6: MEASURING THE THERMAL PROPERTIES OF FABRIC MEMBRANES.

6:1. INTRODUCTION.

In the previous chapter, a test cell was described whose purpose was to allow the thermal behaviour of fabric membranes to be studied under a variety of conditions. It was considered that these membranes might affect the thermal conditions found within a space enclosed by them through their internal surface temperature and the amount of solar radiation they direct into that space.

The test cell proved unable to accurately record the quantity of solar radiation directed into it by the membrane samples investigated, however a comprehensive data set was obtained describing their internal surface temperatures under a variety of conditions.

Analysis of this data suggested that fabric membranes can be considered to be perfectly smooth and that they have insufficient mass to affect their overall thermal behaviour. This meant that their internal surface temperature was only significantly affected by their *solar absorptance* and *long wave infra red absorptance*. In order to understand the thermal behaviour of spaces enclosed by such membranes however, it was apparent that it would also be necessary to quantify their *solar transmittance* and *solar reflectance*. Collectively, these properties are known as *thermal optical properties*[1].

An attempt was made to compile a data base of these properties based on the information available from membrane manufacturers, but this produced disappointing results. The available information was on the whole incomplete, unsubstantiated and entirely inadequate for the purposes of predicting the thermal behaviour of fabric membranes.

Following the general trend within the fabric structures industry, the available information tended to concentrate on structural rather than environmental properties. A typical example of this was provided recently by an independent survey of 34 commercially available fabric membranes published by '*Fabrics and Architecture*'[2]. 42 standard properties were requested from membrane manufacturers, of which only three related to environmental properties. Even at such a basic level it was found that manufacturers could only complete around 10% of this part of the survey and little of the information they provided was of any practical use.

It appeared that the only way to acquire the appropriate properties information necessary for this research would be to actually measure those properties. In this chapter therefore, the thermal optical properties of fabric membranes are defined, techniques for measuring those properties are discussed, and the results obtained by selected techniques are analysed. The information obtained by these techniques was then used in order to simulate the thermal behaviour of fabric membranes, as described in the next chapter.

6:2. THE GENERAL APPROACH ADOPTED FOR MEASURING THE THERMAL OPTICAL PROPERTIES OF FABRIC MEMBRANES.

6:2.1 The Categorisation of Thermal Optical Properties.

The thermal optical properties of a material describe its characteristic radiant behaviour within the thermal spectrum[3]. All bodies which are hotter than 0^{o}K emit thermal radiation. According to Kirchoff's law the emissivity of a surface is equal to its radiant absorptivity at a given temperature and wavelength. The difference in the total amount of radiation emitted and absorbed by a body at any given moment however may result in a net heat transfer which will produce a change in the temperature of that body.

Thermal optical properties are treated as a function of three basic parameters; *transmittance*, *reflectance*, and *absorptance*, describing the ratio of the transmitted, radiated or absorbed radiant flux to the incident radiant flux[4]. According to the Kirchoff relationship, within any specified waveband of the electromagnetic spectrum the sum of the absorptance, transmittance and reflectance of a material will equal one[5].

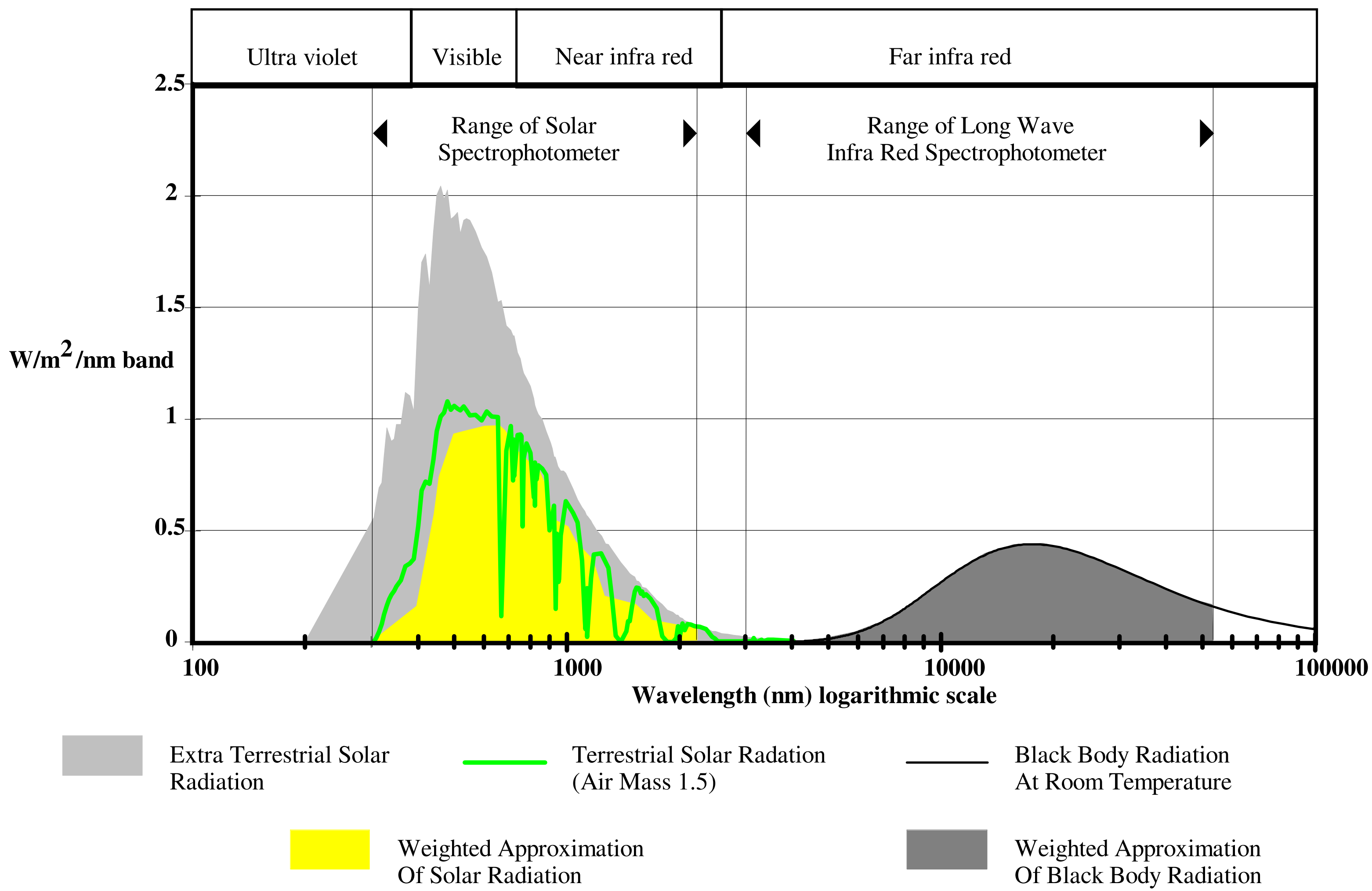
Radiation has direction. The directional quality of radiation is generally categorised as:-

- *Direct beam,* which includes all *collimated* radiation[6].
- *Diffuse*, describing radiation propagated in many directions, i.e. that which is not direct[7].
- *Hemispherical*, referring to the total hemispherical flux about the normal to a surface, i.e. the sum of diffuse and direct beam radiation.

As the directional nature of radiation incident upon a material changes, so the relative proportion which is absorbed, transmitted or reflected may vary significantly. This means that in order to properly quantify the optical properties of a material it is necessary to measure its transmittance, reflectance and absorptance as a function of angle of incidence.

Thermal radiation includes all those wavelengths of the electromagnetic spectrum which will heat a body when absorbed by it, ranging from about 100nm to 100,000nm[8]. In general, the higher the temperature of a body, the lower the average wavelength of the radiation it emits. The range of terrestrial temperatures experienced within the built environment is comparatively small, and relative to the temperature of the sun this range is very cold and hence radiating within a much higher waveband. This anomaly allows us to categorise thermal radiation as *solar radiation* and *terrestrial* or *long wave infra red radiation*. *Figure 6:2.1* overleaf shows the spectral distribution of this categorisation, and indicates the range of thermal radiation which can be investigated using the measurement techniques described in the next two parts of this section.

Figure 6:2.3 Diagram to Illustrate the Categorisation and Measurement of the Thermal Wavelengths of the Electromagnetic Spectrum.



6:2.2 The Solar Optical Properties of Fabric Membranes.

Solar radiation may be considered to include the *ultra violet*, *visible* and *near* or *short wave infra red* wavebands. Around 97% of the solar radiation incident upon the earth's surface is within the range 300 to 2,300nm. Its spectral profile is roughly analogous to that of a black body at 5762^{o}K[9], and as terrestrial temperatures are unlikely to reach anything like this temperature, solar radiation reaching the earth may be treated as a pure thermal gain.

The continually changing position of the earth relative to the sun, and the diffusing nature of the atmosphere gives solar radiation incident upon the earth's surface a complex directional composition. For simplicity however, this is usually considered to consist of entirely *diffuse*, and entirely *direct beam* components. If the direct beam solar optical properties of a material are known for all angles of incidence, then its diffuse properties may be calculated by integration.

The specific techniques used in order to measure the angular direct beam solar optical properties of fabric membranes will be described in detail in the next two sections of this chapter, however in order to explain the format of the chapter, the overall methodology is summarised in outline below.

Optical properties are measured by shining a beam of radiation of known wavelength onto the surface of a sample, and then comparing the intensity of the incident beam with that of the reflected, transmitted or absorbed radiation. Because of the slightly irregular surface and translucent nature of fabric membranes, the radiation they reflect and transmit is likely to be partially diffuse. Measuring diffusely transmitted solar radiation is a relatively simple process simply requiring that samples are placed in front a standard integrating sphere which will collect all the transmitted radiation. Measuring diffusely reflected radiation however is far more complex because the incident and reflected components are both on the same side of the sample.

In order to detect both transmitted and reflected hemispherical flux, whilst allowing the angle of the incident radiation to change, it is necessary to use an Edwards type integrating sphere. This allows samples to be placed on a rotating holder inside the sphere itself, so that their orientation can be varied relative to a fixed direction source beam. Because the sample is completely contained by the integrating sphere, all the reflected and transmitted flux is collected, irrespective of its direction.

When a sample within such a sphere is fixed to a totally transmitting sample holder, both reflected and transmitted solar radiation are detected. When it is fixed to the front of a totally absorbing sample holder, only the reflected solar radiation is detected. This allows the transmitted proportion of the first measurement to be determined, and hence absorptance can be calculated according to the Kirchoff relationship.

The equipment necessary for such measurements is not commonly available, and it proved impossible to accurately determine the intensity of the source beam striking the samples. This meant that it was necessary to establish the solar optical properties of samples at a single fixed point, in order that a scale of optical properties relative to the radiation intensity detected within the sphere could be calculated. For this purpose the near normal solar optical properties of the membrane samples were measured using a calibrated solar spectrophotometer. The exact procedure used for this purpose will be discussed further in the next two sections of this chapter.

6:2.3 The Long Wave Infra Red Optical Properties of Fabric Membranes.

Most '*terrestrial*' radiation occurs within the *far* or *long wave infra red* wavebands. The wavelength of terrestrial radiation varies with temperature, however at room temperature approximately 97% of the radiation emanating from perfect emitter will be within the range 3,000nm to 50,000nm[10].

Terrestrial surfaces emit long wave infra red radiation in all directions within a hemisphere about their azimuth. This hemisphere can include a wide variety of thermal bodies, ranging from the clear night sky to relatively '*hot*' solid bodies all of which will be emitting different intensities and wavelengths of thermal radiation themselves. In order to simplify this complex situation terrestrial radiation is generally treated as an average heat transfer based on hemispherical emissivities and average hemispherical surface temperatures.

The hemispherical emissivity of surfaces is usually measured with an emissometer, however, for such thin materials, fabric membranes actually have a relatively poor thermal conductivity, and this can make emissometer measurements unreliable. This problem is compounded further by the slightly rough surfaces of many fabric membranes.

Because of this it was necessary to approximate the hemispherical emissivity of the membrane samples by measuring their near normal long wave infra red absorptance using a long wave infra red spectrophotometer. The reasons for this will be discussed in more detail in Section 5 of this chapter.

6:2.4 The Choice of Membranes to be Examined.

The techniques by which optical properties were measured only required the use of small samples, and this allowed a wider range of membranes to be tested than had been possible with the test cell investigations described in the previous chapter:-

- It was possible to obtain a large enough sample of the AELTC Covered Courts membrane in order to measure its thermal optical properties. Because this membrane was tinted green on its outside surface but was white on its inside surface it was possible that its internal and external properties would be different. For this reason it was felt necessary to test the thermal optical properties of both of its surfaces.

- A particular complication associated with PTFE coated membranes is that whilst PTFE is manufactured in a cream colour, over a period of six months to a year the sun bleaches it white. It seemed likely that this would affect its thermal optical properties. In order to determine the extent of this affect, a small sample was cut in two, then one half was exposed to solar radiation for six months whilst the other was kept in its original condition. The thermal optical properties of both halves were then measured.

