12 METER MILLIMETER WAVE TELESCOPE
MEMO NO. 233

Membrane Material Development

The millimetre wave telescope enclosure provides 'bad' weather protection for the antenna but under most observing conditions the viewing aperture will be covered by a membrane. The general requirements of this membrane are set out in table 1 and a lengthy search has been undertaken over a period of a few years to find a material to meet this specification. The purpose of this report is to record the major points in this search and to highlight the detailed results of measurements on the most promising material. A complete list of the materials investigated will be found in appendix 1.

At the time of writing the 1976 feasibility study report (blue book) a number of potential membrane materials, including commercial radome fabrics, had been investigated. Although none of them satisfied the specified requirements the most promising material was nylon spinnaker cloth where areas of potential development could be seen to offer hope of improvements. In particular for its sailing application it is wind proofed by coating with clear polyurethane varnish and in this form its mm transmission properties were acceptable, figure 1. The thermal problems associated with the effects of solar heat being transmitted by the membrane were recognised and it was proposed that TiO_2 white pigment could be added to the varnish to produce a 'whiter' finish.

Once the project was approved a development programme was started which in the first instance concentrated on the development of solar reflecting coatings for spinnaker cloth. The varnish used by the sailmakers is polyurethane based as this provides the necessary strength and life to withstand the flexing demanded of a sail. Somewhat similar properties would be required for the membrane coating. A series of experiments were undertaken to investigate the effect on the mm transmission of loading the varnish with TiO_2 and UV inhibitors. The latter was an important additive since the strength of nylon cloth deteriorates after comparatively short exposures to solar UV. Measurements were made on different thicknesses of films of plain polyurethane varnish, varnish loaded with TiO_2 and coated fabric. Black coatings were also investigated since at that time it was not clear what membrane finish or combination of finishes would provide the best thermal protection for the antenna. Measurements of the solar (340-2100nm) reflectance and transmittance were also made. The results indicated that the addition of TiO_2 (or carbon black) to the varnish did not have a significant effect on the mm transmission. The major contribution to the transmission loss came from the varnish so that the thickness of coating required to achieve a given solar reflectance was such as to significantly reduce the transmission, figure 2. It thus became clear that a single skin membrane based on white coated nylon cloth could not simultaneously provide the required mm transmission and high solar flux rejection.

At this time a series of experiments were being undertaken on La Palma to investigate the thermal interaction of membrane combinations and antenna panels. The acceptable temperature gradient between front and back skins of the 'thick' panels was 1.5°C and it was found that this could only be achieved by having a double skin membrane with ambient air being blown between the skins. Both membrane skins were based on spinnaker cloth and the outer was coated white to reflect as much of the solar flux as possible while the inner was black in order to absorb the remainder. Although this combination satisfied the thermal requirements each of the membrane skins was more absorbing of mm waves than the specification allowed, particularly at frequencies above 300 GHz. Since there was no likelihood of improving the overall properties of this class of membrane material other potential fabrics were investigated.

Woven fabrics using threads of glass fibre and kevlar were examined, figures 3A and 3B, and both of these were coated with PTFE for the applications for which they were manufactured. This coating effectively rendered them wind proof for our application. A series of mm transmission measurements of various thread count samples of these materials were made, but the transmission did not meet our specification. In addition the fabrics as made were light-brown, as a result of oxidation of size used in the coating process, and translucent. A significant development programme would have been required to produce white and black samples. However some significant basic data on the effects of thread type and thread counts were gained from these studies. For woven fabrics there are three loss mechanisms namely reflective, absorption and scattering. The first two are constants for a particular bulk material, while the third is a function of the characteristic weave dimensions. Where the latter are of the order of the wavelength, scattering effects can be dominant particularly for low loss man-made fabrics. Homogeneous sheets do not show scattering effects and the transmission properties are easily predicted. Nylon spinnaker cloth is woven from threads at a density of about 44 threads/cm. However, the threads are made up of 10 fine fibres which in the weaving process become dissociated so that prior to weaving the thread is a round collection of fibres and on weaving it becomes a rectangular collection of fibres wider than the thread in the plane of the fabric. This has the effect of greatly increasing the effective thread count so that scattering effects associated with the regular spacing of fine fibres occurs at high wavenumbers outside the range of interest to the current work. Both glass and kevlar on the other hand have twisted fibre threads which stay together on weaving. Thus with thread counts of the order of 20/cm scattering effects occured in the middle of the spectral range of interest to us. The possibility exists with these materials of adjusting the thread count to place the effect in a region of the spectrum where for example the atmosphere is opaque. Both of these fibres also show strong absorption effects.

A material based on nylon sailcloth coated with an expanded PTFE film was investigated next, figure 4 and while it looked a good potential material because the PTFE film was intrinsically white further investigations were superseded by another fabric manufactured by the same firm, W L Gore. This new material was a white all PTFE laminate made up of a woven fabric covered on one side with a thin film. A black form of the material is not made. PTFE is potentially an ideal material for a membrane from the mm transmission point of view in that its refractive index is low by man-made fibre standards and so is its absorption coefficient. The former property means that its reflective loss is small and the latter that comparatively thick samples will be very transparent. The major problem with PTFE is that in its normal form its mechanical properties are very poor. Gore, however have produced a form of PTFE known as expanded PTFE which by aligning the fibres greatly improves its mechanical strength. The basic material consists of a woven fabric made up of rectangular threads of approximate dimensions 80 x 250µm, these threads are not made up of fibres but are a thin triple folded sheet. The fabric is then coated with a 20µm film of PTFE sheet on one side and this coating renders it waterproof up to a water entry pressure of 50lb/in^2. The mm transmission properties are shown in figure 5 and its mechanical, solar and infrared properties in table 2, sample A. Because of the g transmission results a small sample was woven by hand with a compacted weave, sample B. This sample had better mm transparency, figure 6 and was expected to have better strength and solar reflecting properties. Unfortunately the commercial weavers could not reproduce the cloth.

