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A World-Wide Program for the Continuous Monitoring of Solar UV Radiation Using Poly(phenylene Oxide) Film, and a Consideration of Results

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Synopsis

The use of poly(phenylene oxide) film to monitor UV radiation is demonstrated, and the results from the continuous monitoring of solar UV radiation at 24 sites throughout the world are presented. The global and diffuse measurements from a temperate and from a tropical site are analyzed in detail, and the effects of season and weather conditions on the UV contribution to solar radiation and the relative importance of the diffuse and direct components of solar UV are discussed.

INTRODUCTION

Although it accounts for less than 5% of the total energy, the ultraviolet (UV) portion of the solar spectrum reaching the Earth's surface is in general the wavelength region which is most effective in degrading organic polymers.

To help predict confidently the useful "lifetime" of organic polymers in different climatic regions of the world, it would be necessary to know the UV environment of these regions. World-wide data on this part of the solar spectrum are not available, however, primarily because of practical difficulties. Photoelectric devices have been used because of their high sensitivity, but to date they have not been used extensively because of their complexity, high cost, and questionable reliability in continuous use. Robertson[1] has succeeded in overcoming some of these problems for measurements in the erythema range; and recently, photoelectric sensors developed by the Building Research Establishment[2] have become commercially available. Nevertheless, more widespread programs remain handicapped as long as only sophisticated and expensive methods are available. This report describes a simple method of continuous UV monitoring developed at the Explosives Research and Development Establishment and presents results obtained using the method.[3]

From studies in these laboratories, it has been found that a thin film (20 microns) of pure poly(phenylene oxide) (PPO) darkens when exposed to wavelengths shorter than 400 nm (Table I). This darkening is measured as

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TABLE I
Wavelength Dependence of the Colour Change ($\Delta OD_{340\ nm}$) Induced in PPO by Exposure to Solar Radiation[a]

Wavelength range of "window," nm	Peak wavelength, nm	Contribution to overall $\Delta OD_{340\ nm}$, %	Estimate of solar energy transmitted by window using data of Luckiesh[5]	Relative contribution to $\Delta OD_{340\ nm}$ for constant incident energy
290–345	306	26.5	4.3	410
300–395	369	28.5	11.8	161
335–390	353	21.0	19.6	71.3
350–410	390	17.0	31.0	37.6
395–450	412	2.8	30.2	6.0
400–500	450	1.5	101.6	1.0
480–infrared	—	2.7	—	—

[a] Determined by a method described previously[4] and which is based on exposing films of PPO under a range of cut-off filters outdoors and relating the difference in the degree of color change between films under successive pairs of filters to the notional "light window" obtained by considering the difference in transmission characteristics of the same pairs of filters.

the increase in optical density of the film at 340 nm ($\Delta OD_{340\ nm}$) and is to a first approximation proportional to the product of time and intensity. Initially, $\Delta OD_{340\ nm}$ increases autocatalytically until a limiting dose is reached; thereafter, it increases linearly with dose. For an accurate measure of the dose, and the one which is used in this report, the $\Delta OD_{340\ nm}$ of a film which has been exposed to solar radiation is expressed as the time in hours the film would have to be exposed to a standard black fluorescent lamp (intensity 3×10^{17} quantum sec^{-1} mm^{-2}) to give the same $\Delta OD_{340\ nm}$. For simplicity, the units are referred to as black lamp equivalent time units (BLETs).

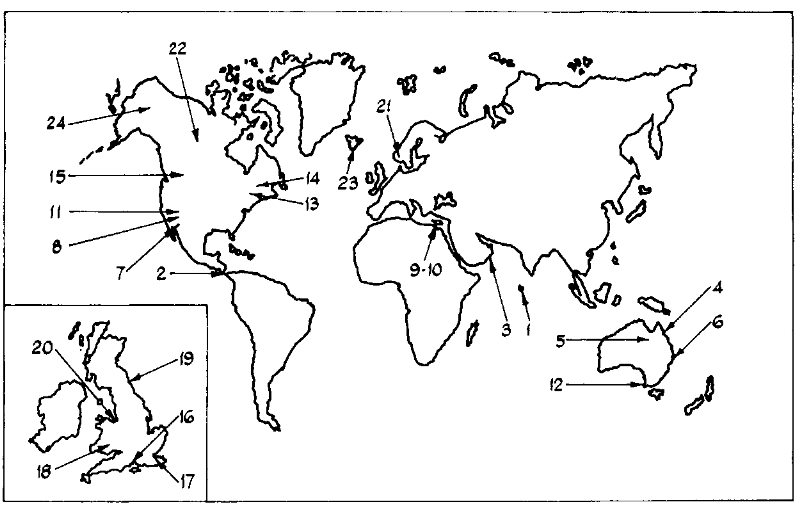

Fig. 1. Location of UV monitoring sites. Key to site numbers given in Table I.

