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Hourly and monthly variations in surface temperature of opaque PVC during exposure under clear skies

R. S. YAMASAKI (1), A. BLAGA (1)

To characterize weather as it affects plastics, measurements of surface temperature of opaque PVC panels subjected to outdoor exposure at five orientations in Ottawa, Canada, have been taken hourly for a year. Readings taken during Clear Hour periods, both day and night, have been selected, and for each panel the corresponding average daily surface temperature-time curve for each month was determined. These curves should be generally applicable to other common opaque plastics in service. They provide better appreciation of the temperature conditions to which plastics may be subjected, permit attainment of more realistic laboratory simulation of weathering, and provide input for equations predicting the behaviour of plastics on exterior exposure.

1. INTRODUCTION

To understand the behaviour of plastics during weathering it is necessary not only to determine how they respond to various weather elements but also to identify the nature and characteristics of the weathering factors throughout the exposure period. Although numerous studies have been carried out on the effect of weather on plastics, relatively little has been done to characterize weather itself as it affects them.

Weather elements act on exposed plastic, the nature and extent of their action depending on the material characteristics (e. g., colour) and exposure variables (e. g., direction). As a result, an environmental condition which may be called a micro-environment is produced at the plastic. It is this micro-environment that determines how the elements of weather degrade plastics. This paper presents the results of a study of one component of the micro-environment, the surface temperature of plastics during outdoor exposure.

It has been demonstrated that high temperature accelerates the rate of photodegradation of polypropylene [1], hastens the development of discoloration and haze of translucent rigid PVC [2], and renders low density polyethylene sufficiently brittle to break under impact when aged for six months at 70°C [3]. Low temperature may cause embrittlement and cracking of rigid PVC [2] and, in general, reduces the elongation and impact resistance of most plastic materials [4]. Thermal cycling can cause the plasticizer to be exuded from the PVC, causing it to become more rigid [5]. Finally, thermal shock may induce rupture or cracking of plastics, especially where internal tension already exists ([6], [7]). Thus, plastics can be adversely affected by both the level of temperature and its variation during weathering. In view of the fact that an increasing number and volume of plastics are utilized for diverse outdoor applications, with probable increase in types of degradative behaviour, it is desirable to determine accurately and comprehensively what the temperature conditions of plastics are during weathering.

Air temperature data are readily available for various locations on an hourly basis, but they are of limited use because solar radiation may raise the surface temperature of plastics by as much as 27°C above ambient air temperature ([8], p. 87). Surface temperatures of test panels of various materials and colours have been reported ([8], p. 87) for a few sunny

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days; extreme temperatures at the outer surfaces of buildings have been estimated [9]; and equations have been formulated to predict maximum surface temperatures of wood [10] and other materials ([11], p. 489) in exterior exposure. The latter, although useful for design purposes, have limited application for weathering studies because surface temperatures are usually not extreme. Measurements were taken, therefore, of the surface temperature of plastic panels exposed to weathering. Such information should provide a better appreciation of the temperature conditions to which plastics may be subjected, allow more realistic laboratory simulation of weathering, and provide input for equations predicting the behaviour of plastics during exterior exposure [12].

Data obtained when plastic panels were exposed to solar radiation under clear sky conditions are reported in this paper (results for other weather conditions will be presented at a later date). Solar radiation plays an important role in the degradation of plastics and during insolation under clear sky conditions radiant heating of the panel as well as photo-chemical effects from ultraviolet (UV) radiation are maximal. Information on the variation in intensity of ultraviolet, visible and near infrared bands of terrestrial solar radiation under clear sky conditions is already available [13] and can be combined with surface temperature data to permit more realistic simulation of weathering in the laboratory.

2. BASIC CONSIDERATIONS

At any instant the surface temperature of a plastic panel subjected to insolation under clear sky conditions is at a level at which the heat gained by the surface of the plastic is equal to the heat lost [9].

2.1. Heat gain

Heat received by a plastic panel from radiation depends on the following factors:

2.1.1. *Intensity of solar radiation and the fraction of incident radiation absorbed by the plastic*

The intensity of the solar radiation impingeing on a surface depends on the length and clarity of the path of the direct rays of the sun through the earth's atmosphere, the angle at which direct radiation strikes the surface, and the intensity of scattered radiation from the sky and reflected radiation from surroundings [13]. Thus the surface temperature of a plastic panel is a function of the orientation of the panel with respect to the sun, the condition of the atmosphere, and the nature of the surroundings. As the position of the sun with respect to the earth is continuously changing, the surface temperature of a panel also depends on time.

The fraction of incident solar radiation absorbed by the plastic is dependent on albedo, α, the percentage of incident radiation reflected by the surface. The intensity of the absorbed radiation is

$$R_a = \left(1 - \frac{\alpha}{100}\right) R_i,$$

where R_i is the intensity of the incident radiation. Albedo depends primarily on the colour of the plastic.

2.1.2. *The intensity of long-wave terrestrial radiation, L_i, incident on the plastic and the fraction of the radiation absorbed*

Long-wave radiation is emitted by the sky and all objects, its value depending on their effective emissivity and temperature. The amount absorbed by the plastic panel is given by

$$L_a = \varepsilon L_i,$$

where L_a is the intensity of the absorbed radiation and ε is the emissivity of the surface of the plastic. L_i depends on the orientation of the surface.

2.2. Heat loss

Heat is lost by the following processes:

2.2.1. *Emission of long-wave radiation*

The rate of emission of this radiation is given by

$$I_0 = \varepsilon \sigma (t_s + 273.16)^4,$$

where ε is the emissivity of the material, σ is the Stefan-Boltzmann constant, and t_s is the surface temperature.

2.2.2. *Convective heat transfer*

This rate of transfer can be estimated using the equation

$$q_v = h \Delta t_{s,a},$$

where h is the heat transfer coefficient and $\Delta t_{s,a}$ is the temperature difference between surface and air at a surface ([14], p. 116).

The heat transfer coefficient has been found to increase with increase in rate of airflow parallel to vertical plane surfaces ([15], p. 249]. Wind therefore increases the heat loss from the surface and lowers the surface temperature of the plastic.

2.2.3. *Conductive heat flow through the plastic*

Heat flow per unit area is given by the equation

$$q_c = -k \frac{dt}{dX},$$

where k is the coefficient of thermal conductivity of plastic and dt/dX is the temperature gradient in it ([11] p. 33). A backing of insulation will lower the temperature gradient in a plastic panel that is being heated and thus will decrease conductive heat loss and cause surface temperature to increase.