Measurements of the mm transmission properties parallel to the warp and weft directions indicated a significant polarization effect and it was clear that the cause of this effect probably lay in the unsymmetric nature of the weave pattern.

Table 1

Membrane Material Requirements

1. Millimetre Transmission:-

22 - 300 GHz	>	92%
300 - 450 GHz	>	85%
600 - 900 GHz	>	80%

2. Real Refractive Index:- Over above frequency range

   < 1.5 (to minimise reflective losses).

3. Visible Transmission:-

   Averaged over range 0.34 - 2.1 μm < 0.2.
   (Most of the loss should be by reflection rather than absorption in the material).

4. Mechanical:-

   Breaking load > 35 KNm^{-1}
   Elongation at break < 17%

5. Weathering Resistance:-

   Good resistance to weathering, particularly to solar ultraviolet radiation and water absorption. Operational life of at least 1 year on a mountain site without major changes of strength or RF properties.

From one side of the fabric the weave pattern is different in the two directions, however, when the fabric is viewed from the other side the pattern is rotated through 90°. The transmission properties were found to follow this rotation of the fabric and so various alternative symmetric weave patterns were suggested to the weaver. The pattern selected is a 2 x 2 basket weave in which pairs of threads are woven in an alternative over and under arrangement. The transmission properties of this material are shown in figure 7 and its other properties are given as sample C in table 2.

Table 3 presents a comparison of the power transmission properties of the materials reported here. The comparison is at two wavenumbers, 10 and 23 cm^{-1} (300 and 690 GH

At the present time no further improvements to the fabric are planned although it has been suggested to Gore that finer 'threads' with a corresponding increase in thread count might improve the material for our application by shifting the worst effects of scattering loss to higher frequencies. However, we have been adapting a commercial fabric to meet our requirements and it is already costing of the order of £100/m^2 (for 600 sq m) and without another large potential customer further improvements would be expensive to achieve.

R L T Street
17 May 1983

Note: A32 looks good for $k \leq 10$ cm^{-1}, which matches our requirements for the 12-m and Kitt Peak

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Table 2 Other Properties of All PTFE Woven Materials.

Sample	Thread Count (cm^{-1})		Nominal Thickness (μm)	Tensile Strength (kNm^{-1})		Elongation at Break (%)		Absolute Solar Properties (0.34 - 2.1μm)			IR Properties (5 - 56μm)		
	Warp	Weft		Warp	Weft	Warp	Weft	Reflectance	Absorption	Transmittance	Reflectance	Absorption	Transmittance
A	28	27	278	36	34	16	18	0.69	0.06	0.25	0.10	0.64	0.26
B	42	32	290	-	-	-	-	-	-	-	-	-	-
C	41	36	300	68	51	16(?)	18(?)	0.73	0.06	0.21	0.12	0.64	0.24

Table 3 Membrane Transmission Properties at $10cm^{-1}$ and $23cm^{-1}$

Material	Power Transmission	
	$10cm^{-1}$ (1mm) (300GHz)	$23cm^{-1}$ (0.4mm) (690GHz)
Wind proofed nylon spinnaker cloth (fig 1)	0.98	0.85
White varnished nylon spinnaker cloth (fig 2)	0.85	0.65
PTFE coated glass fibre (fig 3A)	0.65	0.70
PTFE coated kevlar (fig 3B)	0.77	0.85
TFE coated nylon sailcloth (fig 4)	0.94	0.82
Standard laminated PTFE cloth (fig 5)	0.95	0.85
Compacted weave PTFE cloth (fig 6)	0.95	0.90
2x2 basket weave laminated PTFE cloth (fig 7)	0.96	0.85

