8: MONITORING THE THERMAL BEHAVIOUR OF SPACES ENCLOSED BY FABRIC MEMBRANES.

8:1. INTRODUCTION.

In Chapter 4 a simple pilot study of the thermal behaviour of spaces enclosed by fabric membranes was described. The complex behaviour observed suggested that the investigation presented in this thesis would be much simplified if it were carried out in two parts:-

- An investigation into the thermal behaviour of fabric membranes.
- An investigation into the thermal behaviour of spaces enclosed by fabric membranes.

In chapters 5, 6 and 7 the first of these two parts was described. This investigation culminated in the development of a thermal model with which information describing the thermal state of fabric membranes could be generated. It was shown that this model could predict the thermal behaviour of a representative selection of fabric membranes with reasonable accuracy.

In this chapter, and Chapter 9, the second part of the research, *the investigation into the thermal behaviour of spaces enclosed by fabric membranes* is described:-

- In this chapter a programme of monitoring is explained which was undertaken in order to investigate the thermal behaviour of a representative selection of existing spaces enclosed by fabric membranes.
- In Chapter 9, the approach necessary to simulate the behaviour observed during the course of this monitoring programme is discussed, and the accuracy and appropriateness of such an approach assessed.

8:2. THE MONITORING PROGRAMME.

8:2.1 The Aims of the Monitoring Programme.

The purpose of the monitoring programme was similar to that of the pilot studies, but the data collected was more detailed and the range of buildings and conditions investigated was more comprehensive. This process had two fundamental aims:-

- To assess which of the characteristics of spaces enclosed by fabric membranes it is necessary to model in order to be able to properly simulate their thermal behaviour.
- To provide a comprehensive data set against which the accuracy of a model used to simulate that behaviour might be tested.

As with the test cell study described in Chapter 5, in order to provide adequate information with which to satisfy the aims of this monitoring programme, it was necessary to record two sets of conditions simultaneously:-

- The thermal conditions within the enclosed space itself.
- Those external thermal conditions which could significantly affect the behaviour of the enclosed space.

8:2.2 The Approach Adopted in Order to Monitor the Thermal Behaviour of the Enclosed Spaces.

- *Aims.*

The pilot studies presented in Chapter 4, had made it clear that establishing a strategy suitable for positioning sensors within the spaces monitored was essential if conditions representative of their characteristic behaviour were to be recorded. Ideally a great number of points would have been monitored throughout the enclosures, however the limited availability of equipment, and the practicality of monitoring a large number of positions without actually disturbing the behaviour of the spaces, meant that it was necessary to adopt a selective strategy.

It was suggested in Chapters 3 and 4 that the most characteristic thermal feature of such spaces was the difference between the sensitive thermal behaviour of high level fabric membranes, and the more stable behaviour of lower level surfaces such as the floor. The significance of the resulting thermal stratification within such spaces had already been identified by Wu et al[1] Sinofsky[2] and others and so it seemed appropriate to adopt a strategy which would record this effect. For this purpose it was decided to take simultaneous readings from a number of points distributed vertically between the membrane roofs of the spaces studies, and the floors over which they spanned.

As was also discussed in Chapter 4, it was very important to ensure that an appropriate parameter was monitored at these points. For simplicity, a single value was required representative of the conditions experienced by the occupants of the spaces. It was also desirable that this value could be duplicated by the spatial model which will be discussed in Chapter 9.

The model described in Chapter 9 adopts the CIBSE *resultant temperature* (t_{res}), in order to determine occupant comfort, representing '... *the temperature recorded by a thermometer at the centre of a blackened globe 100mm in diameter*' [3]. Where the resultant temperature may be calculated as described overleaf.

$$t_{res} = [\, t_r + t_i \sqrt{(10V_i)}\,] / [\, 1 + \sqrt{(10V_i)}\,] \qquad [4]$$

where t_r is the *radiant temperature*, t_i the *inside air temperature* and V_i the *internal air speed*. At low internal air speeds, where V_i is less than 0.1 m/s this equation reduces to :-

$$t_{res} = (\, t_r + t_i\,) / 2 \qquad [5]$$

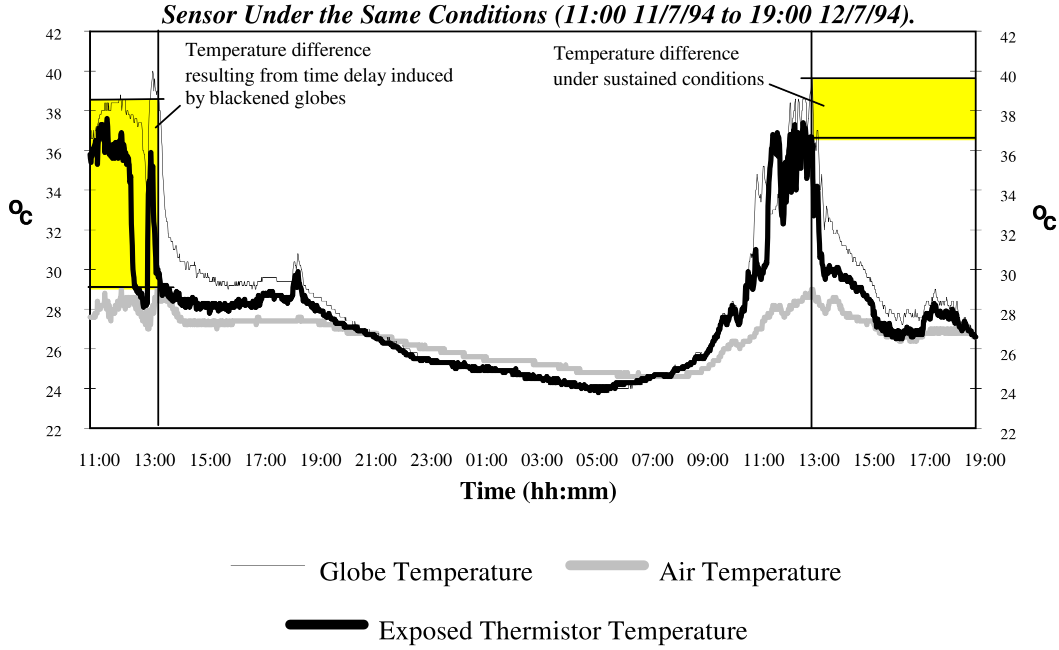
- *Apparatus.*

  To measure the resultant temperature at a large number of points within the spaces would have been cumbersome and could have proved difficult because the blackened globes would have required a substantial supporting structure. It was also considered that such globes may have been a little inappropriate for this sort of investigation as they could take up to 20 minutes to reach an equilibrium temperature[6]. This may have resulted in sensors responding too slowly to thermal changes within the spaces which could be rapid.

  The temperature sensors which had to be used in order to provide an electrical output that could be easily recorded, were bead thermistors. These thermistors could be selectively shielded from various environmental parameters using blackened globes, radiant shields and so on in order to ensure that they detected only the required temperature conditions.

  In a controlled experiment, the performance of thermistors enclosed by blackened globes was compared to that of completely exposed thermistors (which are themselves black) and thermistors enclosed by radiant shields in order to record only the air temperature. The relative values recorded by each method during this experiment are illustrated below.

Figure 8:2.2 Comparison Between the Temperatures Recorded by Three Different Types of Sensor Under the Same Conditions (11:00 11/7/94 to 19:00 12/7/94).



It can be seen that the exposed thermistor temperatures followed the globe temperatures fairly closely despite the fact that they were exposed to bright sunshine (illustrated by the difference between globe and air temperatures), a situation unlikely within membrane enclosures. Whilst under prolonged periods of bright sunshine, the thermistors underestimated the resultant temperature by up to 3 or 4^{o}c, the delay induced by the transmission of conditions through the blackened globe produced discrepancies of almost 10^{o}c. This suggested that the slow response CIBSE method for measuring resultant temperatures may not be appropriate for monitoring the behaviour of fast response spaces enclosed by fabric membranes.

It was decided therefore that the simplicity, fast response and light weight which resulted from simply monitoring the output of exposed thermistors probably outweighed the small increase in accuracy at peak conditions which would result from the use of the slower response blackened globes. In order to validate this approach however, a single position was chosen within each space investigated at which to monitor a shielded globe temperature in addition to the exposed thermistor resultant temperature.

Type U bead thermistor temperature sensors were used for this investigation. These are accurate to within 0.35^{o}c in the range -30 to +100^{o}c[7]. The use of three 1200 series Squirrel meter / loggers allowed up to twelve positions to be monitored within each space. As one position was used to check the radiant / air temperature, eleven vertically distributed, exposed thermistor readings could be taken.

The thermistors were split into two groups of 6, each group being connected along the length of a 15 core cable to the data loggers. One cable was made 24m long, and the other 12m long, with 1.5m of slack cable available between thermistors to allow adjustable spacing. It was considered that this would provide enough data to be representative of the characteristic thermal behaviour of even the tallest spaces.

As the temperature sensing capability of the thermistors was based on electrical resistance, it was possible that the 314mW/m resistance of the cables connecting the sensors to the data loggers could result in small inaccuracies in the recorded values. It was calculated however that the maximum error which could be produced by a cable length of 24m within the range of conditions found within the built environment was just 0.25^{o}c, and this was not considered significant enough to justify the complex procedure necessary to correct the recorded values.

It was likely that high level access would be difficult in some of the buildings, and so a telescopic Clarke Mast was obtained which could be used to support the sensor cables vertically up to a height of 11m.

8:2.3 The Approach Adopted in Order to Monitor External Conditions.

- *Aims.*

  This involved monitoring those external conditions which could significantly affect the thermal behaviour of the enclosed spaces, either directly by transmitting through the spatial enclosure, or indirectly through their affect on the thermal state of the spatial boundary. As with the interiors of the spaces studied however, it was not possible to monitor every environmental condition, and so it was necessary to strike a balance between collecting comprehensive data, and providing easy to interpret information. When enough characteristic conditions were monitored, it was possible to use environmental theory in order to estimate additional information as described in the chapter 7.

  For this purpose, the conditions listed below were monitored, as previously discussed in Chapter 4:-

- *Apparatus.*
- *Horizontal global solar radiation*, measured using a solarimeter calibrated such that one milivolt represents 104.78 W/m^2.
- *External air temperature*, measured using a type U thermistor with radiant shield.
- *Wind speed*, measured with a pulse count Porton Anemometer for which every 47.3 rotations of the rotor per minute represents the passage of a one meter of air per second.
- *Membrane surface temperature.* Measured using a Type K Chromel Alumel thermocouple. This gives a voltage output based on the difference in temperature between the thermocouple and the reference junction at which the voltage was recorded such that:-

$$\text{Actual Temp} = \{[\ \text{Junction Temp} / 24.82593\ ] + [\ \text{Voltage (mv)}]\} \times 24.82593 \qquad [8]$$

Unfortunately, monitoring the internal surface of these membranes was almost impossible because of their inaccessibility and non stick surface. This meant that external surface temperatures had to be monitored, despite an awareness of the limitations of this approach, as discussed in Chapter 5.

All of the external conditions described above were recorded using a 1200 series Squirrel meter / logger, sealed in a weather tight meteorological box.

8:2.4 The Method Adopted for the Monitoring Programme.

In order to obtain a comprehensive range of information describing the characteristic thermal behaviour of spaces enclosed by fabric membranes, it was necessary to monitor a number of spaces under a variety of conditions.

As discussed in Chapter 1, the main criteria for the selection of the spaces studied was that a thin fabric membrane should form a major part of their external envelope. In order to limit the complexity of the spaces monitored however, it was also decided that the membrane should be frame supported rather than air supported, that it should form an actual enclosure, not just a canopy and that the buildings should be available for study whilst unheated.

In 1993, when the arrangements for this programme of monitoring were being made, the choice of appropriate spaces in the UK was limited. During the course of the study, an increasing number of membrane enclosed spaces were completed, however at the time only 8 were available:-

	Building	Completed
•	***Building***	***Completed***
•	*Judy's Pantry* (originally The Clifton Nurseries).	1981
•	*Schlumberger 1.*	1985
•	*Landrell Fabric Engineering.*	1987
•	*The AELTC Indoor Tennis Centre, Covered Courts.*	1989
•	*Imagination Headquarters, Central Atrium.*	1989
•	*Project 184, MOMI Hospitality Tent.*	1991
•	*The Cheriton Passenger Terminal, Administration and Amenity Building.*	1992
•	*The Royal International Eisteddfod Pavilion, Main Arena.*	1992

After visiting *Judy's Pantry* and the *Imagination Headquarters*, it was decided that both spaces were too complex to consider that their fabric roofs were the most significant boundary features influencing their thermal behaviour. Access to *Schlumberger 1* was refused and the *MOMI Hospitality Tent* designed by Future Systems was destroyed during storms in December 1993. This left just four relatively simple but diverse structures available, to study:-

- *Landrell Fabric Engineering.*
- *The Royal International Eisteddfod Pavilion, Main Arena.*
- *The Cheriton Passenger Terminal, Administration and Amenity Building.*
- *The AELTC Indoor Tennis Centre, Covered Courts.*

Access to each of these spaces was obtained, and the behaviour of each was monitored a number of times. This was however a very time consuming and expensive process. Each time a space was monitored, two round trips were required, one to set up and one to remove equipment. In the case of the Administration and Amenities Building, this involved travelling over 1200 miles. This meant that whilst the aim was to obtain data from all of the spaces under as many different conditions as possible, practically, it was only possible to visit each of the buildings two or three times.

The findings of the pilot study suggested that in order to obtain informative and comprehensive data, it was necessary to monitor the behaviour of the spaces for a period of not less than two days for each of the visits made. The finite memory of the monitoring equipment meant that a logging interval of one to two minutes had to be adopted for this purpose, depending on the number of data loggers available at the time.

In the next four sections of this chapter each of the spaces investigated is briefly described, some of the data obtained from monitoring their behaviour is presented, and a number general observations are made about their characteristic thermal behaviour. In Section 7, these observations are briefly summarised, and their implications for the approach necessary to simulate such behaviour is assessed.

8:3. CASE STUDY 1: LANDRELL FABRIC ENGINEERING.

8:3.1 Description of the Landrell Fabric Engineering.

- *Credits.*
- Owned and occupied by Landrell Fabric Engineering Ltd.
- First erected in 1987.
- Originally used as a training / conference facility by National Westminster Bank Plc.
- Sold to Landrell Fabric Engineering Ltd by the Network Christian Trust in 1991.

- *Site.*
- Station Road,
  Chepstow,
  Gwent.
- Longitude: 2.667^{o} West.
- Latitude: 51.642^{o} North.
- Altitude: Finished floor level 30m above sea level.
- Site: Urban industrial estate on level ground at the base of a severe north facing, cliff.

