4: METHODOLOGY.

4:1. INTRODUCTION.

In Chapter 3 the existing body of knowledge relating to the thermal behaviour of spaces enclosed by fabric membranes was critically reviewed. It was suggested that previous researchers had attempted to simplify analysis of this subject by adopting techniques developed for investigating the thermal behaviour of more '*conventional*' spaces, and that such techniques were inappropriate when applied to spaces enclosed by fabric membranes.

Analytical techniques had not developed in step with empirical knowledge, and this left researchers unable to accurately predict the characteristic behavioural patterns which they observed. This suggested that comprehensive research was required within most areas of this subject, ranging form simple studies of the properties of fabric membranes themselves to more complex attempts to simulate the behaviour of space enclosed by such membranes.

In this chapter, the development of a general methodology used to structure the research presented in this thesis is described. Because of the complexity of the subject however and the over simplistic nature of the existing body of knowledge, it seemed necessary first to undertake a series of simple pilot studies. These were carried out in order to provide more clear information about the characteristic thermal behaviour spaces enclosed by fabric membranes and to identify what problems were likely to be encountered in predicting that behaviour.

4:2. THE PILOT STUDIES.

4:2.1 **The Purpose of the Pilot Studies.**

Because of the lack of existing research relating to the thermal behaviour of spaces enclosed by fabric membranes, a number of simple pilot studies were undertaken and for this purpose limited monitoring of a range of existing unheated spaces was carried out. These studies were intended to satisfy three basic aims:-

- To gain an overall impression of the characteristic thermal behaviour of spaces enclosed by fabric membranes.
- To clarify how such behaviour could best be studied if a more comprehensive monitoring programme was undertaken.
- To establish what information would be required if an attempt was made to simulate that behaviour.

4:2.2 Apparatus used for the Pilot Studies.

Detailed information about the apparatus used to monitor the thermal behaviour of the spaces selected for the pilot studies, and the reasons for their use are described as part of the main study in Chapter 8, however the equipment is listed briefly here:-

- *Internal apparatus.*
- A series of Type U bead thermistors for measuring internal and external temperatures.
- Two radiant shields, and two blackened globes for selectively shielding these thermistors, respectively allowing air temperatures and resultant temperatures (a measure of human thermal comfort described in more detail in Chapter 8) to be monitored.
- Two relative humidity sensors.
- A 1200 series Squirrel meter / logger with which to record the monitored data.

- *External apparatus.*
- A radiant shield allowing the external air temperature to be monitored.
- A solarimeter for monitoring the intensity of horizontal global solar radiation.
- A 1200 series Squirrel meter / logger with which to record the monitored data.
- A weather tight box in which to store the external data logger.

4:2.3 Method Adopted for the Pilot Studies.

The internal apparatus allowed comfort temperature, air temperature and relative humidity to be monitored at two locations, and this enabled a strategy to be adopted that allowed the potential variations in internal conditions to be investigated. A representative selection of external thermal conditions close to the enclosures were also monitored, and this provided an insight into the mechanisms affecting the recorded internal conditions.

At the time that the pilot studies were undertaken, only three buildings were available that were considered appropriate for this study . The reason for the choice of these buildings, and detailed descriptions of their thermal characteristics are presented along with the main monitoring study in Chapter 8, however the buildings were:-

- Landrell Fabric Engineering.
- The Main Arena of the Royal International Eisteddfod Arena.
- The All England Lawn Tennis and Croquet Club, Covered Courts.

Simple illustrations indicative of the basic form of these spaces are shown overleaf.

Figure 4:2.3a Landrell Fabric Engineering.
North Elevation, 1:500.

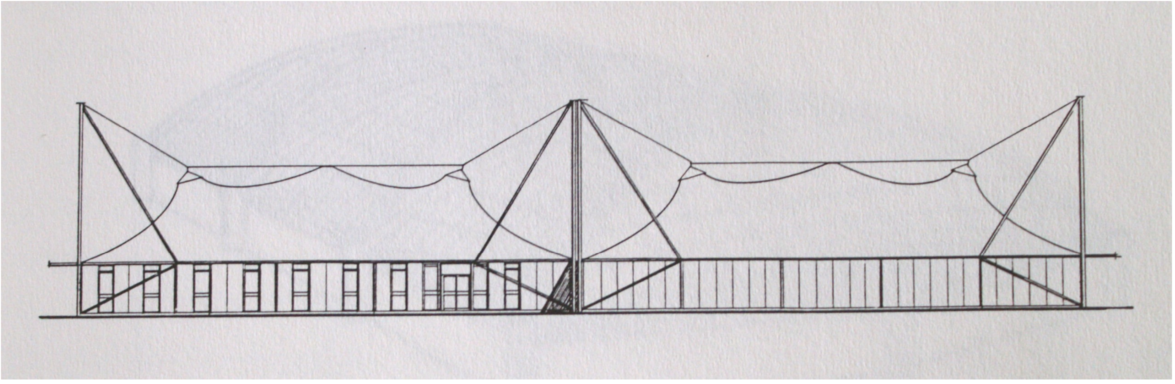


Figure 4:2.3b The Royal International Eisteddfod Pavilion, Main Arena.
Section, 1:1000.

