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THE PASSIVE SOLAR HEATED SCHOOL IN WALLASEY. V

ENERGY REQUIREMENTS FOR A PASSIVE SCHOOL BUILDING

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SUMMARY

The near-south-facing glazed wall of the Wallasey School admits large solar gains in sunny weather, sufficient to meet in full the heat need in cold weather. It permits large heat losses, however, and during dull weather, and during the long winter nights there is little or no compensating solar gain. The net effect of such glazing over a season might be either to save, or to waste energy as compared with a windowless building, according to the sunniness and coldness of the climate and the window characteristics. To examine the action of the glazing, use was made of 50 years of daily mean ambient temperature, and contemporary sunshine hours, in conjunction with the solar gain factor for the translucent and pinboarded areas of the solar wall, and for certain values of design temperature and ventilation rate. It is concluded that such glazing leads to modest savings, of around 5 to 10 W/m² daily average. Most of the saving appears to be achievable by around 30 per cent glazing; further glazed area tends to supply unwanted solar gain in sunny periods while increasing the losses in sunless conditions. The annual electricity consumptions are noted for the 20 year life of the building. Their costs suggest that the building has been economical to heat.

KEY WORDS Solar heating Passive solar design

INTRODUCTION

In the early days of its existence, the Wallasey School was considered by many to be a success, since solar gain, the heat from the lighting system and body heat proved to be sufficient to ensure an equitable temperature in the building. This included the very cold period of January 1963.

The solar wall, however, permits very large losses of heat and it might be that if the solar wall were replaced with an opaque construction having the excellent insulating properties of the remainder of the structure, less energy (whether supplied by electricity or some other fuel) might be needed than the building needed with its solar wall. This question does not appear to have been aired. The popular belief was that the wall saved energy since it admitted so much solar gain; the loss it permitted was simply ignored.

The architect produced figures to show that the fuel consumption of the Annexe might be less than that of the Main School, but this might have been the result of larger losses in the Main School building. No rational theory about the value of passive solar gain emerged in the early 1960s in the U.K.

However, in the U.S.A. such an enquiry had been conducted and led to a classic equation due to Hutchinson and Chapman (1946). They provided an equation for the annual saving in heating energy due to replacing (following their notation) one square foot of non-transmitting south wall with a double glazed window which might be partly shaded by an overhang:

$$Q = F \sum_{n=1}^{5088} \nabla_n - 5088\ (U_c - U_w)(t_i - t'_o) \qquad (1)$$

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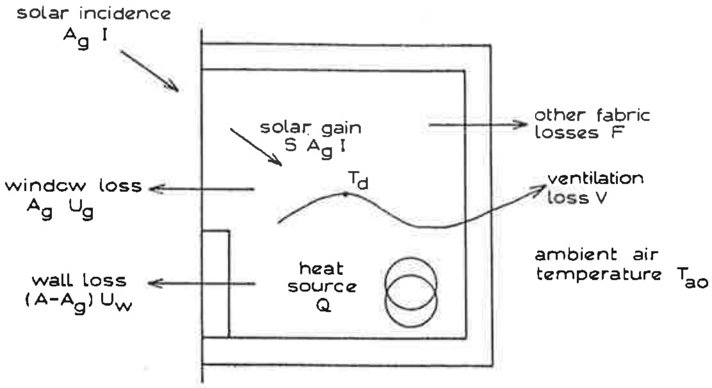


Figure 1. Diagrammatic representation of heat transfer in an enclosure receiving solar gain

The heat to be supplied by the heating system and casual gains is thus

$$Q = (T_d - T_{ao})[A_g U_g + (A - A_g) U_w + V + F] - SA_g I \tag{2}$$

To see the implications of an increase of window area it is convenient to rephrase the equation to become

$$E_\gamma = \frac{Q}{C_r} = (T_d - T_{ao}) + \gamma(T_d - T_{fx}) \tag{3}$$

This converts the units of the equation from Watts (the units of Q) to K (the units of temperature elevation, denoted by E).

C_r denotes the losses of heat $(A - A_g) U_w + V + F$ by all mechanisms other than through the solar collector area. Since U_w is likely to be small, corresponding to a well-insulated wall, C_r is almost independent of A_g.

$$\gamma = \frac{\text{heat loss conductance through the solar collector area}}{\text{heat loss by other mechanisms}} \tag{4}$$

and an increase in window area implies an increase in γ.

T_{fx} is a flux temperature, made up of a real temperature together with an increment due to a heat flux:

$$T_{fx} = T_{ao} + \frac{SI}{U_g} \tag{5}$$

T_{fx} takes account of the ambient temperature, together with solar radiation as it is affected by the window.

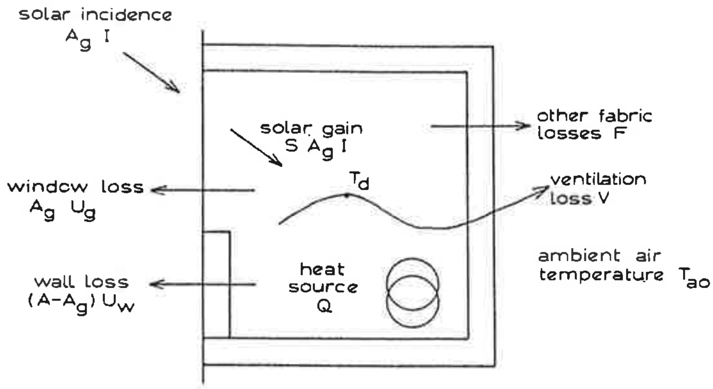
Consider now the three days indicated in Figure 2(a). If the weather is cold and dull, T_{ao} is low, I is small and T_{fx} is less than T_d. In this case E_γ, and so the heat needs, increase with γ or window area.

If the day is cold, but sufficiently bright, then T_{fx} exceeds T_d; the heat need decreases with window area.

Thus the window is advantageous or disadvantageous as a net energy collector depending on weather and window U and S factors, and choice of comfort temperature; the criterion does not depend on how big the window is or on how big the ventilation and other fabric losses are, or on how much internal heat has to be supplied.

If the window area is made larger on a day when T_{fx} exceeds T_d, E_γ eventually becomes zero; no heat is needed. Any further increase in window area is valueless. Thus there is a maximum value of γ on any one day beyond which it is not advantageous to go:

$$\gamma' = -\frac{T_d - T_{ao}}{T_d - T_{fx}}$$



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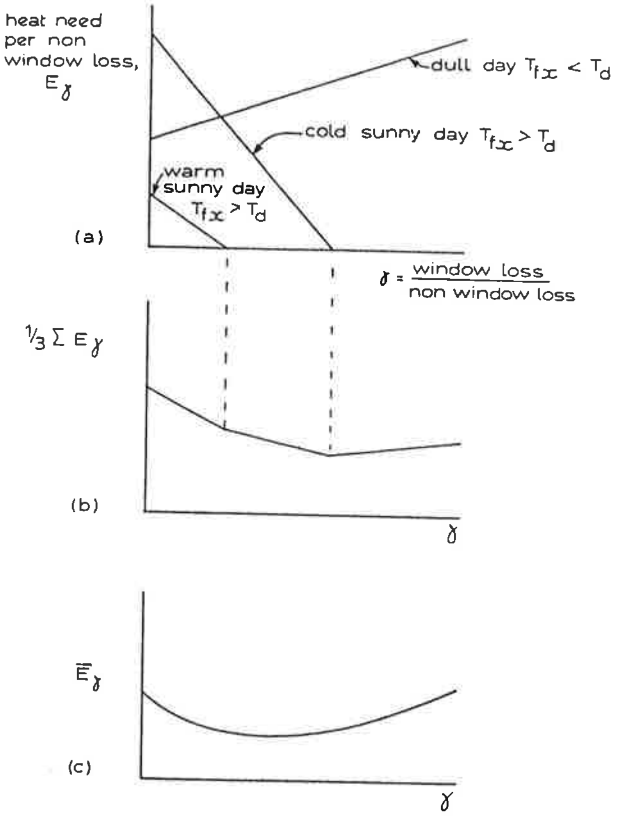


Figure 2. To illustrate how the supplementary heat requirement should increase with window area, or, more generally, the ratio of window to non-window heat losses: (a) heat need on three days of differing weather characteristics; (b) combined need over the three days; (c) generalized heat need

γ' is also a function of the above-mentioned variables. The corresponding window area A'_g is

$$A'_g = \frac{\gamma'(AU_w + V + F)}{\gamma' U_w + U_g}$$

The maximum appropriate sized window here now does depend on the ventilation and other losses.