As, at any instant, heat gained by the surface of a plastic panel is balanced by the heat lost,

$$\left(1-\frac{\alpha}{100}\right)R_i+\varepsilon L_i = \varepsilon\sigma(t_s+273.16)^4+h\,\Delta t_{s,a}-k\frac{dt}{dX}. \quad (1)$$

For a horizontal surface, L_i from clear skies can be estimated by [16]:

$$L_i=-17.09+1.195\,\sigma(t_a+273.16)^4, \quad (2)$$

where t_a is the air temperature.

For a panel at a surface temperature of t_s surrounded by air at a temperature of t_a ([17], p. 21),

$$\varepsilon\sigma(t_s+273.16)^4 \simeq \varepsilon\left[\sigma(t_a+273.16)^4+4\,\sigma(t_a+273.16)^3\,\Delta t_{s,a}\right]. \quad (3)$$

Integrating along the path of constant heat flow rate ([11], p. 34),

$$q_c=-k\frac{dt}{dX}=-k\,A\,\Delta t_{s,a}, \quad (4)$$

where A is a constant.

Substituting equations (2), (3) and (4) in (1) and letting net solar radiation

$$Q_{NS}=\left(1-\frac{\alpha}{100}\right)R_i \quad (5)$$

and net long-wave radiation

$$Q_{NL}=\varepsilon\left[-17.09+0.195\,\sigma(t_a+273.16)^4 -4\,\sigma(t_a+273.16)^3\,\Delta t_{s,a}\right], \quad (6)$$

the increase in surface temperature of a plastic panel above that of ambient air,

$$\Delta t_{s,a}=\frac{[Q_{NS}+Q_{NL}]}{[h-k\,A]} \;\; (^2). \quad (7)$$

3. EXPERIMENTAL PROCEDURE

To determine how the temperature of plastic surfaces in an outdoor environment varies with time, hourly measurements were taken over a year for rigid, opaque PVC siding panels exposed at Ottawa, Canada. This material is widely used in exterior applications such as sidings, window frames, shutters and eavestroughs. The panels (1.4 mm in thickness) were made from a typical UV-stabilized PVC siding formulation that includes a small amount of plasticizer, acrylic impact modifier, colorant and filler.

The climate of Ottawa is humid continental, with no dry season, a mean daily temperature ranging from −11°C in January to 21°C in July, and record minimum and maximum temperatures of −36 and 38°C, respectively.

To evaluate the effect of albedo on surface temperature, PVC panels in three colours were chosen (white 66 % albedo, light grey 46 % albedo and black 6 % albedo after six months of outdoor exposure). The albedo was determined by measuring the spectral reflectance of a panel of each colour, taking as incident radiation the spectral distribution of total solar radiation on a horizontal surface, as given by Schulze [18], and substituting appropriate values in the equation,

$$\alpha=\frac{\sum_{300\text{ nm}}^{2250}[\text{spectral reflectance}\times\text{irradiance}]\;100}{\text{irradiance of total radiation}}$$

The effect of the backing on PVC panels was assessed by mounting half the panels on a backing of 9.5-mm thick fibreboard fastened, in turn, to 13-mm thick plywood. The thermal conductance of such an assembly was calculated to be 8.2×10^{-5} cal/s/cm²/°C. Estimation by Wengert's equation [10] shows that maximum surface temperature of PVC with such a backing is only 4°C (at 51°C) below maximum possible surface temperature when conductive heat loss is considered to be negligible. The thermal conductance of the PVC panel itself was 3.5×10^{-3} cal/s/cm²/°C.

To monitor surface temperature a 30-gauge (B and S) copper-constantan thermocouple was installed at the centre of the top surface of each panel so that there was a 12-mm length of junction plus a 38-mm length of lead wire in contact with the surface to provide good thermal contact. The 50-mm length of thermocouple was secured, in each case, with a short length of siding material of the same colour as the panel, cemented and coated with a film made from the same siding material dissolved in tetrahydrofuran. The set-up for the backed PVC panels is illustrated in figure 1. The black panel is smaller than the other panels because siding was not available and it had to be specially made; its composition is the same as that of the light grey and white panels except for the filler.

Five sets of three backed and three unbacked panels were mounted on racks with different orientations: south, vertical (S/V); south, 45° (S/45); horizontal (H); east, vertical (E/V); and west, vertical (W/V). The backs of the vertical panels were shielded from the sun with burlap, and average height was 1.35 m from the ground, which was grass-covered. Ambient air temperature was measured with a thermocouple junction located inside a Stevenson screen and positioned at the same average height as the panels. All panels were cleaned after six months of exposure.

Temperature readings were taken from 1 November 1971 to 31 October 1972 on three multipoint recording potentiometers with printout at 4- to 6-min intervals. Temperatures at the beginning of each hour were read from the charts and entered on punch cards for computer processing.

(2) $\Delta t_{s,a}$ term in Q_{NL} was not considered as an unknown since $\Delta t_{s,a}$ is measured and is used to calculate Q_{NL}.

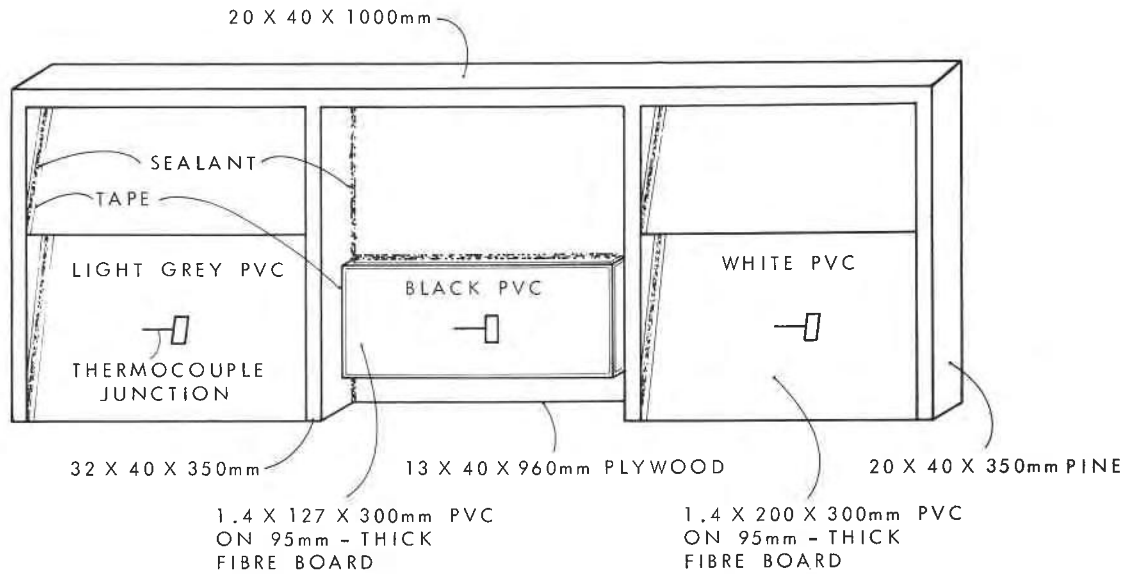

Fig. 1. — Backed PVC panels.