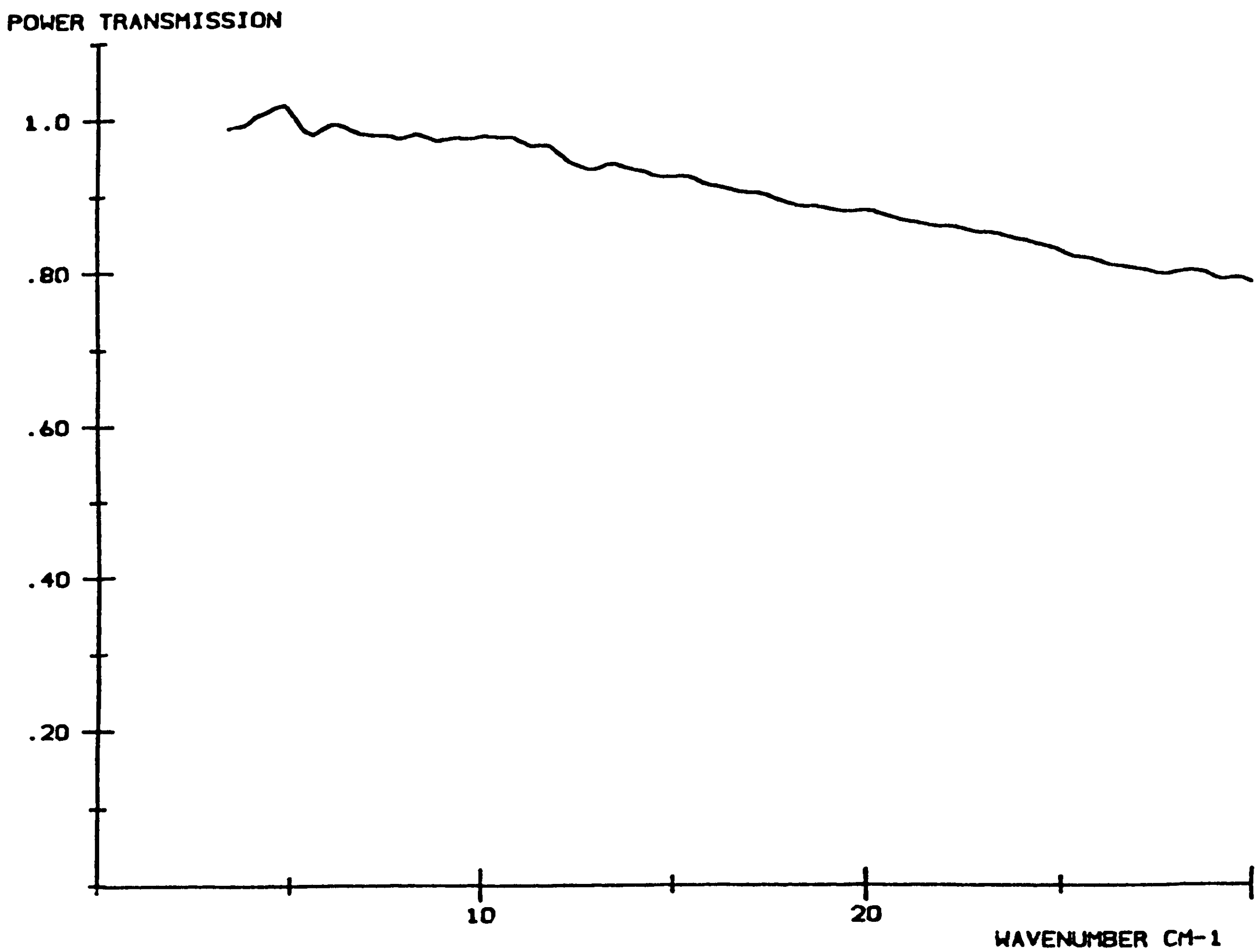

Figure 1 Nylon Spinnaker Cloth Wind Proofed with Polyurethane Varnish.

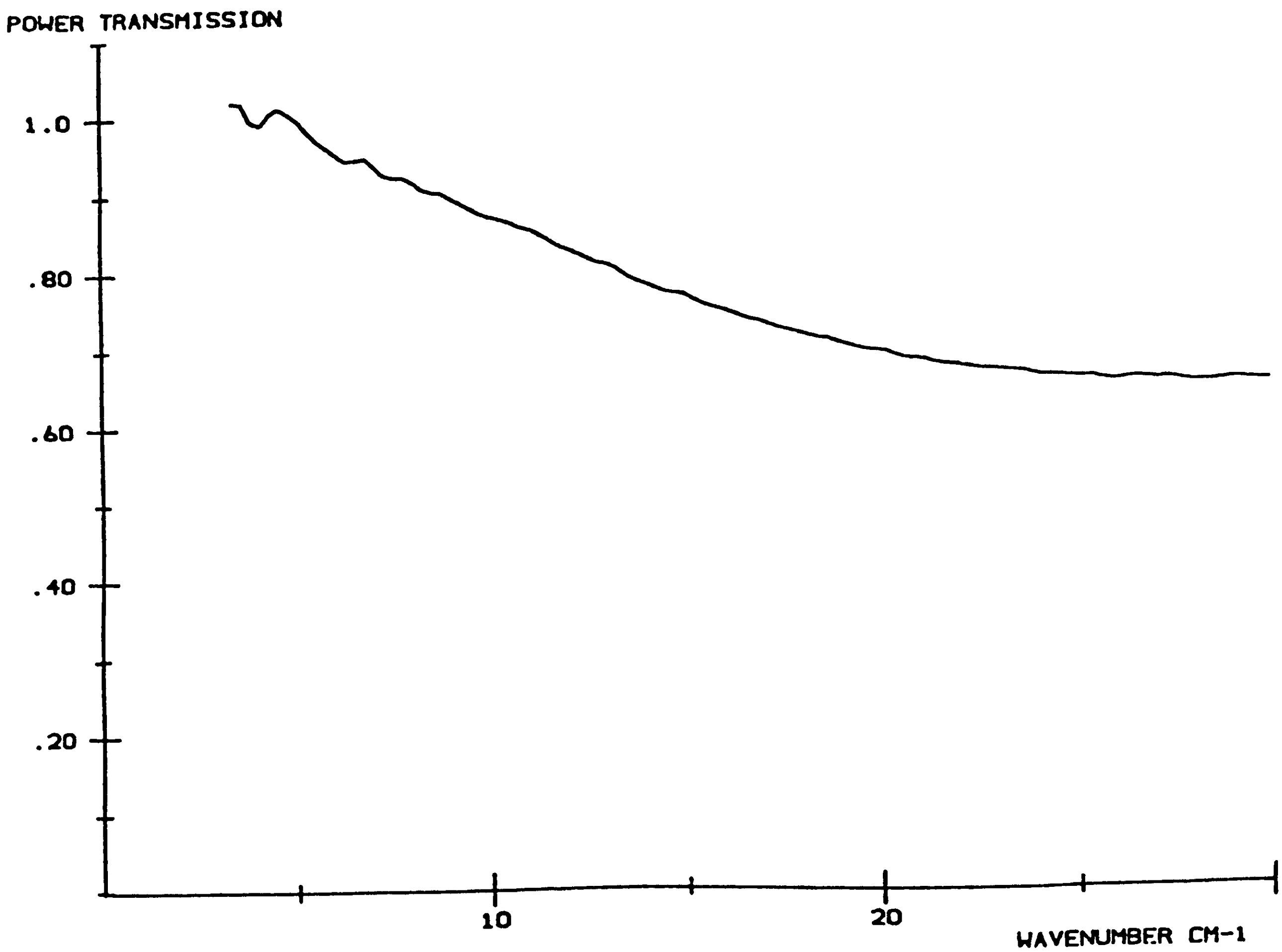

Figure 2 Nylon Spinnaker Cloth Coated with 24grm/m^2 of White (TiO_2) Polyurethane Varnish.
Solar Reflectance 49%, Solar Transmittance 43%.