The combined internal heat needs of the room during the two above days, together with a warm sunny day, are shown in Figure 2(b). ΣE_γ at first decreases with increasing γ but when E_γ for the warm day becomes zero, its heat need stays at zero; it cannot go negative. ΣE_γ then derives from energy needs on two days, and finally one day only.

The effect of combination of many days with a distribution of values of T_{ao} and I is to produce a smooth curve for the mean value $\bar{E}_\gamma$ of E_γ (Figure 2(c)). The curve may or may not have an initial negative slope; it must have the curvature shown.

Some heat needs calculated along these lines are illustrated by Davies (1980a). Heat needs are estimated as a function of fractional glazed area A_g/A. The results show the needs month by month from October to April, for single glazing, double glazing and double glazing with night insulation, for various values of fabric and ventilation losses and for assumed values 18°C and 22°C of comfort temperature. Davies (1980b) provides similar estimates for a mass wall with single or double glazing attached. Davies (1982a) gives both window and wall estimates for a full year.

These results were based on 50 years of day-by-day information on ambient temperature and sunshine hours from Bidston Observatory, about 2 km from the Wallasey School. This information can be summarized in statistical form and two methods of processing the meteorological data in this way are presented by Davies (1982b, 1983).

THE IMPOSED TEMPERATURES

According to equation (3), the heat input Q of non-solar origin needed to maintain a comfort temperature T_d within the building can be expressed as the temperature elevation $E_\gamma = Q/C_r$. E_γ is the sum of terms involving T_{ao} and the flux temperature T_{fx}, and these have the status of temperatures imposed upon the building.

Ambient air temperature T_{ao} is normally the only temperature considered as imposed upon a building. Its distribution over the winter months for a period of 50 years is shown in Figure 3. Since the weather station, Bidston Observatory, is so close to the school, these distributions provide a reliable guide to the local temperatures. Winter temperatures are invariably below comfort temperatures, and so the degree day value for, say, October is the moment of this distribution about 15·5°C (the usual base).

In a building which allows substantial solar gains, distribution of the flux temperature too becomes of interest. It was computed as follows. Since the solar wall is composed of a number of different constructions, equation (5) has to be expressed as

$$T_{fx} = T_{ao} + \frac{\Sigma\, S_i A_i I}{\Sigma\, U_i A_i}$$

where the dummy subscript i refers to the various constructions whose overall effect is required. S_i differs for single and double glazing and by month. S_i also differs over the double glazed section according to whether the short-wave transmitted energy penetrates into the room or is interrupted by the pinboard enclosure. As mentioned in the third of these articles (Davies, 1986b) the angle of slope of the openable single glazed window, the large recess into which it fits, and the surrounding frames make it difficult to model the single glazed portion though these factors must reduce transmission. Since double glazing admits rather less radiation than single glazing, it seems best to lump the window area with the translucent window area and treat it as a double glazed area. The assumed solar gain factors (the heat input at environmental temperature due to unit irradiance on the solar wall) are given in Table II. The area of the classroom and artroom solar wall to be taken for this calculation are then translucent area 44·66 m^2, pinboard backed area 10·78 m^2. Details are given in Table I, which also provides U values. $\Sigma U_i A_i$ = 144·3 W/K. $\Sigma S_i A_i$ = 10·78 S_p + 44·66 S_t, units m^2, and of course varies a little with month.

The information on solar irradiance in the vertical wall was obtained from the 50 years of sunshine hour measurements. These were converted to energy units using the observed solarimeter values from the present project.

$$I = a_m H + b_m$$

where I (W/m^2) is the daily mean irradiance on the vertical wall, H is the observed sunshine hour count for the day and a_m and b_m are the least squares regression coefficients, obtained monthly. On a totally overcast day $H = 0$, and the value of b_m = 7·63 W/m^2 in December represents the irradiance for such a day. Values for a_m, b_m and the correlation coefficient between daily values of I and H are given by Davies (1980a, Table 1).

The solar input term $\Sigma S_i A_i I$ was thus computed from the daily values of H and monthly parameters as

$$S_i A_i I = \text{frames factor} \times \{(10{\cdot}78\, S_{pm} + 44{\cdot}66\, S_{tm}) a_m H + (10{\cdot}78 S_{pd} + 44{\cdot}66\, S_{td}) b_m\}$$

where the subscripts p and t denote, respectively, the pinboard and translucent sections, m denotes monthly values, and d values for diffuse radiation.

The T_{fx} distribution, so calculated, is shown in Figure 3. If a comfort temperature T_d of 20°C is selected, on those days when T_{fx} exceeds 20°C, the effect of the term $(T_d - T_{fx})$ in equation (3) will be to reduce the heat need, that is to say the solar wall acts as an energy saver. On days when $T_{fx} < 20$, the wall loses more energy by conduction than it gains by solar transmission.

As remarked earlier, this result does not depend upon what the current value for heat losses through other parts of the fabric or by ventilation may be. It only depends upon meteorological factors, solar wall design and choice of comfort temperature.

A number of points may be noted:

(i) The area under the T_{fx} distribution above 20°C during December is the smallest of the areas. This gives a quantitative expression, relevant in this context, of the low maximum values of solar irradiance in midwinter and the extensive cloud cover of the U.K. climate during this period.

