CRANFIELD UNIVERSITY

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THE APPLICATION OF SOLAR ENERGY TO THE DESIGN OF SCHOOL BUILDINGS, AND THE DEVELOPMENT OF A MODEL OF SOLAR IRRADIANCE.

SCHOOL OF MECHANICAL ENGINEERING

PhD

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Supervisor Dr W J Batty

September 1994

ABSTRACT : THESIS PART ONE.

The thermal performances of two schools with central atria, and a typical primary school class-base, were assessed using the SERI-RES computer model. The design conclusions were that the:

(i) orientation of both buildings, with a central atrium, had little effect on their energy use;

(ii) width of the single storey atrium should not exceed seven metres, to avoid excessive heat loss in winter and summertime overheating;

(iii) main glazed vertical apertures should face within 30 degrees of south to derive benefit from significant useful solar gains in winter, and

(iv) overhangs of more than 300 mm, over southerly aspect windows, served little purpose, in terms of shading or improved daylight.

A design guide was produced, based on the results of this study, and examples of passive solar schools in the United Kingdom. The main conclusions were that, passive solar buildings need not cost more than ordinary school designs, and can result in at least a 10% reduction in energy use.

ABSTRACT : THESIS PART TWO.

To improve the modelling of sunlight and daylight, measured values of solar radiation, recorded at one minute intervals, were used to examine the relationship attributed to Lui & Jordan(1960), between the fraction of the solar radiation which is received on a horizontal surface, and the equivalent diffuse fraction, and the hypotheses that the:

(a) characteristic diurnal distribution of the fraction of the solar radiation available outside the atmosphere, which is received on a horizontal surface, (τ_{gm}) should be expressed as an exponential curve, having the form $\tau_{gm} = A.e^{-k.mr}$ in which A is a scaling coefficient, mr is the relative air mass, and k is an extinction coefficient and sensitive to the angle of incidence;

(b) clear-sky diffuse fraction might reasonably be approximated as $\tau_{dm} \approx 1 - B.mr - \tau_{gm}$, where the coefficient B is also sensitive to the angle of incidence, and

(c) relationship between the fraction of total solar radiation τ_{gm} and that received in the visible spectrum $\tau_{gm\,(vis)}$ should be linear.

The measurements did not support the relationship attributed to Lui and Jordan, but did support the hypotheses.

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(ii) Dr D Harris for providing the monitoring data on the atrium schools; Mr C. Deal of Essex County Council, and Mr M. Ogden of Perkins, Ogden & Partners respectively for providing construction data, on the two schools modelled; the respective Headmistress and staff of both schools for the detailed information provided on occupancy etc for the period studied, and the Department for Education(DFE) for directly financing the school building aspects of this study;

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(iv) The Ove Arup Foundation, the Sir Kirby Laing foundation, and Cranfield University, for their joint financial support during research into the modelling of solar radiation and daylight.

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NOTATION: ABBREVIATIONS.

A&B	Architects and buildings.
AIR	dry bulb temperature. degrees celsius.
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers.
Av	Average.
BRE	Building Research Establishment.
BRS	Building Research Station.
CIE	Committee Internationale de l'Eclairage
CLASP	Consortium of Local Authorities Special Programme.
CR	Classroom.
DES	Department of Education and Science.
DFE	Department for Education.
EEC	European Economic Communities.
GFA	Gross floor area.
HORSA	Hutted accommodation for raising the school age.
IES	Illuminating engineering Society.
IRC	Internally reflected component of daylight. %
LEA	Local education authority.
MBE	Mean bias error.
Min	Minute.
NASA	National Aeronautics & Space Administration.(USA).

NOTATION: ABREVIATIONS.

PEU	Primary Energy Unit.(allowing for generation & distribution losses).
PSAL	Permanent supplementary artificial lighting.
RAD	black globe temperature. degrees celsius.
REGS	Regulations.
RMSE	Root mean square error.
SCOLA	Second Consortium of Local Authorities.
SERI	Solar Energy Research Institute.
SVP	Solar Pre-heat of ventilation air.
TAI	International Atomic Time.
Tas©	Thermal analysis software.
TDT	Terrestrial Dynamical Time.
UK	United Kingdom.
UT	Universal Time.
UTC	Co-ordinated Universal Time.
WRC	World Radiation Centre, Davros, Switzerland.
WMO	World Meteorological Organisation.
affl	above finished floor level.
incl	including.

NOTATION: UPPER CASE.

A	total area of ceiling, floor and walls including window. m^{-2}.
AU	astronomical unit of distance, 1 AU = 1.496×10^8 km.
B	absorption:scattering coefficient.
B_s	Schuepp's turbidity coefficient.
C	monthly average fraction of the daytime sky obscured by clouds.
C_i	cloud amount.
C_w	coefficient having values dependent on an obstruction outside a window.
D	constant of 2.2 (for SI units).
D_R	ratio of daily mean diffuse irradiance to global irradiance.
D_{Rc}	ratio of daily mean diffuse irradiance to global irradiance for a clear-sky.
D_r	ratio of hourly diffuse irradiance to global horizontal irradiance.
D_{rc}	ratio of hourly diffuse irradiance to global horizontal irradiance for a clear-sky.
E	luminance of sky at angle of elevation. lux.
E_e	luminance of the sky. lux.
E_i	internal illuminance. lux.
E_t	equation of time. minutes.
E_z	luminance of the sky at the zenith. lux.
H_d	total daily diffuse irradiance.
H_g	total daily global solar irradiance.
H_{cg}	total daily clear-sky global solar irradiance.

NOTATION: UPPER CASE.

H_0 total daily solar extraterrestrial irradiance, MJ m^{-1} day^{-1}.

H_{on} total daily beam normal solar extraterrestrial irradiance

H_g total daily global horizontal solar irradiance at the surface of the Earth

I_b hourly beam solar irradiance on a horizontal surface.

I_{bc} hourly clear-sky beam solar irradiance on a horizontal surface.

I_{bn} hourly beam normal solar irradiance.

I_d hourly diffuse solar irradiance.

I_{da} hourly diffuse solar radiation due to effects of atmospheric aerosol

I_{dc} hourly clear-sky diffuse solar irradiance.

I_{dr} hourly diffuse solar radiation due to effects of Rayleigh scattering.

I_{dm} hourly diffuse solar radiation due to effects of multiple reflections between the surface and the atmosphere

I_g hourly global horizontal solar irradiance.

I_{gc} hourly clear-sky global solar irradiance.

I_0 hourly extraterrestrial irradiance on a horizontal surface.

I_{on} hourly beam normal extraterrestrial solar irradiance on a horizontal surface.

I_{sc} solar constant irradiance at the mean Sun-Earth distance

K luminous efficacy. lumens per Watt.

K_T daily mean clearness index.[H_g/H_0]

K_t hourly mean clearness index. [I_g/I_0]

NOTATION: UPPER CASE.

L_e longitude of the Sun at the Epoch. degrees.

L_{loc} longitude of the location. degrees.

L_p longitude of the Sun at perigee.

L_s longitude of the Sun on specified date. degrees.

L_{st} standard meridian for the local time zone. degrees.

N number of minutes aperture is open per hour.

N_h number of hours in a solar day.

N_s maximum possible number of sunshine hours.

Q_{unu} unuseful portion of heat loss. W m^{-2}.

R resistance. ohms.

R_a atmospheric refraction. degrees.

R_{av} average reflectance of ceiling floor and walls, including window. fraction.

R_{fw} average reflectance of the floor and those parts of the walls, excluding the window wall, below the mid height of the window.

R_{cw} average reflectance of the ceiling and those parts of the walls, excluding the window wall, above the mid height of the window.

SC sky component of daylight factor.

T_{bg} black globe temperature. degrees celsius.

T_{dp} dew point temperature. degrees celsius.

T_{dry} dry bulb temperature. degrees celsius.

T_{Env} Environmental temperature. degrees celsius.

NOTATION: UPPER CASE.

T_L Linke turbidity factor.

T_{rad} mean radiant temperature. degrees celsius.

T_{res} resultant temperature. degrees celsius.

T_{sol} solar time.

Vis_{km} visibility in the direction of the horizon. kilometres.

NOTATION: Lower case.

a_0 coefficient: Hottel clear-sky.

a_1 coefficient: Hottel clear-sky.

a_0^* atmospheric constant: Hottel clear-sky.

a_1^* atmospheric constant: Hottel clear-sky.

a coefficient(value defined).

b coefficient(value defined).

c coefficient(value defined).

cf_0 climate type correction factor: Hottel clear-sky.

cf_1 climate type correction factor: Hottel clear-sky.

cf_k climate type correction factor: Hottel clear-sky.

cm centimetre.(one hundredth of a metre).

d_{TDT} day number and fraction of day.(terrestrial dynamical time).

d_{UT} day number and fraction of day.(universal time).

d_{UTC} day number and fraction of day.(co-ordinated universal time).

e 2.71828

e_s eccentricity of orbit of Sun.

f_h elevation correction factor.

$f_{(mr)}$ spectrally integrated function of relative air mass.

h height of station above sea level. metres.

h_{km} height of station above sea level. kilometres.

NOTATION: Lower case.

h_0	height of homogeneous atmosphere. kilometres.
k	extinction coefficient.
k_a	integral optical thickness of atmosphere.
k*	atmospheric constant: Hottel clear-sky.
k_R	integral optical thickness of clean dry air.
km	kilometre. (1,000 metres).
ly	langley. cal cm^{-2} min^{-1}.(1 ly = 4.184 x 10^4 J m^{-2} s^{-1}).
m	metre.
m_a	optical path length (depletion by aerosols)
m_o	optical path length for ozone depletion
m_r	optical path length(air mass) relative to that at the zenith
mm	millimetre.(one thousandth of a metre).
n	number of readings.
nc	number of cloud layers observed.
n_d	day of the year. 1 <= n <= 365, Jan 1st = 1.
n_o	refractive index of air at ground level.
n_s	recorded number of sunshine hours.
p	atmospheric pressure at the site of interest. mbar.
p_o	atmosheric density at ground level kg/m^3.
p_r	ratio of station pressure to standard pressure at mean sea level. non dimensional.

NOTATION: Lower case.

r	length of radius. mm.
r_a	actual Sun-Earth distance
$r_{d1,d2}$	Sun-Earth distance for day 1, day 2.
r_e	mean radius of the Earth, km.
r_0	Mean Sun-Earth distance, 1 AU.
v	air velocity. $m\ s^{-1}$.
v_s	true anomaly: solar position. degrees.
w	precipitable water. centimetres (water equivalent).
z_0	height of homogeneous atmosphere of density p_0 (8.4 kilometres).

GREEK NOTATION.

α wavelength exponent : Ångstrom turbidity eqn.

α_b absorption of direct beam solar radiation.

α_d absorption of diffuse solar radiation.

$\alpha\rho$ product of absorption, scattering coefficients.

α_o absorption of solar radiation by ozone.

α_w absorption of solar radiation by water-vapour.

β acrosol content coefficient : Ångstrom turbidity cqn.

Γ day ∠ of Sun. degrees.

γ angular elevation above horizontal.

γ_{obs} observed angular elevation above horizontal.

δ declination of plane of equator : ecliptic plane.

θ_z angular distance zenith.

$\theta_{z\,obs}$ observed angular distance zenith.

λ wavelength.

μm micrometre (one millionth of a metre).

ρ scattering reflection coefficient.

ρ_o reflection of surface reflected solar radiation.

ρ_g reflection of solar radiation (ground albedo).

π 3.14159

τ_a transmittance of radiation allowing for aerosol.

τ_b transmittance: beam radiation.

τ_c transmittance: cloud field.

τ_d transmittance: diffuse radiation.

τ_{dm} transmittance: diffuse radiation (function of air mass)

τ_g transmittance: global radiation.

τ_{gas} transmittance of solar radiation by a mixed gas.

τ_{gm} transmittance: global radiation (function of air mass).

$\tau_{i(c)}$ transmittance of individual cloud.

τ_o transmittance of radiation through ozone.

τ_r transmittance of radiation (Rayleigh scattering).

τ_w transmittance of radiation (absorption by water vapour).

ϕ latitude. degrees.

ω hour ∠. degrees.

1.0 GENERAL INTRODUCTION: THE ORDER OF THE THESIS.

1.1 The thesis is arranged in two main parts. The first relates to an earlier research project sponsored by the Department for Education, which involved a survey to identify passive solar schools(Hobday & Norton 1989), and the monitoring of six schools for several months over a period of two years(Harris 1991). Two of the monitored schools with central atria were selected for the present study, which used monitored data and computer simulation to assess their thermal performance. The computer simulations also allowed a study of the effects of varying the physical dimensions of the atria in proportion to the attatched buildings. A notional class-base to present day standards was also used to assess the environmental performance of a typical teaching space in relation to sunshine, daylight, electric lighting use, overheating, heat loss, and electric loads.

1.2 A design guide, in the form of a building bulletin of the Department for Education, was commissioned as part of this study, to provide design and teaching professionals with the results of the present study, together with general information, advice, and some selected case studies of passive solar school buildings. Work on this has been undertaken, with some assistance from others. The results of the cost and energy appraisal of the case studies are given in chapter nine, and a sample of some of the building case studies analysed in the bulletin is included as appendix E. The completed draft bulletin has been peer reviewed, and subsequently approved by the Secretary of State for Education for publication by HMSO later in 1994.

1.3 The weather files, required to model the performance of the monitored schools, were to have been prepared from empirical data collected during an earlier stage of the research project. Problems were identified with the instruments used to measure the diffuse component of solar radiation, and existing, statistical procedures were used to estimate this component from the measured global solar radiation. In researching existing procedures, it was apparent that the modelling of the components of solar radiation warranted more detailed examination. This was undertaken, with new instrumentation, allowing data retrieval at one minute intervals,and is presented as part two of the thesis.

2.0 INTRODUCTION TO PART ONE: THE SCHOOL BUILDING STUDY.

2.1 The character of teaching spaces in schools, reflect ideas about the curriculum, educational practice, architecture, building construction and regulation. For most of the period from the late nineteenth century there have been significant changes. A noticeable trend has been that, as the 20th Century progressed, new schools built in the United Kingdom admitted more daylight and sunlight directly to the teaching spaces than earlier examples. This peaked in the late 1970's, and the trend has either remained static, or reversed during the last decade. School buildings designed during the period from the mid 1940's to the late 1970's reflect the imposition of mandatory minimum standards and a preferred target level of daylight in teaching areas. Most of these buildings have predominantly glazed facades. Those of the 1950's and 1960's were mainly built of a relatively lightweight, flat-roofed, form of construction, typical of the immediate post-war period. The requirement was for low initial cost and a rapid method of building to deal with an expansion of basic needs, at a time of a general shortage of materials, finance and craft skills. This was also a time of relatively low energy costs, and with some significant exceptions, little thought was given to thermal performance, climate modification, or comfort. Consequently, most of the school buildings of the 1950's and 1960's tended to be thermally inefficient, being subject to substantial heat losses during the heating season, and excessive overheating and glare from solar gain at other periods.

2.2 After the international oil crises of the 1970's, energy conservation was considered to be a more important design factor. This was reflected in the methods of construction, and regulation. The previously mandatory minimum standard for daylight in teaching areas was relaxed to permit smaller windows and supplementary electric lighting as a means of fulfilling the required standard of illuminance on the working plane. It was assumed that this would be more energy efficient. A design note(DES 1979) was issued, which set targets and performance requirements for environmental design and fuel conservation in education buildings. Although a version of this is still current(DES 1981b), the standards are somewhat out of date, and have recently been reviewed with a view to amendment. Four criticisms of the DN17 guidelines are that: the beneficial effect of a passive solar design approach was not considered; the requirement for fresh air lacked credibility; the dynamic performance of buildings was not assessed, and the DN17 design procedures force the provision of low aspect ratio buildings, which tend to be deep planned, reducing the interaction between the interior, and the external spaces and environment.

2.3 Today, many school buildings are better insulated, and have more moderate space heating demands. However, their environmental performance, during the rest of the school year, is often poor. Nationally, electric lighting and small power loads have shown a disproportionate increase in real terms, bearing in mind that the number of school places is much reduced(DES 1992). In contrast, a good passive solar design aims to provide thermally efficient buildings, in which internal spaces have ample daylight, take advantage of available useful solar gains, and avoid overheating. The first passive solar school in the United Kingdom was St George's,(later renamed St Mary's) and was built in 1961 at Wallasey. It was designed, by A.E. Morgan, to relatively good insulation standards for the time, and featured a large, southerly aspect, glazed solar collector wall. This school demonstrated the potential of such a climate responsive design, and that solar energy might be a viable, renewable, and clean energy option for school buildings. However, although space heating demand was met by solar and internal gains, from occupancy and electric lighting, the air quality was judged to be poor, and glare was considered to be a problem.(Crisp et al 1988) It is also doubtful whether the organisation of the teaching spaces would satisfy the requirements of current educational practice. Passive solar school buildings are not commonplace in the United Kingdom. However, many commercial buildings have sun-spaces and other features, associated with passive solar design, and the popularity of these solutions, and their aesthetic appeal to designers, has now led to them being used in school design. It could be argued, that with improved insulation standards, there is a risk of discomfort from the use of such features, an insignificant benefit in terms of energy consumption, and unjustifiable additional capital costs might be incurred if a passive solar school design option was promoted. The DES commissioned the Department of Applied Energy of Cranfield University to undertake a survey of passive solar schools in the United Kingdom (Hobday & Norton 1989). A steering committee selected six schools for detailed monitoring(Harris 1991).

2.4 The present study was commissioned by the DFE to:

(i) assess the performance of the two monitored schools with central atria;

(ii) carry out some parametric analysis to establish design principles concerning the size, orientation, glazing specification, and heating of a central atrium at a primary school;

(iii) undertake an assessment of the environmental performance of a typical class-base in relation to glazed areas, daylight, electric lighting, heat loss, overheating, and

(iv) prepare a building bulletin to explain and illustrate the principles and features of passive solar design, and present these results, together with a review and assessment of selected case-studies of passive solar school buildings.

3.0 BACKGROUND.

A brief outline of the development of provision for State education in the United Kingdom.

3.1 The provision for State education has undergone significant changes and development since the late nineteenth century. The main public provision for schooling, following the 1870 Education Act of Forster, was with Education Boards, County, Borough, and Urban District Councils. By the turn of the century, this organisation was regarded as a muddle(Webb 1901). The 1902 Education Act of Morant imposed a coherent framework, leading from elementary schools to university, by way of a scholarship system, and created a decentralised system of local education authorities (LEA's) to administer and oversee schooling. Following this, Morant published his code for public elementary and secondary schools. (Board Edn 1904). This incorporated a new concept and philosophy of teaching. There was some conflict between the purely academic goals of a secondary education modelled on the 'public school system', and the national and individual need for the development of artistic, practical, technical, and craft skills, as well as the attainment of appropriate academic knowledge. Fisher's Education Bill sought to remove part time education, and greatly increase the general education of the majority of the population. It reached the statute book in 1918, but apart from strengthening the powers of the education authorities, very little of the provisions of the Act were ever implemented.

3.2 During the years of the second world war, there was pressure to change the system. A white paper(Board Edn 1943) set out the Government view on education reconstruction, and what should be done about reforms. The keynote of the new system was to be a 'child centred education', in which all pupils would, as far as possible, receive the type of education, which best suited their individual needs. Butler's Education Act of 1944 created a Ministry of Education, introduced the primary school idea of Hadow (Hadow 1926), and the need for nursery and special schools. Although it was vague about secondary education, the 1944 Act was clear about a three tier education system comprising primary, secondary and further education. There have been subsequent changes affecting: the school leaving age; the selection for, and nature of secondary schools, and also the type of further education provision. This three tier structure of education, with transfer to secondary school at the age of twelve, is still the predominant system for state education in the UK. The primary schools catered for children from five to eleven years of age. They were often sub-divided into infant schools for the children from five to seven years of age, and junior schools for pupils aged eight to eleven years. This subdivision was to provide a more appropriate, and sheltered learning environment for the younger children, even when both schools were accommodated on the same site. At first, all pupils entering secondary education were tested during their eleventh year of age by an examination for admission to grammar schools, secondary modern, or technical schools. To overcome the shortcomings of this selection(Lowe 1989), and fulfil the original aims of the war time white paper(Board Edn 1943), comprehensive secondary schools were introduced gradually from 1950. Despite selection anomalies reported in the White paper(Min Ed 1958), and the good GCE results by secondary modern schools.(TES 1961), selection at eleven plus was largely unchanged, until the government request for LEA's to submit plans to reorganise schools along comprehensive lines(DES 1965). This invitation introduced the option of a four tier system comprising first, middle, and high schools for statutory provision, plus sixth form, tertiary or further education colleges for young adults. It was argued that, the middle schools, permitted by the 1964 Act(Min Ed 1964), were more appropriate for the development of pupils between the ages of either eight to twelve years, or nine to thirteen years, as they provided a better transition from the early, less formal, years of primary schooling to the formal, subject-based, teaching of secondary schools. The resultant first schools were considered to be more appropriate for the younger primary school children. The high schools for pupils from thirteen or fourteen years of age, could be smaller than would otherwise be the case, which was considered to be better for older pupils. The middle schools were allocated minimal specialist facilities, compared with normal secondary school provision, and were a low cost option. Within the decade, most 9-13 middle schools were judged to be underachieving.(DES 1983)

3.3 The Plowden report (Plowden 1967), had a big impact in shaping education policy, and school designs for children of primary school age. It was the first study to focus on the educational and social needs of children of this age group, since Hadow coined the phrase 'primary', (Hadow 1926), and reaffirmed it(Hadow 1931). Plowden also covered the relationships between the home, neighbourhood and school, and with other schools within the education system. The Education Act of 1979 removed the requirement for LEA's to submit plans for reorganising their secondary schools along comprehensive lines. A National curriculum was introduced for all schools under the Education Reform Act of 1988(DES 1988), in which measures were also introduced to give individual schools more autonomy in how they were run, and responsibility for their own budgets.

Illustrated outline of some aspects of the development of school buildings in the UK.

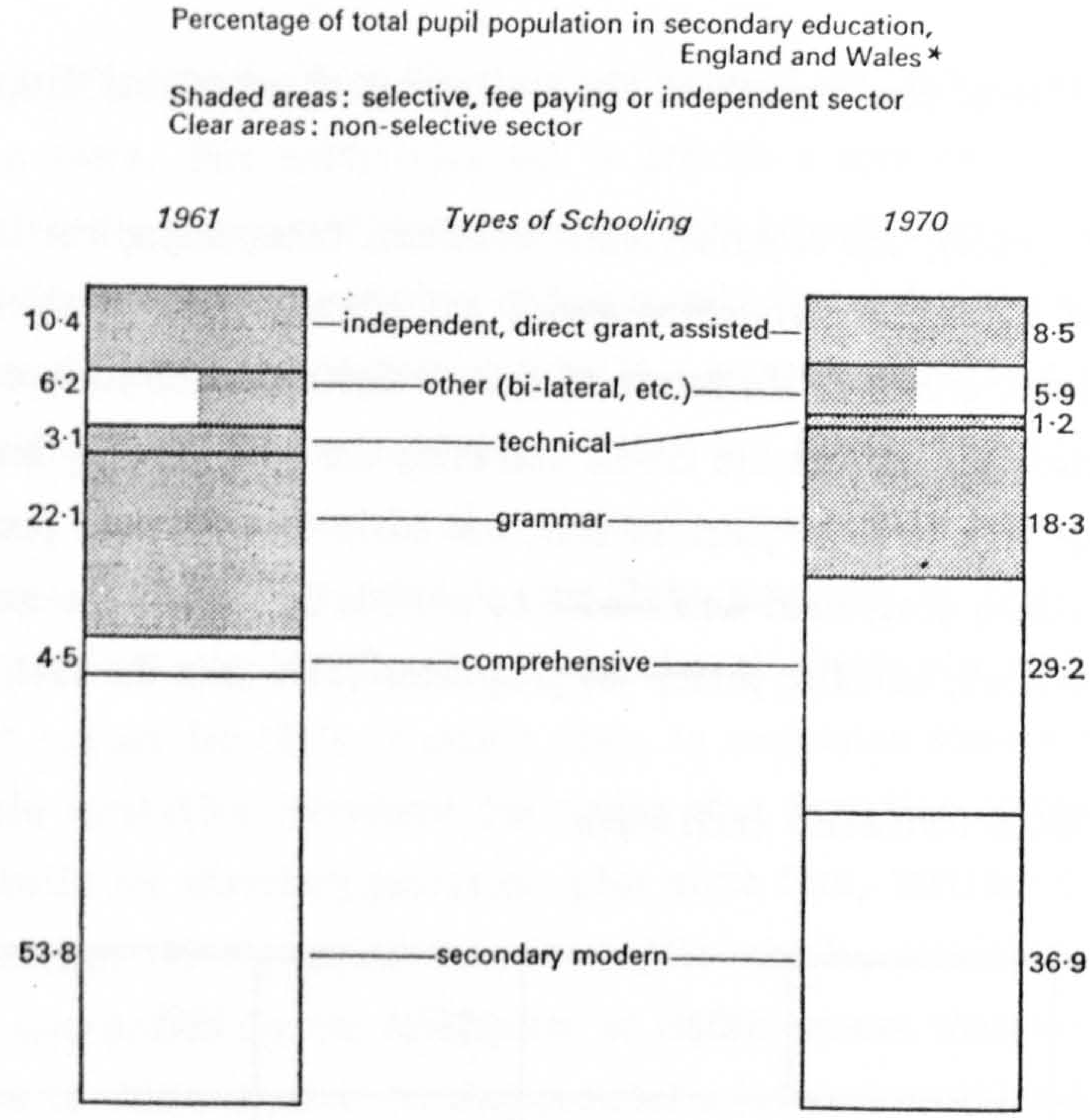
3.4 These political, policy, and organisational decisions, taken during the last one hundred years, were made in the context of developing social and educational aspirations. They were accompanied by a significant growth in the nature of the provision for statutory education, and a changing school population from demographic trends including the post-war baby boom, the raising of the school leaving age from 14 to 15 years in 1947, and again from 15 to 16 years in 1972, and curriculum changes. Building programmes were needed to provide for this. The most far reaching changes in education provision, building policy and programmes ,flow from the 1944 Eduction Act of Butler.

TABLE 3.1 MAINTAINED SCHOOLS POPULATION (millions)

TYPE	1895	1938	1947	1965	1981
Board	2.4	-	-	-	-
Voluntary	1.9	-	-	-	-
Elementary	-	5.2	-	-	-
Primary	-	-		5.0	4.1
Secondary	-	0.4(a)		3.2	4.4
TOTAL	4.3(a)	5.6(b)	5.0(c)	8.2(d)	8.5(e)

Sources: a(Batho 1989), b(MinEd 1957), c(MinEd 1948), d(DES 1966), e(DES 1982)

3.5 Overall population numbers often concealed significant changes. For example, although there were fewer children just after the second world war than immediately before it, there was a substantial increase in the birth rate during the years 1942 to 1948. From 1947 to the 1960's this was represented by a bulge in certain age groups in the school population, with attendant accommodation need. Building work was also required whenever the school leaving age was raised, or the age range of pupils, and distribution and type of school was changed. For example, when comprehensive schools were introduced, they required more specialist facilities for a wider curriculum, than either the grammar or secondary modern schools provided.



*1961 figures from p. 124, *Social Trends*, HMSO, 1970; 1970 figures from vol. 1, p. 2, DES *Statistics*, 1970.

Figure 3.1 Secondary Education 1961-1970 (Benn & Simon 1970).

3.6 From the late nineteenth century to date, the character of schools, classrooms and other teaching spaces has altered to reflect these political decisions, and changes in educational philosophy, curriculum, and teaching practice. Architecture, health considerations, cost, and building regulation or construction techniques, have also had a direct influence. It was recognised, from the earliest arrangements made to provide for the State education of children in the UK that, ample daylight, and sufficient fresh air, were essential pre-requisites for the attainment of conditions, which were conducive to learning and good health. The Board schools of the nineteenth century, invariably had high ceilings and large windows, but whilst these designs did produce levels of natural illumination, which were better than the norm for other buildings of the time, they were not particularly good. The windows were not designed to provide a view, or good and controllable, levels of natural ventilation, since the cills were usually above head height, and opening lights were often very small. The early Board schools were also poorly heated, and were considered to be to 'poor law standard'. In the late nineteenth century, some school buildings were therefore designed to take advantage of north light, in order to provide a high level of glare-free daylight in the classroom, and avoid the problems of overheating due to direct sunlight.

A late 19th century northlight school.

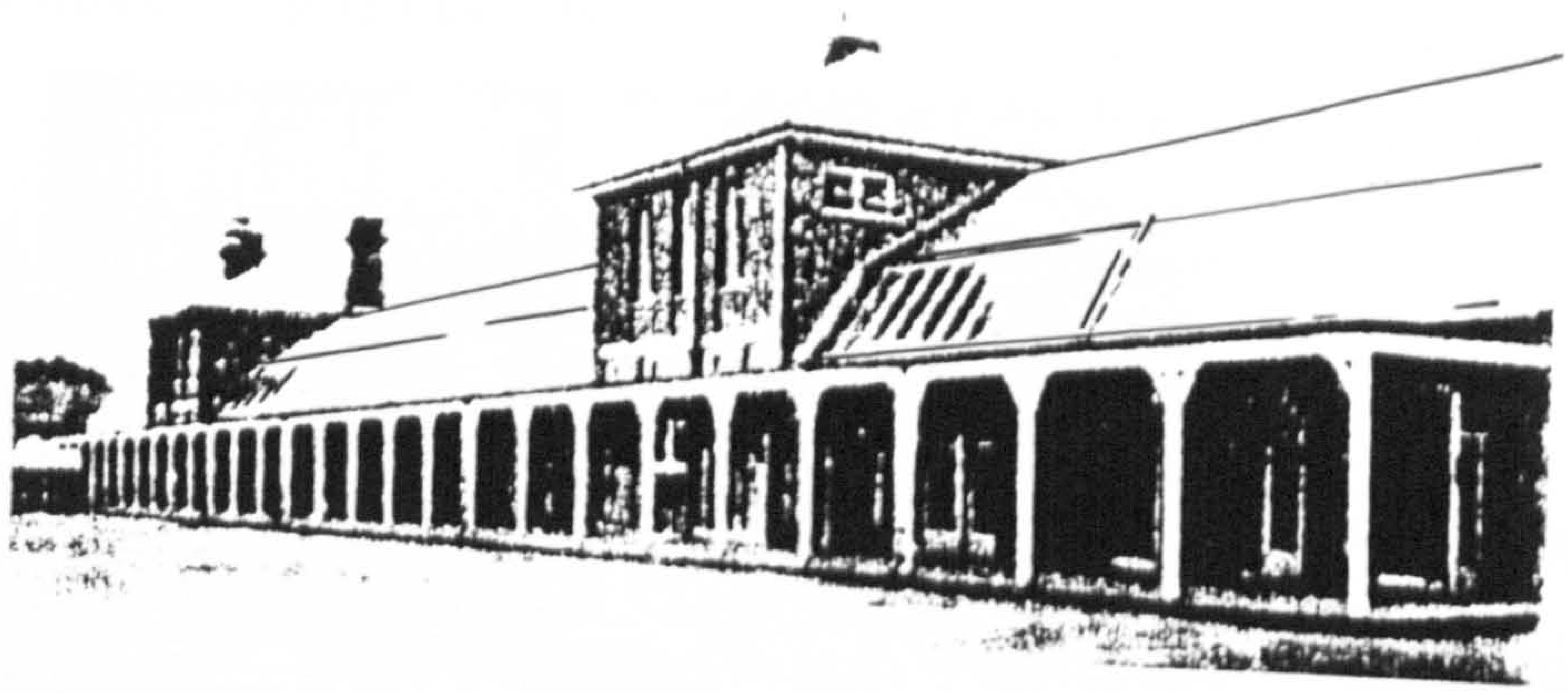


Plate 3.1 Exterior

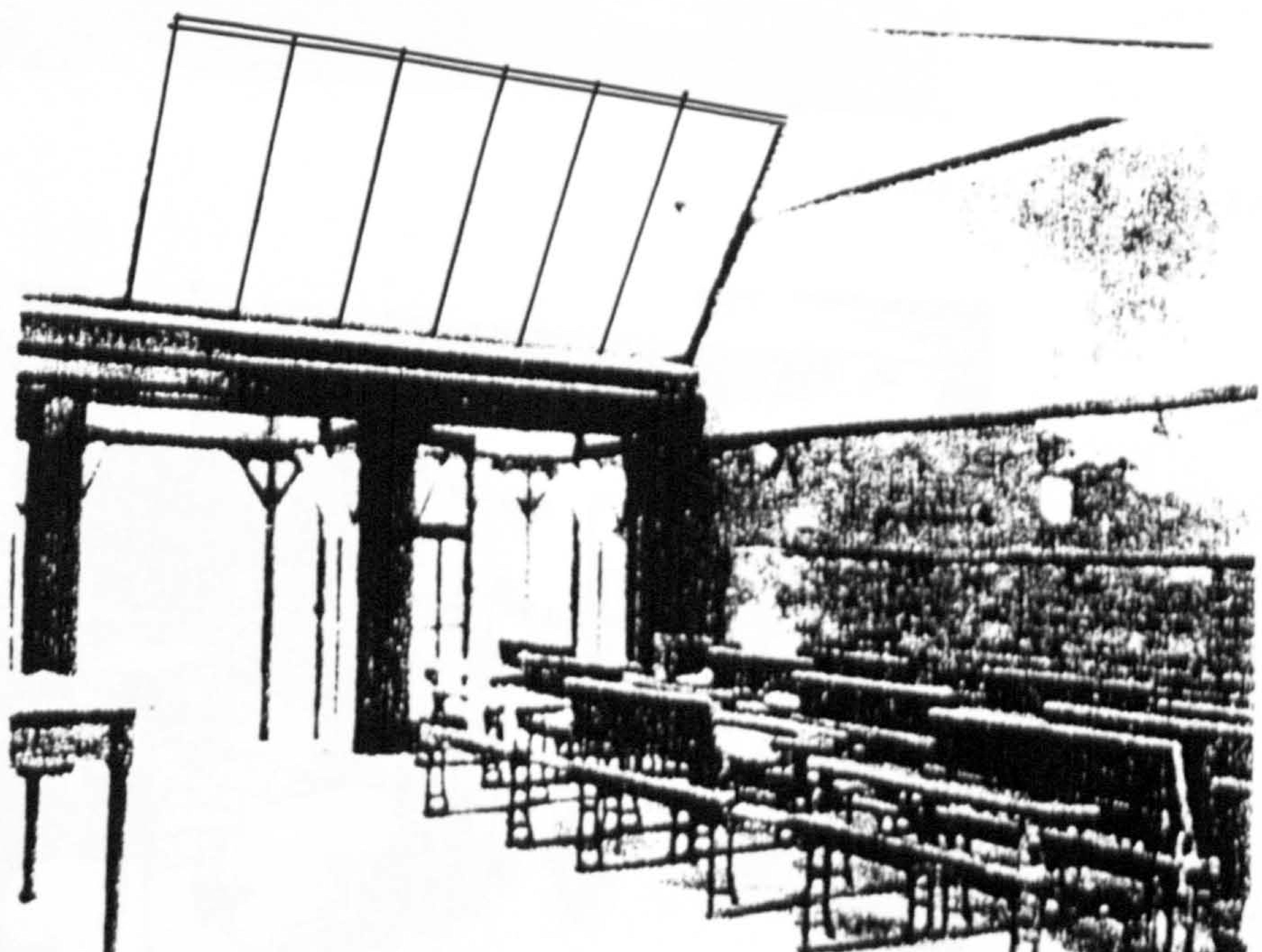


Plate 3.2 Interior

3.7 However, from the turn of the century to the 1930's, there was also an increased emphasis on the importance of direct sunlight, daylight and fresh air, for the health and well being of children. This led to the introduction of 'open air' schools, as a means of combatting disease, particularly for frail children with respiratory problems, and to minimise the risk of tuberculosis. These schools were often orientated to have a southerly, east or west aspect to teaching spaces, and classroom windows were designed as sliding/folding features, which enabled the external wall to be opened fully, or at least a significant proportion of it, to admit sunshine and fresh air into the classroom for part of the school day.

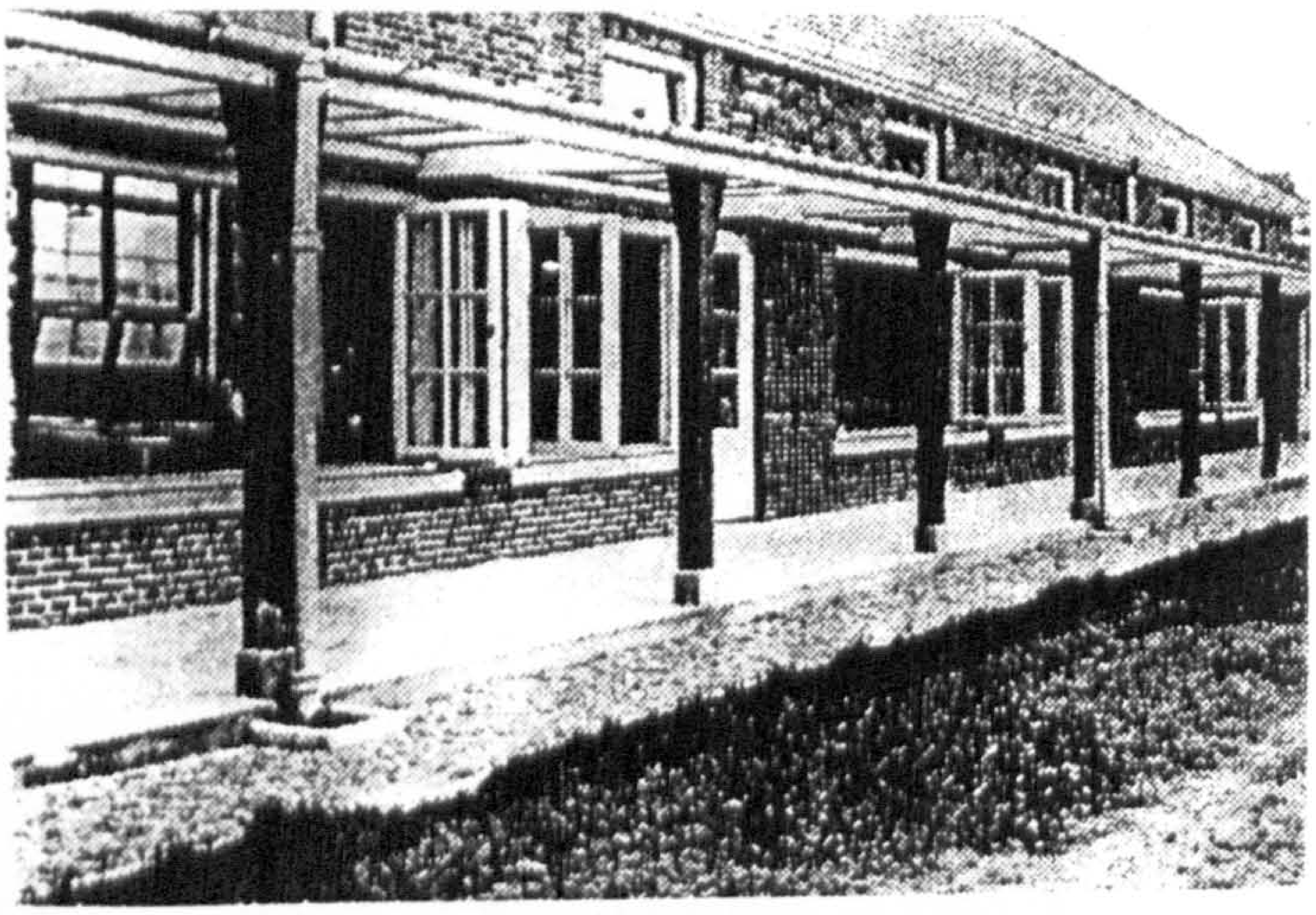


Plate 3.3 Open air school.

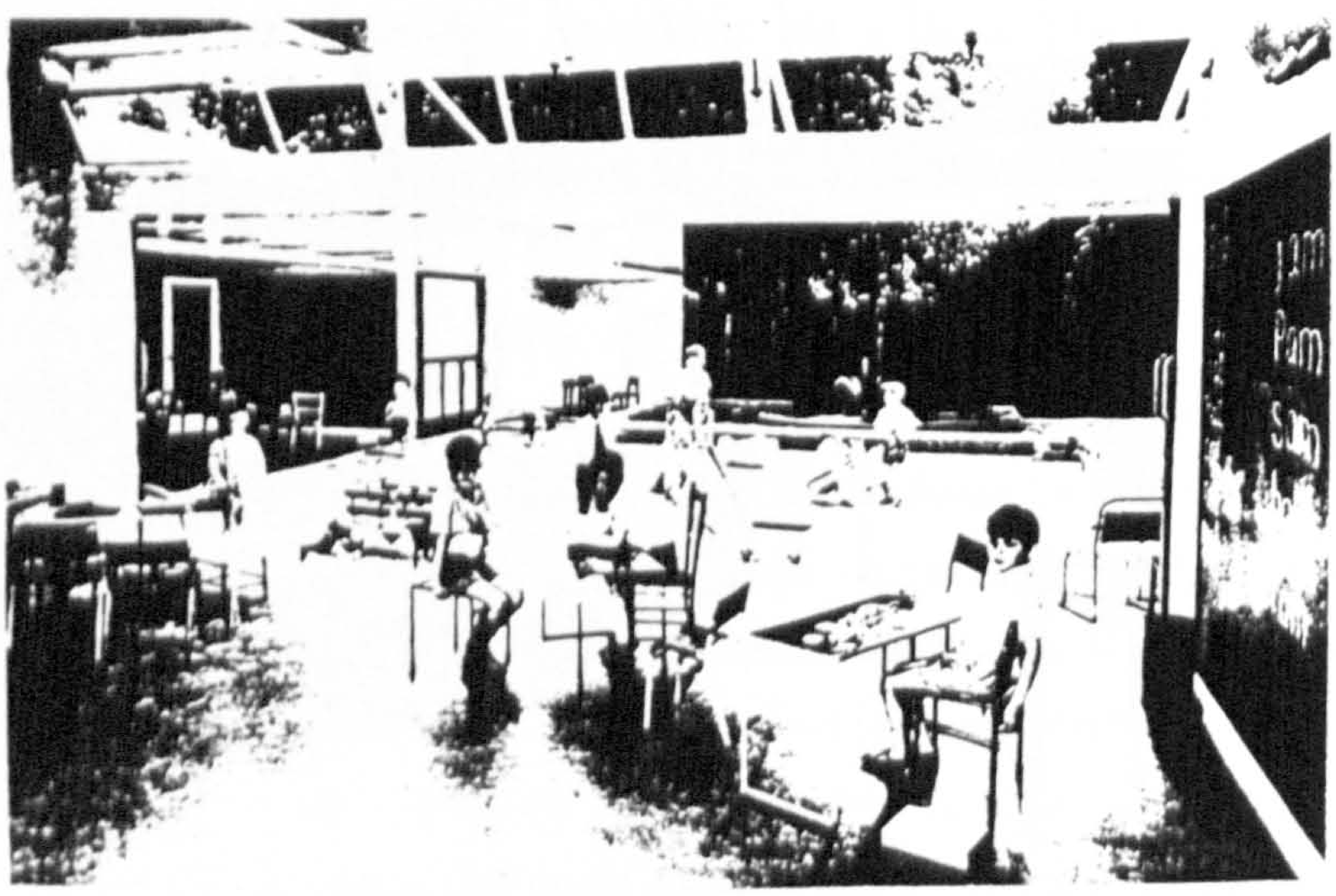


Plate 3.4 Open air school.

3.8 Teaching methods in the classroom did not change much prior to the 1944 Act. Plates 3.5 to 3.7 illustrate this from photographs taken of the interiors of some classrooms for younger children.(source Min ED 1957)

Plate 3.5 circa 1900

Plate 3.6 1928

Plate 3.7 early 1940's

3.9 Plates 3.8 to 3.9 illustrate an example of a type of school hall provided in 1880 and in the 1930's.(Min Ed 1957)

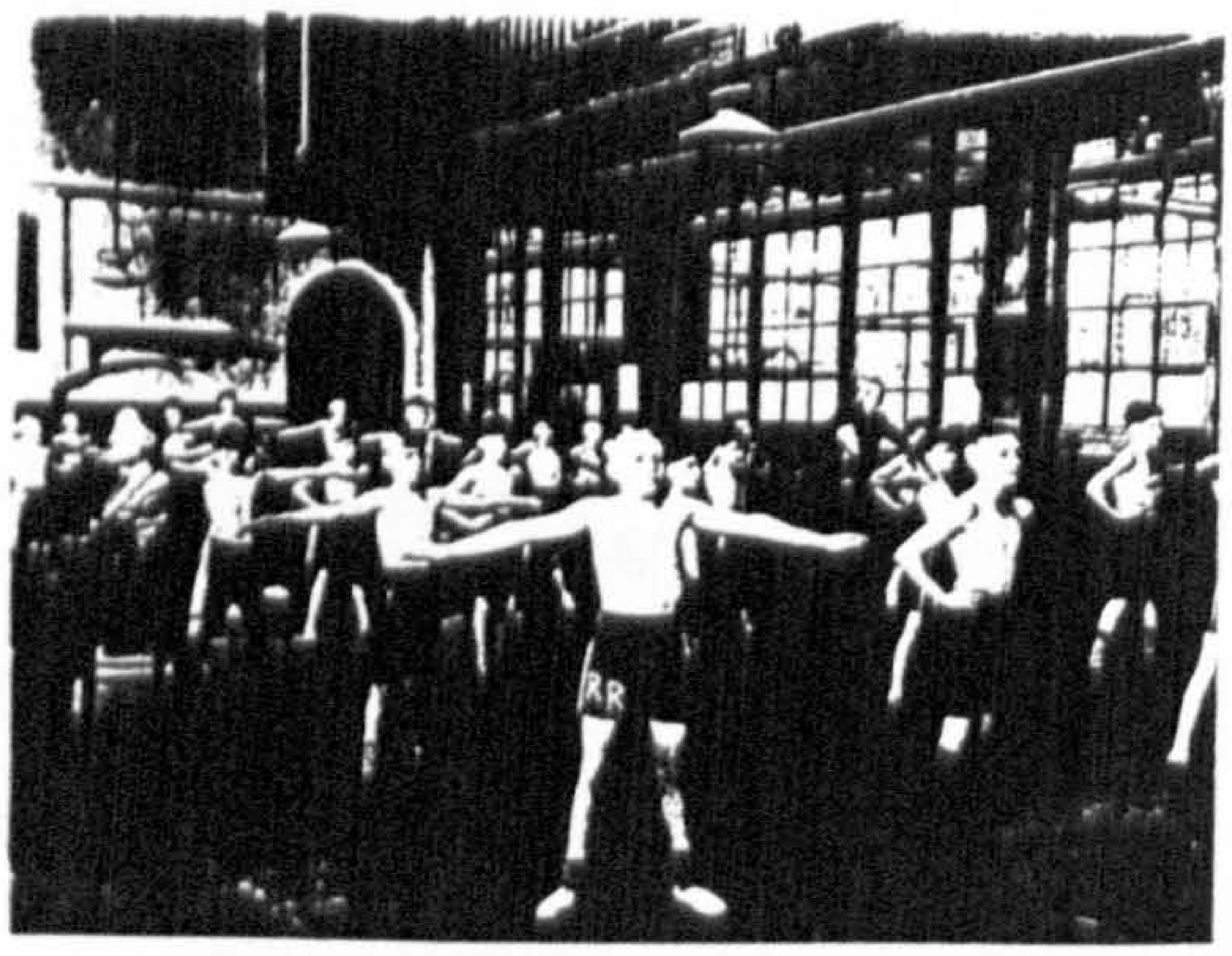


Plate 3.8 1880

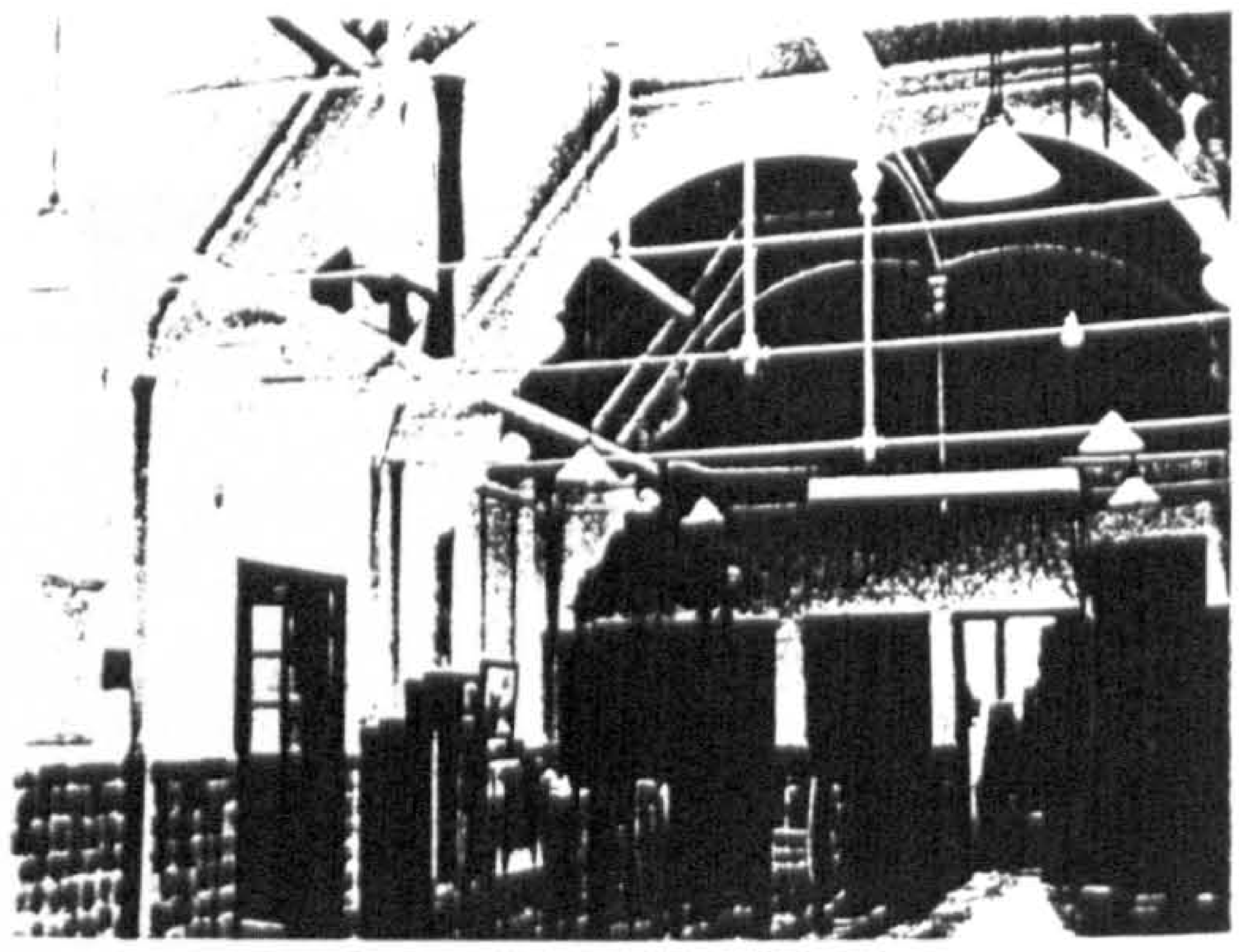


Plate 3.9 1930's

3.10 Prior to the 1940's, the number of toilets provided for pupils was usually adequate, but the accommodation provided was often very basic, and usually housed in unheated outbuildings with poorly designed fittings.

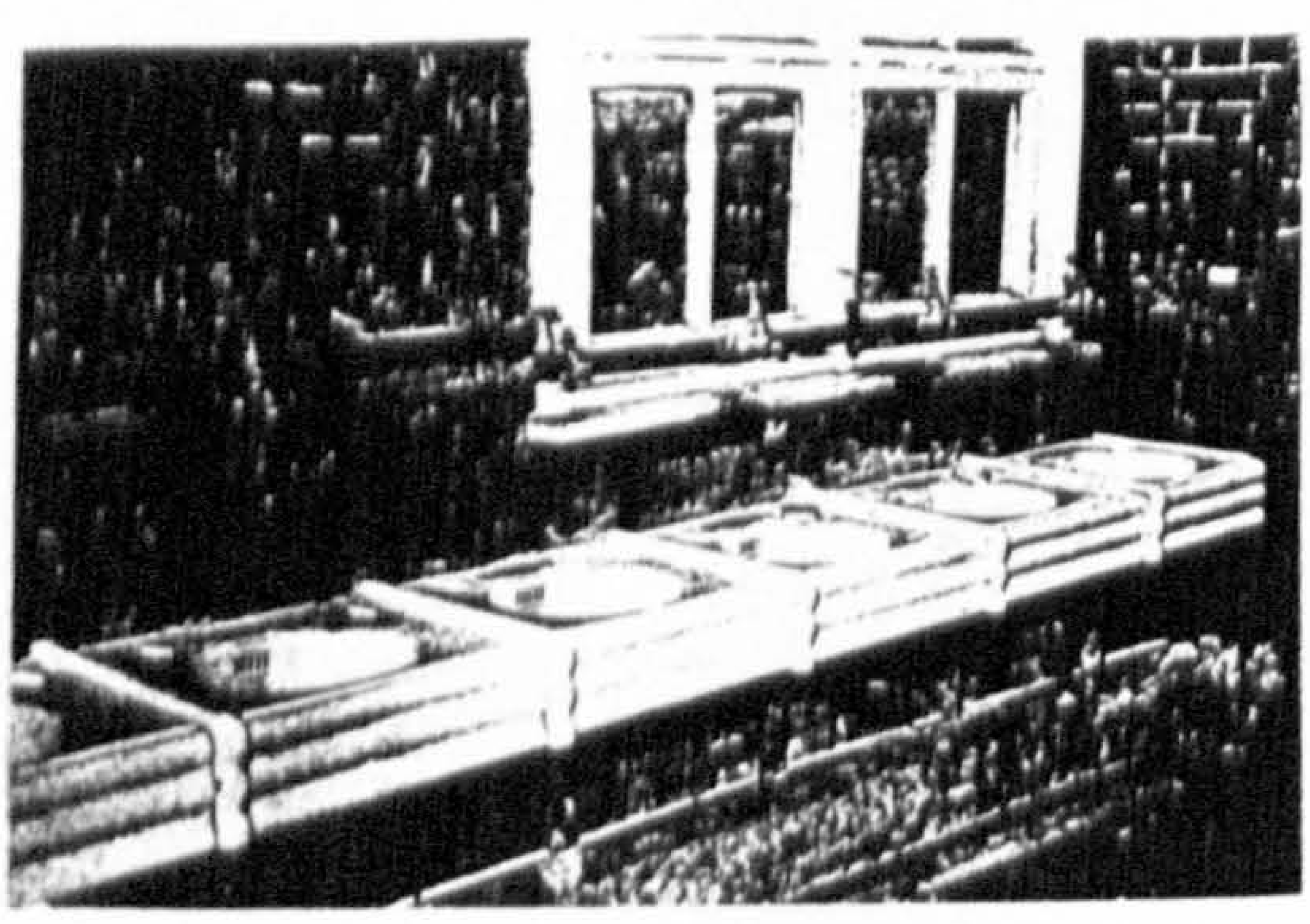


Plate 3.10 circa 1870

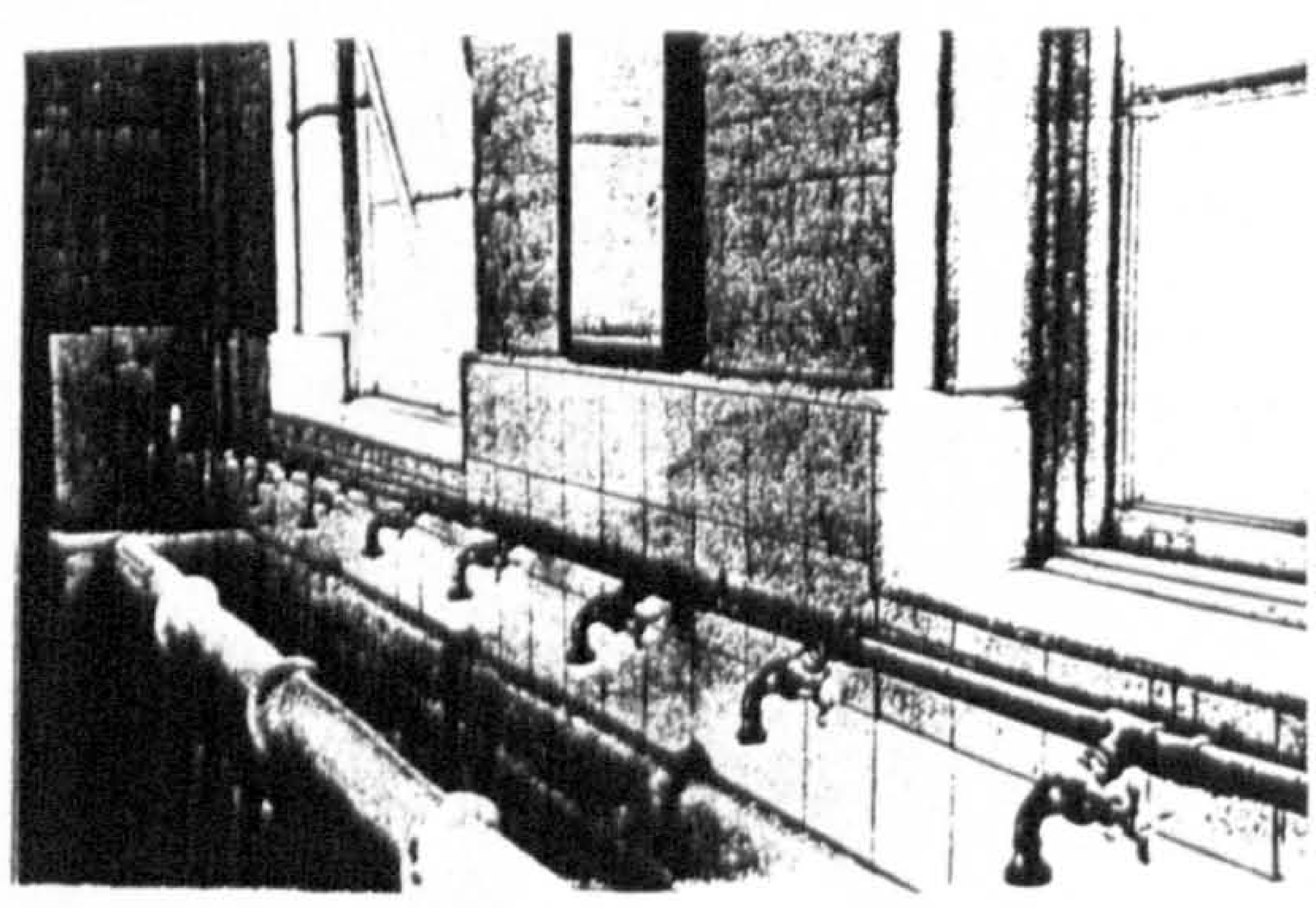


Plate 3.11 1927

3.11 Plates 3.12 and 3.13 illustrate the difference, in style and fenestration, between an example of a 'Board school' and a school from the 1930's(Min Ed 1957).

Plate 3.12 circa 1900

Plate 3.13 mid 1930's

3.12 Before the 1940's, school plans were often of one room depth, with either external covered ways or lengthy enclosed corridors to provide access to classrooms. This plan form is often referred to as 'finger plan'. Most general teaching activity was confined to the continual use of a classroom. A well known secondary school of the 1930's was the Village College at Impington near Cambridge. It was designed by the internationally famous architects, Walter Gropius and Maxwell Fry for Henry Morris, the equally well known educator of the time.