WORLD-WIDE UV MONITORING

The PPO technique is being used to monitor continuously the solar UV radiation incident on horizontal surfaces, i.e., global UV, at 24 sites throughout the world (Fig. 1) thanks to the helpful cooperation of individuals, unfortunately too numerous to mention by name, of the organizations listed in Table II. Exposure periods range from two to three days in the tropics in summer to monthly periods in the Arctic in winter; measurements for these intervals are available,[3] but only monthly totals are presented here (Table II). Each of the sites shows the expected seasonal trends, but it is noticeable that there is not a simple relationship between latitude and dose. Consideration of the dose for the three summer months as a function of site latitude, an upper limit in the relationship which is defined by those sites which experience cloudless conditions in their summer months is indicated (Fig. 2). The sites which are known to be subject to periods of cloudy conditions depart in varying degrees from this relationship. The results from this monitoring program are currently being analyzed, but some of the factors which can affect the solar UV radiation reaching the Earth's surface have become apparent from a detailed investigation of a tropical and of a temperature site.

DIFFUSE AND DIRECT SOLAR UV IN A TEMPERATE AND A TROPICAL SITE

In addition to measuring the global solar UV, the diffuse component of solar UV has been continuously monitored at ERDE and the Joint Tropical Research Unit using a shadow ring[6] and the direct component (global total = diffuse + direct) estimated. The diffuse and direct components of total UV at JTRU for 1972 are shown in Figure 3. Measurements were also made at

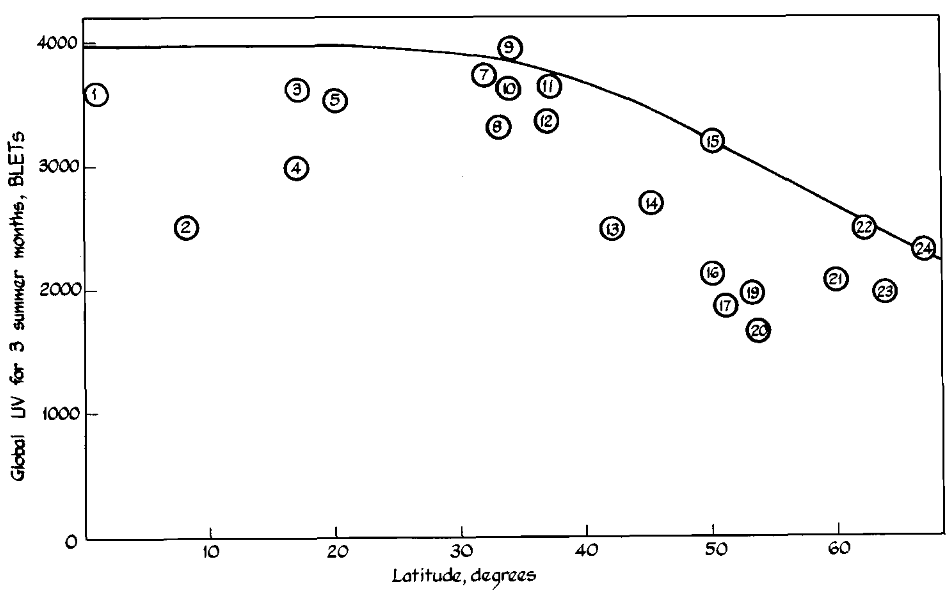

Fig. 2. Total global UV measured at each site for the three summer months as a function of site latitude.