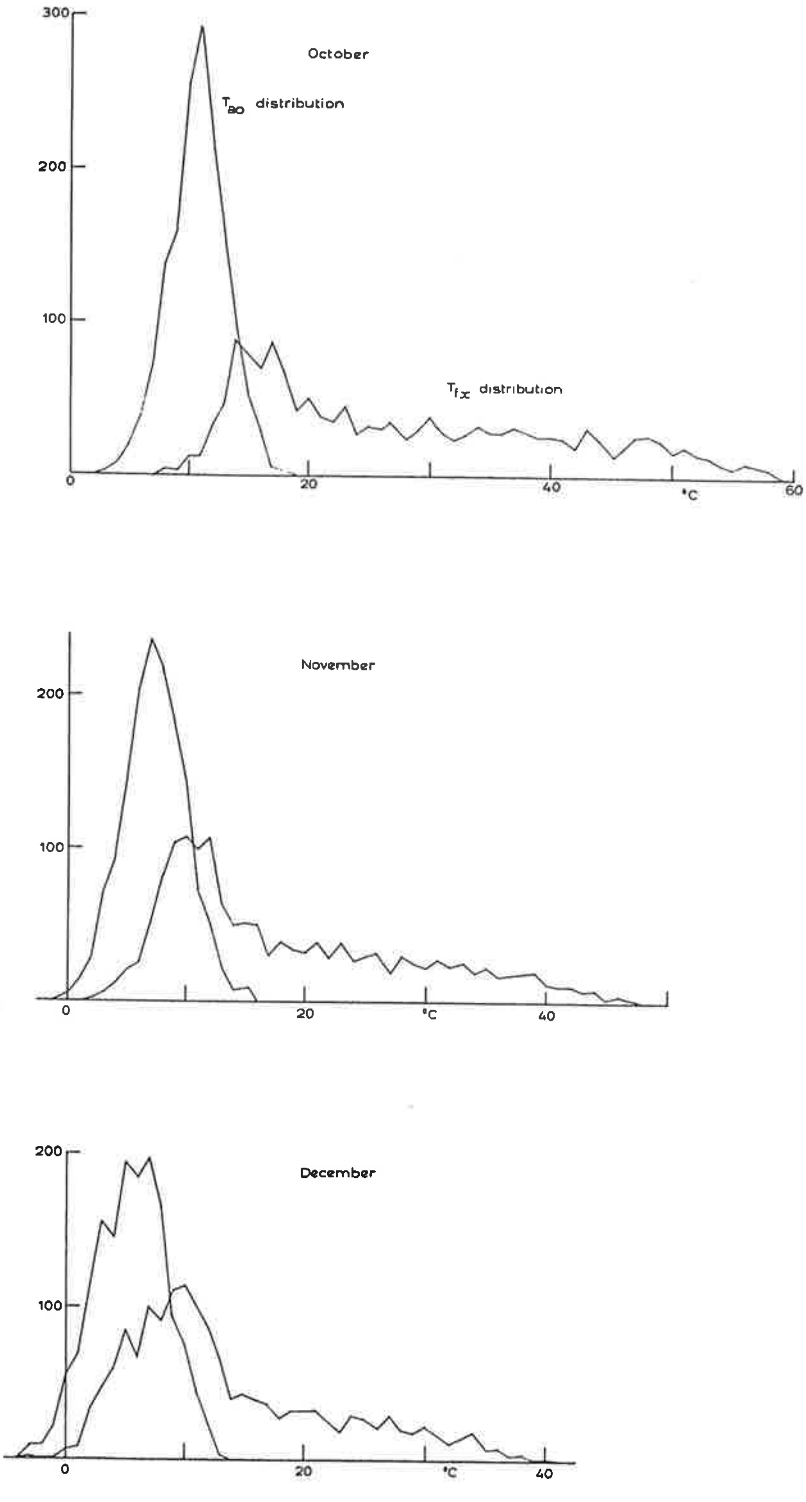
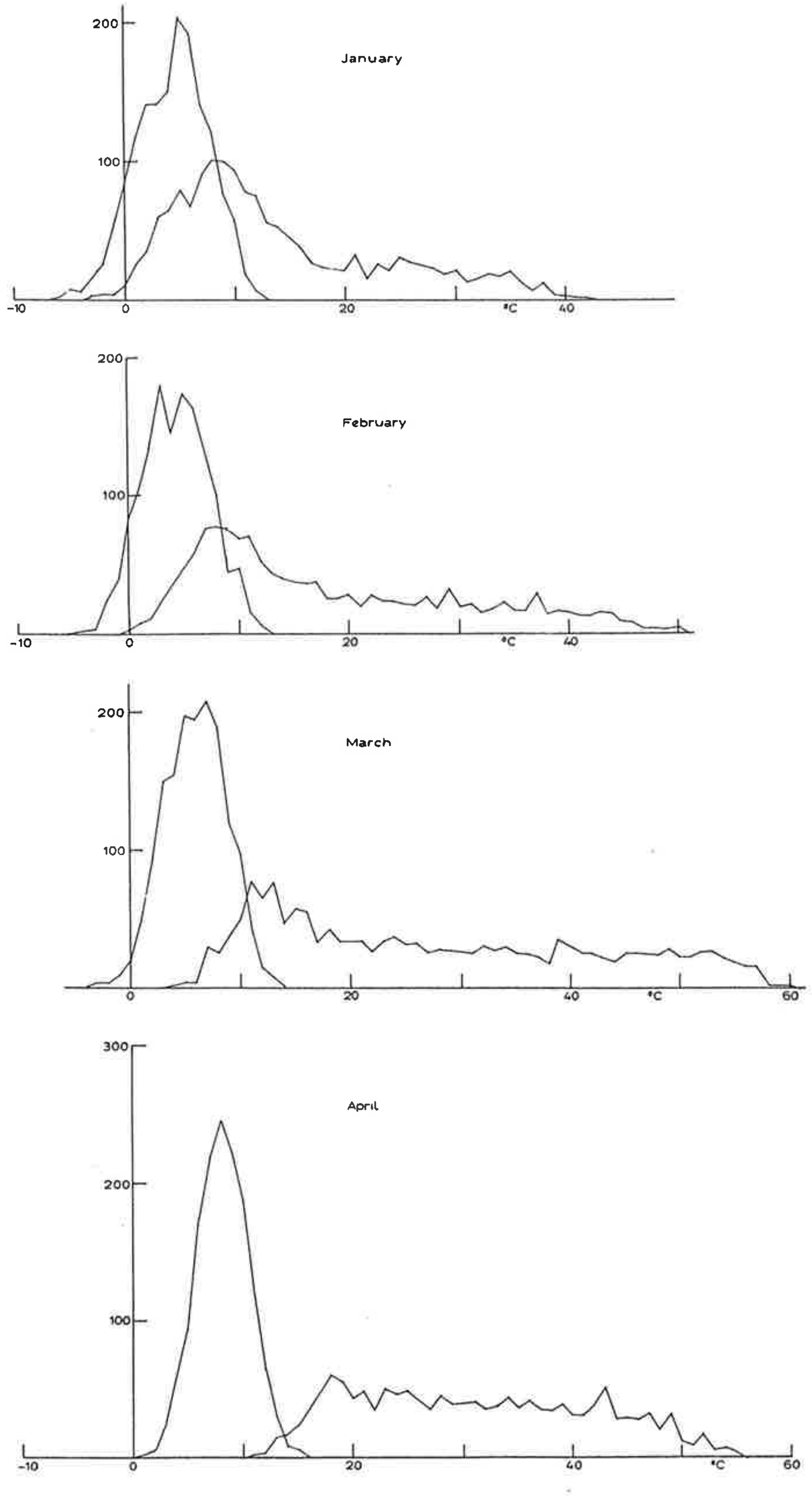


Figure 3. The Figures indicate for the month noted the distribution of daily mean air temperature T_{ao} in the Wallasey area for the period 1930–1979. (The moment of this distribution about 15·5°C provides the degree day value for the month.) The flatter distribution is that of the flux temperature T_{fx} which includes T_{ao}, sunshine levels and window characteristics. Ventilation exchange is proportional to $T_d - T_{ao}$ and always represents a loss of heat. The exchange through the window is proportional to $T_d - T_{fx}$ and on any one day this may be positive or negative according to weather conditions


200
100
January
-10
0
20
°C
40
200
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February
-10
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200
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March
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20
40
°C
60
300
200
100
April
-10
0
20
40
°C
60

Table I. Solar wall transmittance and solar gain factor

	Vertical area, m^2	Transmittance W/m^2K	Conductance W/K
Downstairs—within the two window bays			
double glazing above window	1·28	2·8	3·58
single glazing above window	1·04	5·6	5·82
window (nominal aperture)	2·85	2·4(1)	6·19
window (superficial areas)	(2·68)	2·5(2)	6·70
below window (projection on vertical)	1·07	2·8	3·00
Downstairs—remaining solar wall			
figured glass above pinboards	5·99	2·8	16·77
pinboards without aluminium	1·12	1·2	1·34
pinboards with aluminium inserts	4·27	1·0	4·27
figured glass below pinboards	1·39	2·8	3·89
clear glass below pinboards	2·19	2·8	6·13
	21·20		
Upstairs—within the two window bays			
double glazing above window	3·92	2·8	10·98
single glazing above window	1·04	5·6	5·82
window (nominal aperture)	2·85	2·4	6·84
window (superficial area)	(2·68)	2·5	6·70
Upstairs—remaining solar wall			
figured glass above pinboards	14·98	2·8	41·94
pinboards without aluminium	0·90	1·2	1·08
pinboards with aluminium inserts	2·94	1·0	2·94
figured glass below pinboards	0·27	2·8	0·76
entire concrete upstand and floor behind flanking walling	7·34	1·3	9·54
	34·24		144.3
	55·44		

Table II. Solar gain factors for the double glazed wall

	Translucent section including windows	Pinboard section			
January	0·773	0·621	July	0·560	0·449
February	0·732	0·587	August	0·583	0·468
March	0·662	0·531	September	0·639	0·513
April	0·611	0·491	October	0·718	0·576
May	0·576	0·462	November	0·770	0·618
June	0·559	0·449	December	0·786	0·631
			diffuse	0·673	0·480

(ii) The March air temperature (T_{ao}) distribution differs little from that of December, but the T_{fx} distribution is considerably shifted to higher T_{fx} values. Conventional heating calculations are based on T_{ao} information alone, and would thus suggest that the heat needs in December and March were about the same. For rooms with a southerly aspect, this may not be so.

