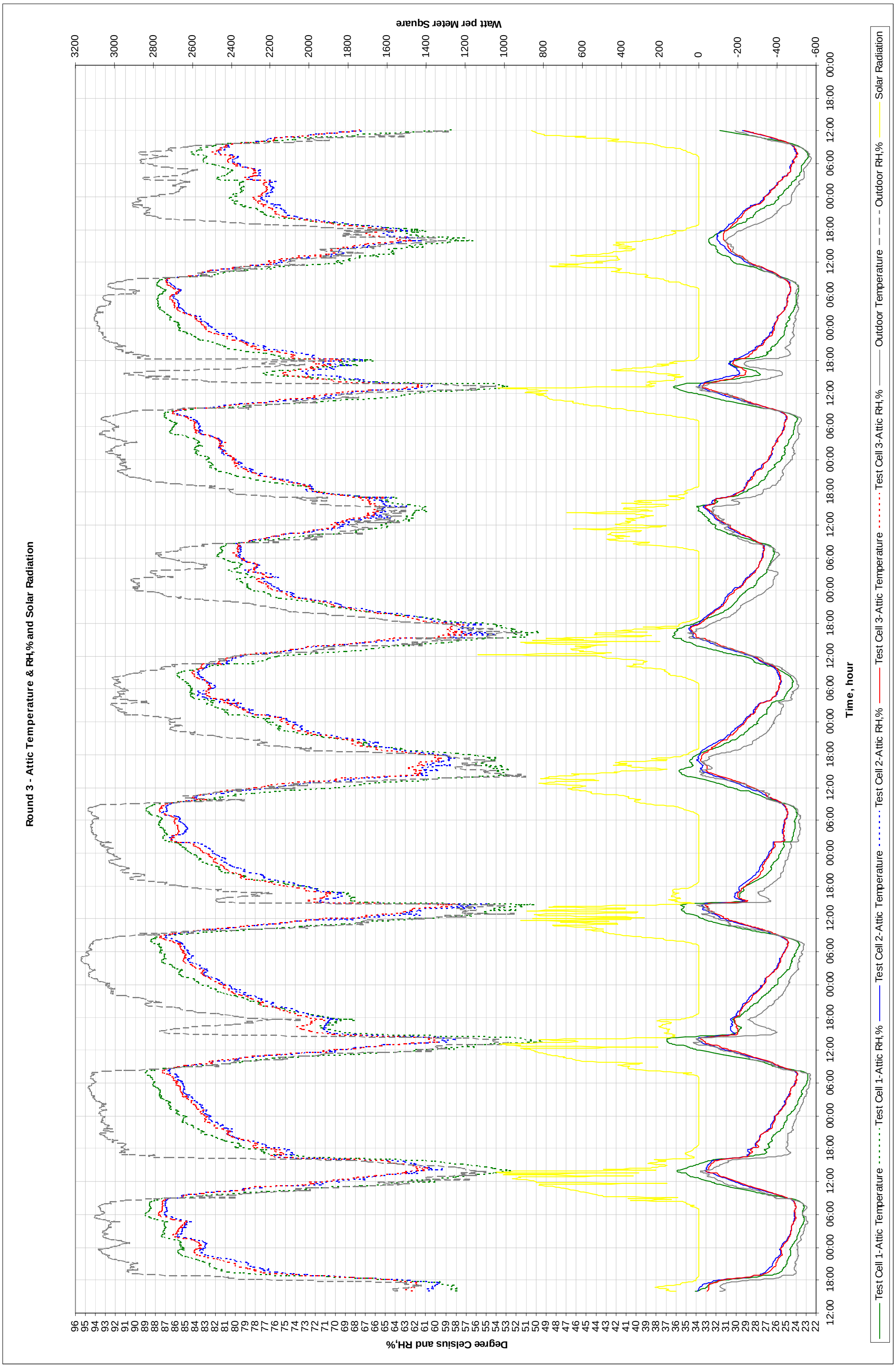

Round 1 - Room Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Room Temperature
Test Cell1- Room RH,%
Test Cell 2-Room Temperature
Test Cell 2-RH,%
Test Cell 3-Room Temperature
Test Cell 3-RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