The membranes investigated therefore, were the same as those discussed in Chapter 5, plus a sample of weathered PTFE coated glass, and two samples of the AELTC Covered Courts membrane:-

- Type 1 PVC coated polyester, gauge 0.6mm.
- Type 2 PVC coated polyester, gauge 0.7mm.
- Type 3 PVC coated polyester, gauge 0.85mm.
- Type 4 PVC coated polyester, gauge 1.1mm.
- Eisteddfod Arena PVC coated polyester (Clyde Canvas), gauge 0.7mm.
- AELTC Covered Courts: Duraskin PVC coated polyester, outside surface, gauge 1mm.
- AELTC Covered Courts: Duraskin PVC coated polyester, inside surface, gauge 1mm.
- Verseidag Indutex Type B PTFE coated glass (new), gauge 0.75mm.
- Verseidag Indutex Type B PTFE coated glass (weathered), gauge 0.75mm.

As described by the next three sections of this chapter, the *near normal solar optical properties*, *angular solar optical properties*, and *long wave infra red optical properties* of each of these samples was determined. Other than the Wimbledon membrane, each of these 9 samples was tested with radiation incident upon their external surface only.

6:3. THE NEAR NORMAL SOLAR OPTICAL PROPERTIES OF FABRIC MEMBRANES.

6:3.1 The Purpose of Measuring the Near Normal Solar Optical Properties of the Membrane Samples.

The purpose of measuring the near normal solar optical properties of fabric membranes was to provide a set of fixed points at which their angular direct beam solar optical properties were known. This then allowed the calibration of the Edwards type integrating sphere with which the direct beam solar optical properties of the membrane samples at angles of incidence other than near normal could be determined. The results obtained by this process could then be integrated in order to calculate the diffuse solar optical properties of the samples. Carrying out these measurements also served to identify any anomalies in the spectral transmission characteristics of the samples.

The term *near normal* refers to direct beam radiation which strikes a sample at an angle of incidence close to its surface normal. Properties are measured at *near normal* rather than *normal* angles of incidence in order to prevent incident radiation simply reflecting off the sample straight back along the path from which it came.

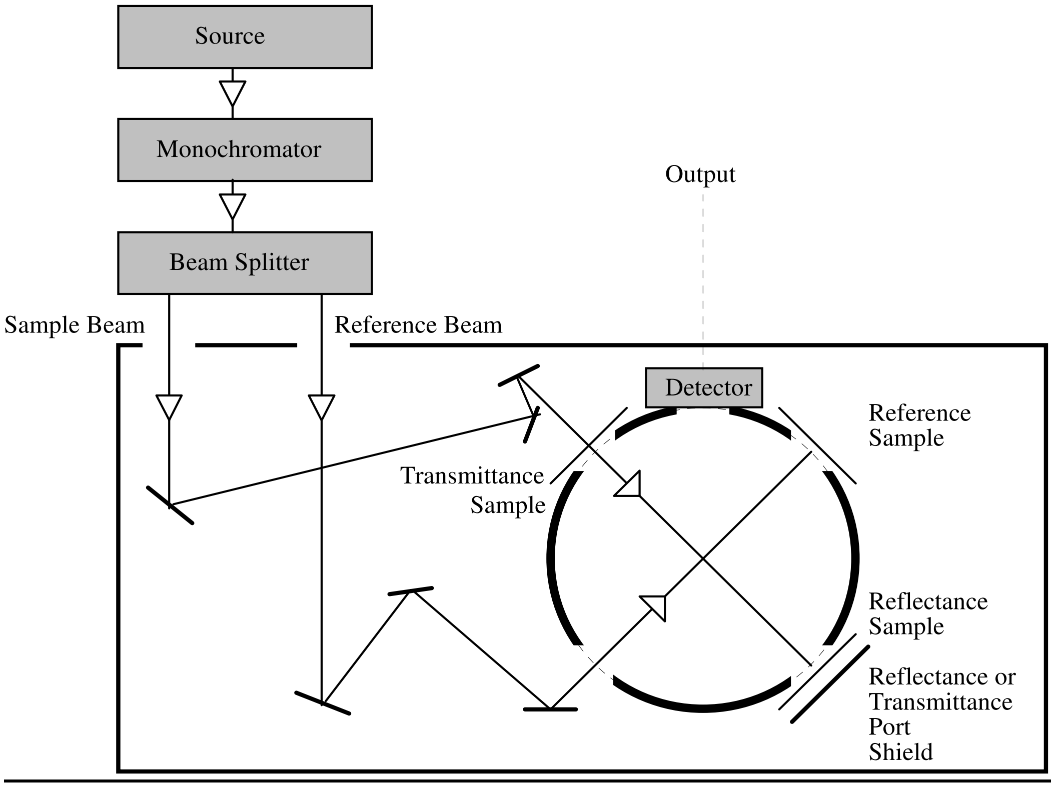
6:3.2 The Apparatus used to Measure the Near Normal Solar Optical Properties of the Membrane Samples.

Because of the diffusing nature of fabric membranes, the transmitted and reflected portions of incident solar radiation had to be measured hemispherically using an integrating sphere solar spectrophotometer. For this purpose a Perkin Elmer 330 Solar Spectrophotometer was used. Once the near normal hemispherical spectral transmittance and reflectance of the nine membrane samples had been determined, their absorptance could be calculated according to the Kirchoff relationship.

This particular type of solar spectrophotometer scans properties from 300nm to 2,300nm covering the ultra violet, visible and short wave infra red wavebands. A deuterium source and photo multiplier detector are used to measure properties up to 750nm, and then a tungsten source and a lead sulphide detector continue up to 2,300nm. The specific waveband required during the course of the scan is obtained by filtering the source beam through monochromator gratings to remove the higher and lower wavelengths.

The overall configuration of the apparatus is illustrated schematically by *Figure 6:3.2* overleaf.

Figure 6:3.2 Schematic Representation of the Operation of the Integrating Sphere Solar Spectrophotometer[11].



As illustrated by the diagram above, the monochromated source beam is first chopped by a beam splitter to produce a *sample* and a *reference* beam. In order to measure transmittance, samples are placed over the integrating sphere's entrance port in the path of the sample beam and a shield of known reflectance is placed over the spheres exit port. To measure reflectance, samples are placed over the sphere's exit port, and an absorbing port shield is placed behind the samples to prevent any transmitted radiation re entering the sphere. In both cases the reference beam enters the sphere unobstructed.

The integrating sphere collects and diffuses the transmitted or reflected hemispherical flux producing a uniform radiation level inside the sphere. This allows the total remaining radiation within the sphere to be calculated based on the output of a detector at a single point within it. Transmittance and reflectance factors can then be calculated for each wavelength by comparing the intensity of the sample and reference beams detected within the sphere.

In order to account for any potential bias produced by the different paths taken by the sample and reference beams, the transmittance and reflectance factors are then corrected according to a base line stored within the spectrophotometer. This base line compares the intensity of the sample and reference beams throughout the solar spectrum when no sample is present. A further correction can then be applied to the reflectance factor to account for the less than perfect reflectance of the exit port shield.

6:3.3 The Method used to Determine the Near Normal Solar Optical Properties of the Membrane Samples.

In order to calculate the overall solar optical properties of the membrane samples from the spectral scan produced by the spectrophotometer, it was necessary to define the spectral characteristics of the solar radiation which was likely to be incident upon them in use.

Whilst the composition of extraterrestrial radiation is well known, the spectral characteristics of the solar radiation which actually reaches the earth's surface can vary significantly. These variations depend upon complex atmospheric conditions such as the mass of air through which the radiation has to pass, the turbidity of the atmosphere, the precipitable water content of the atmosphere, cloud cover and so on.

To simplify this situation it is usual to adopt a standard solar spectrum typical of the observed conditions at the location in which the sample materials are to be used. In the UK the air mass 2 solar spectrum is generally used. This is represented by 20 weighted solar ordinates which are characteristic of the average solar spectral intensity in the UK[12]:-

402, 458, 498, 537, 576, 614, 652, 690, 730, 775, 820, 869, 923, 1003, 1064, 1170, 1258, 1532, 1689, 2292 (nm)

When an average is taken of the near normal solar spectral optical properties measured at these ordinates, this should be representative of near normal properties under typical solar conditions[13].

6:3.4 The Results Obtained Using the Solar Spectrophotometer.

The near normal hemispherical solar spectral optical properties measured by the method described above are illustrated by the graphs presented on the next three pages. These properties are represented by area so that the total area covered is always 100%.

The next part of this section then analysis these results, and tabulates their average values for the air mass 2 solar spectrum.

Figure 6:3.4a Near Normal Solar Optical Properties: Type 1 PVC Coated Polyester.

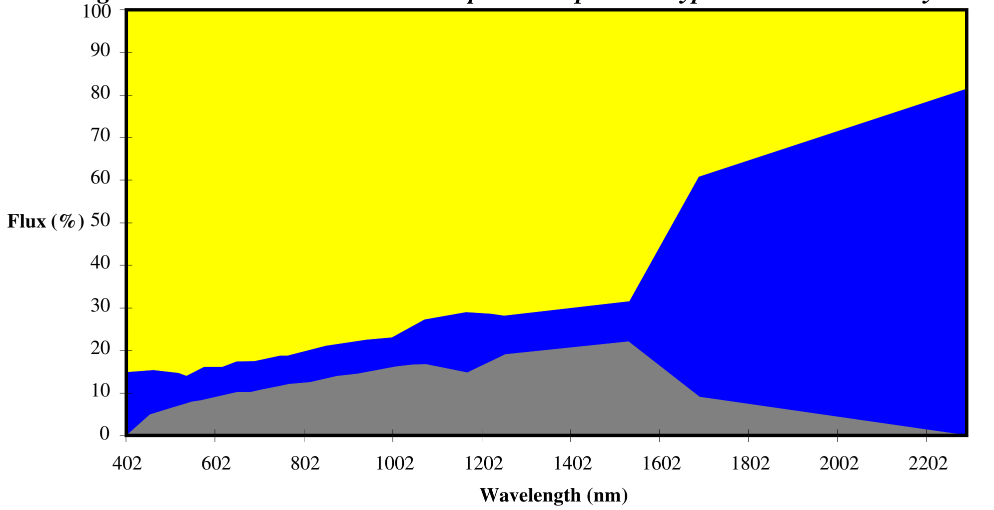


Figure 6:3.4b Near Normal Solar Optical Properties: Type 2 PVC Coated Polyester.

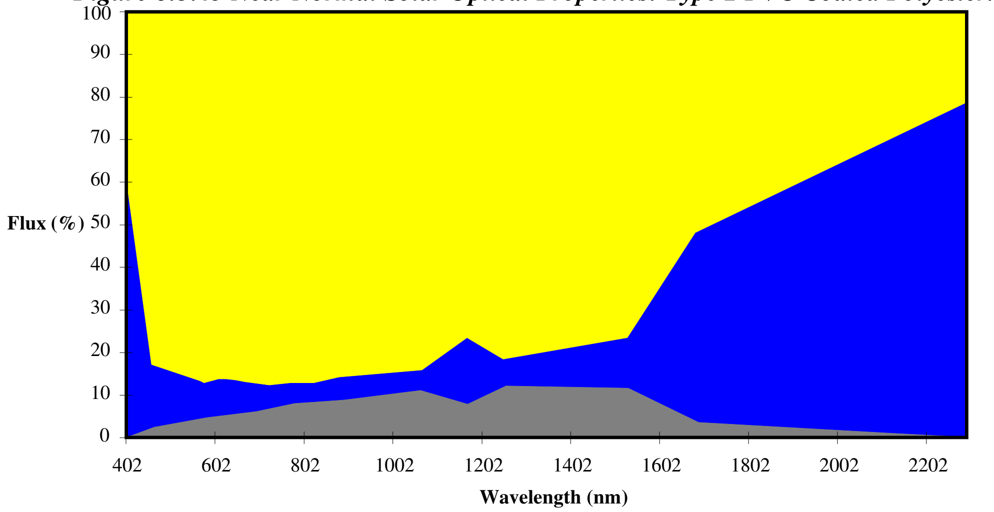


Figure 6:3.4c Near Normal Solar Optical Properties: Type 3 PVC Coated Polyester.