(iii) The T_{fx} distribution for March extends to rather higher values than does that for April. This comes about since the total solar flux on a south wall on a cloudless day has maximum values in the U.K. in March and September. April however provides more useful sunshine than does March.

(iv) These distributions are based on transmittance of the solar wall as it is. If curtains were drawn, or some other form of insulation were used during the hours of darkness, the T_{fx} distributions would be shifted to higher T_{fx} values.

ENERGY NEEDS

The discussion of the last section indicates the potential of solar gains for reducing heat needs. The actual heat need itself depends additionally on fabric conduction and ventilation losses.

$$Q = (T_d - T_{ao})(\Sigma U_i A_i + V + F) - S_i A_i I$$

V and F are evaluated in the Appendix.

Q was evaluated day by day using the 50 year database described above. Q was summed when positive. (If Q is negative it implies that cooling would be needed to maintain a daily mean value of T_d. Since cooling is not supplied, on such days, the indoor temperature rises above T_d.)

Values for the whole year are shown in Figure 4(a) for $T_d = 16°C$ and Figure 4(b) for $T_d = 20°C$. (16°C is too low to be considered as a comfort temperature. During the winter period, values around 18°C may be found, and the values of 16 and 20°C were chosen to be on either side of the winter temperatures as actually experienced during occupation.) Since the ventilation is low in winter, but is otherwise unknown, ventilation rate in air changes per hour is taken as the independent variable. The heat need is expressed as supplementary (non-solar) heat need in units of W/m² heat input on a vertical wall, and averaged over the year.

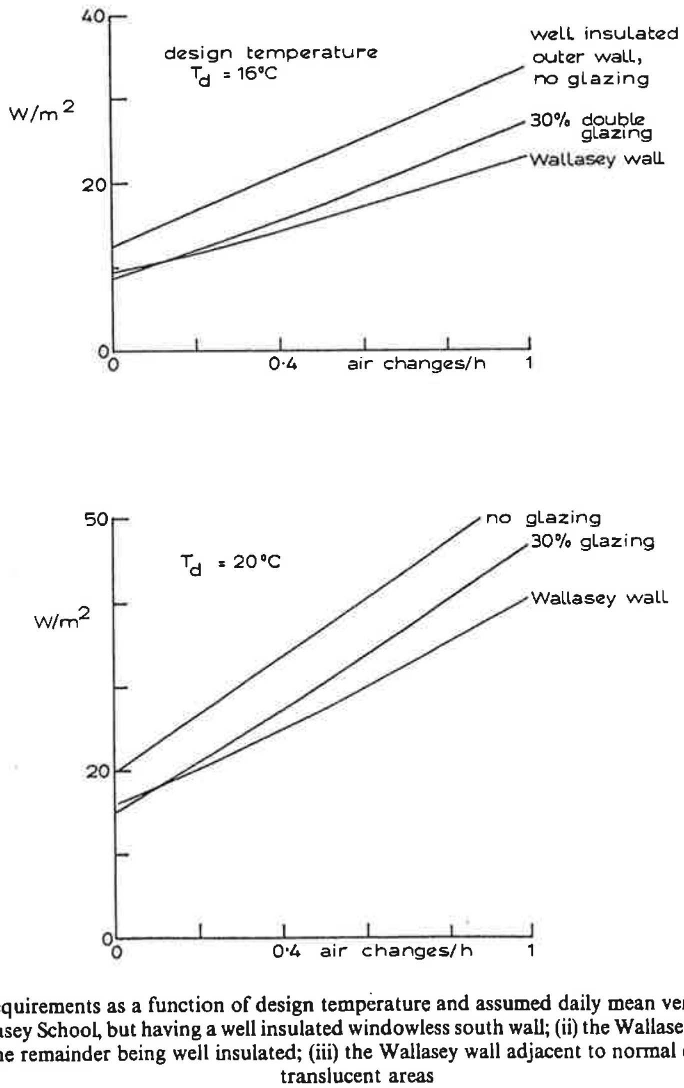

Figure 4. Estimated heat requirements as a function of design temperature and assumed daily mean ventilation rate; (i) for a building having the form of the Wallasey School, but having a well insulated windowless south wall; (ii) the Wallasey School with 30 per cent of the south wall double glazed, the remainder being well insulated; (iii) the Wallasey wall adjacent to normal classrooms, with pinboard and translucent areas

For comparison, two other cases are provided:

(a) A building having the same shape as the Wallasey School, but the solar wall area is totally opaque with the same insulation levels as the roof. Thus there are no solar gains to the building, but the conduction losses through the south wall are small.

(b) A building having the same shape as the Wallasey School, but whose solar wall area is 30 per cent double glazed, and the remainder has the high insulation standard of the roof.

The following results appear.

(i) The heat need of the 'no glazing' building increases strictly linearly with ventilation rate, as must be the case. (The intercept is proportional to the total conduction loss.)

(ii) At low ventilation rates, the heat needs of the Wallasey building differ little from the 'no glazing' building, but they increase less rapidly with ventilation rate. At 1 air change per hour, the annual saving at 18°C for the westerly block would appear to be around $(43{\cdot}6 - 31{\cdot}0\,\mathrm{W/m^2}) \times (3600 \times 24 \times 365\,\mathrm{s}) \times (70{\cdot}2 \times 8{\cdot}7\,\mathrm{m^2})$ or 240 GJ/yr.

(iii) This value applies at the comfort temperature of 18°C. At 20°C the absolute heat need is of course greater, whereas the saving is nearly the same.

(iv) Solar gain alone is sufficient to meet modest heat needs. Information on the proportion of days in the year when no supplementary heating may be needed is shown in Table III. The proportion of 'no-heating' days decreases as the ventilation rate increases, and as the choice of comfort temperature increases.

(v) At low ventilation rates, there is little to choose between the Wallasey construction and the 30 per cent glazing wall.

(vi) Night insulation during the winter months would much reduce the energy consumption.

(vii) The energy consumptions for monthly periods throughout the year are given in Table IV.

(viii) According to one of the specification documents, the total installed lighting in the building is 44,750 kW. Taking the external area of the solar wall to be a total of 829·6 $\mathrm{m^2}$ (this includes the main teaching block and the gymnasium block), the maximum electrical input must be 54 $\mathrm{W/m^2}$ of solar wall. Some of the values in Table IV are above this value. In these cases, the lighting system alone could not sustain the design temperature assumed during the month concerned and at the assumed ventilation rate.

ELECTRICITY CONSUMPTION

The energy estimates given in Figure 4 and Table IV represent the heat inputs of non-solar origin which are needed to maintain certain temperatures. Some of this energy is supplied metabolically but most of it comes from the electric lighting system and so can be measured.

Monthly consumption

Meter readings were taken by the Clerk of Works effectively from October 1962 onward. Data for November 1964 to October 1966 are missing. From June 1968 until observations were discontinued in late July 1970, additional meter readings were taken by the Liverpool team twice weekly during service visits. No meter readings are available for November 1968. Sixty-nine months of data are thus available.

Table III. Proportion of days in the year when no supplementary heat is needed

Comfort temperature	Ventilation rate (air changes per hour)					
	0·0	0·2	0·4	0·6	0·8	1·0
16	0.66	0·63	0·59	0·56	0·54	0·51
20	0·54	0·49	0·44	0·39	0·35	0·31

The initial and final meter readings for each month were estimated by interpolation and the monthly consumption found by differencing. The values in kWh were reduced to the common expression of energy used here for heat balance considerations by dividing the monthly consumption by the length of the month in seconds and the area of the total solar wall. The actual energy inputs, estimated from the meter readings as discussed above, are listed in Table V. It will be seen that the consumption is very much heavier in winter than summer. The maximum monthly value of 36·4 W/m^2 (22,450 kWh), found in January 1963, corresponded to the lights being left on for 16·2 h/day. (Undoubtedly they were switched off during the Christmas holidays and then left on 24 h/day for a while to warm the building up.) The consumption varied considerably from month to month. For example, the minimum and maximum values in March were 7·6 and 33·3 W/m^2.