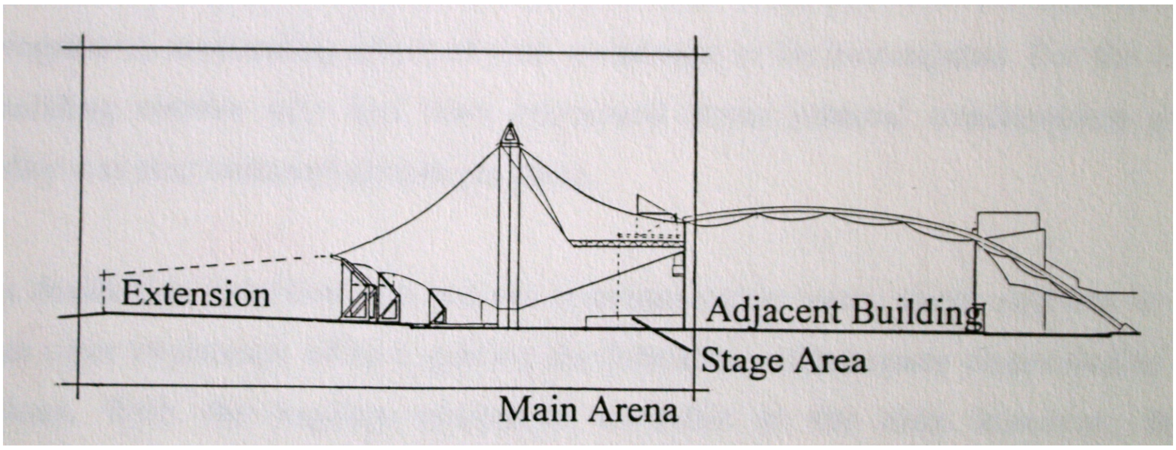
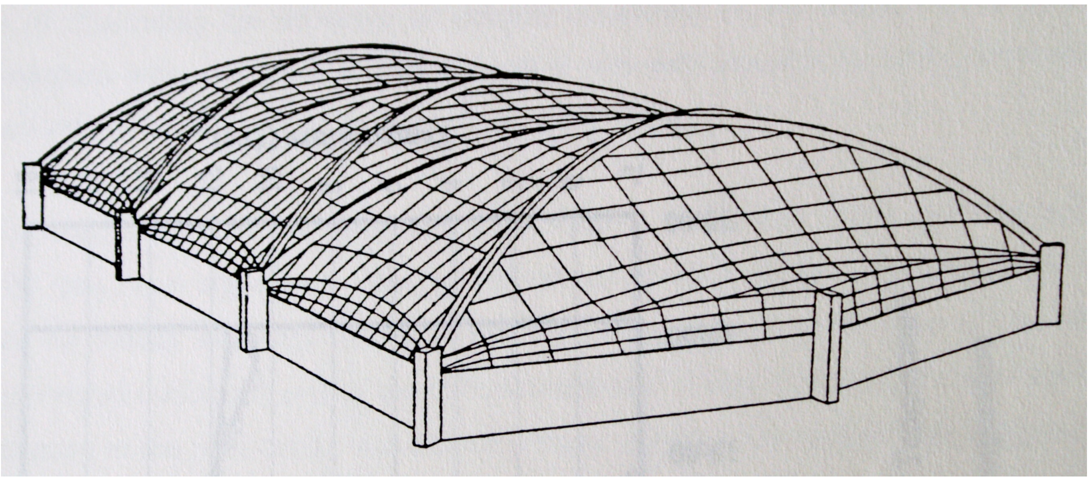


Figure 4:2.3c The AELTC Indoor Tennis Centre, Covered Courts. Perspective Sketch.



4:2.4 Case Study 1: Landrell Fabric Engineering.

The Landrell factory was enclosed by an unusual double membrane envelope with a very low combined translucency and a large air cavity between the two membranes.