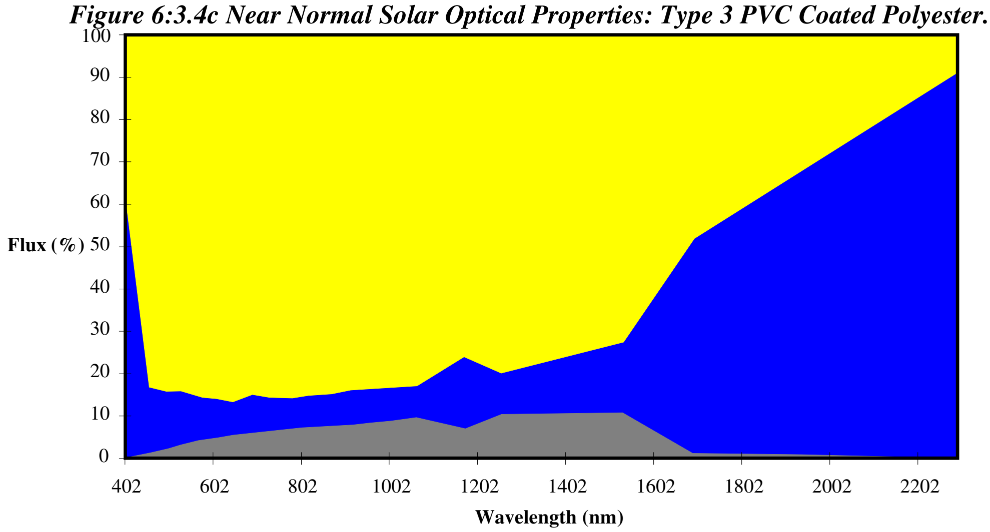


Figure 6:3.4d Near Normal Solar Optical Properties: Type 4 PVC Coated Polyester.

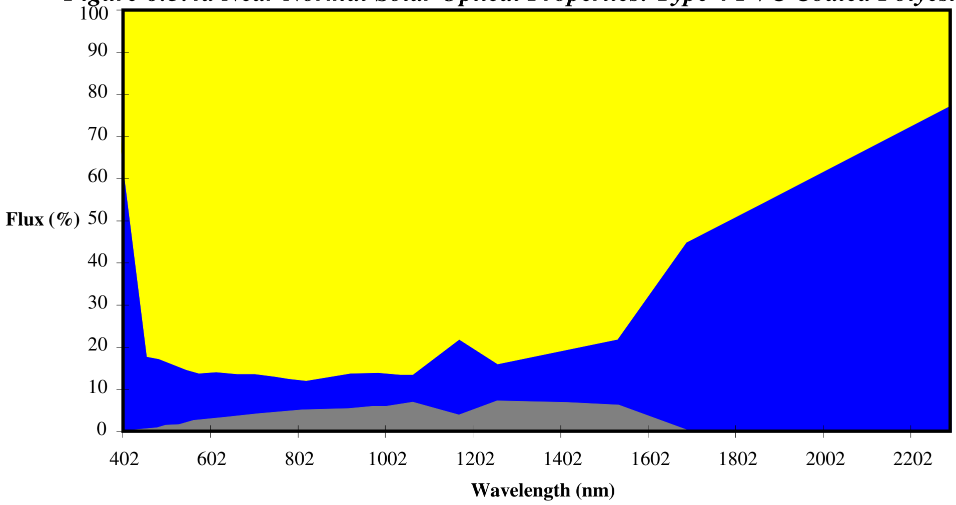


Figure 6:3.4e Near Normal Solar Optical Properties: Eisteddfod Arena Membrane.

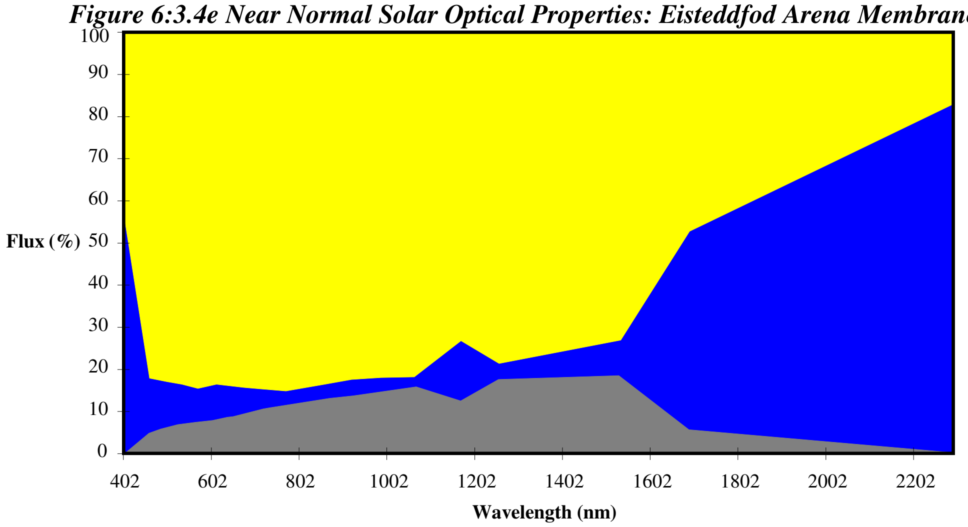


Figure 6:3.4f Near Normal Solar Optical Properties: Wimbledon Membrane (Outside Surface).

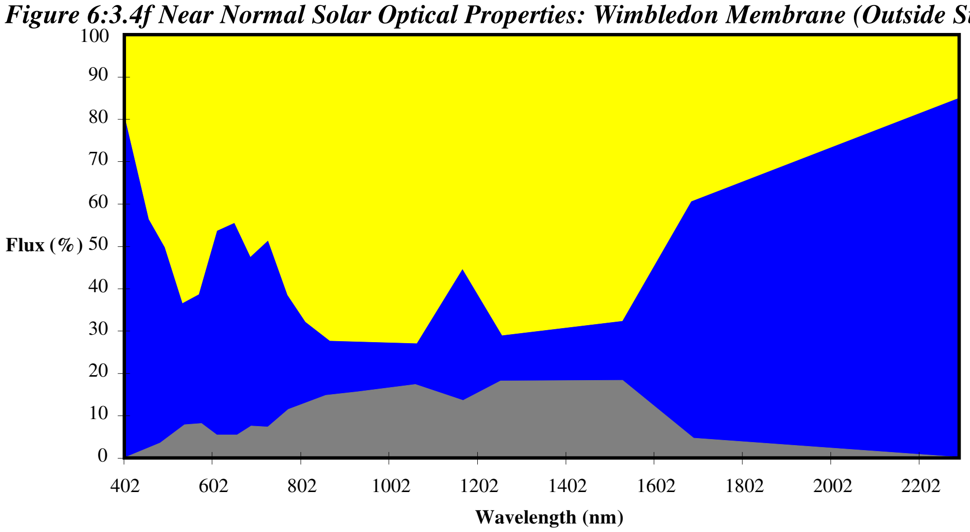


Figure 6:3.4g Near Normal Solar Optical Properties: Wimbledon Membrane (Inside Surface).

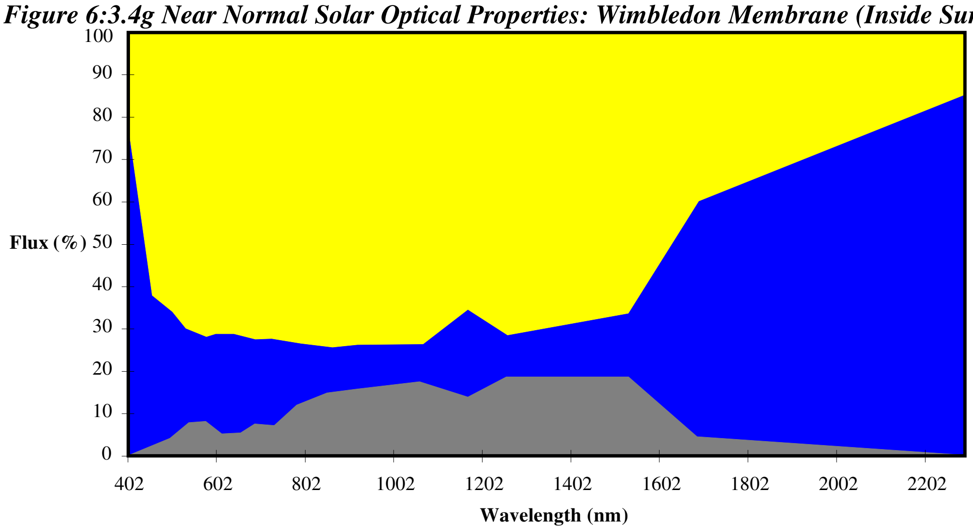


Figure 6:3.4h Near Normal Solar Optical Properties: Type 1 PTFE Coated Glass (New).

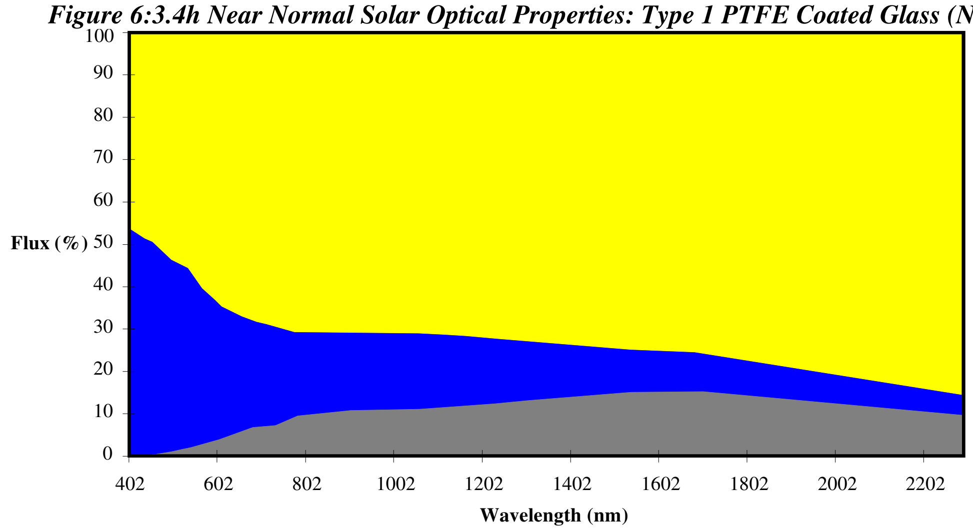
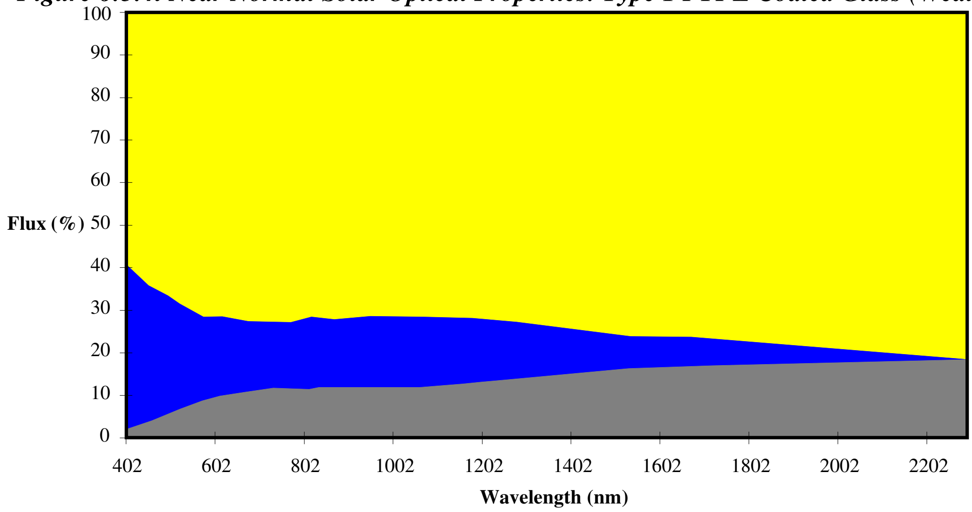


Figure 6:3.4i Near Normal Solar Optical Properties: Type 1 PTFE Coated Glass (Weathered).



6:3.5 Analysis of the Results Obtained Using the Solar Spectrophotometer.

The spectral variations in the near normal solar optical properties of the four standard PVC coated polyester membranes were characterised by high transmittance and reflectance up to about 1,600nm, but these then began to decrease at higher wavelengths. Absorptance tended to spike at around 1,200nm and generally increased sharply beyond 1,600nm to reach 70 or 80% by 2,300nm.

The spectral profile of the AELTC Covered Courts membrane and the Eisteddfod membrane showed similar trends to the standard PVC coated polyester membranes. It was apparent however that the green tinting of the AELTC Covered Courts membrane produced more variable properties within the visible spectrum.

Both the PTFE coated glass membrane samples were characterised by smoother variations in spectral properties. They showed continually decreasing absorptance and increasing transmittance and reflectance with increasing wavelength with the most severe variations occurring in the visible spectrum.

The fairly constant spectral properties of the PTFE coated glass membranes suggest that they would behave similarly under any solar spectral conditions, however the more erratic nature of the PVC coated glass membranes meant there was some possibility that their solar absorptance would be underestimated under non standard solar conditions.

The overall near normal solar optical properties of the nine membrane samples weighted for the air mass 2 solar spectrum are listed in the table below.

Figure 6:3.5 Weighted Near Normal Hemispherical Solar Optical Properties (Air Mass 2).