Consumption per unit floor area and per child

The mean annual electricity consumption for the above period was 78,260 kWh/year. This can be expressed in terms of certain representative quantities: 36 kWh per square metre of total floor area (Love, 1968); 59 kWh per square metre of teaching space; 260 kWh per child.

Consumption and outdoor air temperature

It is clear that the lighting load will vary according to the outside air temperature. Monthly mean values for air temperature were obtained from records at Bidston Observatory. The distribution of averages of lighting power and temperature is shown in Figure 5. Although high lighting power is associated with low temperatures, there is clearly a very large variation. For example with $\overline{T}_{ao}$ = 4·5 K, an approximate mean winter temperature, lighting powers between 12 and 37 W/m^2 have been noted. There is evidently no precise power consumption associated with monthly average air temperature.

Figure 5 suggests a curvilinear relation between power consumption and outdoor air temperature. This is not as expected. Power consumption is often assumed proportional to $(\overline{T}'_{ai} - \overline{T}_{ao})$ where T'_{ai} is some reference temperature and we should expect a scatter of points about a straight line passing through $T = T'_{ai}$ rather than a scatter about a curvilinear line.

The data of Figure 5 are based on the period 1962–1970, Bidston air temperature measurements, meter readings by the Clerk of Works, etc., which refer to the building as a whole, and in particular are monthly means. To examine the relation more closely, use was made of the present observations for January 1969–July 1970, which refer to the classroom alone and in particular are daily rather than monthly mean values. Power consumptions are based on when the lights were known to be on. These values of power against $\overline{T}_{ao}$ are shown in the scattergram of Figure 6.

If we set aside the large number of days (with a large range of $\overline{T}_{ao}$) during which the power input is zero, the power against $\overline{T}_{ao}$ relation appears roughly linear. If the data of Figure 6, however, are reduced to monthly means (including days of zero consumption), the 19 points for the period concerned show the same curvilinear trend.

The power input, P, is zero during school holidays and during summer months. Such days should be omitted when finding the variation of power consumption with outdoor air temperature. The observed relation between daily mean power input due to the lighting system and mean outdoor air temperature (based on the 284 days in the 19 month period when the lights were used) was found to be $P = 2{\cdot}03\ (19{\cdot}8 - \overline{T}_{ao})$ W/m^2.

The correlation coefficient is −0·72. (Surprisingly this is less than the correlation coefficient of −0·77 found when all 494 days were included. The 210 days of zero power input however make the power/temperature distribution highly skewed and will lead to high correlation coefficients as noted.)

Independent evidence of power consumption is provided by the meter readings taken by the Merseyside and North Wales Electricity Board. MANWEB supplied the present author with values up to 1972. The list has been brought up to date by Mr. D. Johnson. See Table VI, which provides quarterly consumptions, and also annual consumptions according to the financial year, April to March.

Information on air temperatures is available from Bidston Observatory up to the end of 1979, from which the degree day values (base 15·5°C), up to the year April 1978 to March 1979 can be found. Consumption and degree day values are shown in Figure 7. There is evidently no substantial relation between them, such as is

Table IV. Daily mean heat need, in units of W per square metre of vertical wall, to maintain the building at a daily mean temperature of 16°C or 20°C

Design temperature		No. of air changes per hr.	Yearly average	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
16°C	Well insulated wall	0·0	12·5	22·4	22·5	19·4	15·2	9·6	4·6	2·3	2·3	4·9	10·3	16·8	20·5
		0·2	16·8	30·0	30·2	26·0	20·3	12·8	6·1	3·1	3·1	6·6	13·7	22·4	27·4
		0·4	21·0	37·6	37·8	32·6	25·5	16·1	7·6	3·8	3·8	8·3	17·2	28·1	34·4
		0·6	25·3	45·2	45·5	39·2	30·6	19·4	9·2	4·6	4·6	10·0	20·7	33·8	41·3
		0·8	29·5	52·8	53·1	45·8	35·8	22·6	10·7	5·4	5·4	11·6	24·2	39·5	48·3
		1·0	33·8	60·4	60·8	52·4	40·9	25·9	12·3	6·2	6·1	13·3	27·7	45·2	55·2
	Well insulated wall, 30% glazing	0·0	8·6	23·4	19·6	11·9	5·0	1·2	0·2	0·0	0·0	0·8	4·6	14·5	22·0
		0·2	11·9	31·0	27·0	17·3	8·4	2·5	0·6	0·0	0·1	1·3	6·8	19·8	28·9
		0·4	15·5	38·6	34·5	23·3	12·5	4·3	1·1	0·1	0·2	1.9	9·3	25·4	35·8
		0·6	19·3	46·2	42·1	29·6	17·0	6·5	1·7	0·2	0·4	2·6	12·1	31·0	42·8
		0·8	23·1	53·7	49·8	36·0	21·9	9·0	2·4	0·4	0·6	3·5	15·0	36·6	49·7
		1·0	27·1	61·3	57·4	42·5	26·8	11·7	3·3	0·6	0·8	4·4	18·1	42·3	56·7
	Wallasey wall	0·0	9·3	28·5	21·7	10·8	2·4	0·1	0·0	0·0	0·0	0·3	4·1	16·4	27·0
		0·2	11·6	34·9	27·2	14·2	3·9	0·4	0·0	0·0	0·0	0·5	5·5	20·3	33·0
		0·4	14·2	41·6	33·0	18·0	5·7	0·8	0·1	0·0	0·0	0·8	7·0	24·6	39·3
		0·6	17·0	48·6	39·2	22·1	7·8	1·4	0·2	0·0	0·0	1·2	8·7	29·1	45·9
		0·8	19·9	55·8	45·7	26·5	10·2	2·1	0·4	0·0	0·0	1·6	10·4	33·9	52·6
		1·0	23·0	63·2	52·6	31·4	12·9	3·0	0·6	0·0	0·1	2·0	12·3	38·8	59·3

20°C		0·0	20·0	30·1	30·3	27·1	22·9	17·2	11·7	9·0	8·9	12·4	18·0	24·5	28·2
		0·2	26·7	40·3	40·5	36·3	30·6	23·0	15·6	12·0	12·0	16·5	24·0	32·8	37·8
	Well insulated wall	0·4	33·5	50·5	50·8	45·5	38·4	28·9	19·6	15·0	15·0	20·7	30·1	41·1	47·3
		0·6	40·3	60·7	61·0	54·7	46·2	34·7	23·5	18·1	18·0	24·9	36·2	49·3	56·9
		0·8	47·1	70·9	71·3	63·9	53·9	40·5	27·5	21·1	21·1	29·1	42·3	57·6	66·4
		1·0	53·8	81·1	81·6	73·1	61·7	46·4	31·4	24·2	24·1	33·3	48·4	65·9	76·0
		0·0	15·2	34·4	30·2	21·0	12·6	5·8	2·6	0·9	1·4	4·3	11·8	24·9	32·9
		0·2	21·1	44·6	40·4	29·8	19·7	10·3	4·8	2·1	2·6	6·7	17·0	33·2	42·5
	Well insulated wall, 30% glazing	0·4	27·3	54·8	50·7	38·9	27·2	15·4	7·7	3·7	4·2	9·5	22·6	41·4	52·0
		0·6	33·7	65·0	60·9	48·0	34·9	20·8	11·0	5·7	6·0	12·8	28·5	49·7	61·6
		0·8	40·2	75·2	71·2	57·2	42·6	26·4	14·5	8·0	8·2	16·3	34·5	58·0	71·2
		1·0	46·8	85·4	81·5	66·4	50·4	32·1	18·1	10·5	10·7	20·1	40·5	66·3	80·7
		0·0	16·1	43·2	34·2	20·0	7·8	1·9	0·6	0·0	0·3	3·1	11·5	29·0	42·1
		0·2	20·4	52·7	42·6	26·0	11·6	3·4	1·3	0·1	0·6	4·4	14·8	35·9	51·3
	Wallasey wall	0·4	25·0	62·6	51·7	32·7	16·0	5·5	2·2	0·4	1·1	5·8	18·5	43·2	60·7
		0·6	29·9	72·7	61·2	39·9	21·0	8·1	3·3	0·8	1·8	7·4	22·4	51·0	70·1
		0·8	35·1	82·9	71·0	47·6	26·6	11·2	4·8	1·4	2·5	9·2	26·7	58·9	79·7
		1·0	40·6	93·1	81·1	55·8	32·7	14·8	6·4	2·2	3·4	11·2	31·3	67·0	89·3