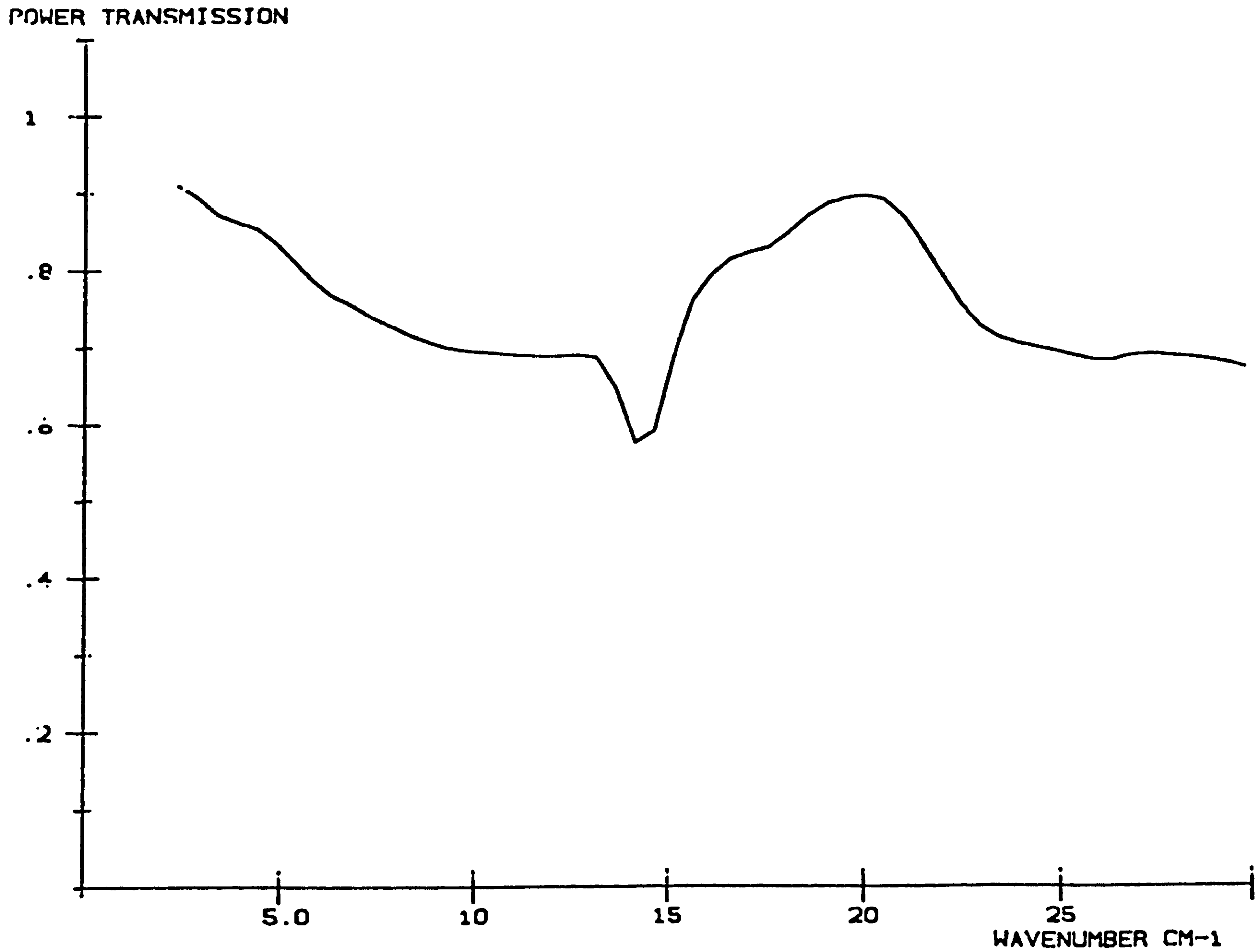

Figure 3A Glass Fibre Cloth Coated with PTFE.