- *Form.*
- Three standard units, each 30m by 24m giving a total footprint of 2160m^2.
- Approximately 10,000 m^3 is enclosed under the external fabric roof.
- Approximately 5,000 m^3 is enclosed under the internal liner membrane.

- *Double Membrane Envelope.*
- Outer membrane: low translucency white / cream PVC coated polyester membrane.
- Inner membrane: permeable proban treated cotton calico.
- Combined U-value quoted by manufacturers as 2.5- 3.0 W/m^2^{o}c.
- The membranes have an expected life of 15-20 years.
- The membranes were 7 years old during the period monitored.
- They were showing no visible signs of deterioration other than an accumulation of dirt on both surfaces of both membranes.

- *Occupancy.*
- The space was substantially unoccupied during the monitored periods, however there is considerable activity during working hours, and machinery within the space can generate significant quantities of heat.

- *Environmental Control System.*
- The original gas burners have been replaced with a primitive air conditioning system intended to combat condensation problems.
- Optional natural ventilation is possible through the apex of each internal cone to the roof space, and then through the vents in the external membrane to the outside.
- Small destratification fans are suspended from the peaks of the internal membranes.

- *Comments.*
- The space was not entirely appropriate for the purposes of this research, but it was easily accessible making it ideal for testing monitoring techniques.
- Condensation had been such a problem in this building that a collection and drainage system had been welded to the internal surface of the outer membrane. Even with these precautions however, the unpredictability of condensation means that moisture still drips from the surface of the membrane back into the space.
- It was anticipated that the complex and unusual double membrane roof configuration would make the behaviour of this space very difficult to simulate.

- *Building Illustrations.*

Figure 8:3.1a Landrell Fabric Engineering, Section A-A

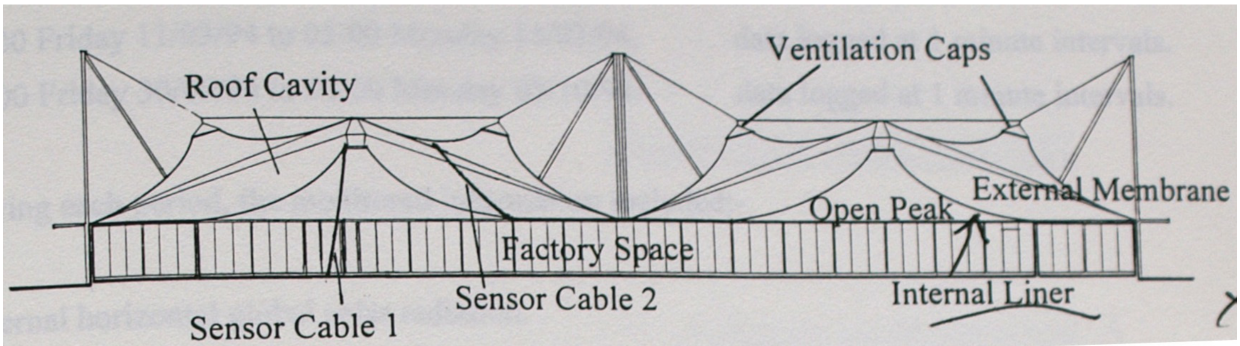
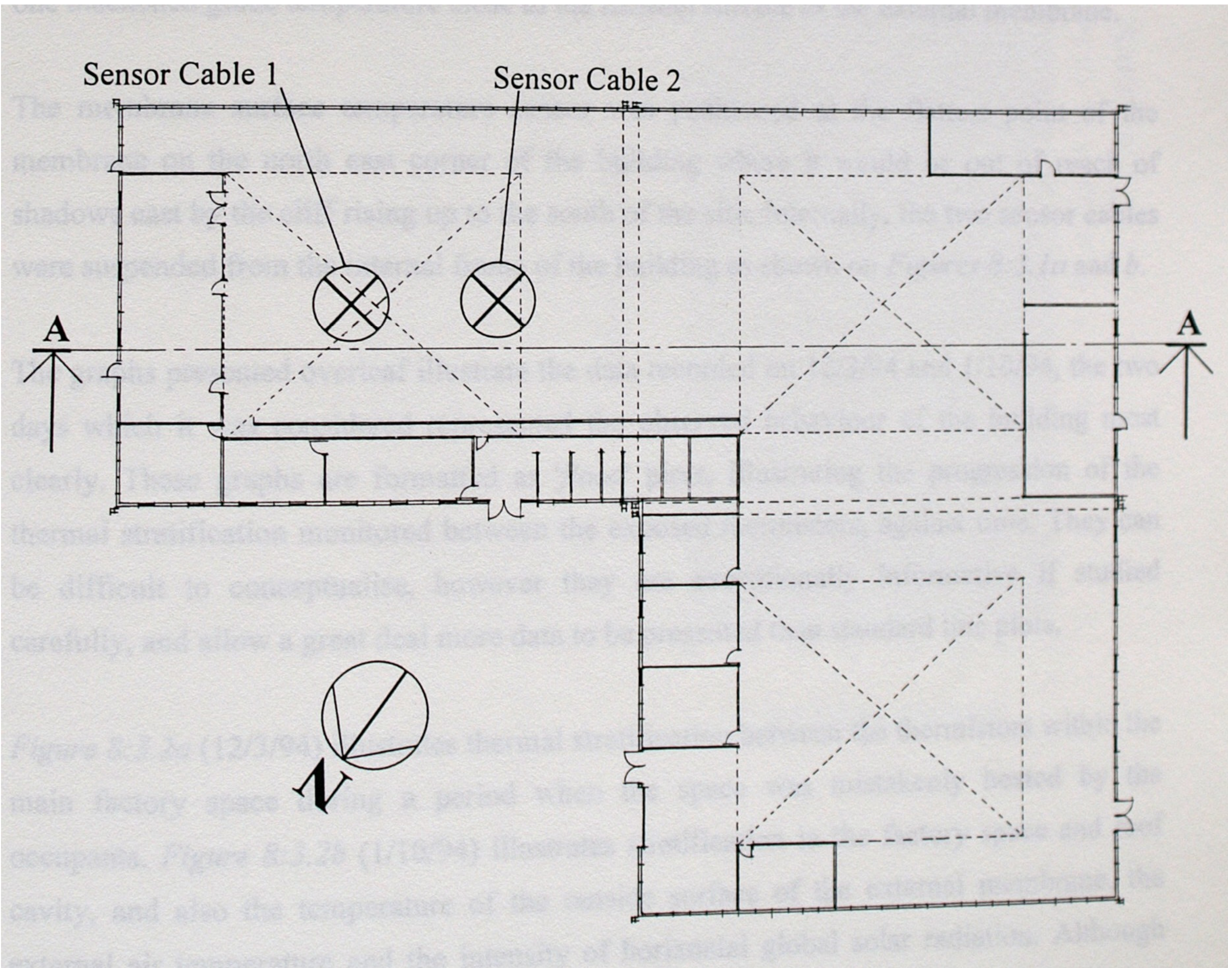


Figure 8:3.1b Landrell Fabric Engineering, Floor Plan



8:3.2 Information Monitored at Landrell Fabric Engineering.

Data was collected which covered the following periods:-

- 17:00 Friday 11/03/94 to 05:00 Monday 14/03/94. data logged at 1 minute intervals.
- 19:00 Friday 30/09/94 to 05:00 Monday 03/10/94. data logged at 1 minute intervals.

During each period, the monitored information included:-

- external horizontal global solar radiation.
- external wind speed.
- external air temperature.
- the temperature of the external surface of the membrane.
- 4 exposed thermistor temperatures, vertically distributed within the roof space with 1m between each sensor.
- 7 exposed thermistor temperatures vertically distributed within the factory space with 1m between each sensor.
- one blackened globe temperature close to the internal surface of the external membrane.

The membrane surface temperature sensor was positioned at the flattest point of the membrane on the north east corner of the building where it would be out of reach of shadows cast by the cliff rising up to the south of the site. Internally, the two sensor cables were suspended from the internal frame of the building as shown on *Figures 8:3.1a* and *b*.

The graphs presented overleaf illustrate the data recorded on 12/3/94 and 1/10/94, the two days which it was considered represented the observed behaviour of the building most clearly. These graphs are formatted as '*flood*' plots, illustrating the progression of the thermal stratification monitored between the exposed thermistors, against time. They can be difficult to conceptualise, however they are exceptionally informative if studied carefully, and allow a great deal more data to be presented than standard line plots.

Figure 8:3.2a (12/3/94) illustrates thermal stratification between the thermistors within the main factory space during a period when the space was mistakenly heated by the occupants. *Figure 8:3.2b* (1/10/94) illustrates stratification in the factory space and roof cavity, and also the temperature of the outside surface of the external membrane, the external air temperature and the intensity of horizontal global solar radiation. Although wind speed was monitored, it is not illustrated so as to retain the clarity of the images.

These figures are supplemented by more conventional forms of graphical analysis in the rest of this section.

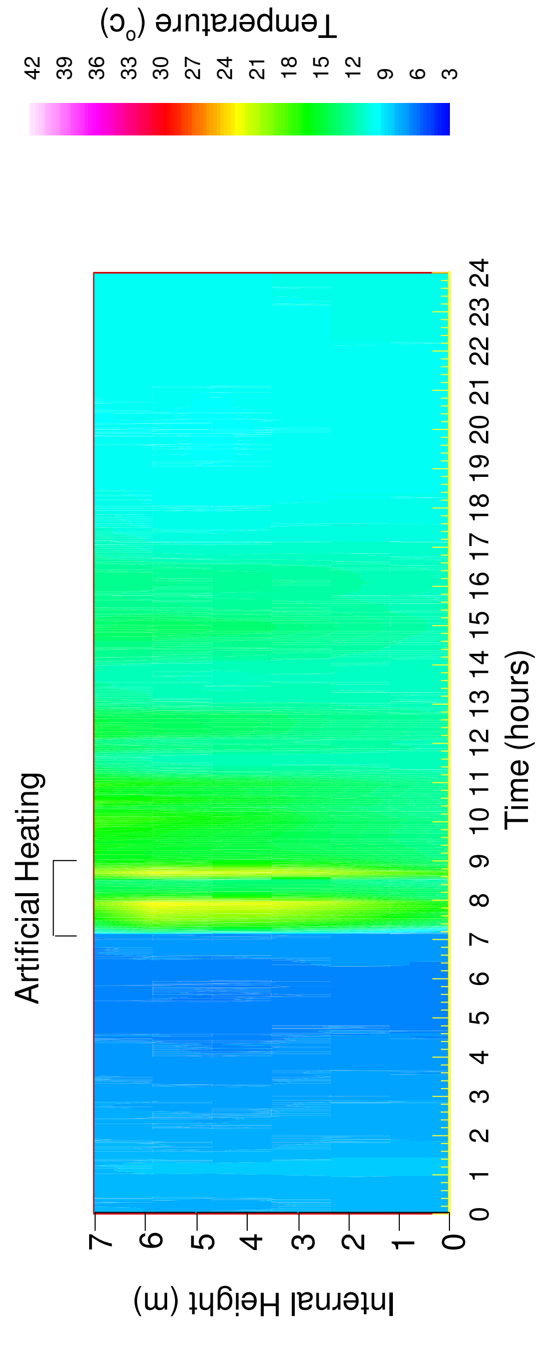


Figure 8:3.2a Landrell Fabric Engineering. 12/03/94.

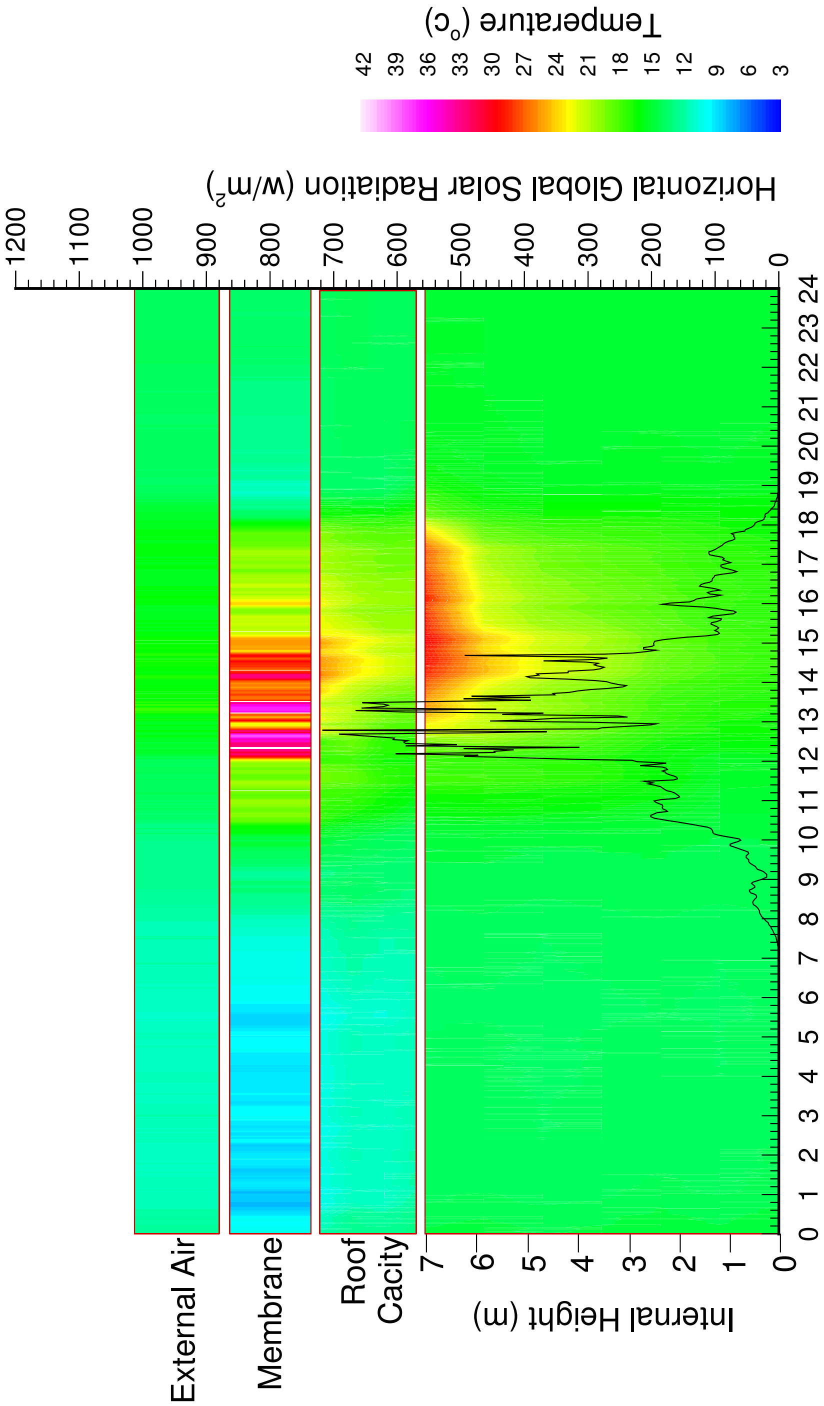


Figure 8:3.2b Landrell Fabric Engineering. 01/10/94.