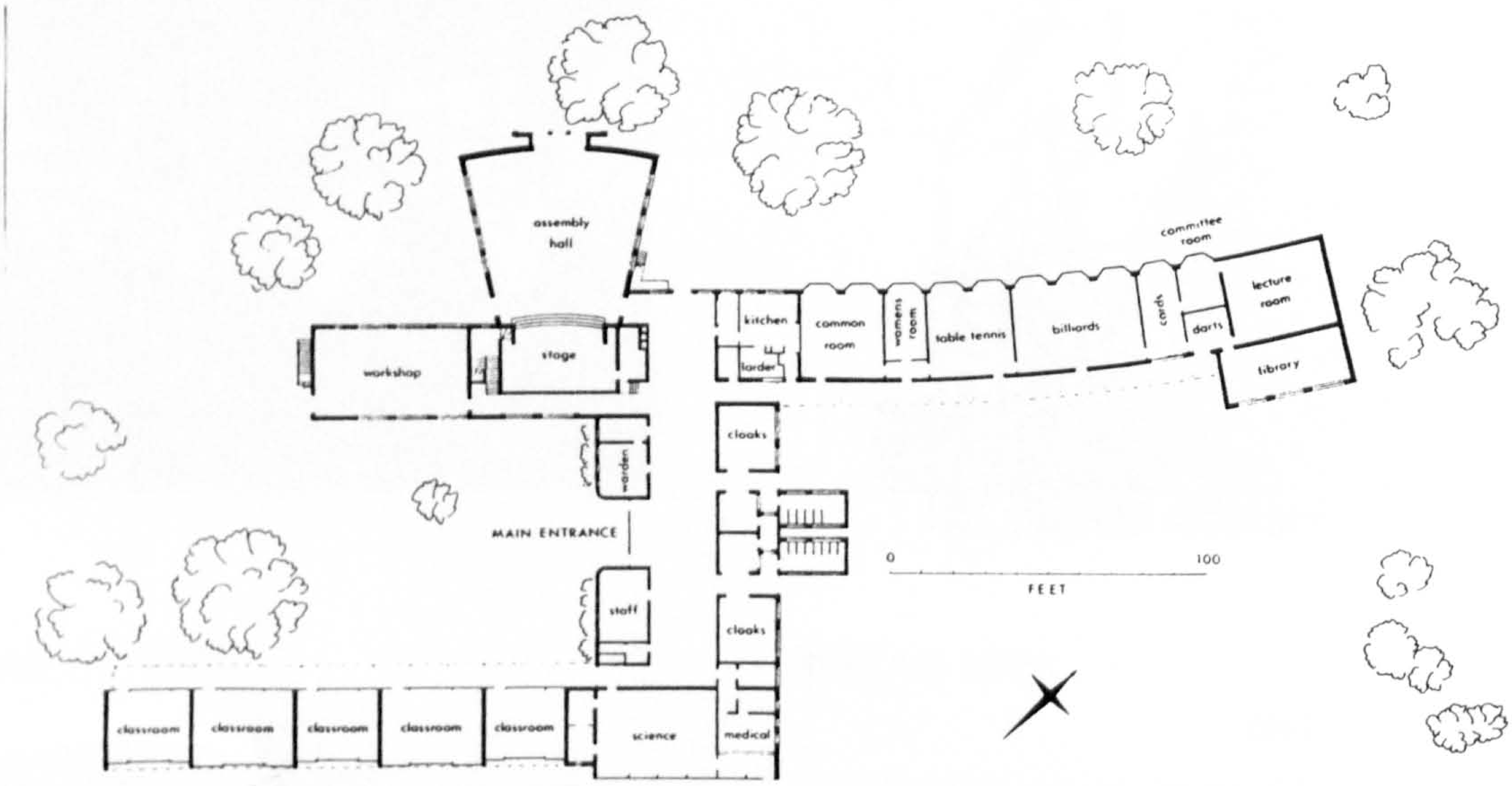


Figure 3.2 Impington Village College. 1938-1940.

3.13 Prior to the passing of the 1944 Act, doctors and educators were concerned about the poor vision of children of the inter-war years. Following the 1944 Act, a development group was established within the Ministry of Education, which issued circulars, premises regulations, and memoranda to LEA's. Building regulations for public elementary schools and secondary schools had been issued in 1914, but they were not statutory. Their intention was to provide guidance and general principles for school planning, and examples of the best current practice. The regulations for elementary schools were withdrawn in 1926, and both sets of regulation were superseded by handbooks of suggested practice(Board Edn 1931, 1936).

3.14 Section 10 of the 1944 Act, required the Minister to prescribe, by regulation, the standards for primary and secondary school premises. A set of draft standards was published(Circ.10. 1944), which was formally adopted as a statutory instrument on 1st April 1945 (Min Ed 1945a), and was usually referred to as the building regulations. These were novel, because they were statutory, and prescribed minimum standards to be achieved, not the maximum.

3.15 The 1945 regulations introduced a new standard governing the level of natural illuminance to be achieved in schools. This re-emphasised the earlier perceived importance of admitting sunlight directly to the classroom. Prior to this, the recommendation had been one half of one per cent of the luminance of an unobstructed sky. The new minimum value specified was a daylight factor of two per cent, but it would be more correct to call this mandatory requirement a 'sky factor', since the illuminance specified was to be the percentage of the sky luminance directly visible from the working plane within a classroom. The new standard did not include for the contribution to the illuminance on the working plane from reflected daylight. An accompanying memorandum recommended that a 'higher figure of up to five per cent should if possible be secured, eg. in rooms where clerestory lighting or top lighting can be arranged'.(Min Ed 1945b)

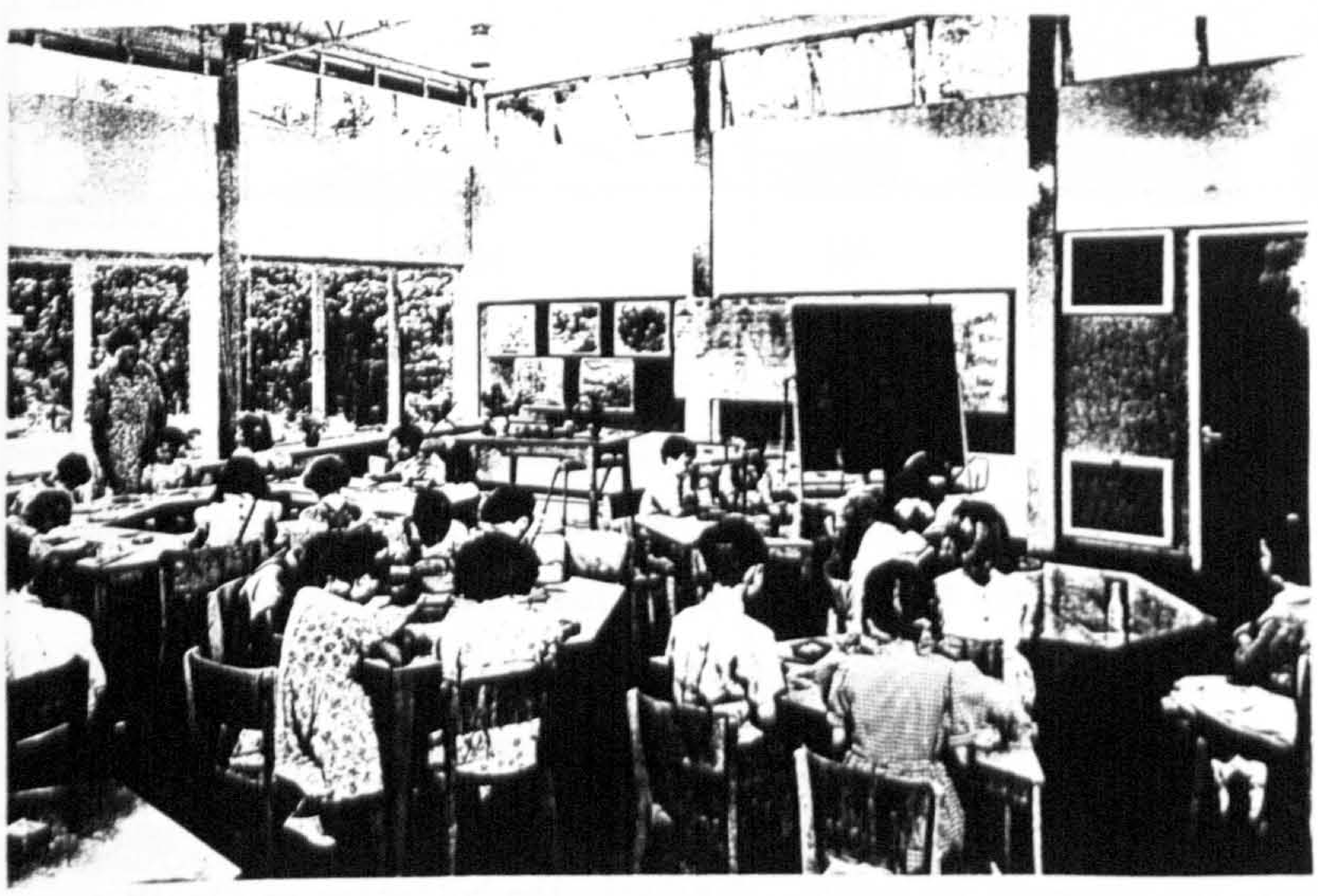


Plate 3.14 Monkfrith school, East Barnet. 1949-1950. The 1945 standard of daylight.

3.16 Collaborative work was undertaken between scientists of the Building Research Station (BRS), and the architects at Hertfordshire County Council, which demonstrated that, when the reflected component was taken into account, both the 1945 minimum, and recommended standards were found to be rather exaggerated. Medical evidence had also indicated that the onset of myopia in children had little to do with levels of daylight in schools,(Saint 1987) and the Ministry of Education's mandatory minimum 'sky factor' for daylight was therefore effectively reduced in 1951, by the inclusion of a component for reflected light, thereby changing to a mandatory minimum 'daylight factor' of two per cent (Min Ed 1951a) rather than the earlier 'sky factor'.

Plate 3.15 A 1954 school.

3.17 The development group's activities for specific LEA's also stimulated innovative methods for the planning, design, and construction of school buildings. By 1951, over 240 circulars on school building matters had been issued by the new Ministry of Education. Notable amongst these were the draft building regulations(Circ.10), and the circular on development plans.(Circ. 28), and of the series of Building bulletins produced, those written by David and Mary Medd on new primary schools(Min Ed 1949), and John Price on the cost studies, based on his work at Hertfordshire county architects department (Min Ed 1951b), had enormous influence. Similarly the bulletins on fire(Min Ed 1952a), colour(Min Ed 1952b) and kitchen design(Min Ed 1955) were both relevant and of immediate, practical value to architects. Over seventy bulletins, and fifty subsidiary design notes were published. Indeed, from 1949 onwards, the building bulletins published by the Ministry of Education were one of the most influential means of transforming the schools. The flair of the architects' ideas and thinking illustrated in them, stimulated teachers and design teams alike. These bulletins contained exciting plans, and showed that it was possible to provide teachers and pupils with a wide variety of indoor and outdoor spaces appropriate to their needs.

3.18 The immediate post war period was a time of acute shortages of building materials and craft skills, but relatively plentiful fuel and therefore relatively low fuel costs. In 1946-1948, the building industry was struggling into action. The pre-war schools had generous spaces, with large halls, and often separate dining rooms and gymnasia. They also had ample circulation areas. Overall, the circulation space might amount to one third of the total area of the school. At that time, architects were free to determine the area and cost of the school, providing they met recommended standards. In 1945 minimum space standards were introduced for teaching areas. The size of school being defined by the number of infant and junior forms of 40 pupils, or secondary schools for 11-14 year olds in senior forms of 30 pupils, to enter the school per year(FE).

TABLE 3.2 MINIMUM TOTAL TEACHING AREA OF SCHOOL(m^2) (adapted: Min Ed 1957).

FORMS OF ENTRY(FE)	PRE-WAR (a)	1945 REGS	1951 REGS	1954 REGS
INFANT				
1	231	245	251	251
2	453	433	482	473
3	638	660	623	644
JUNIOR				
1	334	389	353	353
2	566	650	582	569
3	773	948	800	785
SENIOR				
1	427	777	787	607
2	955	1500	1289	1189
3	1118	2017	1880	1803

(a) Source pamphlets 86 & 107.(Board Edn 1931, 1936)

3.19 The size of the post-war baby boom was also becoming apparent. It was estimated that 200,000 new school places would be necessary each year to 1955 to deal with the replacement of war damaged schools, substandard premises listed since 1925, and the new birth rate. The architects and buildings (A&B) branch was formed at the Ministry of Education in 1949 at a time when the economy was worsening, and the current school building programme was not affordable. Building cost limits per school place were introduced in 1950 on the advice of the A&B branch. Building costs had risen annually from 1939. From 1945 to 1949 the rate of the annual increase varied throughout the country. Up to and including the 1949 building programme, there had been no prescribed limit on the cost of projects. Between 1949 and 1956 the cost of building rose by over fifty per cent. Despite the steady increase in the cost of building from 1950 to 1961, the cost limits introduced in 1950, were only adjusted in 1951 in line with the amended space standards, in 1953 for inflation, and in 1955 to cover the 1954 regulations and an inflationary allowance(Min Ed 1957). Two factors justified the reduced costs between 1949 and 1955/56. The first was the fundamental way in which the use of space in schools was studied. The second was the introduction of elemental building cost analysis and planning. For example it was found that:

(i) ideally, primary school classrooms should be grouped in pairs, with direct access to cloaks, toilets, and outside spaces; the only circulation space, which could be justified, was from the classroom to the assembly hall/dining facility; smaller gross areas were feasible, and

(ii) there was considerable discrepancy between expenditure on particular elements of school construction from one LEA area to another(Saint 1987), suggesting that construction standards could be rationalised, and overall costs reduced.

TABLE 3.3 BUILDING COSTS : £ PER PLACE. (compiled from: Min Ed 1957)

	BUILDING COSTS : £ PER PLACE				
YEAR	1949	1950	1951	1953	1955
Primary School	200.00	170.00	140.00	146.00	154.00
Secondary School	320.00	290.00	240.00	250.00	264.00

3.20 Saint(1987) reports that the cost limits did not rise above the 1955 level until 1961, because the Minister wished to avoid contributing to inflation. A seemingly foolhardy political decision, because such action inevitably contributed to the widespread major building failures of later years, associated with the specification of short-life, low cost materials for the construction of schools erected during the post-war school building boom in this period of arbitrarily fixed cost limits.

3.21 It was also considered acceptable for one of a pair of classrooms to gain access to the hall, by passing through the neighbouring classroom. Planted courtyards were also favoured as a means of providing daylight, visual links with the outside, and direct access to pleasantly sheltered outdoor spaces.

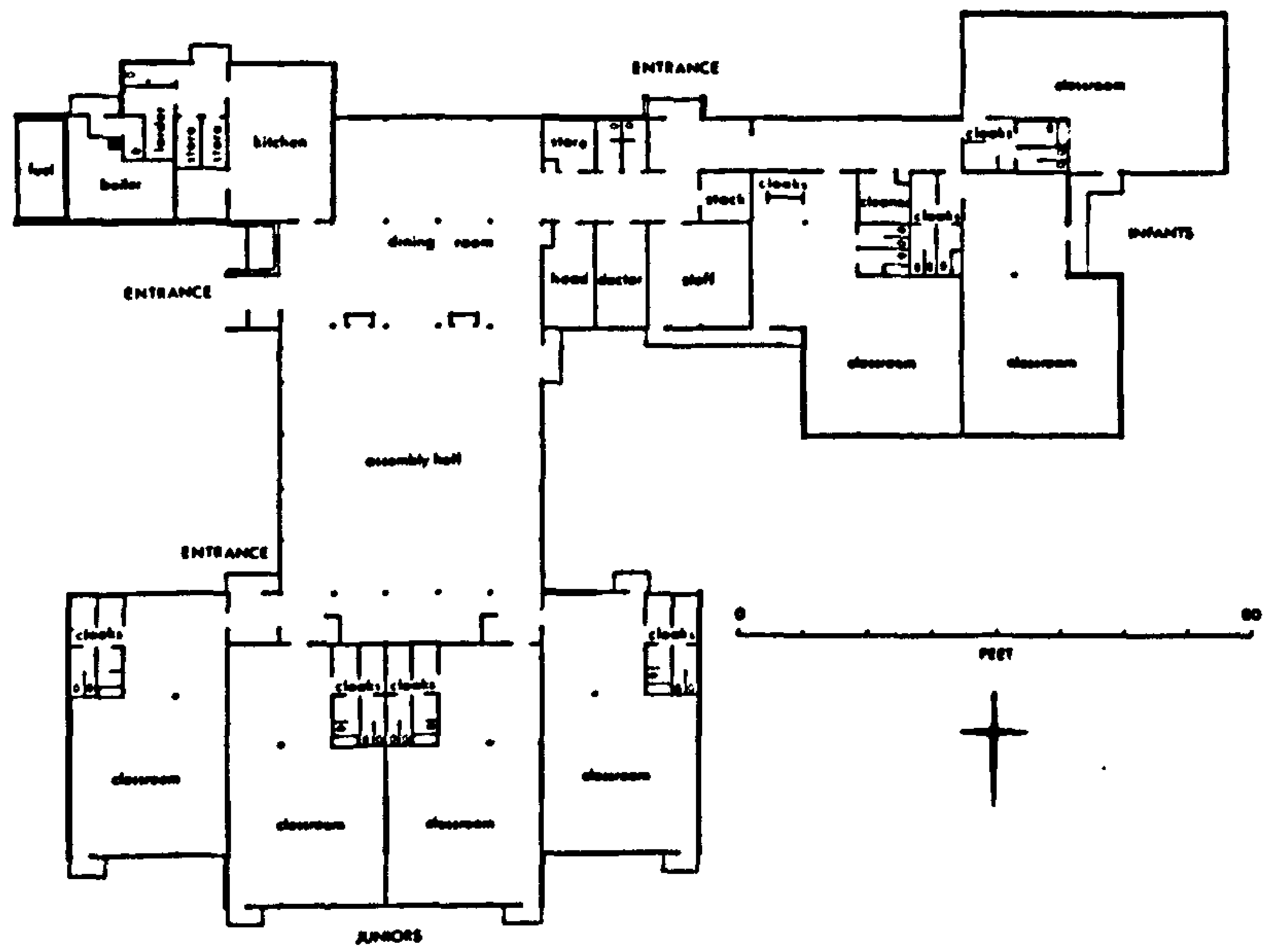


Figure 3.3 Kenilworth school, Herts (1951-1952). Example of a more compact plan form.(Saint 1987)

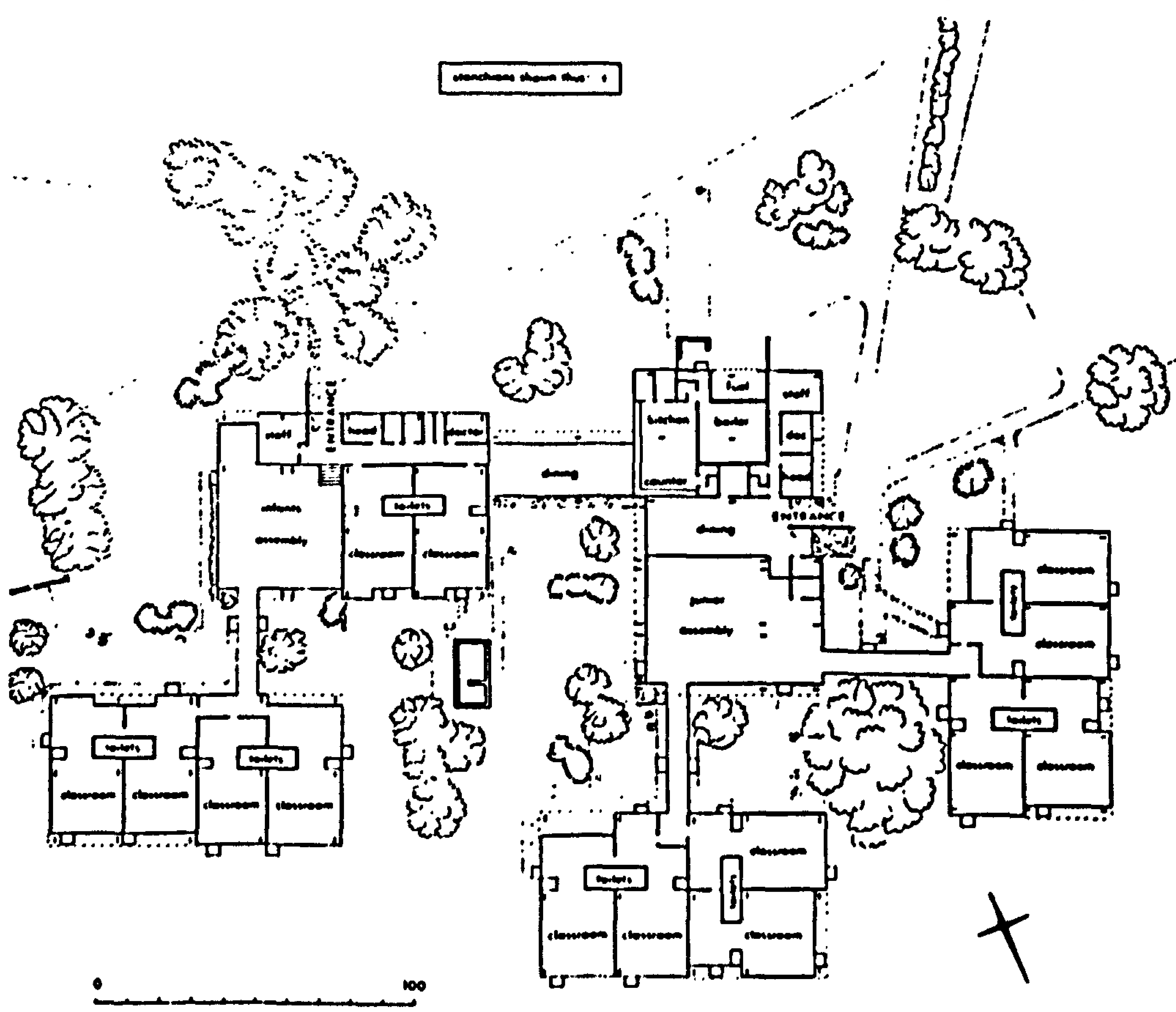


Figure 3.4 Roebuck primary school, Stevenage. 1953-54.

3.22 The A&B branch maintained a development group, and, from time to time, collaborated with LEA architects on the design of individual schools as development projects. The purpose of these projects was to expand the boundaries of thinking about the design of schools. Plate 3.16 illustrates the first example of an open plan primary school in England. It was designed by David and Mary Medd and Pat Timball of the development group, for Oxfordshire county council, and built in 1958-1959. This school had fairly generous space provided per pupil. Each class had its own base and the use of a large activity area, which was shared with another class. The idea was extensively copied, but without the same success. This was usually attributed to tighter space allocation and planning, with a consequent lack of acoustic separation for the class-base area.

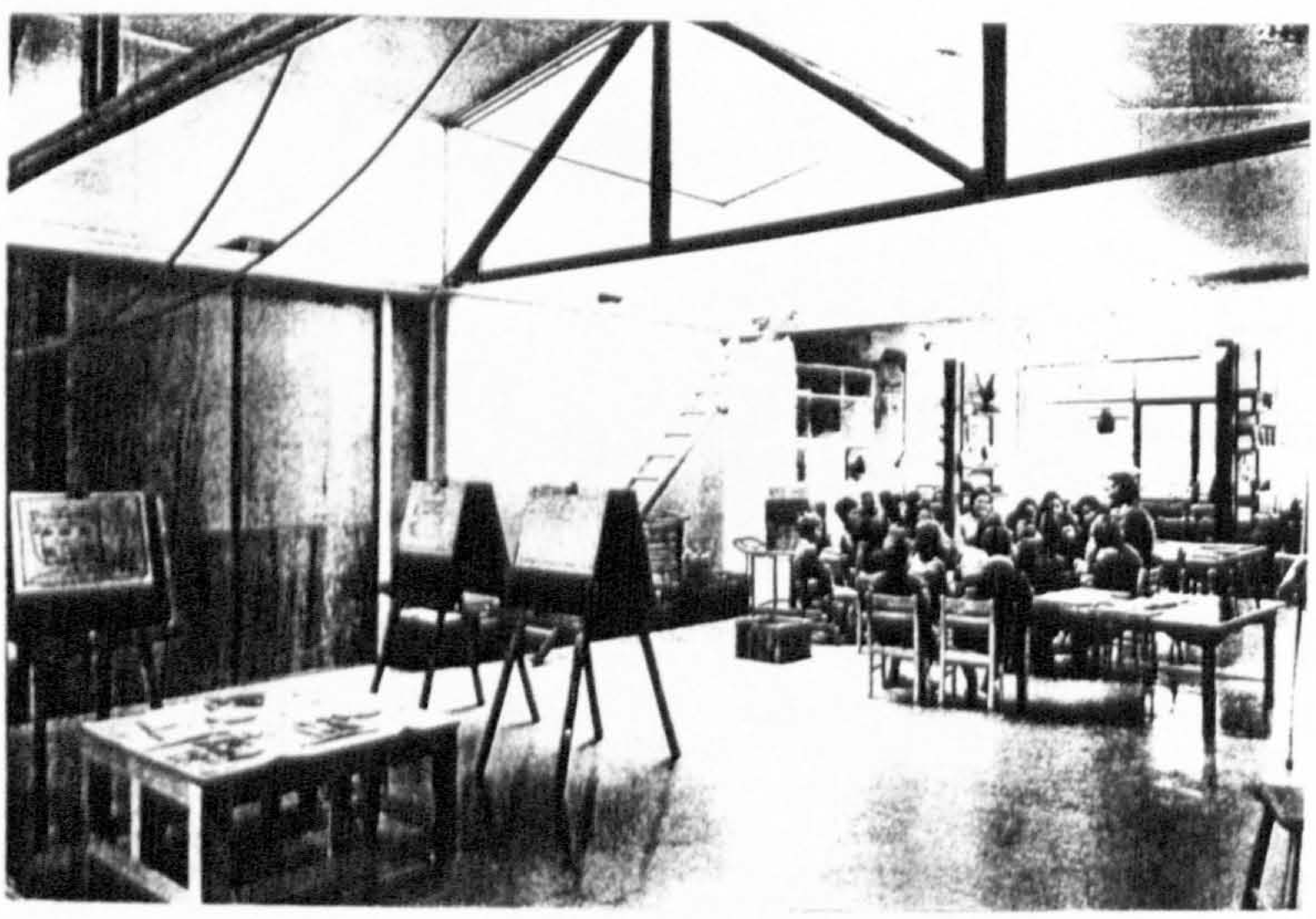


Plate 3.16 The first 'open plan' English primary school. 1958-59.

3.23 In 1957 the Ministry encouraged the co-ordination of the building efforts of six local authorities with subsidence problems, by the formation of a consortium for school buildings, known as the consortium of local authorities special programme.(CLASP) A second consortium of local authorities (SCOLA) was also formed to concentrate on methods of building schools as fast as possible, using standardised components and prefabrication techniques. These arrangements were successful in producing economies of scale from bulk purchasing, without which the standards of components and finishes specified would not have been affordable, and rapid construction times on site.

3.24 Figure 3.5 shows the plan of James Peacock infants school, Ruddington. It is a CLASP system building, with classrooms in pairs grouped around a hall, and has small courts to admit daylight into the heart of the school.

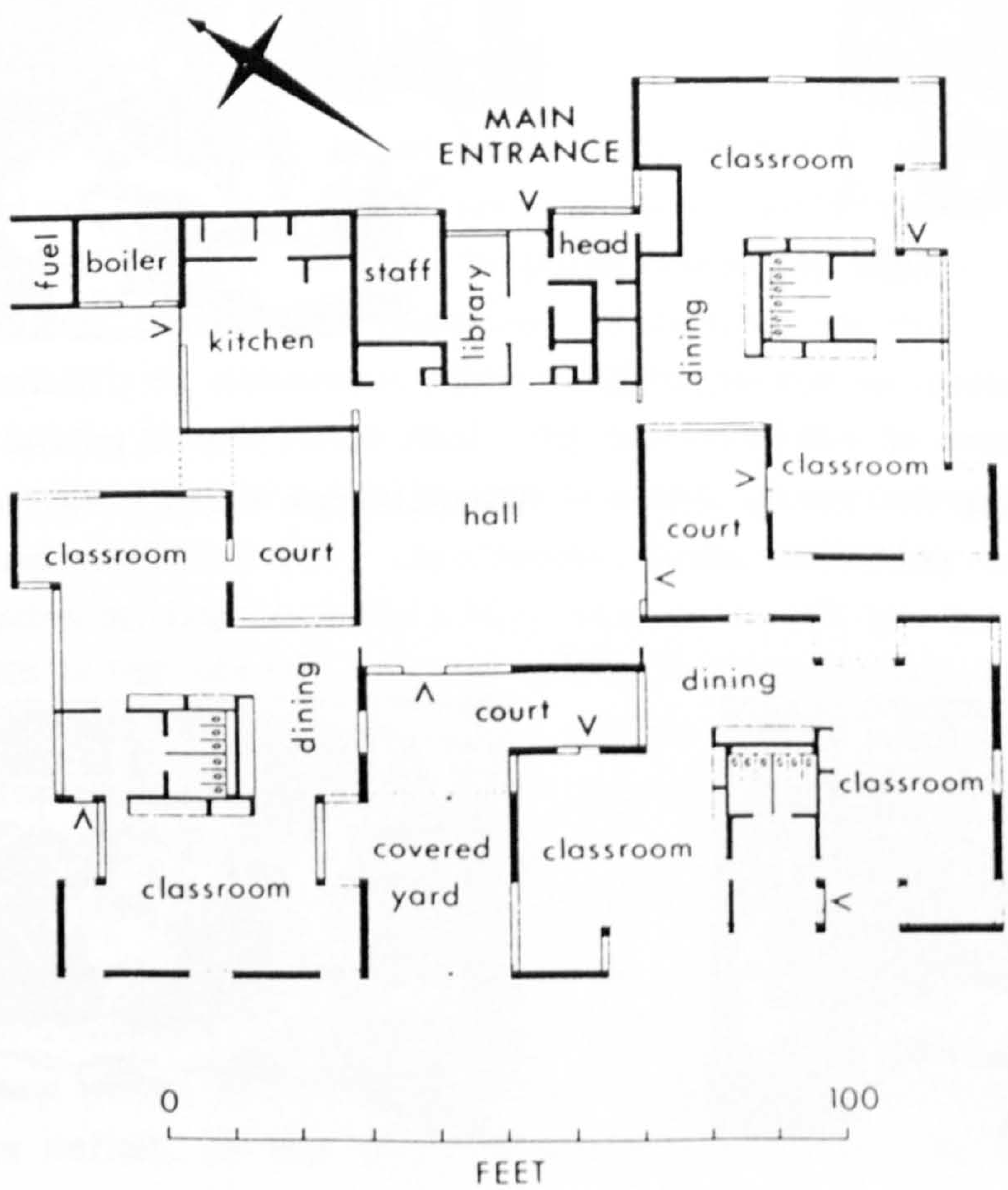


Figure 3.5 A 1966 CLASP infants school.Nottinghamshire county architect.

3.25 The Plowden report(Plowden 1967) gave an indication of the interaction which had already taken place between teachers and architects, since the formation of the A&B branch at the Ministry in 1949. This collaboration had been used to improve the understanding of the types of spaces and finishes needed for the very wide range of educational activities to be found in primary schools, and to provide innovative design solutions based on this work. Plates 3.17 to 3.22 are a representative sample of these activities illustrated in the Plowden report, showing that much had already been achieved by the mid 1960's.

Plate 3.17 Experiment

Plate 3.18 Craft

Plate 3.19 Group work

Plate 3.20 Reading

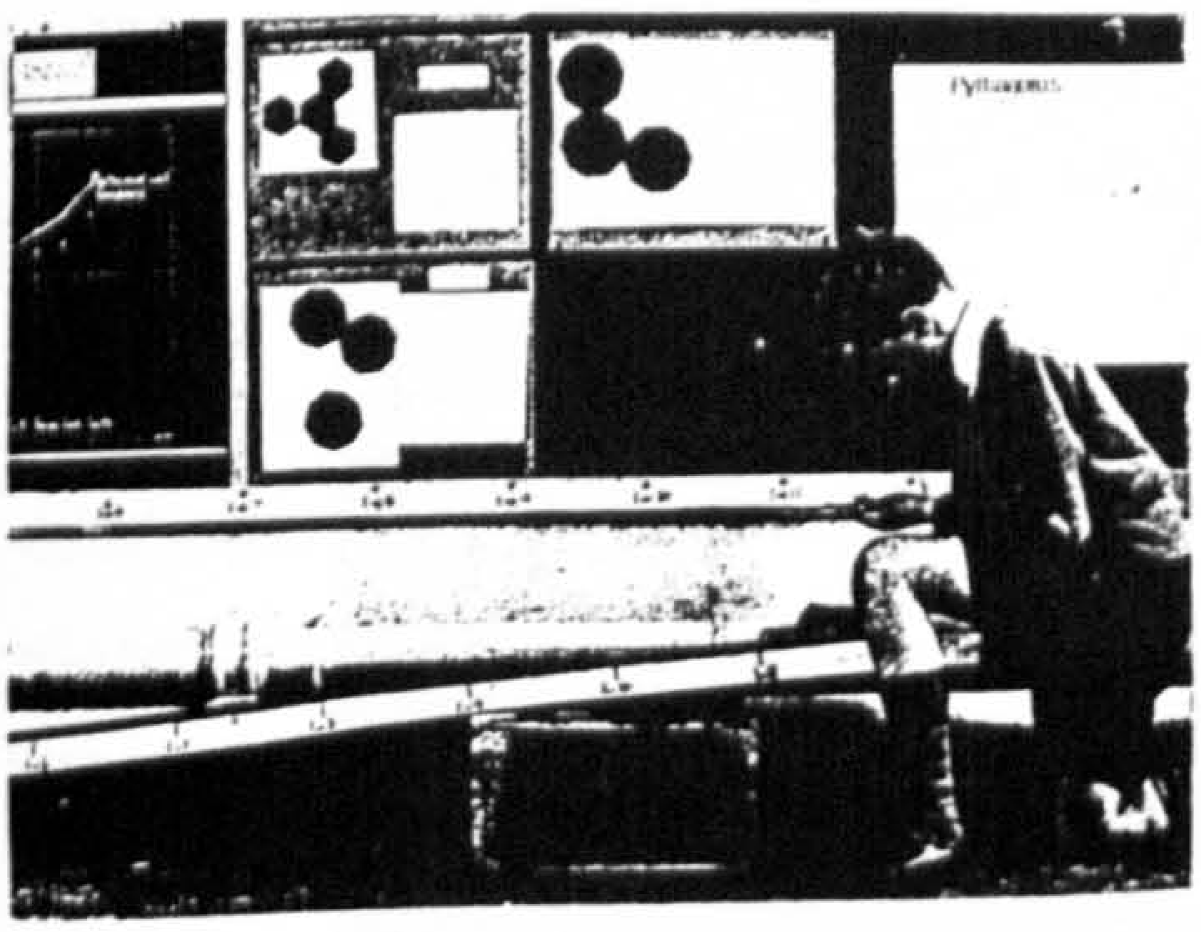


Plate 3.21 Mechanics

Plate 3.22 Movement.

3.26 However the overall effect of: post war shortages; inadequate lead times for new school places, and fixed cost limits, space, and daylight standards, was that buildings of the period 1945 to the 1961 were usually built of relatively lightweight construction, with low-cost flat roofs, and large window areas, irrespective of orientation. At the time of the 1944 Education Act, the principal responsibility for environmental science in building was with the Architectural physics section of the Building Research Station (BRS). They collaborated with the county architect of Hertfordshire to evaluate the 1945 daylight standard for schools, and were instrumental in bringing about the reduced standard of 1951. Unfortunately heating, ventilation, and the thermal performance of school buildings was another matter, and it was not until 1950 that the A&B branch persuaded the BRS to look into this. The BRS again collaborated with Herfordshire, who were already committed to the Andrews Weatherfoil warm air system for space heating, and so the BRS study was less fundamental or objective than possibly required at that time. The BRS results did however form the basis of subsequent policy advice to LEA's for many years. Unfortunately therefore, although often very well planned, detailed and furnished to provided reasonable well thought out teaching spaces and heating systems, which were capable of providing adequate warmth, many of the schools built from 1950 to the 1970's were poorly insulated and thermally inefficient. They had very large windows, irrespective of orientation, with associated problems of glare and overheating from sunlight, and were subject to high heat losses during the heating season. Although school toilet provision was indoors and much improved, with a consequent ease of supervision in primary schools, there was often little attention paid to air quality.

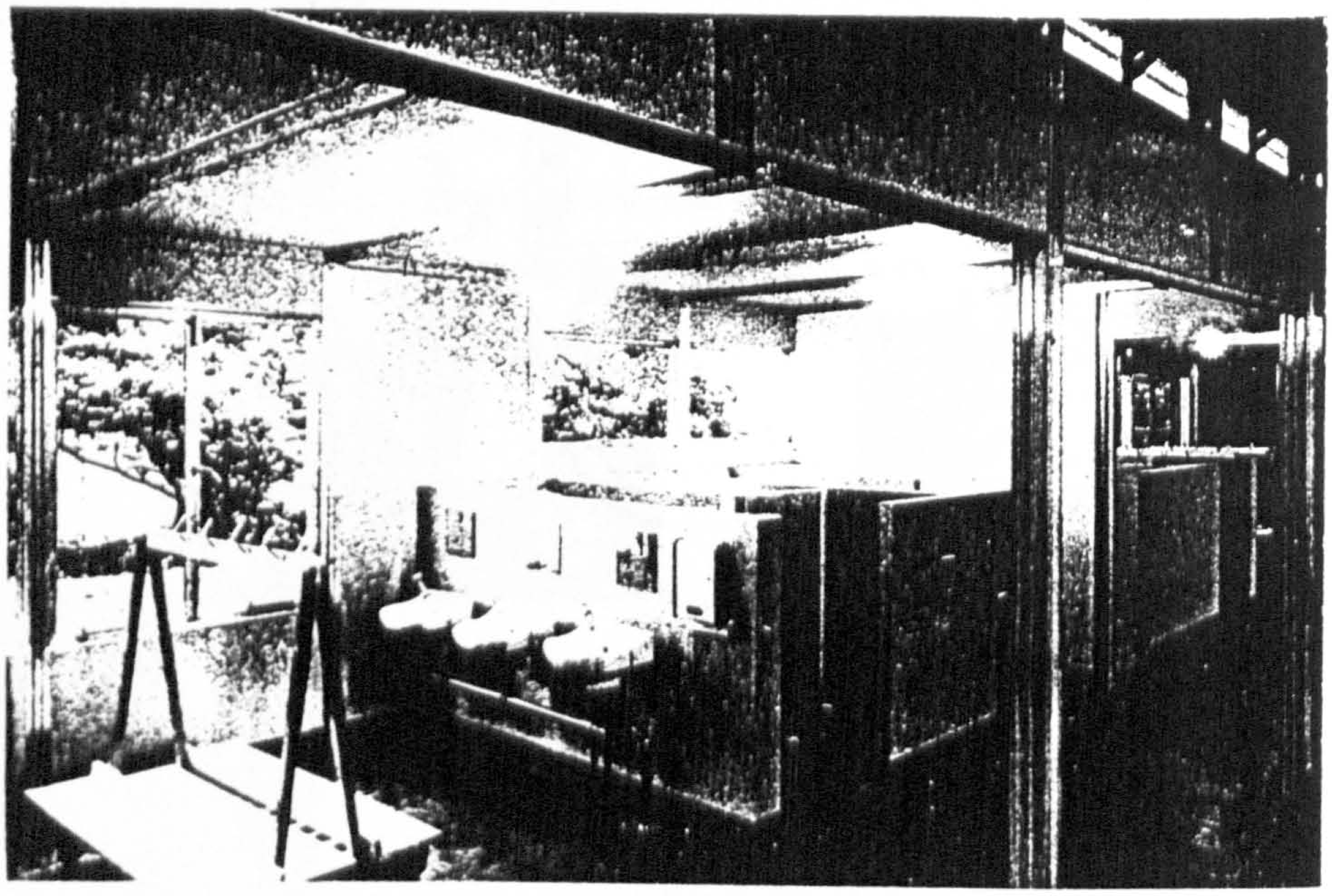


Plate 3.23 Example of 1952 primary school toilet provision(Min Ed 1957).

3.27 There were many successful aspects of this development of design policies for post war school buildings, for which the Ministry of Education's initiatives with the LEA's were largely responsible. However, although the permitted maximum number of days for temperatures of 27 degrees celsius and over, and cost analysis and control methods were defined, the policy areas of building design performance, which were most neglected during the 1950's to the 1970's relate to the absence of any holistic appraisal of the interaction of individual policy statements on:

(i) capital cost, revenue cost, major maintenance cycles, and cost limits per place, and

(ii) year round environmental performance, daylight, air quality and comfort.

3.28 The sound environmental design of buildings for daytime use should aim to provide thermally efficient buildings, in which many of the internal spaces have ample daylight, take advantage of available useful solar gains, and avoid overheating. The form and performance of such architecture needs to be carefully evaluated and resolved at the initial design stage in relation to its use, site, orientation, sun path and climate, to ensure that the solution is an economical, functional, and sound building structure, which is comfortable, and has an interior and exterior which delights the senses. This climate sensitive approach to design is often referred to as 'passive solar', because the external fabric or 'envelope' of the building is designed to achieve desirable climate modification, benefits from available ambient energy, and a reduced heating season, and energy loads. Alternatively, an energy conserving strategy might prove more efficient, particularly when site conditions with orientation or overshadowing problems exist, in which case a climate excluding environmental design might be more appropriate.

3.29 The first passive solar school in the United Kingdom was built in 1961 at St Mary's(formerly St George's) Wallasey. It was designed by A.E. Morgan, and built of heavyweight construction, which was well insulated externally. It had a very large, southerly aspect, double-glazed solar collector wall to the teaching spaces. A secondary heating system was installed, but not generally used, because the space heating from useful solar gain and internal gains from occupants and tungsten lighting was considered adequate. Plate 3.23 and figure 3.6 illustrate the school. The Building Research Establishment (BRE) monitored the performance of the school in 1986. They were critical of the amount of glare in teaching spaces, and the poor air quality, attributable to the fact that the arrangements for natural cross ventilation were rarely used(Crisp et al 1988). This indicates the importance of the consideration of occupant behaviour as a design parameter.

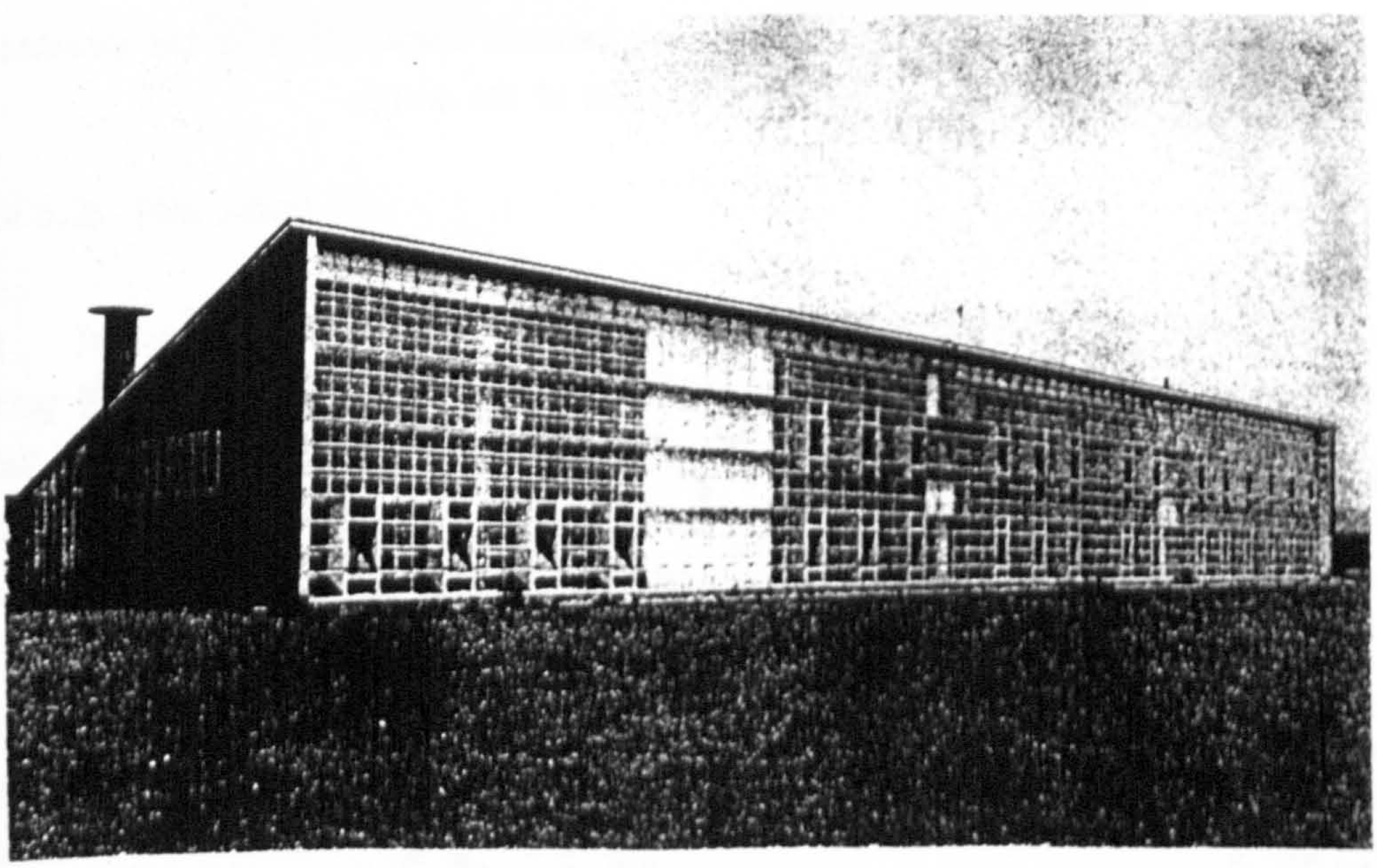


Plate 3.24 St Georges school, Wallasey 1961

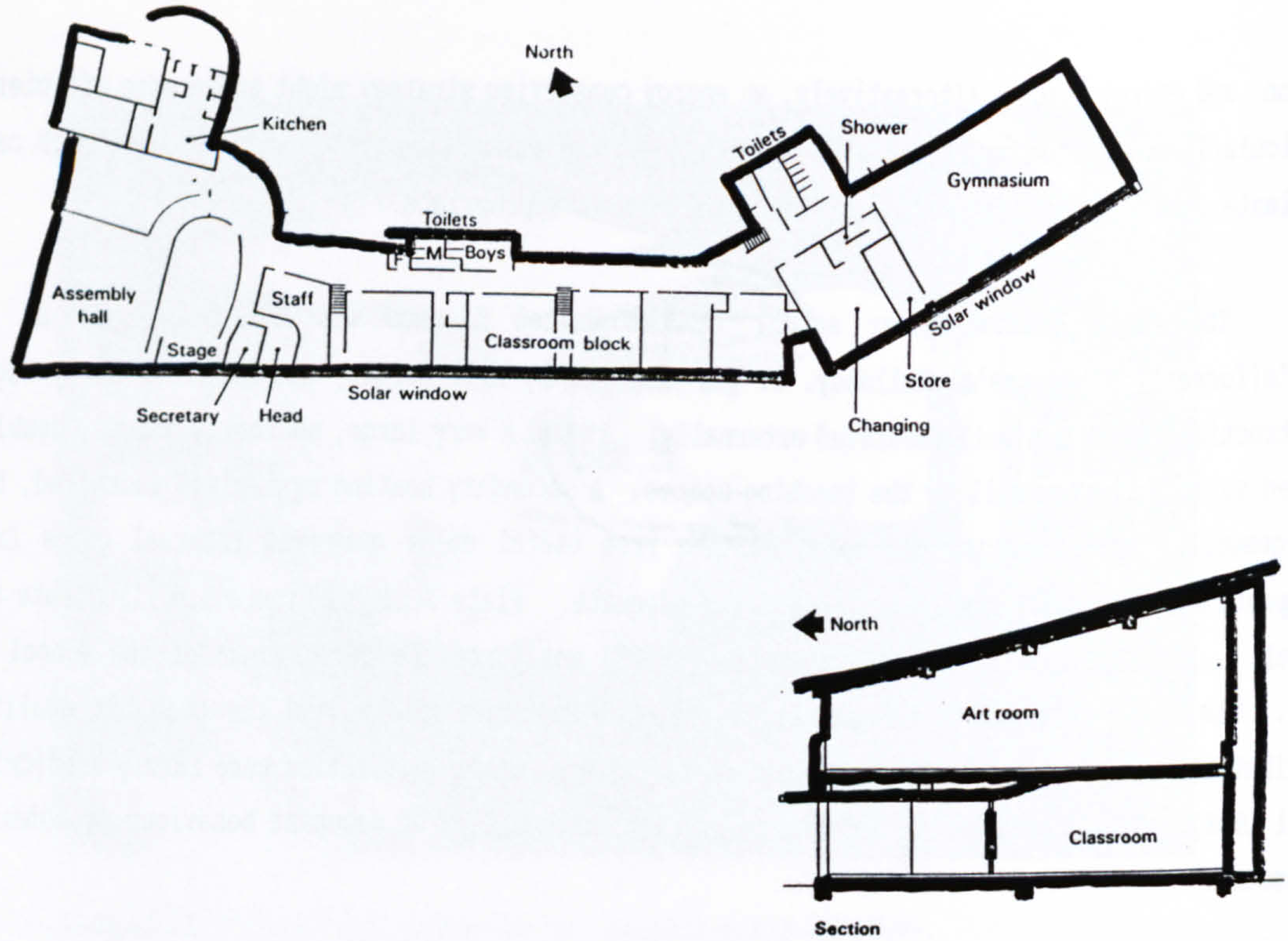
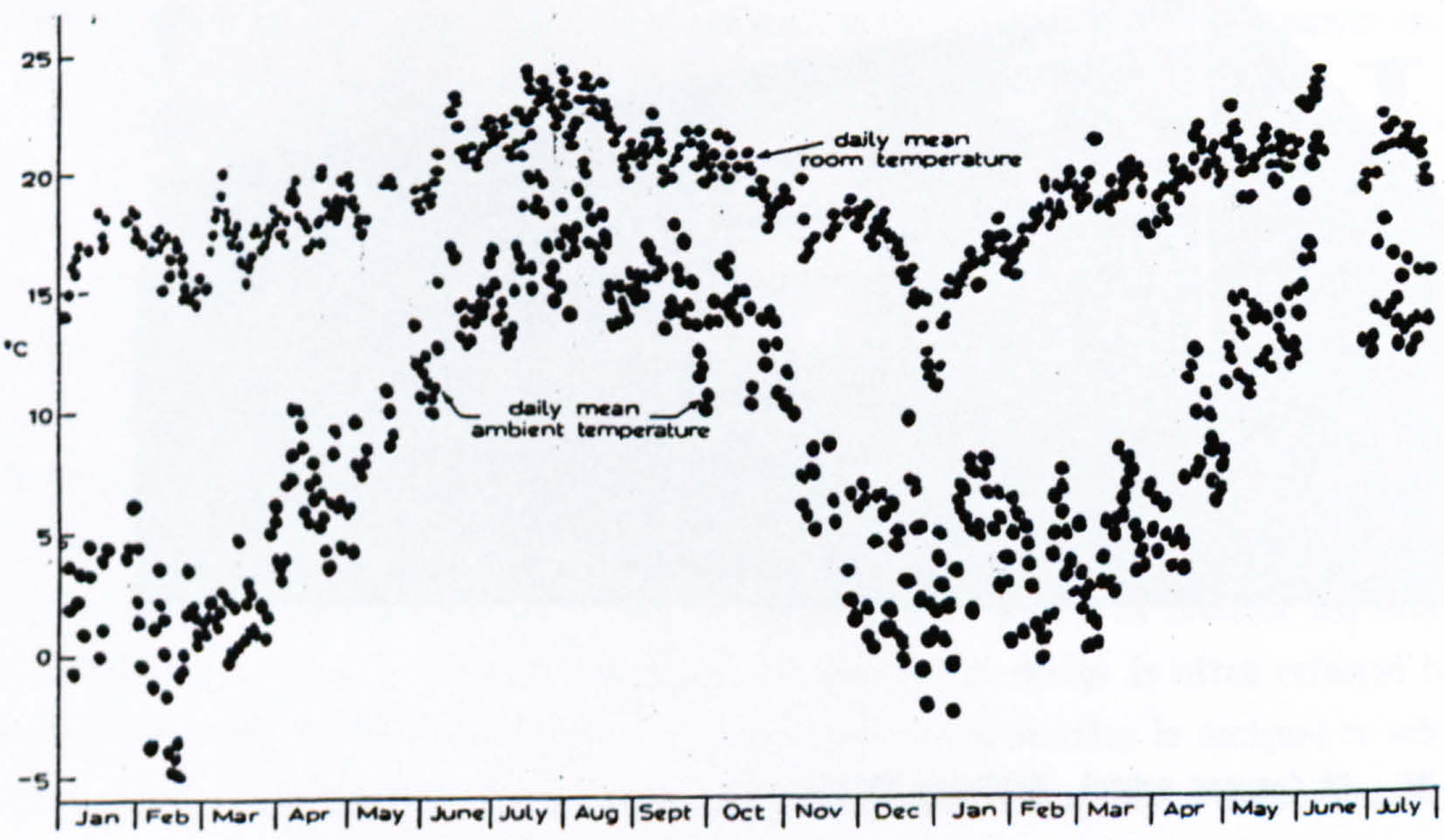


Figure 3.6 St George's school ground floor plan & section.

Figure 3.7 shows a graph of the mean daily ambient and internal temperatures in the unheated building, and clearly demonstrates the thermal effectiveness of the design.



Each dot or circle represents the mean temperature for the day, based on up to 72 daily values.

Figure 3.7 Monitored results St Georges School.

3.30 Following the international oil crisis in the late 1960's and early 1970's, there was increasing emphasis on the conservation of energy. The previous mandatory standards, concerning the minimum provision of daylight in teaching areas, (Min Ed 1951a) had been relaxed to permit smaller windows, and permanent supplementary artificial lighting(PSAL) to be used instead of daylight,(DES 1967) and it was assumed that this combination would be more energy efficient.(DES 1979)

Plate 3.25 PSAL school

3.31 During the 1970' and 80's, local authorities were experiencing considerable difficulty in meeting the escalating costs of school maintenance, due to the scale of replacement and repair needed of major elements of the post-war schools constructed during the period 1950 to the mid 1960's. Following the oil crisis of 1973, fuel prices and the poor thermal performance of these schools were also a cause for concern. The LEA's unit costs of education in maintained schools was increasing at a time when the moneys from the Exchequer were reducing due to the effect of falling pupil numbers. School buildings were exempt from the provisions of the general building regulations, which until 1976, contained only a very modest requirement for the insulation of the solid areas of walls and roofs. There was no limit to the area of glazing, which could occupy the whole of a wall. Since 1976 the general building regulations(DOE 1976, 1978, 1981, 1984, 1985, 1989, 1991) became progressively more stringent, with much improved thermal resistance, and permitted areas of glazing were regulated.

Table 3.4 BUILDING REGULATION MAXIMUM U-VALUES (W/m^2 K):
(a)OFFICE, SHOPS, AND ASSEMBLY BUILDINGS; (b)DWELLINGS.

ELEMENT	1976 REGULATIONS (a)	1976 REGULATIONS (b)	1985 REGULATIONS (a)	1985 REGULATIONS (b)	1990/1991 REGULATIONS (a)	1990/1991 REGULATIONS (b)
exposed walls	-	1.00	0.60	0.60	0.45	0.45
semi-exposed walls	-	1.70	-	-	0.60	0.60
windows	-	-	5.70	5.70	5.70	5.70
exposed floors	-	1.00	0.60	0.60	0.45	0.45
semi-exposed floors	-	1.00		-	0.60	0.60
ground floors	-	-	-	-	0.45	0.45
roofs	-	0.60	0.60	0.35	0.45	0.25
roof lights	-		5.70	5.70	5.70	5.70
windows % external wall area.	-	-	35%	-	35%	-
rooflights % roof area.	-	-	20%	-	20%	-
windows plus rooflights % external wall area.	-	-	-	12%	-	-
windows plus rooflights % total floor area.	-	-	-	-	-	15%

3.33 The introduction of thermal performance criteria in the general building regulations put pressure on the DES to either comply with the general building regulations, or issue appropriate regulations for schools. Design Note 17 was issued (DES 1979) to provide more detailed guidelines than previously available on environmental design and fuel conservation in school buildings. Although these were intended as guidelines, they were in effect obligatory, since it was necessary in practice to satisfy the DES that schools complied with them, particularly when applying for loan sanction for capital projects. Although a version of the guidelines is still current,(DES 1981b) it does not take account of either, the generally improved thermal insulation standards now in use in relation to other types of building, or the evidently beneficial effect, which a passive solar design approach may have, as identified by the Watt Committee (O'Sullivan 1988). Consequently, the DN17 procedures encourage poor overall thermal performance, and to some extent force, the provision of low aspect ratio buildings. These tend towards a climate excluding design solution, by reducing the interaction between interior and external spaces and environments.

4.0 COMPUTER MODELS

4.1 The four computer models used in this study were:

(i)	Seri-Res.
(ii)	Tas^0.
(iii)	Daylight.
(iv)	Calculux.

Seri-Res.

4.2 The Seri-Res dynamic building thermal simulation model was produced for the Solar Energy Research Institute (SERI) at Golden, Colorado, by Larrie Palmiter and Terry Wheeling of Ecotope Group, Washington.(Palmiter & wheeling 1981) It was used extensively for the evaluation of passive solar housing projects in the United States, and has been validated(Judkoff 1988). The original version 1.0 was assessed for use in the UK passive solar building programme, and various improvements were proposed (Haves & Littler 1987). Some of these improvements were sanctioned, and carried out by the Central London Polytechnic and Cap Scientific, to extend the capacity of the model, make it particularly appropriate for use with low-rise domestic and non-domestic buildings(such as schools), and improve its realism with regard to:

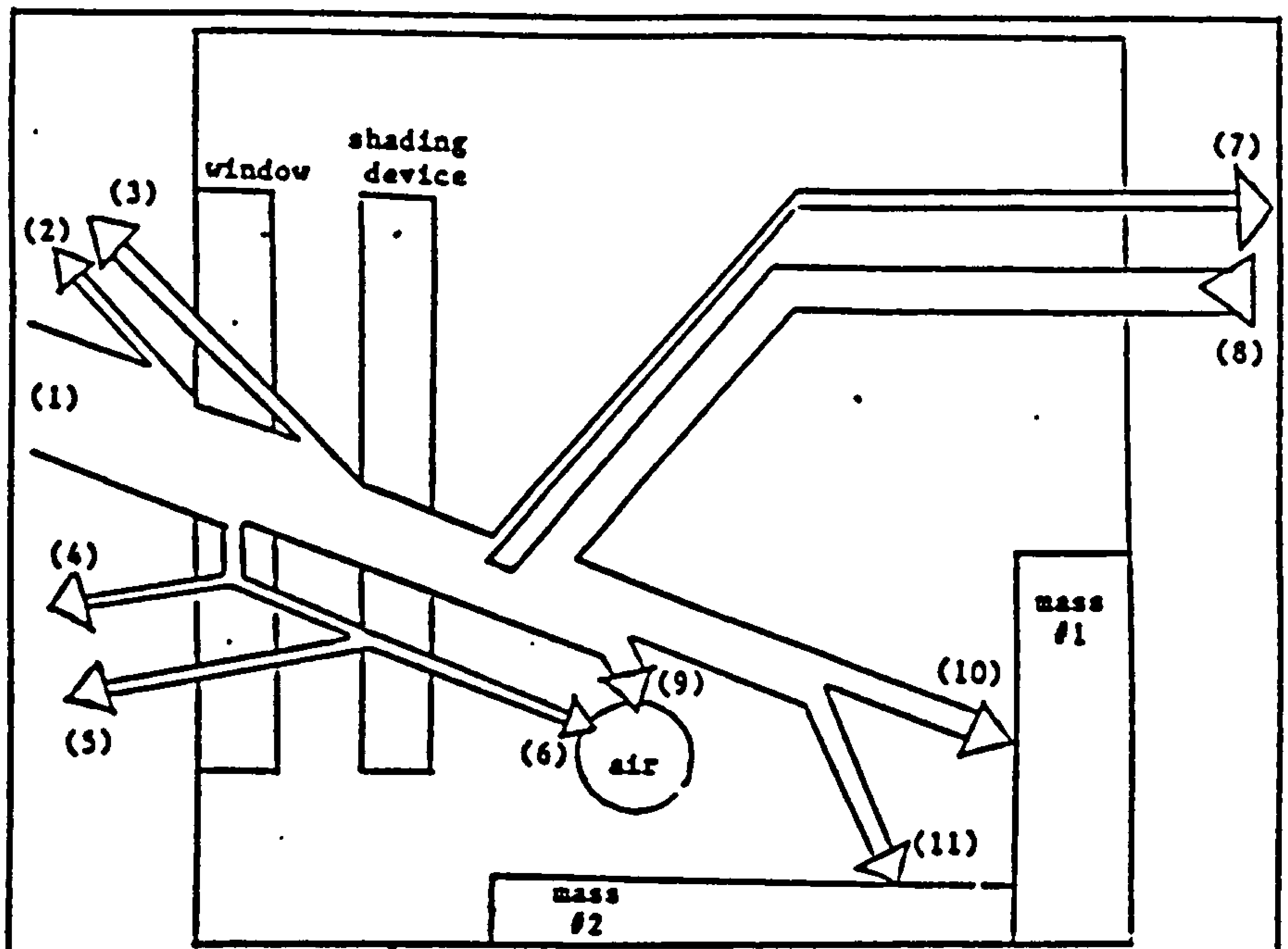
(i) shading, fan operation, and internal glazing to provide more rigorous modelling of suns-spaces and atria;

(ii) lighting and daylight, by the introduction of a facility to calculate the thermal consequences of electrical loads, and modify the BRE daylight factor method to calculate daylight levels, electric lighting use, and hence electrical demand.