	Gauge (mm)	Transmittance (%)	Absorptance (%)	Reflectance (%)
Type 1 PVC Polyester	0.6	10.98	14.54	74.48
Type 2 PVC Polyester	0.7	6.46	16.09	77.45
Type 3 PVC Polyester	0.85	5.64	18.94	75.42
Type 4 PVC Polyester	1.1	3.73	18.46	77.80
Eisteddfod	0.75	9.97	14.73	75.30
Wimbledon (outside)	1.0	9.77	35.51	54.72
Wimbledon (inside)	1.0	9.80	26.42	63.78
PTFE Glass (new)	0.75	7.90	25.20	66.90
PTFE Glass (weathered)	0.75	11.01	17.61	71.37

The weighted properties of the four standard PVC coated polyester membranes appeared to be most significantly affected by the thickness of the sample, but this relationship was not as simple as may have been expected. Solar radiation incident upon the sample membrane surfaces was first either reflected away from them, or it was allowed to transmit into sample cores. The tendency for the membrane samples to reflect incident radiation appeared to be dependent upon the relative thickness and smoothness of the membrane coating. Generally this reflectance increased with membrane gauge as the surface coating became necessarily thicker and so smoother in order to properly cover the fabric substrate.

That radiation which was not reflected away was then progressively absorbed and scattered as it crossed the membrane section, and only that which remained at the opposite surface to the incident beam was considered to have been transmitted. Inevitably the trend here was for transmittance to decrease and absorptance to increase as the membranes became thicker. The Eisteddfod Arena membrane displayed similar characteristics, but the transmittance to gauge ratio suggested that it was a high translucency variety.

Because of the green tinting of the Wimbledon membrane, the solar optical properties of both its surfaces were measured. Both sets of measurements recorded an unusually high transmittance for its gauge, suggesting a loose weave fabric substrate. The external surface inevitably had a low reflectance due to its tinted coating, but the internal surface also had a low reflectance because of the relative roughness of its coating which did not have an additional surface topcoat. The solar absorptance of the Wimbledon membrane was exceptionally high, and went some way towards explaining the failure of the original membrane which had to be replaced when its seams pulled apart under bright sunshine.

The weathered PTFE coated glass sample had a higher weighted transmittance and reflectance than the unbleached sample and as a consequence its absorptance was almost 8% lower. The significance of these changes however is difficult to determine because of the difficulties involved in weathering the sample. These included water wicking up between the fibres at its exposed edges, dirt accumulation and fact that performance changes were likely to continue beyond the six month period studied. As a consequence of this it is likely that no two weathered samples will display the same properties.

The issue of weathering and deterioration is a difficulty with all membranes. Although optical changes are more noticeable in the bleaching of PTFE coated glass membranes, dirt accumulation was apparent on all membranes exposed to the weather and it was likely that this affected their optical properties. This is an area which may require further research, but for now it must be recommended that membranes are regularly inspected and cleaned in order to ensure that the properties listed in their design specification are maintained throughout their lives.

6:4. THE ANGULAR SOLAR OPTICAL PROPERTIES OF FABRIC MEMBRANES.

6:4.1 The Purpose of Measuring the Angular Solar Optical Properties of the Membrane Samples.

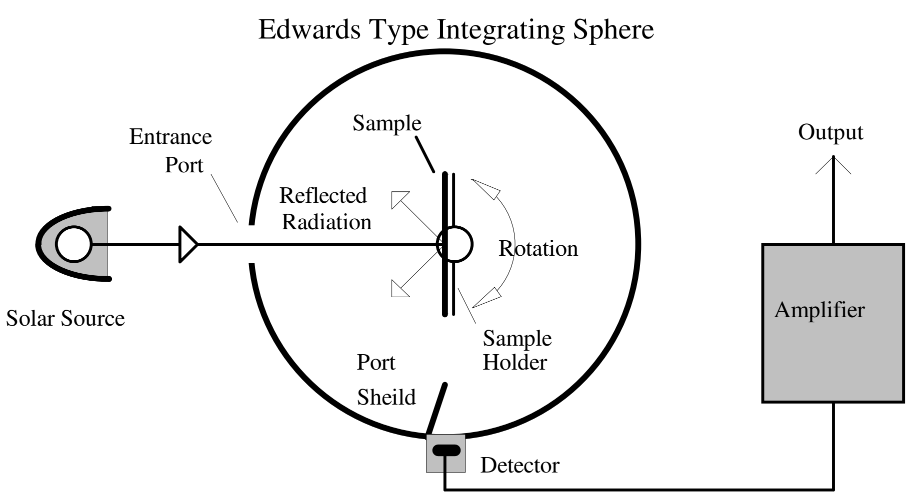
In the previous section, a series of experiments were described which were carried out in order to determine the near normal solar optical properties of a range of fabric membranes. These near normal properties were measured in order to provide fixed points at which the angular solar optical properties of the samples were known.

In this section a technique is described which allowed those fixed point values to be used in order to calibrate an Edwards type integrating sphere. This sphere was then used to measure the angular solar optical properties of the nine membrane samples. From these values, it was then possible to calculate the diffuse solar optical properties of the samples by a process of integration.

6:4.2 The Apparatus Used to Measure the Angular Solar Optical Properties of the Membrane Samples.

Although the angular radiation incident upon the membranes for the purpose of these measurements was unidirectional, the radiation reflected or transmitted by the membrane samples was likely to be at least partially diffuse, and this could only be properly detected *hemispherically*. In order to allow the angle at which a solar beam is incident upon a surface to vary whilst detecting the intensity of hemispherical reflected radiation, an Edwards type integrating sphere was necessary.

Figure 6:4.2 Schematic Illustration of the Apparatus Used to Measure the Angular Solar Optical Properties of the Sample Membranes[14].



The Edwards type integrating sphere forms a complete enclosure about a rotating sample holder which is designed so that the angle of the sample may be varied relative to a fixed direction solar beam. The solar radiation reflected by the sample is then uniformly diffused by the internal surface of the integrating sphere so that its relative intensity can be determined by taking a measurement at a single point.

Measurements of this kind are usually only carried out for opaque materials, and in order to accept the translucent membrane samples a new sample holder had to be constructed. This was painted matt black on one side, and was coated with a highly reflective material on the other. The membrane surface was then attached to the black surface, so that all the solar radiation which it transmitted was absorbed by the sample holder. As a consequence only the reflected component of the incident solar radiation was detected within the integrating sphere.

In order that the angular solar transmittance of the samples could be determined, a second sample holder was constructed which consisted of a simple hollow frame that would not interfere in any was with radiation transmitted by the samples. This meant that both transmitted and reflected radiation were detected within the sphere, but as the reflected component of the incident beam had already been measured using the opaque sample holder, the transmitted component could be determined. The absorbed component of the incident solar radiation could then be calculated according to the Kirchoff relationship.

Radiation was generated with an Oriel Corporation 24v solar source, and an Alrad Instruments Model 2M thermopile detector was used to measure the level of solar radiation within the integrating sphere. This is a voltage generating multi junction thermopile detector which produces a flat response output of 19.2v/W throughout the solar spectrum. Because of the very low intensities being detected, this output was then amplified to a more manageable level using an Alrad Instruments Model 1010 low noise amplifier.

6:4.3 The Method Used to Determine the Angular Solar Optical Properties of the Membrane Samples .

With a solar source beam of constant dimensions, the greater the angle of incidence, the larger the sample has to be in order that the entire beam strikes its surface. This makes measurements at large angles of incidence very difficult as the size of the sample begins to interfere with the operation of the integrating sphere. Reducing the size of the source beam allows greater angles of incidence to be investigated, but lowers the level of radiation within the sphere, making it less accurate. Similarly, increasing the size of the sphere reduces its efficiency.

In order to achieve a compromise between these contrasting limitations, a 20cm diameter Edwards sphere and a 1cm solar beam width were chosen. With a sample holder 3.75cm long this allowed angles of incidence up to 75^{o} to be investigated. It was then possible to extrapolate the trend of these properties from 75^{o} to 90^{o}.

It was likely that the size of the sample holders would have some impact on the efficiency of the sphere, however because of the entirely diffuse nature of the radiation being detected, this was constant for all angles of incidence. As the near normal solar optical properties had already been determined using the solar spectrophotometer, a scale of detector output to solar optical properties could be calculated independent of the efficiency of the integrating sphere:-

with the transmitting sample holder $$\rho(i) = \frac{v(i) \times v(0)}{\rho(0)}$$

and with the absorbing sample holder $$\tau(i) = \frac{v(i) \times v(0)}{\tau(0) + \rho(0)} - \rho(i)$$

and hence:- $$\alpha(i) = 100 - \tau(i) - \rho(i)$$

where v(i) refers to the detector voltage output at angle of incidence (i), for which ρ(i), τ(i) and α(i) refer to the angular reflectance, transmittance and absorptance of the sample respectively. v(0) represents the voltage recorded at a near normal angle of incidence, and τ (0), ρ(0) and α(0) represent the near normal reflectance transmittance and absorptance of the sample.

6:4:4. The Results Obtained Using the Edwards Type Integrating Sphere.

The results obtained for the range of samples previously listed using the method described above are shown on graphs presented over the next three pages. The properties are illustrated by area, so that their sum is always equal to 100%.

The actual measured properties are indicated on the graphs by the square points. The shaded areas represent the average extrapolated trend of the properties, which were calculated according to a set of generalised equations developed from statistical analysis of all the measured data. The derivation of these equations is discussed in the next part of this section.

Figure 6:4.4a Angular Solar Optical Properties: Type 1 PVC Coated Polyester.

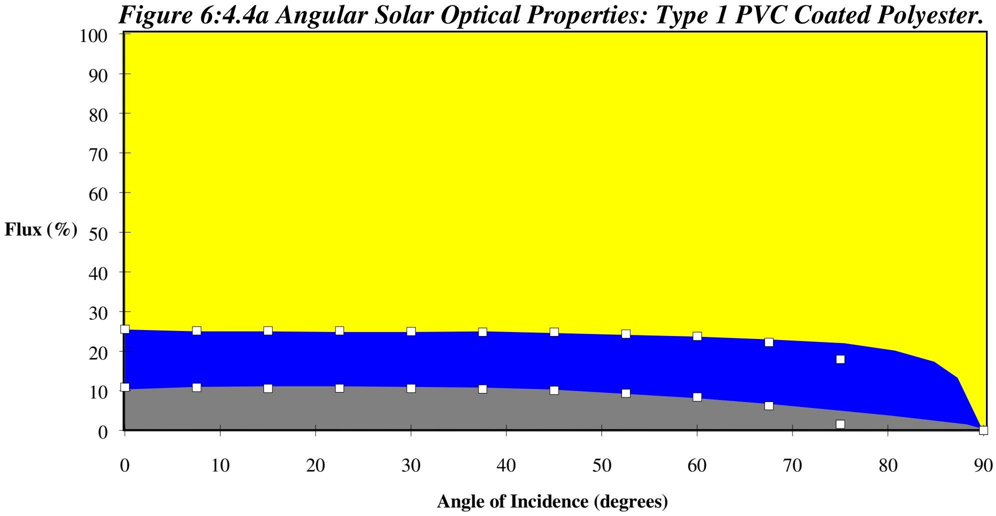


Figure 6:4.4b Angular Solar Optical Properties: Type 2 PVC Coated Polyester.