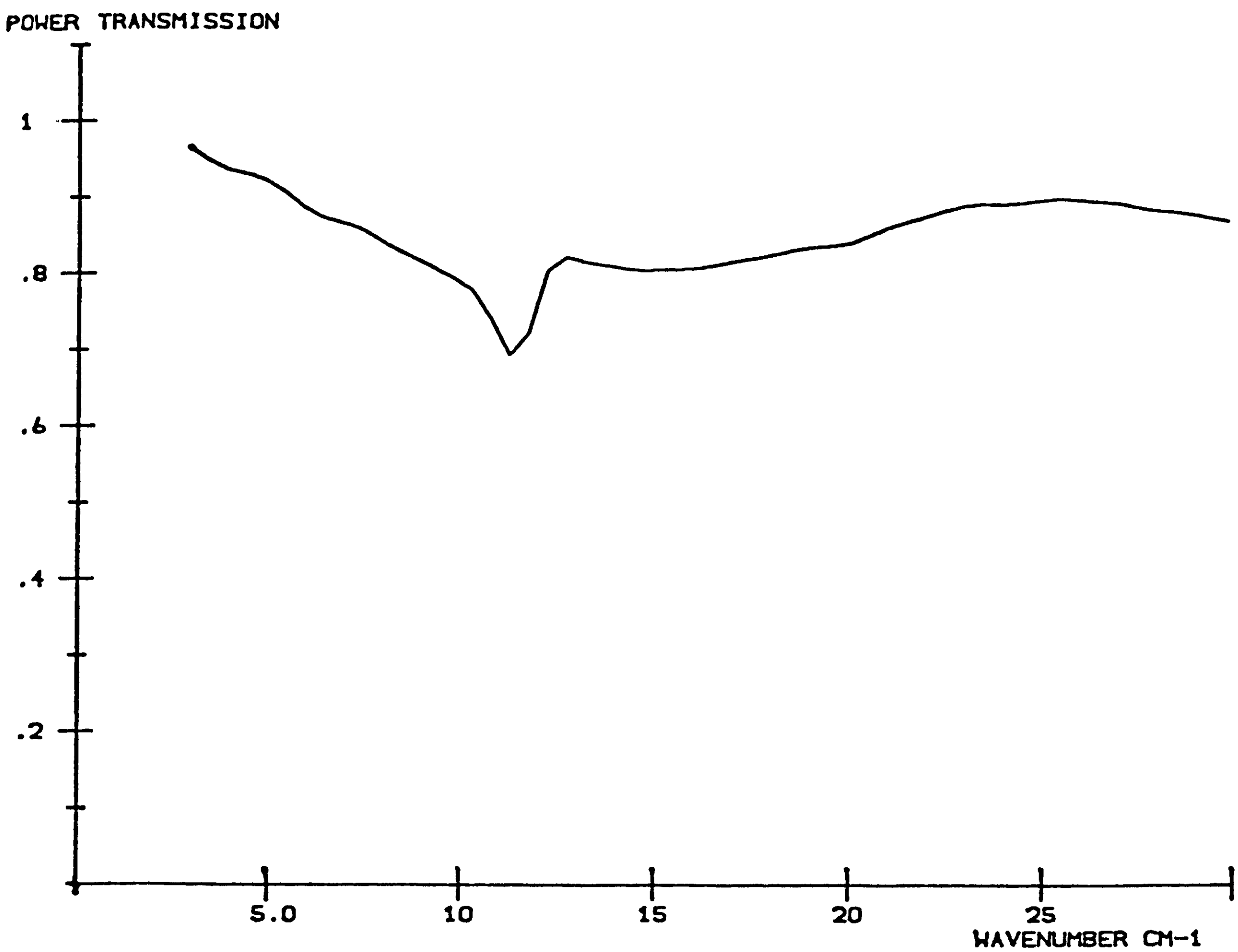

Figure 3B Kevlar Cloth Coated with PTFE.

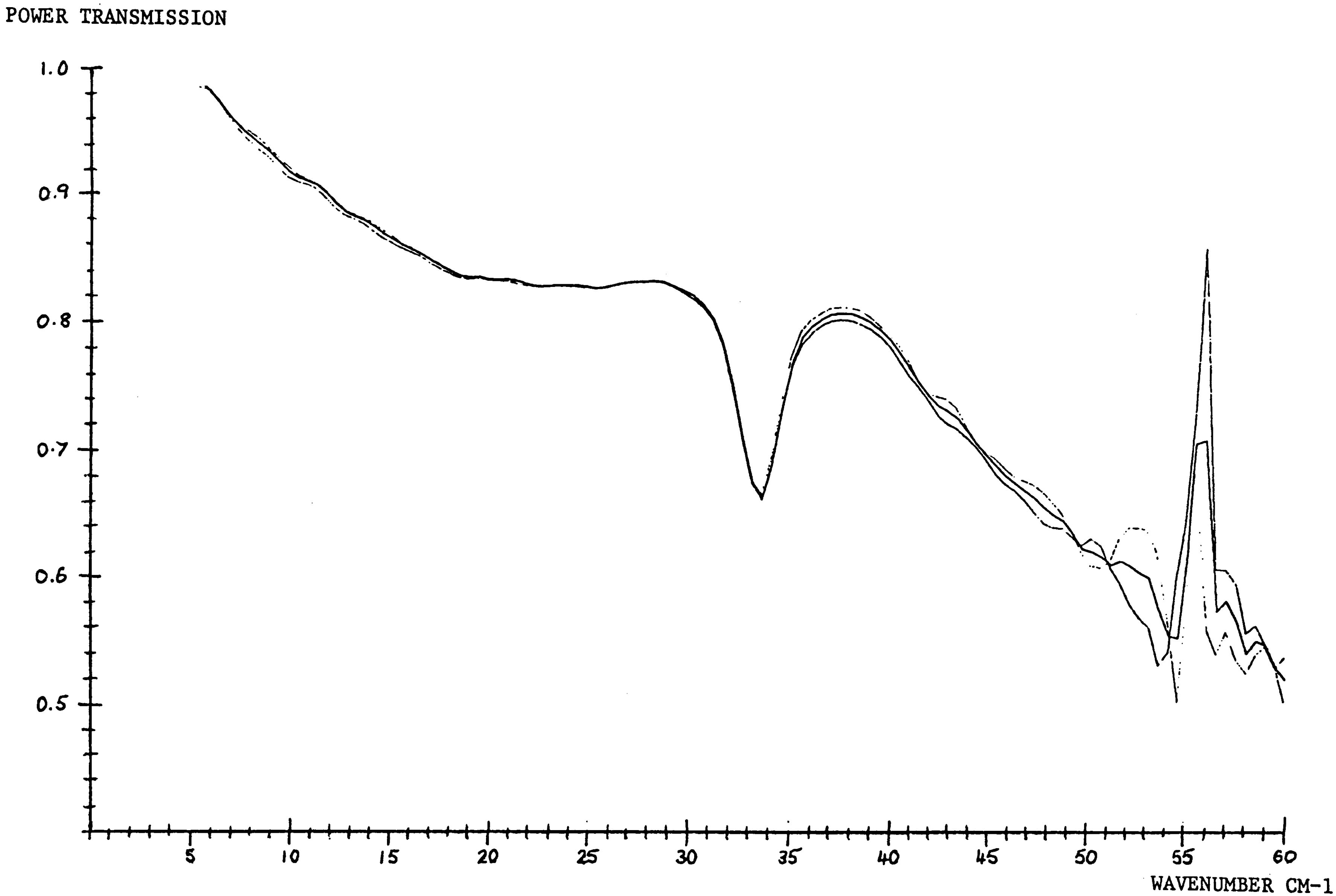

Figure 4 Nylon Sailcloth Coated with a PTFE Thin Film on One Side.