The resultant Version 1.2 (Haves 1987) was adopted by the UK and sanctioned for use in the passive solar programmes of the UK and the EEC. Both the mainframe version of this and a later personal computer version of the program were used in this study for the analysis of the thermal performance of the two schools with central atria, and the notional class-base respectively.

4.3 The program compiles a building description file from the data, entered numerically by the user. The program uses a series of equations, which are solved repeatedly, using finite differences, Jacobian iteration and constrained optimisation techniques, at intervals of less than one hour. The actual interval is determined by stability criterion. The building is represented mathematically as a thermal network having non-linear temperature dependent controls.

4.4 Four parameters affect the magnitude and distribution of solar radaiation in each zone of the Seri-Res model(Figure 4.1):



(1) Total Solar Incident on window.
(2) Reflection Losses from glazing layers.
(3) Reflection Losses from shading device.
(4) Outward flowing portion of solar absorbed in glass.
(5) Loss of inward flowing portion of solar absorbed due to shading device.
(6) Net inward flowing portion of solar absorbed in glass goes to air node.
(7) Shortwave solar loss to other zones.
(8) Shortwave solar gain from other zones.
(9) Shortwave to air node.
(10) Shortwave to mass #1.
(11) Shortwave to mass #2

Figure 4.1 SERI-RES INTERIOR DISTRIBUTION OF SOLAR RADIATION. (Palmiter & Wheeling 1981).

(i) Shading coefficient. Each window may have a user specified shading coefficient which is used to multiply the solar heat gain through the window. The solar heat gain has two components: the short-wave solar radiation transmitted through the window, and the inward emitted fraction of the solar radiation absorbed by the glazing layers. This inward emitted fraction goes directly to the air node of the zone.

(ii) Solar lost coefficient. To account for the fact that a fraction of the incident short-wave radiation is reflected out at the surface of the glazing, and the outward emitted part of the fraction which is absorbed by the gazing layers, a solar lost coefficient is specified.

(iii) Solar to air coefficient. After accounting for any inter-zone radiation transfer via internal glazed screens, a fraction of the remaining available short-wave radiation may be specified to account for that portion of radiation absorbed by non-massive objects such as furniture, and which is converted more or less instantaneously to heat.

(iv) Solar to wall coefficient. The remaining solar radiation within the zone may be distributed onto the walls in two ways. The default method distributes the radiation directly proportional to the surface areas of the zone. The user specified method associates a fraction absorbed by each surface. For each zone. the sum of all the solar to wall coefficients for surfaces within the zone, plus the fraction to air and fraction lost must equal one.

4.5 The daylight facility requires an input of daylight factors, which are used to assess daylight availability, from different sources, in a zone. A maximum of three Daylight factors can be entered per zone, representing the light from up to three separate directions. For situations involving daylight from more than three directions, a horizontal surface has to be defined, and a single daylight factor associated with that surface is used as the representative value for the zone(Haves 1991). Window blinds may be specified, and the blind control seeks to maintain the transmitted direct insolation at the set-point value specified, and determine the effective blind opening for each surface having glazed apertures into each day-lit zone.

4.6 The level of daylight within a zone is then calculated from the solar radiation data in the weather file, and is used to predict the use of electric lighting during specified periods for different control methods. Heat gain from the use of electric lighting is calculated and incorporated in the algorithm used to calculate zone temperature and heating and ventilation loads. Air handling luminaires can be modelled. Manual or automatic lighting controls can be specified. The automatic systems can be either continuously variable, or switched in steps, and each zone can, if required, have a perimeter area which is controlled by a sensor, and a core which is on continuously for scheduled periods. When the manual switching option is selected the level of daylight availability is used together with an empirical probability curve(Hunt 1980) to predict when the lights will be switched on during specified periods of occupancy.

4.7 An environmental temperature, is calculated for each zone by Seri-Res. It is a weighted sum of the dry bulb and black globe radiant temperatures, and used in Seri-Res to reflect the users' perception of comfort, having the form(Haves 1991):

$$T_{Env} = 0.375\ T_{dry} + 0.625\ T_{bg} \qquad [4.1]$$

This relationship reflects the fact that the program was originally written for use in the United States of America, where mean radiant temperature is defined(McQuiston & Parker 1988) as:

$$T_{rad} = T_{bg} + D\,\overline{v}^{-1/2}\,(T_{bg} - T_{dry}) \qquad [4.2]$$

$$\begin{aligned} \text{where } T_{bg} &= \text{black globe temperature} \ldots {}^{o}C \\ D &= \text{constant of } 2.2 \quad (\text{for SI units}) \\ T_{dry} &= \text{dry bulb temperature} \ldots {}^{o}C \\ \overline{v} &= \text{air velocity} \ldots m\,s^{-1} \end{aligned}$$

for sedentary activity, and the resultant temperature is then given by:

$$T_{res} = \frac{T_{dry} + T_{rad}}{2} \qquad [4.3]$$

4.8 Although the CIBSE guide, used in the UK, uses the same expression as eqn 4.3 for the resultant temperature(for indoor conditions with air speeds of 0.1 $m\ s^{-1}$), the UK version differs, in that it defines mean radiant temperature as the black globe temperature(CIBSE 1986: A1.2). By definition, the CIBSE value is therefore actually based on the mean value of the sum of the dry bulb and black globe temperatures:

$$T_{res} = \frac{T_{dry} + T_{bg}}{2} \qquad [4.4]$$

and would normally return a different value for the resultant temperature, because of the reduced weighting given in the CIBSE definition of mean radiant temperature. Figure 4.2, illustrates the difference between the resultant temperatures calculated by these methods, based on some hourly black globe and dry bulb temperatures recorded in the atrium at Barnes Farm school, typical of those recorded during the monitoring period. This indicates that the Seri-Res environmental temperature output in a sun-space returns a value between the values of resultant temperature calculated by either method, and that the difference is marginal.

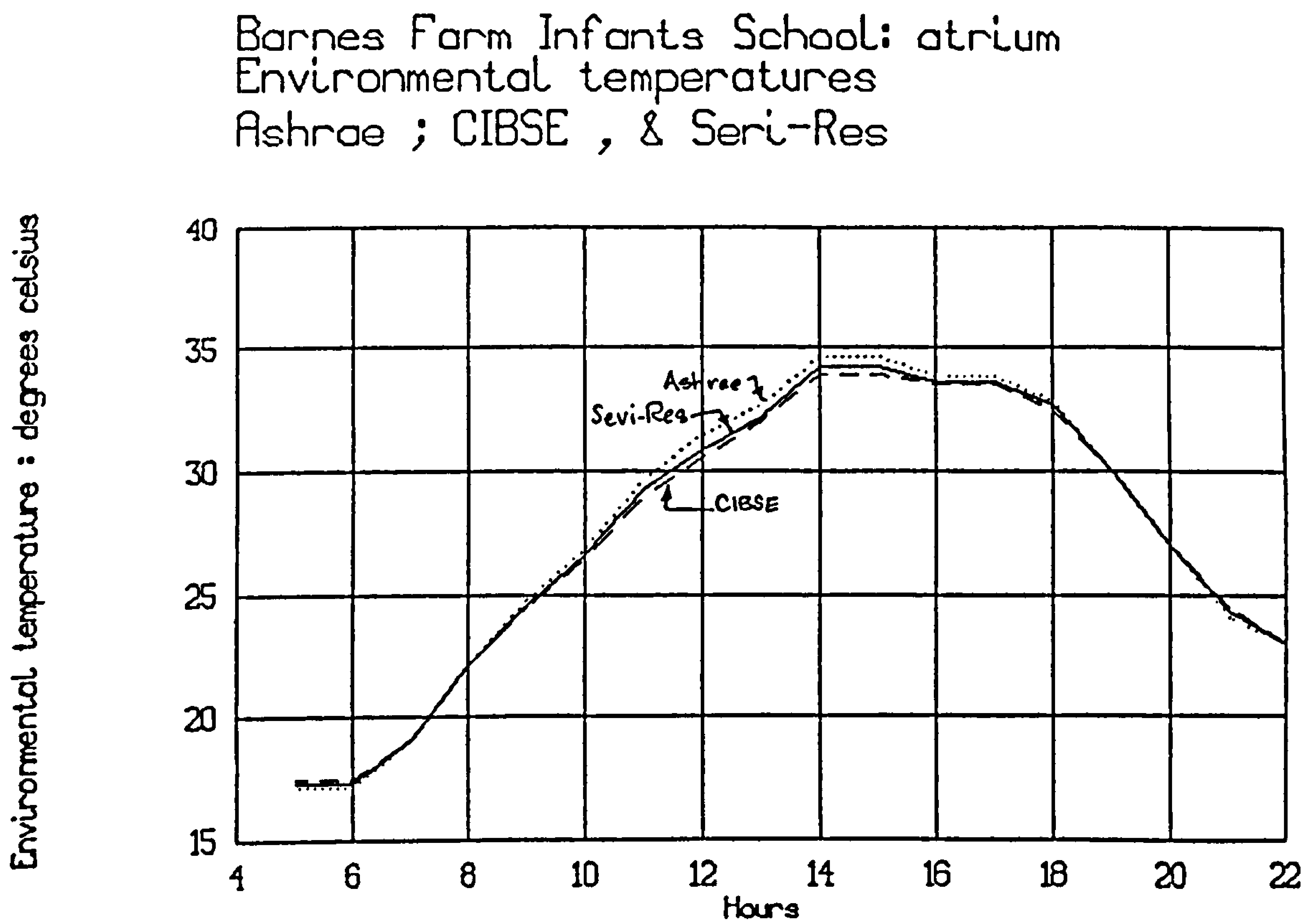


Figure 4.2 COMPARISON OF SERI-RES ENVIRONMENTAL TEMPERATURE OUTPUT WITH RESULTANT TEMPERATURES CALCULATED BY THE CIBSE & ASHRAE METHODS.

4.9 The choice of a suitable resultant temperature for a system design resolves itself into choosing that temperature which should give optimum comfort for the occupants concerned, taking into account their clothing and level of activity, and the CIBSE guide states that the there should be no significant increase in dissatisfaction so long as the actual temperature is within +/- 1.5 ^{o}C of the value of resultant temperature chosen to represent comfort conditions. The CIBSE resultant temperatures required for comfort conditions in schools are given in DN17(DES 1981b). The Seri-Res output is therefore reasonably close to the CIBSE defined resultant temperatures(Figure 4.2).

4.10 If the zone environmental temperature does not exceed the optimum comfort temperature, all gains are useful. In calculating the useful gain, casual gains take precedence over solar gain, and the sum of the casual and solar gains is defined as the useful loss. However if the zone temperature is excessive, the gains causing this are not useful, and useful loss is calculated as the difference between the actual loss and an estimate of the portion of the loss, which results from the excessive zone temperature. The "unuseful" portion of the actual loss is taken to be:

$$
\begin{aligned}
Q_{unu} &= (T_{env} - 21^{o}C) \times UA \qquad && for\ T_{env} > 21^{o}\,C \\
&= 0 && for\ T_{env} < 21^{o}\,C
\end{aligned}
$$

[4.6]

where UA represents the total conductance from the zone to ambient, ground and unoccupied buffer zones. The assumed optimum comfort temperature value may be changed by editing the data statement in the "loads" program, and recompiling the fortran computer code. The useful loss calculation of Seri-Res is an attempt to provide some indication of the thermal benefits of solar gain in a building.

Tas^{0}.

4.11 The Tas dynamic thermal analysis software was developed at Cranfield, then by Amazon Computers, and later by Environmental Design Services Limited(EDSL), who continue to market and develop the software. Tas^{0} uses a response factor method of calculation, and treats the radiative and convective components of heat transfer separately, unlike Seri-Res, which uses a combined parameter for these processes for speed of calculation.

4.12 There was no facility to model daylight within the version of Tas^{0} available for this study. Because Tas^{0} is a commercial product, the code was not available for examination, and independent validation was not available. Use of this model was therefore restricted to one aspect of the evaluation of the performance of the notional class-base, since Tas^{0} was considered more appropriate for that particular application.

Daylight.

4.13 The program used was produced by Ian Frame and Sheila Birch of the construction systems development group of Anglia Polytechnic. Version 4.1 for IBM PC compatible computers calculates daylight factors for a CIE overcast sky as follows:

(i) The sky component for a vertical glazed window is given by: (Hopkinson et al 1966. p66)

$$SC = \frac{3}{14\pi} - (\phi - \phi_1 \cos\gamma) + \frac{2}{7\pi} \sin^{-1}(\sin\phi \sin\gamma) - \frac{1}{7\pi}(\sin 2\gamma \sin\phi_1) \times 100\, percent.$$

[4.7]

where

γ = angles of elevation above the horizontal.
with ϕ, ϕ_1 = azimuth angles.

(ii) The resultant sky component is multiplied by a transmission factor, T, obtained by interpolating between values given for glazing under a CIE sky. (Littlefair 1982)

(iii) The externally reflected component is taken as one fifth of the equivalent sky component, and the internally reflected component is based on the formula published in BRS Digest no 42.(BRS 1964)

[4.8]

$$Av\,IRC = \frac{0.85}{A(1 - R_{av})} \times (CR_{fw} + 5\,R_{cw}) \quad \%$$

(iv) The reflectance of any window area is taken to be 0.1, and the coefficient C is obtained by interpolating between the values of table 1 in BRS digest no 42 which is incorporated in the software.

Calculux.

4.14 This software package was produced by Philips Lighting Division. The indoor lighting module version 2.0 allows the dimensions and particulars of a room to be entered, includes a data base of the manufacturer's light fittings, and calculates the energy consumption per square metre of the room from the specified light fittings. The software also calculates the light output from the fittings.

5.0 PREVIOUS WORK.

Energy conservation requirements: school buildings.

5.1 Following the report on solar heat and overheating(DOE 1975), the work of the Building Research Station on daylight(BRS 1964), and condensation(BRS 1972), the introduction of building regulations of 1976 for other buildings(DOE 1976), and the building bulletins on lighting, acoustics, and energy conservation in education buildings(DES 1967,1975,1977a), the guidelines on environmental design and fuel conservation of the department of Education and Science(DES 1979), were issued and subsequently updated (DES 1981b). The 1981 guidelines covered acoustics, lighting, the thermal environment, including ventilation and energy conservation. The main requirements concerning the thermal environment were summarised as follows:

(i) In daytime, daylight should be the main source of light in working areas except in special circumstances, and every teaching space should have a window area of at least 20 per cent of the internal elevation of the external wall, through which an adequate view out can be obtained.

(ii) The lowest level of maintained illumination, whether daylight or electric light, at any point on the working plane should not be less than 150 lux, and where florescent lighting is used the general level of illumination should not be less than 300 lux.

(iii) The glare index(Anon 1977) for electric lighting should not be more than 19 in teaching spaces, and due regard should be paid to the control of glare from daylight.

(iv) In the design of lighting, regard should also be paid to the need to conserve energy.

(v) During hours of occupation, the heating system should be capable of heating a minimum of 10 cubic metres of fresh air per person per hour for the resultant temperatures required at a height of 0.5 metres above floor level, when the external temperature is -1^{0} C.

(vi) The required resultant temperatures are 21^{0}C for areas, where the occupants are lightly clad and inactive (eg Medical inspection rooms), 18^{0}C in areas where there is an average level of clothing and activity (eg classrooms), 15^{0}C in dormitories, and 14^{0}C in areas where the occupants are lightly clad and activity is vigorous(eg gymnasia).

(vii) The temperature in circulation spaces should be not more than 3^{0} C below the temperature of the spaces they serve.

(viii) All working areas, halls, sick rooms, and dormitories should be capable of being ventilated at a minimum rate of 30 cubic metres of fresh air per hour for each person normally occupying these areas, or at such higher rates as may be necessary to maintain comfort conditions.

(ix) Adequate measures should be taken to prevent condensation in, and to remove noxious fumes from every kitchen and other room in which there may be steam or fumes.

(x) All lavatory accommodation, changing areas and cloakrooms in which adequate cross ventilation to give at least six air changes per hour cannot be achieved by natural means should be mechanically ventilated.

(xi) In the design of the thermal environment due regard should be paid to the need to conserve energy.

(xii) In the heating season, any swing in temperature was to be within 2°C of the required temperature, and during the summer, the resultant temperature for all spaces should be 23°C, with a swing of not more than 4°C about the optimum. It was undesirable for internal temperatures to exceed 27°C, but an excess for ten days during the summer was considered a reasonable predictive risk.

(xiii) Annual energy consumption targets, in primary energy units, were to be achieved by all new school building designs.

A procedure was included, which required applicants for new, or major extensions to existing, schools to submit steady state design calculations giving the energy value of the proposed building. This was to be calculated from the algebraic sum of fabric and ventilation losses, internal gains, hot water and space heating consumption, excluding kitchen loads or other process loads (kilns etc.). The result was expressed in Watts per square metre of floor area, and converted to primary energy units using the fuel factors listed. No allowance was made for solar gains, and the DN17 method was therefore weighted in favour of deep planned, low aspect ratio design solutions.

Passive solar.

5.2 The Building Design Partnership(BDP) produced a report on passive solar design in non-domestic buildings(Duncan & Hawkes 1983). The report included some case studies of UK schools, indicating the limited information available at that time:

(i) St George's School, Wallasey(Anon 1966), in which the 1960-69 estimated heating sources were 50% solar, 34% incandescent lighting, and 16% gains from pupils;

(ii) Roach Vale Primary school, Colchester Essex(Kasabov 1979), which had four air to air heat pumps, one of which used air, pre-heated by solar energy from an internal courtyard covered by a translucent roof, and was operating more efficiently than the others;

(iii) Tendring High School, Walton, Essex(Kasabov 1979), in an extension to which, the air from classrooms enters a solarium at roof level, where it is heated by solar energy, and passed through two heat pumps to supply warm fresh air via the ceiling voids to the classrooms;

(iv) St John's Primary School, Clacton, Essex(Hawkes & Owers 1982), at which conservatories and solar walls were used to supply warmed air, but the principal heating was by heat pump;

(v) Frogmore Secondary School, Hampshire(Kasabov 1979), had an extension, which was designed to control direct gain in summer by shading the glazing, and reduce heat loss in winter by using shutters during the day and night to reduce the amount of glazing exposed to ambient;

(vi) Yatley Primary School, Hampshire(Anon 1981, 1983), in which the classroom windows face South, and receive direct gain during the winter months, and roof-lights are located along the ridge to improve daylight availability, and reduce the dependence on electric lighting (from 60-70% of the occupied time to 30%). The classroom block was separated from the Hall/ music block by a glazed atrium buffer space(described as a conservatory), which was expected to be usable for 60-70% of the school year.

(vii) Netley Abbey Infants School, Hampshire, which was designed with a continuous South-facing conservatory to accommodate the practical areas and provide pre-heating of incoming fresh air in winter and stack-effect ventilation in summer.

Their analysis of primary energy use for the non-domestic buildings sector indicated that, electric lighting in schools in 1976 was 21.75% of the heating energy for schools, compared with 40.8% for all non-domestic buildings. They also used the age related categorisation of school buildings(DES 1977b) to assess the passive solar heating contributions of the existing school buildings, and the potential for improved thermal performance. They concluded that, in the existing building stock, multi-residential buildings and schools seem to hold particular potential for energy savings from passive space heating. The report noted that due to the present lack of passive design experience in the non-domestic sector, it was difficult to draw firm conclusions as to which passive design systems hold the greatest potential for each building type, however the potential for atria and conservatories to contribute to the heating, ventilation, and lighting demands of a number of building types was mentioned. The report identified possible barriers to passive design from: technical; economic; environmental, and institutional considerations, which required further investigation, and recommended that both the Government and the professional institutions might need to take a lead to help overcome them.

5.3 Hunt published a paper on the probability of the use of artificial lighting in relation to daylight levels and occupancy(Hunt 1979), and proposed that the probability of people switching on electric lights in the day-time was most closely related to the minimum working plane illuminance, and almost as closely related to the perceived average daylight factor. This empirically derived probability is incorporated in an algorithm used in the Seri-Res version 1.2(Haves 1987)to determine the switching probability, whenever the manual switching option for electric lighting is selected. However Hunt(1979) also found that the cycle of occupancy of multiply-occupied spaces, such as large offices and school classrooms, determined the pattern of lighting use throughout the day. In continuously occupied spaces, such as large offices, switching was generally confined to the beginning and end of the normal working day, whereas in intermittently used spaces, such as classrooms, switching occurred throughout the day, which produced markedly different lighting use profiles. Thus the Seri-Res manual switching option would be inappropriate and unsuitable for use in evaluating the use of electric lighting in schools.

5.4 A survey was undertaken by Cooper & Crisp(1984) to identify whether UK designers were attempting to use daylight as a means of reducing fuel consumption in office buildings. It was limited to fourteen architects and twelve engineers whose buildings had won an award of the British Institute of Administrative Management(BIAM), between 1978 and 1981.

Table 5.1 DISADVANTAGES & ADVANTAGES ASCRIBED TO DAYLIGHT.(Cooper & Crisp 1984)

Disadvantages mentioned	Frequency of mention.	Advantages mentioned	Frequency of mention.
Problems from solar gain or direct insolation.	15	Psychological or emotional benefits arising from contact with outside.	12
Problems arising from glare.	14		
Variability of intensity of daylight.	9	Variability of intensity of daylight.	7
Need for controls or shading.	6	Quality of daylight/ satisfaction of building occupants' preferences for daylight.	6
Heat loss through windows/ cost implications in terms of construction or energy consumption.	5	Directionality & modelling effect/ free nature of resource.	5
Lack of control over daylight.	4	Reduction in energy consumption.	4
Constricting effect on possible form of buildings/ down draught due to large glazed areas.	3	No advantages stated.	3
Inadequate penetration of daylight.	2	Incidence of sunlight.	2
Risk of condensation/ problems relating to obstruction.	1	Intensity of illumination/ passive heat gain in winter.	1

The report listed the advantages and disadvantages ascribed to daylight(Table 5.1), and also identified, from the interviews conducted, that there was a lack of credibility that the exploitation of daylight could be significant in terms of energy use in non-domestic buildings in the UK, and a lack of information and simple design aids to enable designers to address this issue. The BRE issued a digest on energy conservation in electric lighting(BRE 1979) to ask designers to consider ways of reducing the consumption of lighting installations in buildings, by planning to optimise the use of energy for lighting. The digest concentrated on the need to choose lamps which were energy efficient, reduce the use of electric lighting by sensible controls, and use task lighting were appropriate.

5.5 From the mid 1970's, the Commission of European Communities undertook research and development work on solar energy in buildings. These programmes were primarily concerned with solar collectors in active water, space heating and storage systems. In 1984 the first European Communities conference on solar heating was held in Amsterdam(Oulden 1984). During the early 1980's, architects were very interested in the idea of using large glazed spaces in their buildings, and in 1983 the architect's journal published a series of articles on atria and conservatories. The first(Hawkes 1983) explained the principles of an atrium, and analysed the atrium of Yatley primary school. The second(Baker 1983a) described the Locksheath school, the conservatory of which was regarded as important, both spatially and as a solar energy system. The third article(Baker 1983b) described the advantages and physical characteristics of atrium spaces, and their winter and summer use. The following year, Gordon Nelson wrote an article(Nelson 1984), which described three Hampshire school designs, which incorporated sun-spaces:

(i) Crestwood secondary school, Eastleigh, with a glazed, curved street, providing a dry circulation route between the two halves of the accommodation;

(ii) Yatley primary school with an atrium used as a sheltered buffer space, and for exhibitions, and

(iii) Netley Abbey infants school, with a conservatory designed to provide pre-heated ventilation air, and save energy.

In 1985, a British Standard code of practice BSI 8207 was issued for energy efficiency in buildings(BSI 1985a). The code drew attention to the need to consider energy requirements at the conceptual stage of design, and was based on a check list linked to the plan of work of the Royal Institute of British architects. The code did not recommend any particular method of calculation, and an associated design guide was published(BSI 1985b), which provided worked examples on the application of the code to the early design stages of eight case studies. One of these was a small primary school, and the method of assessment used was design note 17(DES 1981b). The procedure called for a method of estimating an energy requirement, as part of the analysis of the brief, for use as a design target and that design ideas or options should be assessed in terms of energy loads, and cost-effectiveness.

5.6 The UK branch of the International Solar Energy Society held a conference in 1985 on aspects of the thermal behaviour of greenhouses and conservatories. A paper was presented on the thermal design of conservatories for ventilation pre-heating(Baker 1985), identifying three main types of passive solar systems: conservatory; direct gain, and Trombe wall. The paper predicted diminishing benefits from two modes of obtaining useful heat from conservatories in that:

(i) the traditional buffer effect of a conservatory, would reduce as buildings become better insulated;

(ii) the transfer of useful solar gains by natural convective or fan assisted circulation to adjacent accommodation, since studies in the UK had shown that, air temperatures in conservatories were only infrequently above the temperature of adjoining rooms during the heating season, and examined the effectiveness of using conservatories to provide solar ventilation pre-heating(SVP) of fresh air to the adjoining spaces.

A computer model was used to simulate the air flow in a three bed-roomed semi-detached house. The conclusions reached were that:

(a) wind driven ventilation results in a wide variation of ventilation rate and airflow direction, and the best strategy is to shelter the building and allow for ventilation by a natural buoyancy stack effect;

(b) SVP is likely to be the main mechanism by which a conservatory saves energy, at least in a well insulated building;

(c) the SVP contribution can be maximised by careful control of air permeability and factors including sheltering, built form, and the heating system design and controls, and

(d) further simulation work, using a more powerful thermal/air flow model is needed to assess the conclusions more thoroughly.

The second UK-ISES conference was held at Cranfield in 1986, and a paper was presented on Atria and conservatories(Baker 1986), which reported sample air temperatures for a week in February and in June, recorded at the unheated atrium building of Cambridge Consultants, to demonstrate that: the higher than ambient temperatures in the atrium will reduce conduction heat loss from the main accommodation in winter, and could offer the possibility of pre-heating air for ventilation purposes; whereas the maximum atrium temperatures during the June week were only three degrees above the maximum recorded ambient temperature, which indicated that overheating of the atrium could be controlled by shading and ventilation, and, if the floor and wall surfaces of the atrium were massive, night ventilation from stack effect, could be used to reduce the day-time environmental temperature of an atrium. The conclusions were that the energy performance of heated or unheated glazed spaces depends upon factors including area, shape, relative insulation values of glazing and walls, occupancy patterns and heat emitters. With regard to unheated atria, these could increase the energy use in lighting and mechanical ventilation of the adjacent building, and the atrium is likely to perform mainly by reducing the conductive losses from surrounding walls, whereas the conservatory has the potential for major energy saving by SVP mechanism.

5.7 By the mid 1980's there was considerable interest in climate sensitive architecture, but a shortage of information available in a form suitable for design teams to use. The European Communities passive solar programme was underway, and a preliminary edition of a designers handbook was published to provide advice on passive solar architecture(Achard & Gicquel 1986). This provided a brief account of passive solar design principles, a review of fundamental aspects of heat transfer, climate, solar position calculations, and thermal comfort. Section five dealt with passive solar design strategies and surveyed the tools available for shading calculations, daylight, and thermal calculations, using manual and computer methods. The methodology presented for calculating the availability of daylight in buildings was limited to the use of BRE daylight factors. Twenty-six computer thermal simulation programs were reviewed, with a listing of the main features available, either for use on main-frame or personal computers. Twelve of these were considered suitable for passive solar applications, of which only seven were readily available. Those identified as available, good, and easy to use were: ESP, DOE2, and SUNCODE. (In this review Seri-Res was described as Suncode). Seventeen illustrated building case studies were provided and dealt mainly with domestic applications.

5.8 An international conference on energy and the built form was held in 1986 at Cambridge. A paper was presented on glazed courts, or atria as a low energy city building form(Hawkes & Baker 1986). The authors presented the case that:

(i) such spaces, by making maximum use of daylight, natural ventilation in summer, and a compact form with the benefit of solar gains, can provide a high quality working environment in the British climate at considerable energy savings when compared with air conditioned offices.

(ii) glazed arcades and shopping centres, provide a sheltered, traffic free, environment for commercial use with social and financial benefits, and can also reduce the energy consumption of adjacent buildings.

From their analysis of a competition design for a three and four storey urban commercial development with intervening space, and using a simple steady state thermal model, they concluded that the space heating load for the development could be reduced by 22%, simply by glazing over the open space, and an overall reduction of 35% was possible if the resultant atrium was used to pre-heat the ventilation air to the rooms facing the arcade. They also warned that most atria, many of which are heated, cooled, mechanically ventilated, and occasionally lit by electric lighting during daylight hours, consume more energy than they save.

5.9 The Watt committee published a report on passive solar energy in buildings(O'Sullivan 1988). This report included an article on the use of passive solar energy in schools(Curtis 1988), which was substantially based on extracts of the earlier BDP report(Duncan & Hawkes 1983). The Watt Committee report concluded that, since central government had, for the first half of the century, promoted school sites and buildings with southerly aspects, there was great potential for the use of passive solar energy in school buildings, particularly through the use of better control of electric lighting, and the increased use of daylight. The report noted that conservatories added to a south face of a low insulated wall can provide extra amenity, as well as an overall reduction in energy use, but are rarely justifiable in their own right, and that an atrium provides a most attractive increase in amenity, for minimum energy use. No evidence was cited for these assessments of the worth of such passive solar features. The report lists ten examples of passive solar schools, which were considered of interest They included examples of schools with solar collector walls, conservatories, and atria. There was insufficient monitored information about the thermal performance, and the report concluded that to realise the potential identified(Duncan & Hawkes 1983), technical barriers need to be overcome, and design tools and performance data provided to design teams, who must be made aware of design concepts involved, and provided with information on cost benefits and successful examples.

5.10 In 1988, the BRE published a report on daylighting as a passive solar option(Crisp et al 1988), which included an assessment of the visual consequences of the passive solar design of St George's school, Wallasey, which was critical of the amount of glare evident from the very large areas of glazing of this design. Overall, however the report concluded that there was clear evidence of the attractiveness for reducing energy consumption, and achieving cost benefits from exploiting daylight in a range of non-domestic premises. The report recommended that the lighting code(CIBSE 1984), window design guide(CIBSE 1987), design note 17(DES 1981b), building regulations(DOE 1985), and British standard 8207(BSI 1985a) should be reviewed for possible amendment in terms of technical content and the underlying assumptions, which may inhibit the exploitation and beneficial effect of daylight in building design solutions.

5.11 An unpublished report was prepared by the Department of Applied Energy at Cranfield University(Hobday & Norton 1989), based on the survey of schools in the United Kingdom(UK) carried out to identify the extent to which passive solar schools had been provided. This identified 27 existing and 5 proposed school buildings, which were considered to be primarily passive solar, 6 with some passive solar features, and 9 which were not passive solar, but merited comment.

5.12 During the 1980's the research programmes of the European Communities were changed to reflect the growing interest in bioclimatic, and passive solar architecture applications. By the end of the decade, 85% of the 1989 research programme on solar heating was allocated to passive solar research and technology. Working in the City was the title of an architectural competition, promoted to encourage and attract the interest of designers in passive solar design solutions. It emphasised the need for climate sensitive designs, and daylight in passive solar architecture, particularly in working environments, and teaching spaces. The competition was educational, because entrants were issued with an information pack, which included stereographic suncharts, a daylight factor meter kit for self assembly, and background information on daylighting design, and related thermal performance. A means of evaluating this(LT method) was explained, and illustrated. This was a significant improvement on the previously available advice and procedures for evaluating daylight design. There were 186 entries for the competition. Details of the competition and results were published (O'Toole & Lewis 1990).

5.13 Two papers on daylight as part of a low energy strategy were presented at the CIBSE national lighting conference in 1990. One described the design for a competition for a speculative commercial building capable of being used for display, office, research, production or storage(Venning 1990). The design solution featured north-lights and a calculated average daylight factor of 5.6%, and the electric lighting installation was designed and controlled to take account of daylight distribution. The theoretical study was based on a weekday occupancy period 8 am to 6 pm, and 2500 hours per annum. Projected savings of 41% in energy costs were estimated using daylight modelling and thermal simulation studies, compared to a building complying with the CIBSE energy code part 2A. The cost of the lighting control installation had an estimated payback period of 1.4 years. The design solution was accepted and built, however the problem of how the building will be used was unresolved. The other described the use of the Anglia polytechnic Daylight program, and Seri-Res to evaluate the daylight and thermal performance of a well insulated and double glazed study centre at Machynlleth, in Wales(Wilson et al 1990). The glazing area of the initial design solution was varied by +20% and +40%. The minimum and average daylight factors were calculated for different grid sizes, demonstrating that, as expected, the minimum daylight factor increases with fewer grid points. A test reference year weather file(Anon 1985a) was used without any assessment of its relevance to the location of the proposed building. Thermal simulations were carried out for a range of glazing specifications and daylight factors. The conclusions were that the initial design was not over-glazed, most daylight benefits were achieved from daylight factors of between 2% and 4%, and there was some small improvement possible from an increase of glazed areas, but the scope for savings was small.

5.14 Databuild(Anon 1991) produced a report containing an overview summary of 48 case studies of passive and hybrid solar commercial buildings from twelve countries, which included an interim report on Netley Abbey school, based on the monitoring results of the Energy Monitoring Company, and collaboration with the original energy advisor for the design. The building was occupied in September 1984. There were problems during the first heating season attributed to both the building systems and monitoring arrangements. By the start of the second heating season the monitoring difficulties had been resolved, but energy performance in 1985-86 was reportedly worse than expected, and considerable difficulties were experienced in the use and function of control systems. By the third heating season during 1986-87, the systems problems were resolved, and the databuild report concluded that the:

(i) systems commissioning and control design were initially unsatisfactory, and occupants were dissatisfied with conditions during the first two years of occupation;

(ii) third year fuel bills were below comparable schools built at this time by Hampshire County Council, but more attention should have been paid to reducing electricity loads, both by better fan and pump controls, and better daylighting, and

(iii) The use of the unheated conservatory had proved satisfactory.

The final report produced by Databuild(Hobday et al 1992), concluded that the Netley school was less expensive to build than a typical non-solar school, benefitted from the buffering and solar gains obtained from the conservatory, was efficient in the use of energy, with an excellent energy performance, but the stack-effect strategy for ventilation of the school did not achieve satisfactory levels of air quality, and the winter ventilation using pre-heated air as fresh air was not entirely satisfactory. Tests had supported the occupants' unfavourable view of the air quality within classrooms. The report noted that the occupants' would have preferred windows, which opened to the exterior of the building. An energy data analysis by the Energy Monitoring Company is included, indicating that the annual energy consumption per square metre of gross floor area(GFA) was 87 kWh. This would convert to 183 kWh m^{-2} Primary Energy Units(PEU), using the DN17 fuel conversion factors, and although the school has a gross floor area of 1035 m^2, only 835 m^2 is heated. The equivalent annual energy consumption figures per square metre of heated area would be 227 kWh PEU. Databuild also produced a report for a seminar on passive and hybrid solar commercial buildings(Seager 1991), which contained a summary report of the energy monitoring of Looe Junior and Infants school in Cornwall by the Welsh School of Architecture(Alexander et al 1991).

Summertime overheating was a perceived problem, although the physical monitoring did not support this. Poor air quality was a major concern of the staff, and infiltration tests indicated an infiltration rate of 0.25 ac/h. The design of windows did not permit any improved controllable rate of infiltration, when the weather was unsuitable for opening the windows. A Trombe bench was installed, but was unsuccessful. There were also staff complaints of insufficient daylight in the classrooms, and the measurements indicated that the average daylight factor at desk height was less than 2%. Overall, the staff were complimentary about the school design, and working conditions. The energy performance assessment (Alexander et al 1990) showed that: the energy consumption of the school was 210 kWh m^{-2} PEUs; overnight infiltration was very low, typically 0.2-0.4 air changes per hour, and the Trombe bench was not really effective in either storing solar energy to reduce peak solar gains and temperatures, or as an energy source, warming and circulating internal air.

5.15 A more up to date version of the Passive Solar handbook of the European Economic Communities was published (Goulding et al eds 1992) to help designers, who are involved in creating the built environment, to adopt environmentally sensitive design strategies, heighten the general awareness of climate, and use available design tools and technologies. The section on daylighting design included the design tools developed and used in the Working in the city competition.

5.16 The comment and references associated with the case studies considered in this study, are included in the proposed building bulletin on passive solar schools in the UK. A list together with some sample case studies and associated references is included as appendix E.

School fuel costs, energy use, and CO_2 emissions.

5.17 The Department of Education and Science issued a Broadsheet no 29 (DES 1992) on energy use in educational buildings. This showed that the overall expenditure on energy declined from about 2.9 per cent of the total expenditure on education in England in 1980/81 to 1.75 per cent in 1989/90. In LEA schools the expenditure on oil, coal, gas and electricity was £450 million in 1980/81, and £323 million in 1989/90, which represents a saving on fuel purchasing of about 28 per cent. Thermal energy costs represented around sixty per cent of the total energy costs in education buildings, and over this period the thermal energy costs reduced from £303 million to £186 million. This represents a saving of expenditure on thermal energy of approximately thirty nine per cent over the ten year period. It is better than the overall saving, and reflects:

(i) the effectiveness of energy thrift measures taken during the period to improve draught stripping, insulation, boilers and controls,

(ii) the switch from oil to gas, which has generally been cheaper throughout the period, giving gas an increased market share from 37% to 54%, and reduced oil prices in the latter part of the period, and

(iii) reductions due to school reorganisation and closures from falling school rolls.

Annual thermal energy costs per pupil during 1991/92 was £25.70, but it is more significant in terms of energy use to consider the consumption of fuel. During the decade a reduction in total energy consumption amounted to only eight per cent in Giga-Joules, suggesting that only about one third of the financial savings on fuel use are attributable to the more efficient use of energy.

5.17 The relatively small reduction of eight per cent in overall energy consumption was important. It was assessed as representing a fourteen per cent decrease in total annual emissions of CO_2, from an estimated 6.4 million tonnes in 1980/81 to 5.5 million tonnes in 1989/90, when the changes from coal and oil to gas was taken into account. Although electricity consumption represents only 12.6% of the use of fuel by LEA's, in financial terms it represents 42% of LEA expenditure on fuel. The results of the DES analysis show that electricity consumption increased in real terms during the decade from 9.14% of fuel use in 1980/81 to 12.6% by the end of the decade, regardless of the reduction in school places which had occurred. The annual electric energy costs per pupil were £19.00 in 1990/91. The DES concluded that there is still considerable scope for energy savings in schools, and that efforts should be directed towards better housekeeping, improvements to building fabric, removal of surplus places, particularly HORSA buildings and temporary classrooms, and reducing the use of electrical energy.

Seri-Res.

5.18 The Seri-Res model has been used for both inter-model, and empirical comparisons(Judkoff 1988) in which the energy use predictions of Seri-Res and ESP both matched the measured energy use, and there is considerable evidence supporting the validity of the model, since the algorithms are available for examination. In a joint SERC-BRE validation, Seri-Res predictions were in the mid range of the models tested including ESP, Blast, and DOE-21. (Bloomfield 1990) No internal errors were detected in Seri-Res in a three level validation procedure of Lomas, and it was deemed to be validated at level 2. (Lomas 1991) The Energy Monitoring Company reported on a number of calibration studies appropriate to the use of Seri-Res. Three of particular interest, related to work carried out using the ETSU test cell facility at the Cranfield campus, to assess the:

(i) way incoming solar radiation is distributed between the elements of a room, compared to the default distribution in the Seri-Res model.(EMCO 1990a);

(ii) influence of window size and room colour on the fraction of incoming solar radiation reflected back out of a room, in order to quantify the solar lost parameter of Seri-Res (EMCo 1990b), and

(iii) accuracy of predictions of building performance made by the Seri-Res model compared to test cell measured performance. (EMCo 1991)

Table 5.2 SOLAR-LOST VALUES: MEASUREMENT & SERI-RES USERS ESTIMATES. (EMCO 1990a)

	MEASURED	SERI-RES USERS ESTIMATES OF SOLAR-LOST.		
ROOM	SOLAR-LOST	CAP	PCL	BRE
All White interior surfaces and Large window	31% +/- 5%	5%	10%	5%
All White interior surfaces and Small window	16% +/- 5%	5%	5%	2%
White surfaces plus black floor Large window	17% +/- 4%	5%	5%	4%
White surfaces plus Black floor Small window	5% +/- 9%	5%	5%	2%

KEY CAP = Cap Scientific. (Roger James), BRE = Building Research Establishment. (David Bloomfield)
PCL = Polytechnic of Central London. (Paul Ruyssevelt)

They found that the default distribution of solar radiation within Seri-Res is adequate for rooms with internal finishes of uniformly light internal finishes, but may be seriously in error for non-uniform finishes. They also found that solar lost varies considerably with window size and internal finishes, and that the values computed from the test cell measurements were much higher than those used by current practitioners using Seri-Res as indicated in table 5.2. The comparison of the measured performance of the test cell and that simulated by the Seri-Res model demonstrated that, the model predicts the performance of unheated rooms well. However, when auxiliary heat was introduced to the test cell, prediction errors occurred. They attributed this error to the dynamics of the heating system used, and the interaction between the heat source and the room air and surfaces, in a somewhat unrealistic room size.

6.0 THE TWO SCHOOLS WITH CENTRAL ATRIA.

6.1 Six school buildings had previously been selected by a steering committee of the Department for Education & Science(DES) for monitoring and analysis to assess the use of energy during a monitoring period.(Harris 1991) Two of these were first schools, each with a central atrium used for teaching purposes. One atrium was heated and the other unheated. The Hook school had been remodelled from an earlier Scola system-built school(of which there are many examples in existence), and the Barnes Farm school was purpose built, using traditional construction methods. The DES were particularly interested in an assessment of the all-year round thermal performance of the design of both schools, using a method which could assess the useful solar contribution to space heating and thermal comfort, the risk of overheating, and forecast the probable use of electric light, based on the availability of daylight. They were to be assessed in the present study, using the Seri-Res dynamic thermal model, and a weather year of Kew data, because the earlier monitoring period had been reduced to several months in which there was no winter weather data, and covered an unusual and prolonged warm spell. The original intention of the method adopted for this stage of the investigation was to:

(i) Survey Barnes Farm school, to confirm the materials used, details of the services and controls installed, and visit Hook school to confirm that the plans available were as built, and use the equivalent, detailed information, for Hook school from an earlier study(Waterfield 1989);

(ii) Analyse the data recorded at each school, to identify anomalies, inadequacies, or additional information or tests required;

(iii Prepare weather files from the recorded data to represent conditions on each site during the monitoring period;

(iv) Obtain information on how each school was actually used throughout the school year in which the monitoring occured.

(v) Compile building descriptions files for both schools from information supplied, and the working drawings available, and calibrate the performance of the computer model by comparing predicted and measured fuel consumption and zone temperatures, in the atrium and adjoining class-bases, and where possible, identify the possible causes of any major discrepancy;

(vi) Use one year of Kew weather data, and computer simulations, to estimate the thermal performance of the schools, and compare the results with the DN17 guideline for annual energy consumption.

6.2 Information is presented on the: two schools buildings studied, and the associated monitoring schemes, with examples of the analysis and use of the performance data for the

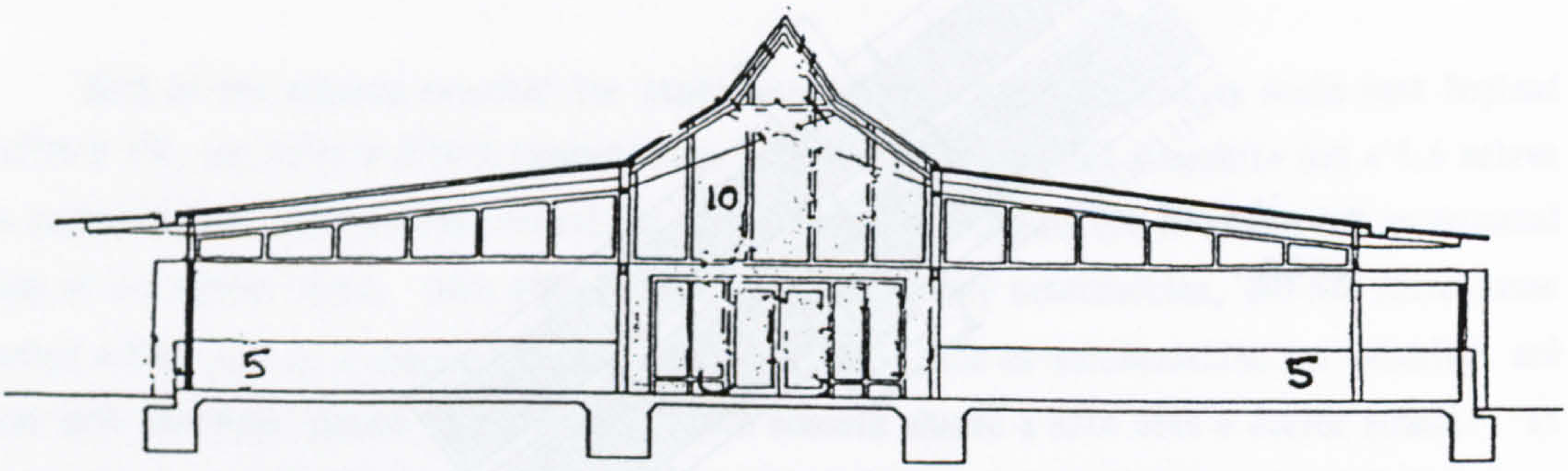


Figure 6.3 Section at Hook.

6.5 Barnes Farm school was of traditional construction, built to moderate insulation standards, with load-bearing dense concrete block cavity walls, and was mainly single glazed, having been built to a design incorporating the Atrium as a covered and lightly enclosed outdoor space.

Plate 6.2 Barnes Farm.

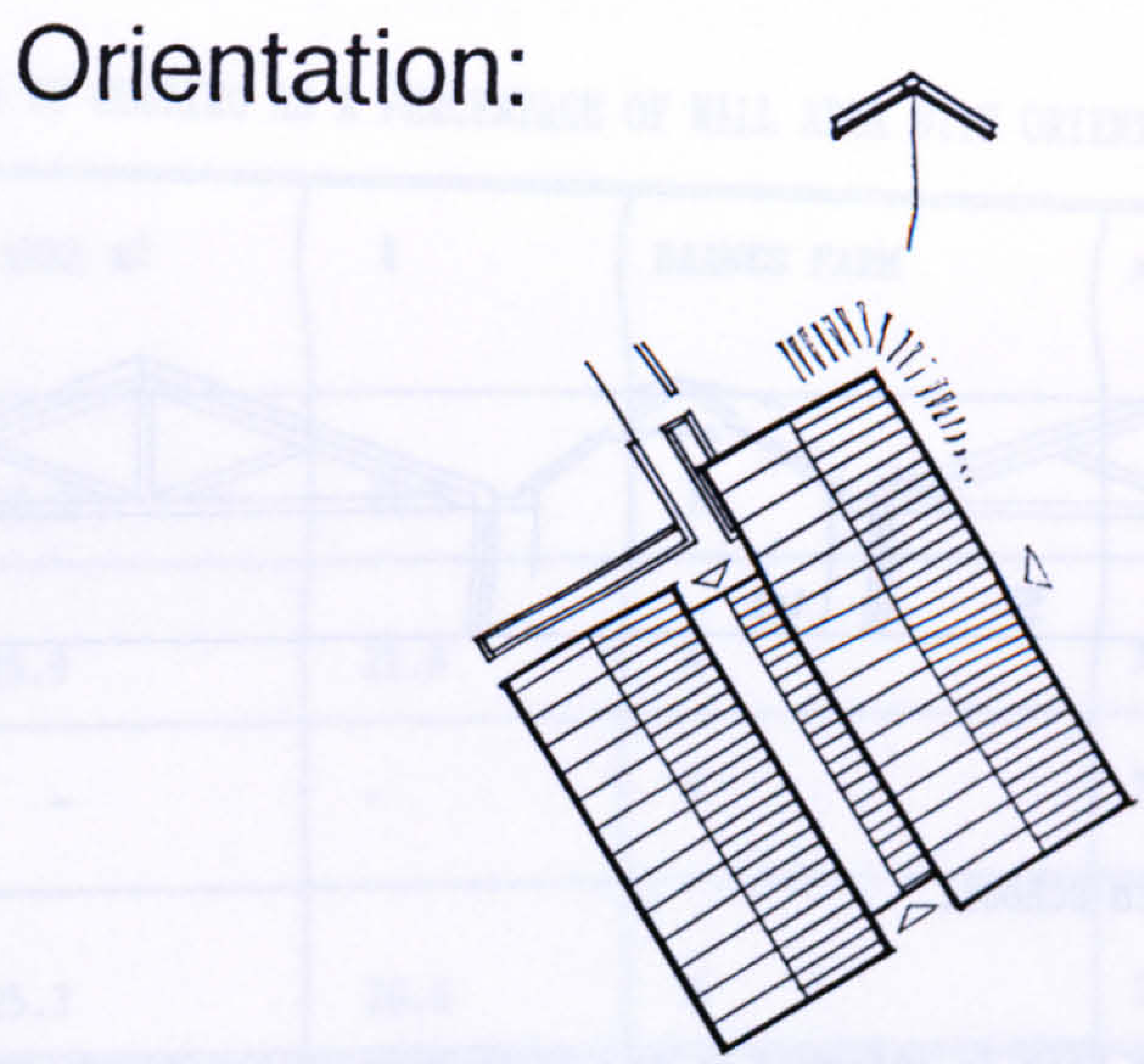


Figure 6.4 Block plan.

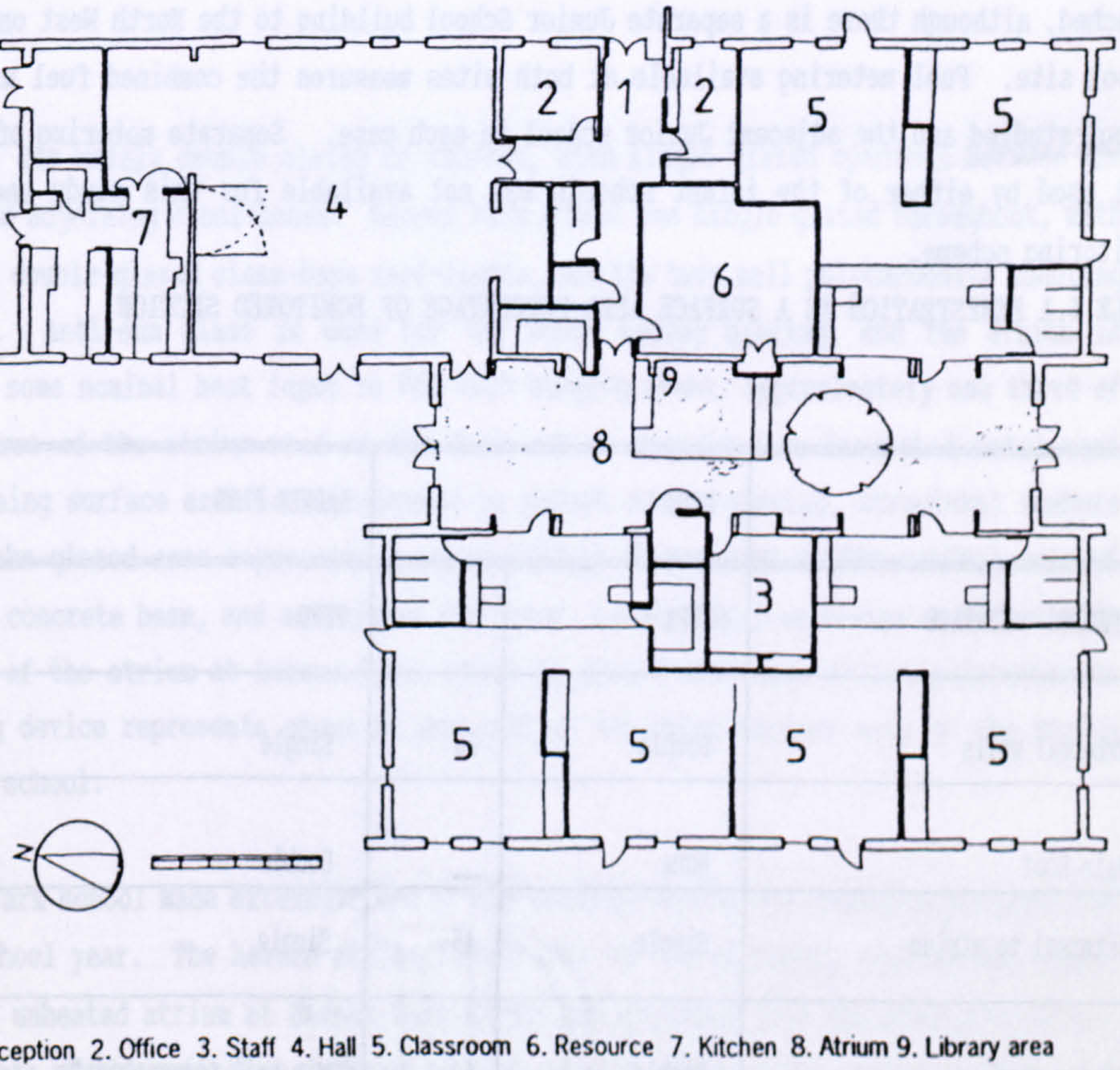


Figure 6.5 Plan.

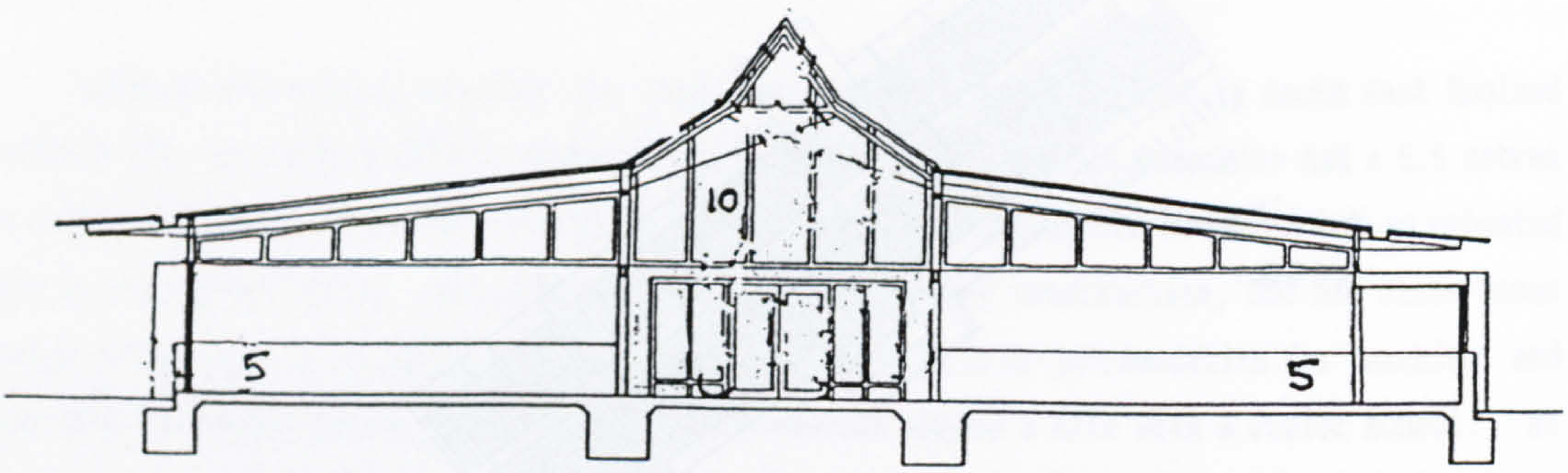


Figure 6.3 Section at Hook.

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Plate 6.2 Barnes Farm.