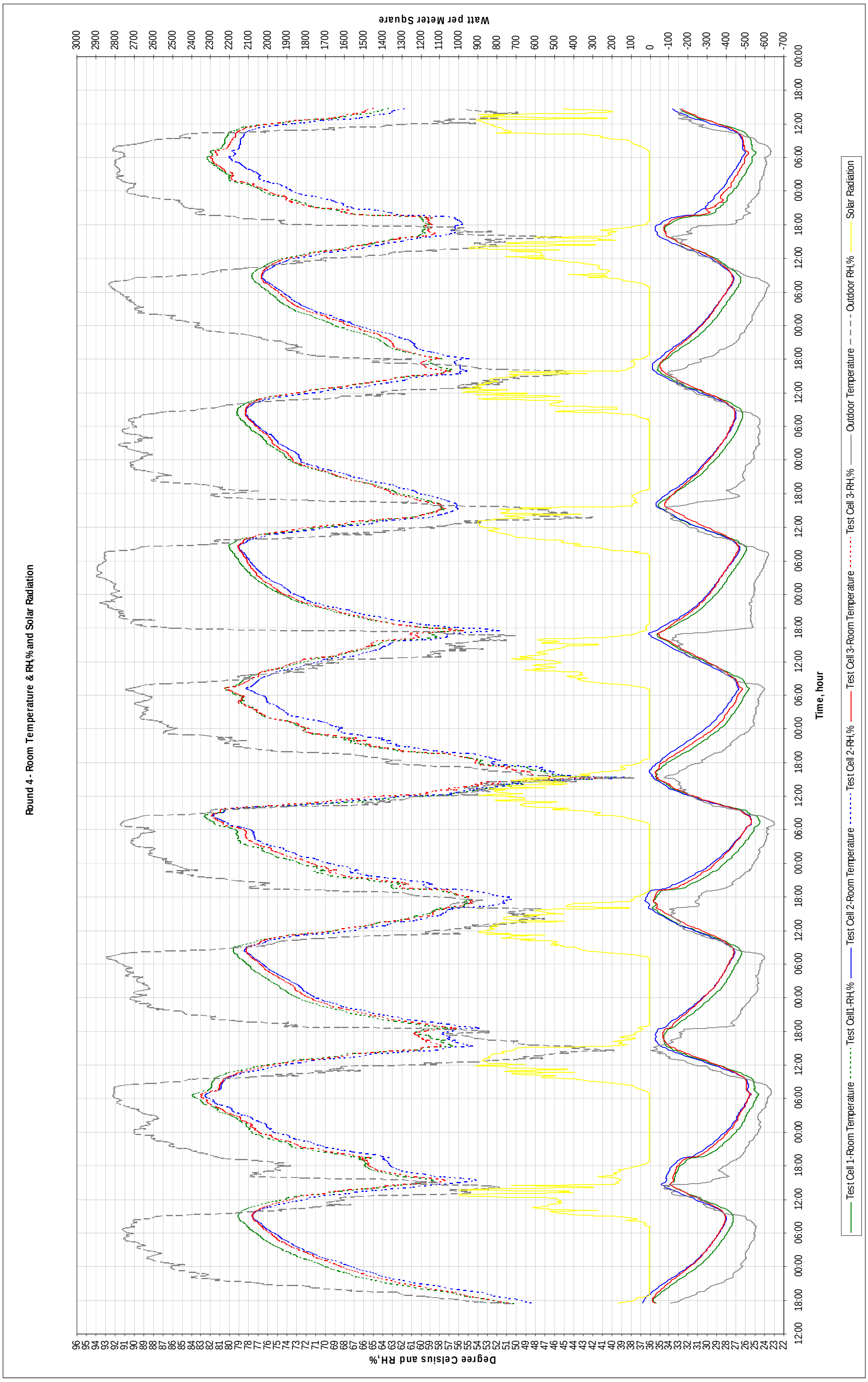

Round 1 - Attic Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

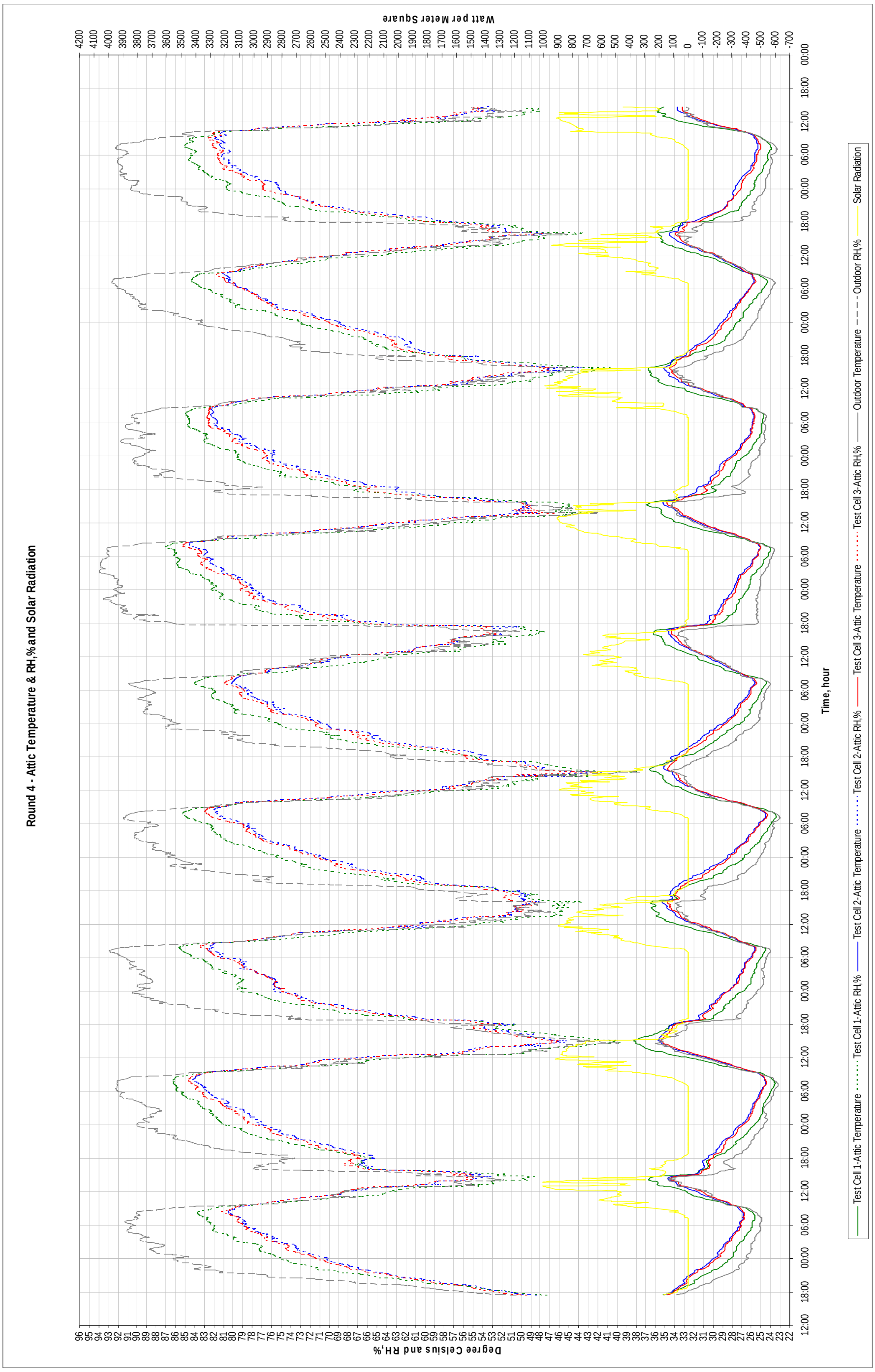

Round 2 - Room Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Room Temperature
Test Cell1-RH,%
Test Cell 2-Room Temperature
Test Cell 2-RH,%
Test Cell 3-Room Temperature
Test Cell 3-RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation


Round 2 - Attic Temperature & RH,%and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation


Round 3 - Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Room Temperature
Test Cell1-RH,%
Test Cell 2-Room Temperature
Test Cell 2-RH,%
Test Cell 3-Room Temperature
Test Cell 3-RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation


Round 3 - Attic Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

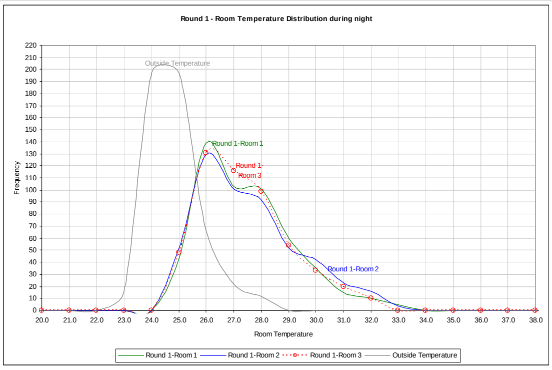