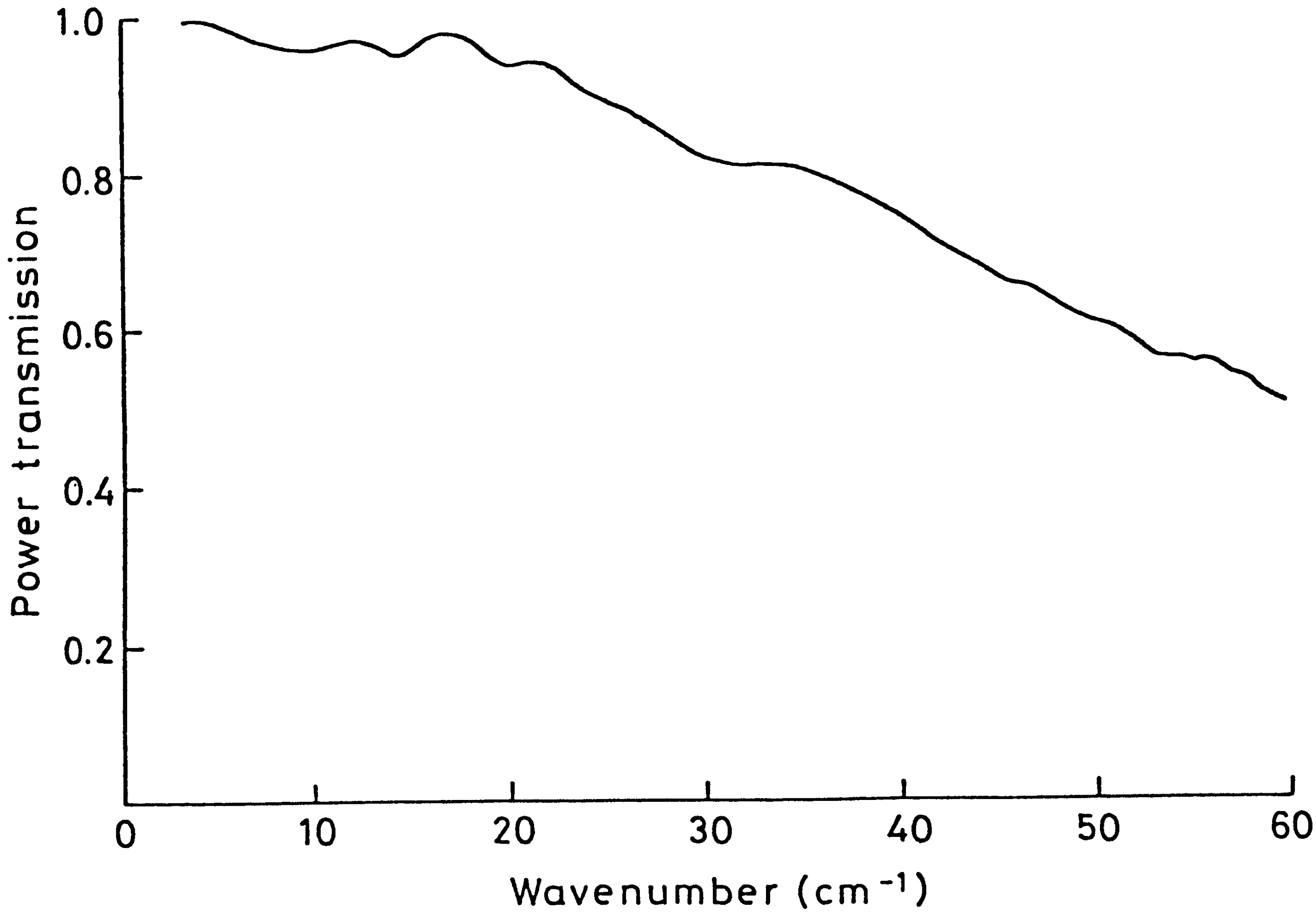

Figure 5 Standard All PTFE Cloth Laminated on One Side to a 20μm PTFE Film.