Orientation:

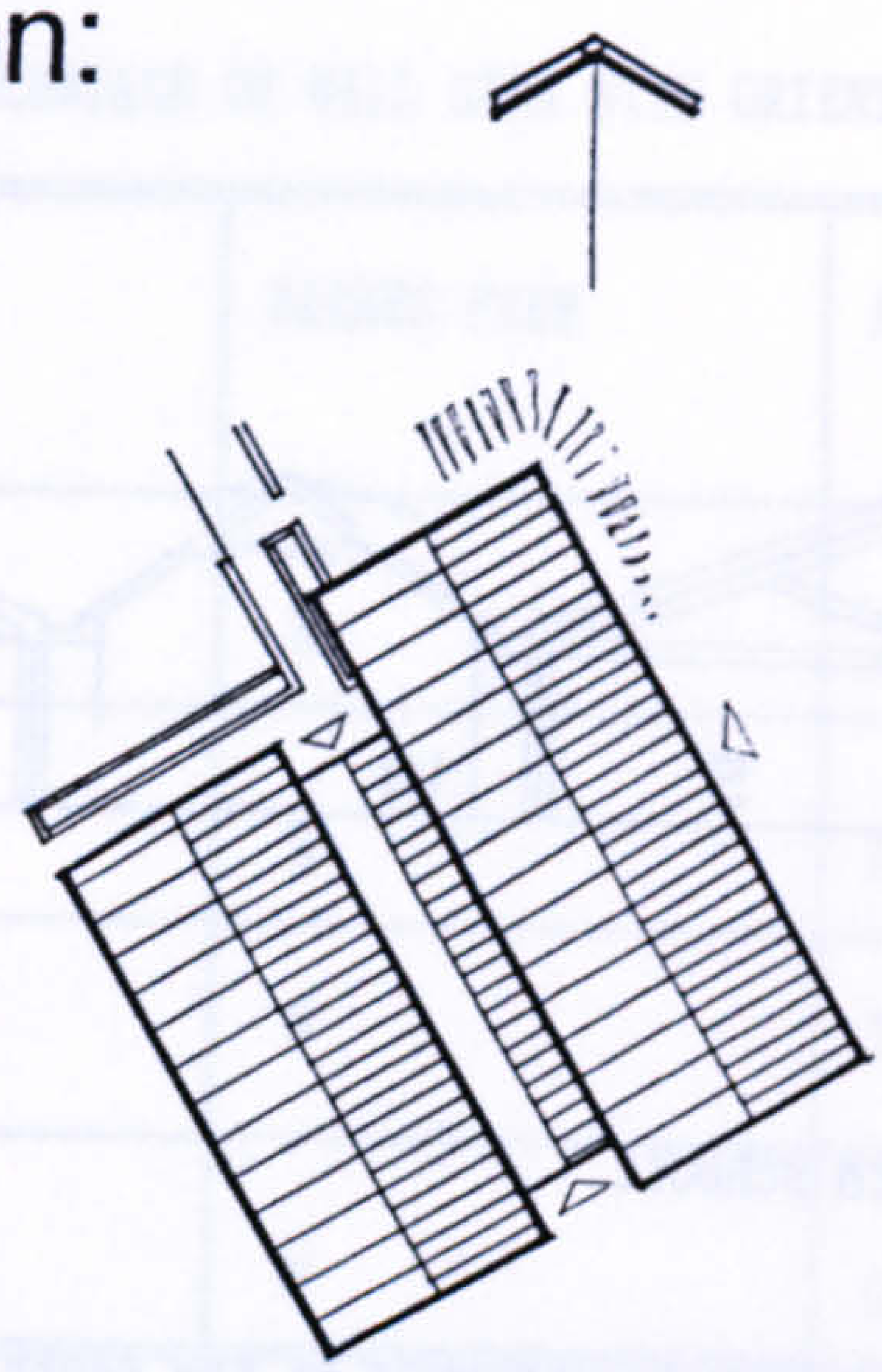
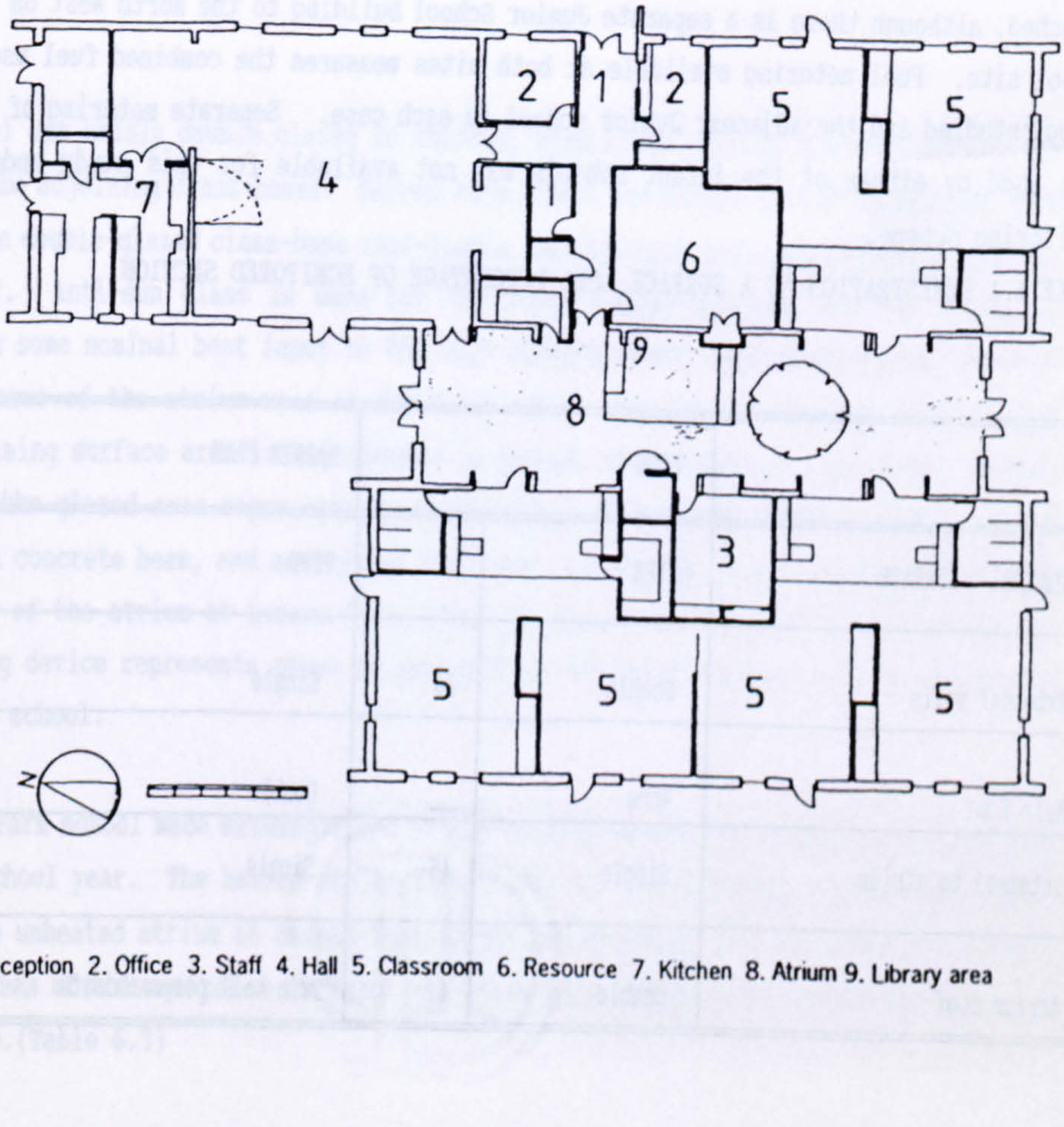


Figure 6.4 Block plan.



1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Resource 7. Kitchen 8. Atrium 9. Library area

Figure 6.5 Plan.

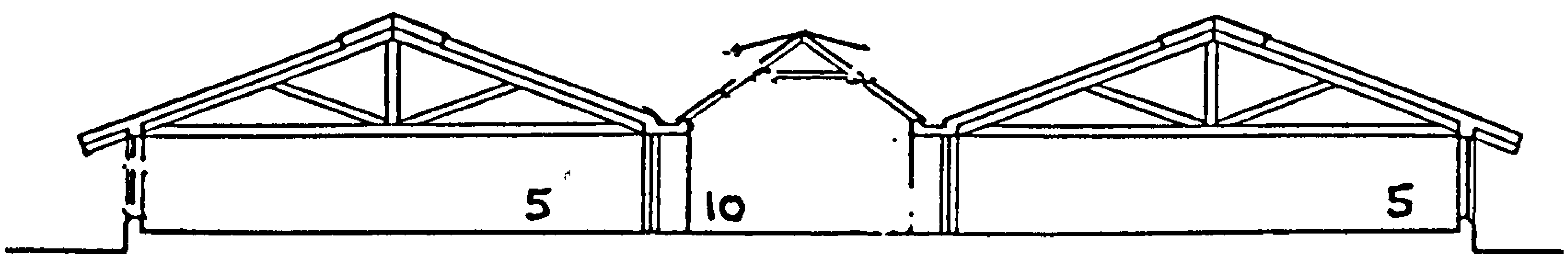


Figure 6.6 Section Barnes Farm school.

6.6 The Junior school at Hook is attached to the South East of the First school. The link with the Junior school provides Hall/Dining, Kitchen and Gymnasium accommodation, which is outside of the area monitored for this study. Barnes Farm school is self contained in this respect and detached, although there is a separate Junior School building to the North West on the Barnes Farm school site. Fuel metering available at both sites measures the combined fuel use of the Infant school studied and the adjacent Junior school in each case. Separate metering of the quantity of fuel used by either of the infant schools was not available for this study under the reported monitoring scheme.

TABLE 6.1 FENESTRATION AS A SURFACE AREA PERCENTAGE OF MONITORED SECTION.

	HOOK		BARNES FARM	
GLAZING SURFACE	TYPE	%	TYPE	%
External walls	Double	26	Single	22
Main Roof	None	—	Double	4
Internal to atrium	Single	45	Single	41
Atrium roof	Double	62	Twin wall polycarbonate	76

TABLE 6.2 VARIATION OF GLAZING AS A PERCENTAGE OF WALL AREA WITH ORIENTATION.

HOOK	AREA m2	%	BARNES FARM	AREA m2	%
NW	30.0	41.5	N	21.6	22.4
NE	25.9	21.8	E	16.6	16.8
SE	-	-	S	33.1	34.3
SW	25.3	20.6	W	15.1	15.2

6.7 Hook school was mainly double glazed to ambient, with single glazed openings between the heated atrium and the adjoining class-bases. Barnes Farm school was single glazed throughout, with the exception of the double-glazed class-base roof-lights, and the twin wall polycarbonate sheeting to the atrium roof. Anti-sun glass is used for the South facing glazing, and the atrium is unheated apart from some nominal heat input to the coat hanging areas. Approximately one third of the total surface area of the atrium roof at the Hook school comprised an insulated metal roof deck, and the remaining surface area is represented by patent double glazing, structural members and flashing, with the glazed area representing approximately 62 per cent of the surface area of the atrium roof. A concrete beam, and associated flat roof, forms a shading device on either side of the pitched roof of the atrium at Barnes Farm, which is glazed with twin walled polycarbonate sheets. The shading device represents about 24 per cent of the total surface area of the atrium roof at Barnes Farm school.

6.8 The Barnes Farm school made extensive use of the unheated atrium for teaching purposes for most of the whole school year. The heated atrium formed part of the statutory area of the school at Hook, whereas the unheated atrium at Barnes Farm school was excluded from the statutory school area. The heated areas of the monitored sections of both schools included the atrium at Hook, and were of similar size.(Table 6.3)

Plate 6.3 Interior of the atrium at Hook school.

Plate 6.4 Interior of the atrium at Barnes Farm school.

TABLE 6.3 SIZE OF MONITORED SECTIONS

ITEM	HOOK	BARNES FARM
Areas: (i) total (ii)heated	676.3 m^2 676.3 m^2	840.2 m^2 700.7 m^2
Atrium: Area Width Length Mean Ht Max Ht	132.0 m^2 5.5 m 24.0 m 4.5 m 5.4 m	139.5 m^2 6.2 m 22.5 m 2.89 m 3.8 m
Class-base:Depth(new) Mean Ht(new) Depth (old) Mean Ht(old)	7.2 - 9.0m 3.3 m 7.2 - 9.0m 2.3 m	11.0 m 3.55 m N/A N/A

6.9 The original SCOLA mark III school at Hook was built in 1973. The oil fired boilers were converted to gas, when the school was remodelled and refurbished in 1988. The space heating was achieved using radiators, and that at Barnes Farm school was heated by gas fired boilers with a conventional wet radiator system. Although there was no provision for space heating in the Barnes Farm atrium, three small low level heating coils were provided under coat hanging positions in the atrium, for drying purposes in wet weather. The Hook atrium had small top-hung, cord-operated opening lights in the atrium roof. The staff complained of overheating, that the few vents provided malfunctioned, were ineffective, and that their staff room, on the mezzanine level under the atrium roof, was unusable in warm weather. In contrast, the atrium at Barnes Farm was provided with a large, mechanically operated, continuous butterfly opening light to both sides of the ridge. This was motorised, and designed to be automatically controlled. Following installation, it had been modified to operate in manual mode only. This change resulted in the atrium overheating prior to the vents being opened manually, presumably because the shared atrium space was not the responsibility of an individual member of staff. However the staff reported that, whenever the vents were opened in overheated conditions, they were immediately effective.

6.10 Both schools were monitored under an earlier research project,(Harris 1991) with the intention of observing the normal way in which the buildings were heated, vented and lit, and to record the weather during the monitored period. To achieve this, sensors and instruments were installed, and readings taken every five minutes. A data logger, manufactured by Delta-T Devices was used to store the hourly mean values in binary format. The data channels allocated are defined in the monitoring scheme. The first task of the present study was to write computer programs to access and analyse the data collected, for use with the computer models described. Some problems were encountered due to the limitations of the monitoring arrangements.

The monitoring scheme.

6.11 The measurement scheme involved:

(i) Global and diffuse horizontal solar irradiance
(ii) Ambient air temperature
(iii) Internal mean radiant and air temperatures
(iv) Status of doors and windows (open or shut)
(vi) Surface temperatures of radiators & heating pipes

The solarimeters used were manufactured by Casella, of Wolsley Road, Kempston, Bedfordshire, for the spectral range 0.3 to 3.0 μm. The response time was stated to be 17 seconds to 66% of the final reading, and the temperature dependence was +/- 1^0 C over the range -20^0 C to +50^0 C, and the cosine response was given as +/- 2% from normal to 70 degrees from normal. The thermocouples used were of copper-constantin type T, manufactured by Micron Sensors & Cables, of 89 Kirkwood Road, Lewston Farm Estate, Luton. The repeatability claimed was +/- 0.25^0 C.

6.12 The following items were not included in the monitoring scheme, and the diffuse irradiance measurements taken were unusable:

(i) Direct beam irradiance
(ii) hours of bright sunshine
(iii) Air movement
(iv) Wind speed and direction
(v) Dew point temperature
(vi) relative humidity
(vii) Metering of energy used

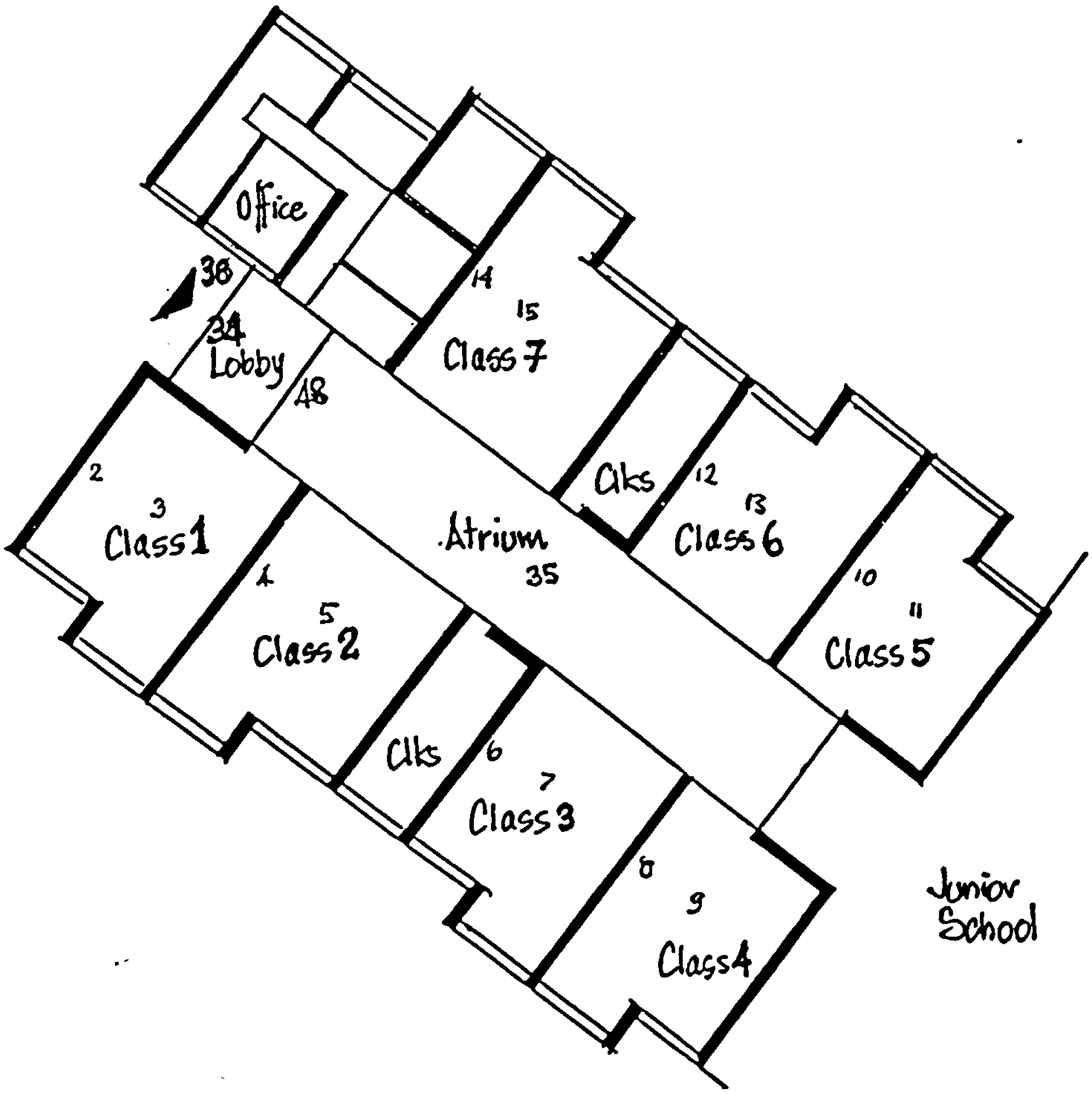


Figure 6.7 Location of sensors at Hook school.

In the following tables, 6.5-6.9, the abbreviation CR signifies classroom.

Table 6.4 Solarimeters installed at Hook school.

CHANNEL	TYPE	LOCATION
34	Global horizontal	Ridge of atrium roof
35	Global horizontal	Interior of atrium
48	Diffuse horizontal	Ridge of atrium

Table 6.5 Temperature sensors installed at Hook school.

CHANNEL	TYPE	ZONE	CODE	TYPE	ZONE (height above floor)
2 3	AIR RAD	CR 1	14 15	RAD AIR	CR 7
4 5	AIR RAD	CR 2	16 17	RAD AIR	ATRIUM
6 7	AIR RAD	CR 3	18 19	AIR AIR	ATRIUM (3.0 m) (3.5 m)
8 9	AIR RAD	CR 4	20 21	AIR AIR	ATRIUM (4.0 m) (4.5 m)
10 11	AIR RAD	CR 5	22	AIR	ATRIUM (5.0 m)
12 13	AIR RAD	CR 6	38	AIR	AMBIENT

KEY. AIR = dry bulb air temperature, and RAD = black globe temperature.

6.13 The reed switches were manufactured by Radiospares Ltd, of Lamas Road, Corby. They had a 2000 ohm resistor, and were configured to read as follows:

Aperture closed for one hour, R = 0 ohms
Aperture open for one hour, R = 2000 ohms

The number of minutes per hour when the aperture is open being given by

$$N = 60 \times \frac{R}{2000} \qquad [6.1]$$

The sensing was at intervals of 5 minutes, recorded as the mean for one hour. There was therefore no indication of how wide an opening was formed and for how long. This measurement was only able to give a general indication of the pattern of use.

Table 6.6 Location of Reed switches installed at Hook school.

CHANNEL	TYPE	ZONE	CHANNEL	TYPE	ZONE
23	Door	External (Atrium)	28	Door	External (Atrium)
24		CR 1	29		CR 5
25		CR 2	30		CR 6
26		CR 3	31		CR 7
27		CR 4	32	Vent	Atrium roof
			33		

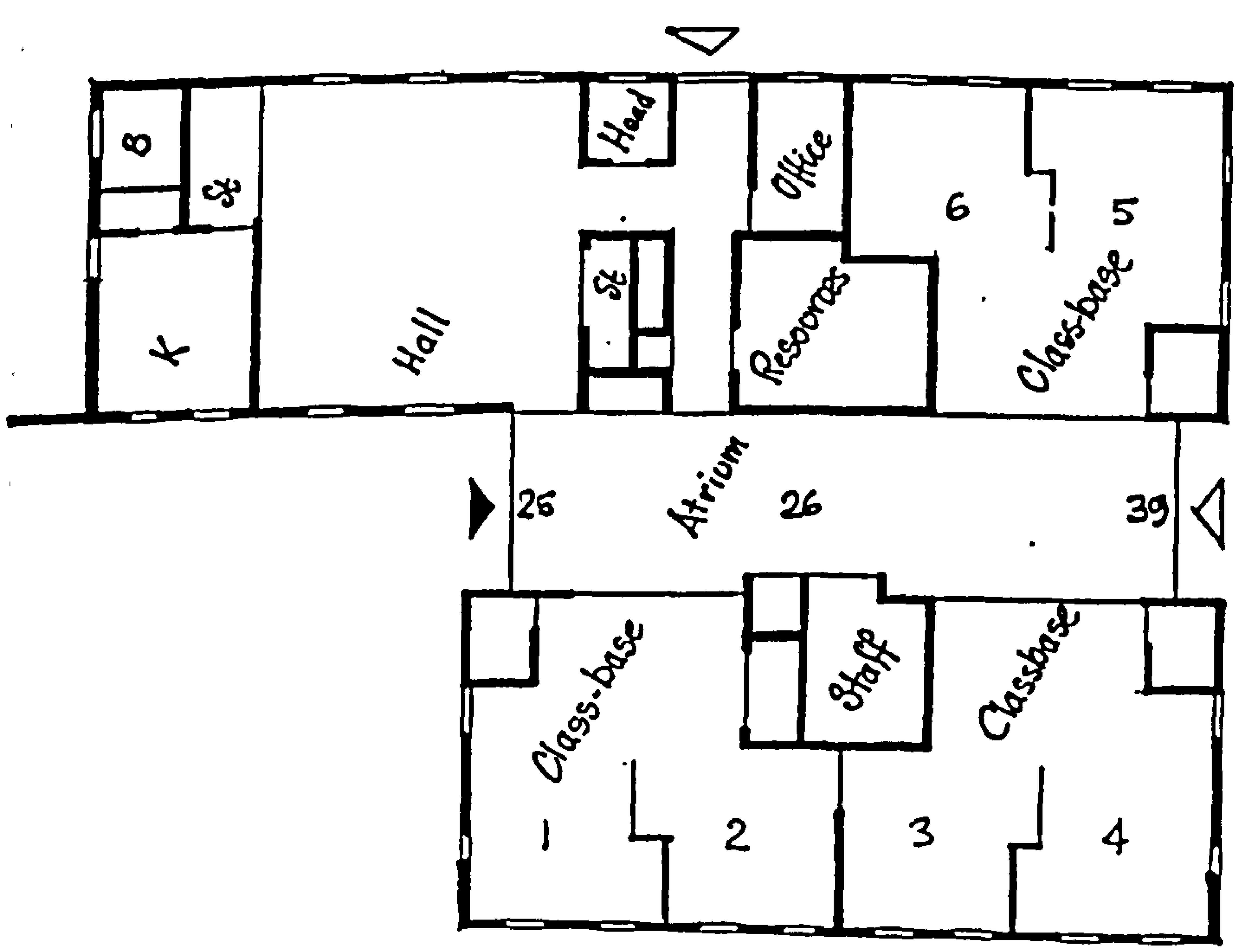


Figure 6.8 Plan of sensors installed at Barnes Farm school

Table 6.7 Solarimeters & light sensors installed at Barnes Farm school

CHANNEL	TYPE	LOCATION
24	photo-electric detector	CR 1
25	global horizontal	Atrium ridge external
26	global horizontal	Atrium internal
39	diffuse horizontal	Atrium ridge external

Table 6.8 Temperature sensors installed at Barnes Farm school.

CHANNEL	TYPE	ZONE	CHANNEL	TYPE	ZONE
2 3 4	Air Rad Air	CR 1	13 14	Air Air	Ambient
5 6 7	Air Rad Air	CR 2	15 16 17	Rad Air Air	Atrium
8 9 10	Air Rad Air	CR 3	18 19 20	Air Air Air	Atrium 2.5 m 3.0 m 3.5 m
11 12	Air Rad	Hall	21 22	Air Air	Atrium 4.0 m 4.5 m

KEY: AIR = dry bulb air temperature.
RAD = black globe temperature.

Table 6.9 Reed switches installed at Barnes Farm school.

CHANNEL	TYPE	ZONE	CHANNEL	TYPE	ZONE
27 28	door	CR 1 external internal	32	door	Hall internal
29 30	door	CR 2 internal external	33 34	vent	Atrium roof
31	door	CR 3 internal			

6.14 In order to assess the thermal performance of both schools using Seri-Res, and carry out some parametric analyses, it was necessary: firstly to amend the utility program of the logger used to read the measured data required for this study; secondly to prepare a weather file from the site data; thirdly to analyse some measurements, carry out tests, and a survey to determine input parameters; fourthly to produce a building description file for each school, and then to calibrate the model by comparing the predicted, and measured performance.

The Seri-Res weather files.

6.15 The weather file was prepared for each school, using hourly insolation and temperature data, which had been recorded for several months at each school as part of the earlier monitoring stage of the project(Harris 1991). However, there were periods when the recording of the data collected at each location was not continuous. Table 6.10 shows how this problem was resolved for the Barnes Farm school, ie a pre-conditioning period was generated by repeating the first day of real data for the requisite number of days. Gaps were closed by using linking days, which repeated the last and first day of real data on either side of periods of actual data. The model was calibrated by comparing Seri-Res output to days when measured results were available.

TABLE 6.10 NUMBER OF PRE-CONDITIONING & LINKING DAYS NEEDED TO ENABLE MEASURED WEATHER DATA TO BE USED TO CALIBRATION OF THE MODEL OF BARNES FARM SCHOOL .

	PRE-CONDITION/LINKING DAYS REQUIRED		MEASURED DATA AVAILABLE	
	No of Days	Inclusive dates	No of Days	Inclusive Dates
	25	19 Mar-12 Apr	32	13 Apr-14 May
	4	15 May-18 May	35	19 May-18 Jun
	5	19 Jun-23 Jun	27	24 Jun-20 Jul
	2	21 Jul-22 Jul	31	23 Jul-22 Aug
	8	23 Aug-30 Aug	32	31 Aug-01 Oct
TOTALS	44		157	

6.16 Table 6.11 indicates the required format and parameters for a Seri-Res weather file.

TABLE 6.11 SERI-RES WEATHER FILE FORMAT.

IRRADIANCE		TEMPERATURE		WIND
Direct Normal	Global Horizontal	Ambient	Dew Point	Speed
tenths of $KJm^{-2}h^{-1}$	tenths of $KJm^{-2}h^{-1}$	tenths of degree C	tenths of degree C	tenths of $m\,s^{-1}$
5 digits	5 digits	4 digits	4 digits	4 digits

6.17 The weather file for the school at Hook was prepared in a similar way. The real data started on the 5th May and ended on the 6th September. The gaps occurring in the real data were fewer, but of considerably longer periods. (15 days and 43 days respectively) There were also problems with the type of meteorological data collected, because only the global horizontal irradiance and ambient temperatures had been measured satisfactorily at each location, instead of the five parameters required. To resolve this problem, it was decided to use:

(i) constant values of 3 metres per second for the wind speed, and, since latent load calculations were not required, 15 degrees celsius was used for the dew point temperature, and

(ii) the correlation for Easthampstead in South-East England (Muneer & Saluja 1986) to determine the diffuse component of the measured global horizontal irradiance.

6.18 The procedure used to calculate the diffuse component of solar irradiance was as follows:

(i) Solar Time was obtained from the expression:

$$\text{Solar time} = \text{Local standard time} + 4(L_{st} - L_{loc}) + E_t \qquad [6.2]$$

(Whillier 1965)

where: L_{st} = the standard meridian for the local time zone.
L_{loc} = the longitude of the location in degrees West.
E_t = 9.87 sin 2Γ - 7.53 cos Γ - 1.5 sin Γ in minutes.

[6.3]

$$\Gamma = \frac{360\,(n_d-81)}{364}$$

n_d = day of year, 1 <= n <= 365, Jan 1st = 1.

(ii) The declination angle for a day was obtained(Cooper 1969) by

[6.4]

$$\delta = 23.45 \sin(360 \frac{284 + n_d}{364})$$

(iii) The angle of incidence for direct beam radiation on a horizontal surface was obtained from spherical geometry, which gives

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \qquad [6.5]$$

(iv) The length of a solar day in hours was determined(Duffey & Beckman 1980) by

$$N_h = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) \qquad [6.6]$$

where θ_z = *solar zenith distance* ∠
δ = *declination* ∠
ϕ = *latitude*
ω = *hour* ∠

(v) Extraterrestrial irradiance for the mid point of an hour period, corresponding to the empirical data collection, was determined from

$$I_o = I_{sc}\left[1 + 0.033\cos\left(\frac{360\,n_d}{\pi}\right)\right]\cos\theta_z \qquad [6.7]$$

(vi) Extraterrestrial irradiance for periods less than an hour period were given(Reddy1987).

$$I_o = \frac{12 \times 3600}{\pi} I_{sc}\left[1 + 0.033\cos\left(\frac{360\,n_d}{365}\right)\right] \times \left[\cos\phi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{2\pi(\omega_2 - \omega_1)}{360}\sin\phi\sin\delta\right] \qquad [6.8]$$

where ω_2 *is the larger of the hour angles.*

(vii) The relationship between diffuse and global irradiance for South-East England was calculated from(Muneer & Saluja 1986):

$$K_t = \frac{I_g}{I_o} = 0.784 + 2.42\,K_t + (-7.999\,K_t^2) + 5.11\,K_t^3 \qquad [6.8]$$

For $K_t > 0.2$, where I_g = global horizontal irradiance.

Transmittance of twin-walled poycarbonate.

6.19 The Barnes Farm school atrium was roofed in twin-walled polycarbonate sheeting, which was discoloured. The measured values of the internal and external solarimeters used to measure global horizontal irradiance were analysed to determine the solar lost component and the transmittance of the glazing material. Seri-Res does not permit the user to schedule the solar lost parameter by the hour. A mean daily value is therefore the best option.

Figure 6.9 illustrates the result of the comparison of these observations.

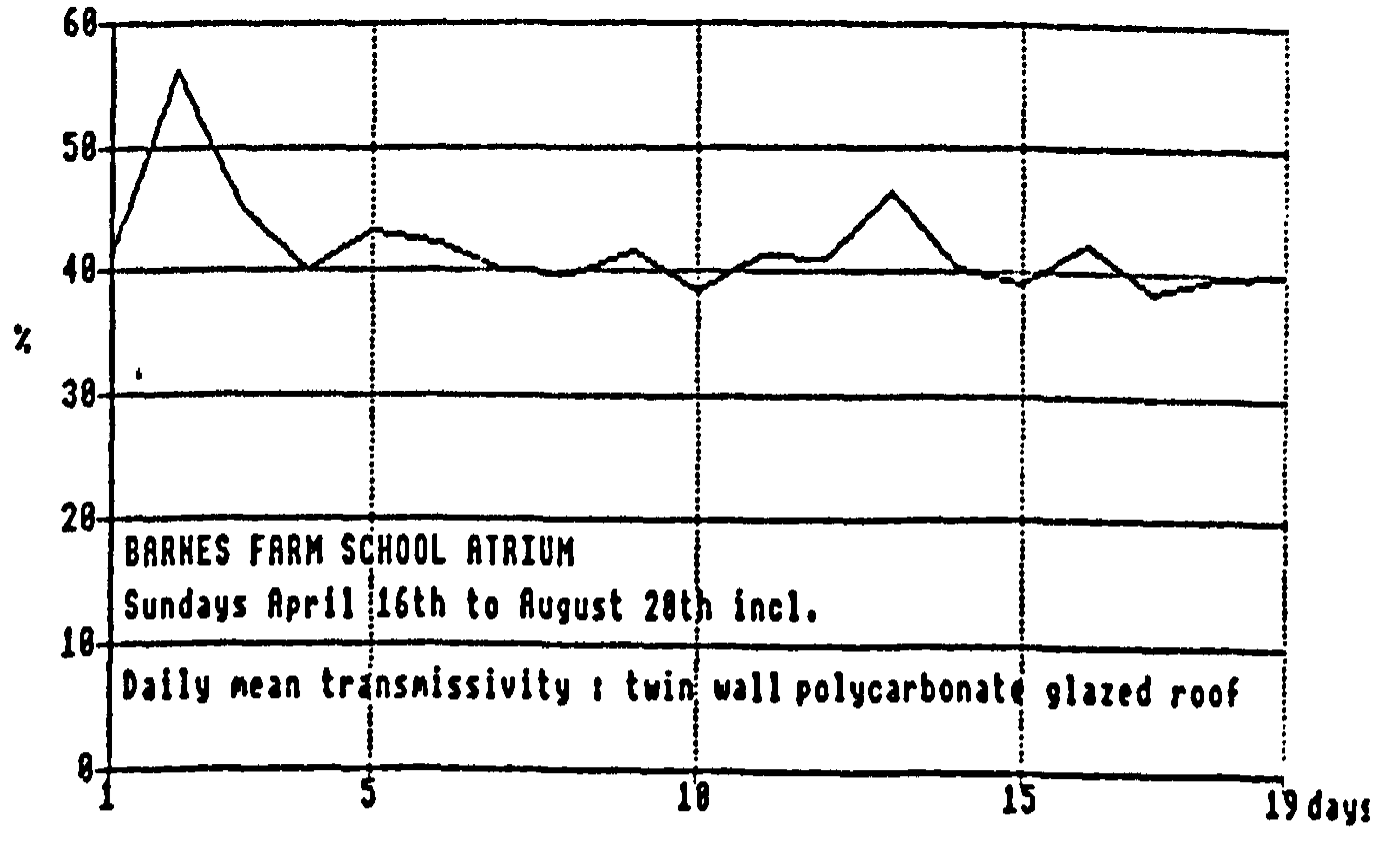


Figure 6.9 DAILY MEAN PERCENTAGE OF EXTERNAL GLOBAL HORIZONTAL IRRADIANCE MEASURED BY INTERNAL INSTRUMENT.

6.20 This daily mean result was low, compared to the results listed in table 6.12 of hourly measurements for new polycarbonate sheeting at Woodbridge Cottage(EDG 1985). Arrangements were made to test the instruments used at Barnes Farm school, but this did not solve the problem. The result may support the proposal on solar-lost(EMCo 1990b), however hourly readings were checked on a daily basis(Figure 6.10).

Table 6.12 ESTIMATED TRANSMISSIVITY OF POLYCARBONATE GLAZED ROOF AT WOODBRIDGE COTTAGE.(EDG 1985)

TIME (hr)	FEB/MAR	JUN/JUL
11.00	77%	76%
09.00 - 13.00	76%	73%
07.00 - 15.00	68%	64%
05.00 - 17.00	59%	49%

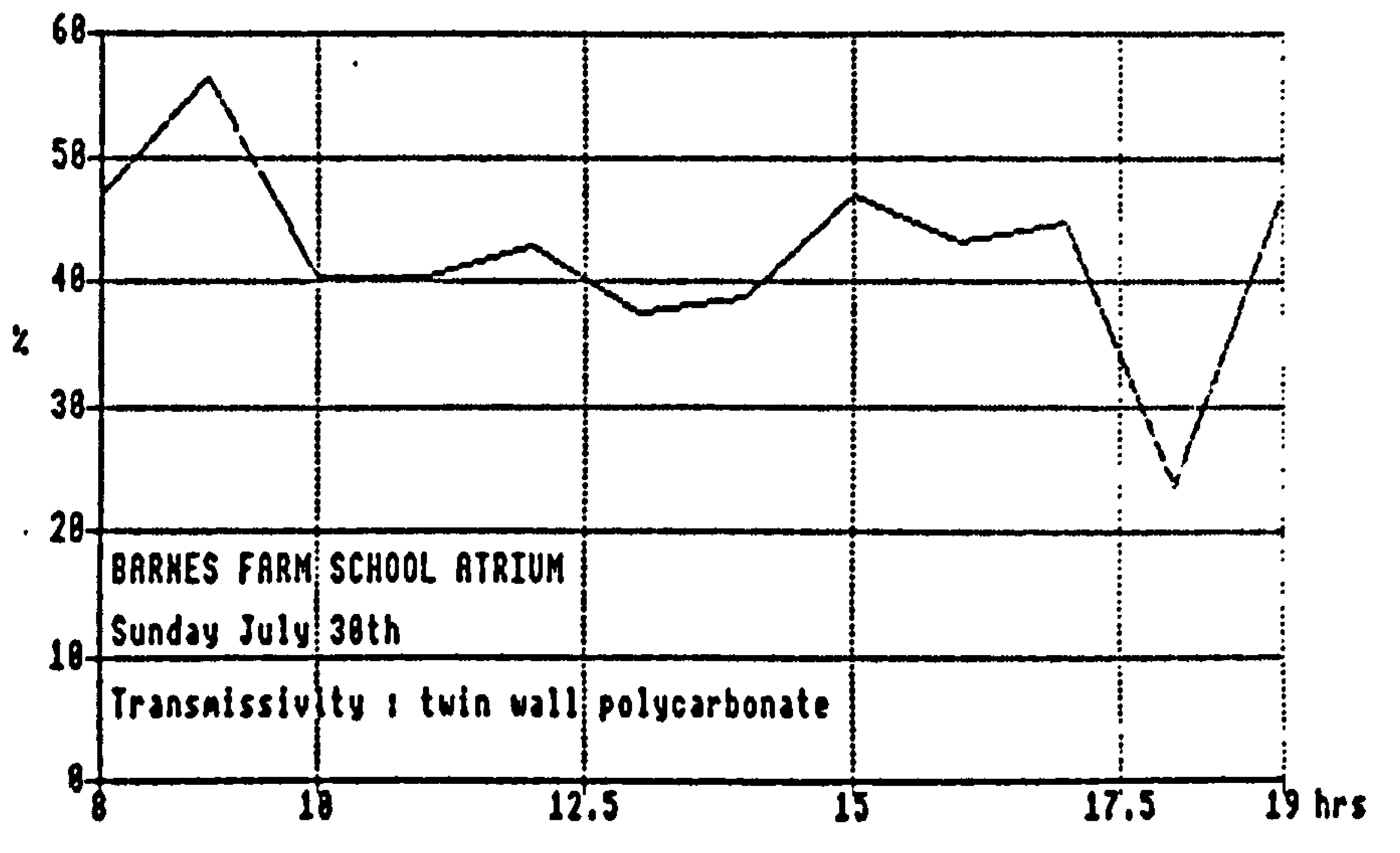


Figure 6.10 MEAN HOURLY PERCENTAGE OF EXTERNAL GLOBAL HORIZONTAL IRRADIANCE MEASURED BY INTERNAL INSTRUMENT.

6.21 Figure 6.11 shows the trace for a series of individual days, and reveals an intriguing pattern, with high and low readings and a repeating fluctuation, suggesting some geometric influence.

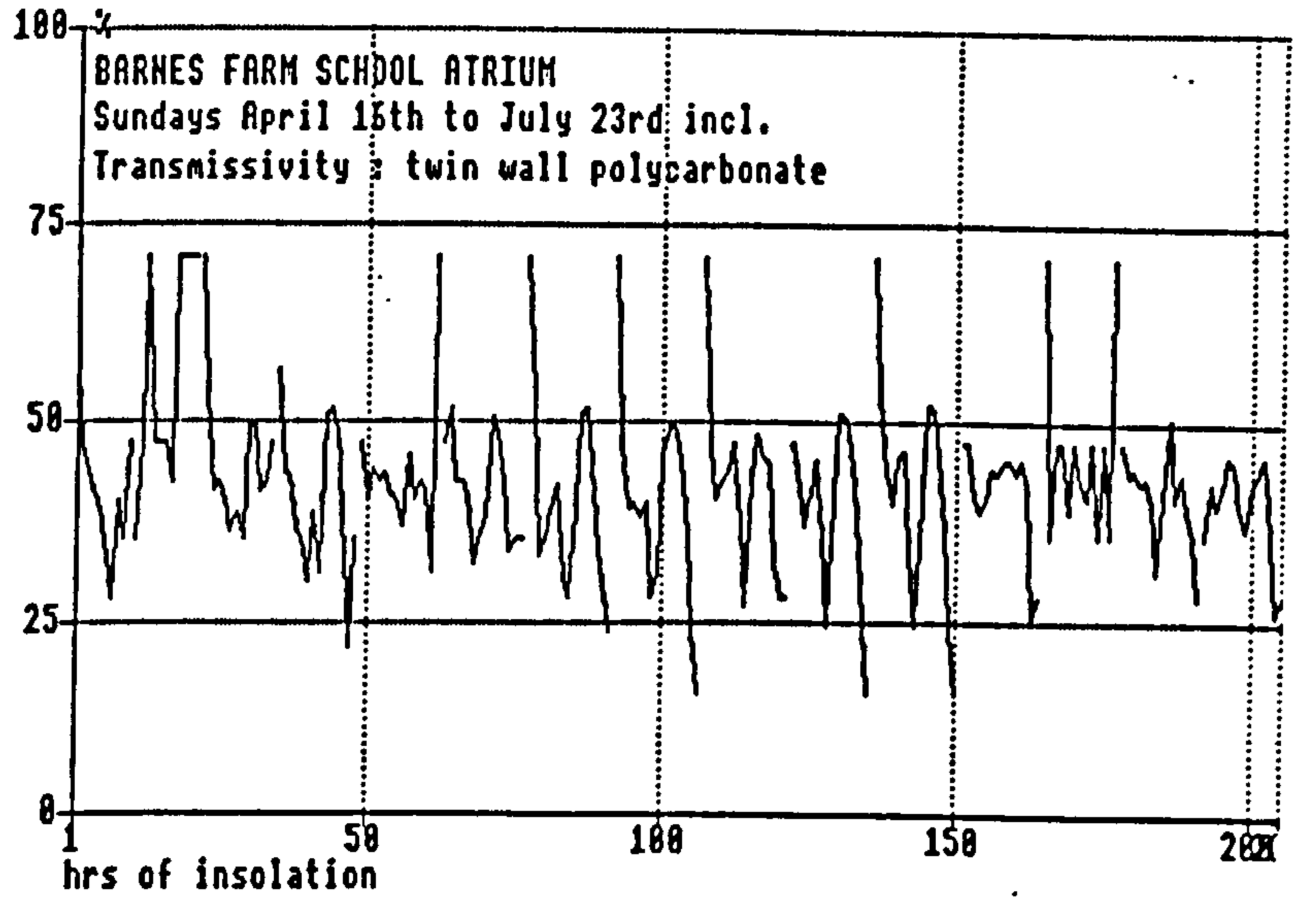


Figure 6.11 MEAN HOURLY PERCENTAGE OF EXTERNAL GLOBAL HORIZONTAL IRRADIANCE MEASURED BY INTERNAL INSTRUMENT.

6.22 The effects of the structure of polycarbonate sheeting, which can give rise to: multiple internal reflection(Hollands et al 1978), affecting the transmittance and forward scattering of insolation (Burek et al 1989), the variation of solar transmittance with angle of incidence (Arthur & Norton 1990), and also the effect of outdoor aging(Rainhart & Schimmel 1975) were considered.

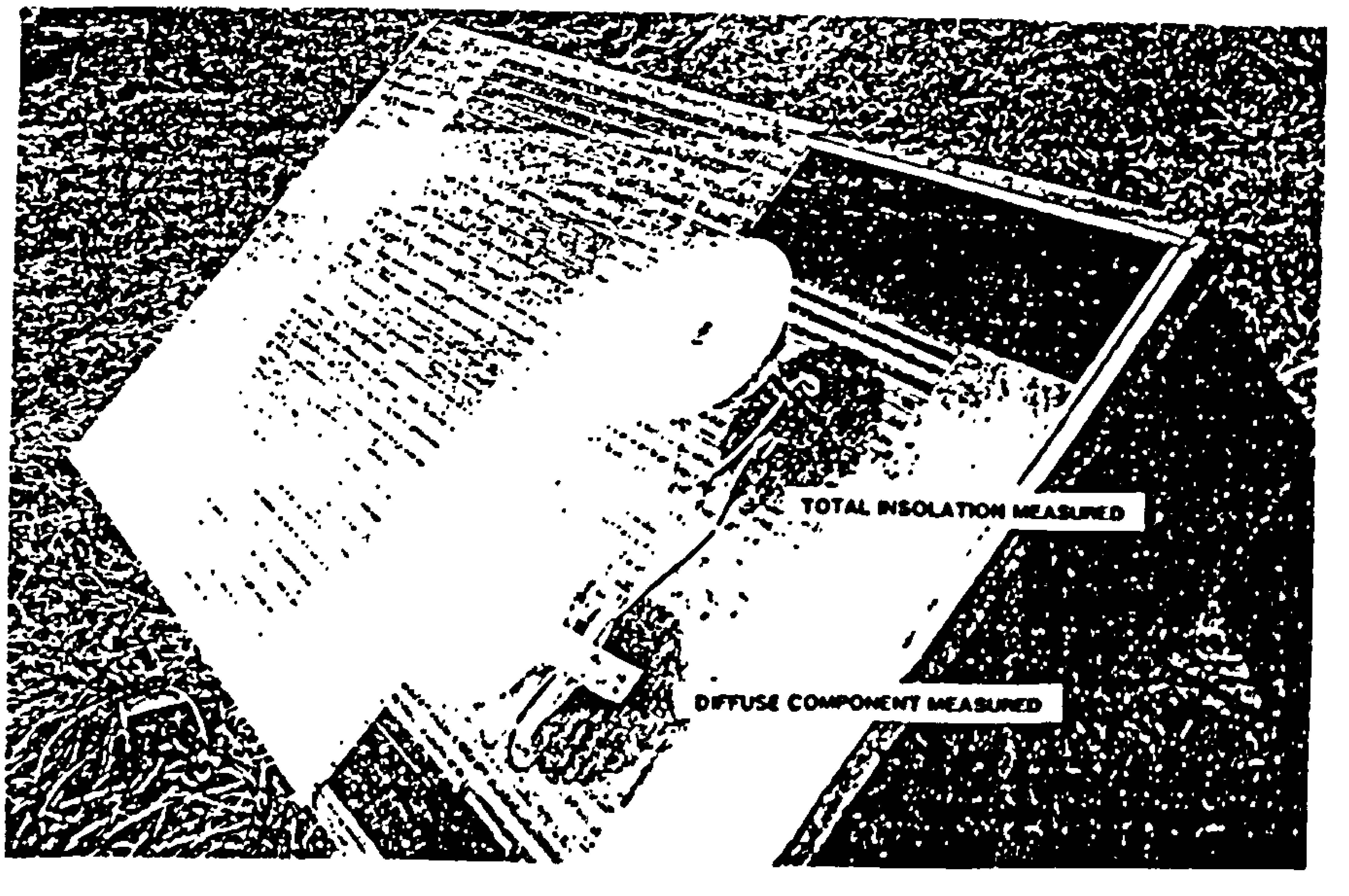


Plate 6.5 PATTERN OF ALTERNATE DARK & LIGHT STRIPS FORMED BY INSOLATION AFTER PASSING THROUGH TRIPLE LAYER POLYCARBONATE SHEETING.(Burek et al 1989)

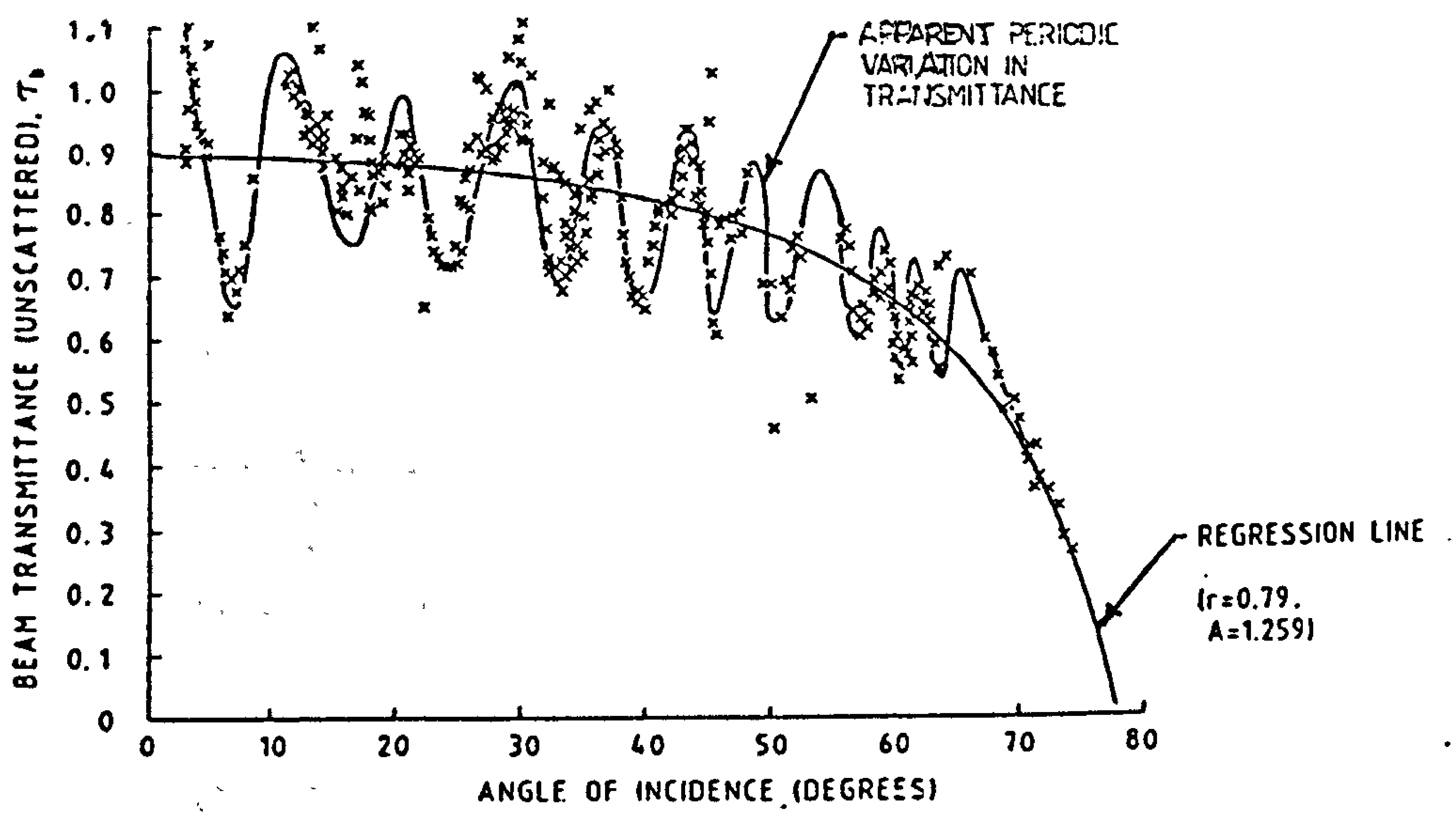


Figure 6.12 VARIATION OF UN-SCATTERED BEAM TRANSMITTANCE WITH INCIDENCE ANGLE FOR 16 mm TWIN-WALL POLYCARBONATE. (Burek et al 1989)

The results and observations of Burek were particularly interesting(plate 6.3, and figure 6.12), however they did not explain fully the pattern of hourly results obtained for a sequence of days. (Figure 6.11). An inspection and survey revealed that the internal instrument had been located in a position which was partly overshadowed by the adjoining roofs to the class-bases, and more significantly by the structural members supporting the atrium roof.(Figs 6.13 to 6.15)

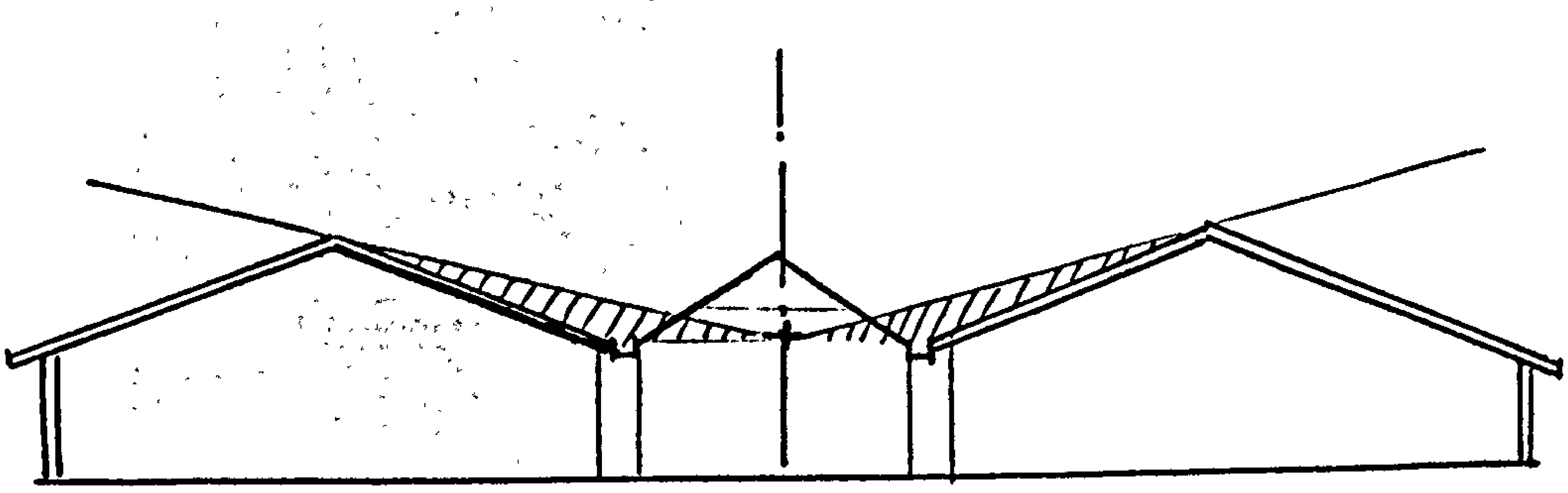


Figure 6.13 LOCATION OF INTERNAL SOLARIMETER.

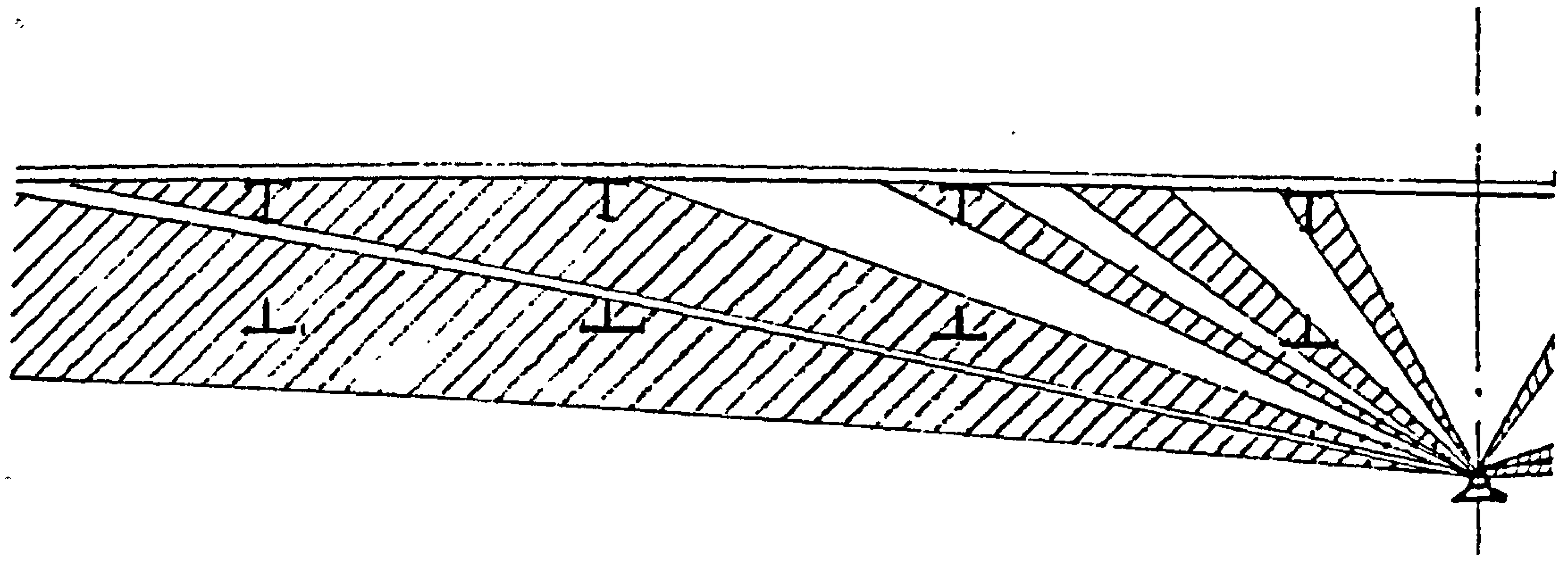


Figure 6.14 SHADING OF INTERNAL SOLARIMETER BY SPARS AND TIES.

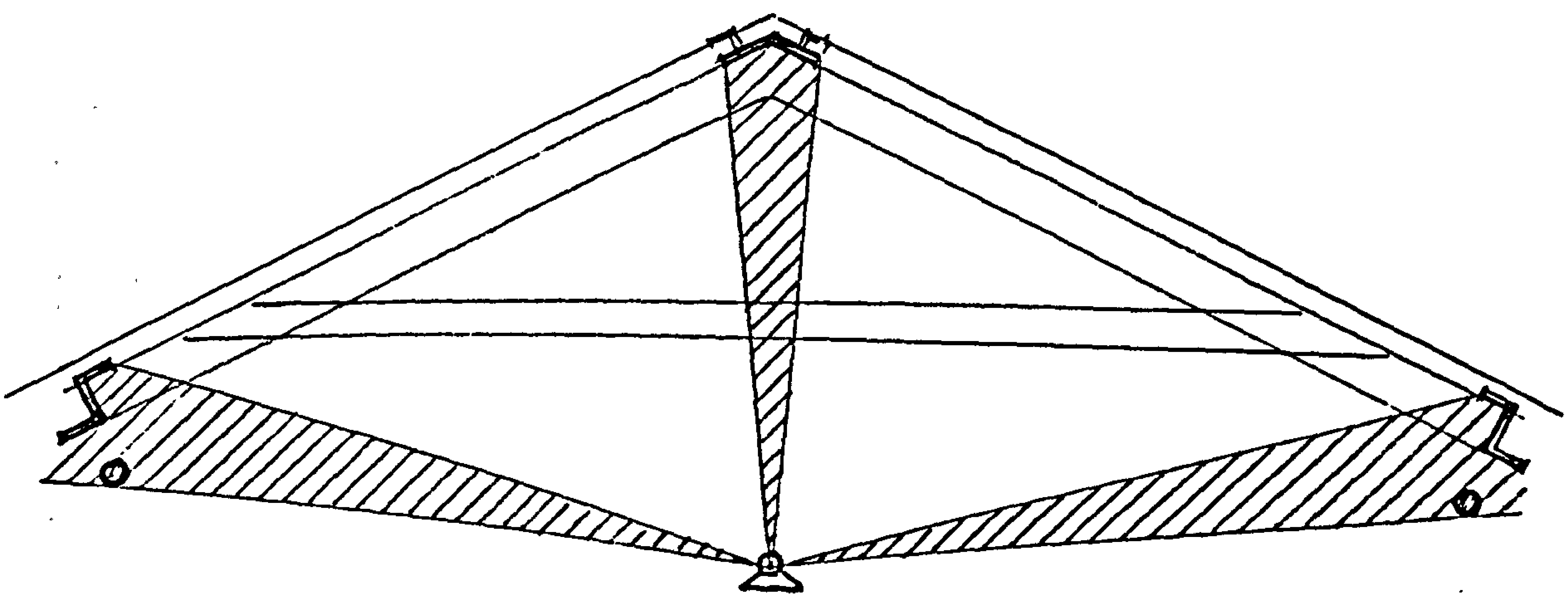


Figure 6.15 SHADING OF SOLARIMETER BY RIDGE AND OPENING LIGHT MEMBERS AND GEARING.

6.23 The solar aperture of the internal instrument was calculated, from this survey information, by determining the amount of the glass hemisphere of the instrument, which would be obscured by these obstructions. The procedure used was as follows:

(i) the shading from adjacent roofs was determined by

$$\text{length of arc on a 50 mm glass hemisphere} = 2\pi r \times \frac{\tan\gamma}{360} \quad [6.2]$$

where γ = angular elevation of obstruction.

$$\text{area of 50mm glass hemisphere} \quad \frac{4\pi r^2}{2} = 3927\ mm^2 \qquad [6.3]$$

similarly the angle of arc on a 50mm glass hemisphere was calculated for each of the relevant structural members, and the effect of overshadowing by different components could then be assessed.(Table 6.13)

Table 6.13 OVERSHADOWING OF INTERNAL SOLARIMETER.