8:3.3 Analysis of the Information Monitored at Landrell Fabric Engineering.

It can be seen from both *Figures 8:3.2a* and b that conditions monitored within the enclosure during the night, tended to be almost completely uniform. The entire space responded quickly to artificial heating, but temperatures higher up within the enclosure were affected considerably more than those in the low level zone occupied by people. This produced internal thermal stratification of up to 8^{o}c despite the internal destratification fans, and this thermal gradient showed no tendency to dissipate as a result of sustained heating. When the heat source was removed, the '*occupied zone*' cooled down more slowly than areas higher up in the space, and so conditions tended to become more uniform again.

This behaviour is shown clearly by *Figure 8:3.3a* below, which illustrates how the range of resultant temperatures monitored within the factory space changed as a result of artificial heating.

Figure 8:3.3a Diagram to Illustrate the Range of Resultant Temperatures Monitored Within Landrell Fabric Engineering 12/3/94.

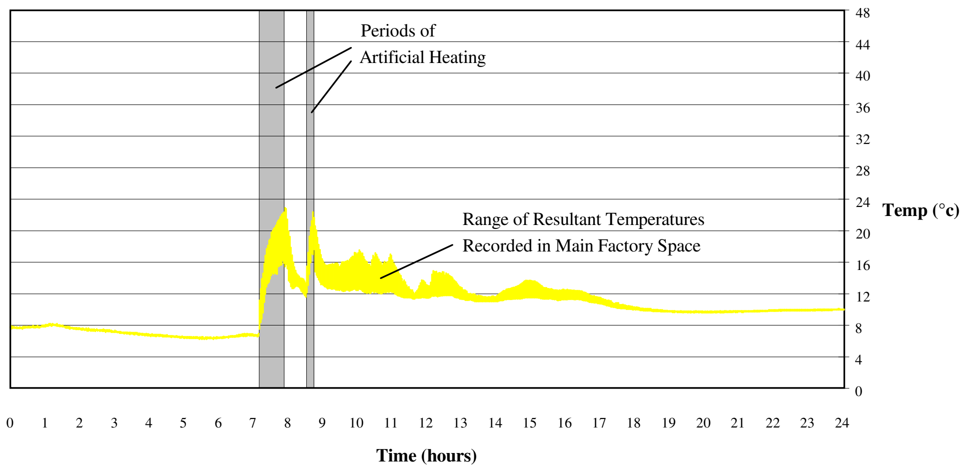
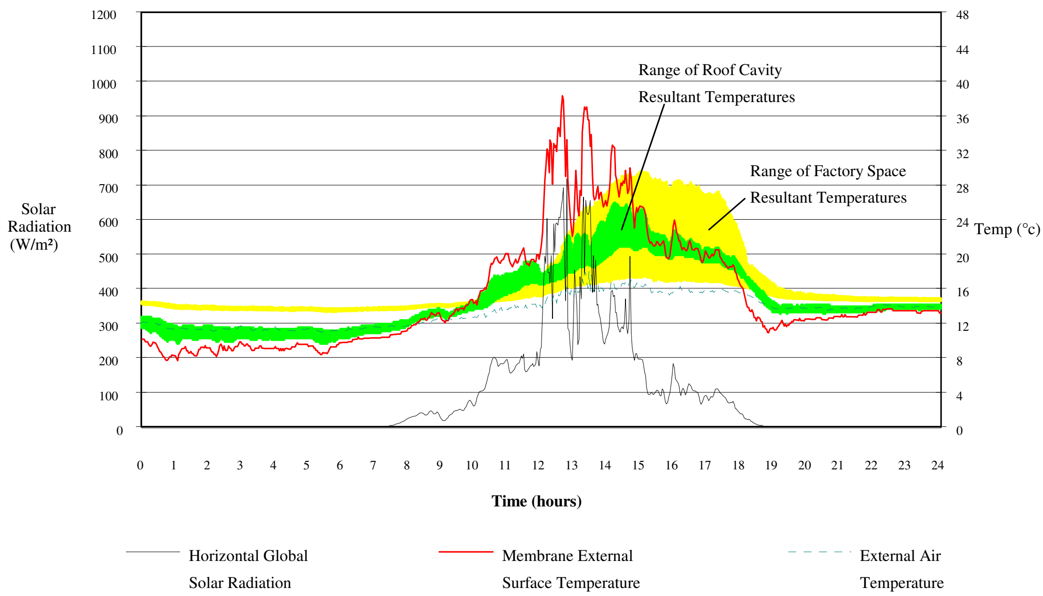


Figure 8:3.2b illustrates a period when the space was totally unheated, and this shows clearly the progressive moderating effect that first the roof cavity, and then the factory space itself had on the thermal conditions able to penetrate into the occupied zone.

During the course of the day, it was seen that the membrane temperature swing, calculated as the difference between the minimum and maximum recorded membrane temperatures, was 31^{o}c. This resulted in a temperature swing within the roof cavity of 16^{o}c. This produced a similar temperature swing of 16^{o}c at high level within the main factory space, but at low level, where the building occupants were likely to be, the resultant temperature varied by just 4^{o}c during the course of the day. This moderating effect is clearly illustrated by *Figure 8:3.3b*, overleaf.

Figure 8:3.3b Diagram to Illustrate the Progressive Moderating Effect of the Landrell Fabric Engineering Roof Cavity and Factory Space (1/10/94).



It can be seen that temperature swings within the enclosure occurred mainly as a result of solar radiation. The different speeds with which various parts of the enclosure were able to respond to this solar radiation produced internal thermal gradients. In particular the high solar absorptance external membrane was seen to heat up very quickly and very significantly during periods of bright sunshine. The contrast between this and the more stable thermal behaviour of other surfaces within the space such as the floor, produced positive vertical stratification of over 12^{o}c.

As with the heated period, there appeared to be little tendency for the overall extent of this stratification to reduce as a result of prolonged solar radiation, and this suggested that the high level heat did not penetrate significantly into the lower levels through time. During both periods however, conditions tended to return to a more uniform '*diffuse*' state when no heat source was present.

It had been recognised that the complex geometry, and double membrane envelope of this building meant that it was not entirely appropriate for a study of this kind, and this was reflected in the monitored data.

The data presented above gives the impression that the factory space became hotter at high level as a result of solar radiation than the roof cavity, however this is a little misleading. The sensor cable within the roof cavity was slightly offset from the sensor cable in the factory space, and the ventilation hole in the peak of the internal liner membrane was open (see *Figure 8:3.1a*). This meant that the high level sensors within the factory space were directly exposed to the '*hot*' external membrane, whilst the low level sensors within the roof cavity were shaded by internal structure.

It was also apparent that the period of peak internal temperatures did not correspond to the period of peak solar intensity. This resulted from the fact that part of the building envelope was shaded from solar radiation during the morning by the severe cliff to the south east of the site. The solarimeter and the membrane surface temperature sensor on the other hand were placed far enough away from the cliff so as to always been in the sunlight.

These anomalies suggested that radiant effects may have a greater influence on the thermal conditions found within this space than had previously been recognised, and this may explain why high level heat tended not to penetrate into the lower levels of the space.

As it was, this could not be considered a thermally successful space. It displayed all the typical disadvantages of membrane construction, but few of the advantages. The double membrane roof configuration, and the low internal ventilation rates meant that its thermal behaviour was less extreme than may have been expected, but because the space was effectively sealed from the outside during cold periods it inevitably suffered from condensation problems. It was also seen that whilst the low transmittance of the external membrane meant that artificial lighting was necessary inside the space, its high absorptance gave it all the disadvantages of solar heat gain.

8:4. CASE STUDY 2: THE ROYAL INTERNATIONAL EISTEDDFOD PAVILION, MAIN ARENA.

8:4.1 Thermal Specification.

- *Credits.*
- Owned and occupied by Clwyd County Council.
- Architects: D.Y. Davies Associates.
- Structural Engineers: Atelier One.
- Contract Value £3 million.
- Completed in July 1992.

- *Site.*
- Abby Road,
  Llangollen,
  Clwyd.

- Longitude: 3.183^{o} West.
- Latitude: 52.142^{o} North.
- Altitude: Finished floor level 92.2 m above sea level.
- Site Properties: The building is located at the bottom of a grass covered valley on a flat, rural site.

- *Form.*
- The permanent area of the main arena covers 1325m^2, but this can be increased to 3500m^2 during the International Eisteddfod by the addition of temporary fabric extensions.
- The permanent enclosed volume of approximately 15000m^3 increases to 27000m^3 when the extensions are added.
- Maximum height 20m.

- *Membrane Envelope.*
- Installed by Clyde Canvas.
- 1300 g/m^2 PVC coated polyester.
- Expected life 15 years.
- The membrane was two years old during the monitoring programme.
- The membrane was showing signs of deterioration, including streaking and a significant accumulation of dirt. This was made particularly obvious from the inside of the space because of the translucency of the membrane.

- *Occupancy.*
- The building was substantially unoccupied during the monitored periods.
- Apart from during the Eisteddfod itself, the arena is used mainly for sporting activities by small groups of 20 or less.
- During the Eisteddfod over 5000 people can be accommodated within the extended arena.

- *Environmental Control System.*
- Totally passive internal environment.
- Apex extract fans were originally considered as a means of combating condensation, but these were not included in the actual building.
- Low level natural ventilation is provided by small openings in the seams of the perimeter fabric wall.

- *Comments.*
- A motorised lighting gantry above the main stage area allowed easy high level access for comprehensive monitoring.

- *Building Illustrations.*

Figure 8:4.1a Royal International Eisteddfod Pavilion, Main Arena, Section B-B

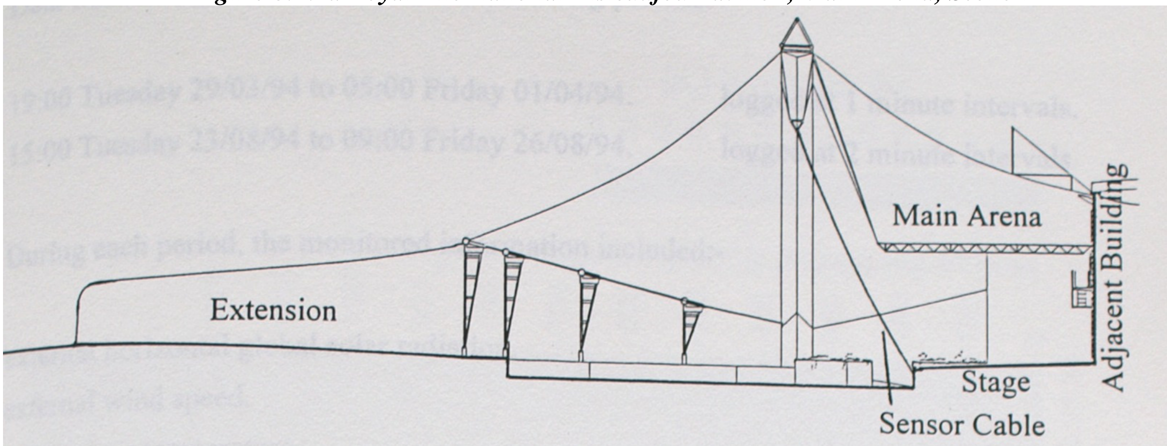
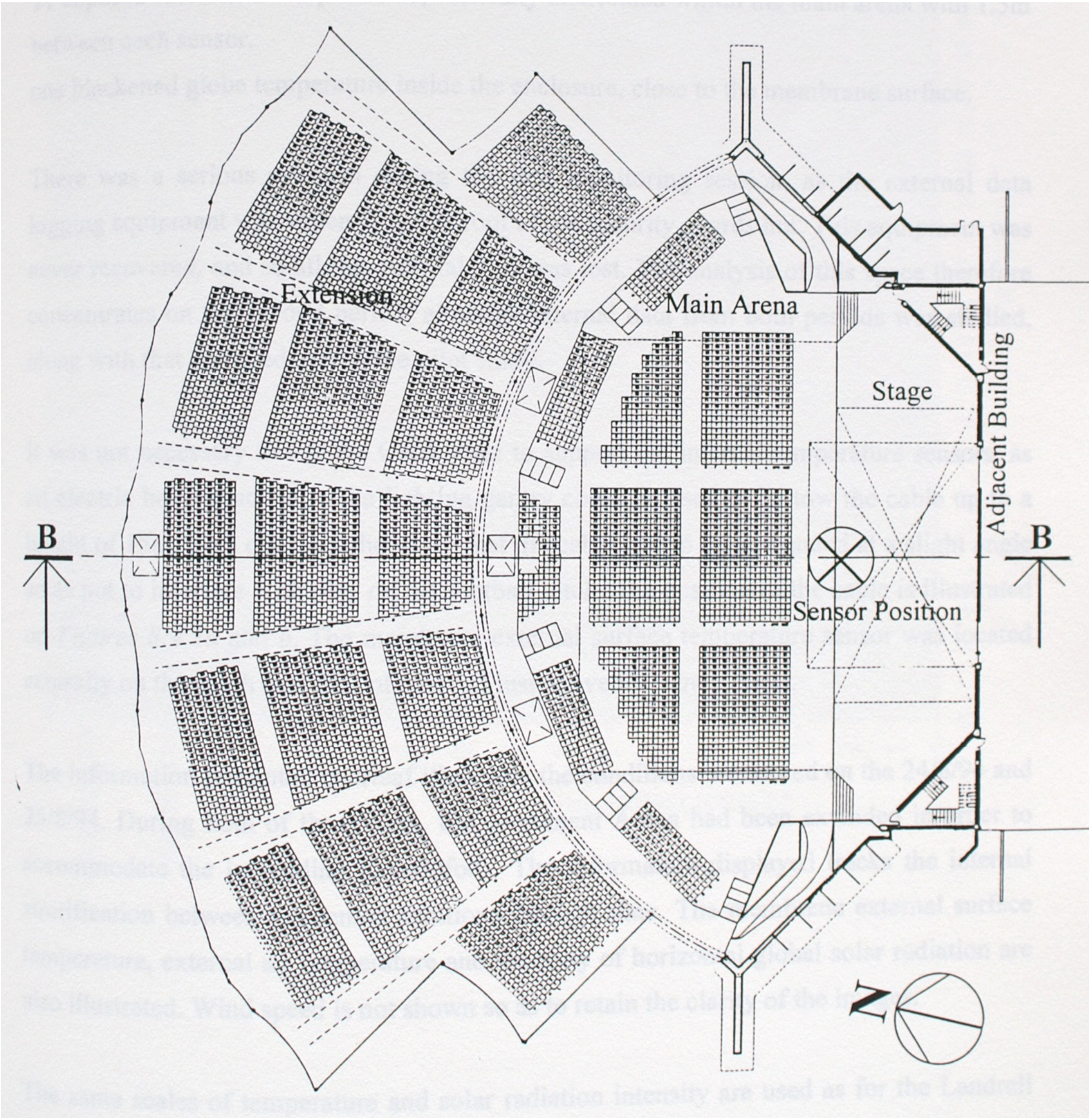


Figure 8:4.1b Royal International Eisteddfod Pavilion, Main Arena, Floor Plan (1:500).