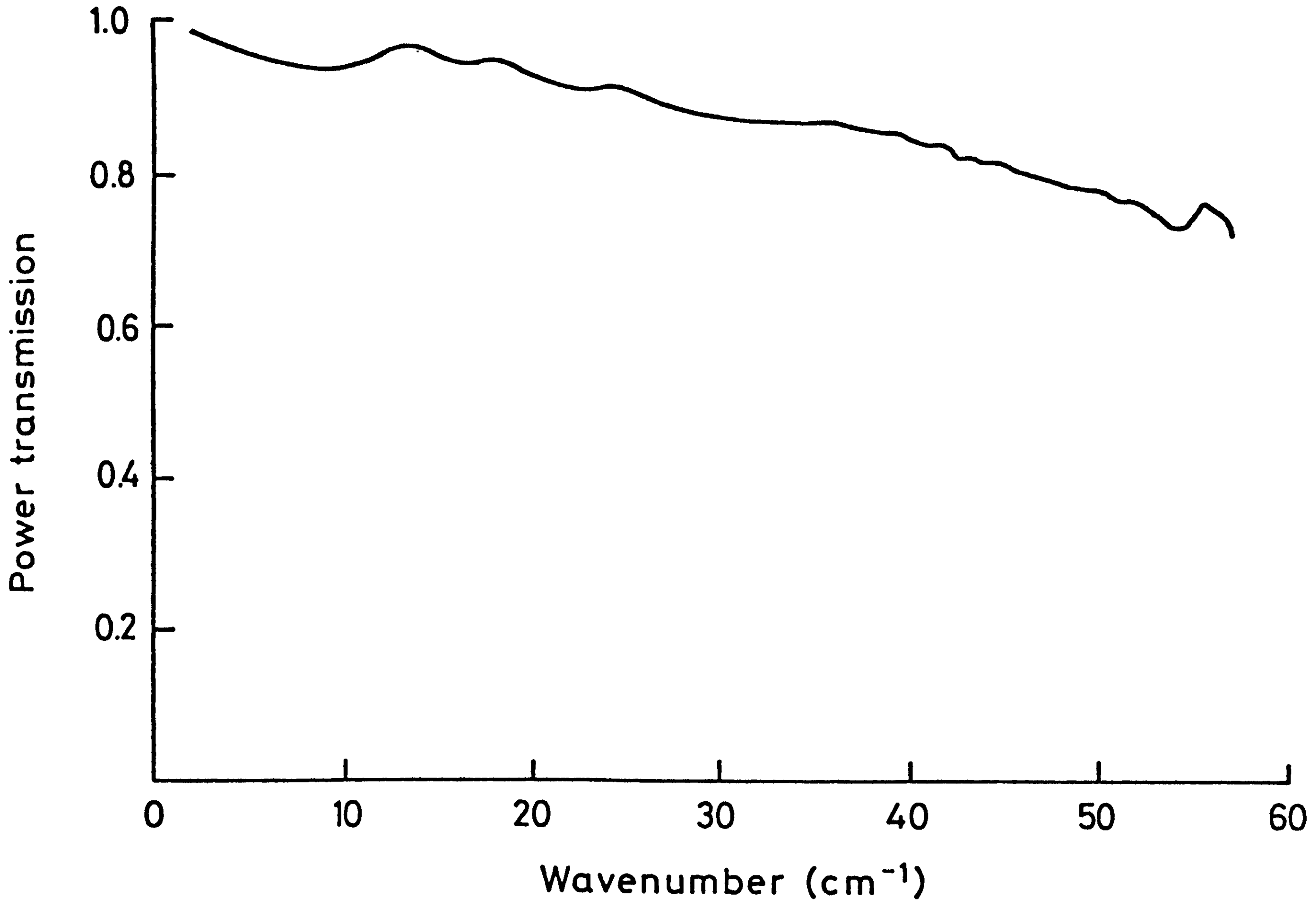

Figure 6 Compacted Weave All PTFE Cloth.