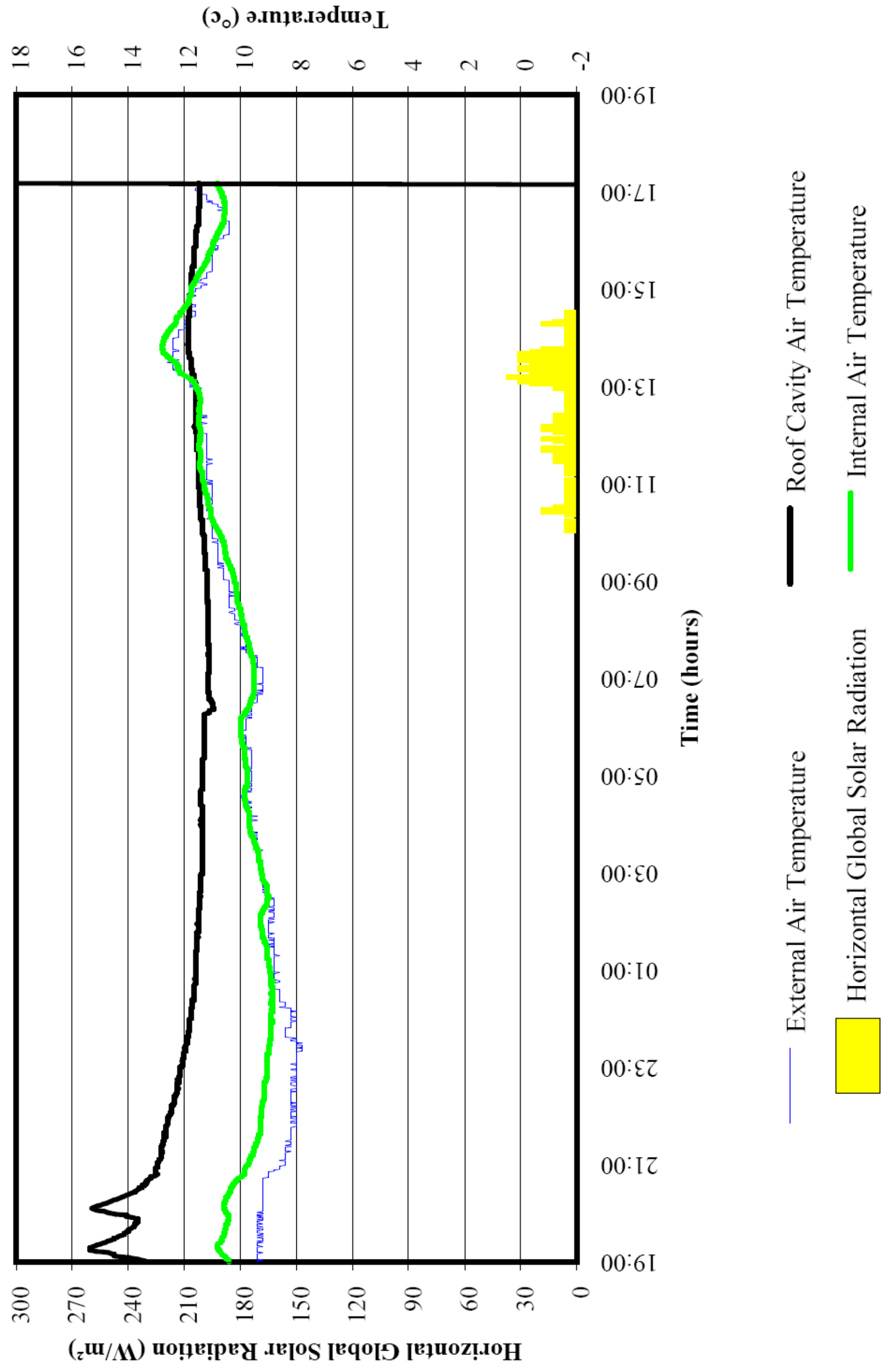
Externally, horizontal global solar radiation and air temperature were monitored. Internally two positions were chosen, one 2m above the ground within the main factory space, and another within the cavity between the two membranes, and at each point shielded air temperature and a globe temperature were recorded. These positions were chosen to allow the progressive moderating effect of each membrane to be investigated. For the benefit of the building owners who had been concerned about internal condensation problems, humidity was also recorded at both positions.

It was decided to record data from the sensors instantaneously every thirty seconds in order to give a clear impression of how quickly the behaviour of the space responded to climatic variations. With the logging equipment available at the time however, this short monitoring interval only allowed data to be collected for 22 hours, and so a period was chosen from 19:00 on Friday 17/12/93 to 17:00 on Saturday 18/12/93. This covered the cool down period on Friday evening after the building was vacated and the full solar day on Saturday when the space was unheated.

Figure 4:2.4, overleaf, presents some of the data monitored during this period. External air temperature, air temperature within the cavity between the two membranes, air temperature within the factory space and horizontal global solar radiation are shown. These conditions were chosen to illustrate the progressive moderating effect of the two membranes simply, without providing so much information as to obscure the underlying trend.

Figure 4:2.4 Landrell Fabric Engineering: Pilot Study.

17/12/93 to 18/12/93.



Unfortunately conditions were very unusual during the period monitored. The external air temperature only varied by 4^{o}c during the whole 22 hour period, but this thermal stability was accompanied by severe gales and a maximum solar radiation intensity of just $40W/m^{2}$. In terms of illustrating the influence of external conditions on the internal environment these conditions were not ideal, and as a result it was only possible to make some very basic observations about the thermal behaviour of the space.

The difference between the air temperature recorded in the factory space and that in the roof cavity was most significant after the antiquated heating system (represented by the two peaks on Friday evening) was switched off. Temperatures in the two spaces then slowly converged during the rest of the period monitored. It was apparent however that the air temperature in the roof cavity was almost always closer to the external air temperature than the air temperature in the factory space. As a result the conditions in the roof cavity were seen to be generally more variable than those in the factory space. This clearly illustrates the progressive moderating effect of the two membranes.

The difference between air and globe temperatures recorded in the factory space was never more 0.4^{o}c, but this may have been as a result of the exceptional stability of the external conditions and the negligible solar radiation intensity. Relative humidity was continually over 90% in the unventilated roof cavity, and reached 81% within the factory space itself. This combined with the low thermal mass of the external roof membrane meant that condensation problems were inevitable.