OBSTRUCTION	area of shade cast on glass of instrument (mm^2)	sub-totals of areas of the shade components (mm^2)	percent of solarimeter glass surface area shaded
East roof	157		
West roof	150		
Atrium ridge	190		
Opening gear & frame	240	737	18.8
Atrium roof ties	337		
Atrium roof spars	1401	1738	44.2
Totals	2475		63.0

Only about 37 per cent of the sky hemisphere was visible from the location of the internal instrument. The diffuse component of the recorded insolation would have been artificially low, and the direct beam component of irradiance would have been obscured intermittently. This could account for the low internal readings (Figure 6.09), and explain the pattern of results seen in

Figure 6.11. It was concluded that, neither the transmittance of the polycarbonate glazing, nor the solar-lost component, could be established from the monitored data. However, measurements of over seventy per cent of the external insolation had been recorded by the internal instrument during periods of bright sunshine, even though part of the diffuse component was missing from these measurements. The performance implied by this was not dissimilar to that claimed by the manufacturer, and reported for Woodbridge Cottage(EDG 1985), and the manufacturer's data was therefore used for the building description file. The solar-lost value could not possibly be as high as that reported by EMCo(1990b), and a value of 4% was eventually adopted for this.

Infiltration.

TABLE 6.14 TRACER GAS TEST: BARNES FARM ATRIUM.

01.09.89 TIME (hr)	WIND SPEED m/s	WIND DIRECTION	CO_2 TRACE % by volume	NOTE
11.30	1.4	N	0.01	BACKGROUND
12.00			0.05	CO2 emission
12.30	1.4	N	0.30	" "
12.45			0.27	" "
13.00			0.27	steady state
13.15	4.0	N	0.17	
13.30	2.2	N	0.12	
13.45	1.1	N	0.09	
14.00	3.7	NE	0.07	
14.15	1.1	NE	0.04	
14.30	0.4	N	0.03	
14.45			0.02	BACKGROUND

6.24 The Barnes Farm school classrooms and atrium were tested, with D Harris, to determine infiltration rates, using a tracer gas technique with carbon dioxide. The gas was released and dispersed in the space, using an electric fan to achieve good mixing, until a steady state was achieved, as indicated by Drager tube (range 0.01% to 0.3% by volume) measurements. The supply of the gas was then shut off, and the rate of decay was determined by measuring the concentration of carbon dioxide at regular intervals using Drager tubes (Table 6.14).

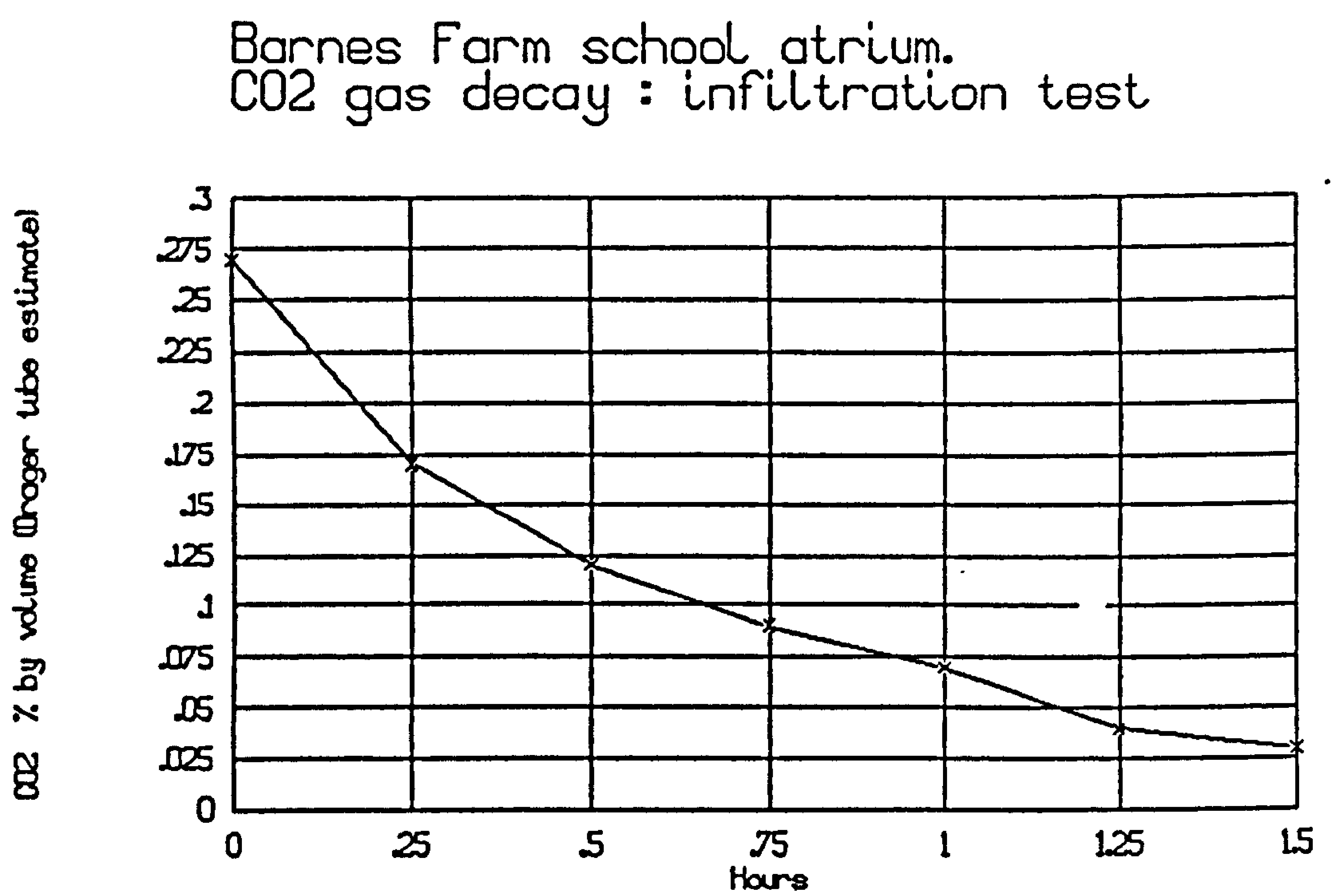


Figure 6.16 CO_2 GAS DECAY TEST: BARNES FARM ATRIUM.

Assuming perfect mixing, and noting the rate of decay(fig 6.16) of the concentration of the CO_2 gas during 105 minutes until the background level recorded at the start of the test was reached, then the average air change rate of the space was measured as approximately 0.5 ac/h. The infiltration rate for an adjoining class-base was measured as 0.25 ac/h. These values were scheduled for unoccupied periods for Barnes Farm school, with an infiltration rate of 1.0 ac/h at times of considerable movement of staff and pupils around the school, and 0.5 ac/h in class-bases during normal lessons. Ventilation rates were separately scheduled. The repeat test for Hook school was carried out by D. Harris, who obtained a result for infiltration of 1.2 ac/h.(Harris 1991)

Daylight.

6.25 Measurements were taken of the luminance of the unobstructed sky on an overcast day, and the illuminance on the working plane in the class-bases and atrium of each school, using a lux meter. The daylight factor required for input to the seri-Res program. was calculated from:

$$DF = \frac{E_i}{E_e} \times 100$$

where:

E_i = *measured internal illuminance.*

E_e = *measured external sky luminance.*

[6.4]

Daylight enters the class-bases of Barnes Farm school from five directions, and a horizontal surface was therefore designated for an average daylight factor in day-lit zones, calculated from:

$$DF_{av} = \sum_{n=1}^{n} \frac{DF}{n}$$

where n = *number of reference point readings*

[6.5]

Building description files.

6.26 Description files were prepared for each building from available construction data, survey and occupancy information. Both sites were sheltered. The information used is listed in tables A.1-A.7(appendix A). The external surface resistances were taken from the CIBSE Guide table A3-6(CIBSE 1986), and Table A.1 indicates the combined heat transfer coefficients used in accordance with Seri-Res procedures(Palmiter & Wheeling 1981)(Haves 1987).

6.27 The variables used for constructions, glazing, and the thermal properties of materials are listed in tables A.2 to A.7 (Anon 1987). The building description files for the two schools were compiled to provide the following defined output for the various set points used:

(i) Heating load. Total auxilliary heating load inclusive of an allowance of 2 W/m^2 for hot water services.

(ii) Ventilation. Total heat removed from the occupied space by venting when the internal temperature rose above 23°C for classrooms, and 25°C for atria.

(iii) Buffer effect. The assessed useful reduction in energy loss as a consequence of the effect of unoccupied spaces such as lofts, and draught lobbies or similar unheated zones. The buffering is calculated as the conductance between the buffer zone and the zones it buffers multiplied by the difference between the buffer zone temperature and the ambient temperature.

(iv) Net loss. The heat loss from the occupied zones equal to the sum of the useful solar gain, the useful incidental gains, and the auxiliary heating. The reference comfort temperature must be not less than 14°C for Gymnasia, or 18°C for other accommodation, and not greater than 21°C for all teaching areas.

(v) Useful solar. Solar gains which assist the attainment of and do not exceed the required comfort conditions.

(vi) Gross loss. Heat loss from fabric and infiltration, including actual buffering effects, but excluding any allowance for useful gains.

6.28 Three levels of detail of construction and zoning were analysed for the Barnes Farm school to check the sensitivity of the computer model in this respect as follows:

(i) Detailed(Fine).

This building description represented as closely as possible, the actual method of construction and hourly patterns of space use within the building. The construction elements were described in detail, and features such as roof joists and studs were allowed for separately, with the intention that the computer file for each school should match as closely as possible the 'as built and used' condition. Zoning arrangements, and associated schedules of use were based on information supplied by the school, which detailed movements within the school, and the regular patterns of use of individual spaces. For example there were nine occupied zones, including the atrium, of which six were used for teaching purposes at Barnes Farm. A smaller number of zones accounted for water closet and lavatory areas, stores, and roof spaces.

(ii) Elementary.

This approach was more in line with environmental design considerations, and assumed that a zone included all the contiguous spaces which were designed to operate at the same temperature, and had similar exposure to ambient conditions. This file had about half the number of zones defined for the fine level of detail.

(iii) Simple.

This approach to modelling of the school concentrated on the basic geometry of form, and the inter-relationship of teaching spaces, sun-spaces and orientation. The building had only three zones, using this approach.

Comparison of building descriptions.

6.29 Seri-Res Computer simulations were carried out, using the three different building description files for the Barnes Farm school, in order to compare the resultant temperatures predicted. It was presumed that the Fine model would be needed for the hourly predictions necessary for this study, the elementary description would be useful for daily predictions, and the simple model would be appropriate for seasonal predictions. Figures 6.16 and 6.17 indicate the similarity evident in the performance of the three levels of detail of building description file in the predicted zone temperatures for Barnes Farm school. Clearly the Seri-Res dynamic simulation model is reasonably accurate, when used with a simple building description.

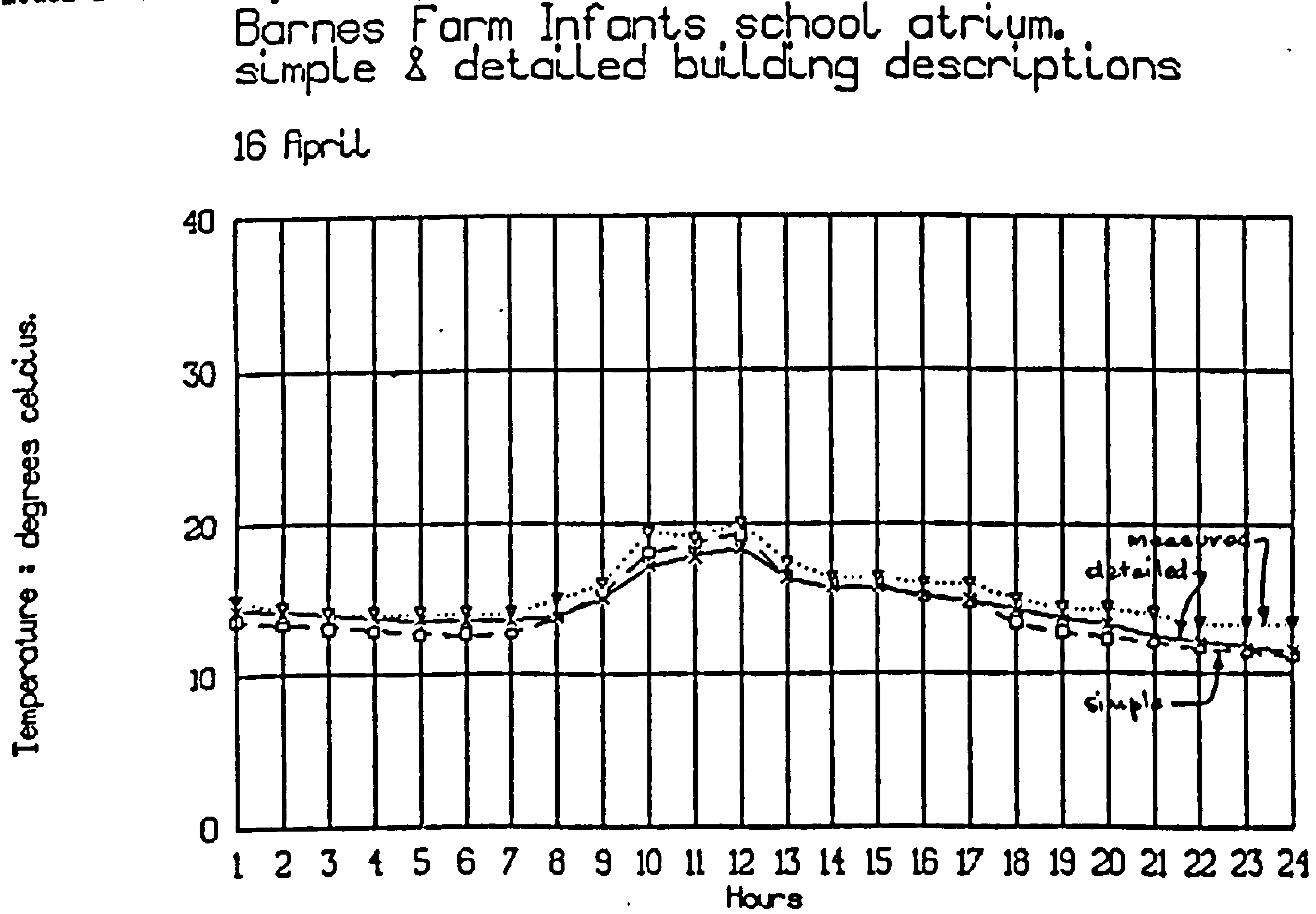


Figure 6.17 COMPARISON OF PREDICTED ZONE TEMPERATURES.

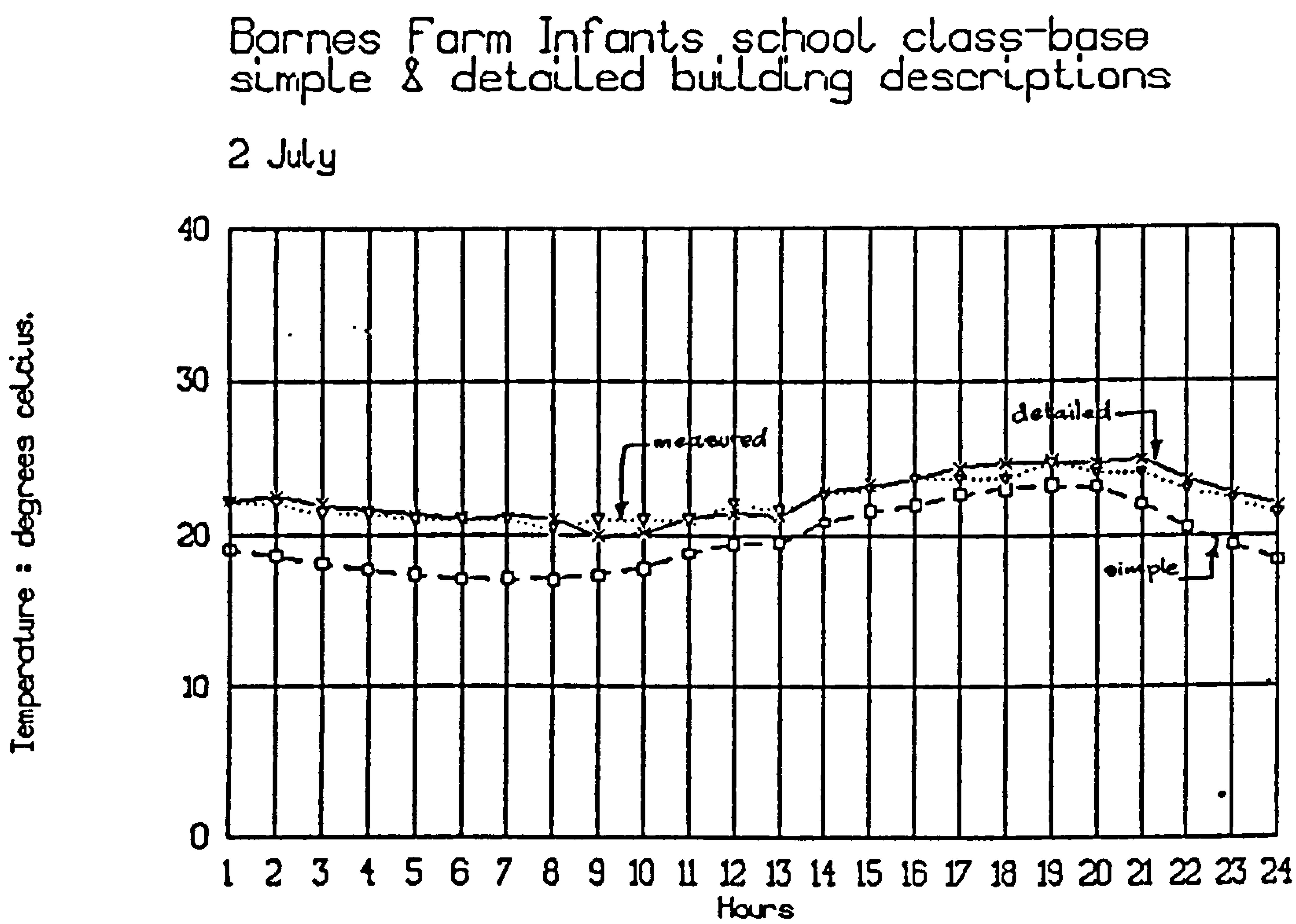


Figure 6.18 COMPARISON OF PREDICTED ZONE TEMPERATURES.

Calibration of the model.

6.30 The building performance predicted by the Seri-Res model was compared with the monitored performance data in order to calibrate the computer model of each building. The absence of fuel metering, in the monitoring scheme, meant that calibration was inevitably limited to zone temperatures. An equivalent environmental temperature was prepared from the measured data, using equation 5.1, to compare directly with the output from Seri-Res. The most precise(Fine) level of building description file for the Barnes Farm school was used for this, and a similar file was prepared for the Hook school, using plans supplied by the architect and services engineers, and the information on the materials used in the construction. (Waterfield 1989) Seri-Res simulations were used to predict the hourly zone environmental temperatures for comparison with those measured for the atrium and adjoining class-bases at each school. The initial results for Barnes Farm school, and the new areas of Hook school were well correlated, but the Seri-Res predictions for the old classrooms at Hook school were very poor. Information supplied by the architect (Ogden 1991) indicated that the roof to the new extension at Hook school over-sailed the old classrooms, which in effect had two roofs not one as assumed by Waterfield. The building description for Hook school was revised, and the calibration of the Seri-Res model was then assessed for both schools using the weather data collected at each site.

Table 6.15 TERM & HOLIDAY DATES 1988/89 BARNES FARM.

TERM DATES	HOLIDAYS
Mon 5th Sept - Fri 21st Oct	Sat 22nd Oct - Sun 30th Oct
Mon 31st Oct - Thur 18th Nov	Fri 18th Nov - Sun 20th Nov
Mon 21st Nov - Fri 16th Dec	Sat 17th Dec - Tue 3rd Jan
Wed 4th Jan - Wed 8th Feb	Thur 9th Feb - Mon 13th Feb
Tue 14th Feb - Fri 17th Mar	Sat 18th Mar - Mon 3rd Apr
Tue 4th Apr - Fri 28th Apr	Sat 29th Apr - Mon 1st May
Tue 2nd May - Thur 11th May	Fri 12th May - Sun 14th May
Mon 15th May - Fri 26th May	Sat 27th May - Sun 4th Jun
Mon 5th Jun - Fri 21st Jul	Sat 22nd Jul - Sun 3rd Sept

Unoccupied periods were selected for calibration to minimise, as far as is possible, the effect of occupancy, although the spaces were pre-conditioned by periods of occupancy. To emulate this, a detailed hourly timetable of the patterns of occupancy of every teaching space within each school, and a note of any closure days, was obtained from the headmistress. There was a temporary classroom at the Barnes Farm school, and the time and extent of the use of the main school facilities by the children from the temporary classroom was also identified. Appropriate schedules were developed from this information, for each half term of the school year. An example of the term dates and holidays scheduled for Barnes Farm school is given in Table 6.15 for the school year 1988/89.

Hook School Atrium.

6.31 Figures 6.19 and 6.20 illustrate the comparison between measured and predicted temperatures for two weekends at the end of the summer term.

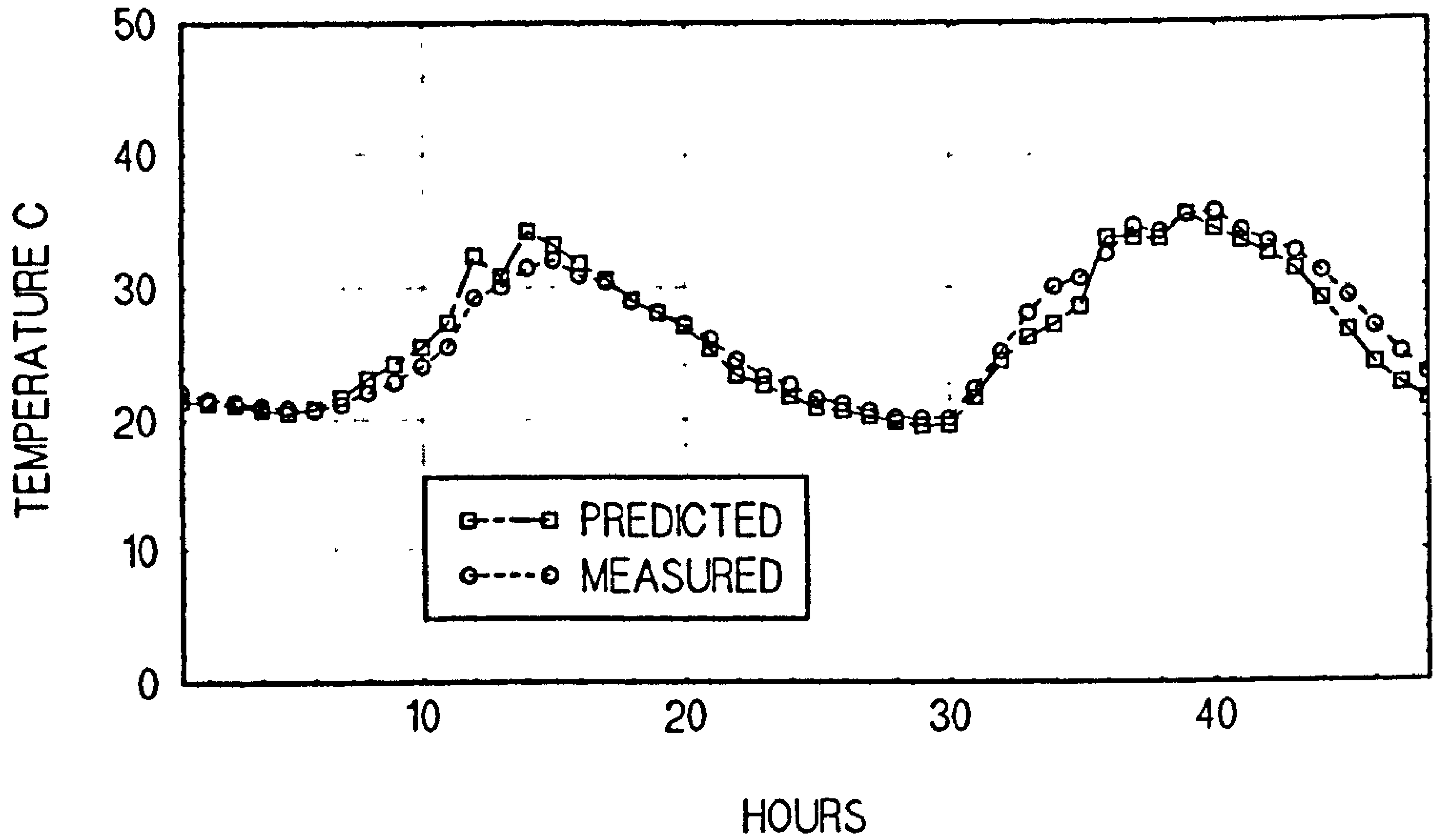


Figure 6.19 HOOK SCHOOL ATRIUM WEEKEND 1ST/2ND JULY 1989.

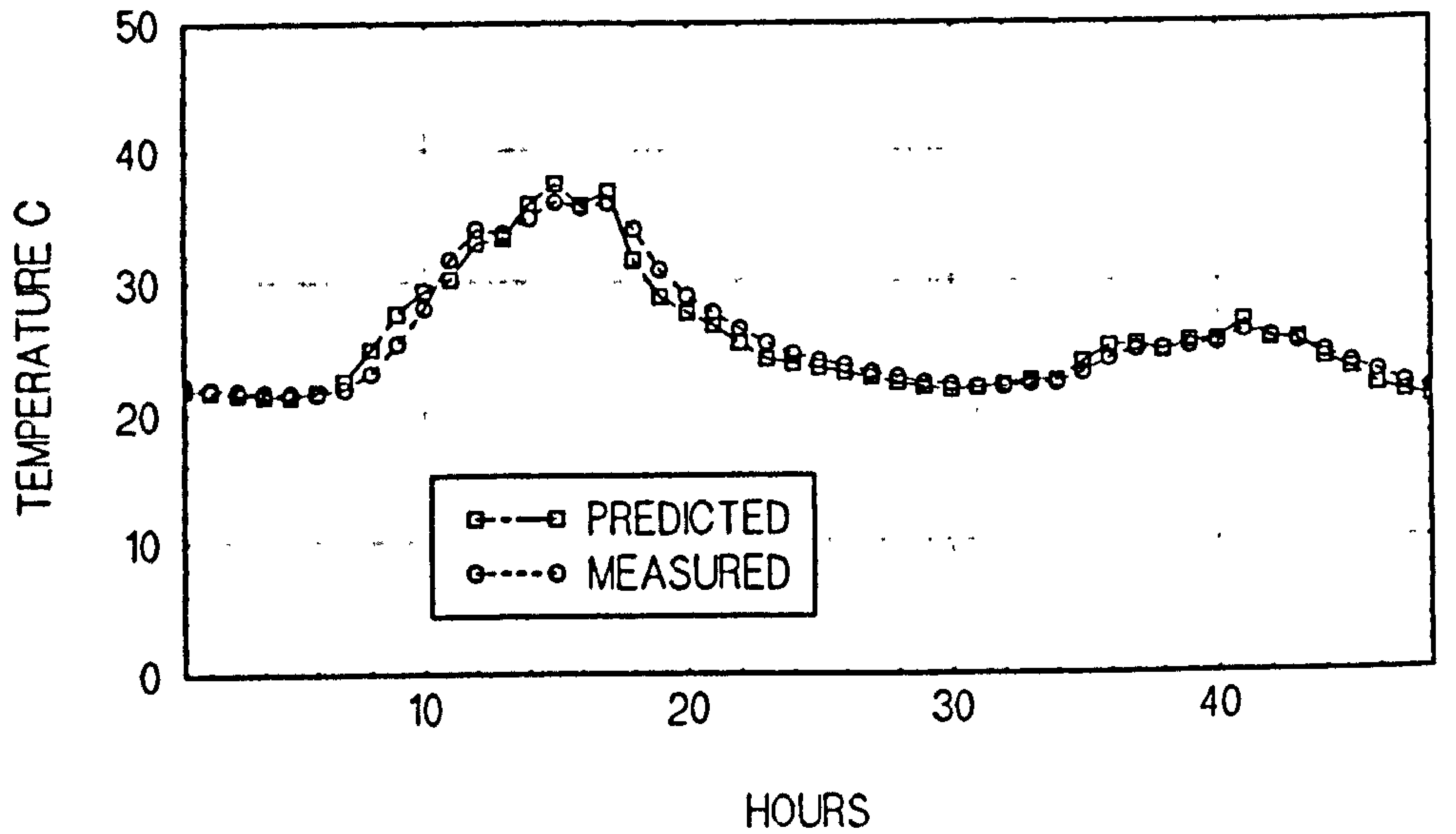


Figure 6.20 HOOK SCHOOL ATRIUM WEEKEND 8TH/9TH JULY 1989.

6.32 Figure 6.21 indicates the correlation of predicted and site measured hourly temperatures in the atrium for all the weekend periods studied from May 1989 to the start of the Autumn term using site weather data gathered during the monitoring period. Figure 6.22 shows the linear regression y = ax + b for this measured and predicted data.

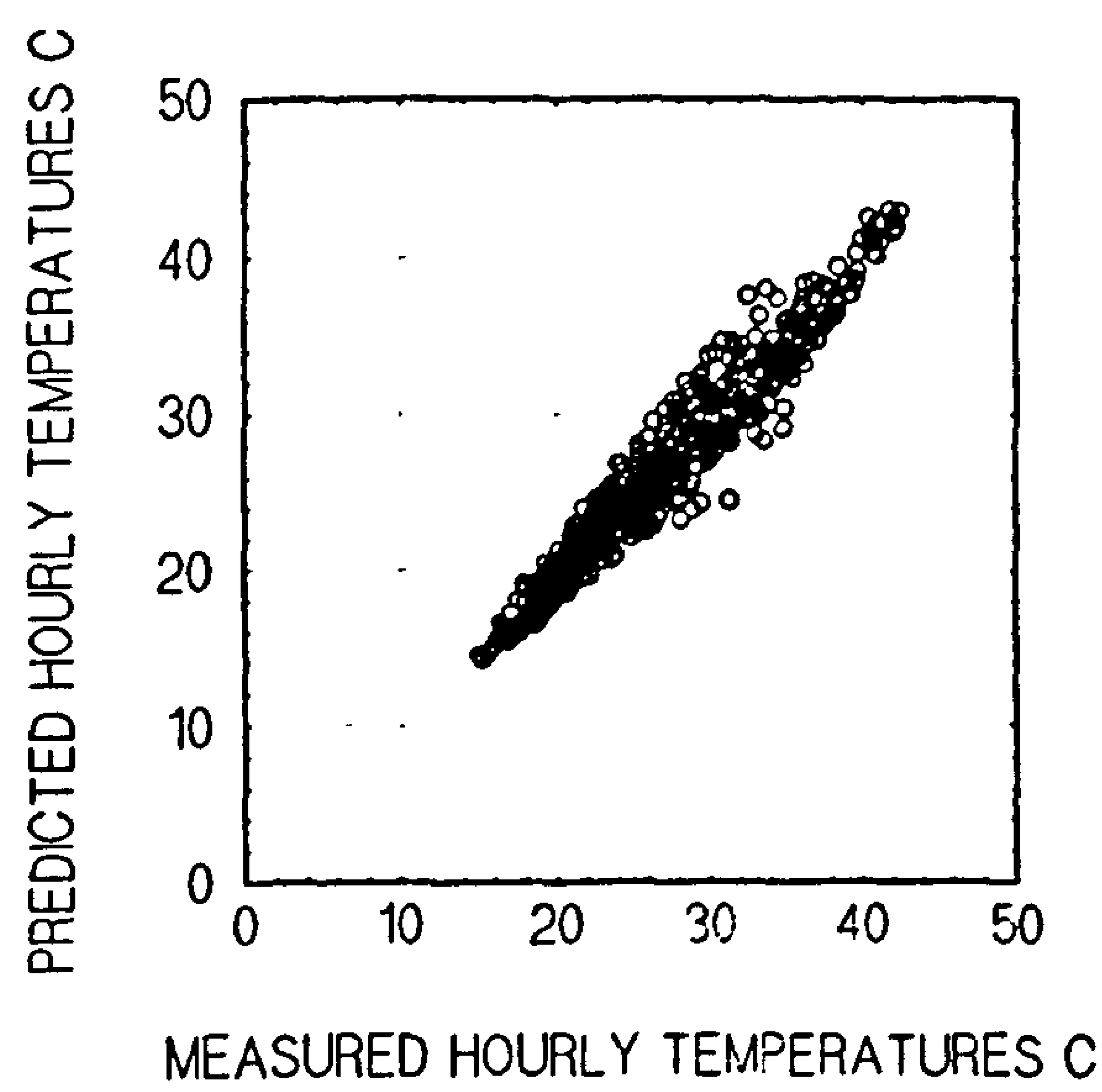


Figure 6.21 HOOK SCHOOL ATRIUM WEEKENDS MAY TO SEPT 1989.

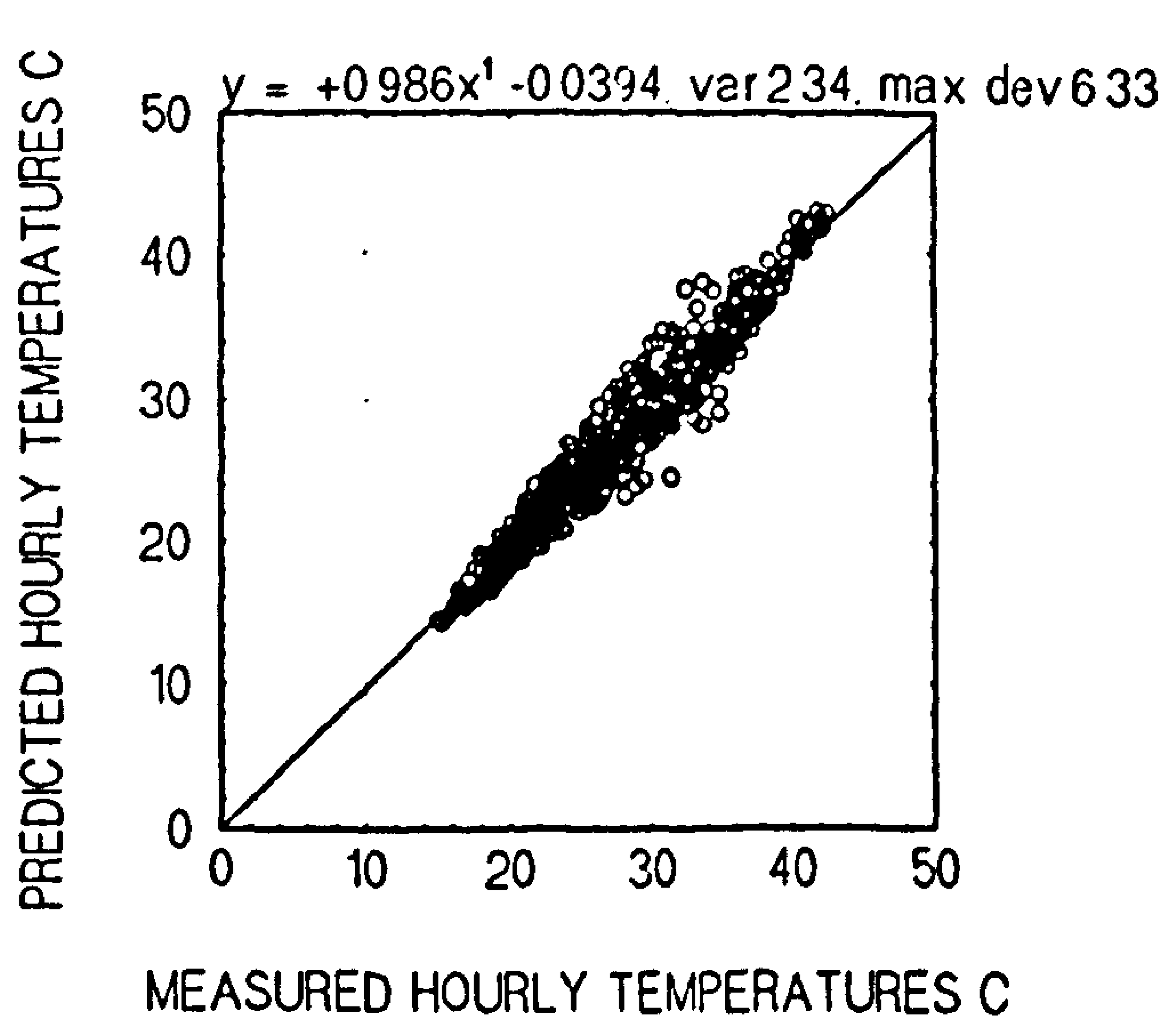


Figure 6.22 HOOK SCHOOL ATRIUM WEEKENDS MAY TO SEPT 1989

Hook school class-bases.

6.33 The comparison between measured and predicted hourly classroom temperatures for the weekends of 27th/28th May and 19th/20th August 1989 is illustrated in figures 6.23 and 6.24.

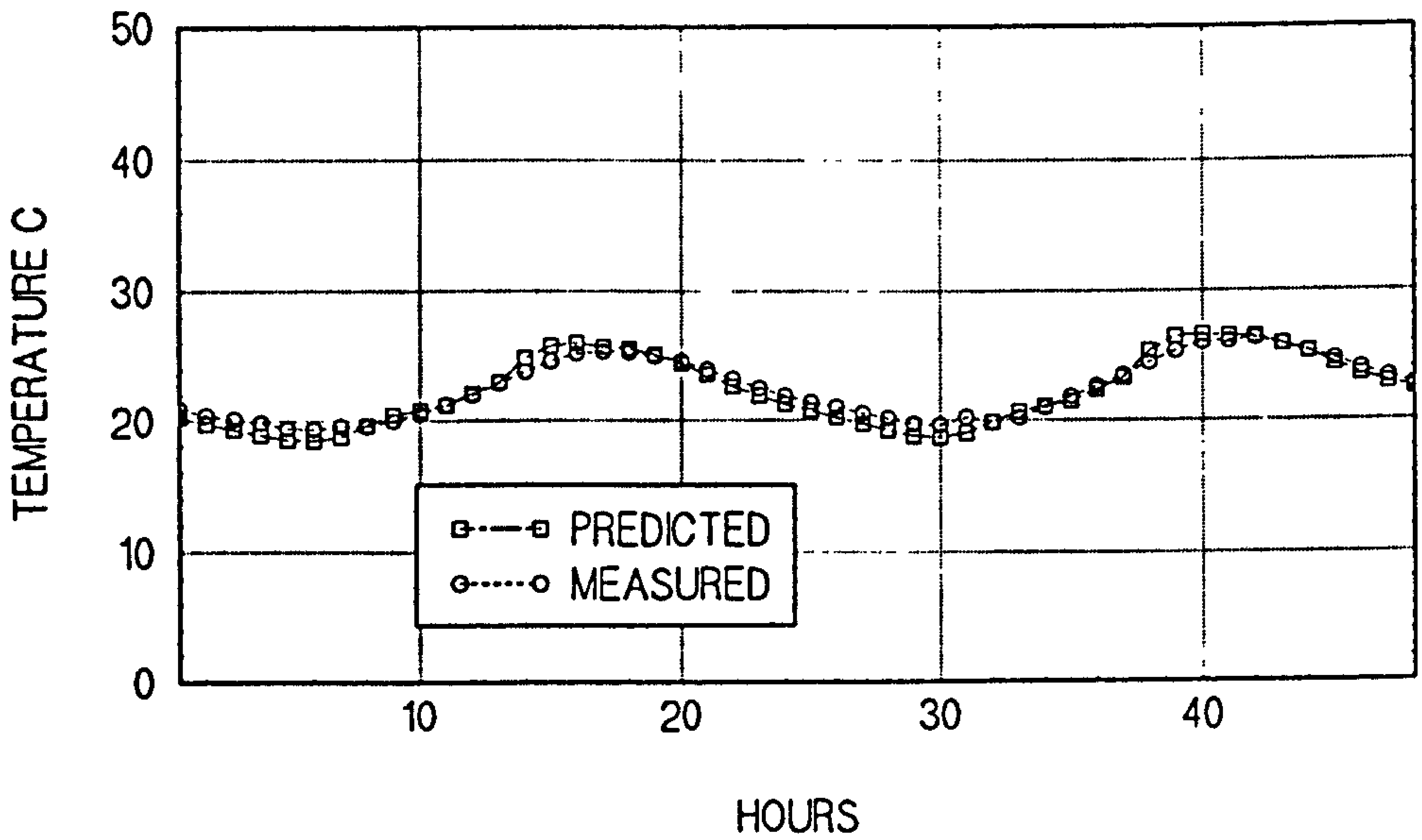


Figure 6.23 HOOK SCHOOL CLASS-BASE WEEKEND 27TH/28TH MAY 1989

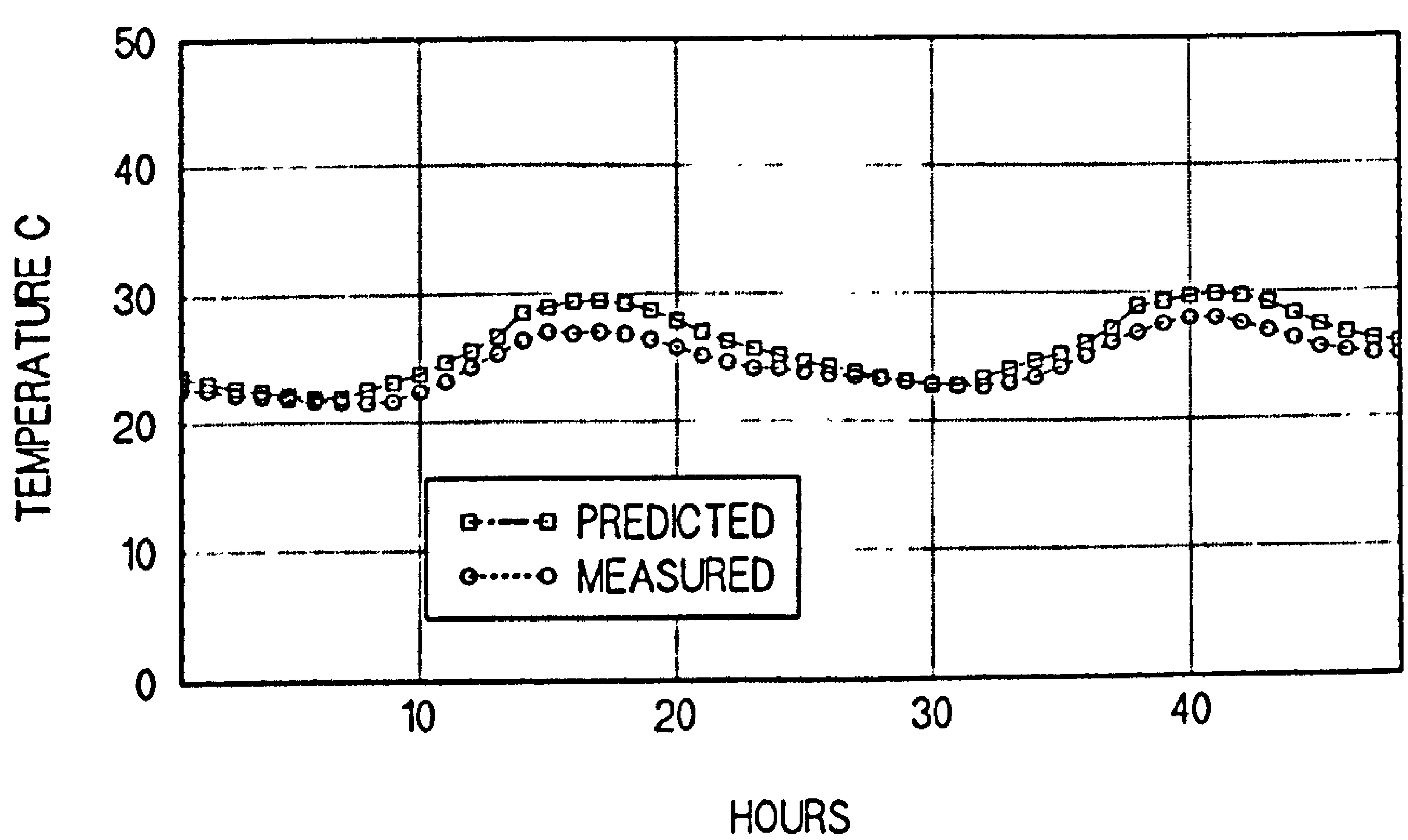


Figure 6.24 HOOK SCHOOL CLASS-BASE WEEKEND 19TH/20TH AUG 1989.

6.34 The predicted classroom temperatures correlate with measured hourly temperatures as shown in figures 6.25 and 6.26 for unoccupied weekends during the period May to September 1989 inclusive.

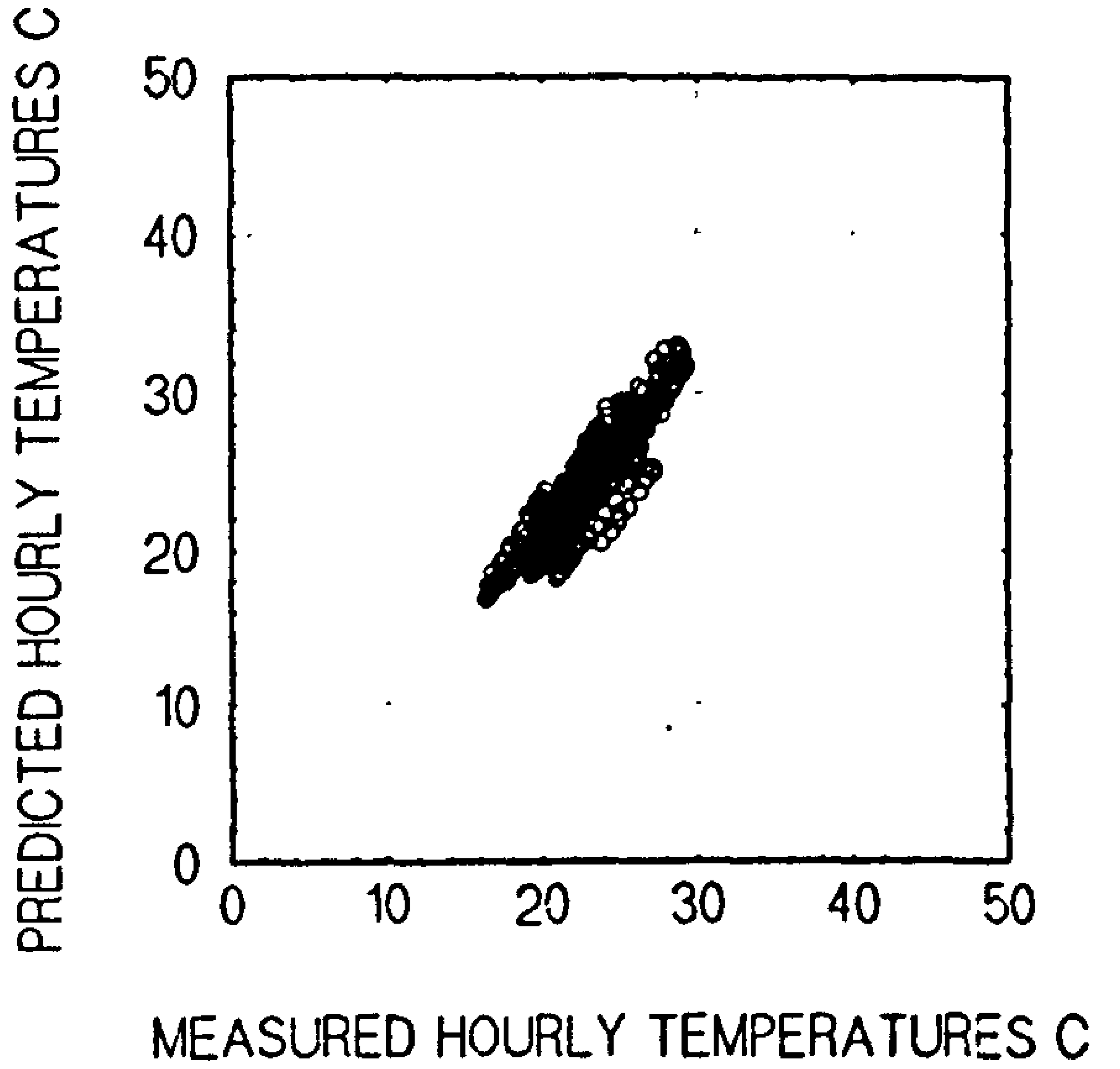


Figure 6.25 HOOK SCHOOL CLASS-BASES WEEKENDS MAY TO SEPT 1989.

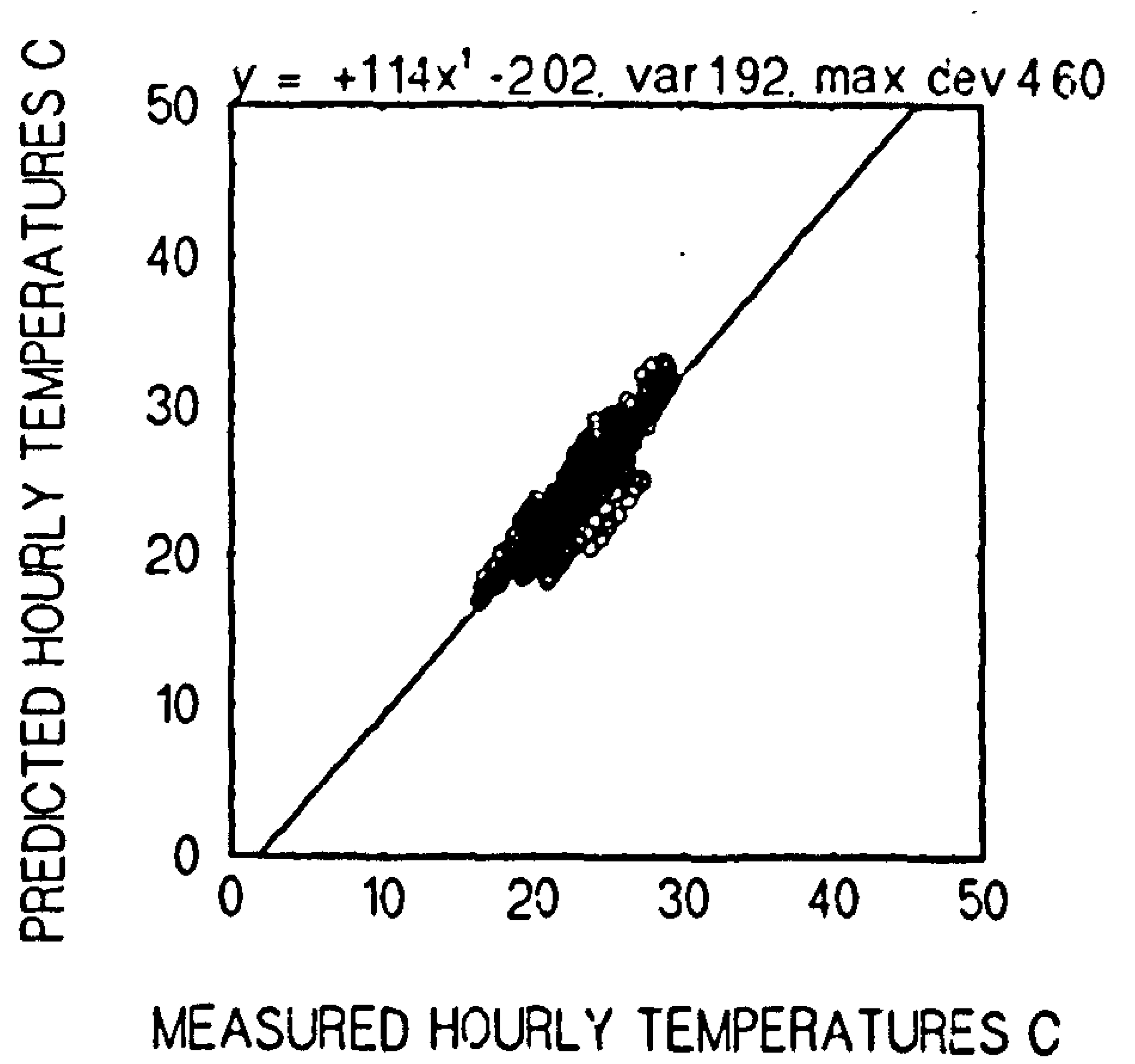


Figure 6.26 HOOK SCHOOL CLASS-BASE WEEKENDS MAY TO SEPT 1989.

Barnes Farm school atrium.

6.35 The predicted and measured temperatures for four of the Sundays studied from April to August 1989 are compared in figures 6.27 to 6.28 inclusive.