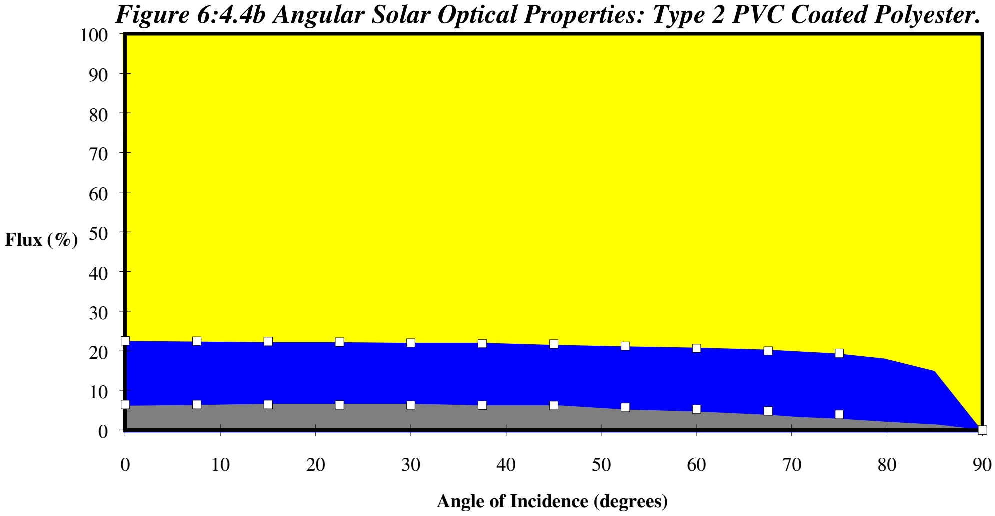
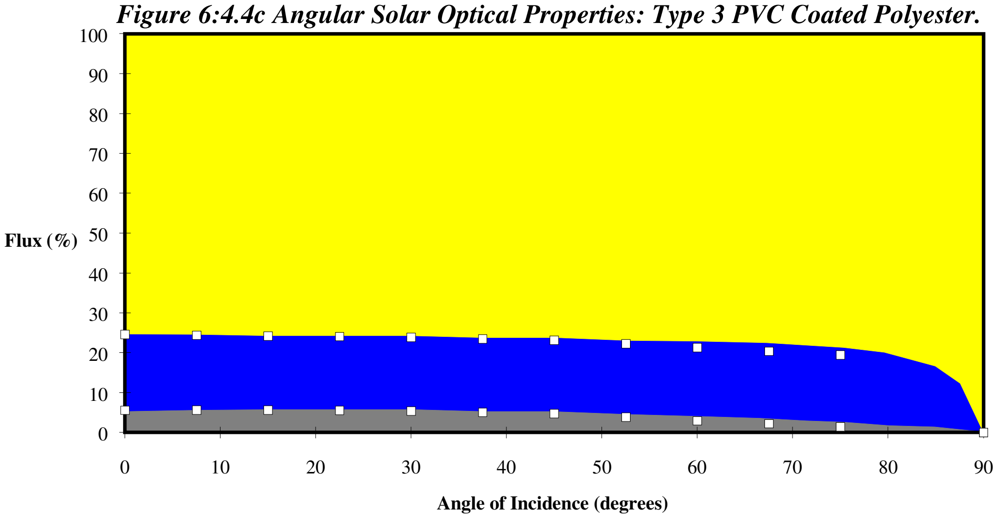


Figure 6:4.4c Angular Solar Optical Properties: Type 3 PVC Coated Polyester.



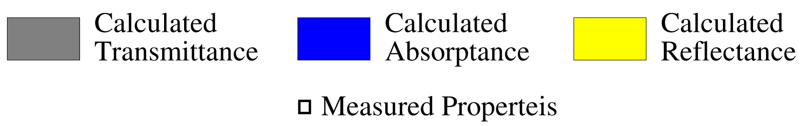


Figure 6:4.4d Angular Solar Optical Properties: Type 4 PVC Coated Polyester.

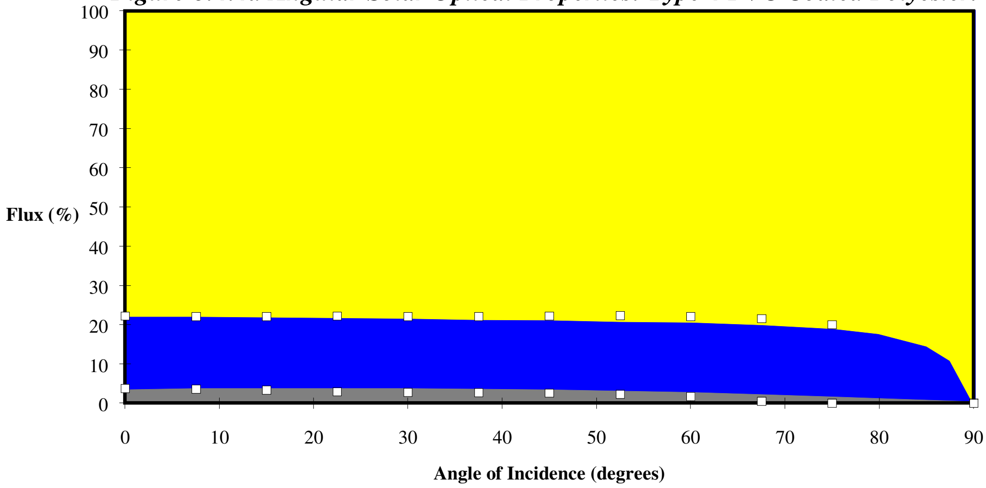


Figure 6:4.4e Angular Solar Optical Properties: Eisteddfod Arena Membrane.

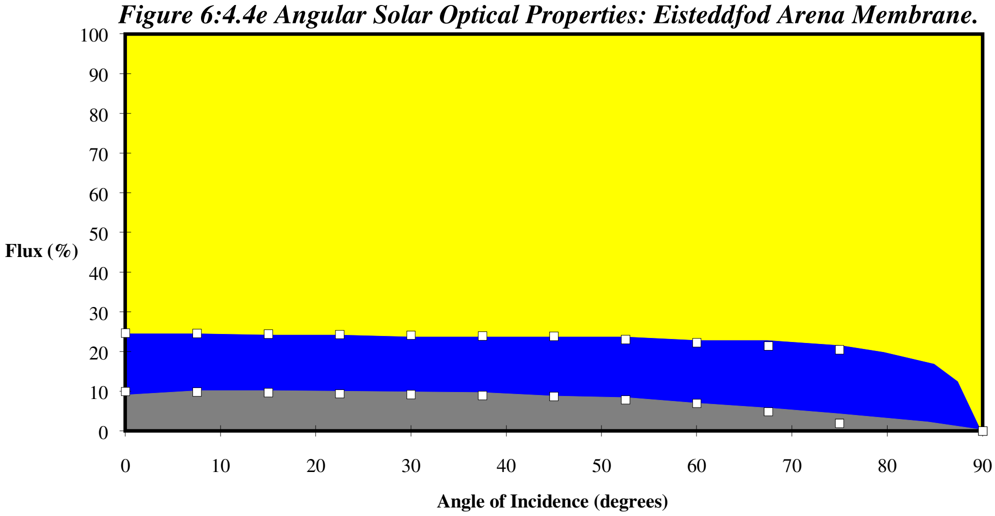


Figure 6:4.4f Angular Solar Optical Properties: Wimbledon Membrane (Outside Surface).

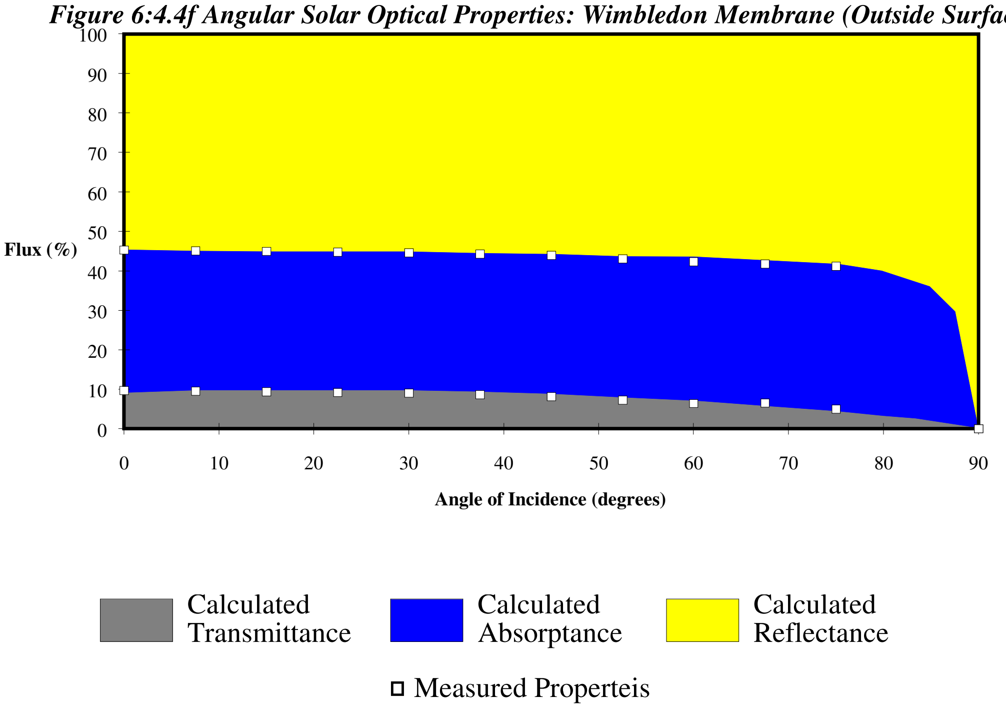


Figure 6:4.4g Angular Solar Optical Properties: Wimbledon Membrane (Inside Surface).

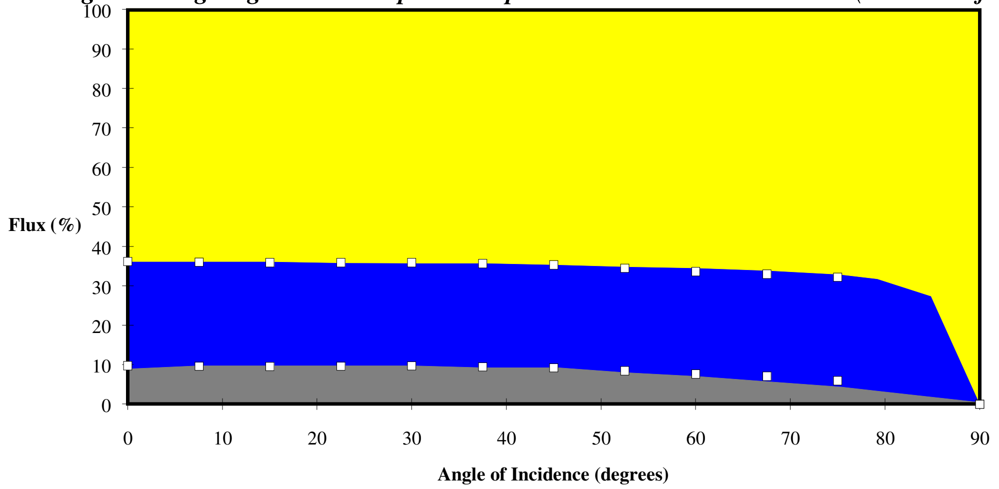


Figure 6:4.4h Angular Solar Optical Properties: Type 1 PTFE Coated Glass (New).

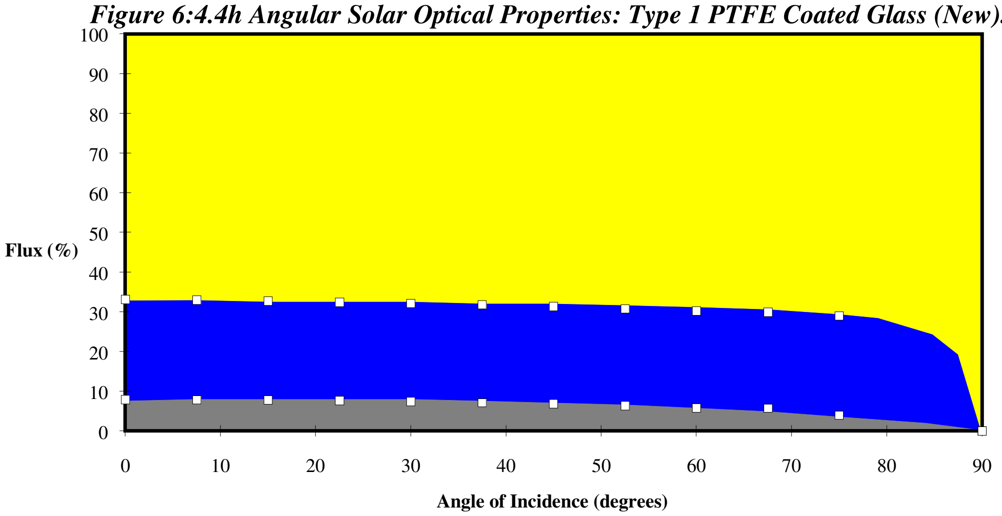
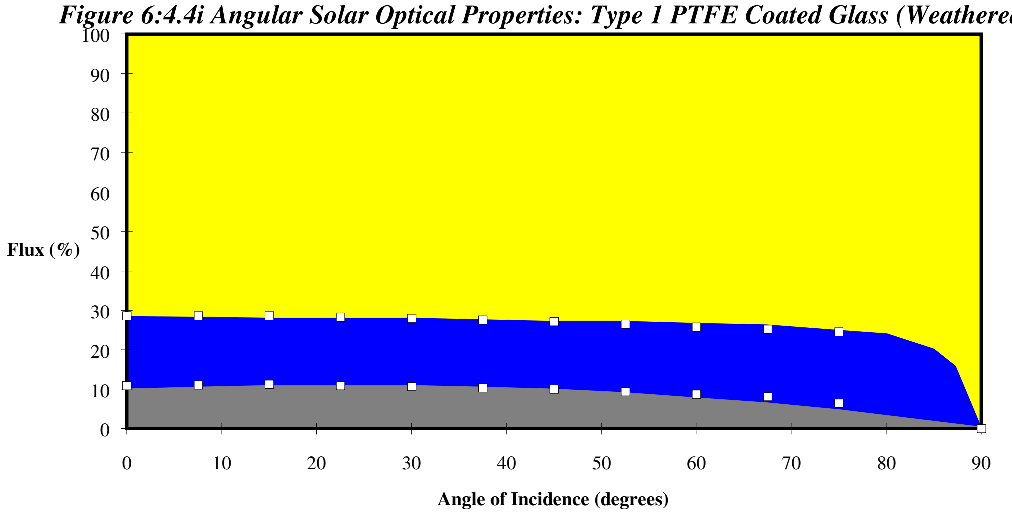
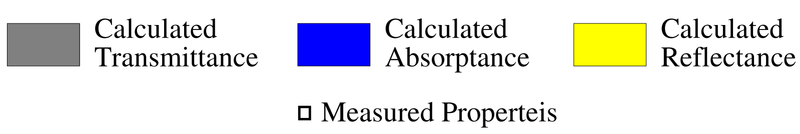


Figure 6:4.4i Angular Solar Optical Properties: Type 1 PTFE Coated Glass (Weathered).