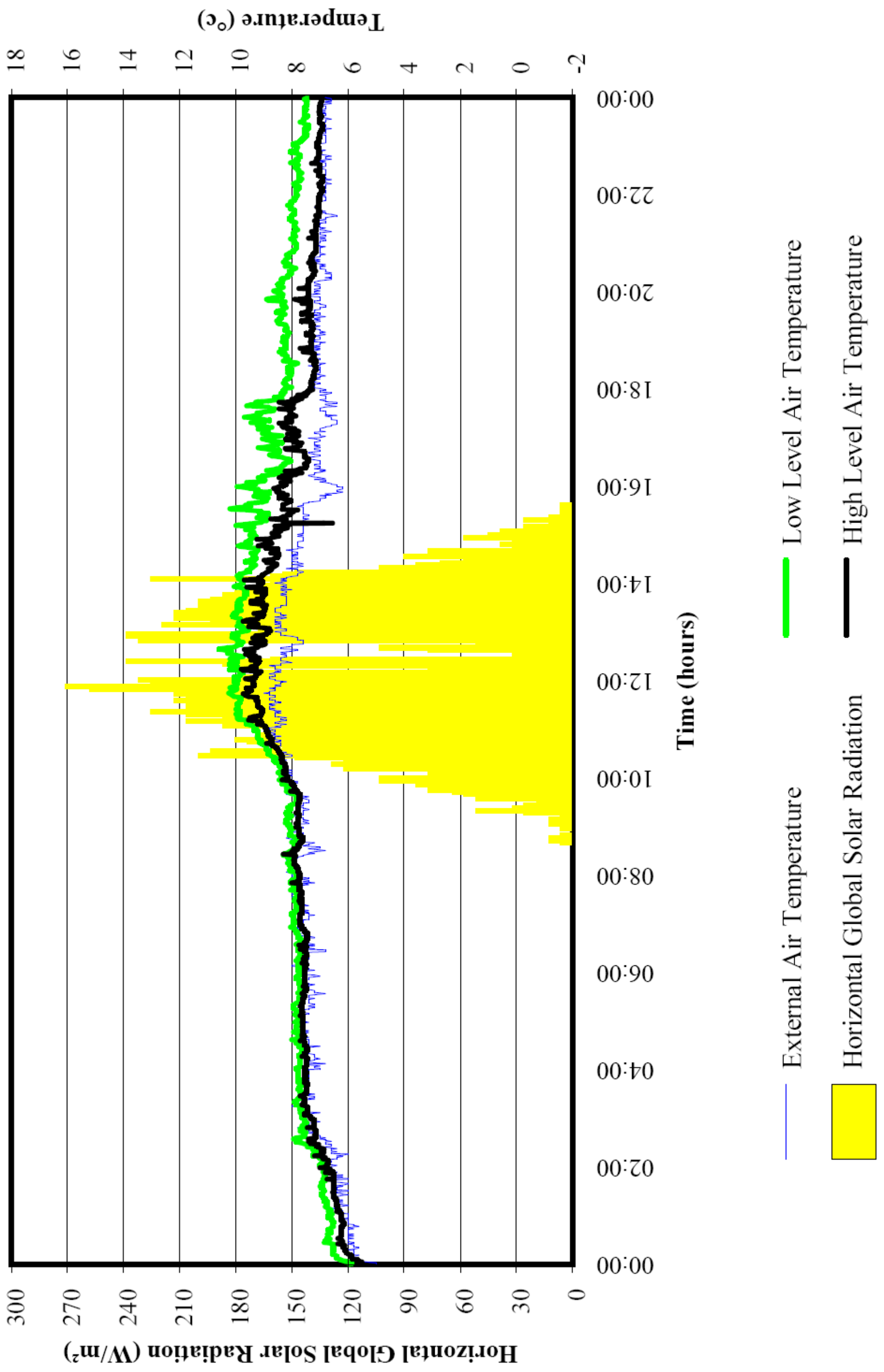
4:2.5 Case Study 2: The Royal International Eisteddfod Pavilion, Main Arena.

Analysis of the data recorded at the Landrell factory space suggested that the thirty second logging interval was unnecessarily short, producing a large amount of repetitive information for just a short period of time. A one minute interval was adopted therefore for monitoring the single membrane Eisteddfod Arena. This meant that more than two full days could be monitored. For this purpose a period was chosen between 15:00 Tuesday 11/01/94 and 09:00 Friday 14/01/94 when the space was unoccupied.

Externally, horizontal global solar radiation and air temperature were monitored. Internally two positions were chosen, one 1m above the stage and the other 5.5m above the stage, and at both positions a shielded air temperature, and a globe temperature were monitored. These positions were chosen in order to give an impression of the thermal stratification within the space. Again, because of concerns voiced by the building owners about condensation, relative humidity was also monitored at both positions. A sample of the recorded data is presented overleaf:-

Figure 4:2.5 The Royal International Eisteddfod Pavilion, Main Arena: Pilot Study.

13/01/94



External conditions during the monitored period were slightly more informative than those recorded at the Landrell factory. The external air temperatures did vary slightly, and there was a significant quantity of solar radiation.

