11: CONCLUSIONS.

11.1 INTRODUCTION.

The aim of the research described in this thesis was to provide a sound theoretical base from which investigations into the thermal behaviour of spaces enclosed by fabric membranes might be undertaken with confidence. In Chapter 10 the findings of this research were brought together so that they could be compared with the work of previous researchers, and a number of remaining problems were then discussed.

In this chapter the main conclusions of the research are briefly summarised.

11.2 THE INCREASING INADEQUACY OF EXISTING ANALYTICAL TECHNIQUES.

The review of the existing literature relating to this subject presented in Chapter 3, revealed that until relatively recently, many designers considered that fabric structures were essentially temporary, and that environmentally they behaved as '*enclosures of external space*'. In the last few years however, it has become increasingly evident that modern fabric membranes can be as durable and permanent as many more conventional materials and as a result fabric structures are now being demanded for a diverse range of new applications.

The simple analytical techniques, developed in order to investigate the thermal behaviour of *temporary enclosures of external space* are proving unable to satisfying the requirements of this emerging market, and it was in order to address this problem that the research described in this thesis was undertaken. This research was 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.

11.3 THE THERMAL BEHAVIOUR OF FABRIC MEMBRANES.

Many previous researchers investigating the thermal behaviour of fabric membranes had accepted the conventional assumption that the affect a building envelope has on spaces enclosed by it can be accurately determined from its *U-value* and *shading coefficient*. More detailed investigations made it apparent that this assumption was inappropriate, and yet today most membrane manufacturers continue to describe the thermal properties of their products in terms of U-values and shading coefficients.

The research presented in this thesis suggests that fabric membranes actually affect the thermal behaviour of the spaces they enclose as a result of their *internal surface temperature* and the amount of *thermal radiation* they direct into those spaces. Because of their low thermal mass and translucency, it was seen that both of these parameters are exceptionally sensitive to changes in environmental conditions, and that the extent of this sensitivity can only be affected by their angular thermal optical properties.

The environmentally responsive thermal behaviour of fabric membranes can only be predicted accurately by using dynamic modelling techniques. It was apparent however that such techniques are more sensitive to the usual uncertainties of theoretical modelling than might have been expected. This seems to result primarily from the low mass of fabric membranes which means that every modelling inaccuracy or oversimplification results instantly in an error within the predicted behaviour. When such techniques are used to simulate the behaviour of more massive, conventional materials, these inaccuracies are generally moderated over time as a result of their thermal storage capacity.

In order to overcome some of these difficulties, it is recommended that future studies are based on more detailed climatic information, and that more realistic internal and external surface convection heat transfer calculations are developed.

11.4 THE THERMAL BEHAVIOUR OF SPACES ENCLOSED BY FABRIC MEMBRANES.

Many of the previous researchers investigating the thermal behaviour of spaces enclosed by fabric membranes had considerably simplified their analysis by assuming that internal conditions were entirely uniform. More recently however, field studies revealed that this was an inaccurate assumption, and in fact strong thermal stratification can exist within such spaces. This they assumed resulted from internal buoyancy forces, suggesting that it would be possible to predict the thermal behaviour of such spaces accurately if internal air movement patterns could be simulated.

The research presented in this thesis however suggests that thermal gradients within such spaces are actually generated by the difference between the extreme and changeable internal surface temperatures of fabric membranes compared to other more thermally stable internal surfaces such as the floor. This means that internal thermal stratification is as likely to result from differences in radiant temperatures as from the differences in air temperatures highlighted by previous researchers. Properly simulating the thermal behaviour of such spaces therefore, requires a model which predicts not only internal air movement patterns, but also the distribution of internal radiant temperatures.

Whilst predicting the distribution of radiant temperatures within enclosed spaces is a well established, mathematically explicit process, predicting air movement patterns within enclosed spaces is exceptionally complex and requires the use of Computational Fluid Dynamics (CFD) techniques.

The adaptation of CFD techniques for simulating the thermal behaviour of spaces in the built environment is a relatively recent development, and the general applicability of currently available models means that they can be inappropriate for certain specific uses. In the case of spaces enclosed by fabric membranes, simplifications in boundary specification and solar modelling techniques appear to result in an inability to accurately predict the stratification of internal air temperatures. Radiant temperatures however are relatively simple to predict, and so with experience it is possible to gain a good overall impression of the thermal conditions found within such spaces.

11.5 THE NEED FOR FURTHER RESEARCH.

The existing body of knowledge relating to the thermal behaviour of spaces enclosed by fabric membranes was considered to be fragmented, over simplistic and largely unsubstantiated.

The research presented in this thesis goes a long way toward providing a more rigorous theoretical framework for the subject. It is apparent however that there is a considerable way to go before it will be possible to undertake investigations into the thermal behaviour of spaces enclosed by fabric membranes with the same degree of confidence that investigations into their structural behaviour can already be carried out.

The range of techniques which had to be adopted for the purposes of this research were fairly complex and not entirely appropriate for actual design investigations. It is possible to adapt these techniques in order to allow such investigations to be carried out, however if such a process is to become viable within the constraints of a tight design schedule then a number of further developments are required:-

- Information that properly describes the complex angular thermal optical properties of fabric membranes must become commonly available.
- The behaviour of membrane boundaries must be simulated dynamically as an integral part of a CFD code.
- Transient investigations must become possible based on detailed time series climatic data.
- Easier and more appropriate geometrical specification techniques are required, possibly based on Body Fitted Co-ordinate grids.

Until such a time as these developments are carried out, the complex approach which had to be adopted for the purposes of this research is likely to remain fairly specialist, only used for the design of membrane enclosed spaces whose environmental performance is seen as a major concern. Perhaps the success of such spaces will motivate further research.