6:4.5 Analysis of the Results Obtained Using the Edwards Type Integrating Sphere.

Despite the material differences, the angular trends recorded were similar for both the PVC coated polyester and PTFE coated glass membranes:-

- Transmittance appeared to increase very slightly to begin with as the angle of incidence moved away from the surface normal. Beyond 45^{o} however transmittance then decreased fairly steadily to reach zero by 90^{o}. It is difficult to explain the initial increase in transmittance from the material properties of the membranes themselves, and it was considered that this probably resulted from a small amount of the diffusely reflected radiation escaping through the entrance port at near normal angles of incidence. With completely specularly reflecting materials this would not happen because of the slight offset of the sample holder from the line of the source beam. It was not considered that this significantly affected the overall accuracy of the results.

- Reflectance tended to change little until the angle of incidence exceeded 60^{o}. It then increased slowly up to about 75^{o} were it began to increased progressively more rapidly to reach 100% at 90^{o}.

- The relationship between solar absorptance and angle of incidence was more complex. Absorptance generally decreased slightly with increasing angles of incidence, then increased a little between 45^{o} and 75^{o} before tailing off sharply to 0% at 90^{o}. This appeared to result from the trade off between increasing reflectance and decreasing transmittance as the angle of incidence moved away from the surface normal.

For the purposes of this research, it was necessary to derive a mathematical representation of these angular solar optical properties. This meant that sample properties could be more easily incorporated into theoretical models (as described in the next chapter) and allowed their diffuse solar optical properties to be calculated accurately. As the characteristic trends of these properties were similar for all the samples investigated, it was decided that this could best be done by developing a set of standard equations appropriate for all the membranes from which their angular solar optical properties could be predicted given that their near normal properties were known.

Because of the complex composition of fabric membranes, these equations could not easily be associated with any physical phenomena, but had to be derived from curve fitting techniques based on the least squares method of selection. This was done by generating average equations to fit the angular data presented above between the known 0% or 100% values of the optical properties at 90^{o} angle of incidence, and their measured near normal properties. The equations developed by this techniques are presented overleaf.

$$\rho(i) = \rho(0) + \tan\left\{ i - \left[\frac{90 - \mathrm{Atan}(100 - \rho(0))}{90} \times \mathrm{i} \right] \right\}$$

$$\tau(i) = \tau(0) \times \frac{10.2031 + 0.0938\mathrm{i} - 0.0022\mathrm{i}^2}{10.985}$$

$\alpha(i) = 100 - \rho(i) - \tau(i)$

Where $\rho(0)$ and $\tau(0)$ represent the near normal solar reflectance and transmittance of the samples, and $\tau(i)$, $\alpha(i)$ and $\rho(i)$ represent their angular solar optical reflectance, transmittance and absorptance at angle of incidence (i).

Because of the complex nature of the angular solar optical properties of partially diffusing fabric membranes, and the slight variations in the characteristic properties of different membrane types, the fit of these curves was not perfect for all membranes. However, the average difference between the intensity of solar radiation reflected, transmitted or absorbed by the membranes calculated using these standard equations and that calculated using the measured properties was just 0.6%, and the maximum difference was only 5.3%.

Integrating these equations through the 2π steradians of the total hemisphere about the surface normal allowed the diffuse properties of the membranes ($\tau(f)$, $\alpha(f)$ and $\rho(f)$) to be predicted. These properties are summarised by *Figure 6:4.5* below.

Figure 6:4.5 The Near Normal and Diffuse Solar Optical Properties of the Membrane Samples.

	τ(%)		α(%)		ρ(%)	
	near norm	**diffuse**	near norm	**diffuse**	near norm	**diffuse**
Type 1 PVC Polyester	10.98	**7.41**	14.54	**15.28**	74.48	**77.31**
Type 2 PVC Polyester	6.46	**4.35**	16.09	**15.45**	77.45	**80.19**
Type 3 PVC Polyester	5.64	**3.81**	18.94	**17.97**	75.42	**78.22**
Type 4 PVC Polyester	3.73	**2.52**	18.46	**16.95**	77.80	**80.53**
Eisteddfod	9.97	**6.73**	14.73	**15.16**	75.30	**78.11**
Wimbledon (outside)	9.77	**6.59**	35.51	**35.46**	54.72	**57.95**
Wimbledon (inside)	9.80	**6.61**	26.42	**26.53**	63.78	**66.86**
PTFE Glass (new)	7.90	**5.33**	25.20	**24.75**	66.90	**69.92**
PTFE Glass (weathered)	11.01	**7.43**	17.61	**18.29**	71.37	**74.29**

6:4.6 Assessment of the Investigation into the Solar Optical Properties of Fabric Membranes.

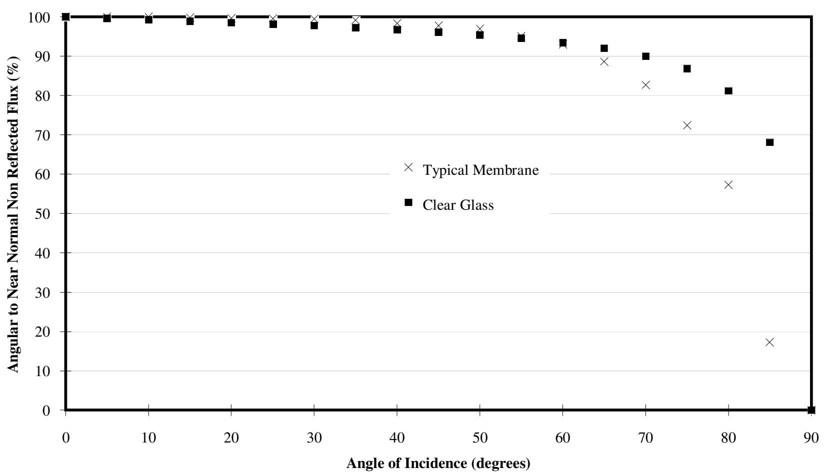
Sections three and four of this chapter described a series of experiments carried out in order to determine the near normal and angular solar optical properties of a range of fabric membranes. The results obtained by this process were used to develop a set of equations from which the diffuse and angular solar optical properties of the membranes investigated could be determined given that their near normal solar optical properties were known.

Whilst it has already been demonstrated by Winklemann[15] and Sinofsky[16] that the shading coefficients previously used to describe these properties are inappropriate it is worth comparing this commonly accepted approach with the use of the generalised equations developed here.

Shading coefficients compare the solar optical behaviour of fabric membranes with that of a single sheet of 3mm clear float glass. The use of this approach assumes that the relative solar absorption and transmission of fabric membranes is directly proportional to that of glass and that this relationship is constant across all angles of incidence.

Figure 6:4.6 below illustrates the sum of the absorbed and transmitted portion of solar radiation incident upon a sheet of 3mm clear float glass compared to the average behaviour of the fabric membranes investigated. This direct comparison was made possible by assuming that the sum of the near normal solar transmittance and absorptance represented 100%, and then the trend of the un-reflected radiation with angle of incidence was compared to this value.

Figure 6:4.6 Comparison Between the Change in the Proportion of Solar Radiation Transmitted and Absorbed by a Sheet of 3mm Clear Float Glass with Angle of Incidence[17] and that of a Typical Fabric Membrane.



It can be seen that there is a significant difference between the average solar optical properties of the fabric membranes investigated and that of 3mm clear float glass. Whilst superficially, the way that their properties change with angle of incidence is similar, the solar transmittance of glass tends to be very much higher, and its reflectance lower than fabric membranes. This means that the significance of the solar reflectance of fabric membranes is higher than for glass, resulting in a tendency for their properties to change more severely at higher angles of incidence.

The significance of this is difficult to assess because shading coefficients take account of a whole range of heat transfers and not just solar properties. It can be seen from *Figure 6:4.6* however that the average difference between the trend of the solar optical properties of glass and those of fabric membranes was 6% and this must bring into further doubt the continued use of shading coefficients in this area.

6:5. THE LONG WAVE INFRA RED OPTICAL PROPERTIES OF FABRIC MEMBRANES.

6:5.1 The Purpose of Measuring the Long Wave Infra Red Optical Properties of the Membrane Samples.

In the previous two sections of this chapter, a series of experiments were described which were carried out in order to determine the angular solar optical properties of a range of fabric membranes. To be able to use this information in order to predict the thermal behaviour of those membranes however, the test cell investigation described in Chapter 5 suggested that it was also necessary to determine their *long wave infra red absorptance* or *emissivity*.

6:5.2 The Apparatus Available for Measuring the Long Wave Infra Red Optical Properties of Fabric Membranes.

Ideally, emissivity would have been measured using the same approach as for the solar optical properties of fabric membranes as described above. Unfortunately it is very difficult to produce the uniform diffusion of long wave infra red radiation which would be required to create an effective long wave integrating sphere. Fine powdered gold can be used to coat the inside a sphere for this purpose, but such apparatus is expensive, rare and not altogether satisfactory[18].

It is also far more difficult to predict the angular nature of long wave infra red radiation incident upon a surface than for the more cyclical solar radiation and for these reasons, it is usual to calculate long wave infra red radiation exchanges based on hemispherically averaged conditions and properties.

Hemispherical emissivity can usually be measured by *calorimetry*. This involves measuring the rate at which long wave infra red radiation is exchanged between a sample of known temperature and a reference surface of known temperature and emissivity. This method was developed primarily for measuring the hemispherical emissivity of metals, however a transient approach based on temperature decay rates has also been developed for the analysis of more complex materials.

Several attempts were made to use calorimetric techniques for measuring the hemispherical emissivity of the fabric membrane samples. Because of their relatively low thermal conductance and slightly rough surfaces however it proved very difficult to achieve a steady state rate of long wave infra red radiation exchange between the reference surface and the samples. Attempts at the transient approach also proved inconclusive as a linear rate of temperature decay could not be properly achieved.

It was recommended by the UWCC Energy Equipment Testing Service therefore that instead, a long wave infra red spectrophotometer should be used to determine the near normal emissivity of the samples, and that hemispherical emissivity could then be gauged form this if necessary based on the properties of similar materials. It was considered that the focusing effect of the large torroid mirrors within such spectrophotometers would result in most of the diffusely transmitted and reflected long wave infra red radiation being detected, but angular measurements would not be possible.

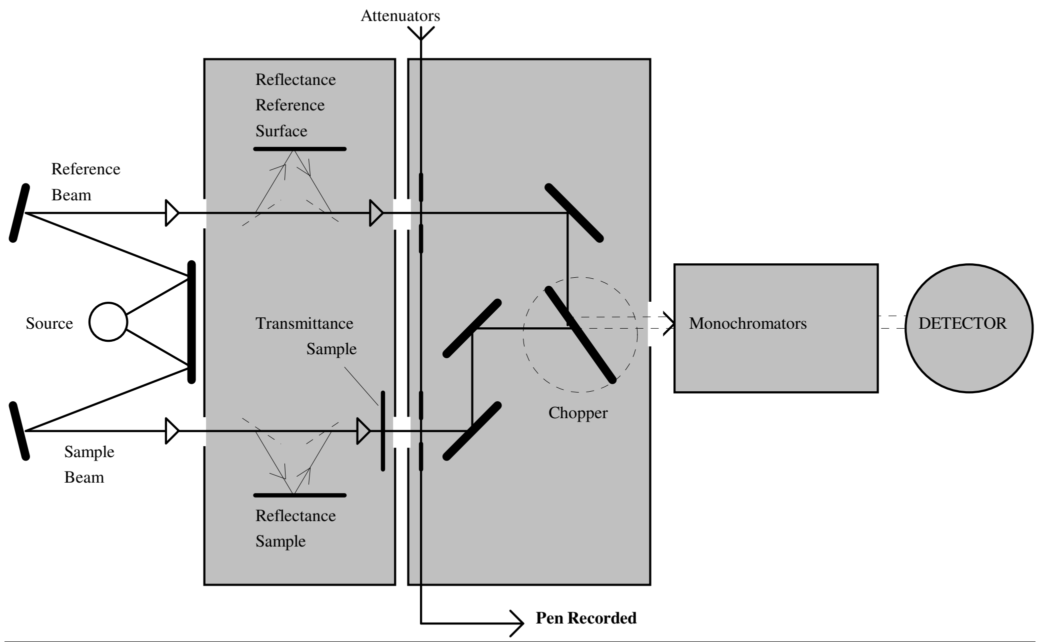
6:5.3 The Apparatus Used to Measure the Long Wave Infra Red Optical Properties of the Membrane Samples.