The occurrence of clear sky conditions was determined from the following records:

1. continuous records of solar intensity (intensity of direct plus diffuse solar radiation on a horizontal surface) measured by a pyranometer at an adjacent site;

2. hourly readings of observed Total Opacity: portion of the whole sky that is concealed by all layers (cloud or obscuring phenomena greater than zero).

These readings were taken by the Atmospheric Environment Service of Environment Canada.

4. RESULTS AND DISCUSSION

From hourly readings of surface temperature, values were selected for periods during which the panels were subjected to solar radiation whose spectral distribution was similar to that determined for Clear Days [13]. As Clear Days occur rather infrequently, about three days per month, it was decided to augment these data with additional data obtained when the sky was clear for one-hour intervals, i. e., Clear Hours.

4.1. Selection of Clear Hours

Clear Hours for daytime were selected according to the following criteria:

A. during the hour Total Opacity was no more than 20 %, so that there was minimal change in spectral distribution of solar radiation from that of a completely clear sky;

B. during the hour the obscuring layer did not obstruct direct solar radiation. Such obstruction was indicated by a significant interruption of insolation measured by a recording pyranometer;

C. during the hour insolation on a horizontal surface was similar to that for the corresponding hour of a Clear Day.

Clear Hours at night were selected by employing the Total Opacity requirement of criterion A.

4.2. Selection of Clear Day

A. Daily insolation on a horizontal surface was maximal for the time of the year, using 1964 to 1969 values at Ottawa as reference.

B. The hourly average insolation on a horizontal surface was symmetrical about the solar noon.

C. Total Opacity of the sky was no more than 20 % throughout the day.

4.3. Factors affecting surface temperature of PVC panel

Results of the analysis of the surface temperature of panels measured during Clear Hours, both day and night, are discussed below.

4.3.1. *Effect of solar and long-wave radiations*

Equation (7) predicts that $\Delta t_{s,a}$ is a linear function of net heat gained through solar and long-wave radiations. To determine whether this is true, corresponding experimental values for both backed and unbacked horizontal panels at low wind speed were plotted in figure 2. The results indeed display linear relation, probably because Q_{NL} is not greatly affected by t_a [*see* equation (6)] over the range of temperature experienced, and tend to confirm the validity of the equation. This means that changing a variable such as panel orientation, which alters the net heat gained through solar and long-wave radiations, changes the value of $\Delta t_{s,a}$ but does not alter its linear relation.

4.3.2. *Effect of colour and backing*

Figure 2 also illustrates the dependence of panel radiant heating on colour or albedo, with the black panel (albedo 6%) attaining the highest temperature and the white panel (albedo 66 %) the lowest for each set of panels. Horizontal panels with backing had $\Delta t_{s,a}$ values about 30 to 50 % higher than those of the corresponding unbacked panels at low wind speeds.

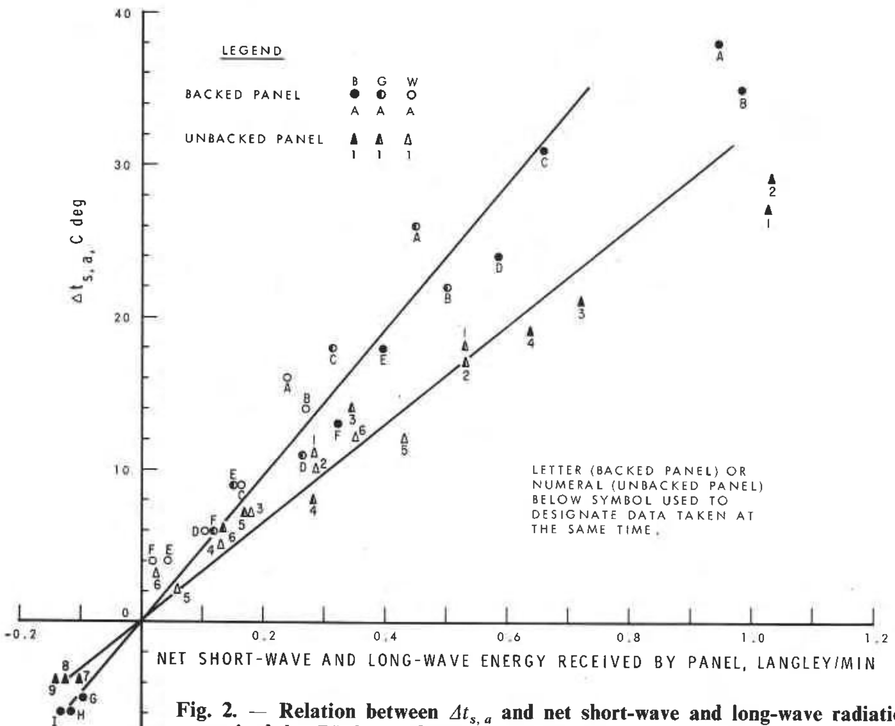

Fig. 2. — Relation between $\Delta t_{s,a}$ and net short-wave and long-wave radiations received by PVC panels at H orientation and low wind speed.

4.3.3. *Effect of ambient air temperature and wind speed*

As $\Delta t_{s,a} = t_s - t_a$, the surface temperature of a panel may be calculated by rearranging equation (7):

$$t_s = \frac{[Q_{NS} + Q_{NL}]}{[h - kA]} + t_a \quad (^3).$$

(3) t_a and $\Delta t_{s,a}$ in Q_{NL} were not considered as unknowns since both are measured and are used to calculate Q_{NL}.

This shows that the contribution of ambient air temperature to the surface temperature of a panel is as an additive term. $\Delta t_{s,a}$ is not significantly affected by the magnitude of the air temperature, as may be seen by comparing values for panels in January with those for corresponding panels in June when pertinent variables other than air temperature are essentially constant (Table I). For example, $\Delta t_{s,a}$ values for backed black panels in January and June are about the same (28 and 26°C, respectively) although the air temperature differs by more than 40°C.