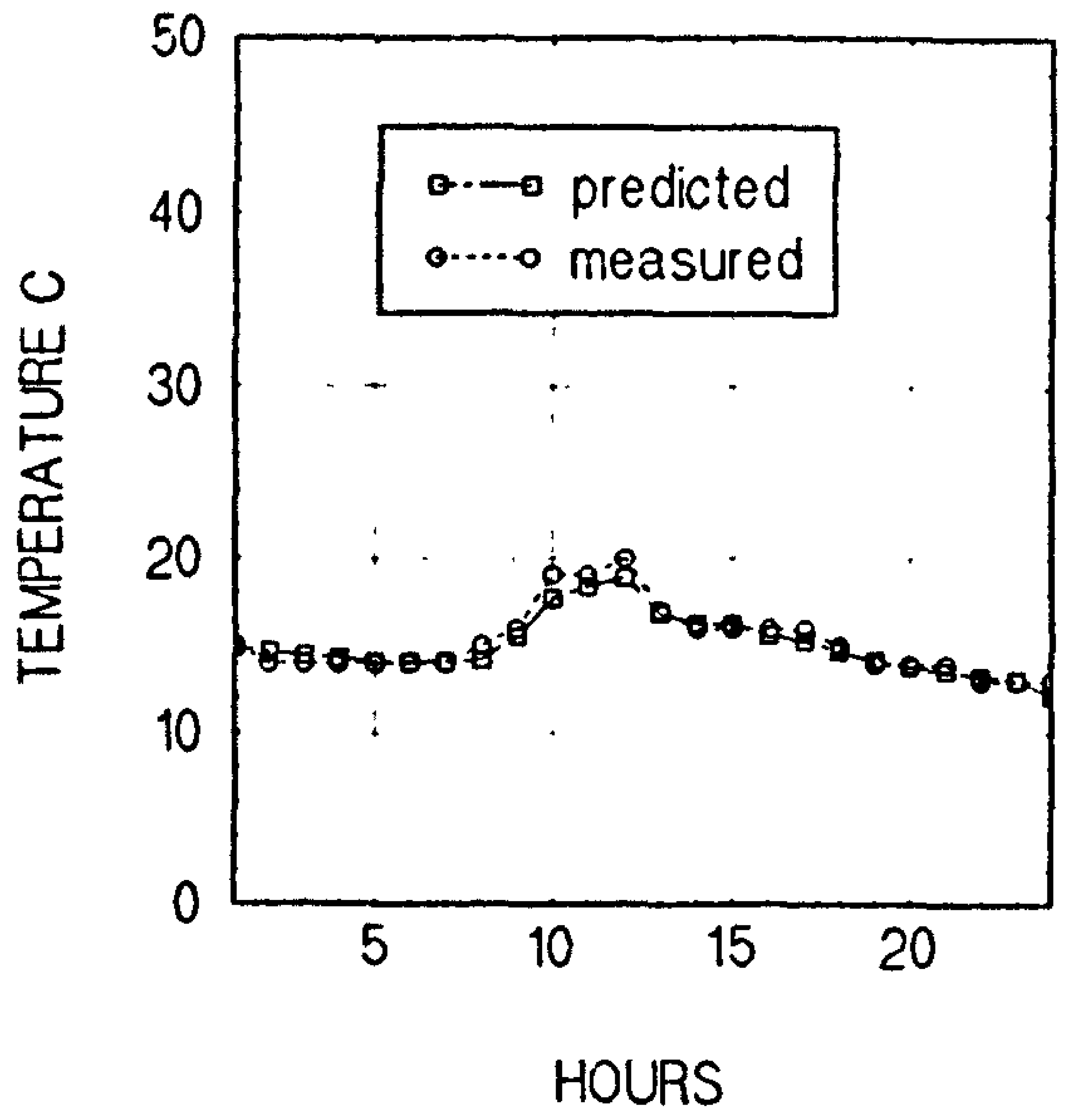


Figure 6.27 Sun 16th Apr 89

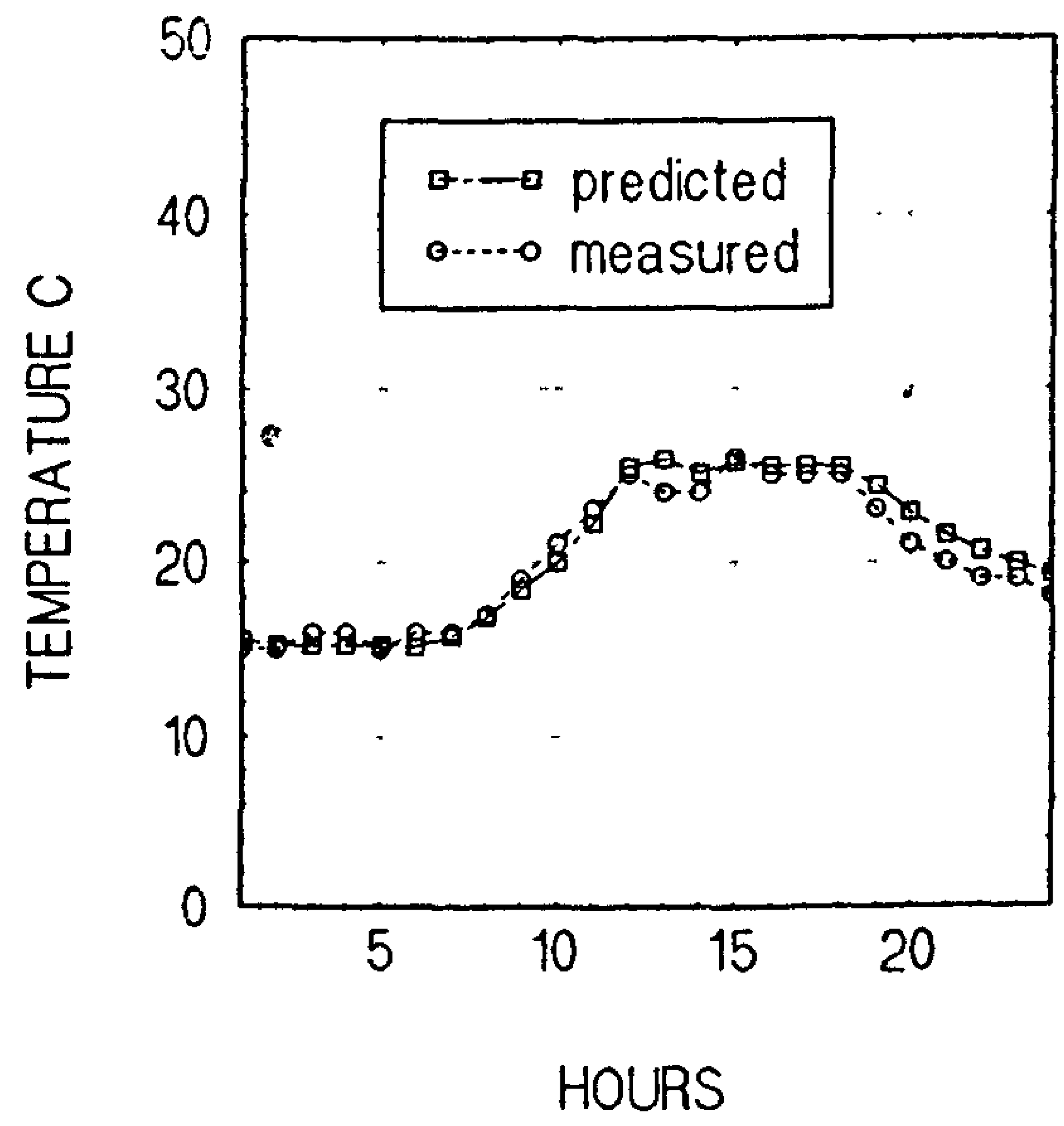


Figure 6.28 Sun 14th May 89

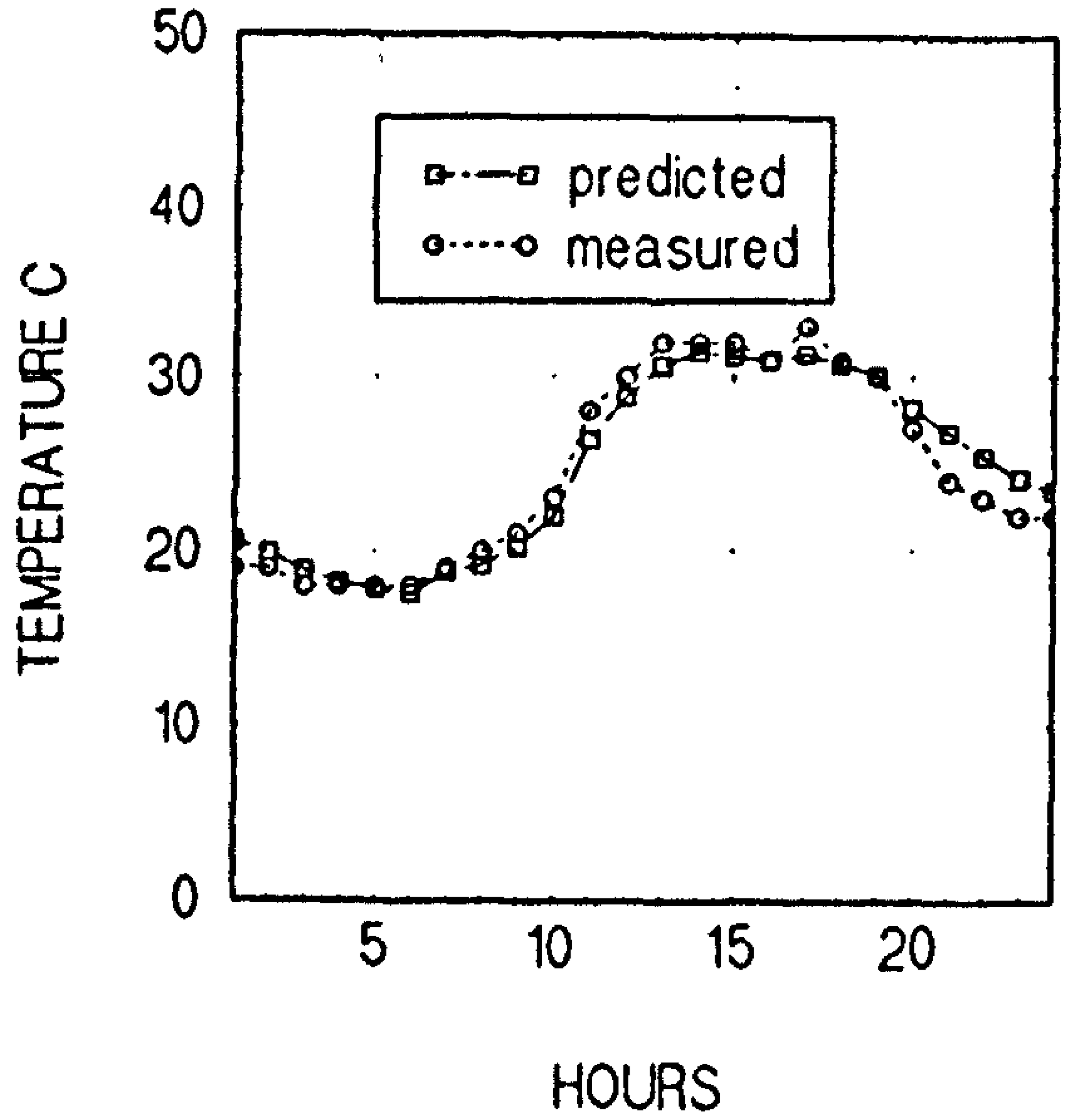


Figure 6.29 Sun 11th Jun 89

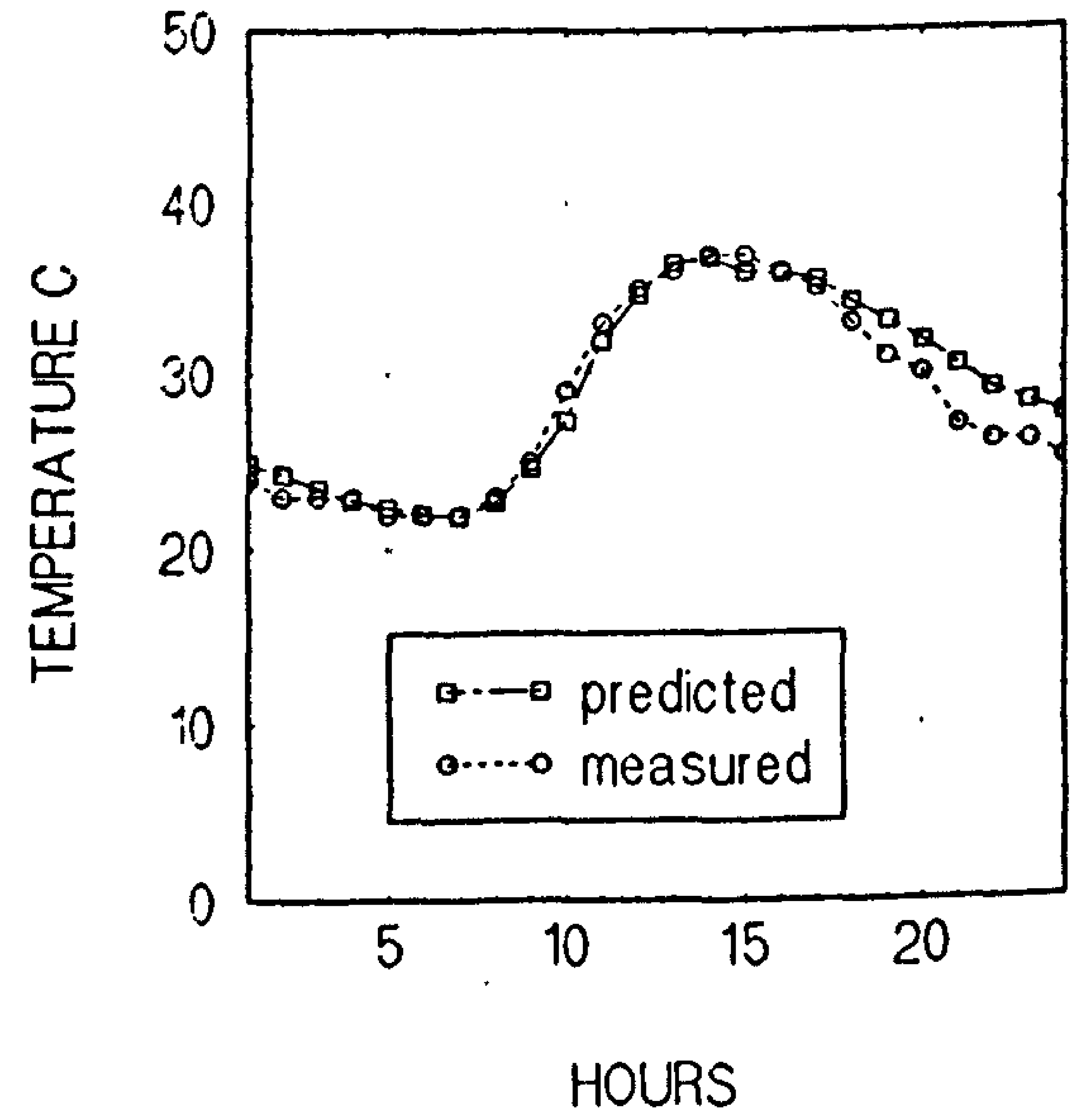


Figure 6.30 Sun 6th Aug 89

6.36 The correlation between predicted and measured temperatures in the atrium of Barnes Farm school, for Sundays from April to August 1989 inclusive, is shown in figures 6.31 and 6.32.

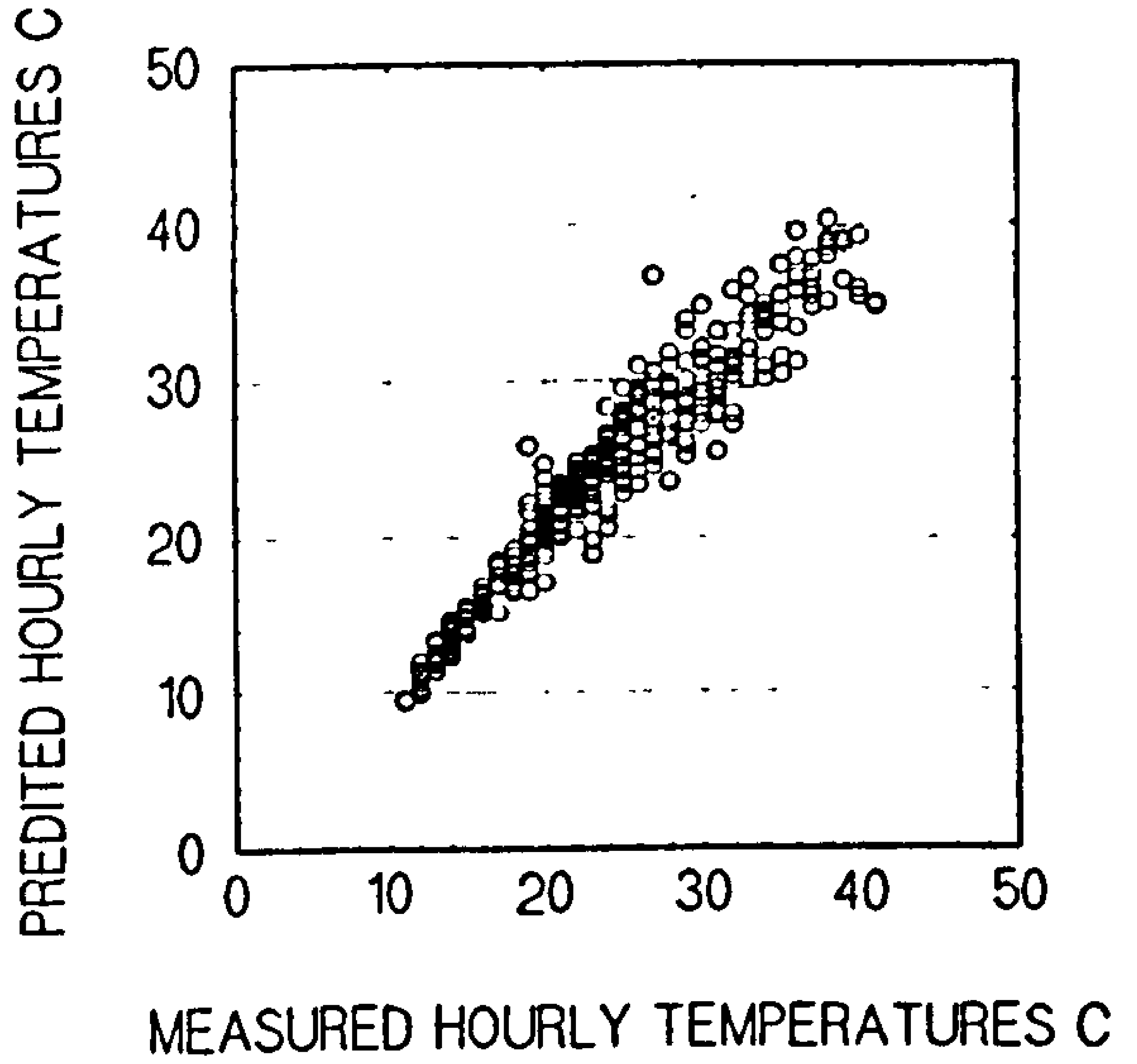


Figure 6.31 BARNES FARM SCHOOL ATRIUM SUNDAYS APR TO AUG 1989.

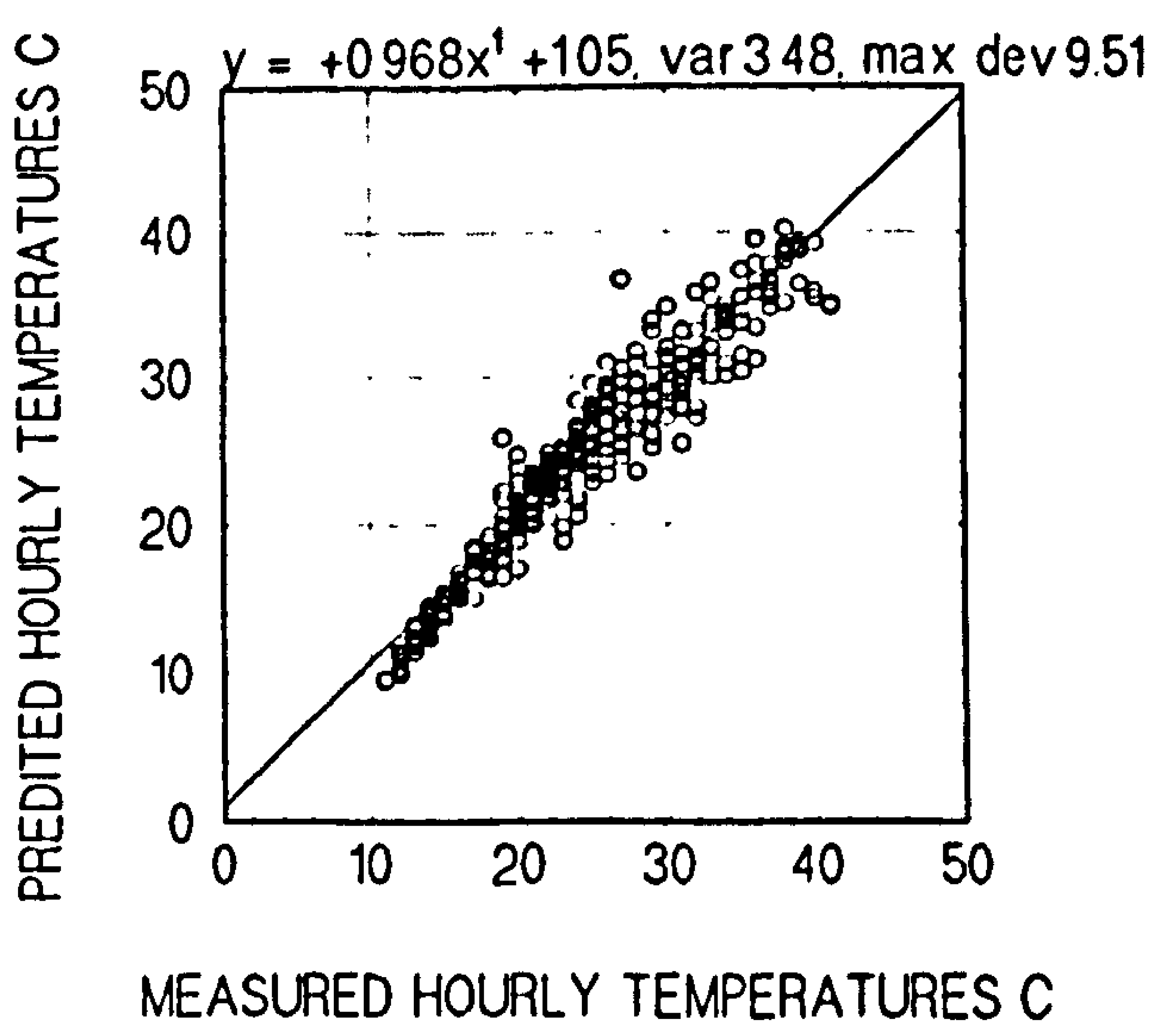


Figure 6.32 BARNES FARM SCHOOL ATRIUM SUNDAYS APR TO AUG 1989.

Barnes Farm school class-bases.

6.37 A comparison between actual and predicted class-base temperatures is shown in figures 6.33 to 6.36.

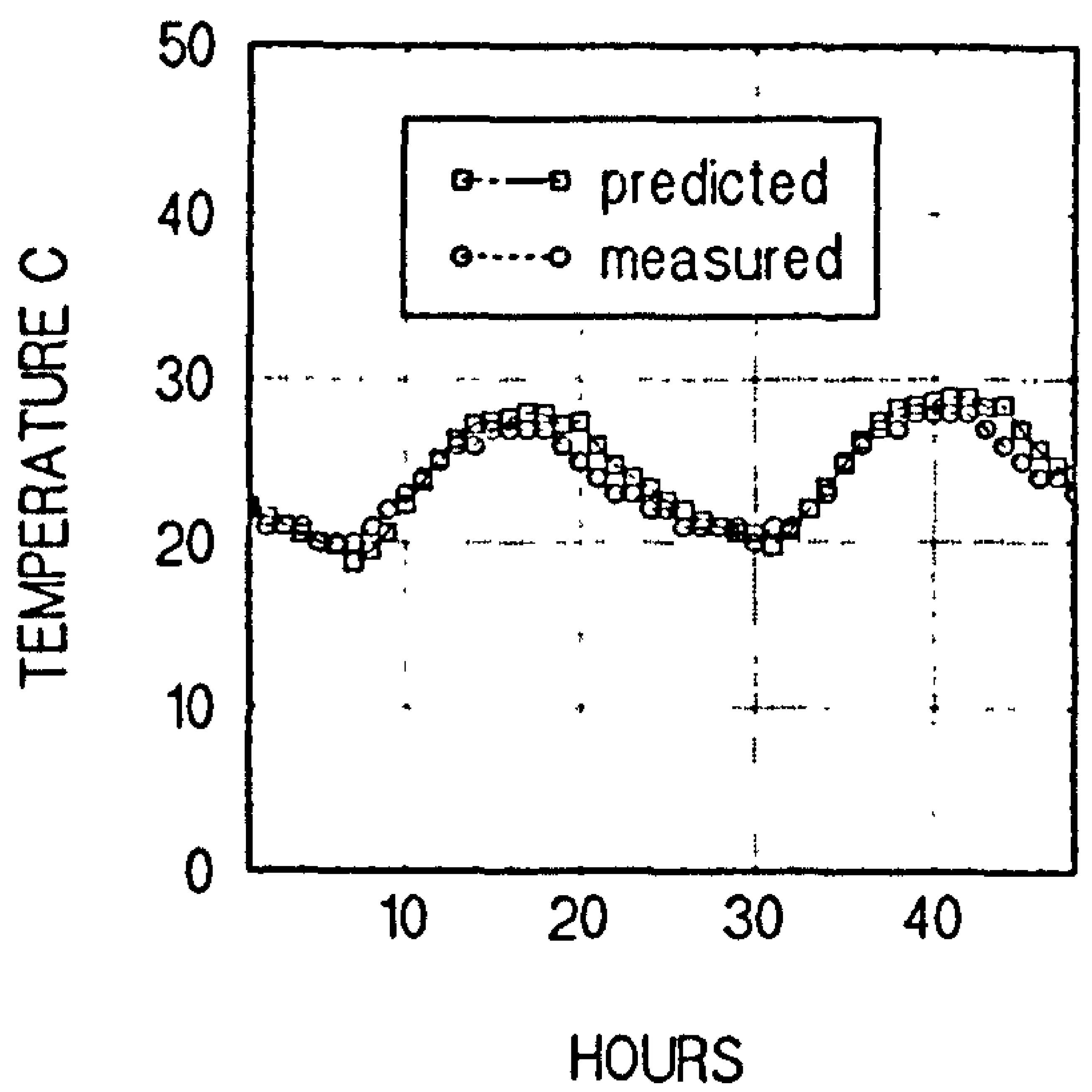


Fig 6.33 WEEKEND 20/21ST MAY

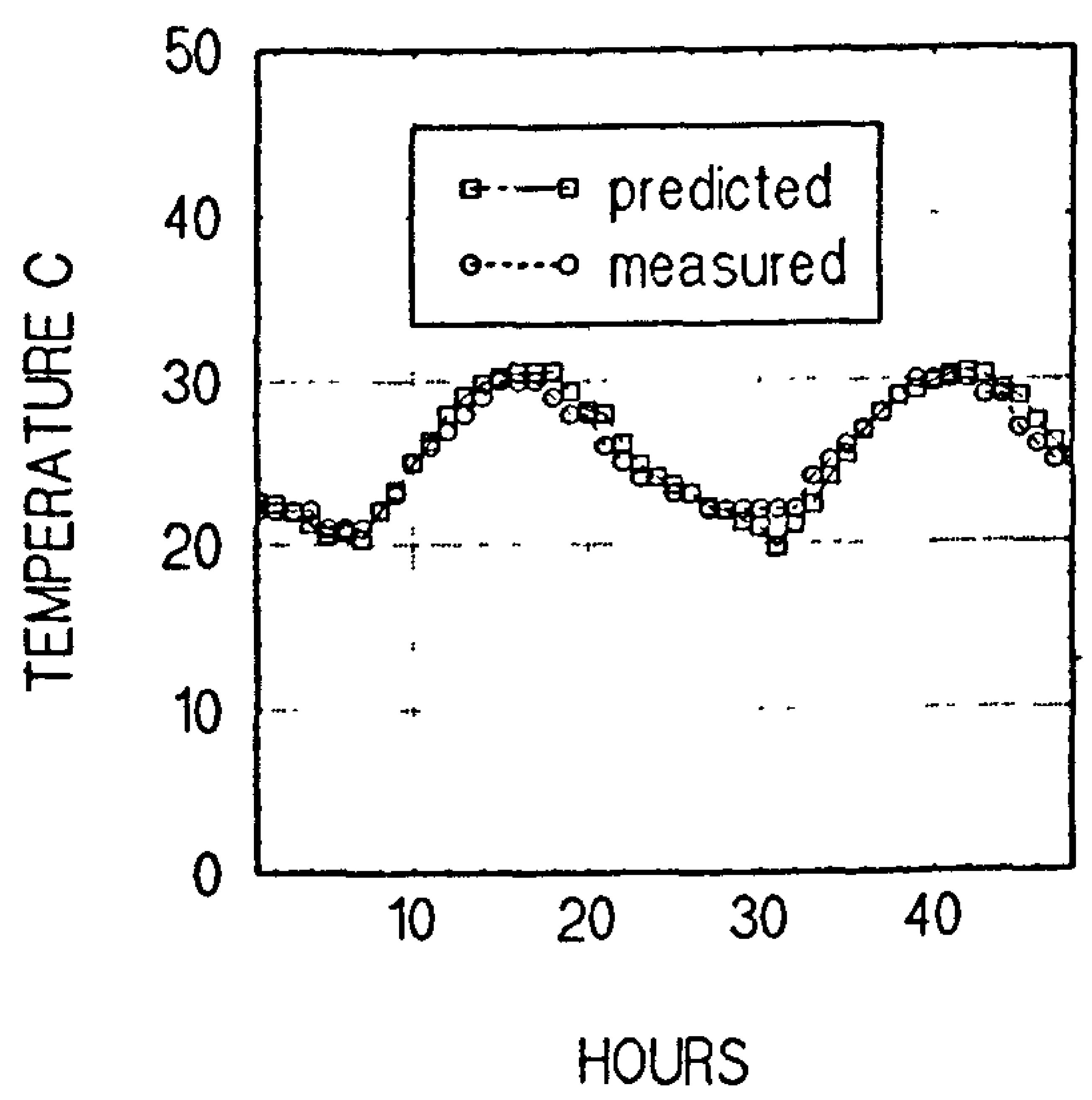


Fig 6.34 WEEKEND 17/18TH JUN

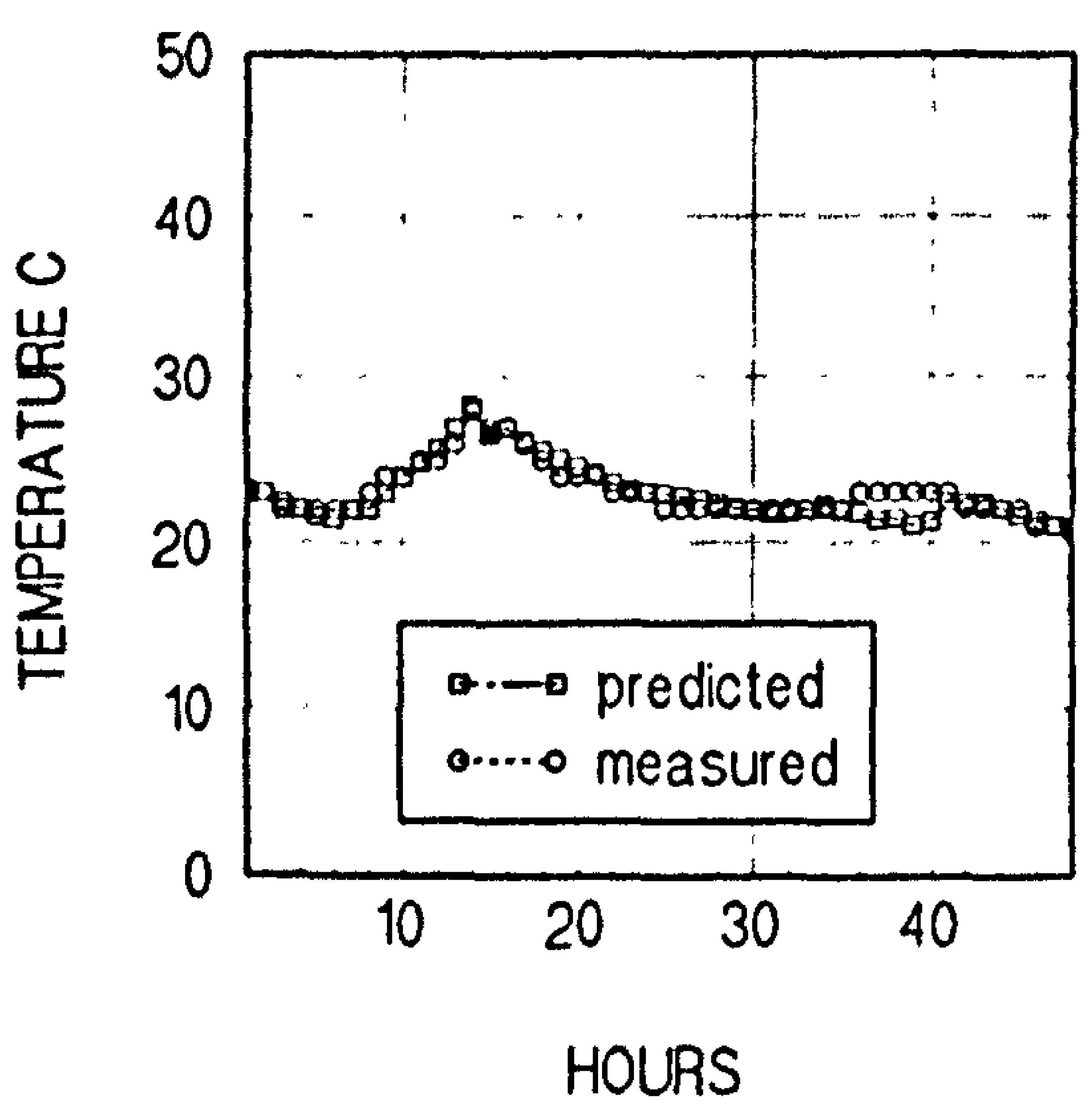


Fig 6.35 WEEKEND 8/9TH JUL

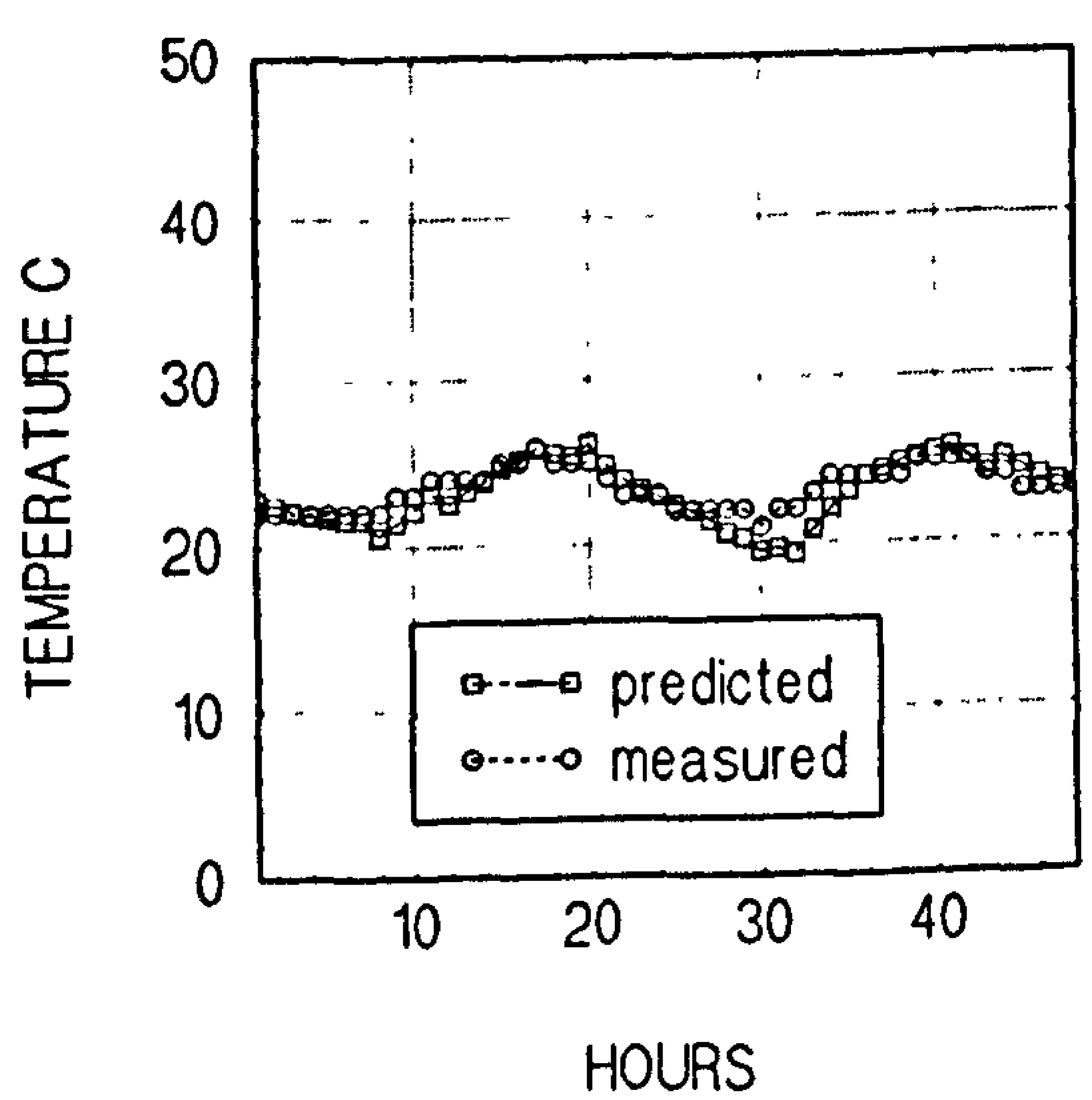


Fig 6.36 WEEKEND 12/13 AUG

6.38 The Seri-Res output during April and May did not correlate with the measured zone temperatures, which apeared to indicate that the heating system was on continuously during the period April to early May. An examination of the boiler controls revealed that this was indeed the correct. The correlation between actual and predicted class-base temperatures for the unheated weekends studied between May and August 1989 is shown in figures 6.37 and 6.38.

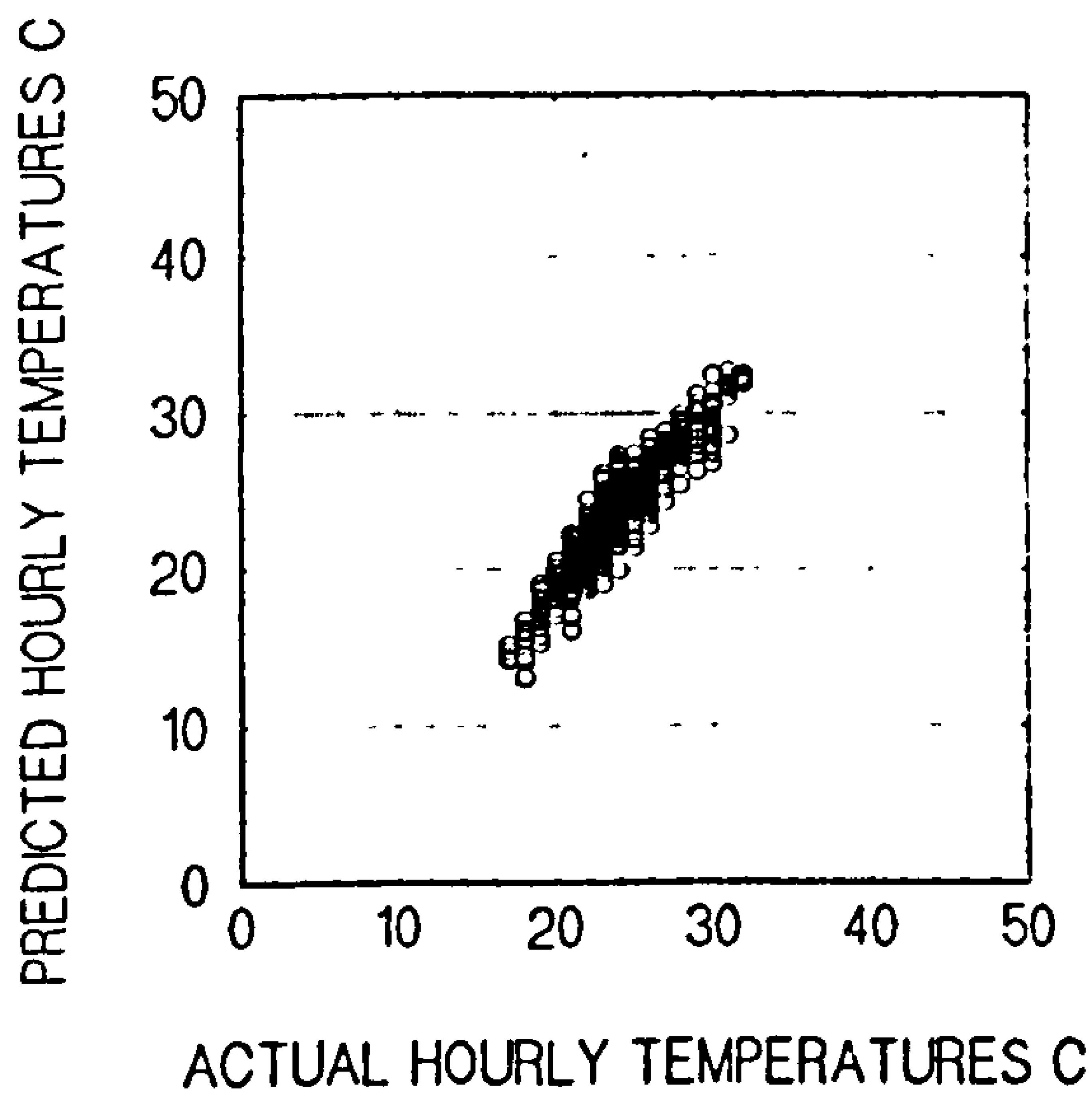


Figure 6.37 BARNES FARM SCHOOL CLASS-BASE, WEEKENDS 20TH MAY TO 20TH AUGUST 1989.

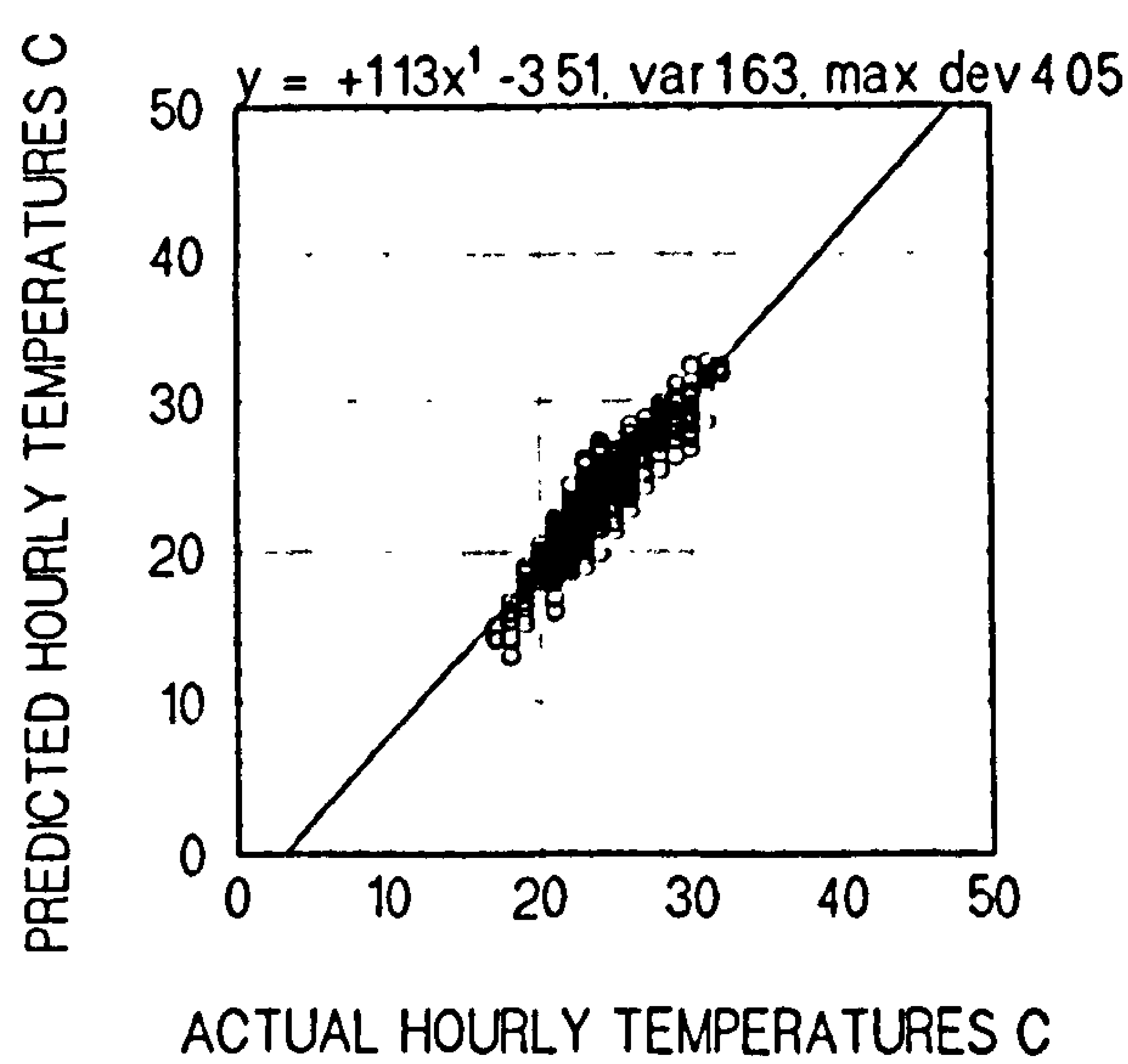


Figure 6.38 BARNES FARM SCHOOL CLASS-BASE, WEEKENDS 20TH MAY TO 20TH AUG 1989.

Comparison of overall design performance.

6.39 The weather during the monitoring period of 1989 was considered unrepresentative, being much warmer than usual. Furthermore, the duration of monitoring was less than one year, and included several weeks during the summer months, when schools would normally be unoccupied. Whilst this was accepted for the purpose of the calibration of the model, the fact that there was no cold weather data available for either of the schools with central atrium was identified as a problem affecting the prediction of overall thermal performance. It was therefore agreed with the the DES at the commencement of this study, that the Seri-Res simulations to assess the annual design performance of the two schools, and any parametric analysis required, would be undertaken using twelve months of actual hourly weather data for Kew 1964/65. It was considered that, as this was a more representative year, more meaningful results would be obtained.

6.40 Figure 6.39 compares the DN17 (DES 1981b Fig 6) curve for maximum annual energy consumption in primary schools, which does not allow for the effect of beneficial solar gain, with the simulated performance of the Hook, Barnes Farm schools, and the monitored result for Looe junior & infants school(Alexander et al 1991), and table 6.16 lists the fabric performance for both schools, calculated using Seri-Res.

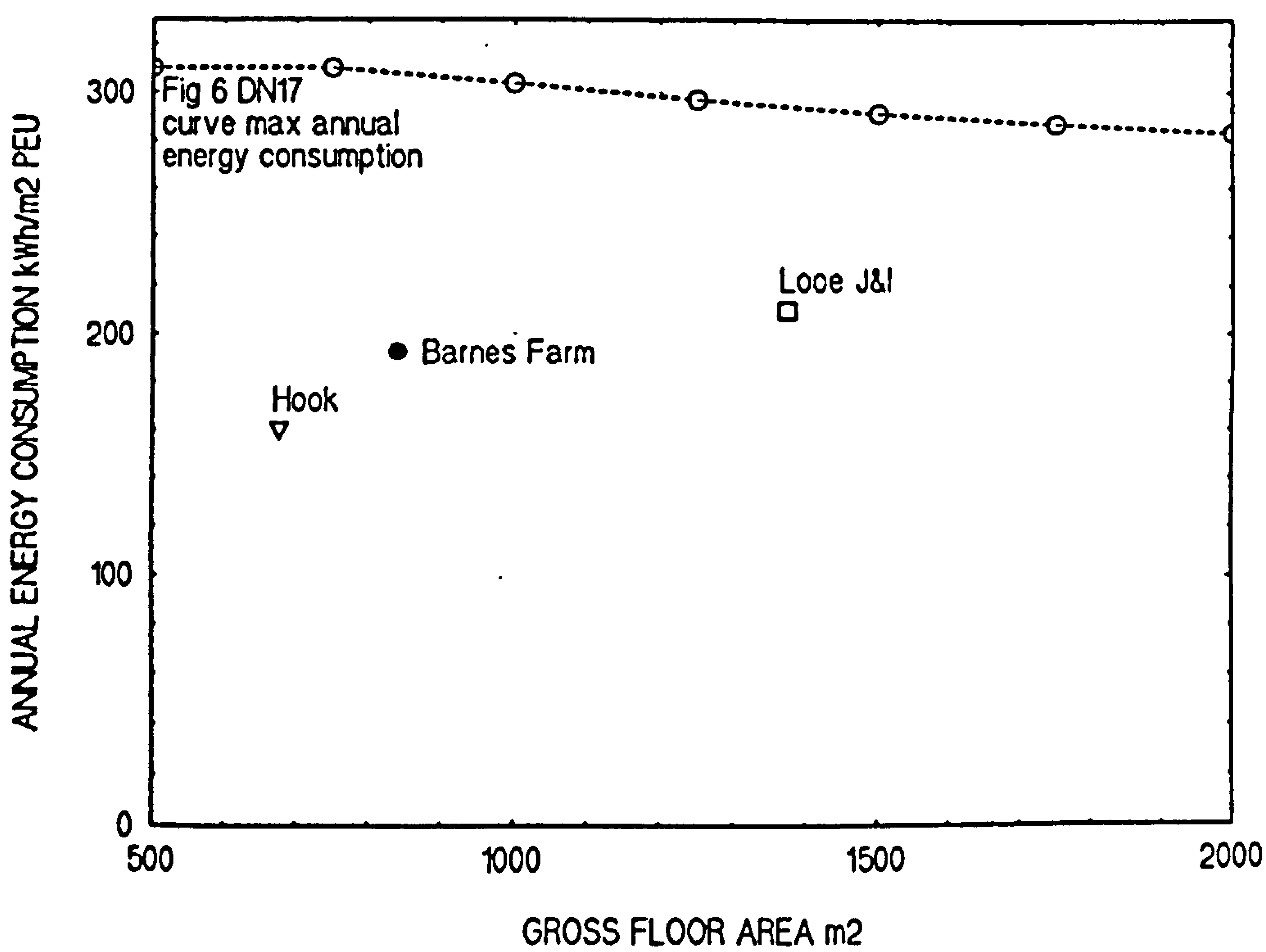


Figure 6.39 ANNUAL ENERGY CONSUMPTION AND DN17 REQUIREMENT.

Table 6.16 BUILDING ELEMENT U-VALUES, $W\ m^{-2}\ K^{-1}$, Seri-Res output.

BUILDING ELEMENT	HOOK SCHOOL	BARNES FARM SCHOOL
	$W\ m^{-2}\ K^{-1}$	$W\ m^{-2}\ K^{-1}$
MAIN BUILDING.		
External cavity wall	0.45	0.58
stud	0.54	2.10
Windows external	2.80	5.40
internal	5.40	5.40
Main roof new	0.23	0.30
old	0.20	N/A
Ground floor	0.61	0.64
ATRIUM.		
Walls external	2.80	0.58
internal	1.40	0.59
Windows external	2.80	5.40
internal	5.40	5.40
Roof opaque	0.27	0.20
glazed	2.80	3.20
Ground floor	0.63	0.66
OVERALL /AMBIENT.	$2.4\ W\ K^{-1}\ m^{-2}$	$1.5\ W\ K^{-1}\ m^{-2}$

6.41 It is clear from the analysis of the data obtained from the monitoring scheme, that even the unheated atrium provided a comfortable environment, during periods of occupancy, for most of the heating season. Figure 6.40 shows the variation of the atrium temperatures during a dull winters day.

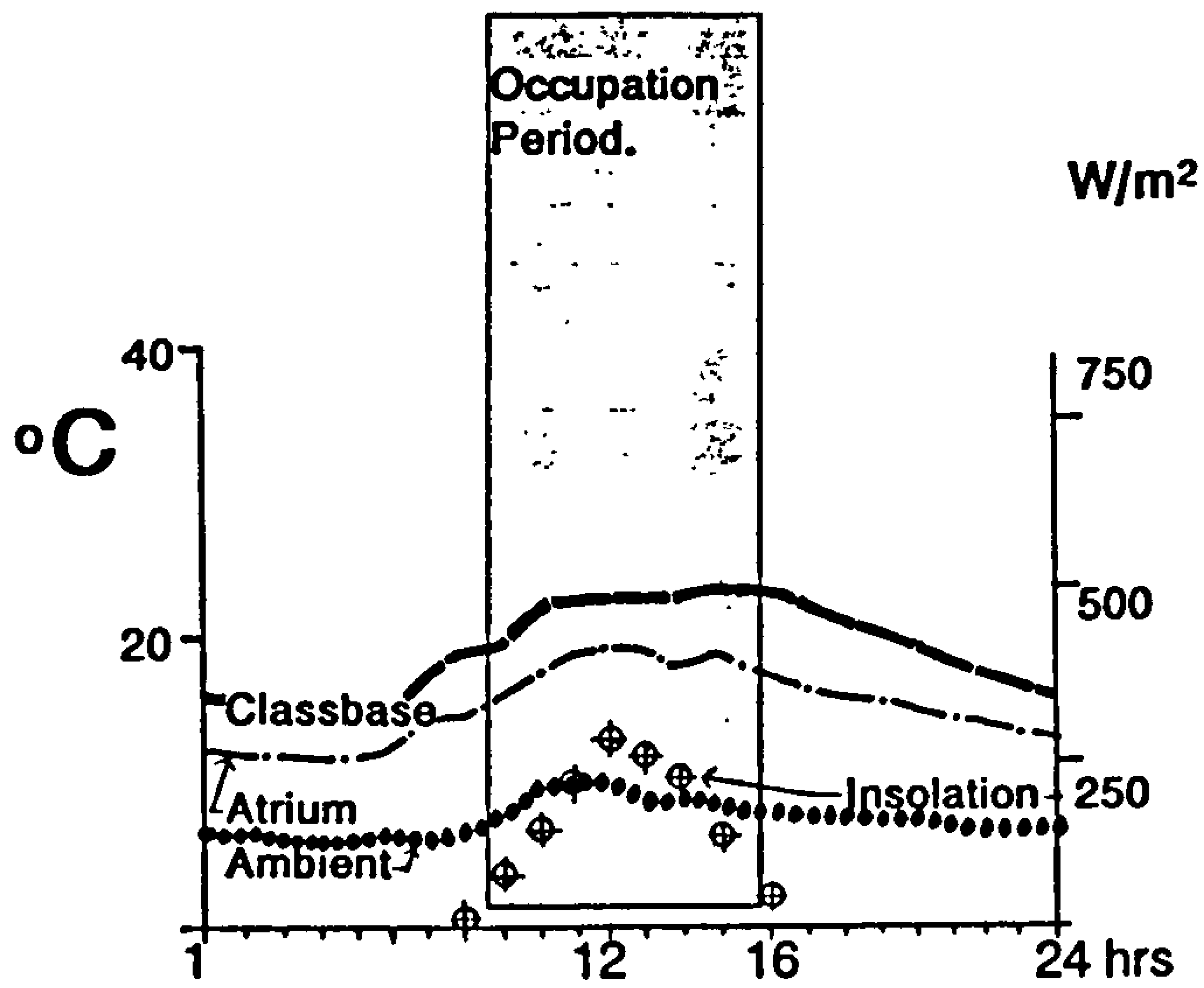


Figure 6.40 Temperature of the unheated atrium at Barnes Farm school on a dull winter day.

6.42 The venting of excess heat from the Barnes Farm atrium was effective once the ridge opening lights were operated.

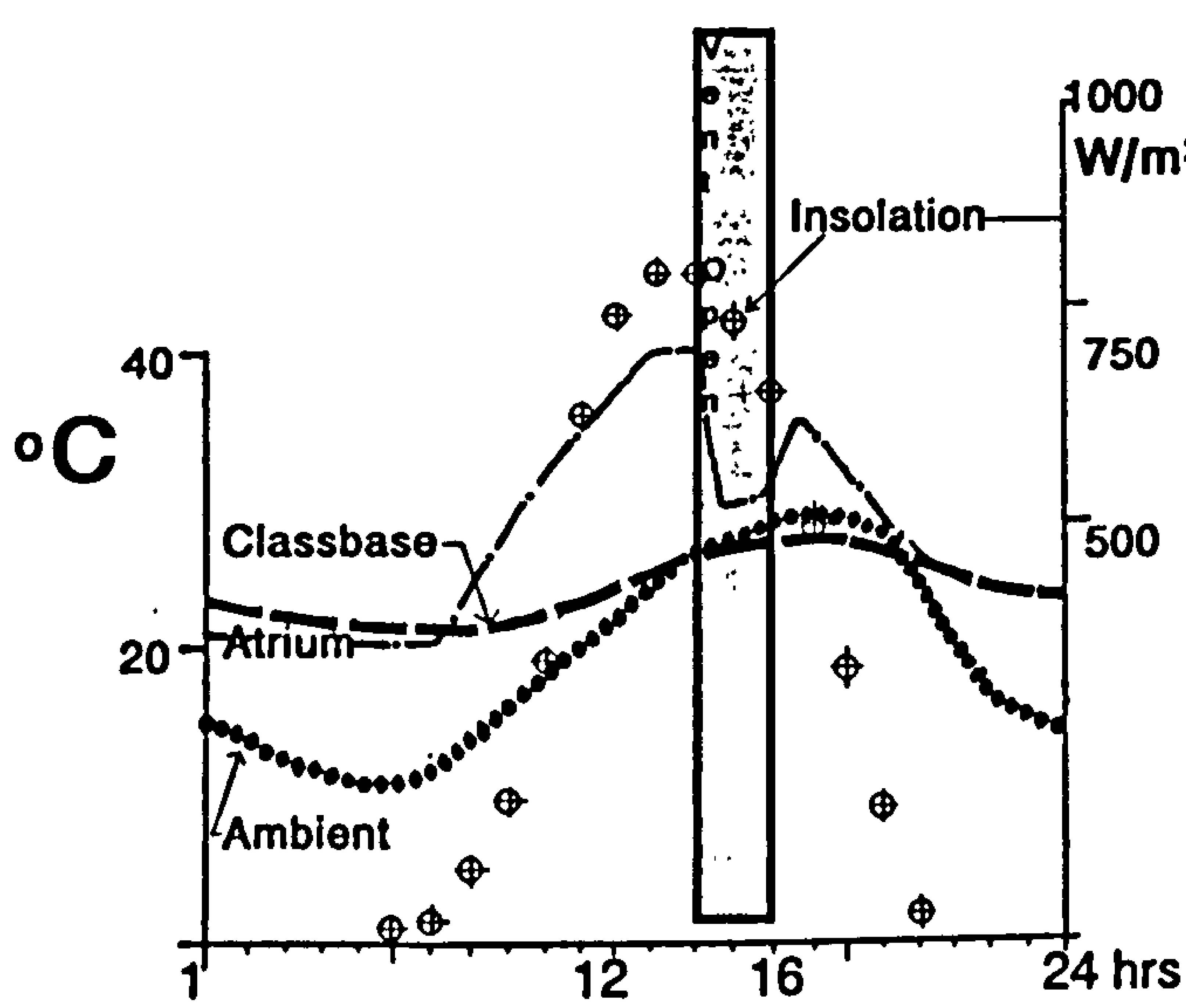


Figure 6.41 Barnes Farm atrium temperature & ridge level ventilation.

7.0 PARAMETRIC ANALYSIS.

7.1 The results obtained from the calibration exercise indicated that: the Seri-Res model was capable of predicting the hourly zone temperatures for different seasons with reasonable accuracy, compared to measured diurnal trends. It was assumed that predicted energy loads would also be reasonably correct, and that the model could therefore be used to address the following questions:

(a) What effect does orientation have on the thermal performance of these schools?
(b) How significant is the glazing specification?
(c) Is there an optimum width of atrium?
(d) Should the atrium be heated?

7.2 The aim was to quantify the usefulness of the passive solar aspects of the design of both schools in terms of energy conservation and year-round comfort, and assess the significance of the following variables:-

(i) Atrium orientation.
(ii) Atrium width.
(iii) Atrium heating.
(iv) Building & atrium glazing specification.
(v) Daylight in class-bases.

ORIENTATION:

7.3 A change in orientation of both buildings was simulated using steps of 15 degrees. An annual run was used to predict the resultant energy performance for each change of orientation of the otherwise 'as constructed' buildings.

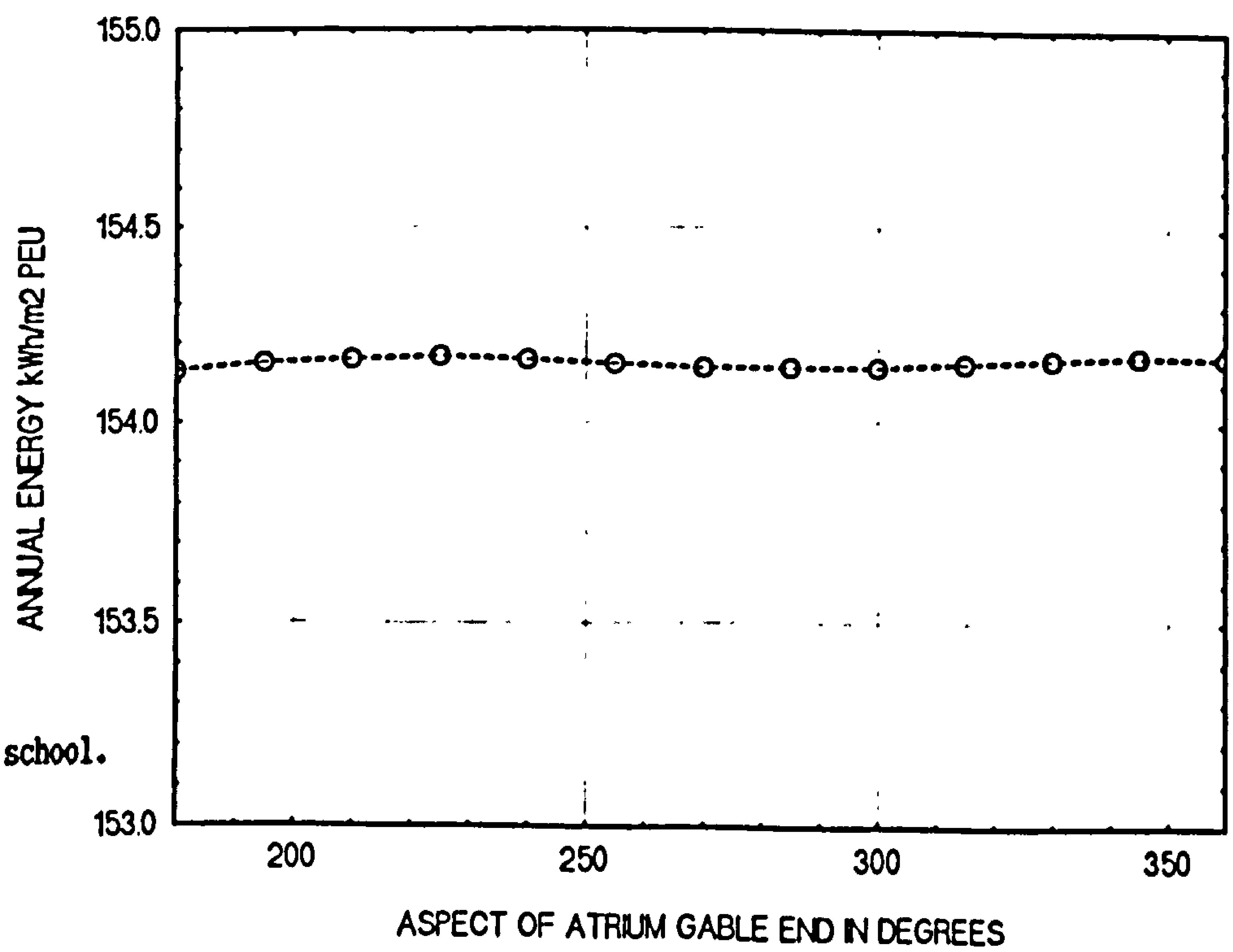


Fig 7.1 Hook school.

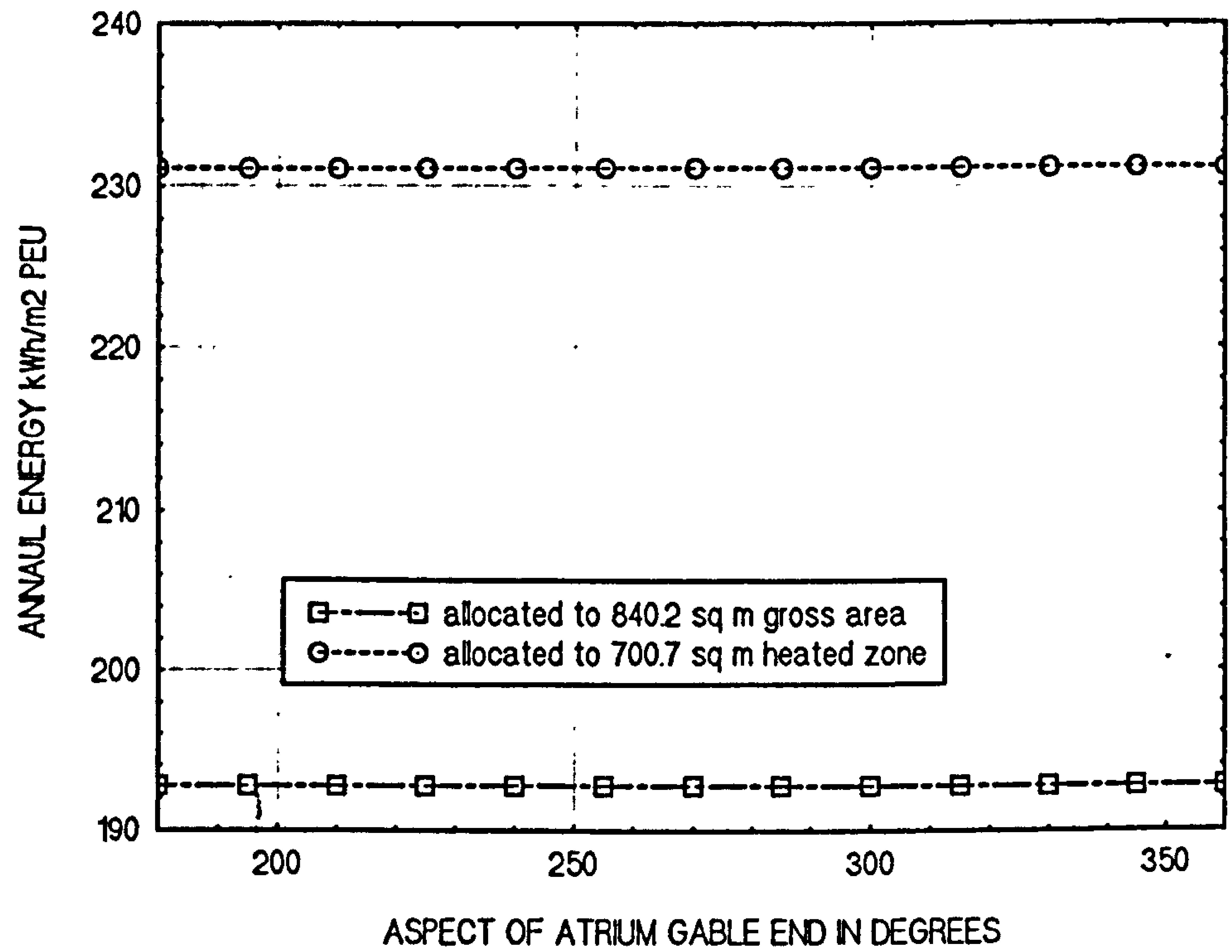


Fig 7.2 Barnes Farm school.