Round 4 - Room Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Room Temperature
Test Cell1-RH,%
Test Cell 2-Room Temperature
Test Cell 2-RH,%
Test Cell 3-Room Temperature
Test Cell 3-RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

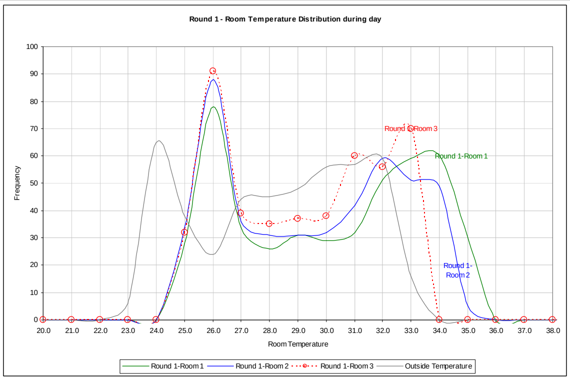


Round 4 - Attic Temperature & RH,% and Solar Radiation
Degree Celsius and RH,%
Watt per Meter Square
Time, hour
Test Cell 1-Attic Temperature
Test Cell 1-Attic RH,%
Test Cell 2-Attic Temperature
Test Cell 2-Attic RH,%
Test Cell 3-Attic Temperature
Test Cell 3-Attic RH,%
Outdoor Temperature
Outdoor RH,%
Solar Radiation

During Daylight Hours: Room	During Night Hours: Room

Round 1





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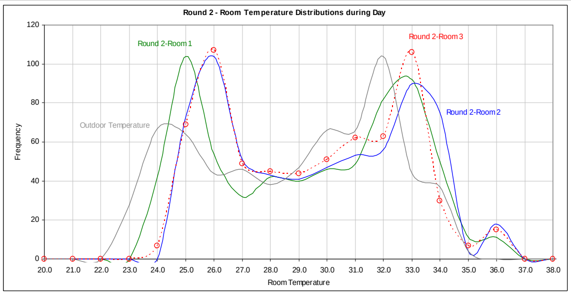
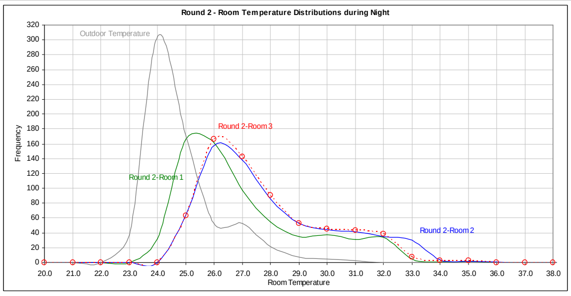
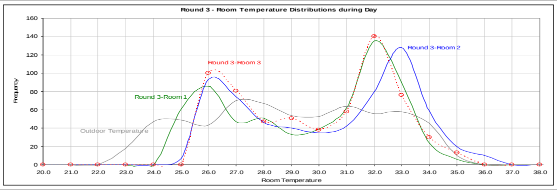
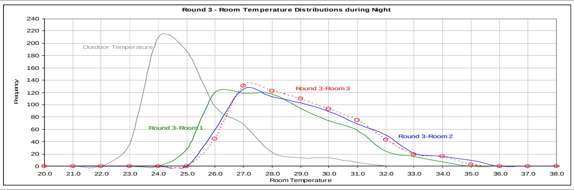