On the whole internal air temperatures followed the external air temperature fairly closely and with little perceptible delay. The air temperatures recorded at the two internal positions tended to be within 0.5^{o}c of each other, but the influence of solar radiation made them diverge by as much as 2.8^{o}c. These temperatures then slowly converged again during the more stable night time conditions.

Unlike the behaviour observed by previous researchers described in Chapter 3, negative thermal stratification was recorded between the two monitor positions. It seemed likely however that this resulted from the infiltration of cold external air through openings in the membrane envelope at eaves level. Such infiltration would affect the higher position more than the lower one, resulting in '*forced*' negative stratification.

Even with the significant solar radiation recorded, the maximum difference between globe and air temperatures was just 1^{o}c and the average difference was just 0.1^{o}c. Variations such as these were as likely to have resulted from the difference in the time which conditions took to reach the thermistors through the different types of sensor shields as from any actual difference between those conditions. Relative humidity averaged over 70% throughout the monitored period, but reached over 90% early in the mornings.

4:2.6 Case Study 3: The AELTC Indoor Tennis Centre, Covered Courts.

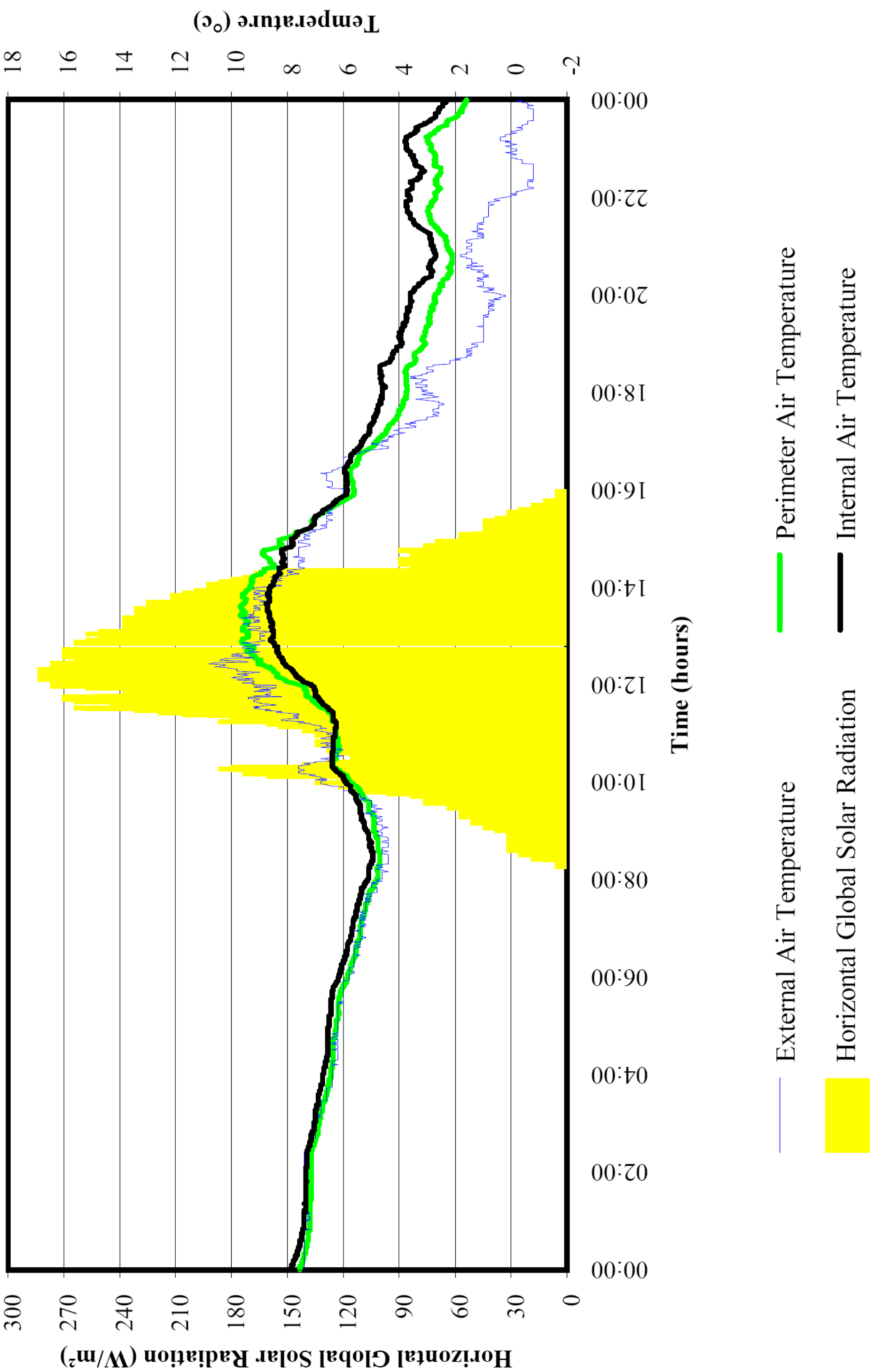
As with the Eisteddfod Arena, conditions at the single skin AELTC Covered Courts were recorded every minute. The Covered Courts were occupied intermittently throughout the week and weekend, but only by small numbers of people, and so a period was chosen arbitrarily which ran from 17:00 on Tuesday 18/01/94 to 11:00 on Friday 21/01/94.