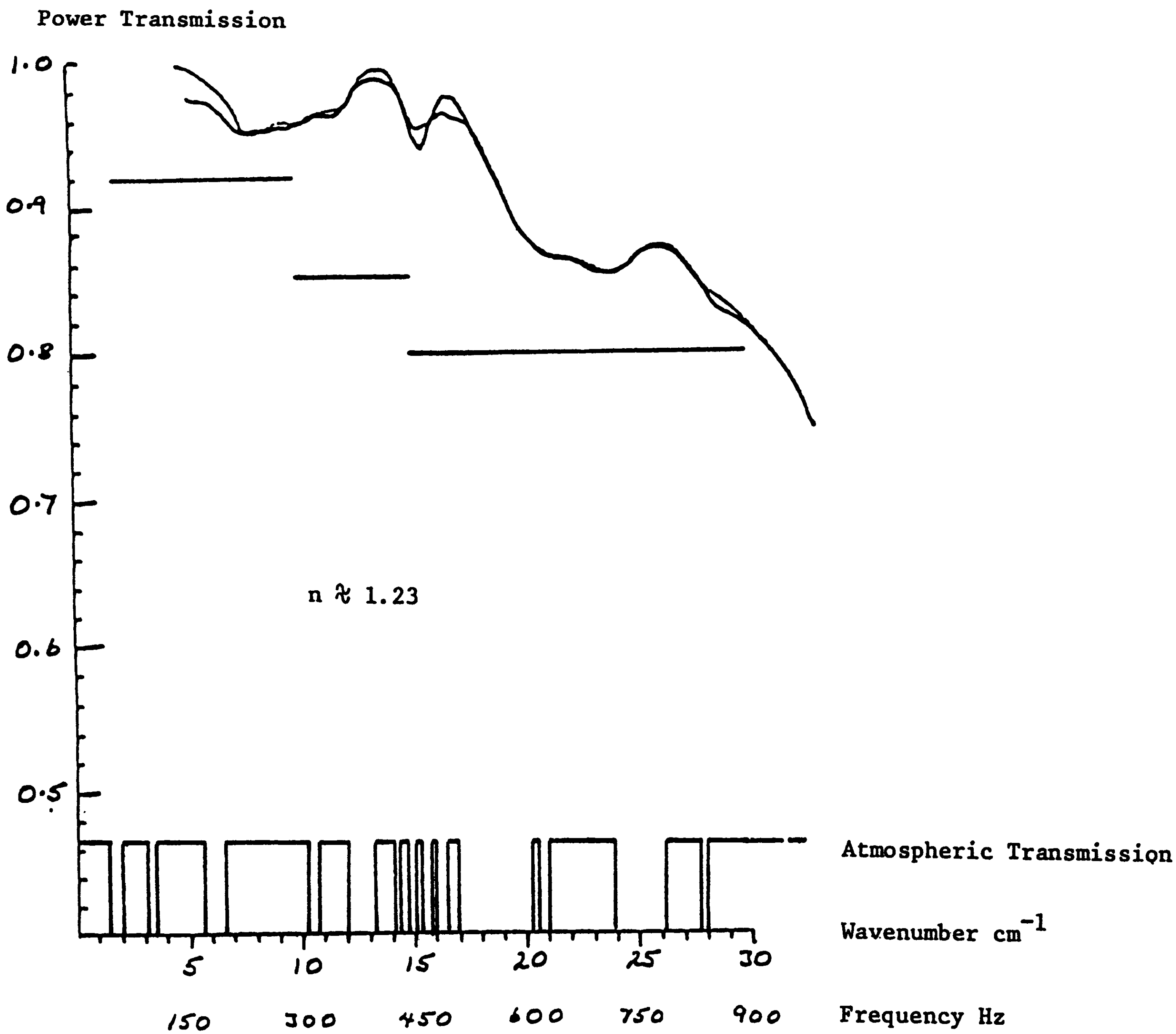

Figure 7 2 x 2 Basket Weave All PTFE Cloth Laminated on One Side to a 20μm Thick PTFE Fibre.

Appendix 1. Potential Membrane Material Measurements

Sheet 1
19.5.83

NPL REPORT NO 1	FILLER	COATING	OVERALL THICKNESS (µm)	SOLAR R	SOLAR A	SOLAR T
Polypropylene			2.0			
Polytetrafluorethylene			9.0			
Nylon Spinnaker Cloth	White, orange,		82.5	.27, .18	0, .22	.74, .60
	blue		140	.26	.34	.40
Nylon Parachute Cloth			300			
Plasticised PVC			762			
Griffolyn			100	.49	.51	0
Polyethylene	TiO_2		47.5			
	Carbon black		72.5	.04	.96	0
Polyurethane			117			
			302			
	Carbon black		62.5			
	Carbon black		612			
Polyethyleneterephthalate		Nickel/cadmium	25			
		Aluminium	47.5			
		Graphite	25			
		Carbon black	32.5			
	TiO_2		37.5	.57	.05	.38
NPL REPORT NO 2						
Terylene Sailcloth	TiO_2	Polyurethane	180	.50	.09	.41
	TiO_2	Polyurethane	185	.55	.09	.36
	TiO_2	Polyurethane	190	.58	.09	.33
	TiO_2	Polyurethane	195	.65	.09	.26
			175	.41	.09	.50
Nylon Spinnaker Cloth (85)	TiO_2	Polyurethane	90	.44	.09	.48
	TiO_2	Polyurethane	100	.61	.09	.30
	TiO_2	Polyurethane	105	.62	.09	.29
	TiO_2/carbon black		125	.61	.39	0
		Polyurethane				
			85	.19	.12	.69
Nylon Spinnaker Cloth (105)	TiO_2	Polyurethane	110	.47	.09	.45
	TiO_2	Polyurethane	125	.68	.09	.23
			105	.25	.08	.67

Appendix 1. Potential Membrane Material Measurements

Sheet
19.5.

NPL REPORT NO 2	FILLER	COATING	OVERALL THICKNESS (μm)	SOLAR R	SOLAR A	SOLAR T
Clear Polyurethane Varnish			30			
			15			
			50			
White Polyurethane Varnish	TiO_2		17	.49	.08	.43
	TiO_2		22	.58	.09	.33
	TiO_2		32	.66	.08	.26
	TiO_2		66	.78	.08	.14
	TiO_2		59	.75	.10	.15
NPL REPORT NO 3						
Glass Fibre Cloth (FH)		PTFE	85			
		PTFE	80			
		PTFE	160			
Kevlar Cloth (FH)		PTFE	130			
Glass Fibre Cloth (Birdair)						
Thread count/cm 18/18			50			
22/22			50			
24/20			50			
28/22			50			
Glass Fibre Cloth (Chemfab)						
Thread count/cm 24/19		PTFE	90			
25/19		PTFE	80			
25/20		PTFE	65			
Glass Fibre Cloth (FH)						
Thread count/cm 20/29			50			
25/20			50			
25/20		PTFE	80			
Kevlar Cloth (FH)			120			
Glass Fibre/Kevlar Cloth (FH)			110			
NPL REPORT NO 4						
Nylon Spinnaker Cloth (Wind-master)	Carbon black	Polyurethane	100			

Appendi[redacted] Potential Membrane Material Measurements

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19.5.83

NPL REPORT NO 4	FILLER	COATING	OVERALL THICKNESS (μm)	SOLAR		
				R	A	T
	TiO_2	Polyurethane	130			
	Carbon black	Polyurethane	105			
	TiO_2	Polyurethane	105			
Nylon Coated Nylon Sailcloth			80			
Nylon Spinnaker Cloth (8grm)	Carbon black	Polyurethane	100	.09	.69	.21
(16grm)	Carbon black	Polyurethane	105	.07	.77	.15
(24grm)	Carbon black	Polyurethane	105	.07	.82	.12
(8grm)	TiO_2	Polyurethane	95	.39	.08	.53
(16grm)	TiO_2	Polyurethane	100	.47	.08	.46
(24grm)	TiO_2	Polyurethane	100	.49	.08	.43
Nylon Spinnaker Cloth (½oz)			50			
(¾oz)			80			
(1oz)			80			
(1½oz)			80			
Tefzel			126			
			260			
NPL REPORT NO 5						
PTFE Laminated Nylon Sailcloth		PTFE	100			
PTFE Laminated PTFE Cloth		PTFE	278	.69	.06	.25
PTFE Cloth			258			
PTFE Cloth, compacted weave			290			
PTFE Laminated 2 x 2 basket weave PTFE cloth		PTFE	300	.73	.06	.21