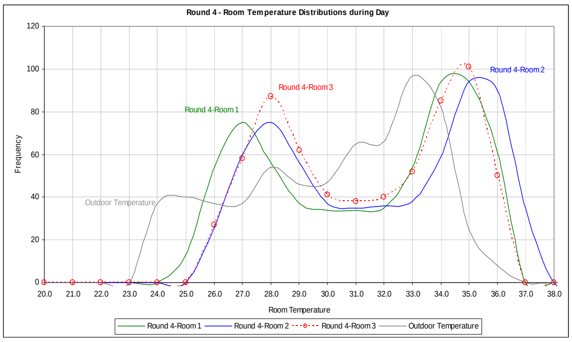


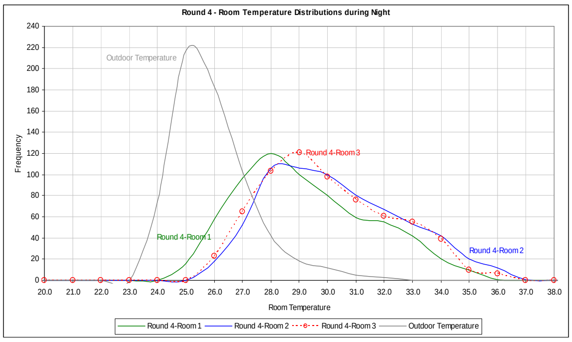
Round 3





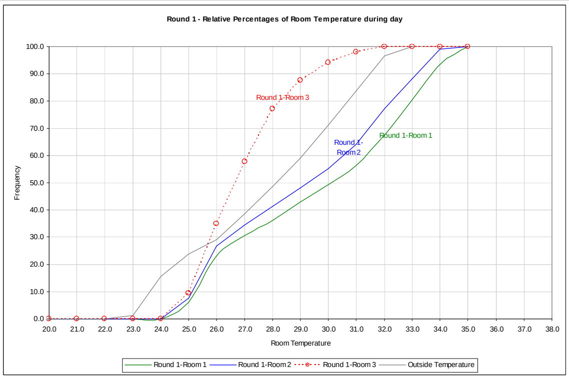
Round 4

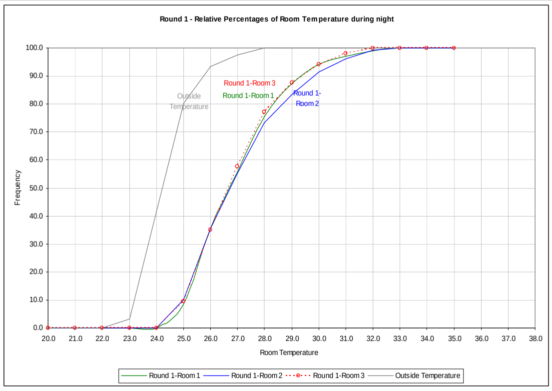




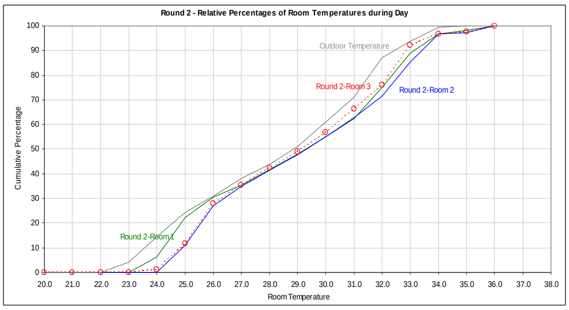
During Daylight Hours: Room	During Night Hours: Room