Externally, horizontal global solar radiation and air temperature were monitored. Inside, two positions were chosen, one three metres above the ground beside the perimeter louvers and the second at a similar height further towards the centre of the space. These positions were chosen in order to give an impression of the rate at which conditions diffused across the space as a result of infiltration. At both positions a shielded air and a globe temperature were recorded. For the sake of completeness, relative humidity was also monitored.

The graph overleaf illustrates a sample of the recorded data characteristic of the observed behaviour.

Figure 4:2.6 The AELTC Indoor Tennis Centre, Covered Courts: Pilot Study.

19/01/94.



External conditions were ideal during the period monitored in terms of the information they provided. There was significant solar radiation on both days, and the external air temperature slowly dropped by 10^{o}c to reach below 0^{o}c during the second day.

Because of the high infiltration rates within this relatively open structure, internal temperatures tended to follow external temperatures fairly closely. During the coldest period however the affects of internal thermal mass meant that it was 3.5^{o}c warmer inside the enclosure than it was outside.

The thermal delay caused by the diffusion of conditions across the 4m between the two sensor positions was clearly noticeable from the monitored data. At the position near to the perimeter louvres the recorded air temperature was almost always closer to the external air temperature than the more central position was. On average the difference between the two recorded internal air temperatures was just 0.3^{o}c however it was apparent that solar radiation tended to cause these temperatures to diverge. The resultant thermal gradient was then sustained for some time after the sun had set as a result of internal thermal mass.

Solar radiation seemed to affect the behaviour of the space both indirectly through external air temperatures and by direct transmission. The sensitivity of the space to even small changes in solar intensity can be clearly seen, but despite this, the difference between recorded internal globe and air temperatures was on average just 0.1^{o}c.

As with the other spaces investigated, relative humidities of over 90% were recorded within the Covered Courts, particularly early in the morning.

4:2.7 Analysis of the Information Obtained by the Pilot Studies.

A number of qualitative observations could be made about the characteristic thermal behaviour of the spaces monitored which made it clear how such behaviour could best be studied if a more comprehensive monitoring programme was undertaken, and what methodology to adopt for the rest of the research presented in this thesis:-

The rate of change of conditions within the monitored spaces was significantly faster than may have been expected within more thermally massive conventional structures. this responsiveness appeared to result both from the quick transmission of conditions across the low thermal resistance membrane envelopes and the direct transmission of solar radiation through them. This could be compounded further by the infiltration of external air which suggested that it would be necessary to monitor wind speed if more comprehensive studies were undertaken in the future.

Internal conditions responded quickly to variations in the external climate, and so significant differences between internal and external conditions only seemed to occur as a result of large energy inputs such as solar radiation or artificial heating. Such fast response meant that future studies should take care to select appropriate temperature sensors. The blackened globes and radiant shields used for the pilot studies meant that internal temperature sensors took some time to reach a '*steady state*' following changes in the conditions they were recording. It was possible that this delay may have affected the accuracy of the data recorded.

There was no significant difference between the radiant and air temperatures recorded within any of the spaces investigated, however this would not necessarily be the case during future studies when solar radiation may become a more important factor. In order for the influence of radiant conditions to be properly quantified, the temperature of the membrane envelopes themselves may have to be monitored, and their solar transmittance determined.

It was seen that conditions recorded at separate positions within the spaces monitored tended to diverge under the influence of external stimuli such as solar radiation or artificial heating, but that these slowly converged again during more stable conditions. Whilst the differences internal temperature gradients recorded during the pilot studies may have been relatively small, the work of the previous researchers reviewed in the Chapter 3 suggested that significant thermal stratification may exist during more unstable conditions or during periods of bright sunshine. This meant that establishing an appropriate strategy for the positioning of internal sensors during future studies would be very important.

Beyond these limited observations however, extracting usable information from the large amounts of data collected was a very difficult process. Direct comparison between changes in the external environment and the resultant behaviour of the enclosed space were impossible without first completely understanding the thermal response mechanism of the building being studied. For example, at a specific instance the air temperature outside may be decreasing at the same time that the air temperature inside was increasing, due thermal storage, delayed transmission through the spatial envelope, and so on.

This meant that in order to properly explain the observed behaviour, it would first be necessary to understand the individual heat transfer mechanisms from which that behaviour resulted. Understanding of this kind could only come from a more elemental approach than had been attempted with the pilot studies which would allow the complex observed behaviour to be broken down into its component parts. Such an approach is described in section three of this chapter, overleaf.

4:3. THE GENERAL APPROACH ADOPTED FOR THE RESEARCH PRESENTED IN THE REST OF THIS THESIS.

4:3.1 **Introduction.**

The specific thermal situations that the pilot studies investigated were peculiar only in that the spatial envelope was formed predominately by a thin translucent fabric membrane. Whilst the resulting thermal behaviour of the enclosed spaces may have appeared unconventional, the internal heat transfer mechanisms which produced that behaviour were no different from those found within any other type of enclosure.