8:4.2 **Information Monitored at the Eisteddfod Arena.**

Data was collected which covered the following periods:-

- 19:00 Tuesday 29/03/94 to 05:00 Friday 01/04/94. logged at 1 minute intervals.
- 15:00 Tuesday 23/08/94 to 09:00 Friday 26/08/94. logged at 2 minute intervals.

During each period, the monitored information included:-

- external horizontal global solar radiation.
- external wind speed.
- external air temperature.
- the temperature of the external surface of the membrane.
- 11 exposed thermistor temperatures, vertically distributed within the main arena with 1.5m between each sensor.
- one blackened globe temperature inside the enclosure, close to the membrane surface.

There was a serious problem during the first monitoring session, as the external data logging equipment was stolen from the roof of the security guards hut. This equipment was never recovered, and so all the external data was lost. The analysis of this space therefore concentrates on the second period, although internal data from both periods was studied, along with that gathered during the pilot study.

It was not necessary to use the Clark mast to support the internal temperature sensors, as an electric hoist attached to the lighting gantry could be used to be tow the cable up to a height of 15m. This did mean however that the cable had to be suspended at a slight angle so as not to interfere with play on the football pitch. The position of the cable is illustrated on *Figures 8:4.1a* and *b*. The membrane external surface temperature sensor was located centrally on the south east face of the roof just above the '*eaves*' level.

The information presented overleaf illustrates the conditions monitored on the 24/8/94 and 25/8/94. During both of these days, the permanent Arena had been extended in order to accommodate the impending Eisteddfod. The information displayed tracks the internal stratification between the sensor positions through time. The membrane external surface temperature, external air temperature and intensity of horizontal global solar radiation are also illustrated. Wind speed is not shown so as to retain the clarity of the images.

The same scales of temperature and solar radiation intensity are used as for the Landrell data, and again the '*flood*' images are supplemented by more conventional graphs in the rest of this section.

Figure 8:4.2a Royal International Eisteddfod Pavilion, Main Arena. 24/08/94.

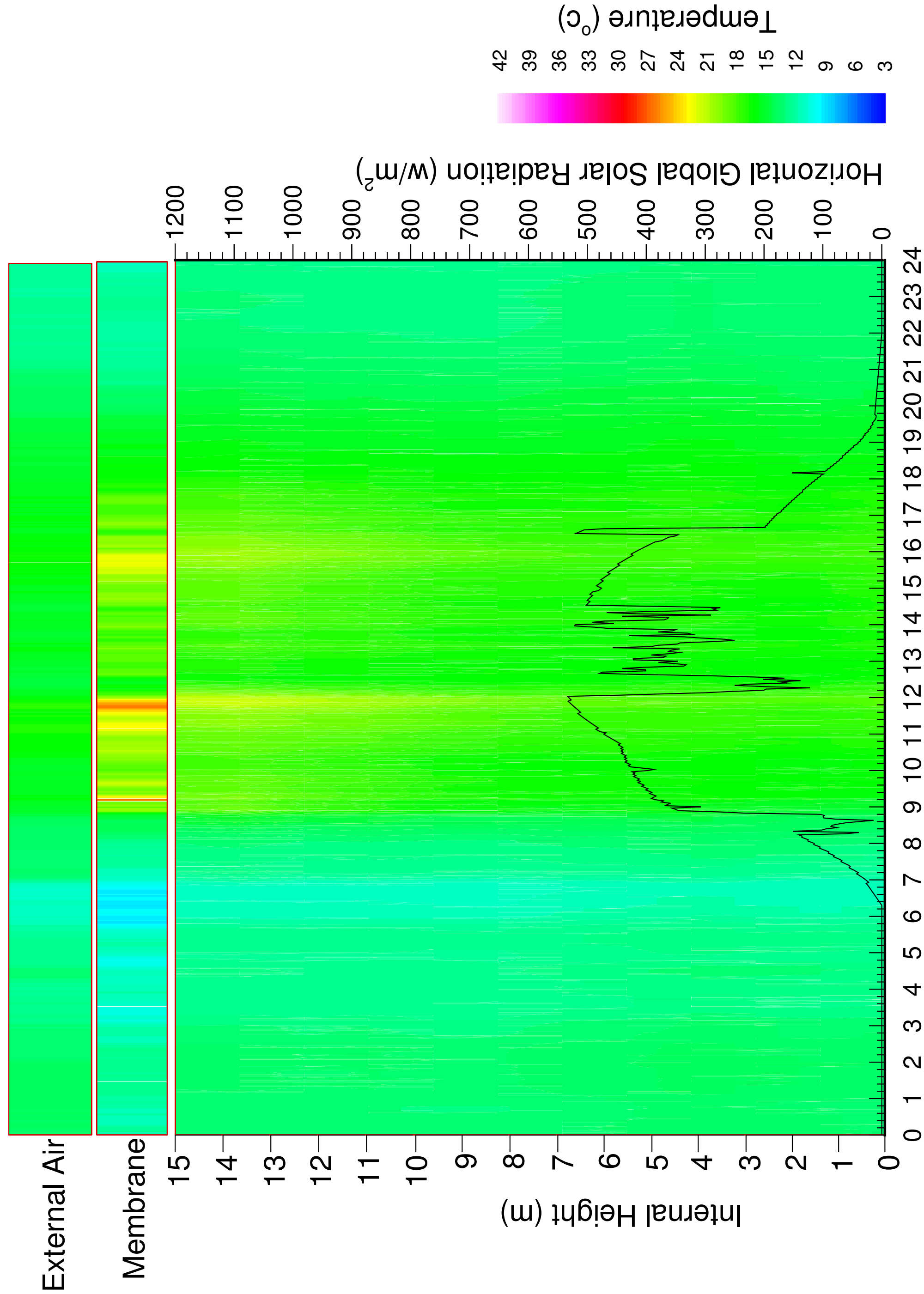
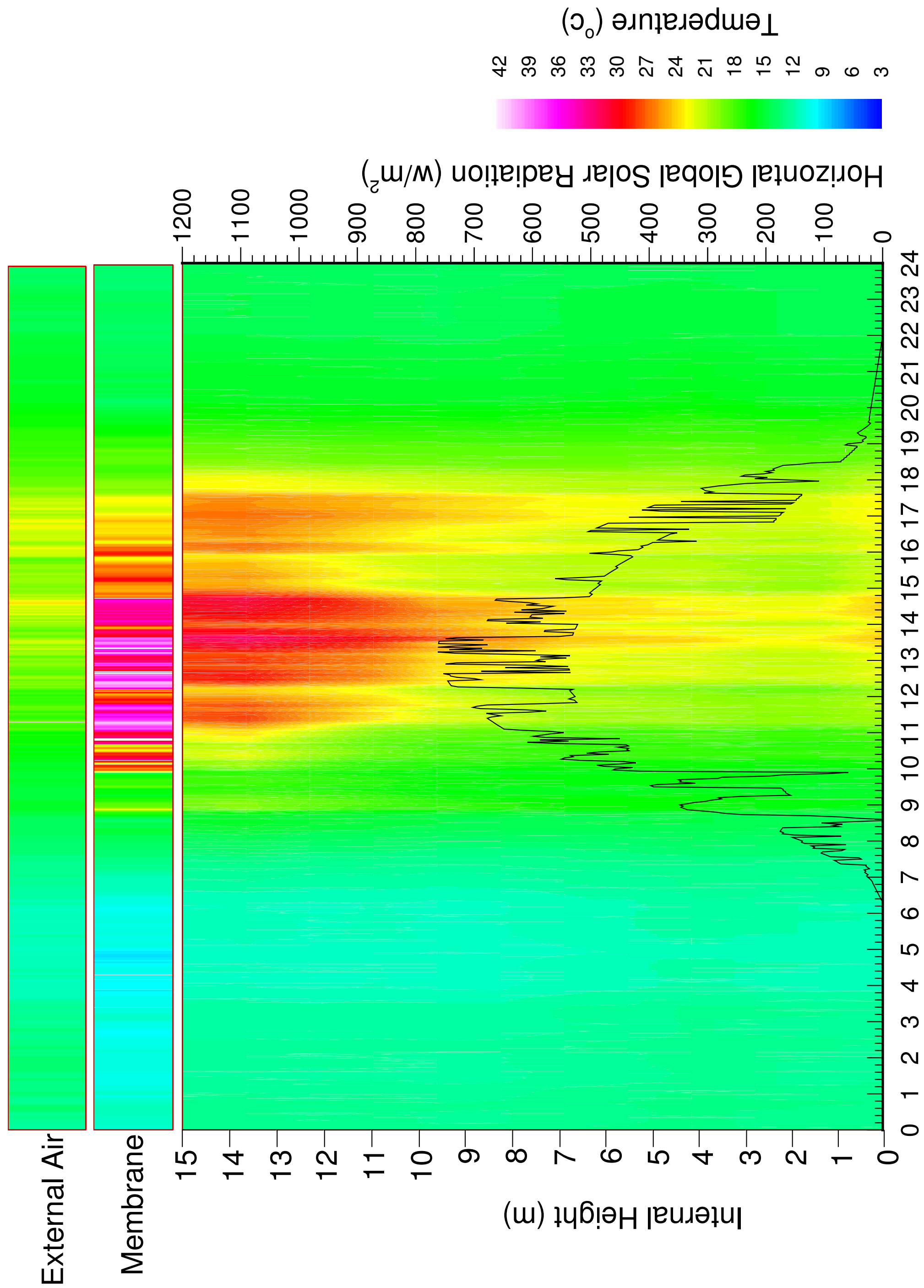


Figure 8:4.2b Royal International Eisteddfod Pavilion, Main Arena. 25/08/94.

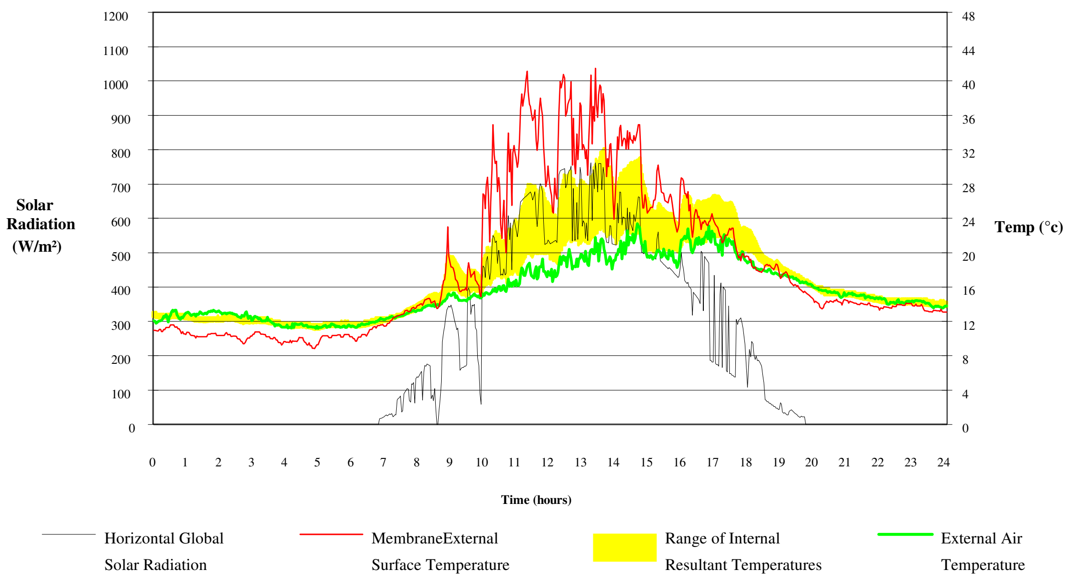


8:4.3 Analysis of the Information Monitored at the Eisteddfod Arena.

Conditions during the first day presented (*Figure 8:4.2a*) were fairly stable. Solar radiation intensities were moderate, and the external air temperature varied by just 6^{o}c during the entire day. In the middle of the day however, bright sunshine caused the membrane to heat up significantly, and as a consequence stratification of over 4^{o}c was recorded within the enclosure. This high level heat slowly penetrated down through the height of the space, but had little impact on the highly ventilated lower levels, which were always within 3^{o}c of the external air temperature.

The data monitored during the more variable conditions of the second day presented (*Figure 8:4.2b*), made it clear that the conditions within the relatively '*open*' Eisteddfod Arena could be significantly more changeable than those within the double membrane Landrell factory. Whilst the temperature swing recorded at the external surface of the Eisteddfod membrane during this period was very similar to that recorded during the second Landrell period illustrated (33^{o}c as opposed to 31^{o}c), the resultant temperature swing at low level within the Eisteddfod Arena was 13^{o}c whilst the temperature swing at low level within the Landrell factory space was just 4^{o}c. This responsiveness is clearly illustrated by *Figure 8:4.3a* below.

Figure 8:4.3a Diagram to Show the Affect of Changing Environmental Conditions on the Range of Resultant Temperatures Monitored Within the Eisteddfod Arena (25/4/94).