Table V. Monthly electricity consumption during 1962–1970

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.
frequency	6	6	6	6	6	6
consumption W/m²	30·7	24·0	18·1	9·0	3·4	2·1
Month	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
frequency	6	5	5	6	5	6
consumption	1·8	0·3	3·0	4·3	13·2	17·6

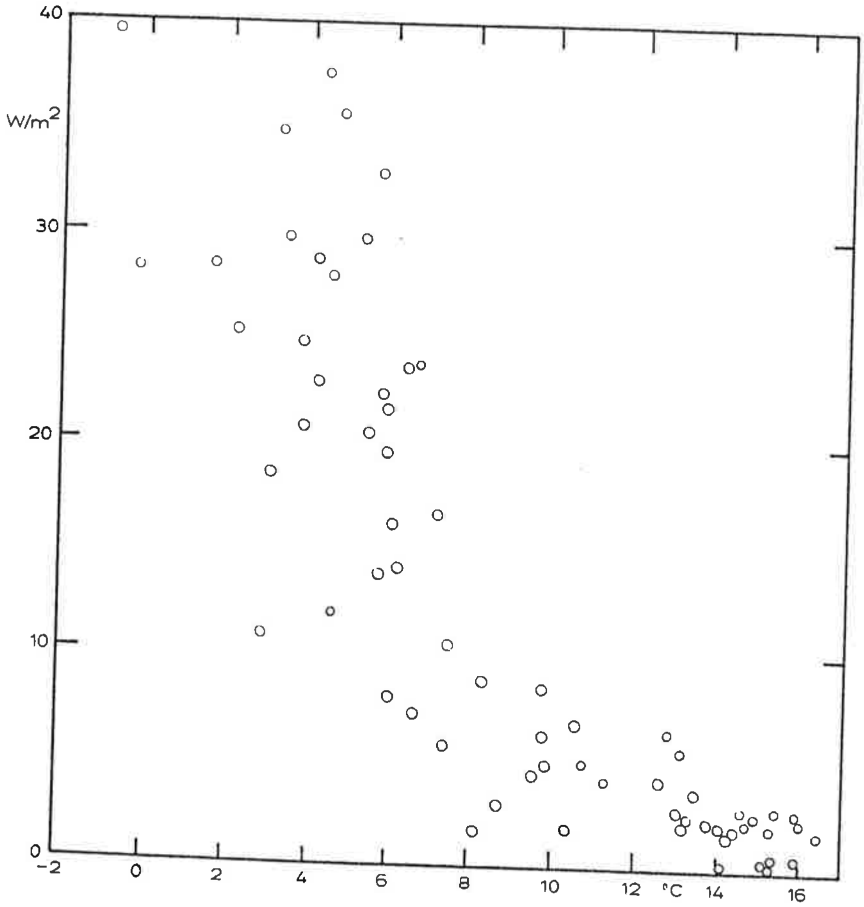

Figure 5. Monthly power consumption (W/m² of solar wall) in the school as a function of the outside temperature, 1962–1970. (Air temperatures are from Bidston Observatory. Power consumption from meter readings made by the Clerk of Works, and later the Liverpool team)

often assumed. Some positive correlation might have been expected. There are however a number of factors which may serve to reduce the covariance of the two quantities in the long term.

(i) Marked correlation is in general unlikely between quantities which are large in themselves and show little variation. Thus the degree day value for 1962–1963, which included one of the most severe winter periods in living memory, is only 36 per cent larger than the mildest year during this period. The variation in power consumption ranges over about 100 per cent.

(ii) As has been made clear earlier, the energy needs in the school depend on two statistical forms, one based on ambient air temperature T_{ai} (the degree day value), and the other on the flux temperature T_{fx}. Figure 3

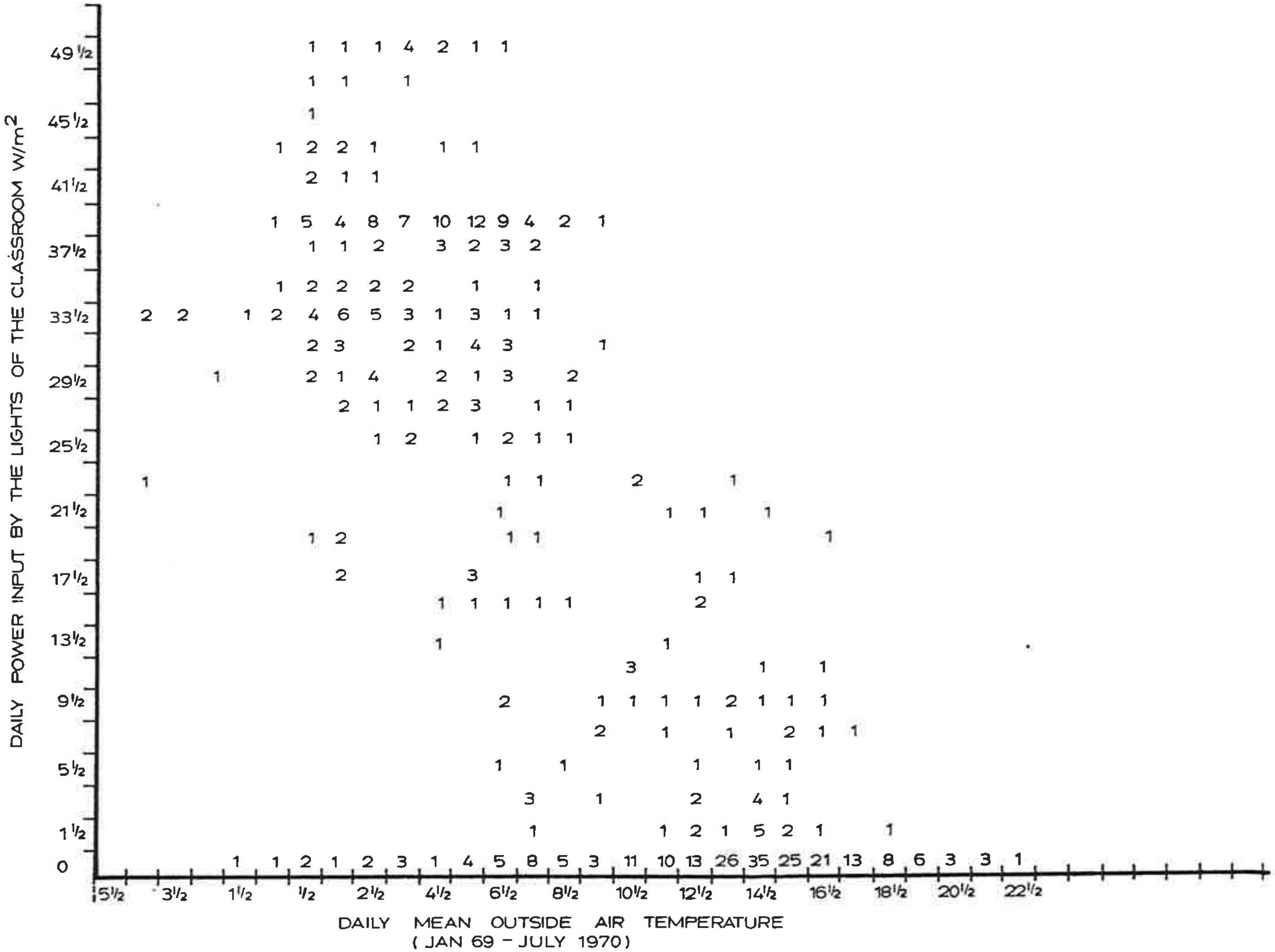

Figure 6. Power consumption in the classroom and daily mean outside air temperature. (Air temperatures and power consumptions are taken from the Liverpool study)