7.4 Figures 7.1 and 7.2 indicate that there was a negligible effect on predicted thermal performance of the whole building arising from the variations simulated in orientation of the building models based on the Hook and Barnes Farm schools respectively, even though the variations meant that for some orientations the large glazed areas to the class-bases faced North. However the solar aperture of the atrium roof would be almost constant throughout, and the extent to which this dominated the overall performance of these buildings in relation to useful solar gain is demonstrated in these results.

ATRIUM WIDTH.

7.5 The width of the atrium in the model based on the Hook School was varied between one half of the actual width of 5.5 metres and one and a half times the present width, with intermediate widths of 4.13 and 6.87 metres. The assumption being that a width of approximately 2.75 metres would represent a minimum practical width for teaching purposes in view of circulation requirements.

7.6 Similarly the width of the atrium in the model based on the school at Barnes Farm was varied between one half and one and a half times the actual width of 6.2 metres, and intermediate widths of 4.6 and 7.7 metres were also analysed.

7.7 Since the area of the heated atrium at Hook school comprises part of the statutory area of the school, unlike that of the unheated atrium at Barnes Farm school, it was necessary, when varying the width of the heated atrium, to also vary the area of the remainder of the school by making an adjustment to the depth of the accommodation adjoining the atrium, so that the total area of the school, the length of atrium, roof pitches and angles of incidence remained constant.

7.8 However, when varying the width of the unheated atrium at Barnes Farm school, the area of the remainder of the school was held constant, as was the atrium length, roof pitch and associated angles of incidence. The glazed pitched roof of the atrium at Barnes Farm school commences 700 mm from the atrium face of the class-base connecting wall either side of the atrium, due to the presence of a horizontal projecting flat roof feature, which is specifically designed to afford direct gain shading of the internal glazed apertures in the connecting walls. The dimensions of this shading was held constant in the simulations.

7.9 The effect on levels of daylight in the adjoining class-bases, from varying the width of the atria, were predicted using the daylight factor method for input to Seri-Res, which predicts the hourly artificial lighting loads by calculating the available daylight from the hourly solar radiation data. In order to assess the effectiveness of the design strategy for daylight, it was assumed in the simulations that the artificial lighting in the teaching areas would be switched on and off in response to the level of daylight calculated to be available for each hour of the school day with a set point of 150 lux. In reality the lights tend to be on for longer periods.

7.10 Simulations for one year were carried out to:-

(i) predict the energy use, excluding catering, of the notional buildings resulting from such changes, and

(ii) assess the useful and adverse effects of solar gain.

7.11 The effect of omitting the heating to the atrium of the Hook School was examined, although this particular variable is technically inappropriate, since the atrium comprises part of the statutory area of that school. The effect of heating the Barnes Farm atrium was also simulated. The result of the simulations, in terms of delivered energy, are shown in figure 7.3 for Hook school with a constant gross area of 676.3 m^2 for the monitored section.

Width of an atrium of the Hook school type of construction.

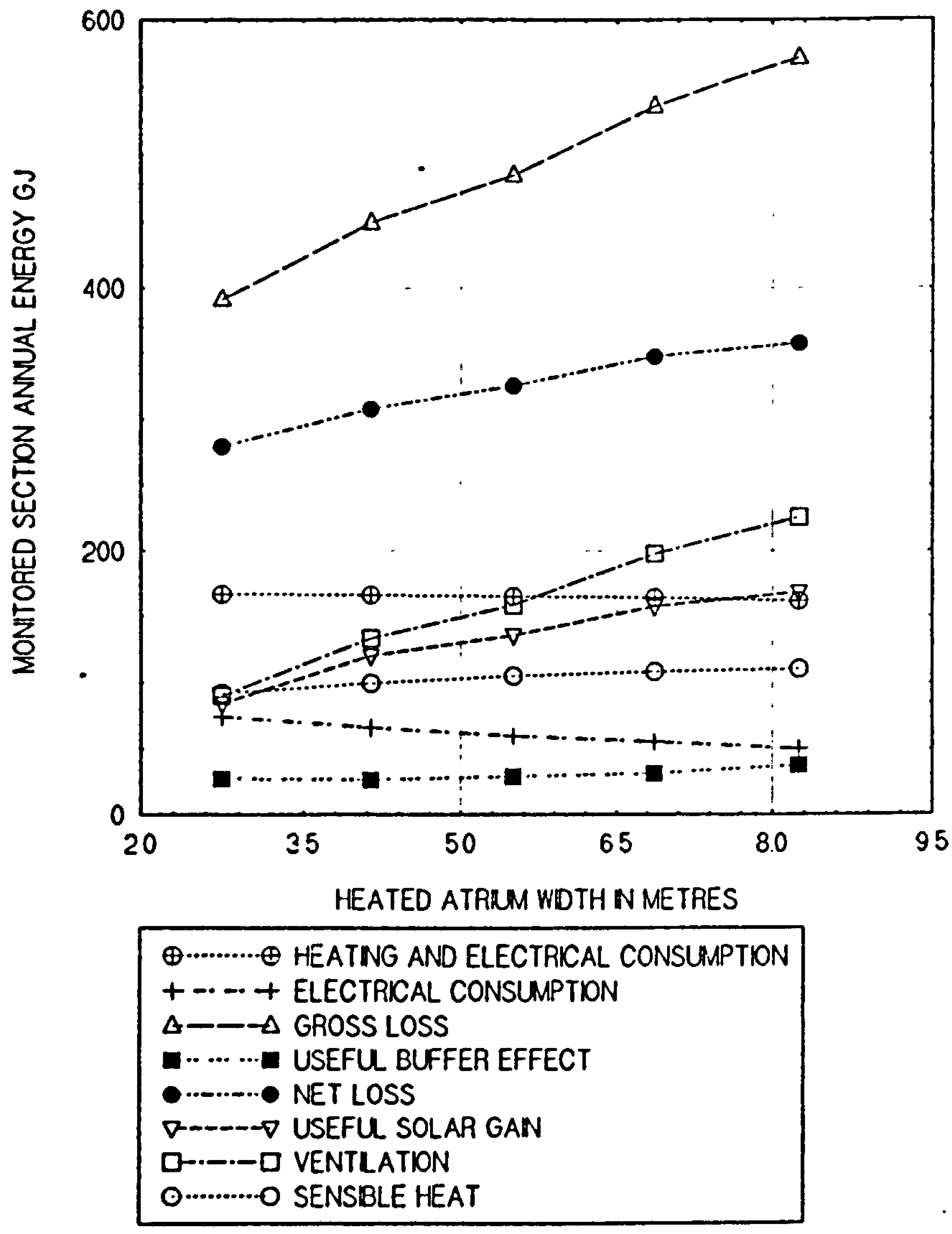


Figure 7.3 DELIVERED ENERGY FOR THE HOOK SCHOOL TYPE OF CONSTRUCTION WITH VARYING WIDTH OF ATRIUM.

7.12 The results for the Hook school type of design and construction with a heated atrium(Figure

7.3) indicated that there was no optimum width of atrium. The wider the atrium the more energy would be used. There was an increased tendency for the atrium to overheat with increased width of atrium, and the ventilation of unwanted heat increasingly exceeds the useful solar gains with increased width of atrium.

Width of an atrium of the Barnes Farm school type of construction.

7.13 Figure 7.4 shows the predicted energy use for the simulation which varies the width of a wholly unoccupied, and unheated atrium from 3.1 to 9.3 metres for a constant gross area of adjoining heated accommodation of 700.7 m as at Barnes Farm school.

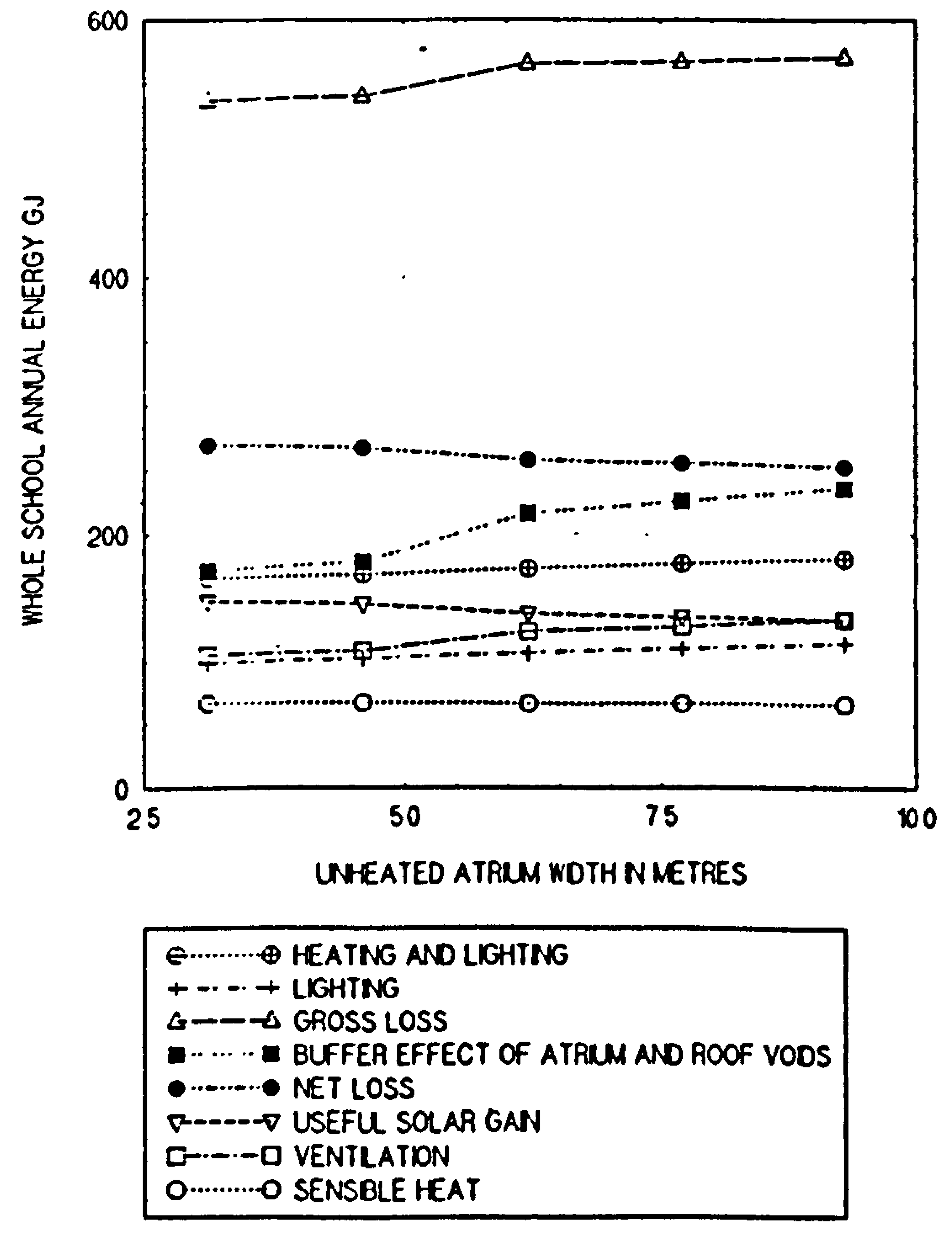


Figure 7.4 DELIVERED ANNUAL ENERGY FOR A SCHOOL OF THE BARNES FARM TYPE OF CONSTRUCTION, WITH VARYING WIDTH OF ATRIUM.

7.14 The net loss was predicted(Figure 7.4) to reduce slightly with increased width of atrium. However, the Barnes Farm school makes extensive use of the unheated atrium for teaching purposes for most of the school year, and whilst there would be a significant buffering effect from the unheated atrium, Ser-Res does not account for any buffering effect from occupied spaces. A more realistic result would therefore probably be somewhere between that simulated for a wholly unoccupied atrium and the fully occupied atrium simulated in Figure 7.5, which shows the predicted delivered energy use of the school, allowing for the venting, incidental gains, nominal heat input to the coat hanging areas, artificially lighting, and scheduled use of the mainly unheated atrium. It can be seen from figures 7.3 to 7.5 that varying the width of the atria was predicted to have a significant effect on the thermal performance of both buildings. It would be necessary to interpolate between figures 7.4 and 7.5 to allow for the buffering effect of the unheated atrium at Barnes Farm school.

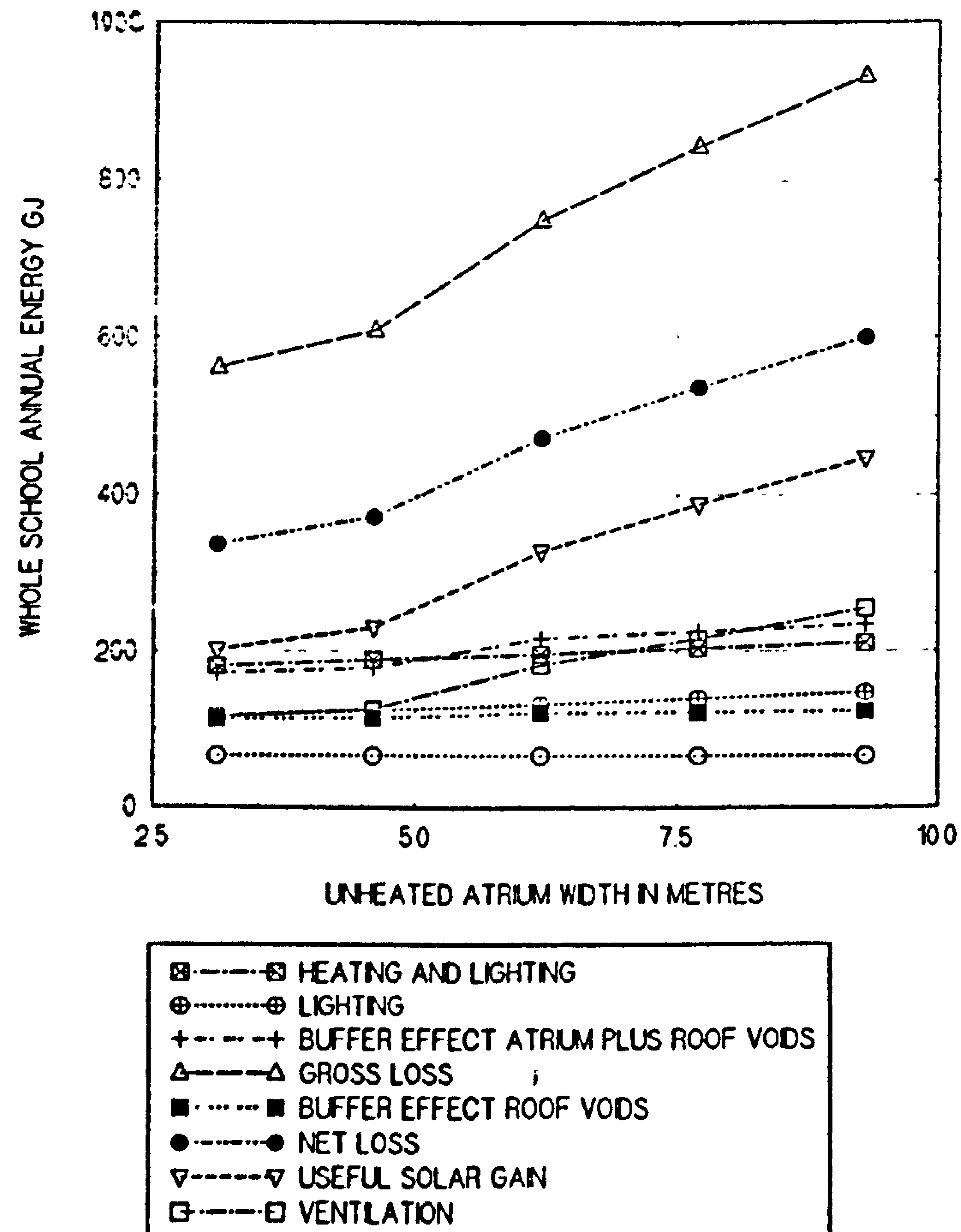
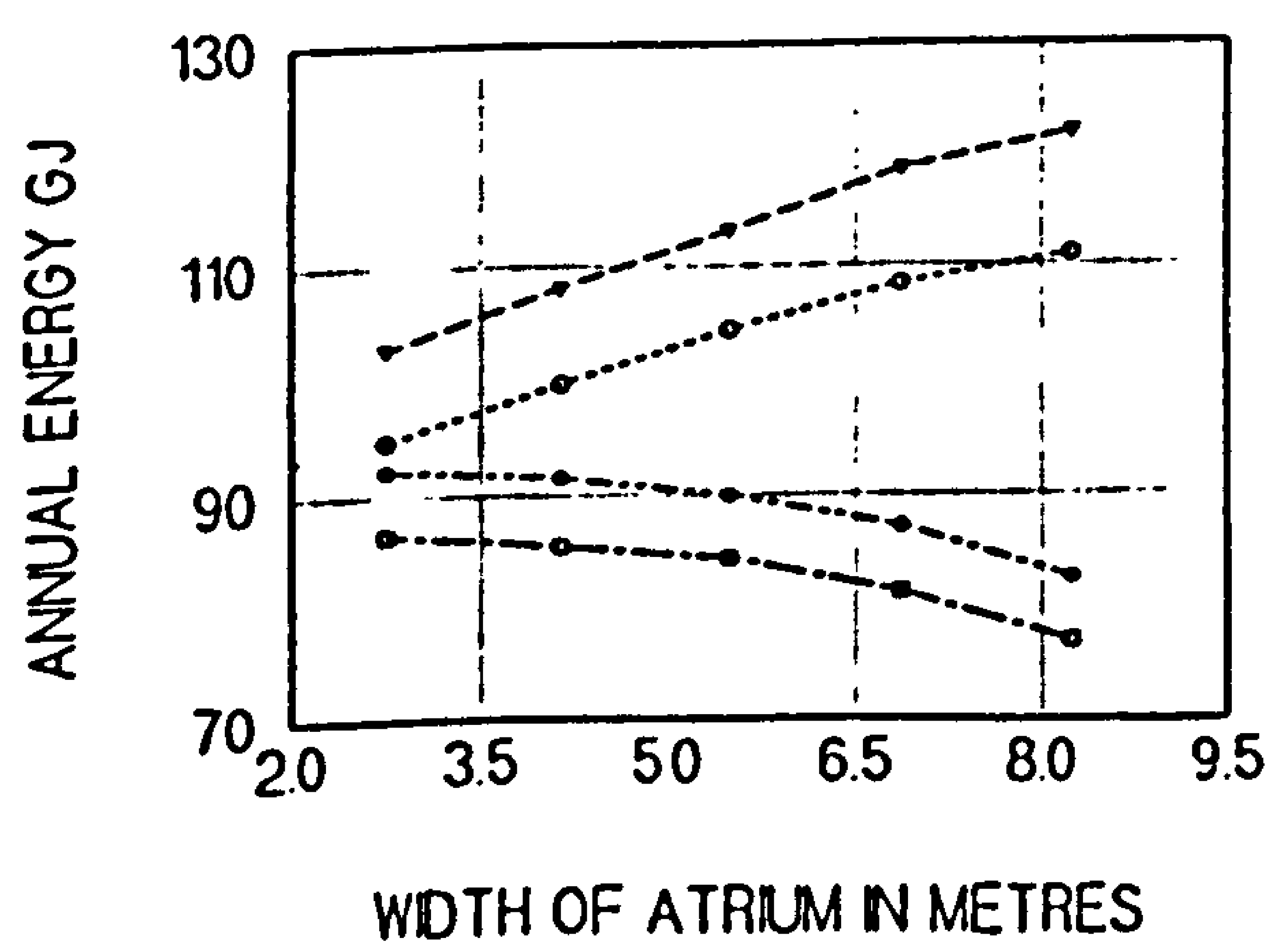


Figure 7.5 DELIVERED ENERGY FOR THE BARNES FARM SCHOOL TYPE OF CONSTRUCTION WITH AN UNHEATED, BUT FULLY USED ATRIUM OF VARYING WIDTH.

GLAZING SPECIFICATION.

7.15 Hook school is mainly double glazed to ambient with single glazed openings between the heated atrium and the adjoining class-bases. Barnes Farm school is single glazed throughout, with the exception of the class-base roof-lights, which were double glazed units incorporating a layer of georgian wired glass, and the atrium roof, which is glazed with twin wall polycarbonate sheets. Anti-sun glass is used for the South-facing single glazing, and the atrium is unheated apart from some nominal heat input to the coat hanging areas. Additional Seri-Res simulations were carried out to predict the annual thermal performance of both schools, with single glazing throughout for Hook school, and double glazing to ambient at Barnes Farm school, with and without heating to the atria. The form of the double glazing to the atrium roof at each school was however unchanged, since single glazing would be inadvisable in such locations due to condensation risk. FigureS 7.6 to 7.8 show the predicted results of these changes. Figure 7.7 predicted that for a building and atrium of the Barnes Farm type of design and construction, the net loss of a single glazed building and atrium with unheated atrium was similar to that of a double glazed building and atrium with heated atrium for widths up to 6.2 metres(as built). Figure 7.8 indicates that this result is reflected in the calculation of useful buffering.

External wall glazing to the Hook school type of building with a heated or unheated atrium of varying width.



single glazed building and atrium with unheated atrium
single glazed building and atrium with heated atrium
double glazed building and atrium with unheated atrium
double glazed building and atrium with heated atrium

Fig 7.6 HEATING LOAD

LEGEND

External wall glazing to the Barnes Farm type of building, with either a heated, or unheated atrium of differing widths.

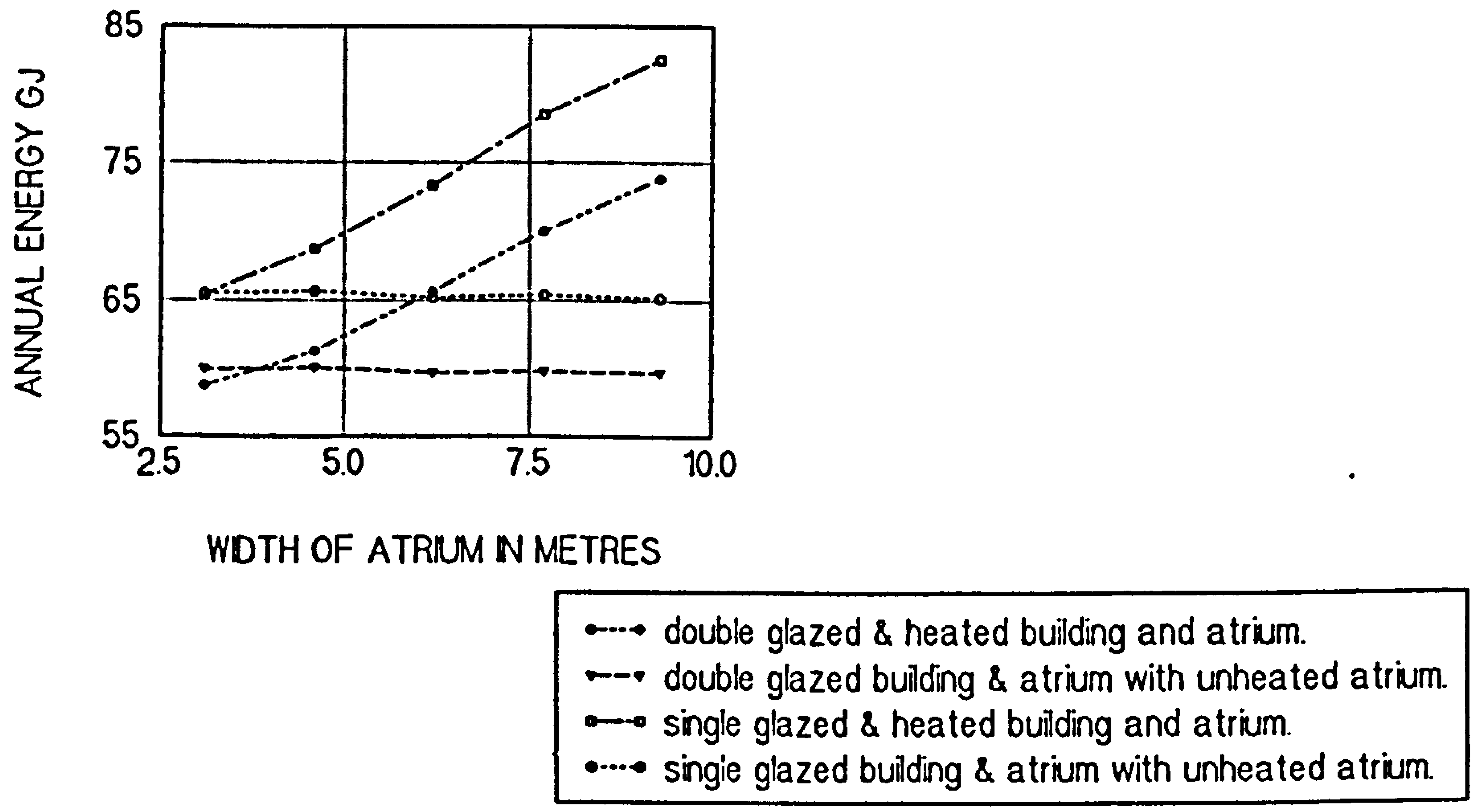


Fig 7.7 HEATING LOAD LEGEND

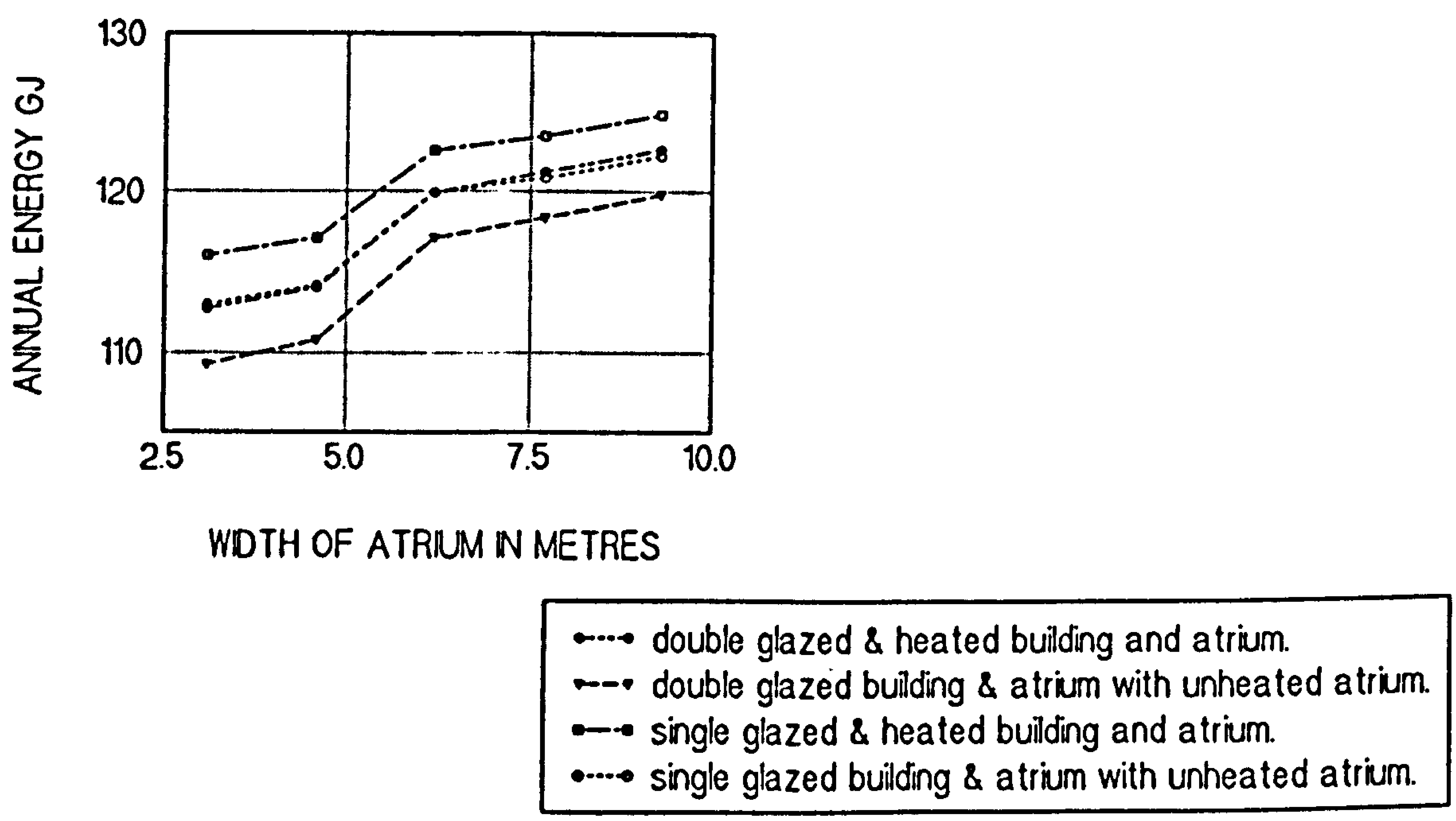


Fig 7.8 USEFUL BUFFER EFFECT LEGEND

8.0 THE NOTIONAL CLASS-BASE.

8.1 Having compared the performance of the two passive solar schools, and carried an assessment of the effect of changing the orientation and glazing specification, and varying the width of the atrium, it was evidently going to be important to allow for the effects of solar radiation and improved thermal insulation, when assessing the thermal performance of teaching spaces for all seasons in relation to thermal comfort, space-heating loads, daylight and the use of electric light. An important question, which was unresolved at this stage of the study, and which would have a bearing on any future amendment to the DN17 guidelines was: what effect does the present preference for pitched-roof construction with sloping soffits, and commonly used levels of thermal insulation, have on the thermal performance of a typical direct-gain teaching space? Accordingly it was decided to use computer models to make an assessment of the thermal performance of a typical class-base, to see the effect, which varying the area of the main glazing to the space as a percentage of the inside face of the external wall, and the provision of large eaves level overhangs to South aspect windows had on:

(i) The level of daylight on the working plane throughout the teaching area;
(ii) The use of electric lighting;
(iii) The incidence of overheating, and
(iv) The space heating loads for different orientation of the main glazing to the space.

8.2 A simple single storey school building consisting of three class-bases, with associated activity spaces and circulation areas, was developed in order to test direct-gain design options. The overall space was 10.5 metres deep, and lit by a single clerestory light, and from both sides by windows. The main teaching space had a sloping soffit and mono-pitched roof, as did the adjoining, but smaller height, activity space and circulation area.

Table 8.1 U-VALUES

CONSTRUCTION ELEMENT	U-VALUE W/m^2 K
Roofs and walls	0.25
Floor	0.45
Windows	2.80

This ceiling and roof arrangement was selected to assess the build up of heat due to the lack of a buffer effect from a normal pitched roof void. Commonly adopted insulation and construction standards were assumed. Table 8.1 lists the U-values for the constructions used. Double glazing was assumed throughout, and pin boarding was provided to door-head height to provide for the display of pupils work.

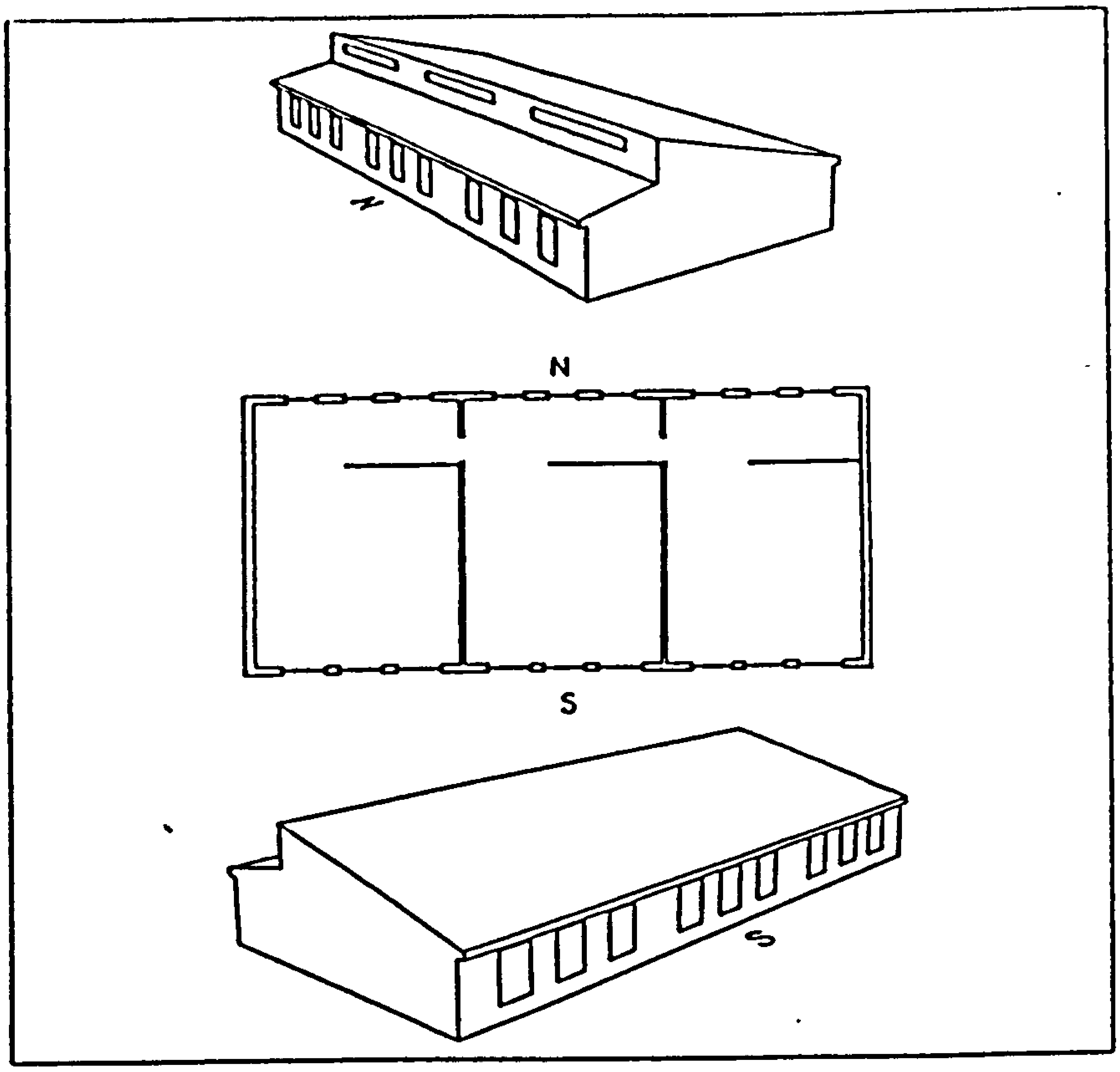


Figure 8.1 The building containing the notional class-base.

Daylight in the notional class-base.

8.3 The central class-base was modelled with a constant area of fenestration, amounting to 20 per cent of the internal face of the external walls area, for the activity and clerestory glazing to the class-base. The main glazing to the class-base was varied between 20 per cent and 40 per cent of the internal face of the external wall. Eaves level projections of 300 mm were assumed as standard throughout, and a variation was simulated to show the effect of 600 mm and 900 mm projections over the South facade.

8.4 Daylight factors within the class-base were predicted for a one metre square grid, using the daylight program. Table 8.2 lists the values used for surface reflection. The program assumed cuboid rooms, and separate runs were therefore made to predict the daylight from each of the three sources, as required for the Seri-Res simulations. This permitted the height of the clerestory glazing to be modelled within the limits of accuracy of the program. The results were added to derive the combined effect for each reference point on a working plane height of 0.7 metres, the minimum daylight factor was identified, and the average daylight factor was calculated. The uniformity ratio was then calculated by dividing the minimum daylight factor by the average daylight factor for the space.

Table 8.2
INTERNAL REFLECTION COEFFICIENTS.

SURFACE	REFLECTANCE fraction
Walls	0.6
Floor	0.3
Ceiling	0.8

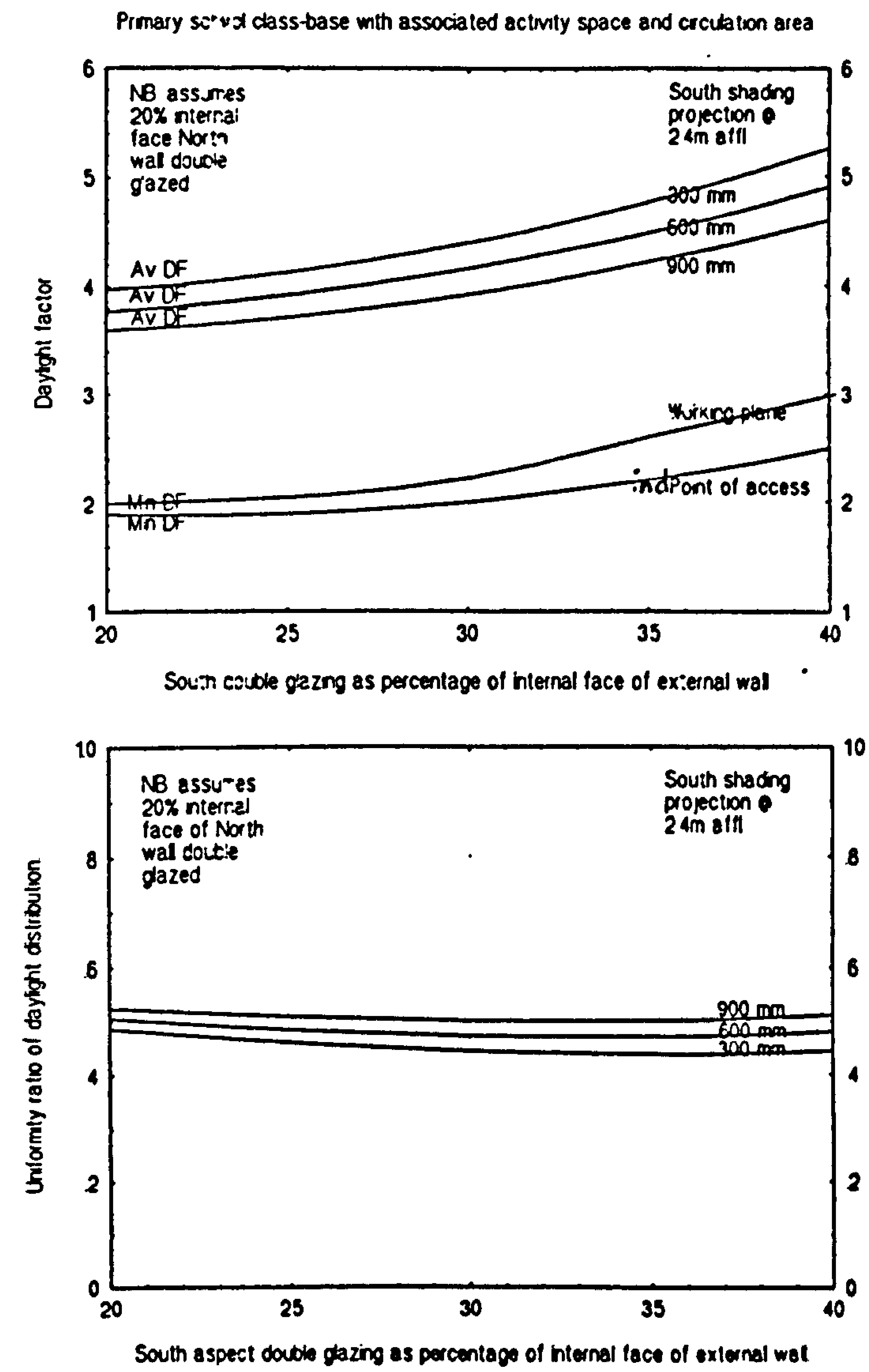


Figure 8.2 UNIFORMITY RATIO & AVERAGE DAYLIGHT FACTORS.

Figure 8.2 indicates the results of the analysis to establish the effect on the average daylight factor and the uniformity ratio of varying the main south-facing glazed area, and the eaves level overhang. A 2% minimum daylight factor was not attainable throughout with 20% glazing.

8.5 The Seri-Res model was used to assess electric lighting required, and overheating hours and days, with and without lights on. The choice of constructions and materials was determined by current practice, and co-ordinated with the data base for the Tas^0 model, which was also used. Tables A.8 to A.11(Appendix A) provide details of the building description used. Table A.8 indicates the scheduled values used governing: infiltration; occupancy and internal gains; ventilation; heating, and the window blind set points, and Table A.9 lists the combined heat transfer coefficients used.

Electric lighting in the notional class-base.

8.6 Electric lighting periods and associated electric loads were predicted, using the Seri-Res program. It was assumed that all use of electric lighting was sensitive to the availability of daylight. This was governed by a set point level of 300 lux, and switched in two equal steps. Figures 8.3 and 8.4 illustrate the Seri-Res predicted hours of 'lamp on' and the electric lighting load for increased percentages of South facing glazing and increasingly deep overhangs at eaves level.

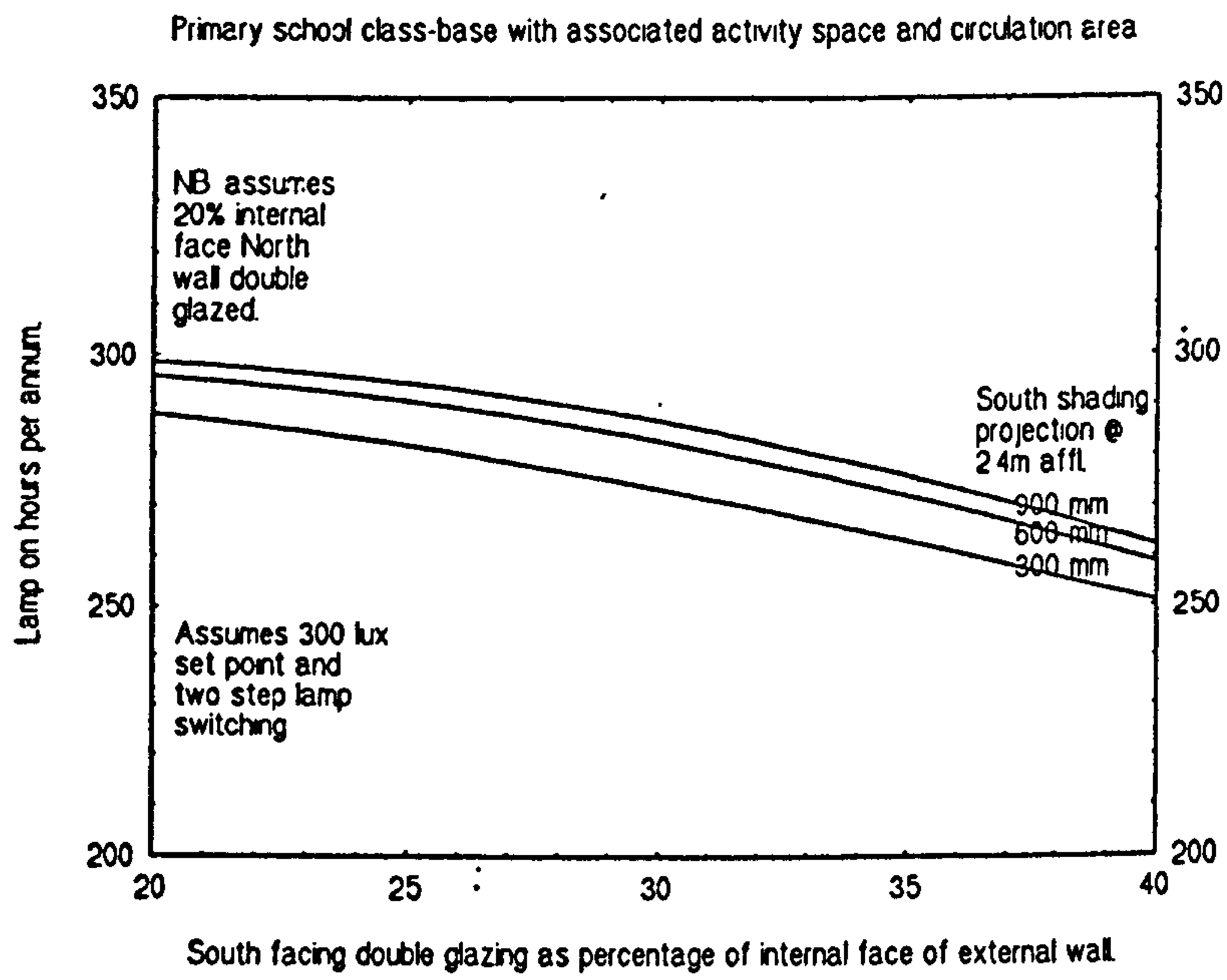


Figure 8.3 HOURS OF LAMP ON

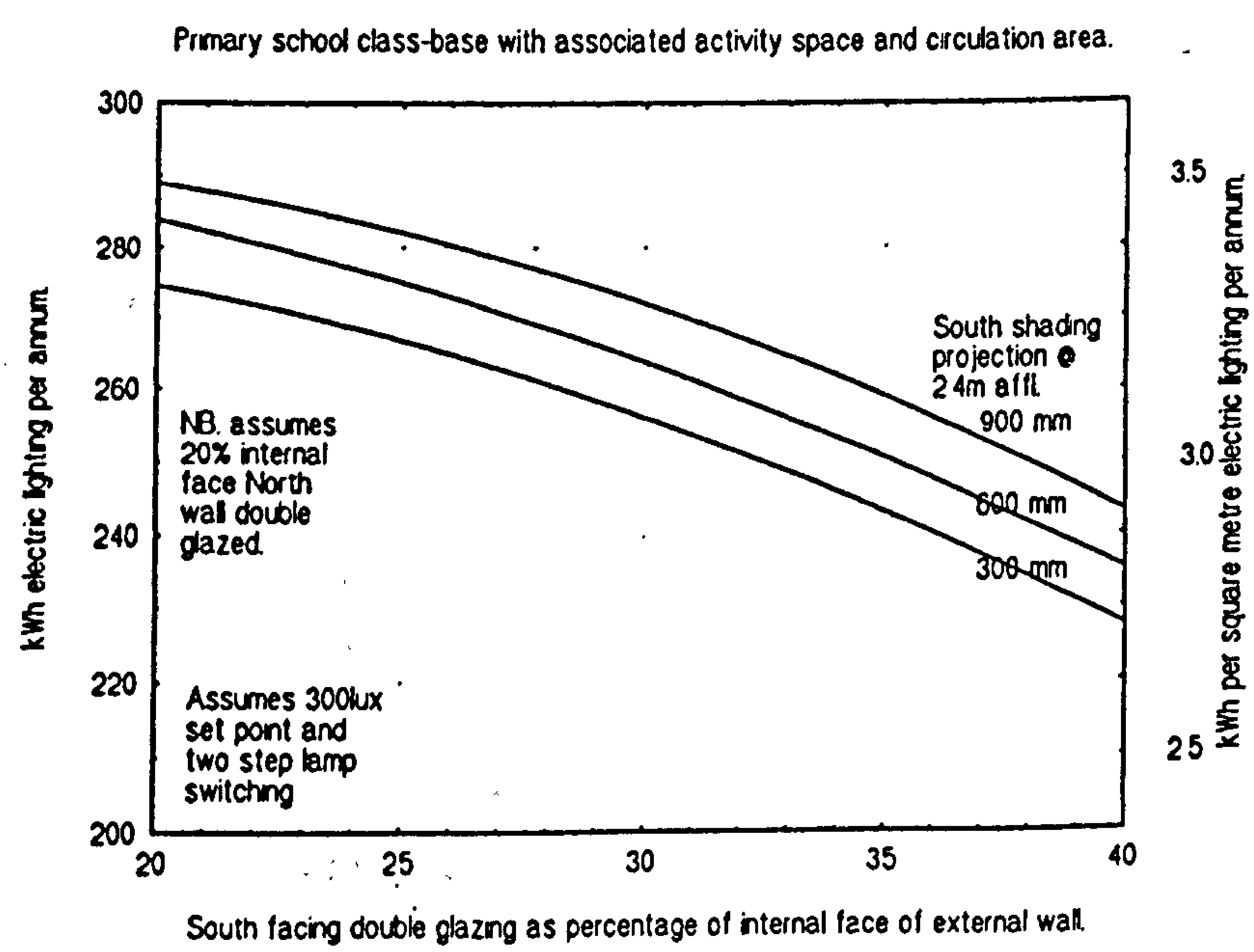


Figure 8.4 ELECTRIC LIGHTING LOAD PER ANNUM.

Overheating in the notional class-base.

8.7 An overheating day is defined(DES 1981b) as any day when a resultant temperature in excess of 27°C occurs within a teaching area during school hours. The hours and days when overheating(over 27°C) occurred during school hours, with and without electric lights on, was predicted for varying natural ventilation rates. The room finishes assumed in the building description were: plastered block walls with pin board up to door head height; acoustic tile ceilings; carpet in the class-base, and floor tiles in the activity and circulation area. Figures 8.5 and 8.6 show the Seri-Res predicted days and hours of overheating during occupation, for varying rates of natural ventilation. Overheating was predicted in the autumn and summer terms.

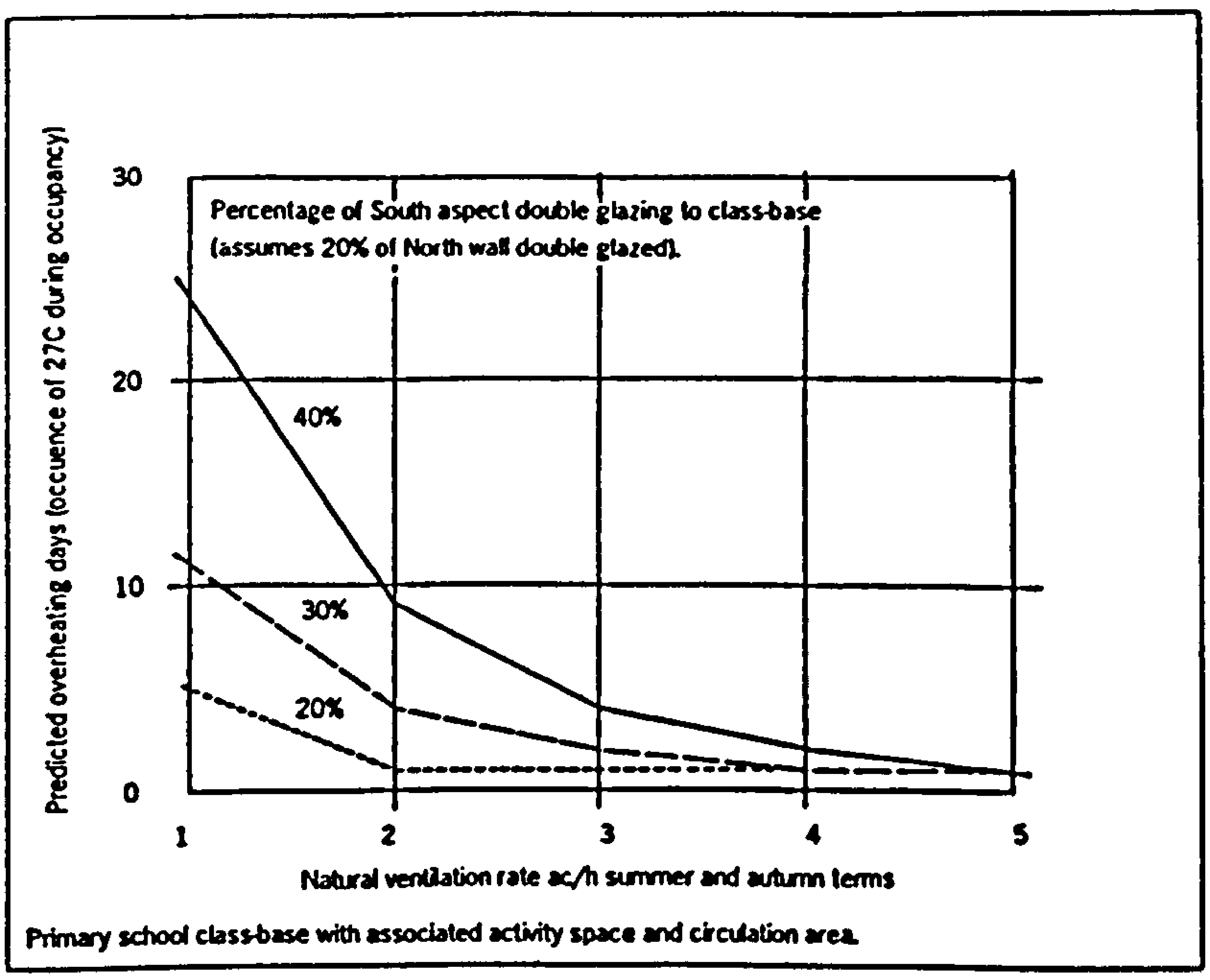


Figure 8.5 OVERHEATING DAYS.

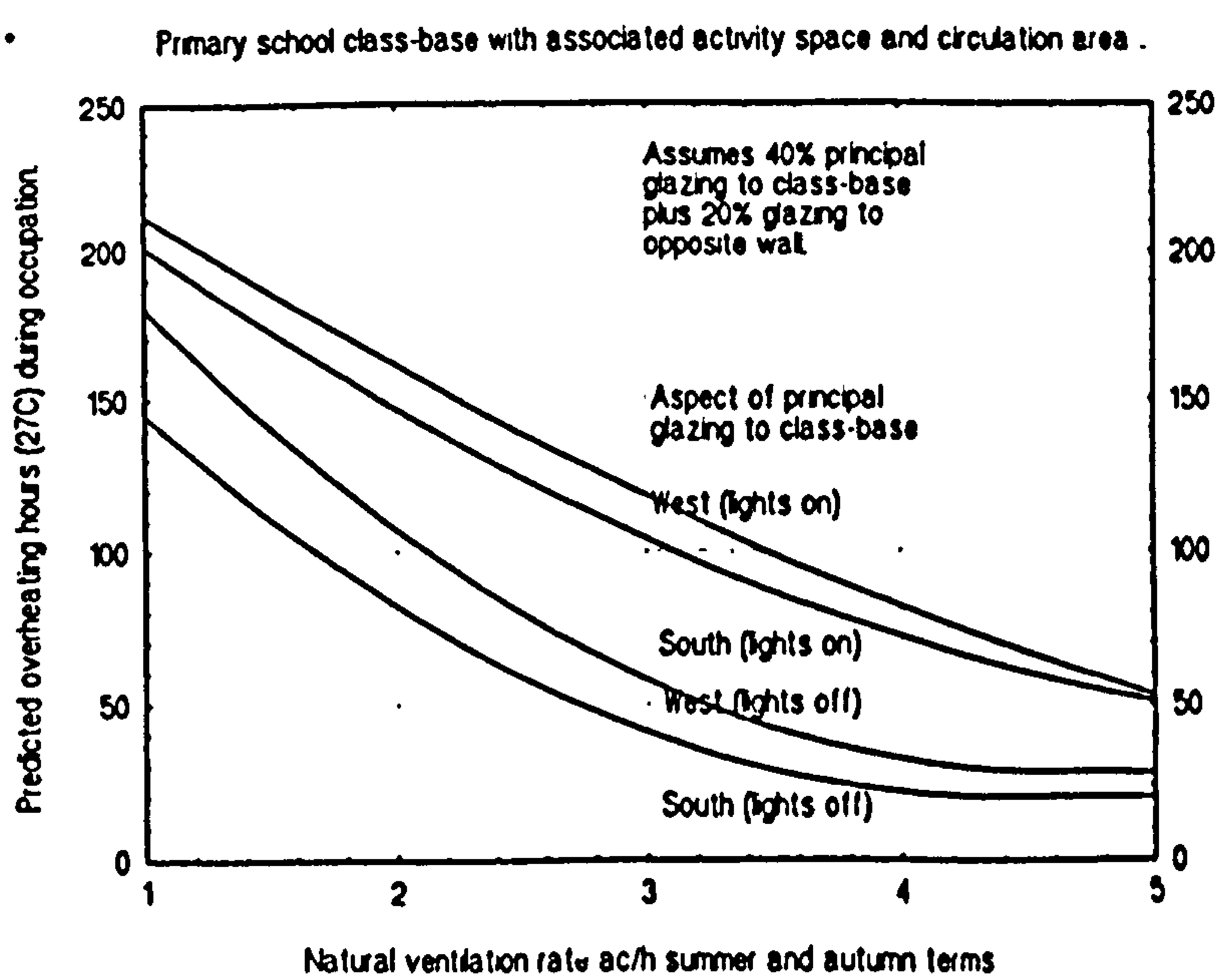


Figure 8.6 OVERHEATING HOURS.

Heating load in the notional class-base.

8.8 A Tas^{0} simulation was undertaken to assess the heating loads for different orientations of the main glazing. The variation in the size of the eaves projection was confined to the South facade. The graph of the result of this Tas^{0} simulation is given in figure 8.7, which indicates that for all orientations except Southerly, the heating loads were predicted to increase with increased percentage of main glazing. For South aspect main glazing the predicted loads decreased with increased percentage of main glazing, indicating the advantage of direct gain. The North aspect main glazing is more thermally efficient than either the East or West aspect main glazing.

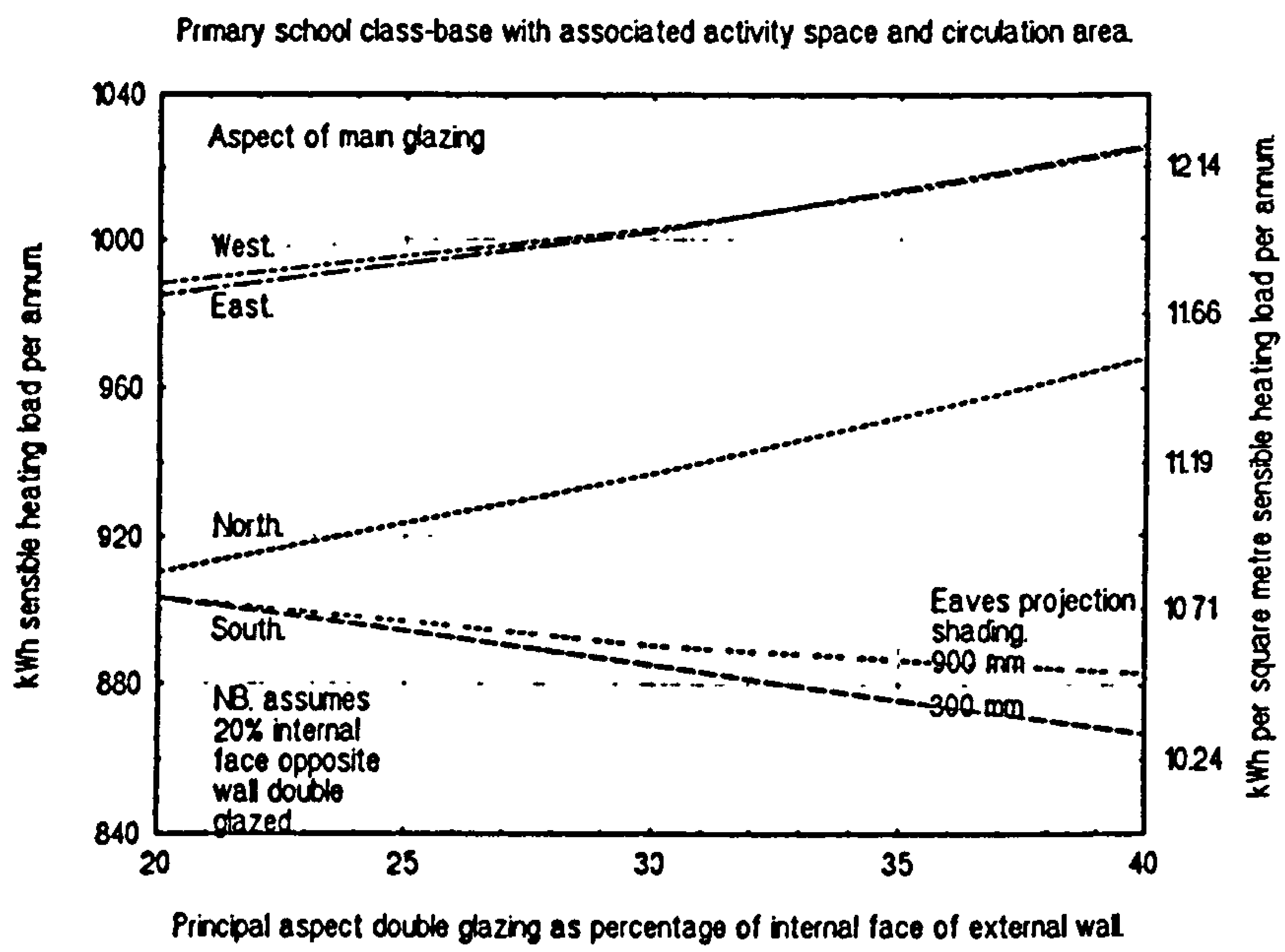


Figure 8.7 HEATING LOADS.