A Model 598 Perkin Elmer Spectrophotometer was used to determine the near normal long wave infra red transmittance and reflectance of the previously described range of fabric membranes. This allowed absorptance and hence emissivity to be calculated according to the Kirchoff relationship.

This particular spectrophotometer is fitted with a ceramic tube radiant source which when heated to 1100^{o}c produces a continuous spectrum of electromagnetic energy between 2,500nm and 50,000nm. As with the solar spectrophotometer, the emitted radiation is first split into two beams, a sample and a reference beam. In order to measure transmittance, the reference beam is directed through the sample area unobstructed, whereas the sample beam is shone through the sample being investigated. To measure reflectance, the reference beam is reflected off a gold mirror of reflectance 99.4%, and the sample beam is reflected off the membrane sample.

The two beams are then combined by a rotating chopper to take a single path, but out of phase with each other. This combined beam is then monochromated to the desired wavelength by a series of diffraction gratings, and directed onto a thermocouple detector. The intensity of the separate beams is then attenuated so that a constant intensity is maintained on the detector through both phases, and the attenuator settings are transferred directly to a pen recorder to give the relevant transmittance or reflectance factor. This basic configuration is illustrated schematically by *Figure 6:5.3* below.

Figure 6:5.3 Schematic Illustration of the Long Wave Infra Red Spectrophotometer.



6:5.4 The Method Used to Determine the Angular Solar Optical Properties of the Membrane Samples.

Results were output as pen recorded scans between 2,500nm and 50,000nm. A manual base line correction was then applied to the spectral reflectance factors in order to compensate for differences between the two reflectance beam paths. This was done by carrying out a full spectral scan with gold mirrors in both the sample and reference reflectance positions. The scanned line was then considered to represent a reflectance of 100%, and corrected reflectance factors were then calculated relative to this. A further minor correction was then applied to account for the imperfect 99.4% reflectance of the gold reference mirrors.

Spectral transmittance could be read directly from the pen recordings, and absorptance could then be calculated according to the Kirchoff relationship.

As with the solar spectral measurements, reducing these spectral scans into single values representative of the long wave infra red optical properties of the samples, it was first necessary to determine the spectral distribution of long wave infra red radiation which was likely to be incident upon their surfaces. For this purpose, weighted properties were calculated in accordance with BS 6993 Part 1 based on the spectral profile of the thermal radiation emitted by a perfect black body at 283°K[19].

The equal interval wavelength power distribution of a full radiator at 283°K was illustrated on *Figure 6:2.3* and this can be calculated using the equation below.

$$P_\lambda = 14388 \times \lambda^{-5}[\exp(14388/283\lambda)-1]^{-1}$$ [20]

From this, the weighted near normal long wave infra red optical properties of the membrane samples (α_{lw}, τ_{lw}, ρ_{lw} and ε_n) could be calculated.

$$\rho_{\mathrm{lw}} = \frac{\int_{\lambda_1}^{\lambda_2} P_\lambda \rho_\lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} P_\lambda d\lambda} \qquad \tau_{\mathrm{lw}} = \frac{\int_{\lambda_1}^{\lambda_2} P_\lambda \tau_\lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} P_\lambda d\lambda}$$

$$\alpha_{lw} = 1 - \tau_{lw} - \rho_{lw} \qquad \text{and} \qquad \varepsilon_n = \alpha_{lw}$$ [21]

where τ_λ and ρ_λ represent the samples transmittance and reflectance at wavelength λ for equal wavelength intervals from λ_1 (2,500nm) to λ_2 (55,000nm). This required that absorptance was measured up to 55,000nm, which was beyond the range of the spectrophotometer however the BS 6993 method allows the extrapolation of results from 50,000nm to 55,000nm based on the trend of readings taken at lower wavelengths.

6:5.5 The Results Obtained Using the Long Wave Infra Red Spectrophotometer.

The near normal long wave infra red spectral optical properties of the membrane samples measured using the technique described above are illustrated on the graphs presented overleaf. These graphs represent properties by area so that the total area always equals 100%. The weighted emissivities are included in the titles of the graphs, and a summary of the properties measured is then presented in *Figure 6:5.6*.

Figure 6:5.5a Near Normal Long Wave Infra Red Optical Properties: Type 1 PVC Coated Polyester (Emissivity 0.92).

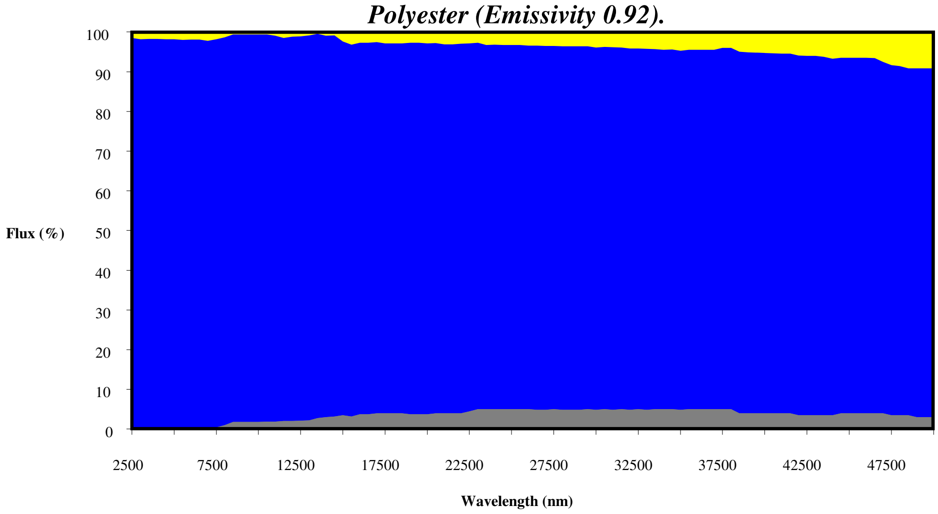


Figure 6:5.5b Near Normal Long Wave Infra Red Optical Properties: Type 2 PVC Coated Polyester (Emissivity 0.90)..''\ƒ graph

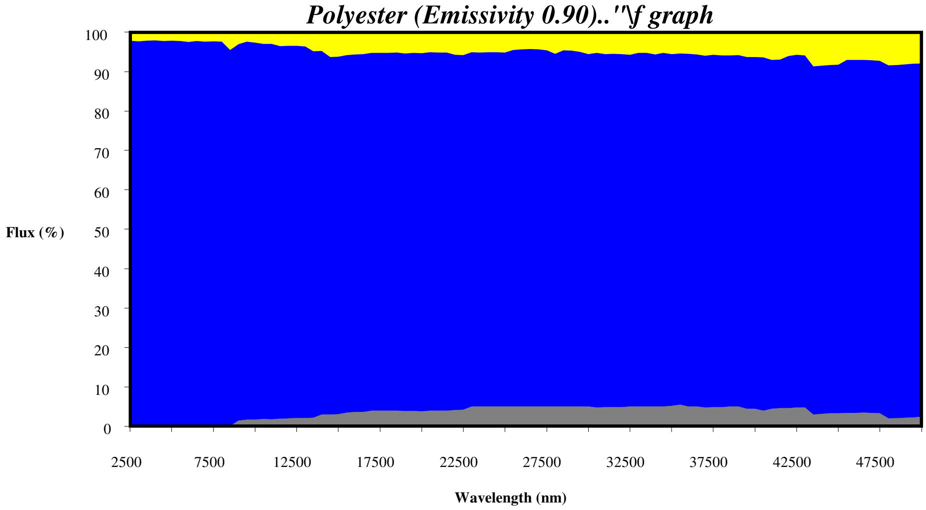


Figure 6:5.5c Near Normal Long Wave Infra Red Optical Properties: Type 3 PVC Coated Polyester (Emissivity 0.90).

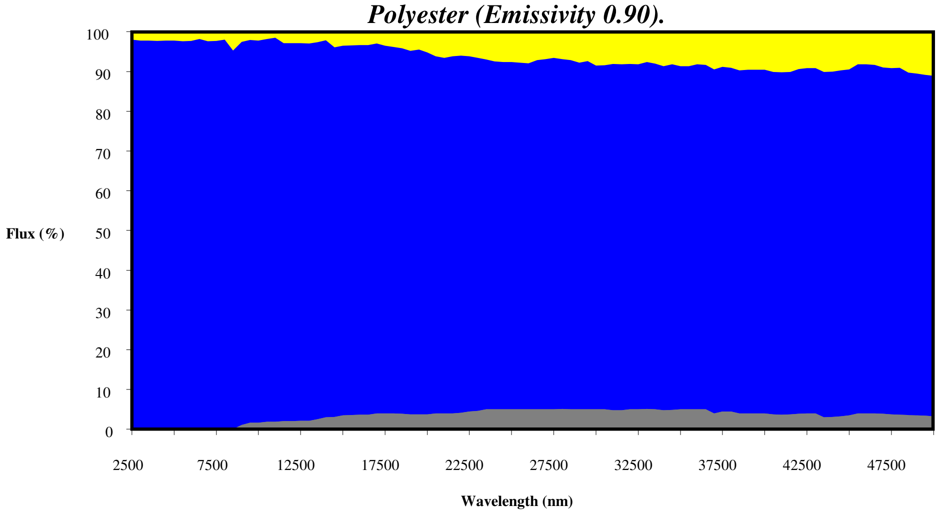


Figure 6:5.5d Near Normal Long Wave Infra Red Optical Properties: Type 4 PVC Coated Polyester (Emissivity 0.91).

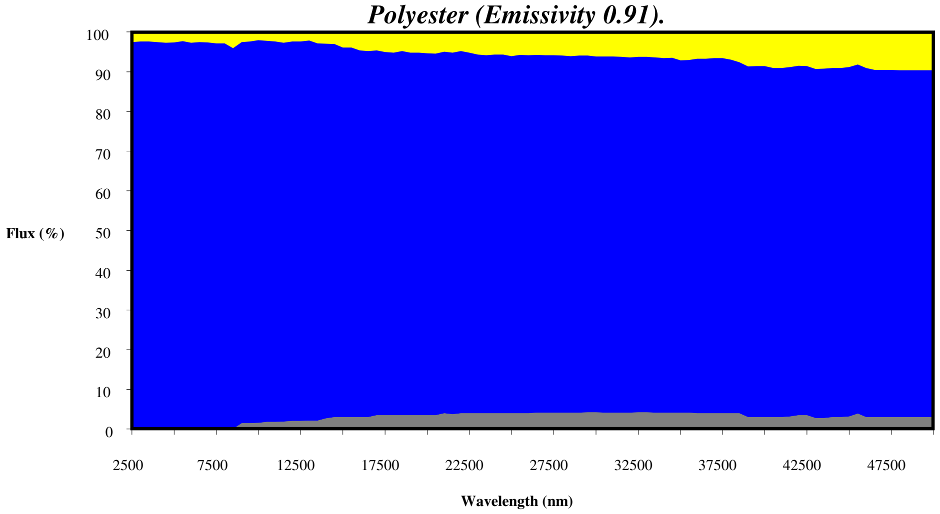


Figure 6:5.5e Near Normal Long Wave Infra Red Optical Properties: Eisteddfod Arena Membrane (Emissivity 0.91).