TABLE II
Monthly UV Doses of Sites in Program

Site	Reference for Figs. 2 and 3	1972											
		J	F	M	A	M	J	J	A	S	O	N	D
Gan, Maldive Islands RAF Met Station	(1)							948	1033	993	1156	1034	1050
Canal Zone, Panama U.S. Army Tropic Test Center	(2)												
Salalah, Muscat, and Oman RAF Met Station	(3)							751	912	1180	1070	956	957
Innisfail, Australia Joint Tropical Research Unit	(4)	1084	875	873	837	562	474	628	852	718	1050	1006	1054
Cloncurry, Australia Joint Tropical Research Unit	(5)												
Brisbane, Australia University of Queensland	(6)		889	915	778	523							
Yuma, U.S.A. U.S. Army Atmospheric Sciences Lab	(7)												
Pheonix, U.S.A. Desert Sunshine Exposure Tests	(8)						1031	1218	1073	898			
Akrotiri, Cyprus RAF Met Station	(9)							1187	1041	851	619	424	402
Mt. Olympus, Cyprus RAF Met Station	(10)							1123	975	815	583	444	364
Menlo Park, U.S.A. Stanford Research Institute	(11)			631	781	984	1050	1112	1065	735	447	356	251
Melbourne, Australia Materials Research Labs	(12)												
Natick, U.S.A. U.S. Army Labs	(13)												
Ottawa, Canada Defence Research Establishment	(14)												
Suffield, Canada Defence Research Establishment	(15)												
Portsmouth, U.K. Central Dockyard Lab	(16)	115	142	355	525	614	601	632	600	403	267	144	153
London, U.K. Explosives Research and Development Establishment	(17)	78	109	280	436	569	606	657	503	306	209	120	120
Glascoed, U.K. Materials Quality Assurance Directorate	(18)												
Teeside, U.K. Tioxide International Ltd.	(19)					530	534	578	573	309	188	109	84
Manchester, U.K. University of Manchester	(20)	129	184	288	410	476	465	549	402	208	172	92	69
Kjeller, Norway Norwegian Defence Research Establishment	(21)				395	550	538	707	560	316	109	45	37
Yellowknife, Canada Canadian Forces, Northern Region	(22)												
Reykjavik, Iceland The Icelandic Met Office	(23)											66	27
Fort Greely, U.S.A. U.S. Army Atmospheric Sciences Lab	(24)												

TABLE II *(continued)*

1973												1974		
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
1222	1064	1360	1173	1130	884	1052	988	1173	1234	1314	1146	1160	1092	1182
					952	978	768	738	1020	749	936	1051	1063	1070
1007	934	1323	1336	1565	1198	845	1086	1298	1094	1051	1070	980	1100	1168
1066	966	955	817	683	588	649	669	750	958	859	929	899	899	800
							932	1057	1176	1198	1310	1070	1116	
					1403	1376	1124	984	774	530	469	466	522	851
387	621	925	1127	1346	1354	1476	1213	1000	869	471	401	378	423	685
372	598	979	1280	1075	1311	1317	998	749	714	471	346	324	445	684
258	373	584	940	1160	1201	1233	1155	921	664	434	375	402	495	581
									876	1073	1149	1184	1026	766
			587	707	772	938	841	617	446	269	185	236	324	478
					892	993	862	628	438	242	177	241	390	572
					1057	1212	1001	793	516	282	201	256	400	535
135	181	371	486	633	709	764	679	513	268	181	126	171	227	361
78	149	285	387	608	724	647	573	384	181	113	88	96	153	254
												122	214	328
114	199	351	550	646	689	674	572	347	194	125	93	105	141	242
68	124	224	347	429	557	617	495	369	205	115	66	92	141	269
43	100	150	392	626	745	727	587	288	110	59	28	36	107	269
		441	684	656	983	889	687	471	246	106	58	106	175	434
34	68	180	337	578	663	771	585	354	200	72	65	37	82	167
					838	859	702	341	149	71	49	52	95	295

TABLE III
UV Monitoring at JTRU and ERDE—1972 and 1973 Annual Totals

	JTRU				ERDE			
	BLET Units		Percentage of global		BLET Units		Percentage of global	
Monitor attitude	1972	1973	1972	1973	1972	1973	1972	1973
Horizontal—global	10349	10223	100	100	4010	4234	100	100
Horizontal—diffuse	7378	7132	71.3	70.8	3420	3727	85.5	87.9
Horizontal—direct	2971	3091	28.7	29.2	580	511	14.5	12.1
45°	9029	9088	87.2	89.8	3595	3980	89.7	94.0

both sites of the UV incident on a 45° plane facing the equator—the angle used normally in exposure trials. A summary of the results obtained for 1972 and 1973 at the two sites are given in Table III.