TABLE I

EFFECT OF AMBIENT AIR TEMPERATURE ON THE SURFACE TEMPERATURE OF PVC PANELS

Date	Intensity of Incident Solar Radiation (langley/min)	$Q_{NS} + Q_{NL}$ on a Backed Black Panel (langley/min)	Wind Speed (m/s)	Ambient Air Temp (°C)	Surface Temp of Panel (°C). (Difference between Surface Temp of Panel and Ambient Air Temp, $\Delta t_{s,a}$ C°): Orientation of Panel (Backing)	Black	Lt. Grey	White
16 Jan (noon)	1.43 (S/45-plane)	1.08	3.6 W	-25	S/45 (Backed)	3 (28)	-9 (16)	-12 (13)
					(Unbacked)	-8 (17)	-11 (14)	-15 (10)
7 June (noon)	1.42 (H-plane)	1.02	4.0 NW	18	H (Backed)	44 (26)	31 (13)	28 (10)
					(Unbacked)	35 (17)	30 (12)	27 (9)

TABLE II

Effect of wind speed on the surface temperature of PVC panels

Date	Wind Speed m/s	Ambient Air Temp (°C)	$Q_{NS} + Q_{NL}$ on a Backed Black S/V-Panel (langley/min)	Difference between Surface Temp of S/V Panels and Ambient Air Temp, $\Delta t_{s,a}$ (C°)						$Q_{NS} + Q_{NL}$ on a Backed Black H-Panel (langley/min)	Difference between Surface Temp of H Panels and Ambient Air Temp, $\Delta t_{s,a}$ (C°)					
				Black		Lt. Grey		White			Black		Lt. Grey		White	
				B⁺	U⁺	B⁺	U⁺	B⁺	U⁺		B⁺	U⁺	B⁺	U⁺	B⁺	U⁺
24 Jan	1.3 W	-6	1.26	48	30	31	22	19	12	0.38	17	11	12	9	7	5
(noon)						29*	18*						10*	7*		
27 Jan	4.0 W	-14	1.42	35	19	22	13	12	9	0.46	10	7	6	5	4	3
(noon)						20*	12*						6*	4*		
26 Jan	5.4 W	-18	1.46	29	14	19	10	9	7	0.46	8	6	5	4	3	2
(noon)						16*	9*						4*	3*		

⁺ B and U designate backed and unbacked, respectively.

* Temperature calculated by interpolation. For details see text.

According to equation (7), $\Delta t_{s,a} \alpha (1/h)$ (kA is constant for a given panel). As convective heat transfer coefficient, h, increases with wind speed, $\Delta t_{s,a}$ is expected to decrease under the same conditions. Table II illustrates the extent of lowering of $\Delta t_{s,a}$ by winds of different speed, and shows that the decrease in $\Delta t_{s,a}$ with increase in wind speed may be relatively large. For example, for the backed black panel at S/V orientation, with an increase in wind speed from 1.3 m/s (24 January) to 5.4 m/s (26 January), $\Delta t_{s,a}$ decreased by 19°C (48-29°C). Further, it is expected that the lowering of surface temperature by wind of a given speed will be greater the larger the differential, $\Delta t_{s,a}$, between the surface and ambient temperatures the panel would have in the absence of wind (or insignificant wind). Referring to the example in which $\Delta t_{s,a}$ value of a panel at a low wind speed of 1.3 m/s was 48°C, the decrease in $\Delta t_{s,a}$ due to wind speed of 5.4 m/s was 19°C. For the backed black panel at H orientation in which the corresponding $\Delta t_{s,a}$ value at the same low wind speed was lower at 17°C, the decrease in $\Delta t_{s,a}$ attributable to wind speed of 5.4 m/s was smaller at 9°C.

In Ottawa the mean yearly wind speed is a significant 4.5 m/s. Because, in general, wind speed near the ground reaches maximum at mid-day ([19], p. 108) when the insolation is maximum and the direction as well as the speed of the wind are continuously changing, wind can have a significant and fluctuating effect on the surface temperature of a panel.

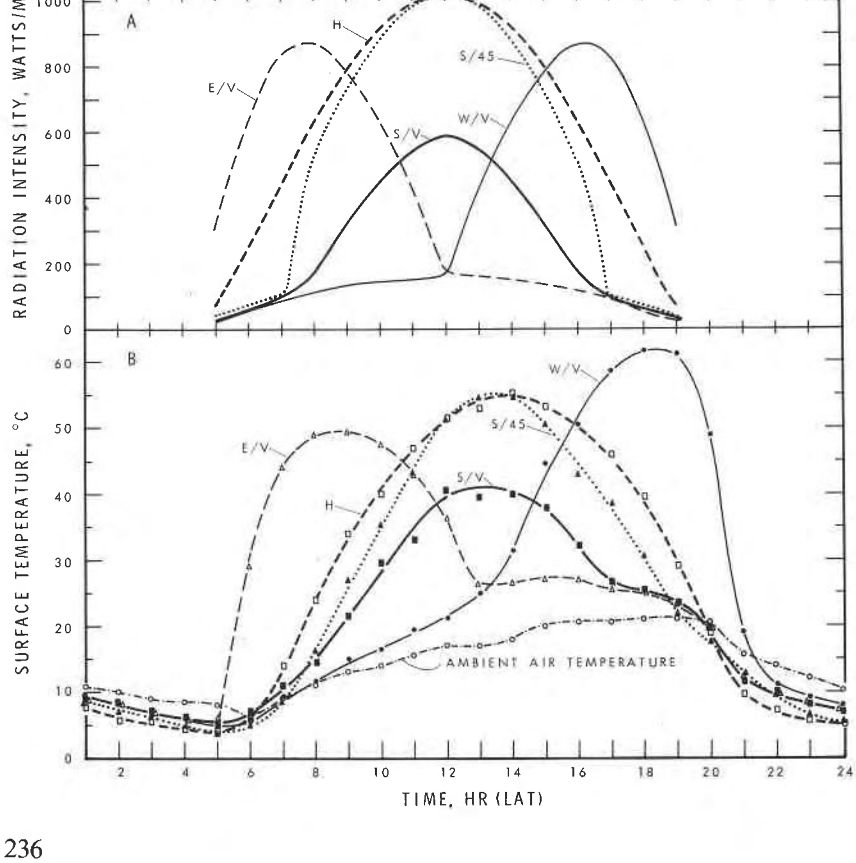

Fig. 3. — Comparison of hourly insolation on, and surface temperatures of, backed, black PVC panels at various orientations on a Clear Day (17 June 1972).

4.4. Characteristics of panel surface temperature on a Clear Day

As the surface temperature of a panel is determined to a large extent by the intensity of incident solar radiation, it is to be expected that the time dependence of the two factors will be similar. The main features for backed black PVC panel are illustrated in figure 3; comparison of (A) and (B) shows that corresponding temperature-time and insolation-time curves display marked similarities but different detail. The maximum temperature (62°C) occurred on a panel at W/V orientation, whereas highest insolation value (1,000 W/m^2) occurred on a panel at S/45 orientation. Surface temperature maxima occur 1 to 2 hrs. after corresponding insolation maxima as a result of lag in radiation heating of the air. Maximum surface temperature occurs earliest for an E/V panel at about 9 LAT (Local Apparent Time for which noon occurs when the sun is located due south) and latest for W/V panel at about 18 LAT.