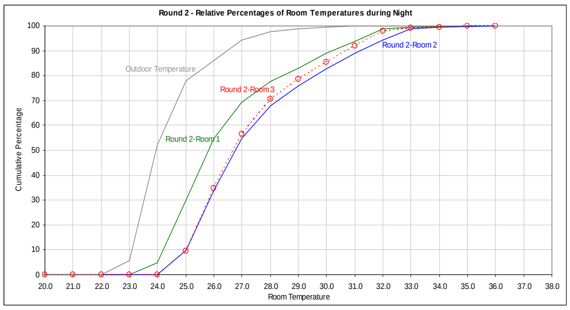
Round 1



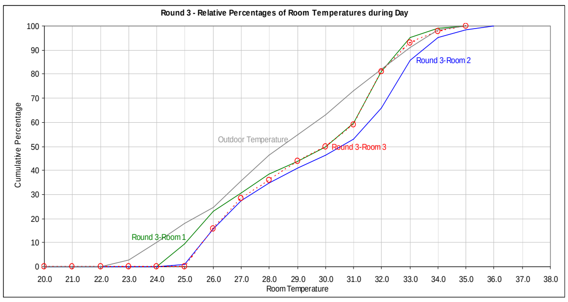


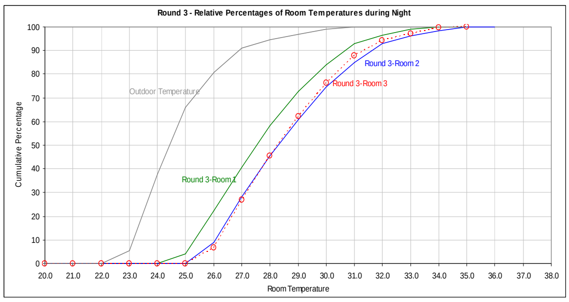
Round 2



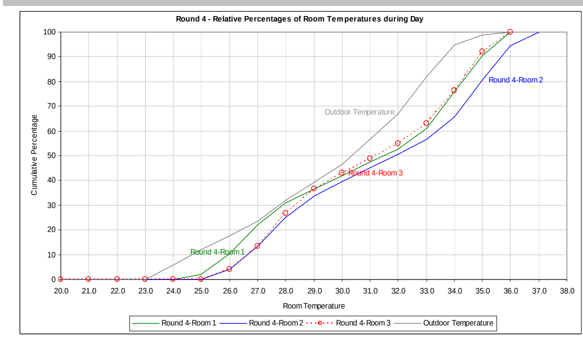


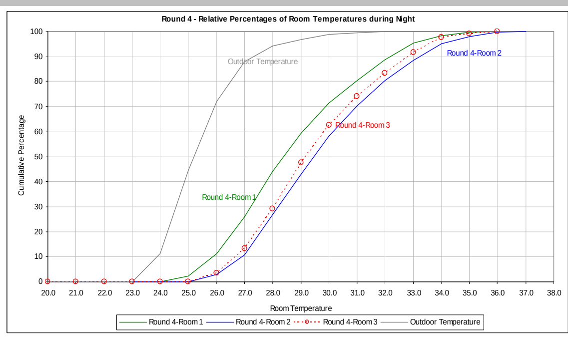
Round 3



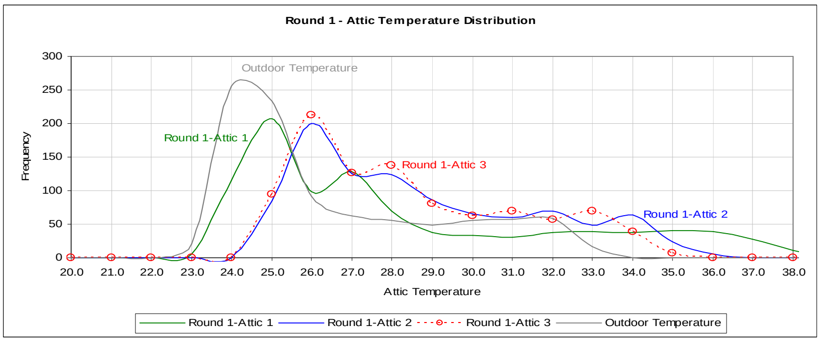


Round 4

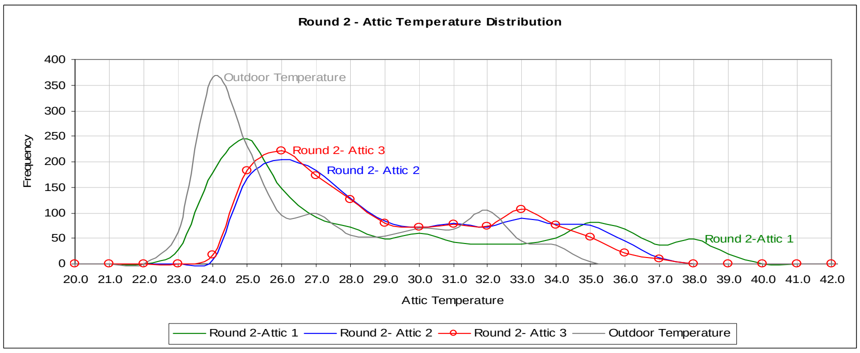




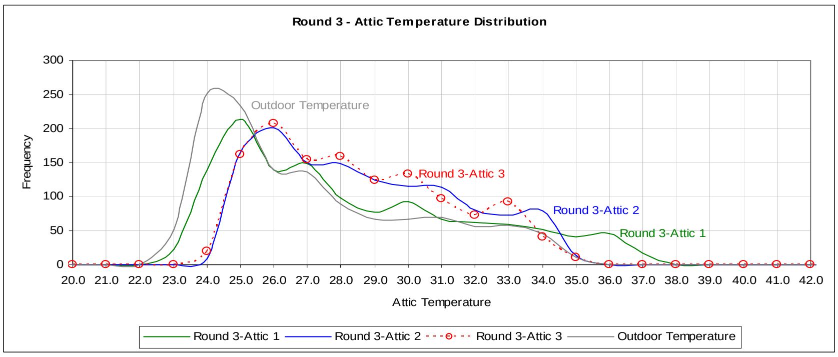
Round 1 – Attic Temperature