Table VI. Quarterly and annual electricity consumption: upper figure for the solar-heated Annexe, lower figure in brackets, for the Main School

Year	March–June	June–September	September–December	December–March	All year	All year
	kWh	kWh	kWh	kWh	kWh	W/m²
1962–1963	—	—	18,083 (8097)	43,036 (9623)	—	—
1963–1964	3589 (3557)	2531 (2201)	16,350 (9102)	47,908 (9450)	70,378 (24,310)	9·69
1964–1965	4490 (4240)	1560 (1738)	13,520 (10,202)	36,750 (10,981)	56,320 (27,161)	7·76
1965–1966	7650 (4303)	3650 (2227)	24,300 (8127)	48,870 (11,390)	84,470 (26,047)	11·63
1966–1967	19,450 (4832)	3330 (2900)	19,490 (12,150)	36,430 (10,698)	78,700 (30,580)	10·84
1967–1968	7520 (4527)	4550 (3601)	23,910 (10,871)	39,320 (14,007)	75,300 (33,006)	10·37
1968–1969	8350 (5313)	3680 (3267)	25,731 (14,417)	53,170 (16,900)	90,931 (39,897)	12·52
		June–November	November–February	February–May		
1969–1970	15,470 (23,159)	14,450 (8260)	48,910 (13,758)	37,960 (6979)	116,790 (52,156)	(16·08)
	May–August	August–November				
1970–1971	3490 (2291)	12,190 (4275)	65,250 (11,411)	40,080 (6,696)	121,010 (24,673)	16·66
1971–1972	2730 (2021)	16,010 (5310)	42,890 (9,520)	11,100 (4325)	72,730 (21,176)	10·02
1972–1973	2320 (2322)	14,490 (5894)	43,100 (—)	16,700 (—)	66,610 (8216 + ?)	9·16
1973–1974	2310	20,750	26,870	16,340 EST	66,270	9·12
1974–1975	N/A	N/A	N/A	N/A	71,350	9·78
1975–1976	N/A	N/A	N/A	N/A	61,290	8·44
1976–1977	15,810	17,200	13,220	34,830	81,060	11·16
1977–1978	14,640	2,820	10,430	46,254	74,144	10·21
1978–1979	16,726	3,889	11,063	40,980	72,643	10·00
1979–1980	21,670	2,580	16,150	38,260	78,660	10·82
1980–1981	19,961	3,998	20,552	38,285	82,796	11·40
1981–1982	19,734	3,860	16,612	33,870	74,076	10·20
1982–1983	17,210	3·018	18,474	44,303	83,005	11·42
1983–1984	21,060	7,120	18,593	36,210	82,983	11·41

N/A = not available

shows the distributions. As compared with a more usual building the school depends relatively strongly on the T_{fx} distribution, and so relatively less on the T_{ai} distribution, or degree day value.

(iii) During the first 8 or so years of the life of the building breakages in the glass of the solar wall were not very common, but over the last decade they have become distressingly frequent. Occasionally some missile has made holes in both the inner and outer leaf. In these cases the ventilation losses increase very considerably, possibly leading to more use of the lights for heating.

(iv) The caretakers may not have been consistent in their policy of setting the times for switching lights on and off. (Against this it must be said that there have been only two caretakers employed in the school since it opened, and the first, who must have retired around 1969, was very devoted to the memory of the architect and to the running of the school.)

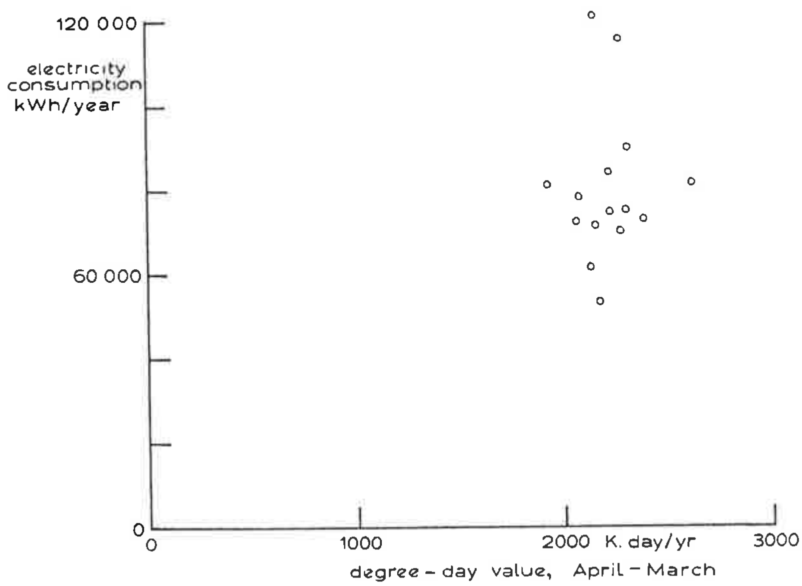

Figure 7. Relation between annual power consumptions (April to March) for the period since 1962, and the corresponding degree day value, (taken from data from Bidston Observatory)

(v) There may have been shifts in the pattern of usage of the building, particularly in the use of windows, over the years.
(vi) There have been periods of power cuts, particularly during the 1970s, and during some of these the hot-water radiator system is known to have been used. The radiators are still used from time to time.

These factors appear to annul the somewhat shorter term covariance of energy consumption with ambient temperature.

Cost of electricity

According to the Merseyside and North Wales Electricity Board, the actual connected lighting load is 43,000 kW and the actual connected total (including lighting) load is 64,413 kW. As a result of an agreement (believed to have been negotiated originally by the architect), both the lighting load and the total load are in fact counted as 28,000 kW. The tariff applicable to the building is the Board's Commercial and Industrial Block Tariff no. 4/1, which defines a first block based on the connected lighting load and a second block based on the connected total (including lighting) load. Thus for example, the prices applicable for a period after 1 May 1972 were

first block 2850 kWh/quarter at 3·497p/kWh
second block 3300 kWh/quarter at 1·523p/kWh
excess consumption/quarter at 0·961p/kWh.

The annual costs of electricity used in the solar heated section of the school (i.e. not including electricity used in the older part of the complex), are listed in Table VII. The values for 1974–1975 onward are the known costs. Earlier records are not now available and the costs were deduced by MANWEB from the known quarterly consumptions and the appropriate tariffs for the periods concerned.

If a nominal occupancy of 300 children is assumed, the costs of electricity per child per year are as listed in column 3 of Table 7. The publication *Education Statistics* provided at one time a large quantity of information of this kind in units of cost per child per year, and other information. The areas concerned were (for 1971–1972) the 83 English County Boroughs, 20 London Boroughs, 45 English Counties and 13 Welsh Counties. The publication lists the cost per pupil per year of fuel, light, cleaning materials and water in Primary and

Table VII. Cost of electricity in the Wallasey School and comparative costs

Year	Cost of electricity, £	Cost, £/child/yr	Information from *Education Statistics* (£/child/yr) A	B	C
1962–1963	—	—	4·07	4·31	103·67
1963–1964	714	2·38	4·11	4·33	109·38
1964–1965	669	2·23	4·52	4·65	117·34
1965–1966	857	2·86	4·99	5·05	133·93
1966–1967	874	2·91	4·90	5·24	141·26
1967–1968	889	2·96	6·19	6·05	150·77
1968–1969	1006	3·25	7·15	6·44	156·44
1969–1970	1200	4·00	7·30	6·52	166·41
1970–1971	1232	4·10	7·21	6·75	183·28
1971–1972	1005	3·35	7·17	7·53	205·37
1972–1973	1240	4·13	7·59	8·01	239·56
1973–1974	1144	3·81		8·62	257·11
1974–1975	1316	4·39	12·05	12·40	343·87
1975–1976	1577	5·26			
1976–1977	1977	6·59			
1977–1978	2350	7·83	18·37		583·83
1978–1979	2515	8·38			
1979–1980	2752	9·17			
1980–1981	3545	11·8			
1981–1982	3520	11·7			
1982–1983	4535	15·1			

A = 'Cost of fuel, light, cleaning materials and water' for secondary schools in the County Borough of Wallasey.
B = 'Cost of fuel, light, cleaning materials and water', average value for all County Boroughs, (83 listed in 1971–1972).
C = Average value of the following items: salaries and wages (including superannuation, national insurance and other employees' expenses), for teachers and non-teaching staff; repair and maintenance of buildings and grounds; fuel, light, cleaning materials and water; furniture and fittings; rent and rates; textbooks and library books; educational equipment; school stationery and materials; other supplies and services; miscellaneous expenses; debt charges.