At night the temperature of all the panels drops below ambient air temperature. This is conducive to dew formation. The temperature of the horizontal panels is the lowest, as much as 7°C below ambient, so that dew can occur when the relative humidity is as low as 63 % at an ambient air temperature of 14°C. Lowering of temperature is caused by radiative losses to the clear sky and is greatest for panels with a horizontal orientation.

4.5. Hourly and monthly variations in average surface temperature of panels during Clear Hours

To determine a representative daily surface temperature-time relation for each panel the average daily surface temperature-time curve was calculated for each month from data taken during Clear Hours. Such a curve incorporates the effects of variation in ambient air temperature, wind velocity, and possible cloud conditions preceding the Clear Hour condition during the month. The results for S/V, S/45, H, E/V and W/V orientations for a period of one year are illustrated in figures 4 to 8, respectively.

4.5.1. *Extreme surface temperatures*

During insolation, backed black [B(B)] panels exhibited the highest surface temperatures, followed generally in order of decreasing temperature by backed light grey [G(B)], unbacked black [B(U)], backed white [W(B)], unbacked light gray [G(U)], and unbacked white [W(U)] panels. The surface temperature-time curve of G(U) panels generally coincided within a few °C with those of W(B) panel, and to a lesser extent B(U) panels coincided with those of G(B) panel. When the sun was not shining, colour had no significant effect on surface temperature.

The surface temperature of the panels displayed daily cyclical variations, with a minimum between 3 and 9 LAT. The maximum occurred between 12 and 14 LAT for S/V, S/45 and H panels; between 9 and 10 LAT for the E/V panel; and between 15 and 18 LAT for W/V panel. The corresponding minimum and maximum for ambient air temperature occurred between 4 and 8, 13 and 16 LAT, respectively.

Extreme surface temperatures were also a function of season. The S/V panels (*Fig.* 4) attained maximum (annual high) temperatures in July ranging from 47°C for the B(B) panel to 32°C for the W(U) panel. Maximum temperatures at other orientations also

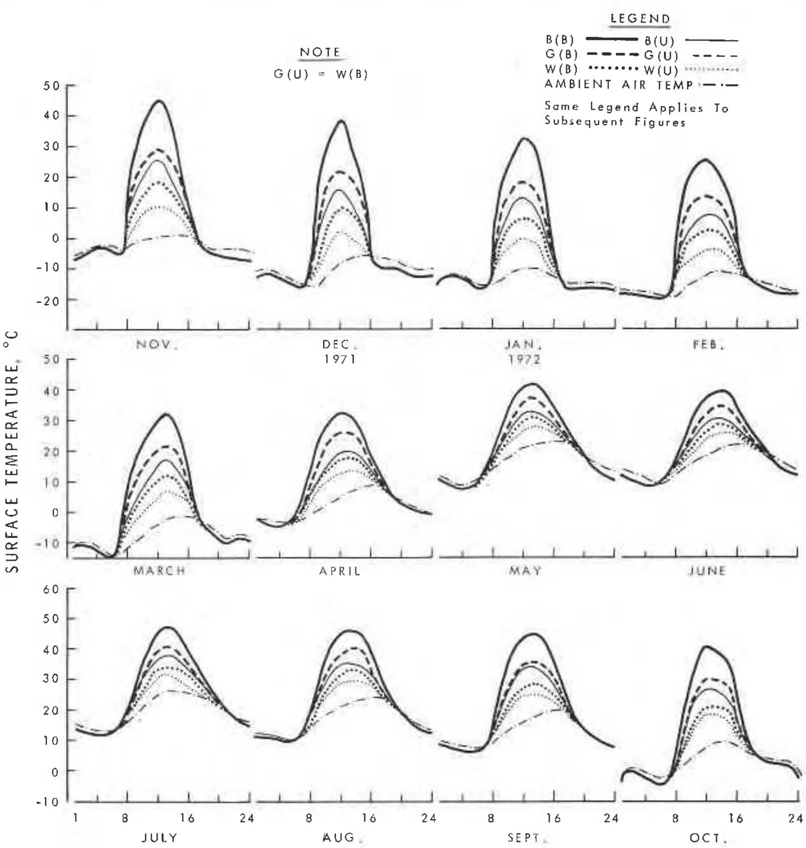

Fig. 4. — Monthly average of the time dependence of the surface temperature for PVC panels at S/V orientation during Clear Hours.

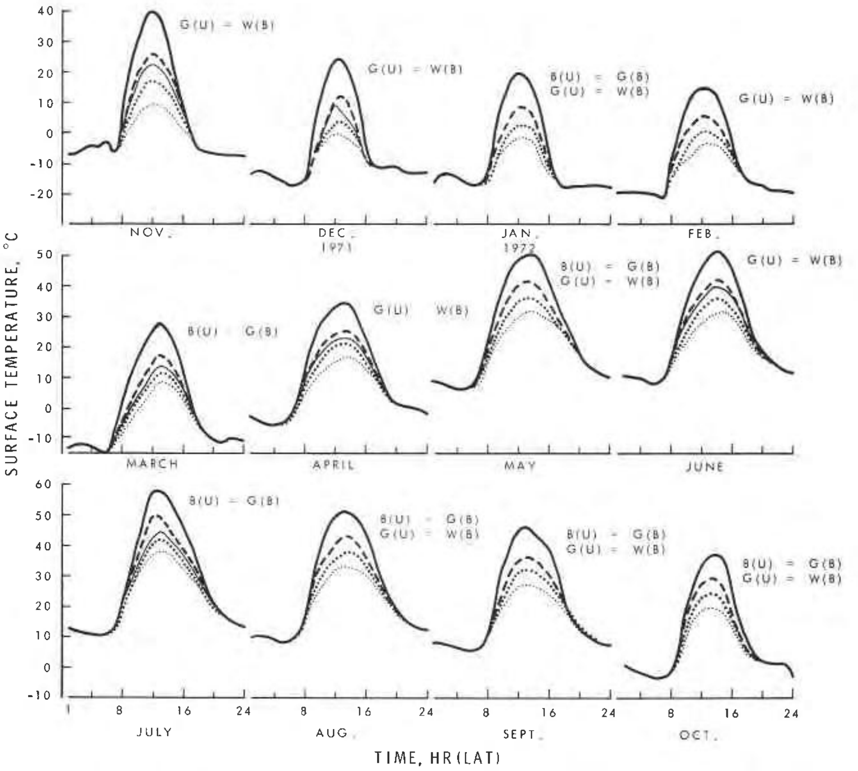

Fig. 5. — Monthly average of the time dependence of the surface temperature for PVC panels at S/45 orientation during Clear Hours.

took place in July, but they were higher: 56 to 58°C [B(B) panels] and 32 to 38°C [W(U) panel]. Minimum temperatures were −22°C for all panels and occurred in February. For ambient air the maximum temperature was much lower at 27°C (July); the minimum was −21°C (February).