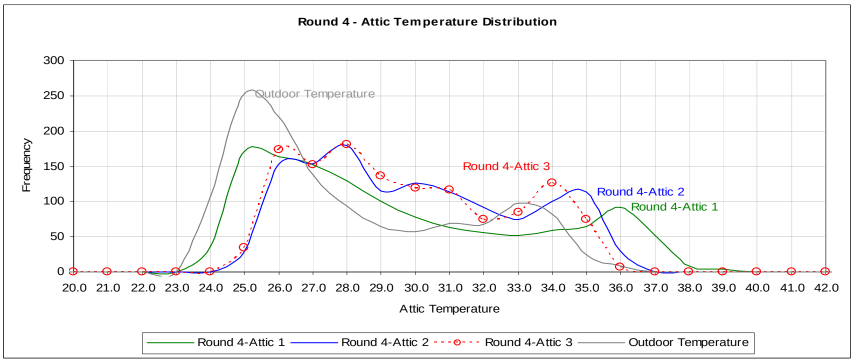
Round 2 – Attic Temperature



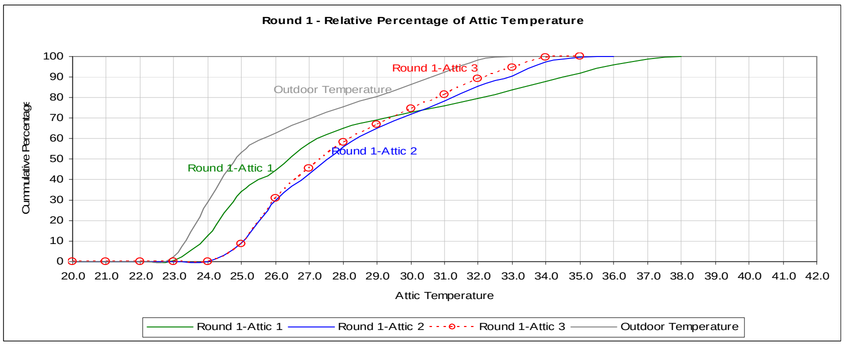
Round 3 – Attic Temperature



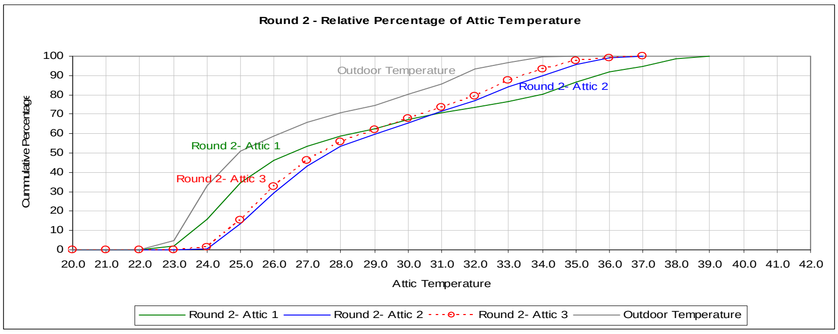
Round 4 – Attic Temperature



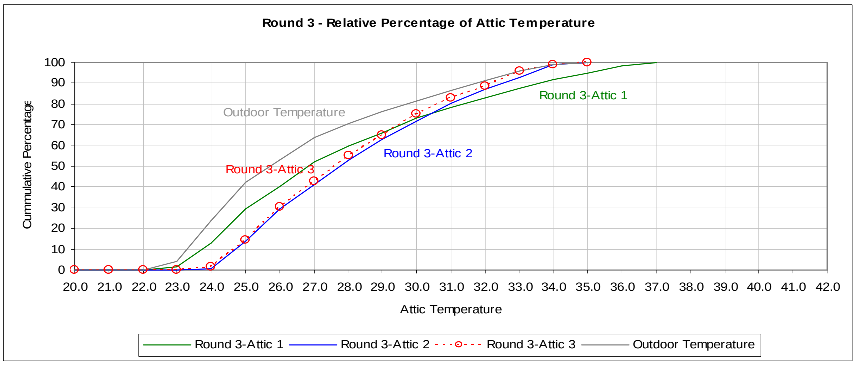
Round 1 – 24-hour with all days data Attic Temperature



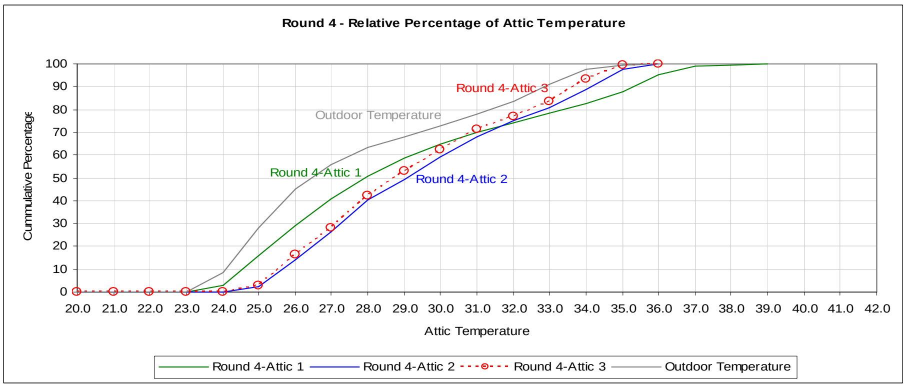
Round 2 – 24-hour with all days data Attic Temperature