Secondary Schools, and the information for the County Borough of Wallasey is given under column A in Table VII. Now column 3 values include all lighting and virtually all heating costs, but not of course the cost of the occasional use of a coke-fired boiler. Nor do they include the cost of cleaning materials and water, but these items probably do not constitute a large proportion of column A values. Thus column 3 and column A do not present exactly comparable quantities. It is clear however that the Wallasey fuel costs have been consistently lower than the comparable local values.

Table VII also lists the national average values for 'Fuel, etc.' (column B). The cost of 'Fuel, etc.' can in turn be placed in relation to the total costs per child (column C). About two thirds of the costs in column C is made up from salaries, etc. of employees. Savings in fuel costs could only be of minor importance in relation to the total cost of the education services during this period.

Unfortunately the comparison cannot be continued beyond the mid-70s. After the reorganization of the counties, Wallasey became included in a larger area, and *Education Statistics* no longer presented information from which the cost of 'Fuel etc.' can be extracted.

Finally, mention may be made of costs of fuel, electricity and plant maintenance for a group of 20 secondary schools selected randomly, for the period 1970–1971 (private communication by Mr. L. J. Dolomore, 1973). Rounding the cost up or down to the nearest pound, the distribution was:

£/child/yr	5	6	7	8	9
frequency	1	7	6	3	3

The mean cost was £7·20/child/year. This is close to the column A and column B values for this year. The Wallasey School costs again compare very favourably with this value. It will be appreciated that these comparisons do not compare exactly alike items. Further there is no information at all on the standard of thermal comfort that the energy input achieved.

DISCUSSION

It is widely recognized that to maintain comfort standards in a building in an economic manner, it is necessary to insulate the structure and restrict air infiltration. Until fairly recently however it has been unclear whether the use of large windows would lead to an increase or a decrease in fuel needs.

Figure 4 provides some indications of energy needs for the Wallasey School and some variations in construction. The energy need for a well insulated windowless building exceeds the energy need of one with double glazing or one with the Wallasey solar wall. The savings in energy need for the cases discussed amount to 5 to 10 W/m^2 of solar wall, averaged over the year. The saving, however, itself depends somewhat on the choice of comfort temperature and the assumed ventilation rate. Energy needs generally increase with increase in both these quantities, but the savings due to glazing also increase with them. This is physically due to the fact that if solar gain on one day were sufficient to achieve a comfort temperature, further solar gain would not be usable. If a higher temperature or higher ventilation rates were assumed, more solar gain would prove useful, leading to larger energy needs, and a larger solar contribution.

In the Wallasey School however the daily mean ventilation rates in winter are low and in these circumstances there seems little to choose on energy grounds between a wall with 30 per cent glazing, otherwise well insulated, and the near fully glazed area of the Wallasey School. A larger fraction may prove advantageous at higher ventilation rates.

If a smaller glazed area were adopted, the whole basis for design alters; in particular the interior thermal storage needed to restrain temperature rises in sunny conditions is less. If a smaller glazed area were used, but provided with insulation suitable for use during the long winter nights, energy needs could be reduced below those indicated in Figure 4. The architect was well aware of the need for some suitable device.

The characteristic expressing the energy/ventilation relation for a conventional building of the 1950s or 1960s lies typically very much above those shown in Figure 4. In cost terms, the Wallasey School would appear to be much cheaper to heat than such buildings.

Two further articles discuss the questions of the occupants reported reactions to the classroom climate, and how they used the windows to control it.

ACKNOWLEDGEMENTS

The results reported here are based on the same study as was reported in the previous article (Davies, 1986c) and acknowledgement is made to those mentioned there. I am indebted to Mrs J. B. Fazakerley for her extensive computational assistance. I am grateful to Mr. L. J. Dolomore for supplying me with information on energy needs in a selection of schools in 1970–1971, to Mr. D. Johnson for the considerable labour in providing further information on energy needs in the Wallasey School itself, and to Mr. W. Hatton and Mr. D. G. McCann of the Merseyside and North Wales Electricity Board for computing the early electricity costs.

APPENDIX: CONDUCTION AND VENTILATION LOSSES

Dimensions for the classroom and artroom were taken mainly from the 1 : 24 ($\frac{1}{2}$ inch = 1 foot) section of this part of the building.

The periphery due to the roof, upper floor north wall, horizontal overhang and ground floor north wall amounted to some 19·35 m. With a width of 8·08 m this makes an area of 156·35 m^2. This area is all encased in 12$\frac{1}{2}$ cm (5 in.) of expanded polystyrene. The U value is thus approximately $(0{\cdot}055 + 5 \times 0{\cdot}0254/0{\cdot}037 + 7 \times 0{\cdot}0254/1{\cdot}4 + 0{\cdot}123)^{-1} = 0{\cdot}27$ W/m^{2}K. The associated conductance is thus 41·7 W/K. To this must be added the conductance due to the skylight in the artroom (8·5 W/K) and the floor (40·6) making a total fabric loss of $F = 90{\cdot}8$ W/K.

The volumes of these rooms were also estimated:

artroom mean height $= \frac{1}{2}(2{\cdot}21 + 5{\cdot}18) = 3{\cdot}695$ m
so the volume $= 11{\cdot}43$ (north–south) $\times 3{\cdot}695 \times 8{\cdot}08 = 341{\cdot}2\,\mathrm{m}^3$
corridor volume $= 2{\cdot}095$ high $\times 2{\cdot}97$ north–south $\times 8{\cdot}08 = 50{\cdot}3\,\mathrm{m}^3$
classroom, allowing for loss of volume due to sloping ceiling $= 151{\cdot}8\,\mathrm{m}^3$
total volume $= 543{\cdot}3\,\mathrm{m}^3$

The ventilation rate is then $V = 543{\cdot}3 \times (1200/3600)n$ where n, is the number of air changes per hour, and $1200\,\mathrm{J/m^3K}$ is the volumetric specific heat for air.

REFERENCES

Davies, M. G. (1980a). 'Useful solar gains through a southfacing window in the U.K. climate', *Building and Environment*, **15**, 253–272.
Davies, M. G. (1980b). 'Useful solar gains through a glazed southfacing wall in the U.K. climate', *Building and Environment*, **15**, 273–282.
Davies, M. G. (1982a). 'Effect of solar gain through walls and windows on annual building needs', *Int. J. Ambient Energy*, **3**, 181–186.
Davies, M. G. (1982b). 'Use of meteorological/constructional statistics to estimate building heat needs', *Building and Environment*, **17**, 263–272.
Davies, M. G. (1983). 'Building energy needs and ambient temperature and solar radiation statistics', *Building and Environment*, **18**, 39–44.
Davies, M. G. (1986a). 'The passive solar heated school in Wallasey. II. Background, preliminary analyses and patent specification', *Int j. energy res.*, **10**.
Davies, M. G. (1986b). 'The passive solar heated school in Wallasey. III. Model studies of the thermal response of a passive school building', *Int j. energy res.*, **10**.
Davies, M. G. (1986c). 'The passive solar heated school in Wallasey. IV. An observational study of the thermal response of a passive school building', *Int j. energy res.*, **10**.
Hutchinson, F. W. and Chapman, W. P. (1946). 'A rational basis for solar heating analysis', *Heating, Piping, Airconditioning*, July 1946, 109–117.
Love, J. (1968). 'Economic comparison of the solar and conventionally heated sections of St George's Secondary Modern School, Wallasey', *T.R.G. Report 1636*, H.M. Stationary Office.
Education Statistics, published annually by the Institute of Municipal Treasurers and Accountants, Buckingham Place, London SWIE 6HS, U.K.