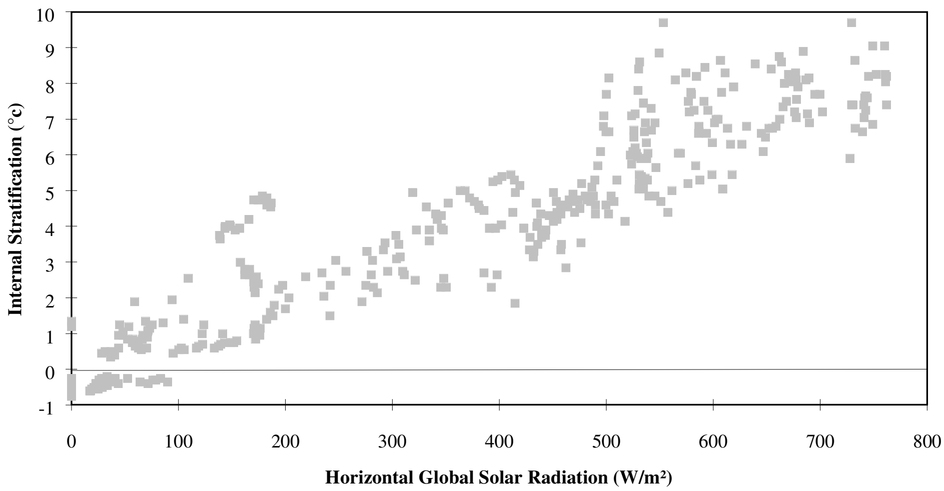


It can be seen from *Figure 8:4:3a* above that low level temperatures during the second day monitored tended to remain fairly close to the external air temperature as a result of infiltration through the perimeter walls. High level temperatures however were up to 12.5^{o}c hotter than the external air and this resulted in internal stratification of almost 10^{o}c.

The recorded internal stratification appeared to result primarily from the affects of solar radiation. During bright sunshine, the membrane reached temperatures of over 40^{o}c (almost 23^{o}c hotter than the external air) whilst at night, the membrane could become over 3^{o}c cooler than the external air as a result of long wave infra red radiation to the clear sky.

The contrast between this sensitive membrane behaviour and the behaviour of more thermally stable surfaces within the enclosure such as the floor, resulted in internal stratification. This relationship is clearly illustrated by *Figure 8:4.3b* below.

Figure 8:4.3b Diagram to Show the Relationship Between the Intensity of Horizontal Global Solar Radiation and the Stratification of Resultant Temperatures Monitored Within the Eisteddfod Arena (25/8/94).



Accumulating high level heat slowly penetrated into the lower levels of the space, but as with the Landrell Factory, this did not significantly affect the occupied zone, and conditions only returned to a more '*diffuse*' state as the intensity of solar radiation itself decreased.

Negative stratification was apparent during the nights of both periods illustrated, and whilst this reached a maximum of just 1.1^{o}c, current understanding of the affects of buoyancy forces suggests that this was unlikely to have resulted from the stratification of internal air. It was more likely that this negative stratification was produced by the radiant effect of contrasting surface temperatures within the space.

This along with the observed behaviour of the Landrell factory suggested that variations in radiant temperatures may have a more significant influence on thermal conditions within spaces enclosed by fabric membranes than had been recognised by previous researchers.

The observed variability of internal conditions, combined with the lack of any controlled ventilation resulted in severe condensation problems within the Eisteddfod Arena. Humid external air was able to penetrate into the space, and on clear mornings this inevitably resulted in condensation forming on the inside surface of the cold membrane. The subsequent dripping of moisture back into the space had rendered it unusable several times.

Neither a properly designed permanent space, nor merely a temporary shelter, the Eisteddfod Arena appeared to have the worst performance characteristics of both approaches. It was partly enclosed, unheated and poorly ventilated. In the cool, damp climate of north Wales, the resulting large temperature swings and condensation which frequently disrupted the use of the space were inevitable.

8:5. CASE STUDY 3: THE CHERITON PASSENGER TERMINAL, ADMINISTRATION AND AMENITY BUILDING.

8:5.1 Description of the Administration and Amenity Building.

- *Credits.*
- Owned by Transmanche Link.
- Occupied by Eurotunnel.
- Architecture and Engineering: Building Design Partnership.
- Completed in 1993.

- *Site.*
- Eurotunnel Passenger Terminal,
  Cheriton
  Kent.
- Longitude: 1.142^{o} East.
- Latitude: 51.092^{o} North.
- Altitude: Finished floor level 64m above sea level.
- Site: A flat, semi rural location, surrounded by car parking and a number of standard industrial buildings.

- *Form.*
- The footprint of the membrane roofed central atrium is 580m².
- Approximately 7500 m^3 is enclosed under the distended cone shaped fabric roof.
- The maximum height of the canopy is 18m.

- *Envelope.*
- The membrane roof was designed and supplied by Birdair.
- Birdair 1010 (Sheerfill II) Teflon coated glass membrane.
- The membrane translucency is quoted as 14% although it is unclear what this value refers to.
- Manufacturers U-value quoted as 4.77 W/m^2 ^{o}c summer, 7.15 winter W/m^2 ^{o}c
- Expected life 20 years.
- The membrane was approximately 1 year old during monitored periods.
- The membrane had bleached totally white, and was showing no signs of deterioration.

- *Occupancy.*
- The central atrium was only occupied by a small number of builders during the monitored periods.
- Once it became operational, the building was expected to have a turnover of some 2400 people / hour throughout the day, seven days a week.
- At the time of this study, it was not known who would occupy the retail spaces adjoining the fabric roofed central atrium, or what activities would be carried out within those spaces.

- *Environmental Control System.*
- The circular apex of the membrane cone is double glazed.
- The space would be entirely air conditioned once it was occupied, however it should have been unheated and essentially sealed during the monitored periods.
- Optional natural ventilation can be provided by openable glass louvers around the perimeter of the atrium at the eaves level.
- An eaves level internal perimeter heating system was included in the building design in order to prevent condensation forming on the internal surface of the membrane, however this was not incorporated into the actual building.

- *Comments.*
- Access for monitoring this space was limited to the period after the major construction work had been completed, early in spring 1994 and before the opening of the complex at the end of June 1994.
- Access to the membrane itself was very difficult both inside and outside, and so it was not possible to measure the surface temperature of the membrane.

- *Building Illustrations.*

Figure 8:5.1a The Administration and Amenity Building, Section C-C (1:1000).

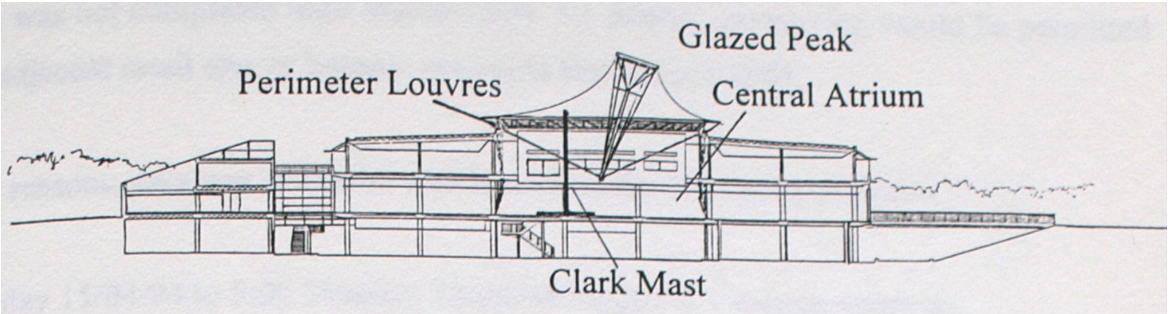
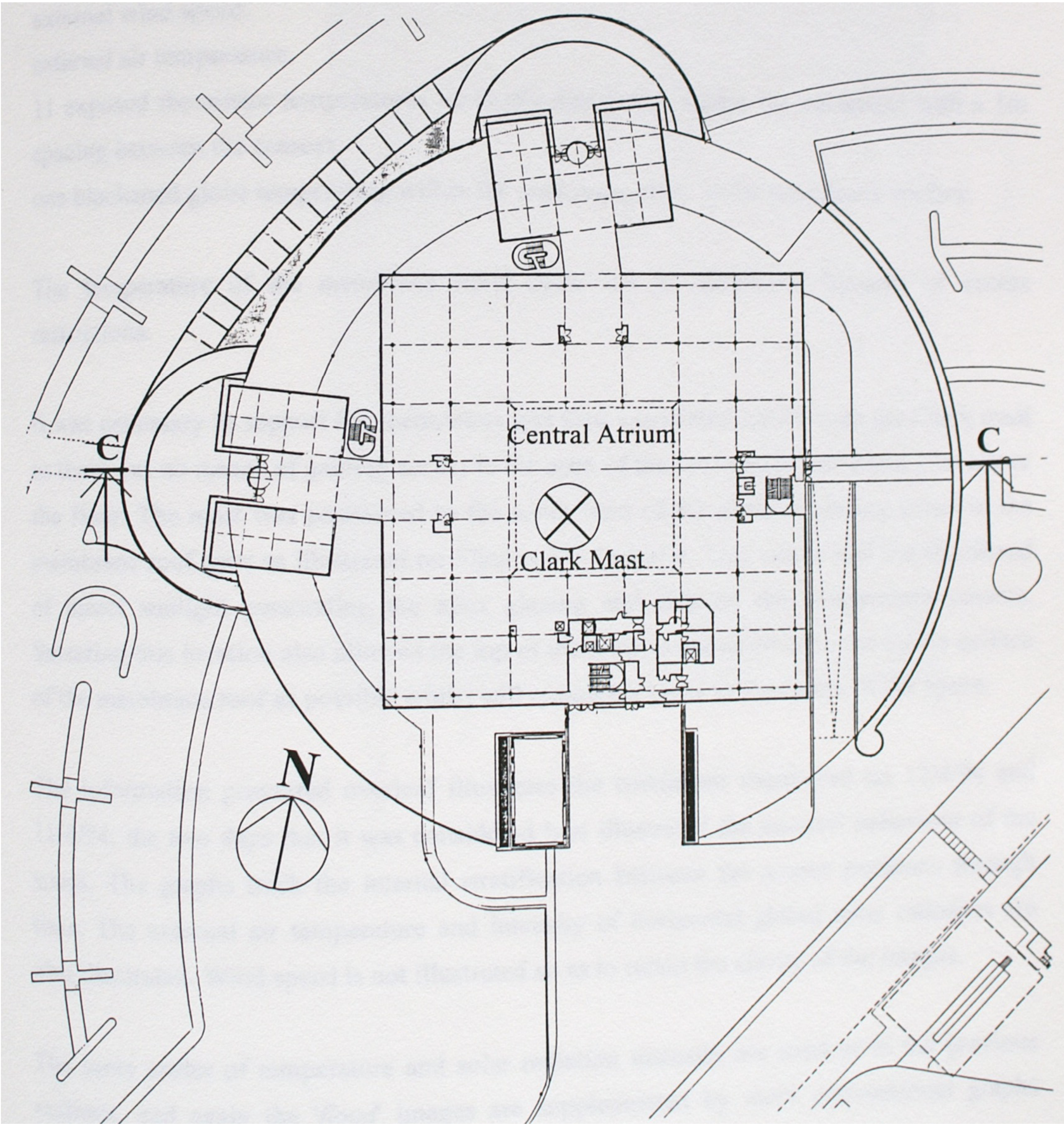


Figure 8:5.1b The Administration and Amenity Building, Ground Floor Plan (1:1000).



8:5.2 Information Monitored at the Administration and Amenity Building.

No pilot study had been carried out at the Administration and Amenity Building because the space was not completed until March 1994. No further monitoring would be permitted after the adjacent retail spaces became occupied late in June 1994.

For these reasons, data was collected which covered the following periods:-

- 19:00 Friday 15/04/94 to 5:00 Monday 18/04/94 logged at 1 minute intervals.
- 19:00 Friday 10/06/94 to 5:00 Monday 13/06/94 logged at 1 minute intervals.

During each period, the monitored information included:-

- external horizontal global solar radiation.
- external wind speed.
- external air temperature.
- 11 exposed thermistor temperatures vertically distributed within the enclosure with a 1m spacing between the sensors.
- one blackened globe temperature within the enclosure, close to the membrane surface.

The temperature of the membrane itself could not be monitored because of access restrictions.

It was necessary to support the thermistors and their associated cables with the Clark mast as their was no means of gaining access to the apex of the roof which was some 17m above the floor. The mast was positioned to the south west of the circular glazing panel in the membrane roof apex as illustrated on *Figures 8:5.1a* and *b.* This minimised the likelihood of direct sunlight penetrating the apex glazing and striking the temperature sensors. Selecting this location also allowed the top of the mast to get as close to the inside surface of the membrane roof as possible whilst still remaining close to the centre of the space.

The information presented overleaf illustrates the conditions monitored on 17/4/94 and 11/6/94, the two days that it was considered best illustrated the unusual behaviour of the space. The graphs track the internal stratification between the sensor positions through time. The external air temperature and intensity of horizontal global solar radiation are also illustrated. Wind speed is not illustrated so as to retain the clarity of the images.

The same scales of temperature and solar radiation intensity are used as in the previous sections, and again the '*flood*' images are supplemented by more conventional graphs throughout the rest of the section.

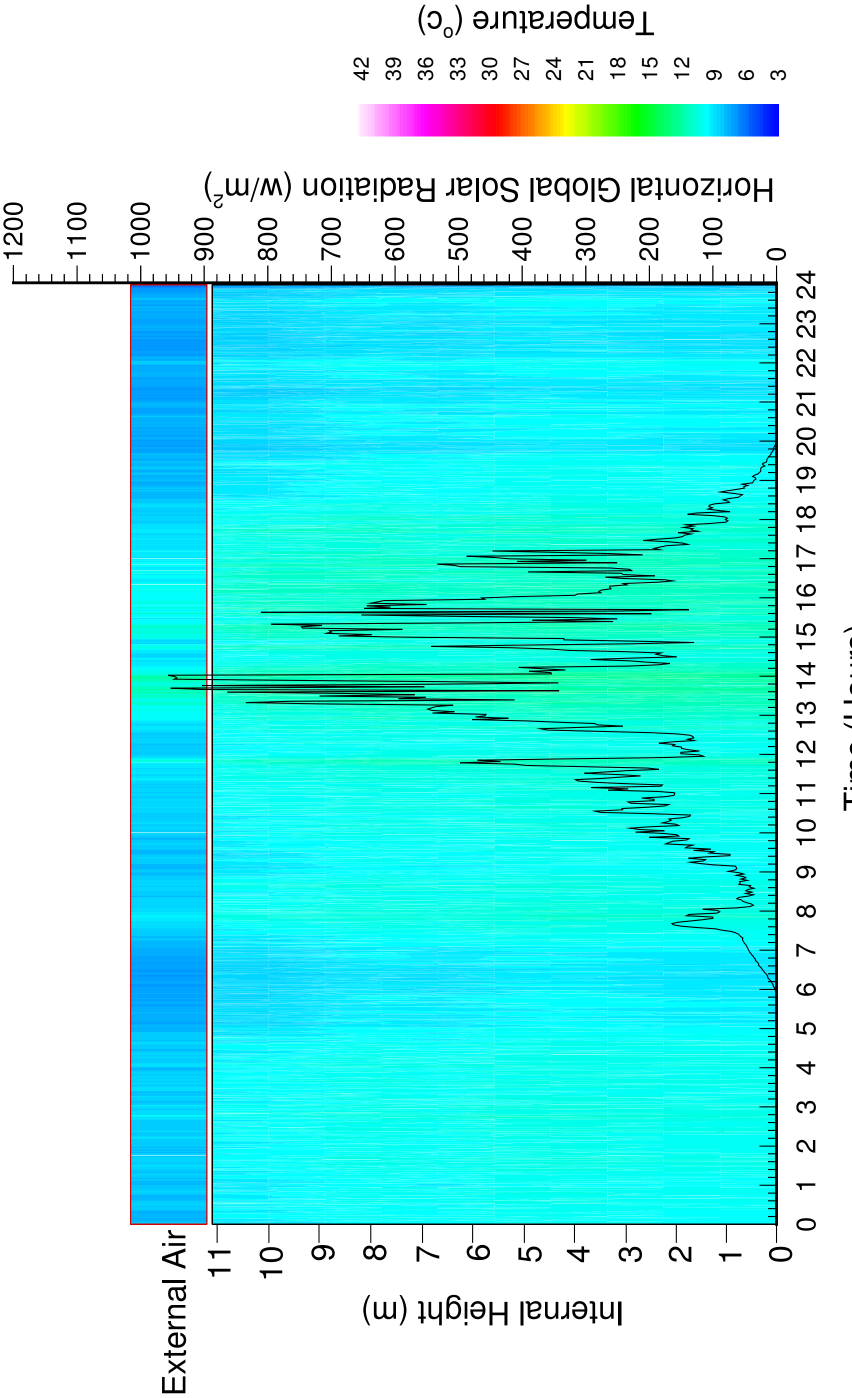


Figure 8:5.2a The Administration and Amenity Building. 17/04/94.