4.5.2. *Extremes in range of daily surface temperature*

Extremes in the range of daily surface temperature (difference between daytime maximum and night-time minimum) of panels at various orientations are given in Table III. Data show that for S/V panels the range varied from a high of 55°C for B(B) panel in December to a low of 16°C for W(U) panel in June. For other orientations the maximum range in daily surface temperature was lower: 46 to 48°C [B(B) panel] in June or July. The minimum range was also lower: 8 to 15°C [W(U) panel] between December and January. The maximum and minimum ranges of ambient air temperature were much lower: 14°C in July and 6°C in January.

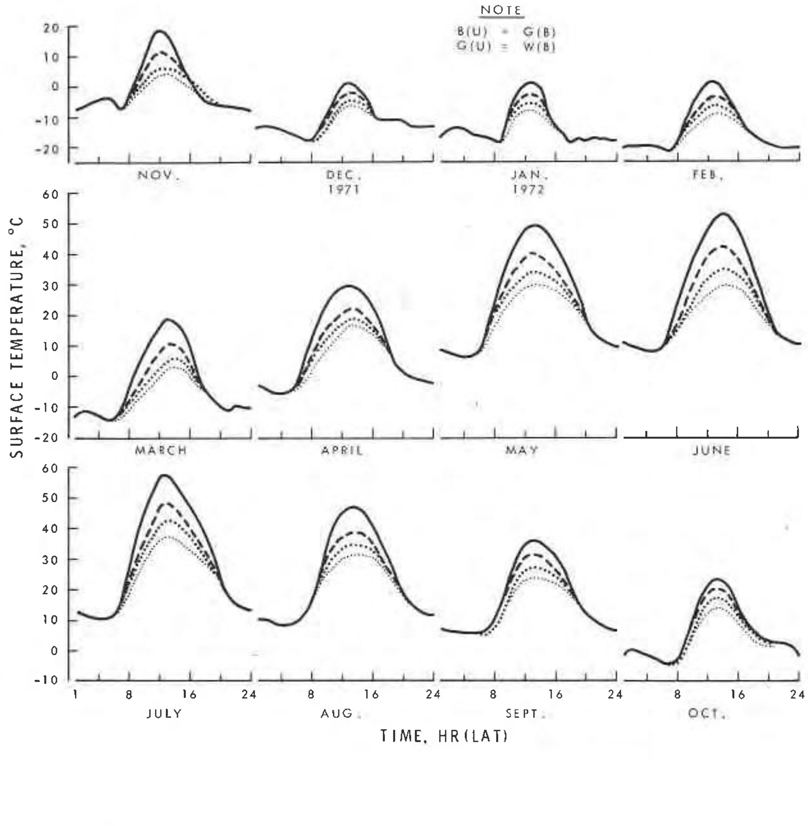

Fig. 6. — Monthly average of the time dependence of the surface temperature for PVC panels at H orientation during Clear Hours.

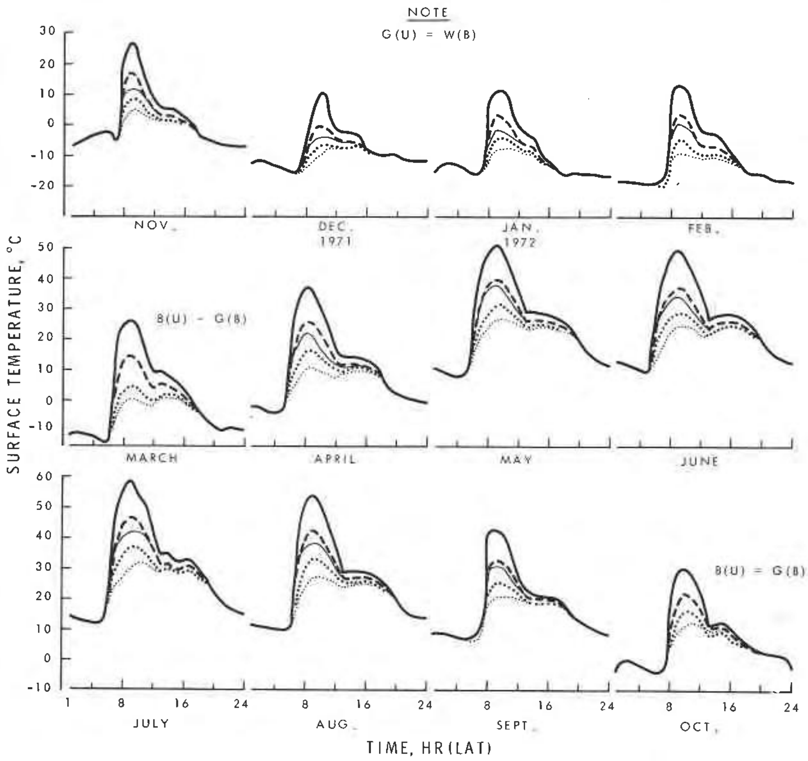

Fig. 7. — Monthly average of the time dependence of the surface temperature for PVC panels at E/V orientation during Clear Hours.

4.5.3. *Relative monthly period of insolation during Clear Hours.*

Table IV gives the period of Clear Hour insolation as a percentage of the maximum possible for each month. It ranged from 11 % in November to 44 % in May, the equivalent of 3 and 14 Clear Days, respectively.