As the results for 1972 and 1973 were so similar, detailed discussion will in general be limited to those of 1972 but should be understood to apply also to the results of 1973.

Considering the relative importance of the diffuse and direct UV radiation, it was found that over the year the diffuse is the major component; 71.3% of the total global UV at JTRU and 85.5% of the total global UV at ERDE for 1972 and much the same for 1973. In fact, only for very few individual periods did the direct match the diffuse component at JTRU (Fig. 3).

Global solar radiation was also measured at JTRU, and it is instructive to consider how the diffuse UV/total UV fraction varies with global solar radiation during the year. It was considered more suitable for comparison to subdivide the year into periods defined by the midday sun declination, 0–10° (12/10 to 1/3), 10–20° (2/3 to 25/3 and 15/9 to 11/10), 20–30° (26/3 to 21/4 and 21/8 to 14/9), and 30–40° (22/4 to 20/8) rather than into monthly periods.

Figure 4 shows that the diffuse UV/global UV fraction varies from about 0.5 for good clear days to 1.0 for cloudy overcast days when the midday sun declination was between 0° and 10°. The relative importance of diffuse UV for a constant level of solar radiation was found to be dependent on sun decli-

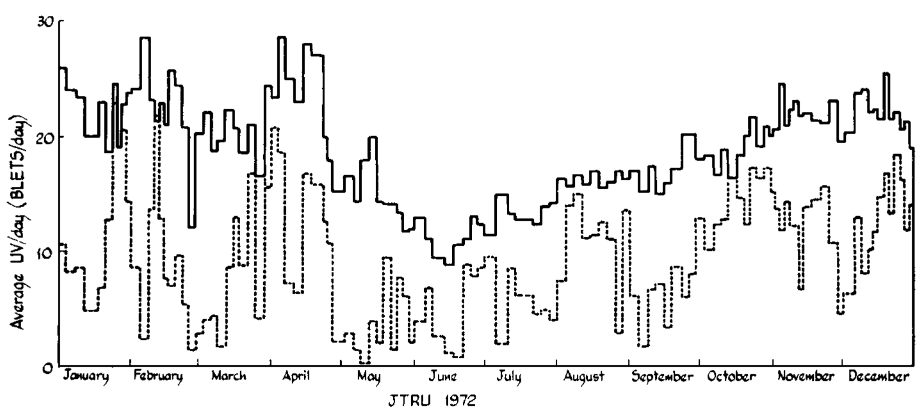

Fig. 3. Average diffuse (——) and direct (- - -) UV/day on horizontal at JTRU Innisfail.

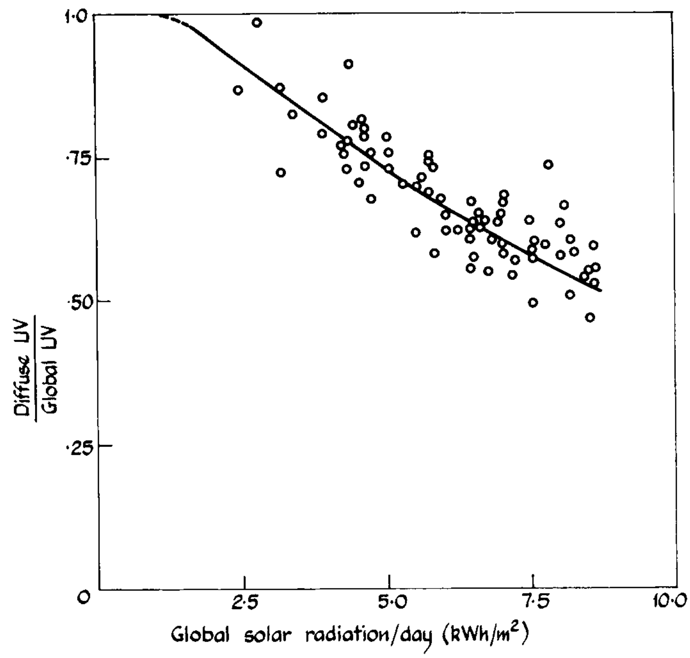

Fig. 4. Ratio of diffuse UV to global UV as a function of global solar radiation for periods at JTRU Innisfail when noonday sun declination was in the range of 0–10°.