Round 3 – 24-hour with all days data Attic Temperature

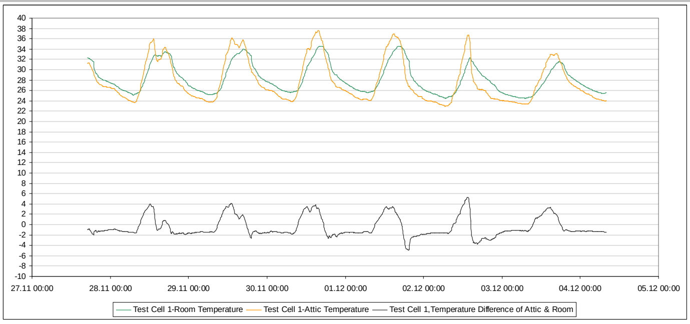


Round 4 – 24-hour with all days data Attic Temperature

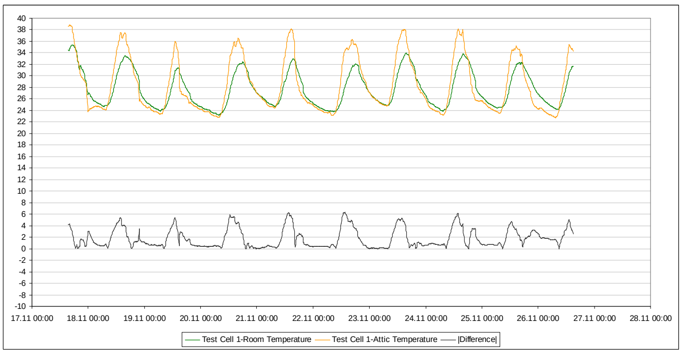


Test Cell 1 – Attic-Room Temperature Difference

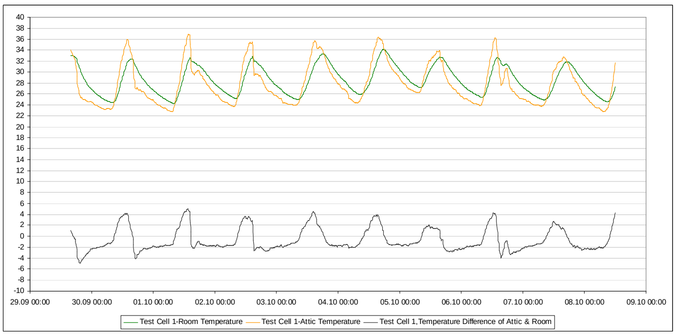
Round 1



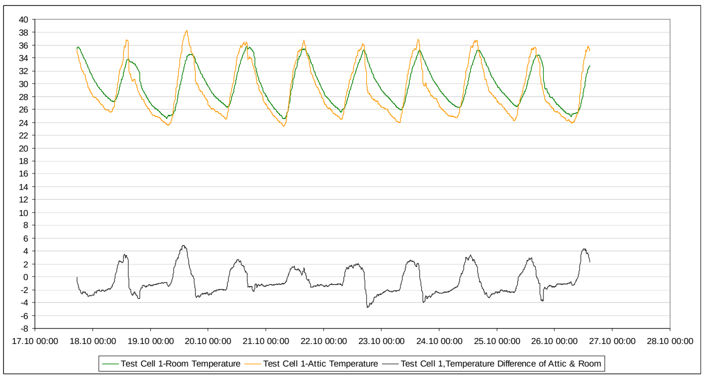
Round 2



Round 3

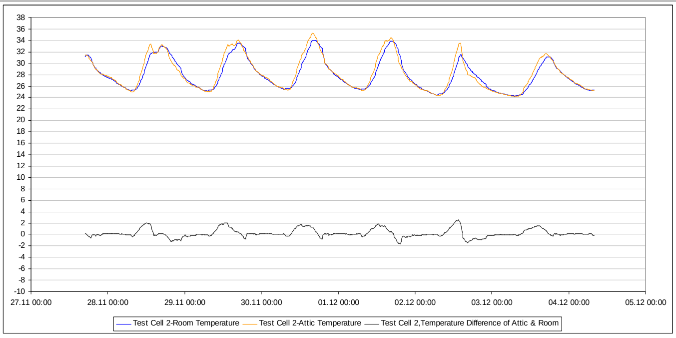


Round 4

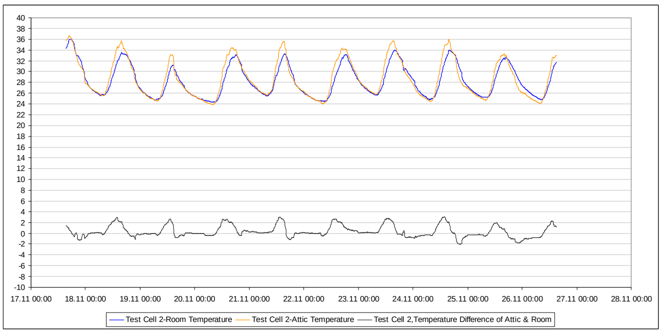