4.6. Application of surface temperature-time curves

Consideration of factors affecting the surface temperature-time curves of opaque PVC panel in exterior exposure shows that the curves should also be generally applicable to other plastics if effects of differences in thermal conductivity, emissivity and albedo are taken into account. The thermal conductivities of common plastics (0.000,3 to 0.001,1 cal/s/cm²/°C/cm) lie within a relatively narrow range of those of rigid PVC (0.000,5 cal/s/cm²/°C/cm) ([20], p. 5). Calculation of the effect of the above extreme values in thermal conductivity on the corresponding maximum surface temperature of plastics (according to the equation of Wengert [10] incor-

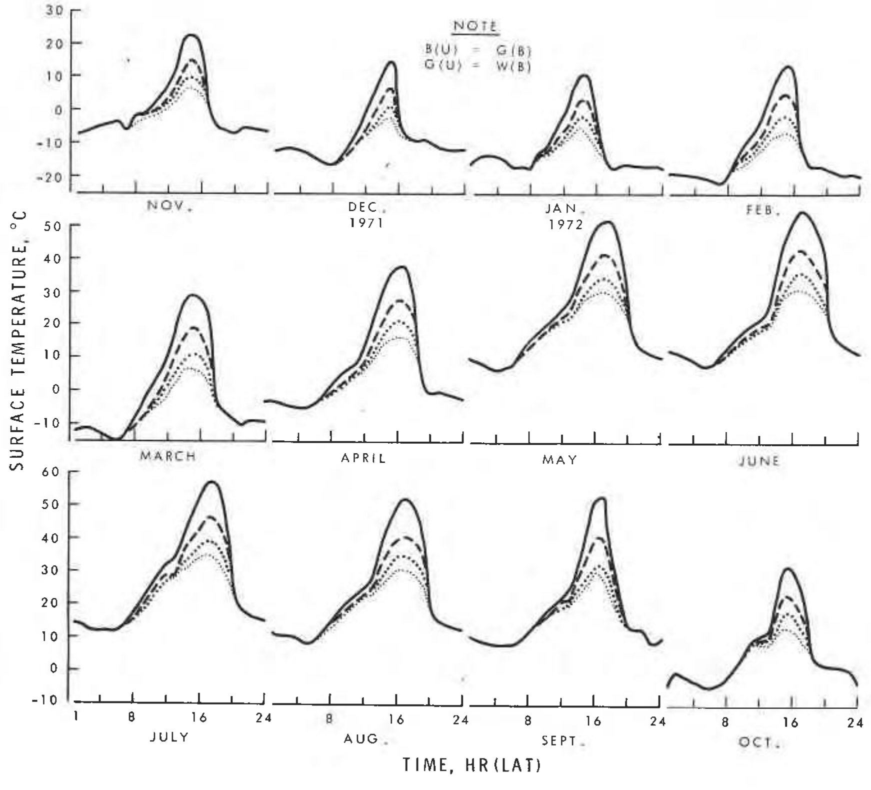

Fig. 8. — Monthly average of the time dependence of the surface temperature for PVC panels at W/V orientation during Clear Hours.

TABLE III

EXTREMES IN RANGE OF AVERAGE DAILY SURFACE TEMPERATURE FOR PVC PANELS

Orientation of Panel	Panel	Max. Range (C°)	Month	Min. Range (C°)	Month
S/V	B(B)	55	Dec.	30	June
	W(U)	22	Oct.	16	June
S/45	B(B)	47	July	36	Feb.
	W(U)	27	July	15	Jan.
H	B(B)	46	July	19	Jan.
	W(U)	27	July	10	Jan.
E/V	B(B)	46	July	26	Dec.
	W(U)	20	July	8	Dec.
W/V	B(B)	48	June	28	Jan.
	W(U)	23	June	12	Jan.
Ambient air temp ——→		14	July	6	Jan.

porating the thermal conductivity term and using the following values: panel thickness = 1.4 mm, $R_i = 1.45$ langley/min., $\alpha = 6$ %, $\varepsilon = 0.95$, $h = 0.020$ langley/min., $t_a = 18$°C, $dt/dX = 19$ and 5.5°C/cm for $k = 0.000{,}3$ and 0.001,1 cal/s/cm^2/°C/cm, respectively) shows that the latter differs by less than a degree. Hence the effect of the differences in thermal conductivities of common plastics on surface temperature was considered to be small enough to be neglected.

Although emissivity values for plastics are unavailable, those for very closely related materials such as paint are available, falling within a relatively narrow range (0.90 to 0.97) in spite of variations in composition and colour ([21], p. 6-160). Furthermore, emissivity for materials not so closely related to plastics, i. e., rubber, paper, glass and plaster, range from 0.91 to 0.94 ([21], p. 6-160), values similar to those for paints. It is quite probable, therefore, that the emissivity of common plastics (including PVC) is greater than 0.90 and does not vary by more than 0.1 from one plastic to another. The difference in net heat gained through long-wave radiation when emissivity differed by 0.1 was calculated to be about 10 % of the total net heat gained, a relatively small amount.

Equations (5) and (7) show that $\Delta t_{s,a}$ varies linearly with albedo (*see* also *Fig.* 9). For plastics with albedo significantly different from that of the rigid PVC studied here, the surface temperature-time curve can therefore be obtained, even in the presence of wind,

TABLE IV

PERIOD OF CLEAR HOUR INSOLATION AS PERCENTAGE OF MAXIMUM POSSIBLE FOR EACH MONTH

Month	Relative Period, %	Month	Relative Period, %
Nov. 71	11	May	44
Dec. 71	23	June	20
Jan. 72	36	July	16
Feb.	35	Aug.	26
March	22	Sept.	30
April	33	Oct.	18