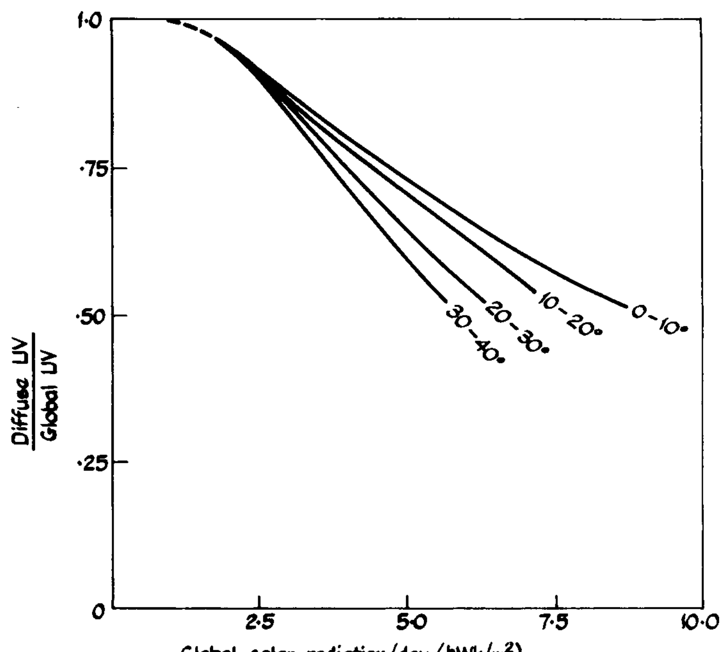

Fig. 5. Ratio of diffuse UV to global UV as a function of global solar radiation at JTRU Innisfail for periods when noonday sun declinations were in the ranges of 0–10°, 10–20°, 20–30°, and 30–40°.

nation, the diffuse contribution to the total UV being least in winter, that is, the period with the highest sun declination (Fig. 5).

From a consideration of data for clear near "ideal" conditions, it has been shown that the UV content of solar radiation is markedly dependent on solar angle.[7] However, the results of this program of continuous monitoring at

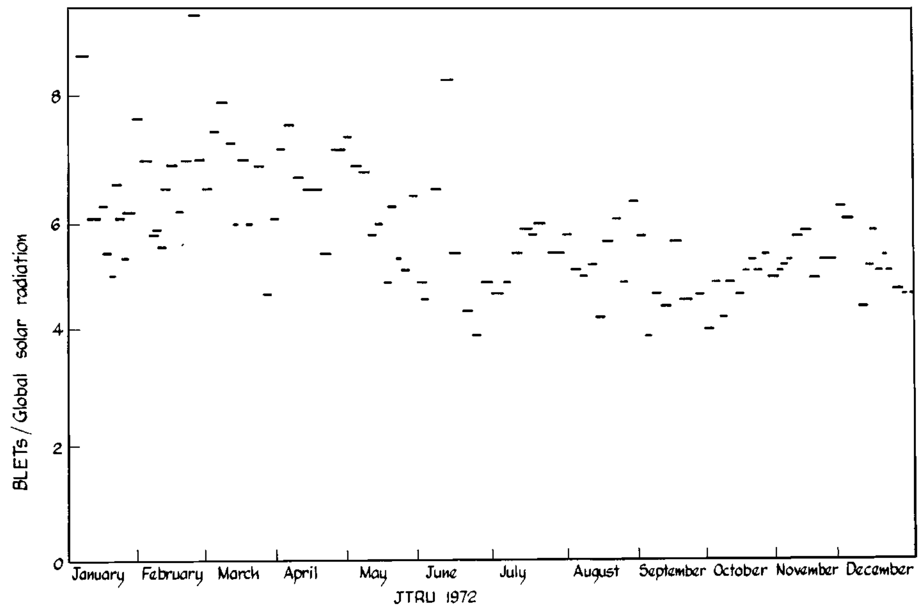

Fig. 6. UV fraction of global solar radiation as function of exposure period at JTRU Innisfail 1972.