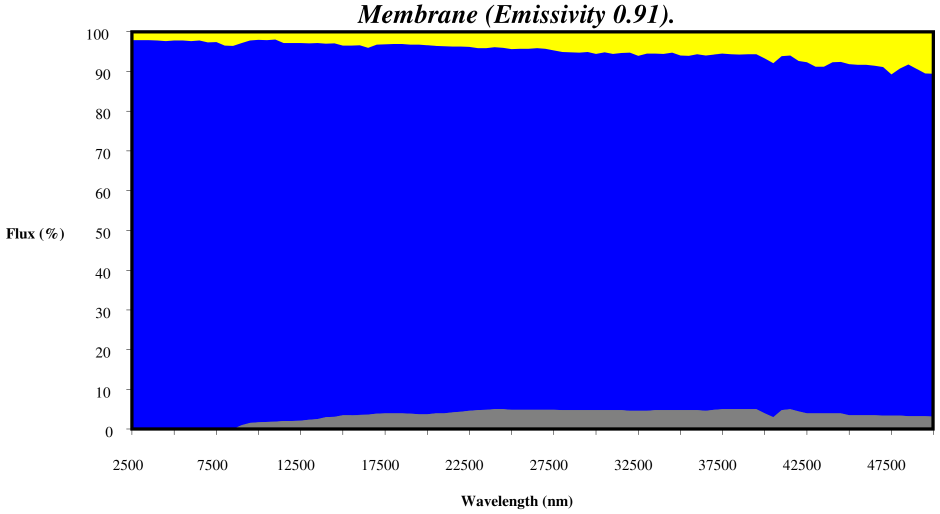
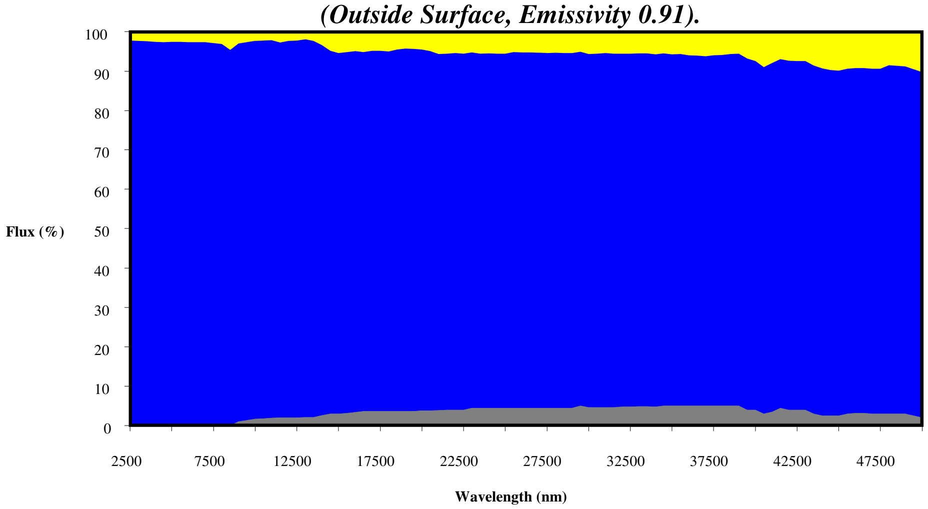


Figure 6:5.5f Near Normal Long Wave Infra Red Optical Properties: Wimbledon Membrane (Outside Surface, Emissivity 0.91).



Transmittance Absorptance Reflectance

Figure 6:5.5g Near Normal Long Wave Infra Red Optical Properties: Wimbledon Membrane (Inside Surface, Emissivity 0.92).

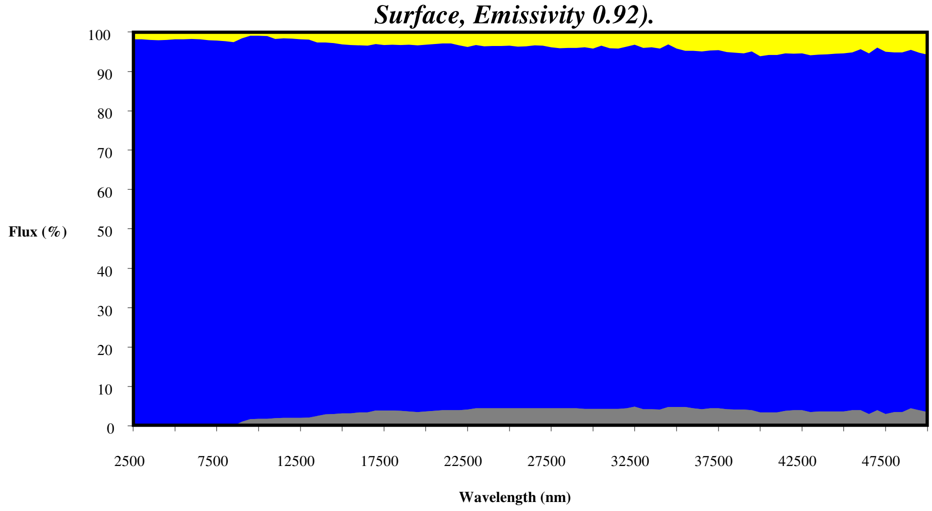


Figure 6:5.5h Near Normal Long Wave Infra Red Optical Properties: Type 1 PTFE Coated Glass (New, Emissivity 0.94).)"\f graph

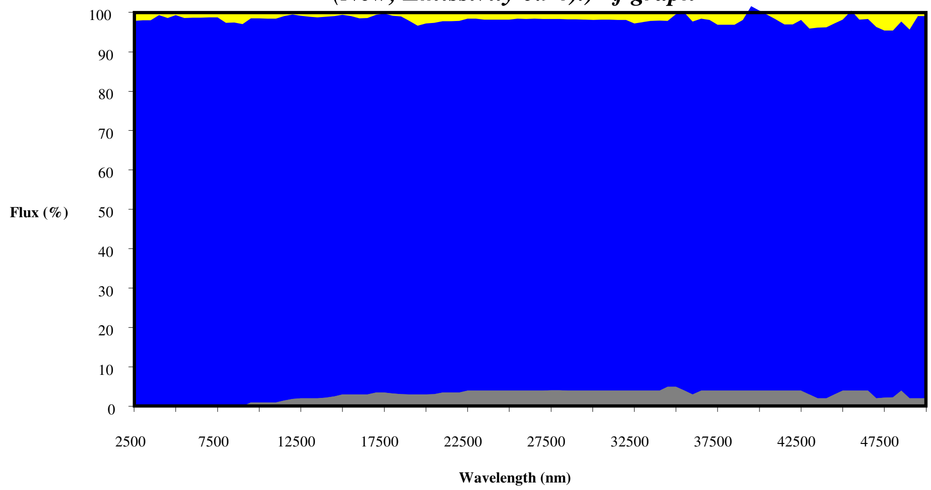
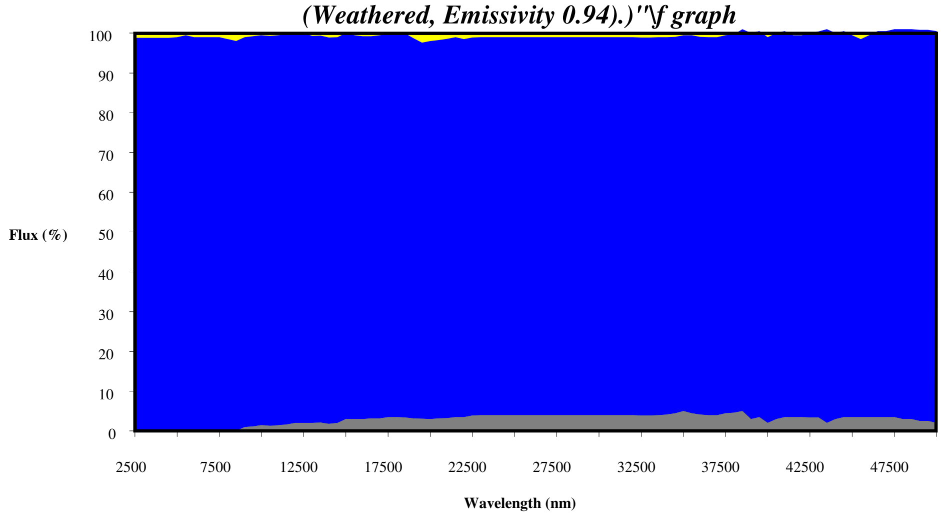


Figure 6:5.5i Near Normal Long Wave Infra Red Optical Properties: Type 1 PTFE Coated Glass (Weathered, Emissivity 0.94).)"\f graph



6:5.6 Analysis of the Results Obtained Using The Long Wave Infra Red Spectrophotometer.

The only significant difference between the properties of the two basic membrane types tested was that whereas both the near normal reflectance and transmittance of the PTFE coated glass membranes tended to decrease with increasing wavelength, the reflectance of the PVC coated polyester membranes continued to go up. As the black body weighting of the long wave infra red region centres around 10,000nm however, these differences were of little significance. Absorptance tended to decrease from almost 100% at 2,300nm to 80 or 90% by 50,000nm for both the PVC polyester and PTFE glass membranes.

The differences between the properties of the various membrane types were slight because of the similar nature their surface coatings. In general however it was noticeable that the emissivities of the PTFE coated glass membranes were slightly higher than those of the PVC coated polyester membranes and that this increased still further as the PTFE coating bleached white following exposure to solar radiation.

In order to predict the likely hemispherical emissivities (ε_h) of the membranes an equation was developed which allowed ε_h to be estimated given that their near normal emissivity (ε_n) was known. This equation was based on a correlation of the near normal and hemispherical long wave infra red optical properties of a range of high and low emissivity types of glass, a material with a low electrical conductivity similar to that of fabric membranes[22]:-

$$\varepsilon_h = 0.9276 \times 0.9926^{\frac{1}{\varepsilon_n}} \times \varepsilon_n^{0.8432}$$

Figure 6:5.6 Weighted Long Wave Infra Red Optical Properties of the Membrane Samples.

	τ_{lw} (%)	ρ_{lw} (%)	α_{lw} (%)	ε_n (ratio)	ε_h (ratio)
Type 1	2.9	5.1	92.0	0.92	**0.86**
Type 2	2.7	7.1	90.2	0.90	**0.84**
Type 3	2.8	6.9	90.3	0.90	**0.84**
Type 4	2.4	6.5	91.1	0.91	**0.85**
Eisteddfod	2.8	6.2	91.0	0.91	**0.85**
Wimbledon (outside)	2.6	6.6	90.8	0.91	**0.85**
Wimbledon (inside)	2.6	5.3	92.1	0.91	**0.86**
PTFE type 1(new)	2.2	3.7	94.1	0.94	**0.87**
PTFE type 1(weathered)	2.3	3.5	94.2	0.94	**0.88**

It was recognised that these calculated hemispherical emissivities could only be considered to be very approximate, and because of the problems involved in this investigation as a whole, the values obtained by this method were compared with the limited data available from two previous researchers:-

Measurements were made by the Chemical Fabrications Corporation to determine the emissivity of their *Sheerfill II* PTFE coated glass membrane and their *Fabrasorb* permeable internal liner membrane[23]. An emissivity of 0.90 was recorded for *Sheerfill II*, 0.91 for dry *Fabrasorb* and 0.88 for wet '*Fabrasorb*'. Unfortunately it is not clear whether these values referred to near normal or hemispherical emissivity, and the method of measurement is not explained.

Sinofsky measured the hemispherical emissivity of three membranes using a D&S emissometer[24] producing an average emissivity of 0.88. However no details were given about the membranes tested, and the problems associated with this technique previously discussed in this chapter must raise doubts about the accuracy of Sinofsky's results.

Little additional data could obtained about the emissivities of fabric membranes, and the validity of these unsubstantiated values is difficult to judge. It is apparent however there is a general similarity between the results presented here and those of previous researchers and this may suggest that whilst the adopted approach was generally unsatisfactory, it may not have been entirely inaccurate.

It is also worth noting that the membrane emissivities were fairly high compared to many more conventional materials. Typically the emissivity of metals is between 0.05 and 0.55[25] and the difference between this and the emissivities of the membrane samples may explain the discrepancy between the temperatures recorded on the inside and outside surfaces of the membranes discussed in the Chapter 5.

6:6 CONCLUSION.

In the previous chapter, a test cell investigation into the thermal behaviour of fabric membranes was described. Analysis of the data collected during this investigation made it apparent that the thermal behaviour of thin translucent membranes could not be explained by traditional properties such as thermal capacity or conductivity but that it was almost entirely dependent upon their thermal optical properties. In this chapter a series of measurements were described which were carried out in order to quantify those thermal optical properties.

The near normal solar optical properties of nine membrane samples were measured using spectrophotometric techniques, and then their angular solar optical properties were measured using an Edwards type integrating sphere. A set of standard equations were then developed from which near normal solar optical properties of the membrane samples could be used to determine both their angular direct beam and diffuse solar optical properties.

In general it was seen that whilst the spectral solar optical properties of the PVC coated polyester samples were quite different from those of the PTFE coated glass samples, their angular solar optical properties displayed very similar trends. These trends were not closely comparable to the behaviour of glass, and it was considered that this must bring into further doubt the continued use of shading coefficients to describe the thermal optical properties of fabric membranes.

The near normal long wave infra red optical properties of the membrane samples were then measured, again using spectrophotometric techniques. Unfortunately it proved impractical however to measure the angular long wave infra red optical properties of fabric membranes. In order to overcome this problem an equation was developed based on the properties of glass from which the near normal long wave infra red absorptance of the samples could be used to predict their hemispherical emissivity. Whilst this technique was not entirely satisfactory, results were in close agreement with those of previous researchers.

In general, the emissivity of the PTFE coated glass membranes was slightly higher than those of the PVC coated polyester membranes, and this increased further as the PTFE coating bleached white on exposure to solar radiation.

In the next chapter, the development of a theoretical model written in order to simulate the thermal behaviour of the fabric membrane samples will be described. This model will be substantiated using the properties information presented in this chapter and validated with the behavioural data discussed in Chapter 5.

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