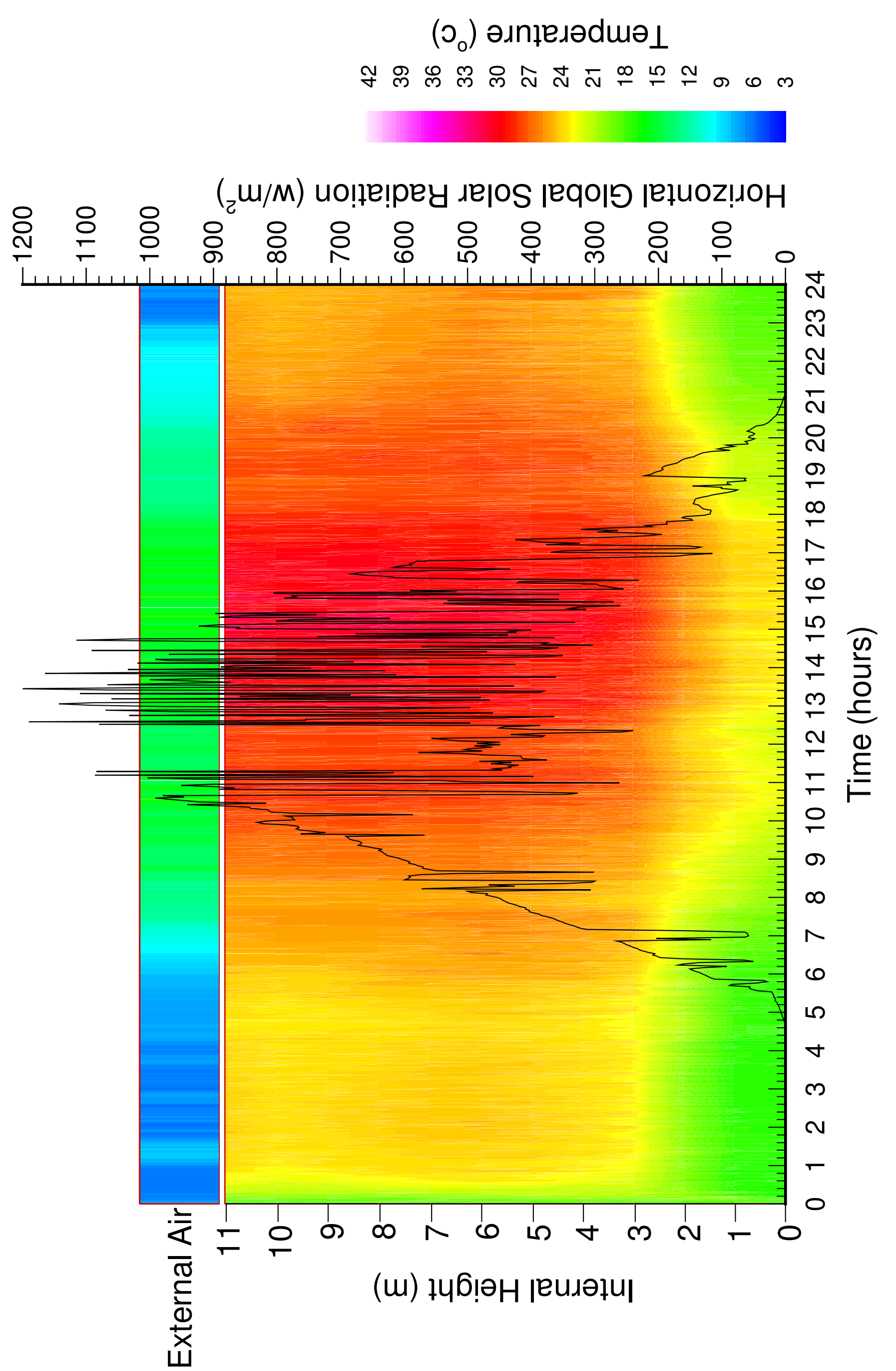


Figure 8:5.2b The Administration and Amenity Building. 11/06/94.

8:5.3 Analysis of the Information Monitored at the Administration and Amenity Building.

The contrasting behaviour illustrated by the *Figures 8:52a* and *b* above is difficult to explain. On both days the peak solar radiation and the range of external air temperatures were similar, however the range of internal resultant temperatures recorded were entirely different. This is illustrated clearly by the fact that the maximum difference between the external air temperature and the resultant temperatures recorded within the space during the first day presented was just 3^{o}c whilst on the second day, the maximum difference was almost 20^{o}c.

This contrasting behaviour is illustrated clearly by the two diagrams below.

Figure 8:5.3a Diagram to Show the Relationship Between External Conditions and the Range of Resultant Temperatures Monitored in the Administration and Amenity Building (17/4/94).

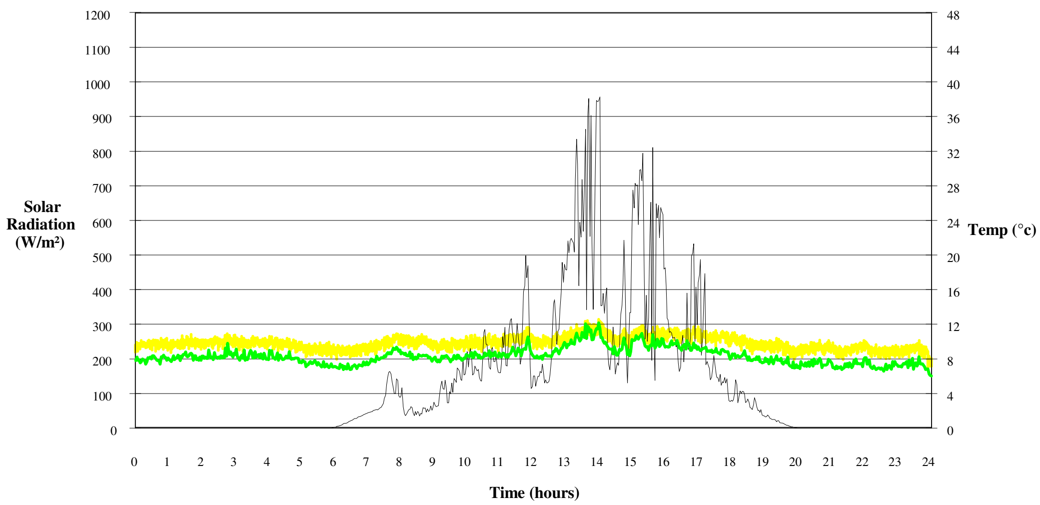
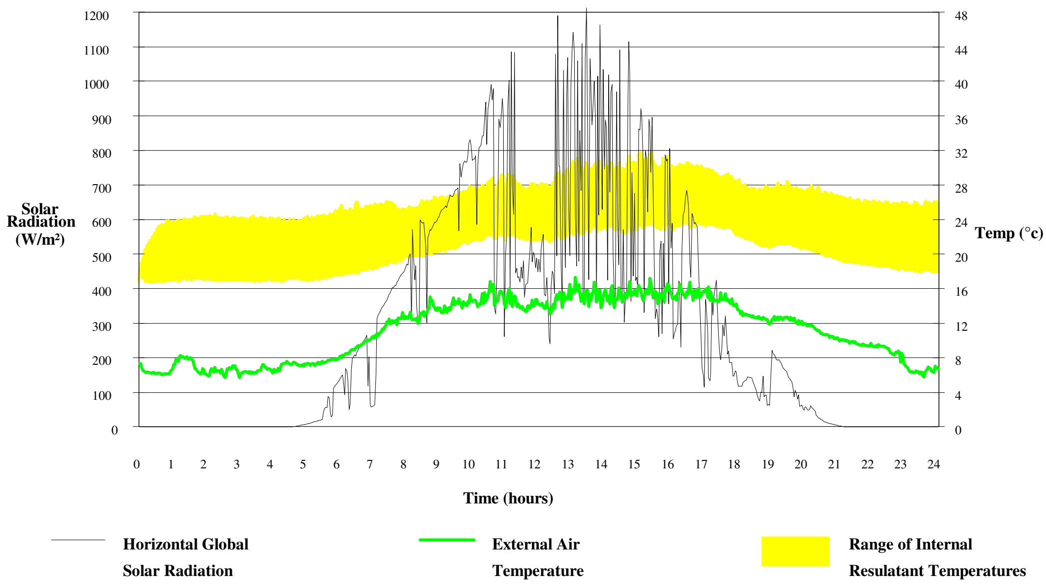


Figure 8:5.3b Diagram to Show the Relationship Between External Conditions and the Range of Resultant Temperatures Monitored in the Administration and Amenity Building (11/6/94).



The behaviour of the space recorded during the second day presented (*Figures 8:5.2b* and *8:5.3b*) is relatively easy to explain. The space was effectively sealed from the outside, and this combined with the significant amount of thermal mass enclosing the central atrium (see *Figure 8:5.1a*) resulted in it behaving in a more conventional manner than either the Landrell factory or the Eisteddfod Arena.

Conditions within the central atrium remained significantly warmer than the external air temperature throughout the day as a result of its thermal mass, whilst air infiltrating from the cooler adjacent spaces at low level produced significant positive stratification, even during the night. During the day, the temperature of the space as a whole increased as a result of solar radiation penetrating through the high translucency membrane, but temperatures close to the membrane tended to become relatively hotter. This resulted in an increase in internal stratification.

The thermal conditions inside the space during the first day presented (*Figures 8:5.2a* and *8:5.3a*) however, are not so easy to understand. At the most simple level of analysis, the peak solar intensity was over 900W/m^2, and this would have been expected to result in the membrane becoming fairly hot, producing a noticeable increase the temperature of the space and motivating a significant internal thermal gradient. Resultant temperatures however continued to follow the external air temperature very closely throughout the space and with no perceptible delay.

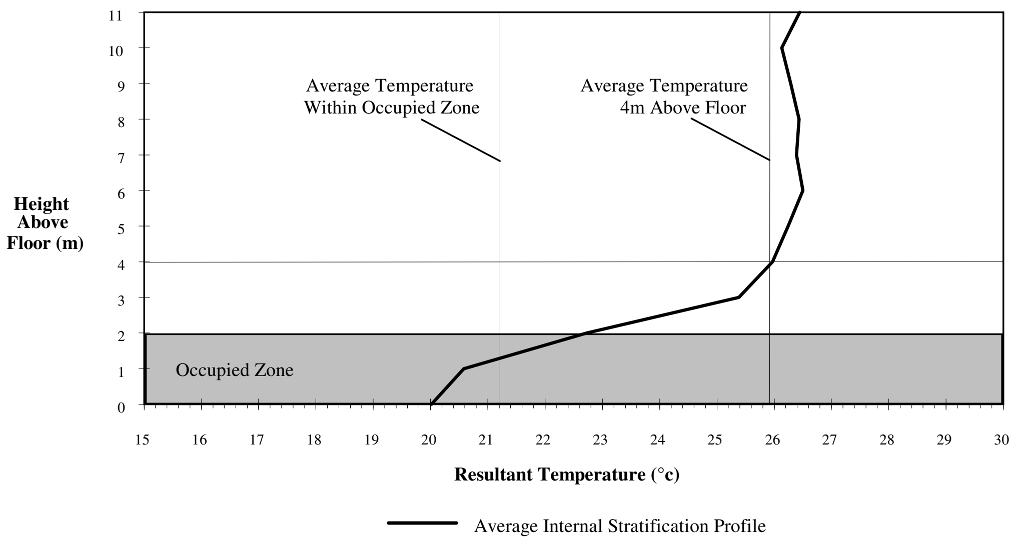
This can only be readily explained if the strong winds monitored during this period had been able to penetrate into the enclosure through the high level perimeter louvres. This would have resulted in internal air temperatures remaining close to the outside air temperature, and high internal air velocities would have prevented the membrane from heating up significantly under the influence of solar radiation. The Site Maintenance Manager however made many assurances that the perimeter louvres had not been open, and that there should not have been any significant infiltration into the atrium.

It was hoped that a definite explanation for this behaviour would emerge from the programme of spatial simulations described in the next chapter, however it was still possible to make some basic observations about the behaviour of the space based on the data obtained during the second monitored period and these are described below.

The space displayed the thermal sensitivity characteristic of spaces enclosed by fabric membranes, however it was generally more stable than the other single membrane spaces investigated because of the thermal mass of the tall side walls surrounding it. This thermal mass combined with the relatively low solar absorptance and high solar transmittance of the PTFE coated glass membrane meant that high level stratification was less noticeable than in the other spaces monitored. Strong thermal gradients only appeared to occur at low level as a result of infiltration from the adjacent spaces.