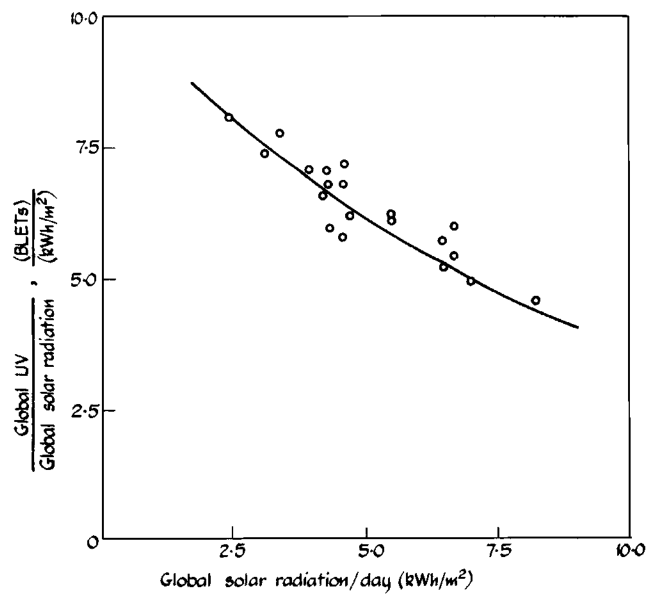

Fig. 7. UV fraction of global solar radiation at JTRU Innisfail for periods when noonday sun declination was between 0° and 10°.

JTRU show that there are pronounced day-to-day fluctuations in the UV content of solar radiation (Fig. 6). These are particularly noticeable in the period January to April and would seem to be related to the wet and changeable conditions experienced in this period. In this context, it is worth noting that Coblentz and Stair[8] observed what they considered to be unexpectedly high UV doses for certain cloudy days.

The dependence of UV content of solar radiation on weather conditions can be clearly observed from a plot of UV/global solar radiation against global solar radiation/day for periods with a midday sun declination of 0–10° (Fig. 7). It is seen that the UV content of solar radiation increases as the daily dose of solar radiation decreases. That is, the more cloudy the day, the more UV there is in a unit of solar radiation. The degree of scatter observed in Figure 8, that is, the range of UV contents observed for a particular level of total global solar radiation, can be partly explained by the fact that, on cloudy days, the total solar radiation can be accumulated at a variety of different times of the day when it is known that the UV content of solar radiation differs.[4] Probably a more important reason for the spread is that the nature of the cloud coverage can vary widely and with it the UV transmission characteristics of the sky.[9] The relationship between UV fraction and global solar radiation shown in Figure 7 was found to depend on sun declination (Fig. 8) and indicated that, for a particular level of solar radiation, the UV content was higher the lower the sun declination.

From Figure 8 it is possible to make an estimate of the UV dose for a defined period if the global solar radiation is known. Also, with the same information and the help of Figure 5, it is possible to estimate the relative contribution of the diffuse and the direct components of solar UV radiation. It is anticipated that as the data for other sites are analyzed in a similar manner,

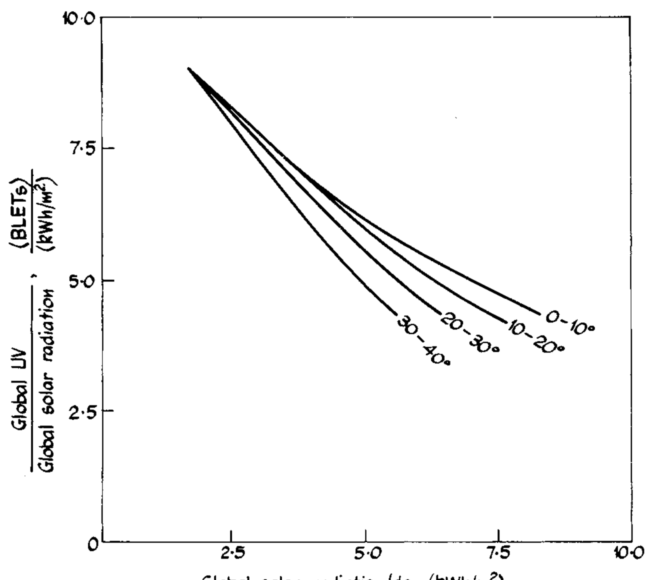

Fig. 8. UV fraction of global solar radiation at JTRU Innisfail for periods when noonday sun declinations were in the ranges of 0–10°, 10–20°, and 30–40°.

the definition of these relationships will improve and their application extended.

The help of Mr. B. V. Howes in developing a computer program to handle the data is gratefully acknowledged.

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