The complexity of the observed behaviour however could not be properly explained until the individual heat transfer mechanisms from which that behaviour resulted were understood. It had been shown by the work of previous researchers that this could not be done properly using conventional analytical techniques for two fundamental reasons:-

- The great number of simplifications adopted by conventional theory which were inappropriate for describing the thermal behaviour of thin fabric membranes.
- The non uniformity of conditions found within spaces enclosed by fabric membranes.

Thermal stratification is now a commonly recognised phenomena within the built environment, and several general purpose thermal models are available with which this may be predicted. The dynamic thermal behaviour of fabric membranes however is something which has yet to be properly quantified.

This suggested that it was appropriate to investigate these two elements separately. Such an approach allowed the unique *thermal behaviour of fabric membranes* to be investigated in detail using specially developed techniques, whilst the resulting *thermal behaviour of spaces enclosed by fabric membranes* could be assessed using complex, but commonly available spatial analysis models.

In order to investigate these two elements thoroughly, an approach was adopted for each which was composed of three basic processes:-

- Comprehensive data was obtained describing actual *thermal behaviour* under a range of conditions.
- A detailed *thermal specification* was developed which could be used to describe individual thermal situations.
- A general *theoretical model* was set up which could be used to simulate individual situations, the accuracy of which could be tested against the monitored data.

The application of such an approach to the two major elements of this research is described in the following parts of this section, below.

4:3.2 The General Approach Adopted for Investigating the Thermal Behaviour of Fabric Membranes.

The first '*half*' of the research investigated the thermal behaviour of fabric membranes themselves. The investigation was carried out according to the three part general methodology described above, covering the *thermal behaviour*, *thermal specification* and *theoretical modelling* of fabric membranes:-

- *Thermal Behaviour.*
  As with the pilot studies, it was considered that monitoring the thermal behaviour of fabric membranes would provide an insight into the characteristic thermal behaviour of fabric membranes upon which a method for predicting that behaviour could be developed. The recorded data would also provide information which could be used to test the accuracy of such a method.

  This obviously required that both the behaviour of the membrane itself and the environmental conditions surrounding it were recorded.

- *Thermal Specification.*
  Specifying the thermal situation affecting the behaviour of individual membranes involved not only describing the environmental conditions surrounding them, but also their thermal properties. How these properties could best be described would be made more clear by the behavioural data obtained by the monitoring programme described above.

  It was considered that properly gathering and explaining these properties was a particularly crucial area which had been lacking in the work of previous researchers discussed in Chapter 3.

- *Theoretical Model.*
  A theoretical model was required to provide a means of predicting that membrane behaviour which may affect the thermal conditions found within a space enclosed by it. This model could be substantiated by the proper measurement of membrane properties, and validated with the behavioural data discussed above.

4:3.3 The General Approach Adopted for Investigating the Thermal Behaviour of Spaces Enclosed by Fabric Membranes.

The second part of the research investigated the thermal behaviour of spaces whose external envelope was formed predominately by a thin fabric membrane. This was done according to the previously described three part general methodology, covering the *thermal behaviour*, *thermal specification* and *theoretical modelling* of spaces enclosed by fabric membranes:-

- *Thermal Behaviour.*

  The aim of this part of the research was to monitor the thermal behaviour found within spaces enclosed by fabric membranes in a more detailed way than had been achieved with the pilot studies. The monitored information provided an insight into the characteristic thermal behaviour of such spaces upon which a method for predicting that behaviour could be developed. This process also provided behavioural data against which the accuracy of such a method could be tested.

  As was discussed in Section 2 of this chapter the thermal behaviour of such spaces needed to be monitored in a way which properly represented their characteristic thermal behaviour. This posed a complex series of problems because of the non uniformity of the thermal conditions found within such spaces and because of their fast response to changes in environmental conditions.

- *Thermal Specification.*

  This involved describing all those characteristics which had been observed to significantly affect the thermal behaviour of spaces enclosed by fabric membranes.

  The physical characteristics of the spaces to be modelled could be based on production information obtained from the building designers or occupants, whilst the thermal state of the spatial boundaries other than the membrane could be estimated from the monitored data described above. The thermal state of the membrane itself, and the quantity of solar radiation which it transmitted into the enclosed space however could only be properly determined using a theoretical model as described in the previous part of this section.

- *Theoretical Model.*

  It was considered that the heat transfer theory necessary to predict the thermal behaviour found inside spaces enclosed by fabric membranes was no different from that which was necessary to predict the variable conditions found inside other complex spaces. This meant that if the thermal state of the spatial boundary could be properly specified, it should be possible to apply general analysis techniques here with as much confidence as in more conventional situations.

A number of commercial packages exist specifically for the purpose of simulating thermal behaviour within complex spaces. It was considered that a carefully chosen existing package in combination with a theoretical model able to simulate the thermal behaviour of fabric membranes, should be able to simulate the data recorded within the monitored spaces.

4:4. CONCLUSION.

In this chapter some basic data describing the thermal behaviour of spaces enclosed by membrane envelopes was presented. The behaviour of such spaces appeared to be extremely sensitive to changes in environmental conditions, and it was seen that internal conditions could vary significantly from place to place throughout the enclosure.