Test Cell 2 – Attic-Room Temperature Difference

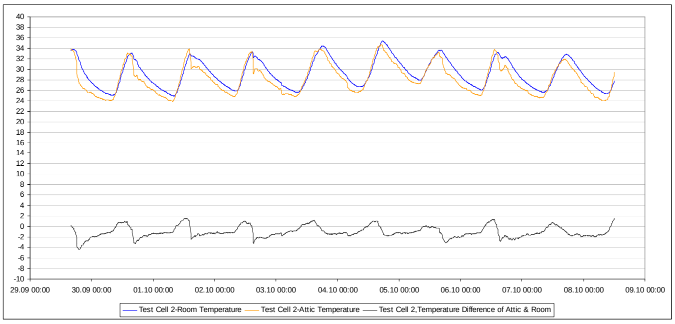
Round 1



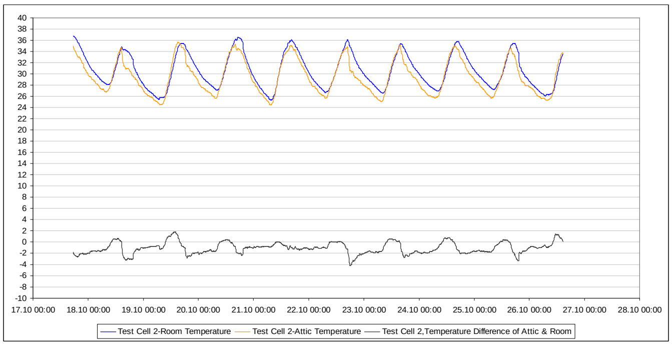
Round 2



Round 3

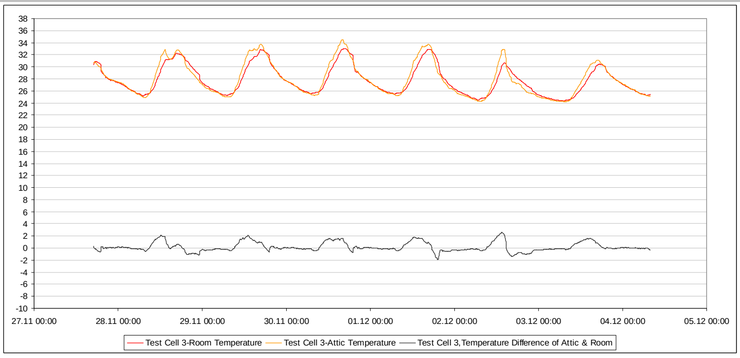


Round 4

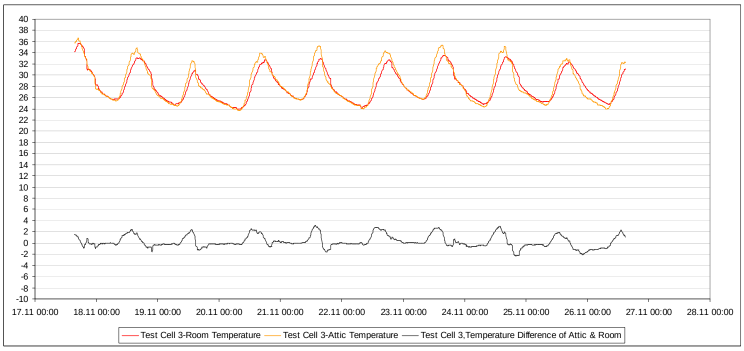


Test Cell 3 – Attic-Room Temperature Difference

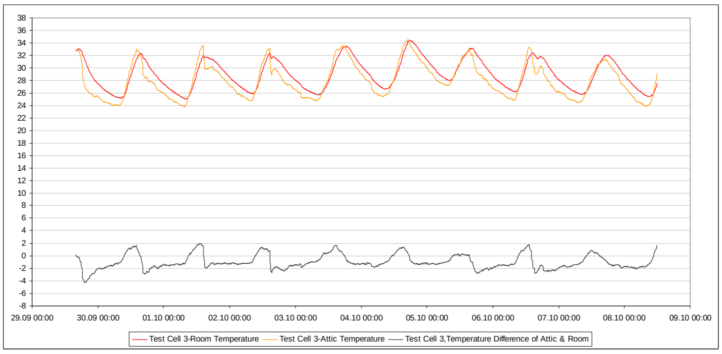
Round 1



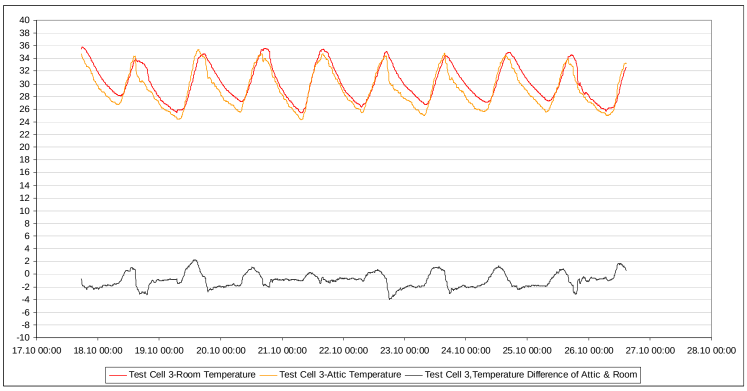
Round 2



Round 3



Round 4



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