Once occupied, the space would be fully air conditioned, and it was apparent from the monitored data that the positioning of the internal temperature sensors upon which air conditioning output would be based was very important. Unless these sensors were positioned within the occupied zone itself, i.e. less than 2m above the floor, they would be likely to overestimate the temperature of the space, and so overcool to compensate. For example during the second monitored period, temperature sensors 4m above the ground would have registered an average temperature of 26°c, whereas the average temperature within the area occupied by people was less than 22°c, as illustrated below

Figure 8:5.3c Diagram to Show the Average Stratification of Resultant Temperatures Recorded Within the Administration and Amenity Building (17/4/94).



This behaviour clearly illustrates the importance of properly understanding the thermal behaviour of such spaces if their internal environment is to be efficiently controlled.

8:6. CASE STUDY 4: THE AELTC INDOOR TENNIS CENTRE, COVERED COURTS.

8:6.1 Description of the AELTC Covered Courts.

- *Credits.*
- Owned and occupied by the All England Lawn Tennis and Croquet Club.
- Architect: Ian C. King.
- Engineer: Horst Berger Partners.
- Completed in 1989.

- *Site.*
- Church Road,
  Wimbledon,
  London.
- Longitude: 0.217^{o} West.
- Latitude: 51.433^{o} North.
- Altitude: Finished floor level 30m above sea level.
- Site: A flat, inner city location surrounded by grass and a number of trees.

- *Form.*
- The membrane roof covers a footprint of 2405 m^2.
- The membrane encloses approximately 20,000 m^3.
- The maximum height of the space is 13m.

- *Envelope.*
- Duraskin PVC coated polyester membrane tinted light green on its outside surface.
- This green tint gives the membrane an unusually high solar absorptance which meant that it was likely to become very hot during bright sunshine.
- The membrane had an expected life of over 20 years.
- The membrane was 5 years old during the monitoring programme and was showing few signs of deterioration other than an accumulation of dirt its outside surface.

- *Occupancy.*
- The maximum occupancy of the space is twelve tennis players plus a handful of spectators, however the building was substantially unoccupied during the monitored periods.

- *Environmental Control System.*
- Adjustable perimeter louvers provide controllable natural ventilation.
- In addition to this, 3 colt whirlwind MK II WA 800-66 ventilators extract air from the space at a rate of 5.1m^3/second each.
- Twelve 4.5 kilowatt infra red heaters are directed towards the base lines of the tennis courts. These can be switched on manually during cold weather, but the space was unheated during the monitored periods.

- *Comments.*
- The repetitive linear form of the space meant that it was likely that its thermal behaviour could be adequately represented by a two dimensional cross section. This made it very suitable for spatial modelling as discussed in Chapter 9.

- *Building Illustrations.*

Figure 8:6.1a The AELTC Covered Courts, South East Elevation (1:500).

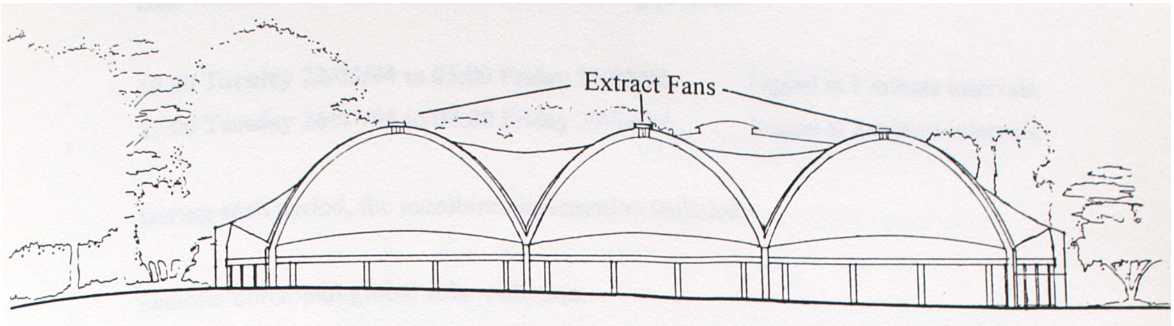
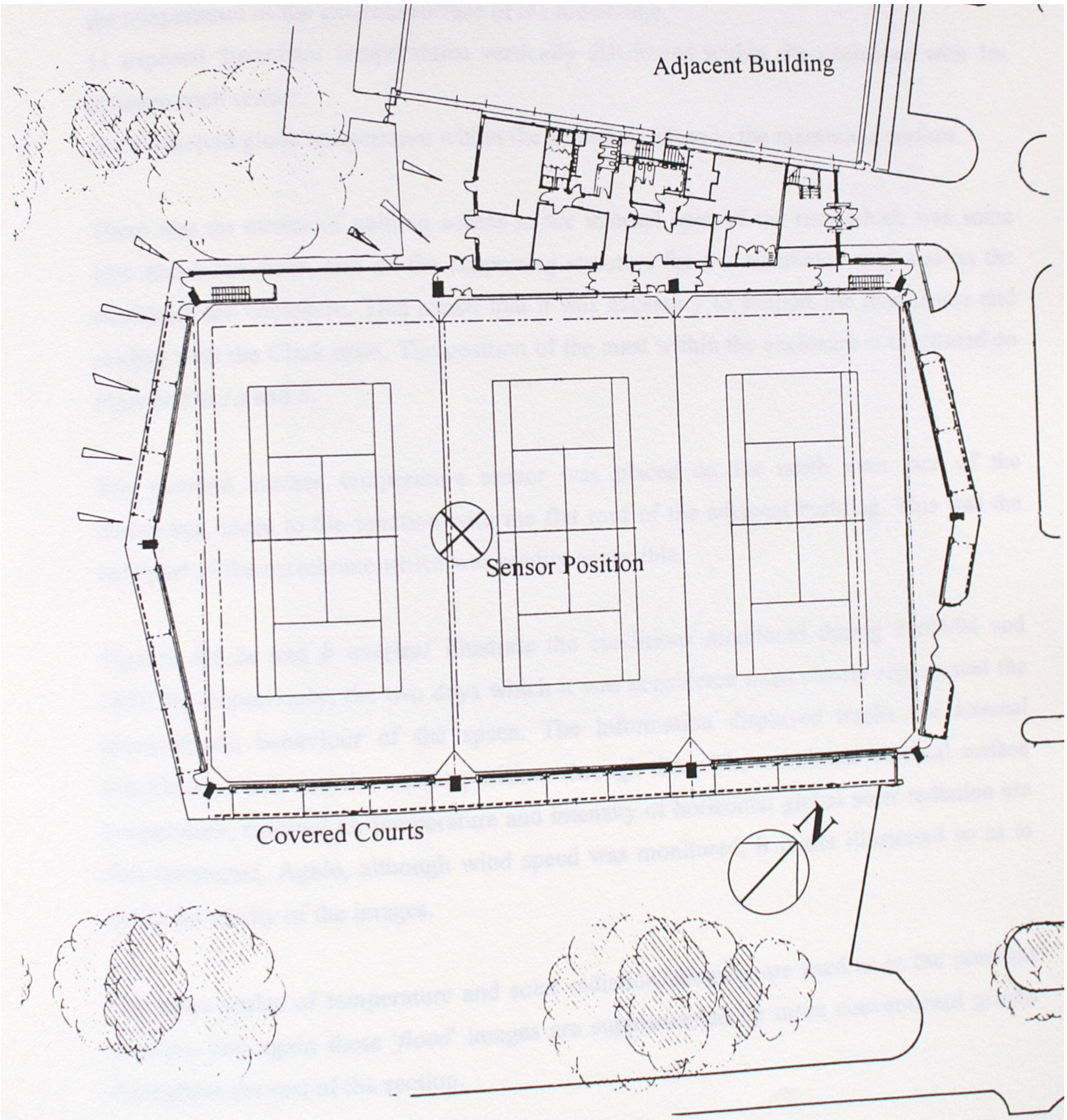


Figure 8:6.1b The AELTC Covered Courts, Floor Plan (1:500).



8:6.2 **Information Monitored at the AELTC Covered Courts.**

Data was collected which covered the following periods:-

- 19:00 Tuesday 22/03/94 to 05:00 Friday 25/03/94. logged at 1 minute intervals.
- 15:00 Tuesday 26/07/94 to 09:00 Friday 29/07/94. logged at 2 minute intervals.

During each period, the monitored information included:-

- external horizontal global solar radiation.
- external wind speed.
- external air temperature.
- the temperature of the external surface of the membrane.
- 11 exposed thermistor temperatures vertically distributed within the enclosure with 1m between each sensor.
- one blackened globe temperature within the enclosure, close to the membrane surface.

There was no means of gaining access to the internal apex of the roof which was some 13m above the floor, and all the supporting structure for the membrane roof was on the outside of the enclosure. This meant that it was necessary to support the thermistors and cabling with the Clark mast. The position of the mast within the enclosure is illustrated on *Figures 8:6.1a* and *b*.

The external surface temperature sensor was placed on the north west face of the membrane, close to the junction with the flat roof of the adjacent building. This was the only part of the membrane which was readily accessible.

Figures 8:6.2a and *b* overleaf illustrate the conditions monitored during 24/04/94 and 28/07/94 respectively, the two days which it was considered most clearly represented the characteristic behaviour of the space. The information displayed tracks the internal stratification between the sensor positions through time. The membrane external surface temperature, external air temperature and intensity of horizontal global solar radiation are also illustrated. Again, although wind speed was monitored, it is not illustrated so as to retain the clarity of the images.

The same scales of temperature and solar radiation intensity are used as in the previous sections, and again these '*flood*' images are supplemented by more conventional graphs throughout the rest of the section.

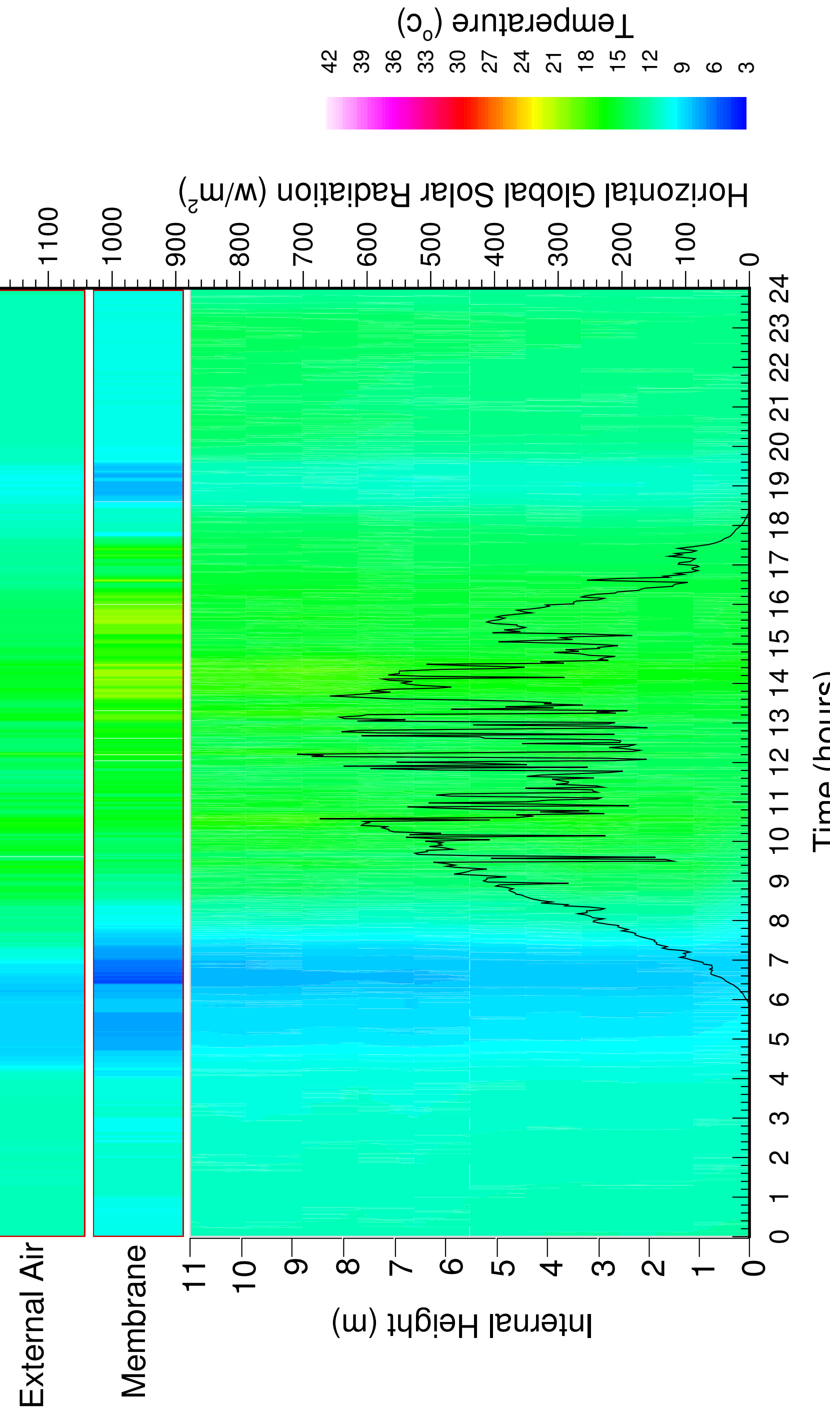


Figure 8:6.2a The AELTC Covered Courts. 24/03/94.