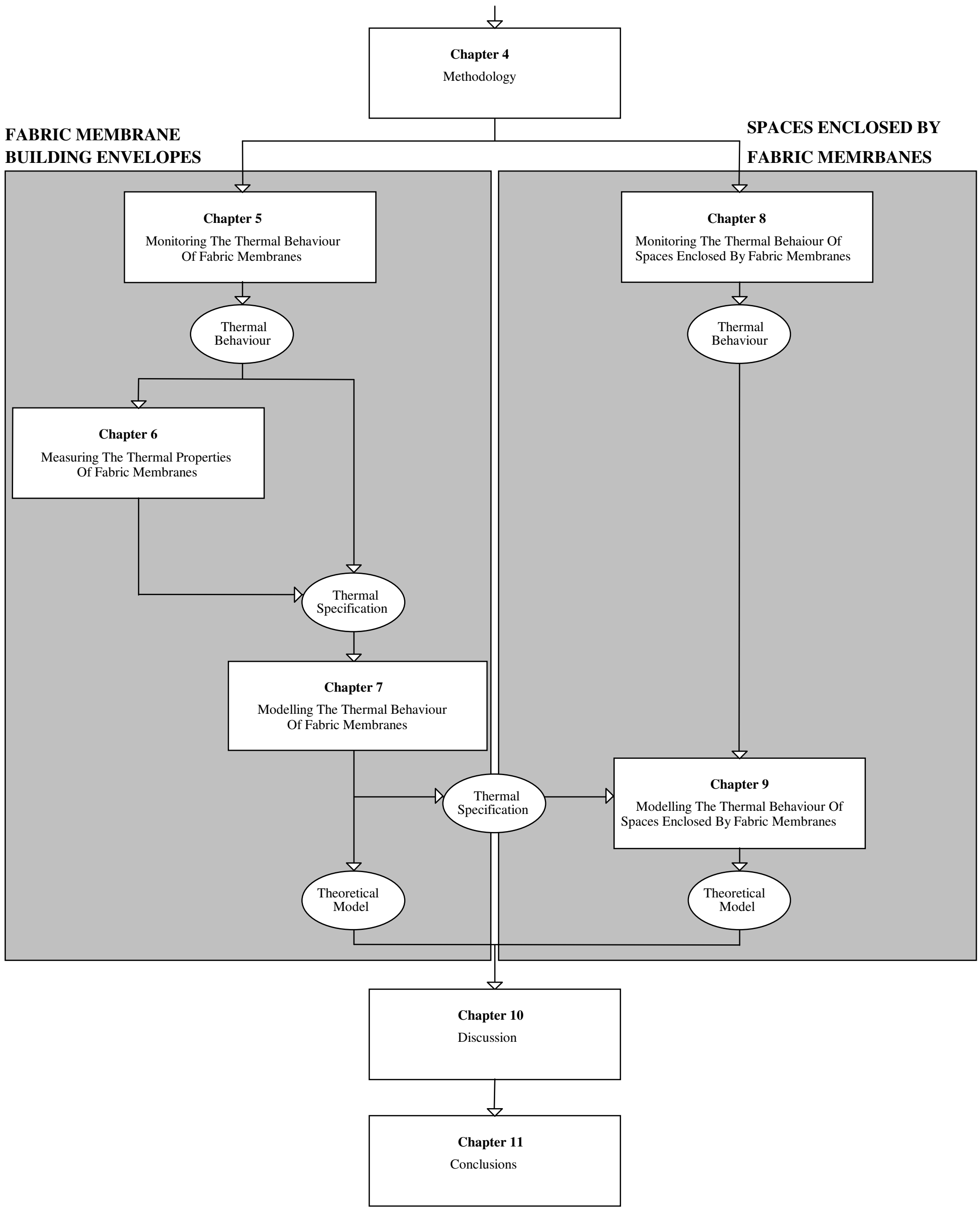
The observed behaviour appeared to be affected most significantly by conditions which were able to infiltrate directly into the space such as external air and solar radiation, but indirect heat transfers between the enclosed space and the internal surface of the membrane boundary also appeared to have some affect.

It was proposed that future investigations of this type should monitor external wind speed and the temperature of the membrane boundary in addition to the parameters recorded during this study in order to provide more complete information. There also seemed to be a need to develop a more structured approach for measuring the variability of internal conditions and that these conditions would have to be monitored using highly responsive thermal sensors.

The complexity of the observed behaviour suggested that the rest of this research could be much simplified if the fabric membrane building envelope, and the space enclosed by it were considered separately. This would allow the unusual thermal behaviour of fabric membranes to be studied in detail using specially developed analytical techniques, whilst the resultant thermal behaviour of the enclosed space could be investigated more effectively by using general theoretical techniques.

The overall methodology proposed for this purpose is illustrated schematically overleaf.

Figure 4:4 Schematic Illustration of the Methodology Adopted for the Research Presented in the Rest of this Thesis.



The next chapter describes an investigation into the first of these parts; monitoring the thermal behaviour of fabric membranes.