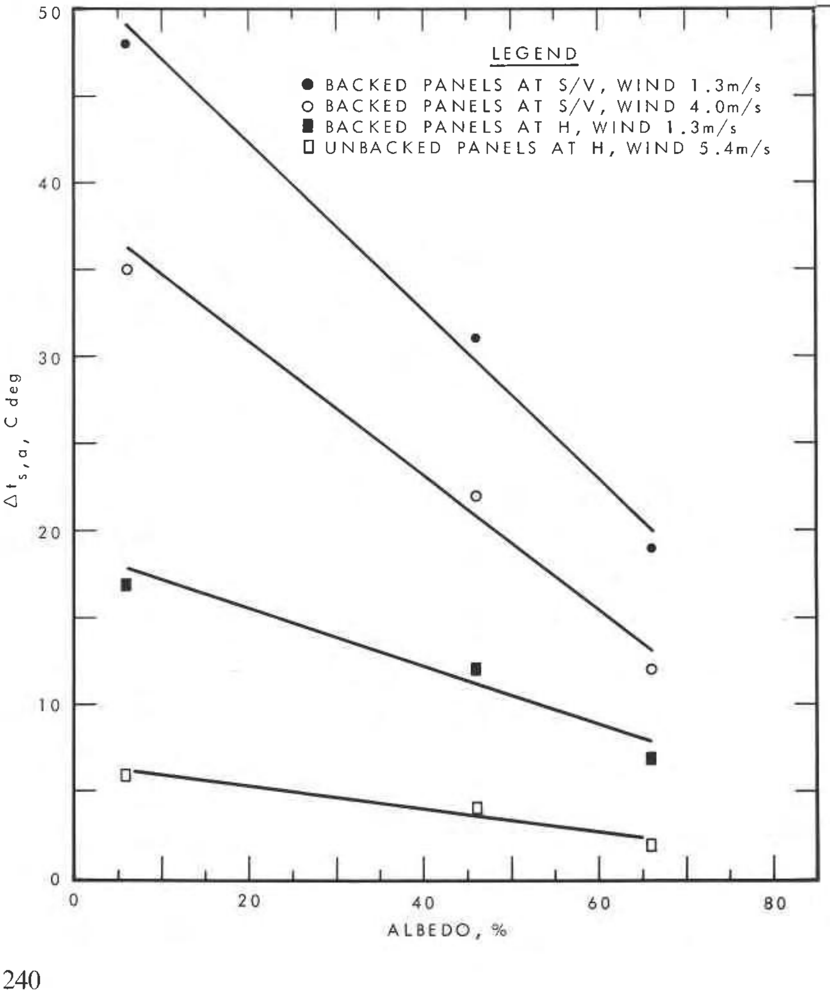

Fig. 9. — Relation between $\Delta t_{s,a}$ and albedo of PVC panels (data from Table II).

by interpolating with respect to albedo. This is illustrated in Table II where, for each light grey panel, difference in temperature of the surface and the ambient air, i. e., $\Delta t_{g,a}$, was calculated from the corresponding measured values for the black ($\Delta t_{b,a}$) and white ($\Delta t_{w,a}$) panels with albedoes of α_b (6 %) and α_w (66 %), respectively. For example, $\Delta t_{g,a}$ of the backed light grey panel (albedo $\alpha_g = 46$ %) on 24 January was calculated using the formula

$$\Delta t_{g,a} = \frac{\alpha_w - \alpha_g}{\alpha_w - \alpha_b}(\Delta t_{b,a} - \Delta t_{w,a}) + \Delta t_{w,a}$$

and found to be 29°C, which is close to the measured value of 31°C.

By using the family of surface temperature-time curves for PVC it is possible to estimate (by judicious selection of the appropriate curve) the surface temperature-time relation for other common opaque plastics subjected to outdoor exposure conditions similar to those for PVC. The appropriate curve for the plastic in question (for a given month) is selected by matching the values of the variables with those of PVC, listed below.

Backing :

— unbacked (thermal conductance $= 3.5 \times 10^{-3}$ cal/s/cm^2/°C);

— backed (thermal conductance $= 8.2 \times 10^{-5}$ cal/s/cm^2/°C).

Albedo :

— 6, 46, 66 %.

Orientation :

— S/V, S/45, H, W/V, E/V.

From figures 4 to 8 the corresponding curve for PVC may be chosen. This curve gives an estimate of the temperature-time relation for the plastic for a given month. For cases in which the albedo of the plastic is significantly different from that of PVC, a more accurate curve may be obtained by interpolating with respect to albedo.

SUMMARY AND CONCLUSIONS

Measurements of surface temperature of opaque PVC panels subjected to outdoor exposure in Ottawa, Canada, at five orientations [facing south at vertical attitude (S/V), south at 45°, horizontal, east at vertical attitude (E/V) and west at vertical attitude] have been taken hourly for a year. Readings taken during Clear Hour periods, both day and night, have been selected, and for each panel the corresponding average daily surface temperature-time curve for each month was determined. The results are as follows:

1. the surface temperature of each panel is determined by the intensities of incident solar and terrestrial radiation, colour and backing of panels, wind speed, and ambient air temperature. During insolation the backed black [B(B)] panel had the highest, the unbacked white [W(U)] panel the lowest, surface temperature;

2. the average daily surface temperature-time curves of the panels display cyclic variations, with a minimum occurring between 3 and 9 LAT and a maximum between 9 and 18 LAT. Extreme surface temperatures varied from maxima of 47°C for B(B) panel at S/V orientation and 58°C for B(B) panels at other orientations, both occurring in July, to a minimum of −22°C in February for all panels;

3. the extremes in the range of daily surface temperature varied from a high of 55°C for the B(B), S/V panel in December and 47°C for B(B) panels at other orientations in June or July, to a low of 8°C for the W(U), E/V panels in December;

4. the number of Clear Hours as a percentage of the maximum possible for each month ranged from 11 % in November to 44 % in May.

The surface temperature-time curves should be generally applicable to other common opaque plastics in service in regions where the climate is similar to that prevailing in Ottawa, e. g., northern United States. They should provide a better appreciation of the temperature conditions to which plastics may be subjected, permit attainment of more realistic laboratory simulation of weathering, and provide input for equations predicting the behaviour of plastics on exterior exposure.

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RÉSUMÉ

Les variations horaires et mensuelles de la température superficielle du PVC opaque exposé par temps clair. — *Malgré les nombreuses études qui traitent de l'effet des intempéries sur les plastiques, il existe peu de travaux qui caractérisent les intempéries à cet égard. Les éléments météorologiques agissent sur les plastiques exposés et produisent un micro-environnement qui détermine la façon dont les intempéries dégradent les plastiques. Afin de caractériser ce micro-environnement, on a mesuré à chaque heure, durant un an, la température superficielle de panneaux de PCV opaque exposés aux intempéries suivant cinq orientations à Ottawa, Canada. On a choisi des données enregistrées par temps clair, jour et nuit, et on a déterminé, pour chaque panneau, la courbe temps-température superficielle quotidienne moyenne correspondante.*

Les résultats indiquent que la température superficielle de chaque panneau est fonction de l'intensité du rayonnement solaire et terrestre incident, de la couleur et de l'enduit des panneaux, de la vitesse du vent et de la température de l'air ambiant. Les températures superficielles extrêmes varient d'un maximum de 47°C dans le cas d'un panneau noir B(B) enduit en position sud verticale (S/V) et de 58°C pour des panneaux B(B) en d'autres positions, en juillet dans les deux cas, à un minimum de −22°C en février pour tous les panneaux. Les valeurs extrêmes de l'écart quotidien varient de 55°C pour le panneau B(B) en position S/V en décembre et de 47°C pour les panneaux B(B) suivant d'autres orientations en juin ou juillet, à une température de 8°C pour le panneau blanc sans enduit en position sud verticale en décembre. Le nombre d'heures de temps clair, exprimé sous forme de pourcentage du maximum possible pour chaque mois, varie de 11 % en novembre à 44 % en mai.

Les courbes temps-température superficielle devraient s'appliquer généralement à d'autres plastiques opaques d'usage courant dans les régions où les conditions météorologiques ressemblent à celles d'Ottawa. Elles devraient permettre de mieux évaluer les conditions atmosphériques pouvant agir sur les plastiques et de mieux simuler le phénomène de l'altération en laboratoire, et fournir des données pour le calcul du comportement des plastiques exposés aux intempéries.