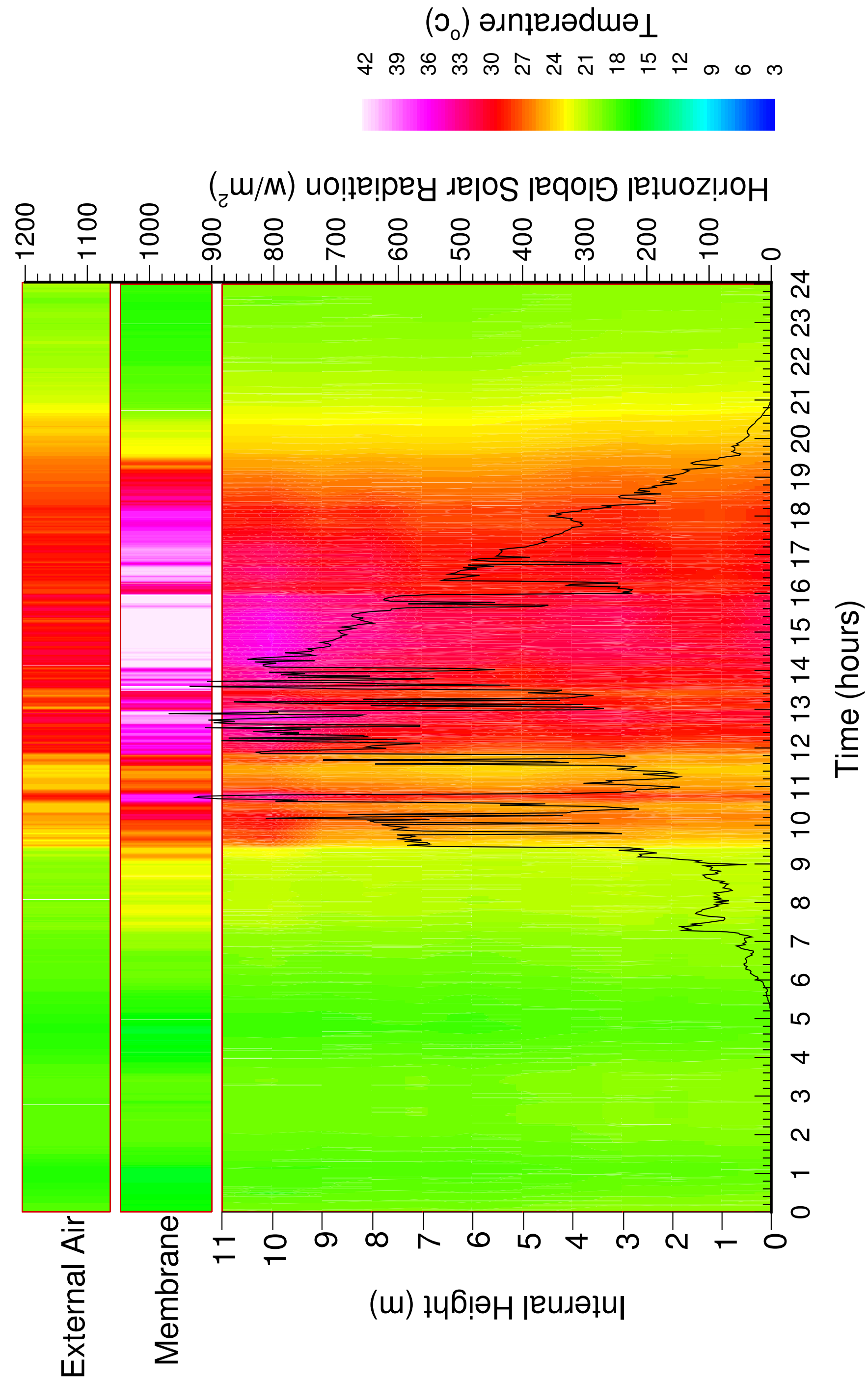


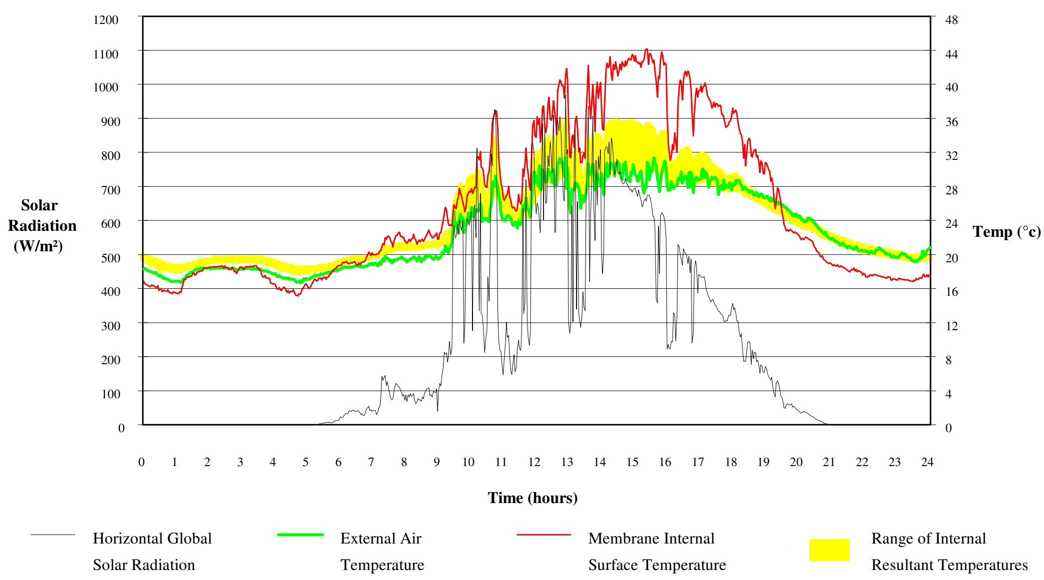
Figure 8:6.2b The AELTC Covered Courts. 27/07/94.

8:6.3 Analysis of the Information Monitored at the AELTC Covered Courts.

The data obtained from the AELTC Covered Courts displayed the characteristic behaviour of spaces enclosed by fabric membranes more clearly and consistently than any of the other buildings monitored. Daytime positive stratification, night-time negative stratification, extreme temperature swings, and quick response were all apparent from the monitored data.

As with the similar Eisteddfod Arena, low level temperatures within the space varied little from the external air temperature. The influence of solar radiation however was seen to cause high level temperatures to increase, resulting in positive internal thermal stratification. As the solar heat source was removed, so the high levels quickly cooled and internal conditions again became relatively uniform. This behaviour was most clearly evident during the second day presented, as shown by *Figure 8:6.3a* below.

Figure 8:6.3a Diagram to Show how the Range of Resultant Temperature Monitored Within the AELTC Covered Courts Varied in Response to Changes in Environmental Conditions (27/7/94).



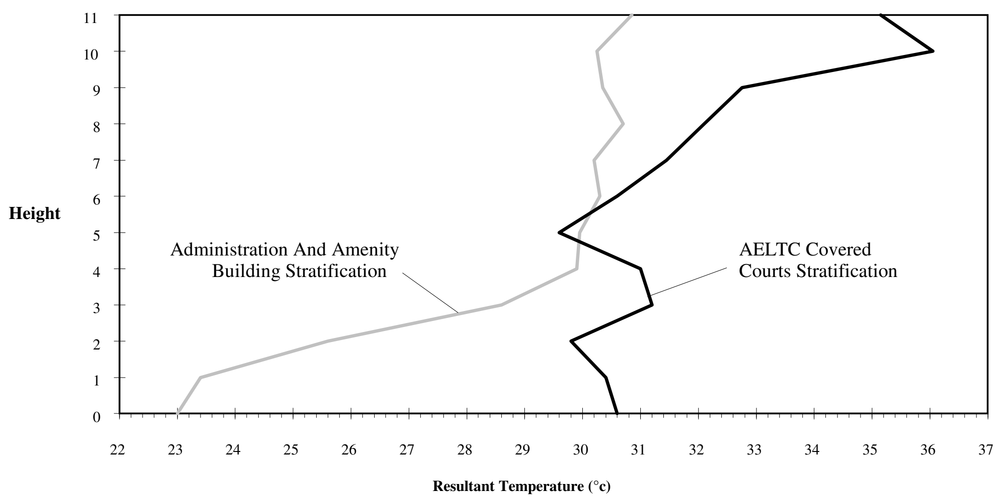
The fact that this characteristic behaviour was evident within the AELTC Covered Courts seemed to confirm that radiant temperatures are as much a cause of thermal gradients within such spaces as the stratification of internal air. This was apparent because high level extract fans were continually forcing large quantities of air through the entire space, and so it was unlikely that buoyancy forces would be able to significantly influence the overall internal air movement patterns. Despite this, internal positive stratification of up to 5.6^{o}c and negative stratification of 1.1^{o}c were recorded within the enclosure. It had to be considered that this resulted predominately from variations in internal radiant temperatures.

As has already been highlighted in the previous three sections of this chapter, the significance of internal radiant conditions seems to have been underestimated in the work of previous researchers, and this is an issue which will be discussed further throughout the rest of the thesis.

Radiant stratification within the AELTC Covered Courts was exaggerated by the fact that the external surface of the enclosing membrane had been tinted light green and, as a result it had a solar absorptance of around 35%. This produced membrane temperatures of up to 45^{o}c during the second monitored period, and the occupants reported that they themselves had recorded membrane temperatures of over 50^{o}c. It was likely that the contrast between these extreme membrane temperatures and the relative thermal stability of the floor would produce significant stratification within the space irrespective of internal air temperatures.

The difference between this and the behaviour of the more conventional Administration and Amenity Building can be clearly seen from the stratification profiles shown below.

Figure 8:6.3b Diagram to Illustrate the Difference Between the Maximum Stratification Recorded Within the AELTC Covered Courts (27/7/94 13:00) and the Maximum Stratification Recorded Within the Administration and Amenity Building (11/6/94 15:08).



It can be seen that low level conditions within the AELTC Covered Courts were relatively uniform, and that strong stratification only occurred at high level as a result of the high internal surface temperature of the enclosing membrane. Within the Administration and Amenity Building however, significant thermal mass tended to produce relatively uniform conditions higher up within the central atrium whilst infiltration from adjacent spaces produced strong stratification at low level.

In the rest of this chapter, the behaviour monitored at the four buildings investigated is summarised, and the implications of this on the techniques necessary to simulate such behaviour discussed.

8:7. OVERALL ANALYSIS OF THE OBSERVED THERMAL BEHAVIOUR OF SPACES ENCLOSED BY FABRIC MEMBRANES.

8:7.1 Summary of the Observed Behaviour.

Several of the buildings investigated during the course of this monitoring programme had relatively '*open*' boundaries which allowed the infiltration of significant quantities of external air. This meant that during periods with little or no solar radiation, internal resultant temperatures throughout the enclosed spaces tended to be close to the external air temperature.

Because of the thermal mass of the ground upon which these spaces stood, it was seen that low level temperatures tended to remain close to the external air temperature throughout the day. Solar radiation however could cause the temperature of fabric membranes to become as much as 20^{o}c hotter than the external air and so resultant temperatures at high level within the enclosed spaces could become up to 12^{o}c hotter than low level temperatures. During the night, the membrane could become as much as 3.5^{o}c cooler than the external air as a result of long wave infra red radiation to a clear sky, and this could produce negative stratification within the space of over 1^{o}c.

When these contrasting surface temperatures persisted, high level stratification was seen to slowly diffuse down through the height of the space, but this rarely reached the very low levels, and so the overall extent of stratification tended not to decrease. As the intensity of solar radiation reduced, and surface temperatures within the spaces became more uniform, so high level temperatures converged on the external air temperature and internal conditions returned to a more '*diffuse*' state.

In the more complex spaces investigated, it was seen that further thermal gradients could be induced by infiltration from adjacent spaces, or artificial heating. This stratification was seen to persist despite internal destratification fans.

The resultant temperatures monitored within the spaces investigated included both *air temperature* and *radiant temperature* components, and because of the contrasting thermal boundary conditions enclosing these spaces, it was seen that both of these temperatures could vary significantly from place to place:-

- The stratification of internal *air temperatures* appeared to result from both infiltration, and buoyancy motivated by contrasting surface temperatures or artificial heating. Air temperatures tended to stratify positively such that high level temperatures were hotter than low level temperatures.

- Variations in internal *radiant temperatures* appeared to result primarily from contrasting internal surface temperatures. Radiant temperatures are calculated based on the relative *view* that a particular point has of the surfaces enclosing it, and as such radiant gradients can be positive, negative or horizontal.

Whilst researchers such as Moseley and Croome, Sinofsky and so on had recognised the significance of the stratification of internal air on the overall thermal behaviour of such spaces, it appears that they had underestimated the importance of variations in internal radiant temperatures.

8:7.2 Modelling Implications of the Observed Behaviour.

At the beginning of this chapter, it was decided to adopt the CIBSE resultant temperature as a measure of how hot or cold the occupants within spaces enclosed by fabric membranes were likely to feel under various conditions. It was shown that in order to predict the resultant temperature at any location within a membrane enclosed space, it is necessary to determine the *air velocity*, *air temperature* and *radiant temperature* at that location.

It was recognised by Moseley that internal air temperatures and air velocities varied from place to place within such spaces, and this was confirmed by the findings of the monitoring programme described in this chapter. Moseley suggested that in order properly account for these variations, it would be necessary to model air movement patterns throughout the entire space. He proposed that this could be best achieved by finite difference modelling of a network of interrelated nodes whose overall behaviour was representative of the air enclosed by the space as a whole[9].

The data collected during the monitoring process described in this chapter however revealed that radiant temperatures can also vary significantly from place to place within such spaces.

This suggests that in order to properly predict internal resultant temperatures, it is necessary to develop a nodal model able to simulate both the behaviour of internal air, and variations in internal radiant temperatures.

8:8. CONCLUSION.

In this chapter a programme of monitoring was described which was carried out in order to investigate the thermal behaviour of a number of spaces enclosed by fabric membranes. The data collected by this process allowed the significance of the various thermal characteristics of such spaces to be assessed and provided a comprehensive data set against which the accuracy of a model used to simulate that behaviour could be tested.

Essentially the monitored behaviour agreed with the observations of the researchers discussed in Chapter 3. The spaces displayed extreme and changeable thermal behaviour, and strong internal thermal gradients were recorded, particularly during periods of bright sunshine or artificial heating. The data presented here however suggested that these thermal gradients were as likely to result from variations in internal radiant temperatures as from the stratification of internal air.

It was apparent therefore that any attempt to accurately predict the thermal conditions within such spaces would require a method which allowed air velocities, air temperatures and radiant temperatures to vary from place to place within a geometrically representative model of the space being simulated. This was likely to require the adoption of a complex nodal approach similar to that recommended by Moseley.

In the next chapter, such an approach will be described, and its accuracy tested against the data collected by the monitoring process described above.

---

1 Wu, H. F; Boonyatikarn, S; Engen, B. W; "The stratification in fabric roof structures- a strategy of energy conservation and system design." *International Symposium on Architectural Fabric Roof Structures*, Orlando, 1984, P192- 196.

2 Sinofsky, M; "Thermal Performance of Fabric in Permanent Construction." *ASHRAE Annual Conference*, June 1985, P3.

3 CIBSE; *CIBSE Guide: Volume A, Design Data,* The Chartered Institute of Building Service Engineers, London, 1986, PA1-4.

4 ibid. CIBSE; *CIBSE Guide...,* PA1-4.

5 ibid. CIBSE; *CIBSE Guide...,* PA1-4.

6 Parsons, K.C; *Human Thermal Environments: The effects of hot, moderate and cold environments on human health comfort and performance. The principles and the practice*, Taylor & Francis Ltd, London, 1993, P61.

7 Grant Instruments (Cambridge) Ltd; *Data Sheet for Model 1201 Squirrel*, Product Information.

---

8 Labfacility Ltd, *Temperature Sensing with Thermocouples and Resistance Thermometers: A Practical Handbook*, Labfacility Ltd, Hampton, 1982, P17.

9 Moseley P; Croome, Dr D; "Air Movement and Ventilation Patterns in Airhouses." The Institute of Structural Engineers, London, 1984, P238- 243.