9.0 THE CASE STUDIES.

9.1 Tender costs for thirty six passive solar schools (details of which are included in the draft building bulletin) were investigated. The costs were obtained from the published sources referred to in appendix E, and from the LEA's. To provide an appropriate incentive for LEA's to submit such information, it was arranged for the Department for Education(DFE) to make the formal request, and verify the data received. All prices were adjusted, using published cost indices(BCIS, 1993) to be correct to the fourth quarter of 1992. The results were compared with the national interquartile average for all new schools, and major extensions to school buildings constructed between 1986 and 1992. At the same time LEA's were requested via the DFE to submit details of their energy consumption monitoring for these schools. The design energy consumption value(DN17 1981b) was compared with the actual annual energy consumption. Both figures were available for only thirteen of the schools(DFE 1993).

Economic appraisal.

9.2 The interquartile average capital cost of the thirty six schools was £461 per square metre, compared to the national interquartile average for all schools of £476.00 per square metre, based on the cost of 918 new schools and major extensions built between 1986 and 1992(DFE 1992). Figure 9.1 indicates the relative capital costs of thirty six passive solar schools.(DFE 1993), and Table 9.1 lists the schools, gross floor areas, costs per square metre, tender date, and unit costs adjusted to the 4th quarter of 1992, using standard cost indices(BCIS, 1993). This suggests that although passive solar schools contain relatively expensive features such as sun-spaces, which other schools do not, the passive solar school designs were no more costly in overall capital cost terms than normal, and for the sample considered the mean cost of the passive solar schools were marginally lower than the national mean for 1986 to 1992.

Energy consumption.

9.3 Figure 9.2 and Table 9.2 compare the design energy consumption value based on DN17(DES 1981b) and the actual energy consumption values available on the passive solar case study schools(DFE 1993). This indicated that overall the estimated performance was reasonably accurate, although there were some notable exceptions. For example the Barnes Farm Infants school had proved much more energy efficient in use than the original estimated thermal performance would suggest, whereas the opposite was the case for the Ravenscroft primary school.

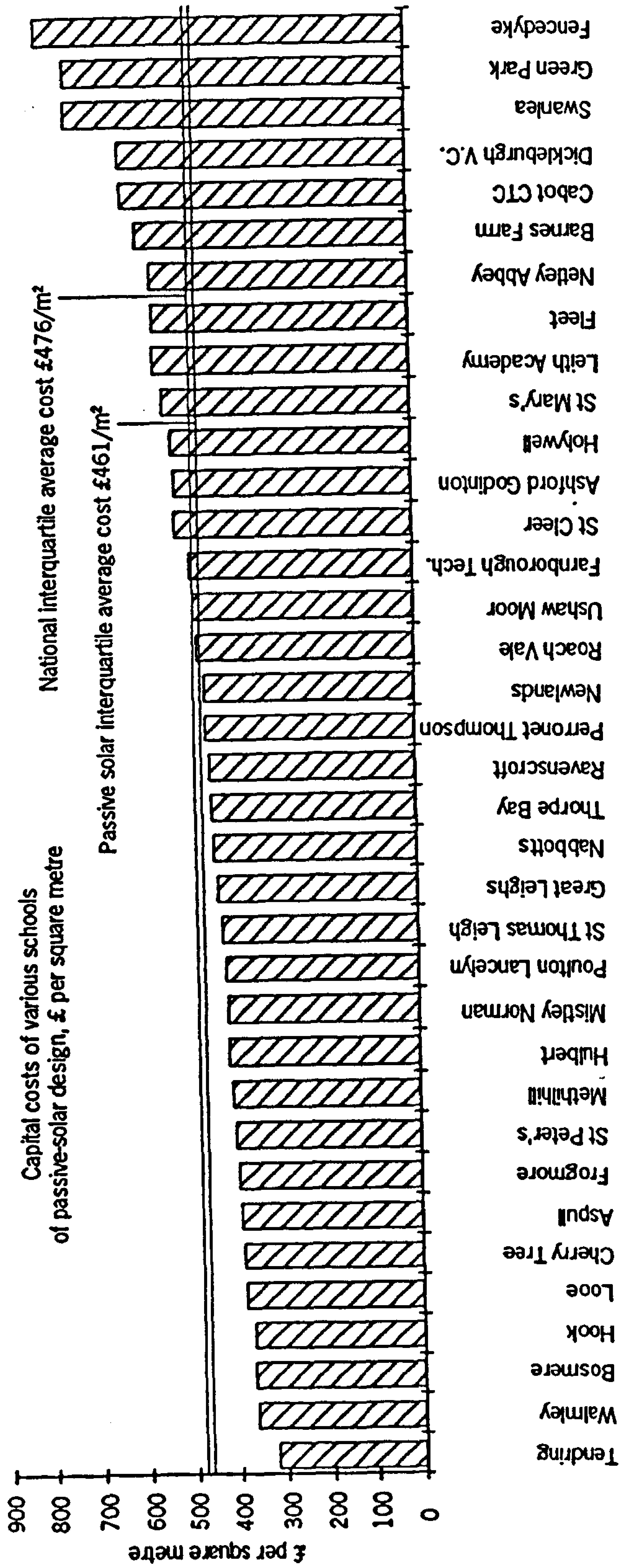


Figure 9.1 Capital costs: £ per square metre of passive solar schools.

Table 9.1 Passive solar schools, costs, and floor areas

School name	Type	Local Authority	Gross Floor area square metres	Capital Cost £/square metre	Date of Tender	Cost at 4Q92 per square metre corrected for location
Tendring	secondary	Essex	1,015	196.45	1Q 79	322.03
Walmley	first and middle	Birmingham	2,161	228.82	1Q79	367.28
Bosmere	middle	Hampshire	1,734	286.21	1Q 82	369.29
Hook	infants and junior	Hampshire	2,586	311.48	1Q 85	370.70
Looe	infants and junior	Cornwall	1,374	299.65	4Q 82	384.47
Cherrytree	primary	Essex	1,059	191.21	4Q 77	389.35
Aspull	primary	Wigan	912	318.12	1Q 81	393.87
Frogmore	secondary	Hampshire	1,611	242.91	1Q 79	398.19
St Peter's	primary	Essex	1,149	339.11	2Q 84	403.58
Methilhill	primary	Fife	3,168	476.6	2Q 88	409.54
Hulbert	middle	Hampshire	1,548	315.28	4Q 81	416.97
Mistley Norman	primary	Essex	726	320.89	1Q 80	418.18
Poulton Lancelyn	primary	Wirral	1,116	410.4	4Q 86	418.97
St Thomas, Leigh	primary	Wigan	661	370.18	4Q 83	425.43
Great Leighs	primary	Essex	699	305.42	1Q 80	434.48
Nabbotts	junior	Essex	880	345.06	4Q 82	442.73
Thorpe Bay	secondary	Essex	7,452	345.33	2Q 82	445.01
Ravenscroft	primary	Essex	1,001	348.04	4Q 80	449.07
Perronet Thompson	secondary	Humberside	9,947	427.57	2Q 86	454.13
Newlands	primary	Hampshire	910	207.51	2Q 77	454.49
Roach Vale	primary	Essex	1,119	201.91	1Q 77	469.87
Ushaw Moor	primary	Durham	1,150	354.83	4Q 81	479.37
Farnborough Tech.	Further Education	Hampshire	11,179	390.52	4Q 83	487.01
St. Cleer	primary	Cornwall	604	378.09	4Q 81	516.34
Ashford Godinton	primary	Kent	847	303.42	2Q 78	517.96
Holywell	primary	Nottingham	810	418.95	2Q 80	523.79
St Mary's	secondary	Wirral	2,133	60.55	1961	538.22
Leith Academy	secondary/community	Lothian	9,295	731.28	2Q 88	560.45
Fleet	Infants	Hampshire	1,188	548.62	2Q 87	562.96
Netley	Infants	Hampshire	835	444.32	1Q 83	564.16
Barnes Farm	Infants	Essex	704	537.44	2Q 86	594.86
Cabot City Tech. Col.	secondary	Avon	8,550	601.26	4Q 92	626.31
Dickleburgh V.C.	primary	Norfolk	520	528.85	1Q 84	628.51
Swanlea	secondary	L.B.Tower Hamlets	9,023	773.78	4Q 93	745.81
Green Park	primary	Bucks	1,400	862.48	2Q 90	746.14
Fencedyke	primary	Strathclyde	1,309	356.82	2Q 76	808.26

Interquartile average of passive solar schools	**461.20**
National interquartile average of 918 new schools and major extensions built between 1986 and 1992	**475.79**

Key: 1Q79 = 1st quarter, 1979; 4Q92 = 4th quarter 1992, etc.

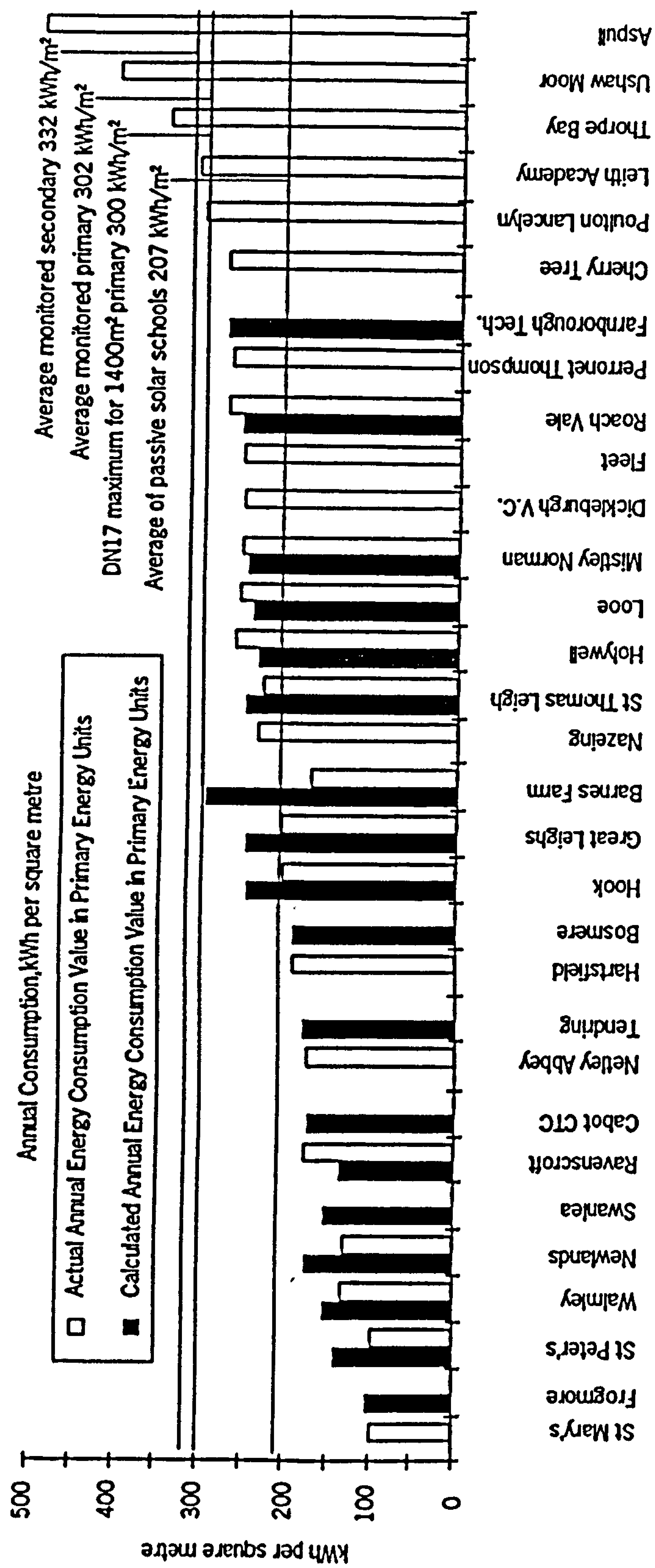


Figure 9.2 Annual consumption of primary energy: kWh per square metre.

Table 9.2 Annual consumption of primary energy (in kWh per square metre of gross floor area)

	Calculated AECV	Actual AECV	Ratio of Actual AECV / Calculated AECV
St Mary's, secondary		97	
Frogmore, secondary extension	103		
St Peter's, primary	141	98	0.70
Walmley, infants	153	131	0.86
Newlands, primary	174	130	0.75
Swanlea, secondary	153		
Ravenscroft, primary	135	177	1.31
Cabot City Technology College, secondary	173		
Netley Abbey, infants		174	
Tendring, secondary	180		
Hartsfield, primary		191	
Bosmere, middle	191		
Hook, infants and junior	246	206	0.84
Great Leighs, primary	249	207	0.83
Barnes Farm, infants	296	171	0.58
Nazeing County, primary		236	
St Thomas Leigh, primary	250	230	0.92
Holywell, primary	236	262	1.11
Looe, junior and infants	242	257	1.06
Mistley Norman, primary	249	255	1.02
Dickleburgh V.C., primary		254	
Fleet, infants		256	
Roach Vale, primary	258	274	1.06
Perronet Thompson, secondary		270	
Farnborough Technology College, F.E.	275		
Cherry Tree, primary		276	
Poulton Lancelyn, primary		302	
Leith Academy, secondary		309	
Thorpe Bay, secondary		344	
Ushaw Moor, junior		405	
Aspull, primary		492	
Average values of passive solar schools	**211**	**207**	**0.92**

Key: AECV = Annual energy consumption value in kWh per square metre of gross floor area.

10.0 CONCLUSIONS AND DISCUSSION.

A: The two atrium schools.

Comparison of building descriptions.

10.1 It had been assumed, at the commencement of this study, that: the simple building description might be appropriate for seasonal predictions of thermal performance; the elemental description ought to be satisfactory for an accurate prediction of daily means, and possibly capable of predicting hourly values with reasonable accuracy for most practical purposes; the fine level of detail would be necessary for accurate hourly predictions of zone temperature, but impractical for normal design evaluation purposes.

10.2 There was very little difference between the predicted hourly results of the fine and elemental levels of detail of building construction and zoning modelled when utilising Seri-Res. Although there was little to choose between them, with a difference of about 1°C between the temperature predictions of these descriptions, there was a significant temperature difference and a slightly poorer diurnal curve fit to the measured data when using the simple building description. The most detailed(Fine) description was used for the remainder of the experiment, because it was available, the most accurate, and had been extensively checked to avoid data entry errors, but the elemental model would appear more practical for general use, and much less open to input error in view of the much reduced number of data entries associated with this building description. The surprising result was that for the simple model, which gave reasonably accurate predictions for the atrium temperatures, where the lack definition of this building description in relation to thermal mass was less significant than for predicted environmental conditions in the class-bases.

10.3 All three building descriptions were used with the same dynamic thermal model, and were relatively fast, using the Vax main-frame computer. There was however about a tenfold increase in processing time required between the simple and fine building descriptions. On balance the elemental building description would seem appropriate, for a detailed study of the predicted performance of either an existing building, or a well advanced design, whereas the simple model could easily be used to test design ideas quickly. This would be feasible, because the simple building description could be produced within an hour, and processor times of only four minutes were required for simulations using a one year run of weather data.

Calibration.

10.4 It was found from the calibration results, using the hourly values of monitored zone temperatures for class-bases and the atrium, during unoccupied periods in both schools, that the Seri-Res model accurately predicted the actual hourly zone temperatures of the sun-spaces and other accommodation. The closeness of fit between measured and predicted temperatures was unexpected, and probably conceals systematic errors, however the similarity of the curves diurnally between measured and predicted values, irrespective of the weather conditions, was considered more important and therefore encouraging. This suggested that the thermal capacity of the buildings and the thermal characteristics of the materials used in the construction were correctly identified. The poorly correlated earlier result of Waterfield(1989) for Hook school, was based on erroneous specification of materials and constructions, and some dimensional co-ordination errors in the building description file. When these errors were identified and corrected for this study, the much improved results presented here were obtained. This suggests that Seri-Res should not be used without a sound knowledge of building materials and construction, as these are clearly important factors for the correct performance of the model. This would be particularly relevant in the assessment of the performance of existing buildings, such as this study, which to some extent relied upon the correct identification of building materials used.

Overall performance.

10.5 Table 6.16 indicated that, in overall terms, the predicted thermal performance per square metre of floor area of the Barnes Farm school with an unheated atrium was better than the more highly insulated school at Hook, which had a heated atrium. This result was based on the simulation of dynamic thermal performance over one year, and indicates the wisdom of such an evaluation in the design of passive solar buildings, and the advantage of an unheated sun-space in terms of the useful buffer effect. However, in terms of the heating season loads, and bearing in mind that the Hook school is semi-detached, and Barnes Farm school use their atrium throughout the year, leaving large sliding doors open between the atrium and the adjacent heated spaces for considerable periods during occupancy, the simulations taking account of this indicated a slightly lower energy consumption for the Hook school(Figure 6.39). Since the Hook school was well insulated and the Barnes Farm school was not so well insulated, the results for both schools suggest that, if the effects of solar radiation are allowed for, the DN17 guidelines(DES 1981b) are shown to be more than generous, particularly in view of the improvements which have occurred in the standard of insulation of buildings since the DN17 guidelines were issued. A substantial reduction of the present annual energy consumption target would appear justified.

10.6 The disadvantage of the lack of any calibration with known fuel use for this study is acknowledged. However it was assumed that, any modelling errors attributable to this would systematically apply to the simulations for both buildings. The comparison was therefore considered to be likely to have indicated the correct relative performance. Seri-Res has been well validated in terms of predicted energy performance(Judkoff 1988), and the predicted annual energy consumption in PEU's for both schools is similar to those reported for Looe school(Alexander et al 1990) and the final results reported for the Nabbots primary school, after two years of commissioning(Hobday et al 1992) to achieve the design performance. The Seri-Res predictions for energy consumption therefore appear reasonable. Care is needed in interpreting the results of figure 6.39, but if this assumption is correct, then further work may be appropriate to test whether a reduction of about one third or more of the present DN17 energy consumption target is feasible.

Orientation.

10.7 The results of the simulations to show the effect of changing the aspect of the gable end of the atrium indicated that, the orientation of a central atrium had a negligible effect on thermal performance of the whole building, even though the variations meant that, for some orientations, the large glazed areas of the class-bases faced North. The solar aperture of the roof of a glazed atrium would be almost constant throughout, and the extent to which this dominated the overall performance of these buildings in relation to useful solar gains is demonstrated in these results. Although these changes of orientation would have had some effect on the angles of incidence of solar radiation diurnally, this effect was less important than the effect of constant solar aperture. The result was similar for both buildings, and appeared to be valid for these single storey atrium buildings. This differs from the conclusion of Kainlauri et al(1991), who suggested that orientation would be an important factor in the performance of buildings with atria.

10.8 There is, of course, a need to consider the effects of glare and direct insolation in relation to orientation, and how these would affect the occupants of accommodation adjoining an atrium. However this result does imply that a design incorporating a central atrium in buildings of this type, might be particularly suitable as an energy efficient design solution for sites where an optimum orientation and aspect for teaching spaces is otherwise impractical.

Width of atrium.

10.9 Figures 7.3 to 7.5 inclusive demonstrated that, varying the width of the atrium had a significant effect on the thermal performance of the schools, for both heated and unheated central atria. The results based on the Hook school, with a heated atrium, indicated that there was no optimal width for a heated atrium of this design for the range of atrium widths simulated. The wider the atrium, the more energy was consumed. In this simulation, the depth of the adjoining class-bases decreased as the atrium width was increased, maintaining a constant heated area for the school, whilst raising the daylight levels available throughout the school. This is reflected in the reduced electric consumption for lighting associated with the wider atrium. A critical factor was the increased tendency of the heated atrium to significantly overheat with increased atrium width. The predicted amount of heat needing to be removed (figure 7.3) exceeded any equivalent benefit from useful solar gain throughout the range of widths simulated. The atrium at Hook had large surface areas of carpet, furniture and relatively lightweight building materials in the atrium, which were directly exposed to solar radiation. In reality the arrangements for natural ventilation of the atrium at Hook school were inadequate, but for the purpose of this study they were specified in the Seri-Res model as being adequate.

10.10 The results for Barnes Farm were considered in two stages. Those which allowed for the maximum useful buffering effect of a wholly unused, and unheated central atrium, similar in construction to that at Barnes Farm school, are shown in figure 7.4. However, it would be somewhat unrealistic to assume that schools would not use such a sun-space, except perhaps during the coldest of weather. It was therefore assumed for the second stage simulations that, the unheated sun-space would be fully used, as at Barnes Farm school, and that, when the atrium was in use, the doors and patio type windows between the heated class-bases and the sun-space would tend to be left open. In this scenario, the sun-space is classified as occupied. The Seri-Res model does not calculate a buffer effect due to occupied spaces. The energy use predicted by Seri-Res, is shown in figure 7.5, which allowed for the extent of the use, which the Barnes Farm school make of their atrium, and the effects of such occupancy, but not the beneficial buffering effect, which in practice is afforded by the atrium, when it is wholly unused during very cold weather. Due to the difficulty of identifying such days in advance, the lack of use from such causes was not scheduled, and therefore could not be taken into account in the simulations. This change was however important, because the predicted net loss for the building with a wholly unused atrium(figure 7.4), reduced slightly with increased width for the range of widths considered, whereas that for the atrium as an occupied space(figure 7.5) increased progressively as the width of atrium increased.

10.11 The heated area of each school was kept constant, when varying the width of atrium at the school, which meant that for Barnes Farm school with an unheated area, the gross area increased directly with increased width of atrium, whereas the gross area of Hook school remained constant, since the gross area was the heated area for that school. The main difference between the results for each building, incorporating a heated and unheated atrium respectively were that, ventilation of unwanted heat increasingly exceeded useful solar gain for increased width of atrium in the simulations for the heated atrium of Hook school, whereas useful solar gains increasingly exceeded the ventilation of unwanted heat in the simulations for increasing the width of the unheated atrium of Barnes Farm school.

Comfort conditions in the atrium.

10.12 Overheating of the atrium was identified as a problem at Hook school, from the monitored data, the thermal performance predicted by the Seri-Res model, and staff comment(Harris et al 1991). Some overheating also occurred at Barnes Farm, but to a much lesser degree than at Hook school. In reality, there is an effective, and much greater provision of opening roof-lights in the Barnes Farm atrium than at Hook school, which had relatively few. At Barnes Farm school, it can be seen from the monitored performance data that, there was a tendency for the atrium to be overheated before the staff opened the roof vents(Figure 6.41). However, once this had been done, the mean dry bulb air temperature recorded in the space was almost identical to the recorded ambient temperature. The Barnes Farm school was originally equipped with automatic sensors and motorised controls for the roof vents to the atrium, but it was reported that the staff had asked for these to be manually switched. The overheating which occurred due to the late opening of roof-lights can in part be attributed to this change, and to the fact that the atrium is a shared space, which is not under the control of an individual teacher, and is frequently occupied by children who are within the sight of teachers located in the adjoining class-bases. From this position the teacher would be unaware of the rising temperature of the air in the atrium. One might also expect that air temperature alone is an unsatisfactory measure of overheating.

10.13 For the parametric study simulations, the provision for ventilation of excess heat was assumed to be equally adequate at both schools, and the control set points were based on the Seri-Res environmental temperature, which is approximately equivalent to a resultant temperature. Figure 7.5 indicates that excess heat becomes a critical factor, within an unheated central atria of the Barnes Farm type of construction, for atrium widths in excess of 7 metres. The ventilation considerations alone imply a preferred width of the unheated atrium of approximately 4.5 metres. There were also times when the Barnes Farm atrium was too cold. However Figure 7.7 predicted that, for a building and atrium, as at Barnes Farm school, the net loss of a single glazed building and atrium with unheated atrium was similar to that of a double glazed building and atrium with heated atrium for widths up to 6.2 metres(as built). Figure 7.8 indicated that this result is reflected in the calculation of useful buffering.

Glazing specification and thermal performance.

10.14 Figure 7.7 also indicates that, for an atrium width of 6 metres, a single glazed, moderately insulated, school building with an unheated atrium matched the requirement for auxilliary heating of a double glazed building with a heated atrium. The decision to heat the atrium of a single glazed building with central atrium, of the type and construction used at Barnes Farm school, is an option worthy of consideration in terms of the benefits to the school, for similar building forms with central atria up to 3 metres in width, since as indicated by Figure 7.7, it should be possible to do so without increasing the annual heating requirement of the school.

B: THE NOTIONAL CLASS-BASE.

The level of daylight.

10.15 Figure 8.2 showed that it was only possible to achieve an illuminance of just under the two per cent minimum daylight factor on the working plane throughout the teaching area, when the glazed area was limited to twenty per cent of the area of the internal face of the two external walls with glazed areas. The provision of large overhangs on the Southerly glazing did not affect the minimum daylight factor, but did reduce the average daylight factor for the space, and therefore marginally improved the uniformity ratio. The daylight program analysis did not allow for the reduction in light transmittance due to windows being used to display pupils work, or for a build up of dirt on window glass. The result would seem to indicate that at the lower limit of the currently permitted range of glazed area, a two per cent minimum daylight factor is probably unattainable without some form of roof-light. The widespread use of window glass in primary schools for display purposes, and the lack of frequent window cleaning, would also reduce the level of daylight availability.

Use of electric light.

10.16 Figures 8.3 & 8.4 indicated the predicted increased use of electric light with the smaller window areas. The restriction of the Southerly aspect fenestration to 20% of the inside area of the external wall standard adopted for other orientations resulted in an increase in the predicted electric lighting load of some 50 kWh per class-base per annum(22%) when compared to that for a Southerly aspect fenestration of 40%. The provision of 900 mm wide projecting eaves at 2.4 m above floor level on the South elevation instead of the standard 300 mm eaves projection, increased the electric lighting loads predicted by about 7% more or less uniformly for all the fenestration percentages modelled. The increased capital and running(revenue) costs associated with such larger overhangs need to be weighed against the benefits of improved uniformity ratios for daylight, reduced incidence of glare, and discomfort from direct insolation close to the window positions. In considering these results it should be borne in mind that the use of electric lighting was assumed to be wholly sensitive to the availability of daylight, because the algorithm(Hunt 1979) incorporated in the Seri-Res program on the probability of people switching lights manually is known to be unsatisfactory when applied to intermittently used spaces, such as school class-bases. The results therefore represent the optimum prediction. In reality the lights could be expected to remain on for longer periods of time. The assumption made about switching was however considered to be a valid means of comparing the effect of design options about the proportion of fenestration.

Overheating days and hours.

10.17 Figures 8.5 showed the number of days during the school year, when the resultant temperature in the class-base studied with 20%, 30%, or 40% Southerly aspect fenestration, was predicted to be 27 ^{0}C or more. This result suggested that the predicted overheating days could readily be controlled to within the acceptable predictable limits defined in DN17(DES 1981b) by natural ventilation giving 2 air changes per hour. This suggests that it should be possible to achieve this target with draught-free natural ventilation, providing window opening lights are properly designed. Figure 8.6 predicted the increased risk of overheating attributable to leaving lights on in a class-base with the 40% main fenestration option. The results for both Southerly and Westerly aspects of main fenestration are compared, and found to be similar, with the Southerly aspect being marginally better. The results do however indicate that although Figure 8.5 suggests that the number of overheating days would be relatively small and confined to within acceptable limits, the overheating hours predicted for these configurations are substantial. This suggests that discomfort will occur throughout the whole school day, and there is a need to design for over three air changes per hour. However this would probably prove problematic, with attendant window design and problems for the use of the class-base, indicating that a detailed study of natural ventilation, air movement and window design would be justified.

Heating loads.

10.8 Figure 8.7 showed the predicted space heating loads for the different orientations, and percentage options for main-fenestration to the class-base. The results indicated that for all orientations of main glazing, the heating loads increased directly with increased percentage glazing, except for the Southerly aspect main glazing, when the predicted loads decreased with increased percentage of glazing. This suggests that the best strategy in terms of sensible heating loads, for glazing for orientations other than the Southerly aspect, would be between 20% and 25% of the internal face of the external wall, and that for the Southerly aspect would be 30%, bearing in mind the potential overheating. The beneficial effect of useful direct solar gains from the 20% South aspect glazing can also be seen in the results for the North orientation of main glazing, which bettered either that for an East or West orientation. The 900 mm eaves projection option on the Southerly aspect main fenestration option increased the heating loads marginally and increasingly, once the main aspect fenestration exceeded 25% of the internal face of the external wall. This suggests that for latitude and climate similar to that of Southern England, there is little to be gained from having large projecting eaves for Southerly aspect facades with less than a 30% fenestration option, and the cost of such a provision on fenestration up to 40% of the internal face of the external wall, is likely to exceed any direct benefits in improved daylight uniformity and reduced glare attributable to such a feature.

C: The case studies.

Economic appraisal.

10.9 The economic appraisal of the thirty six listed case studies of passive solar schools indicated that on average these passive solar schools cost a little less per square metre than the national interquartile average for all schools built between 1986 and 1992, which implies that passive solar schools need not cost more in capital cost terms than ordinary school designs. The unit capital cost for Barnes Farm school is relatively high, because although the cost of the atrium is included, the area of the atrium was excluded from the area of the school for the purpose of this calculation in accordance with DFE requirements. Whereas the area of the atrium, if included, would have effectively increased the area of the school by approximately 20%. Overall the result of this analysis of the case study information may simply reflect the fact that the special passive solar features in the case study schools were incorporated as part of a holistic design consideration. They were not therefore considered additive in any overall design sense, and were evidently provided without incurring cost penalties in terms of the overall capital cost of each school. (Table 9.1)

Energy appraisal.

10.10 The energy consumption of the case study schools indicated that these passive solar schools perform better on average than other school designs. Overall, the passive solar designs were considered to be reasonably energy efficient, having a reduced energy demand and CO_2 emissions. It is however difficult to assess on the basis of this information, how much of the difference relates simply to the fact that the DN17 guidelines are out of date in terms of present day standards of thermal insulation, and how much is attributable to the passive solar design solutions adopted. Clearly these passive school designs were much more energy efficient than the present guidelines require. However, figure 9.2 indicated that there was also a marked disparity between some of the design expectations concerning energy consumption and that found in practice, which suggests that either the DN17 design fuel consumption prediction method is inadequate, or the use of the buildings was not as anticipated at the design stage. The energy consumption of most of the primary schools reviewed would suggests that the present DN17(DES 1981b) guideline should now be amended to take account of both improved thermal insulation standards and solar gains, and permit a passive solar design approach as part of normal design considerations. The energy returns analysed indicate performances similar to that predicted for the two atrium schools(Figure 6.39), bearing in mind that the section of the Hook school modelled was semi-detatched. There would appear to be a case for both improving estimating procedures and reducing the DN17 energy consumption target by around 30% to ensure that designers have realistic assessments and targets. However the anomalies suggest that it would also be prudent and more appropriate to make some allowance for location, and amend the present guidelines according to latitude.

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PART TWO : THE SOLAR RADIATION & DAYLIGHT STUDY.

12.0 INTRODUCTION.

12.1 From ancient times, sunlight was the primary source of light in buildings. There are many examples of the use of light to enhance both the external features of a building, and either heighten dramatic effect, or improve the use and characteristics of an interior space. Both diffuse daylight and direct sunlight have been used to heighten the awareness of form, and create a sense of occasion, surprise and delight. Examples of this were: the general exclusion of daylight and carefully timed admission of beams of direct sunlight in some of the temples of ancient Egypt; the subtle use of optical illusion, as with the columns of the Parthenon seen in sunlight; the use of the oculus skylight and concealed clerestorey lights in the buildings of ancient Rome, and the coloured light from large stained-glass windows in renaissance cathedrals.

12.2 With the building of the Crystal Palace in iron, timber, and glass, and development of the steel and reinforced concrete technologies, the modern movement in architecture was free to explore the possibilities of enclosing large volumes in glass, and visually linking interior and exterior spaces. This often produced the unacceptable internal environmental conditions, of which there are all too many examples. Kinetically variable facades have also been used, which adapt to alter the transmittance of sunlight with time of day. Examples of these are the wholly-glazed geodesic dome designed by Buckminster Fuller for the American pavilion at Expo 67, Montreal, with its computerised sun-blinds to reduce overheating and critical cooling loads, and the Institute du Monde Arab designed by Jean Nouvel, and built in Paris during 1981-87. This building has a glazed curtain-wall, overlaid with a pattern of frames, incorporating motorised, computer controlled filters, to vary the admission of sunlight at predetermined times of the day. These dramatically alter the individual patterns, whilst maintaining an overall decorative motif which alludes to Arabia.

12.3 The oil crises of the 1970's were a rude awakening. Escalating energy costs gave rise to increased interest in the thermal performance of buildings. Dynamic thermal models were developed, and improved thermal regulations were introduced for buildings. The problem is that, although UK schools for example, now have much improved thermal performance, and are primarily occupied during the daytime, the use of electric lighting represents a significant proportion of their energy loads and CO_2 emissions(DES 1992). The requirement to make good use of the available daylight appears to have been overlooked.

12.4 Two basic methods have been widely used to predict the interior daylight illuminance of buildings. The North American empirical method of the Illuminating Engineering Society(IES), which was limited to specific window configurations, and predicted the daylight available in lumens on the window glass. The second was based on the daylight factor method, which predicted daylight availability on the working plane with reference to a standard overcast-sky luminance. This daylight factor method was the standard adopted by the Committee Internationale de l'Eclairage (CIE) for Europe, and the DFE for UK school buildings. Two main criticisms of this procedure are that daylight factors are based on the worst-case scenario of the CIE overcast sky which is likely to be exceeded in practice for most of the working year, and, for present day design purposes, there is a need to relate predictions of daylight in spaces used predominantly during hours of daylight to actual weather data for a particular location, and the hourly thermal performance of the building, all year round.

12.5 There is now an opportunity to use readily available computing power to help designers to make better use of available daylight in their buildings. However, to make full use of this, it would be desirable to interactively model both the dynamic thermal and daylight performance of building designs, for which appropriate weather files would be needed. There are two initial problems to be considered in this respect. The first concerns the need to establish the hourly values of solar radiation, and the second the need to relate this to the amount of daylight available.

12.6 The spectral range used to determine the extraterrestrial solar irradiance covers the wavelengths from 0.25 to 25 microns(Frölich & Brusa 1981). However, 95% of the energy from the Sun is emitted in the spectral range 0.3 to 2.4 microns, with only 1.2% below 0.3 microns and 3.6% at wavelengths greater than 2.4 microns(Iqbal 1983). The pyranometers used to measure the shortwave solar radiation received on Earth therefore usually have a spectral range sensitivity from 0.3 to 2.4 or 2.8 microns. The total (global horizontal) solar energy incident at a given location on Earth can be conveniently measured, and will comprise radiation received directly from the Sun, and a diffuse component, which has been scattered by the atmosphere of the Earth, and distributed over the hemisphere of the sky. The relative amounts of these direct beam and diffuse components are often needed. For example, when detailed information on solar irradiance is required for the design of effective solar energy conversion devices, or the simulation of the daylight characteristics and dynamic thermal performance of building designs. These components of solar radiation are also required for horticultural and meteorological purposes. Such applications require hourly, and possibly daily mean values of the components of irradiance. However the recording of the diffuse and direct beam components is more complex, and requires routine and frequent maintenance and adjustments to be made, which is both expensive and susceptible to error, and therefore often inappropriate for unmanned or remote weather stations. Consequently the components of solar radiation are not measured at all weather stations.

12.7 The visible portion of the extraterrestrial solar spectrum is limited to the wavelengths between 0.38 and 0.78 microns(Henderson 1970). In the literature however, the range is more often defined as between 0.39 and 0.77 microns, representing the colour span from violet(0.39-0.455μm) to red(0.622-0.77μm), with the limits visible to the average person as being between 0.4 and 0.7μm. In addition, the sensitivity of the human eye to light, differs significantly from that recorded in Joules per second or Watts per square metre using actinometric instruments. A different photometric measurement scale is therefore used to record the luminous flux in lumens to represent the sensation of light experienced by human beings. Lumens are therefore the units of measurement used in building design applications, where the quality of light within the interior is an important consideration. The illuminance (E) of a surface is given in lux, with one lumen per square metre representing one lux.

12.8 The weather files used with most building thermal simulation models include measurements of irradiance, but not those for daylight. Existing programs could be adapted to model light. However, although daylight is easy to measure, particularly if global horizontal measurements are sufficient, the levels of daylight are not routinely recorded as the standard procedure at most meteorological stations. They are not therefore readily available for all locations. For practical reasons, therefore, it is necessary to ask:

(i) Is there a satisfactory simple method of establishing the relationship between these components, and the more readily available total irradiance measurements, which are routinely collected at many locations during all sky conditions?

(ii) Can reasonably accurate predictions of the level of available daylight be obtained from broadband measurements of solar irradiance?

12.9 Research has been undertaken in the present study to address these questions, and ascertain the viability of developing a fundamental, but simple, theoretically based approach to predict both the components of global horizontal solar irradiance and the amount of daylight available for clear-sky conditions, and to examine the possibility of using global horizontal irradiance measurements to determine the diffuse and direct beam components of irradiance for other sky conditions.

13.0 PREVIOUS WORK.

13.1 To estimate the amount of solar radiation received on Earth, it is often necessary: firstly to be able to calculate the position of the sun relative to the location on Earth; secondly to know the intensity of solar radiation outside the atmosphere of the Earth for the time and date in question, and possibly its spectral distribution, and thirdly to be able to assess how this solar radiation will be attenuated by the atmosphere of the Earth.

13.2 Various methods of calculating the solar position have been developed. The composition of the atmosphere has been studied, and measurements of atmospheric parameters analysed. A vast number of models have been developed to describe solar radiation received at the Earth's surface. These models are either theoretical or based on empirical observations. The theoretical models deal with the clear-sky atmosphere, and tend to be very detailed. The empirical models can be broadly categorised into those which deal with clear-sky conditions, of which there are both simple and complex versions, and those which are designed to cope with all sky conditions, the models for which tend to be relatively simple.

Calculating the solar position.

13.3 The solar position was usually determined from standard expressions for orbital geometry (Hosmer 1910), (Smart 1931), (Kirth 1959), and Kepler's equation of the centre, appropriately modified (Green 1985). Expressions for solar time to within six minutes, solar declination and Sun-Earth distance are available for engineering applications, using the formulae of Cooper(1969), which, though rather inaccurate, were reasonable for many flat-plate solar collector applications. They have been widely used, having been recommended by Duffey & Beckman(1980). Spencer(1971) provided Fourier series to represent the solar distance, declination and time to an accuracy of: 0.001 for the reciprocal of the radius vector squared; 0.0006 rad (<3') for declination, and 0.0025 rad(35 seconds) for the equation of time, related to the base year 1950.

13.4 Vant-Hull & Hildebrandt(1976) used an accuracy of 1 mrad (0.06^{0}) in their calculations for a solar tracking device, and Walraven(1978, 1979) published an algorithm for calculating the solar position with a claimed accuracy of 0.01^{0}, well within this limit. Walraven's accuracy was been called into question(Zimmerman 1981). However his procedure had the advantage that it did not assume that the sun will have the same position each year. Instead it relied on the sun's astronomical position with respect to a given point in time, by deriving simplified forms of the high precision calculations used in the astronomical almanac.

13.5 For accurate work, it is now more usual to use the approximate expression published in the astronomical almanac, which is simpler than Walraven's method, does achieve an accuracy of 0.01^{0}, and is valid until the year 2050(Michalsky 1988a,1988b,1989). Duffet-Smith(1988) provides a straight-forward, step by step approach to calculating the solar position, using astronomical methods. However, for the most accurate calculations, the actual coefficients and values tabled in the almanac(Anon 1991,1992,1993) and formulae given in the explanatory supplement(Seidelmann 1992), are used to determine the solar position to a stated accuracy of 0.1 arcseconds. Alternative procedures for calculating solar time to within either one second, or three seconds, are also provided. There are therefore well established methods for calculating the solar position to a range of accuracies appropriate for a wide variety of applications.

Solar radiation outside the atmosphere.

13.6 Ground-based measurements of solar spectral irradiance have been made since the beginning of the century, and Moon(1940) produced a set of solar radiation curves for engineering use. Kondratyev(1972) reviewed the work to 1970 on measuring the solar spectral distribution and the calculation of the integral intensity of solar radiation outside the atmosphere at the mean Sun-Earth distance for the World Meteorological Organisation(WMO).

13.7 The American National Aeronautics & Space Administration(NASA) used research aircraft to undertake a series of measurements in the spectral range 0.3 to 15 μm (Thekaekara 1968, 1969, 1970) & (Anon 1971a). These measurements did not give identical results, and adjustments were made in the visible and near infra-red bands(Drummond & Thekaekara 1973). The result was an extraterrestrial solar irradiance value of 1353 Watts m^{-2}, which was reported(Thekaekara 1973), and published as a standard(Anon 1973a).

13.8 There had been advances in instrumentation since the original measurements were made(Anon 1971b), and the calibration of the instruments used were re-examined at the World Radiation Centre(WRC) at Davros. Amended values of the spectral distribution were proposed by Fröhlich & Brusa(1981), based on an examination of eight solar irradiance measurements recorded from 1969 to 1980. This resulted in a revised extraterrestrial solar irradiance value of 1367 Watts m^{-2} for the wavelength range 0.25 to 25 microns, with the adjustment being mainly justified by the availability of alternative data by Neckel & Labs(1981) for the spectral range 0.330-1.270 μm. Apart from this adjustment, their study showed that within the uncertainty of the procedures, no change was detectable in the intensity of solar radiation available outside the atmosphere at the mean Sun-Earth distance during the previous fifteen years. This new value, with a standard deviation of 1.6 W m^{-2} and maximum deviation of +/- 7 W m^{-2}, was adopted for meteorological purposes as the WRC standard at the mean Sun-Earth distance. It is often referred to as the 'solar constant', although it is possible that this value will vary.

13.9 The geometry of the Sun-Earth relationship must also be taken into account when assessing the amount of extraterrestrial radiation available at a particular time and season relative to a

Specific location on Earth. List(1951) produced a graph(figure 13.1), which shows the significance of this effect in relation to latitude and the month of the year.

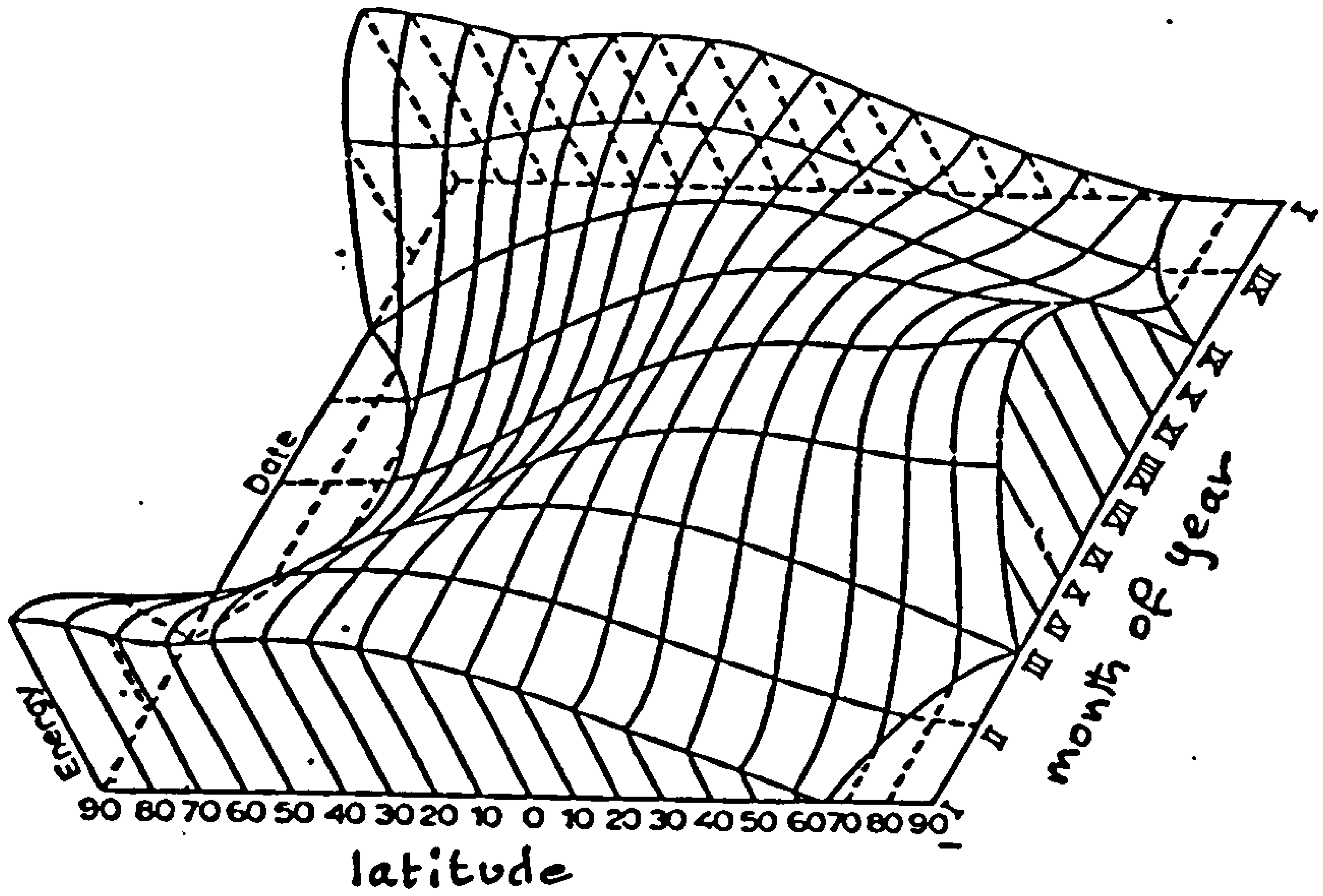

Figure 13.1 distribution of total solar radiation incident on a horizontal surface at the top of the atmosphere as a function of latitude and time of year(List 1951).

Atmospheric attenuation.

13.10 When solar radiation enters the atmosphere, it is scattered and absorbed, not only by the atmospheric gases, but also by particles(aerosols) and clouds. The solar radiation is attenuated by this process, and useful numerical data on atmospheric parameters were given by Van de Hulst(1952) and Horak(1950). The path for radiation passing through the atmosphere is usually defined relative to the optical path length through the atmosphere, when the sun is at the zenith. It is known either as the optical air mass, or relative air mass, and is usually denoted by m_r. In simple geometric terms, the relative air mass can be considered to be equal to the secant of the zenith angle of the Sun. However, whilst this is satisfactory for zenith distances less than 70 degrees, there is a need to allow for the effects of the curvature of the Earth and atmospheric refraction when calculating the relative air mass for larger zenith distances.

13.11 Treve(1964) reported on values of relative air mass refraction for all zenith distances for the 1959 ARDC standard atmosphere described by Minzner et al(1959), and Kasten(1966) used the following formula of Bemporad(1904, 1906,1907) for the relative optical air mass to allow for the effects of the curvature of the Earth and atmospheric refraction:

$$m_{r(\gamma)} = \frac{1}{p_o z_o} \int_0^{\infty} \frac{p\,dh_o}{\sqrt{\left[1 - \left(\frac{r_e}{r_e + z_o}\right)^2 \left(\frac{n_o}{n_h}\right)^2 \sin^2\theta_{z\,(obs)}\right]}} \qquad [13.1]$$

where:

z_o = *scale height (homogeneous atmosphere density p_o) (8.4 km)*
p_o = *density on the ground.* $kg\,m^{-3}$
h_o = *zenith height of a homogeneous atmosphere.* km
r_e = *mean radius of the Earth.* km
n_h = *refractive index of air at height h_o.*
n_o = *refractive index at ground level.*
$\theta_{z\,obs}$ = *the observed solar zenith distance.*

13.12 It is usual to use the refractive index for the wavelength 0.54 µm for studies in the visible spectrum, and 0.7 µm as being more representative of the solar spectrum for the broadband wavelength range 0.25 to 25 microns of the solar constant. Kasten presented tabled values of the relative optical air mass for the air density profile of the ARDC model atmosphere using equation 13.1 with the refractive index n for the wavelength 0.7 µm. Kasten also provided the following empirical formula, which gives an approximate solution to the tabled values:

$$m_{r(\gamma\,obs)} = [\sin\gamma_{obs} + a\,(\gamma_{obs} + b)^{-c}]^{-1} \qquad [13.2]$$

where:

$$\gamma_{obs} = \textit{observed solar elevation}$$

and the constants a. b, and c were given for the original table of the relative optical air mass of Bemporad, and Kasten's new table.

13.13 This approximate formula of Kasten, is appropriate for measurements taken at ground level, and was applicable to clean dry air at the standard pressure of 1013.25 mbar. It was claimed to be accurate to within 0.1% for zenith angles up to 86^0, with the greatest deviation of 1.25% occurring at the solar zenith angle of 89.5^0. The relative air mass stated for the zenith distance of 90^0 was 36.27. Water-vapour is concentrated mainly in the lower atmosphere, and the vertical density profile of a water-vapour atmosphere differs from that for dry air. Kasten therefore gave the empirically derived coefficients for his approximate formula applicable to the relative optical water-vapour mass ($m_{w(y)}$), based on the much earlier work of Schnaidt(1938).

13.14 Rodgers(1967) gave an alternative simple formula for the relative optical air mass, which is sometimes used in the literature instead of Kasten's formula.

$$m_{r\,(\gamma)} = \frac{35}{(1224\cos^2\theta_z + 1)^{1/2}} \qquad [13.3]$$

13.15 The accuracy of Kasten's formula at very large zenith distances was queried, and Kasten & Young(1989) collaborated to correct an error, which was found in the original calculation of Kasten(1966). The effect of their correction for the ARDC atmosphere at a wavelength of 0.7 microns and the zenith distance of 90^0 produced a revised value of 37.92 for the relative air mass, compared to the value of 38.08 reported by Treve(1964), and the original of 36.27 given by Kasten(1966). They also updated the tables, and revised them to take account of the conditions of the ISO standard atmosphere(Anon 1972), which had been adopted by the WMO because of its improved air density data and height definition compared with that of the earlier ARDC atmosphere. The corrected coefficients(table 13.1) for Kasten's widely used approximate formula (equation 13.2) were calculated by Kasten & Young on this basis.

Table 13.1 Numerical values of the constants a, b, and c. for equation 13.2

constant	Water Vapour mass Kasten 1966 after Schnaidt 1938	relative air mass Kasten 1966 after Bemporad 1904,1907	new relative air mass tables Kasten 1966 ARDC	corrected relative air mass tables Kasten & Young1972 ISO
a	0.05480	0.6556	0.1500	0.50572
b (degrees)	2.650	6.379	3.885	6.07995
c	1.452	1.757	1.253	1.6364

13.16 It is interesting that, the revised values of the coefficients by Kasten & Young(1989) are fairly close to those derived by Kasten from the much earlier work of Bemporad(1904), which was based on balloon soundings of the atmosphere. Young(1974) noted that substantial errors occur if unrefracted solar elevations are used.

13.17 Elterman(1968) gave the variation of ozone concentration with altitude, for average conditions at mid-latitudes. It was assumed that all ozone is concentrated in a thin layer centred at height h_0 in kilometres, and Robinson(1966) has shown by simple geometry that, the optical ozone mass can be expressed as:

$$m_o = \frac{1 + \frac{h_o}{r_e}}{\left[\cos^2\theta_z + 2\left(\frac{h_o}{r_e}\right)\right]^{\frac{1}{2}}} \qquad [13.4]$$

Ozone is assumed to exist at an effective height of 22 km. However, the uncertainty in determining the thickness of the ozone layer is much greater than that in the determination of its optical mass. Consequently, either equations 13.2 or 13.3, are often used to calculate depletion by ozone in the literature, instead of eqn 13.4, but it should be remembered that equations 13.2 and 13.3 assume the conditions of a perfectly mixed gas for the thickness of the atmosphere, and are really unsuitable for determining the atmospheric extinction due to ozone.

13.18 A similar problem is that, in locations affected by pollution, the attenuation of solar radiation by aerosols can be significant. Ball & Robinson(1982) found that this effect approached the magnitude of attenuation by water vapour, and could not be safely ignored. However, aerosols present the most uncertain of the parameters to be considered in calculating the solar radiation received at the surface of the Earth. There is little empirical information available, and consequently the attenuation by aerosol can only be incorporated crudely. Equation 13.5 is the method recommended by Iqbal(1983) for calculating the aerosol optical air mass m_a, but this equation is simply a pressure corrected form of equations 13.2 or 13.3, and as such was not intended for aerosol, which is concentrated in the lower atmosphere, and this too would seem to be a similarly unsuitable procedure.

$$m_a = m_r\left(\frac{p}{1013.25}\right) \qquad [13.5]$$

13.19 Traditionally, atmospheric extinction was measured at large zenith distances for astronomical applications, but this procedure introduced a large amount of uncertainty. However, Young(1974) demonstrated that accurate measurements of atmospheric extinction can be made without going to great air masses, and that such measurements are desirable. Variable extinction is due to aerosol, which usually has a scale height of less than 3 kilometres, and more typically close to 1.3 kilometre. In daytime therefore, any asymmetry will be local, unless maintained by local sources or sinks, and any irregularities will be carried away by wind in a short time. Young gives the example of a patch of aerosol at a height of 2 kilometres with a wind speed of 3 metres per second(typical for this height), and comments that the patch will move from the zenith to $m_r = 2$ in 19 minutes, $m_r = 3$ in 31 minutes, $m_r = 4$ in 43 minutes, and across the whole sky to the horizon in one hour. Young concluded that values of $m_r = 2$ to $m_r = 4$ (Zenith angle = 60^0 to 70^0), gave the best results when measuring atmospheric extinction.

13.20 The term turbidity or haziness of the atmosphere has been used to describe the effects of aerosol. Three empirically based procedures have been used to determine the turbidity of the atmosphere. Linke(1922) proposed that the atmospheric attenuation of solar radiation could be represented by a broad-band turbidity factor, defined as the number of clean, dry atmospheres which would produce the equivalent attenuation. Attenuation by a clean, dry atmosphere included Rayleigh scattering by molecules, absorption by the mixed gases, and absorption by ozone. The Linke turbidity factor relates to and is obtained from measurements for the whole solar spectrum, and the real atmosphere which includes the presence of water-vapour and aerosols. Assuming that the integral optical thickness of the atmosphere is given by k_a, and the integral optical thickness of the clean, dry atmosphere is k_R, then the Linke turbidity factor by definition is:

$$T_L = \frac{k_a}{k_R} \qquad [13.6]$$

13.21 The value of the Linke turbidity factor has been found to vary between 1 and 10. Feussner & Dubois(1930) proposed a procedure for calculating the Linke turbidity factor from pyrheliometric measurements. Kasten(1980, 1983) updated this, and Louch et al(1986) recalculated the optical thickness of a clean, dry atmosphere, using the WMO standard for extraterrestrial radiation of 1367 W m^{-1}, with the air mass for standard pressure from Kasten(1966), and the conversion procedure of Kasten(1980) to determine revised Linke turbidity factors.

13.22 Mosby(1936) derived an expression for atmospheric extinction in terms of the solar constant and relative air mass, using an expression incorporating the turbidity coefficient of Linke(1922).

$$I_g = I_{SC} \cdot e^{(-T_L m_r am)} \qquad [13.7]$$

where:

I_{sc} = *solar constant* Wm^{-2}

e = 2.71828

T_L = *Linke turbidity factor*

m_r = *relative air mass*

$am = 0.128 - 0.054 \log m$ (*non-dimensional*) [13.8]

13.23 European irradiance models commonly use Linke's turbidity factor to allow for aerosol attenuation, whereas American models have tended to rely on a procedure, based on spectral measurements, which was proposed by Ångström(1929, 1930) to deal with the extinction of the solar beam radiation by dust in the atmosphere. This was considered to be a convenient way of dealing solely with the amount of aerosols in the atmosphere, and Ångström derived a single formula having a turbidity coefficient beta and wavelength exponent alpha to allow for the effects of scattering and absorption by all aerosols, both wet and dry, given by the following extinction coefficient, which is dependent on wavelength, and the size and vertical distribution of particles:

$$k_\lambda = \beta \lambda^{-\alpha} \qquad [13.9]$$

The value of alpha relates to the size distribution of the aerosol particles, and could vary from 4, when the aerosol particles are very small(of the order of size of air molecules), to 0 for very large particulate size. Usually alpha has been given a value between 0.5 and 2.5. Ångström originally suggested the value of 1.3, and the average value for most natural atmospheres gives alpha as 1.3 +/- 0.5. The value of beta is an index of how much aerosol is present vertically in the atmosphere, and varies between 0 and 1, with a more realistic measured range between 0 and 0.5. The wavelength is in microns, and the transmittance of monochromatic radiation through an aerosol atmosphere is then written as:

$$\tau_{a\lambda} = e^{(-\beta \lambda^{-\alpha} m_a)} \qquad [13.10]$$

which still has the problem associated with the determination of the optical path length denoted by the relative air mass for aerosol(m_a), and requires measurements, or more often assumptions, to be made on particulate size and the vertical distribution of the aerosol.

13.24 Measurements of alpha and beta have been carried out at a number of locations using a dual-wavelength sun photometer. The wavelengths chosen for this were usually 0.38 and 0.50 μm, because at 0.38 microns there is no molecular absorption, and at 0.5 microns ozone absorption is weak. When such measurements are not available, the turbidity factor beta is sometimes determined from the measurement of visibility in the direction of the horizon, since this information is recorded at many airports. McClatchey & Selby determined the following expression for visibilities greater than 5 km:

$$\beta = (0.55)^{\alpha} \left(\frac{3.912}{Vis_{km} - 0.01162} \right) [0.02472\,(Vis_{km} - 5) + 1.132] \qquad [13.11]$$

where Vis_{km} = the visibility in km, and a value for alpha must be assumed. At a fixed value of alpha, a low value of beta signifies high visibility. Table 13.2 gives a comparison of the visibility for differing values of beta with the constant value of alpha recommended by Ångström.

Table 13.2 Parameters for varying degrees of visibility, and atmospheric cleanliness.

Atmosphere	Beta	alpha	Visibility km
Clean	0.00	1.30	340
Clear	0.10	1.30	28
Turbid	0.20	1.30	11
Very turbid	0.40	1.30	<5

Haurwitz(1934) concluded that, neither the Angstrom, nor the Linke turbidity factors were wholly satisfactory, although Fritz(1951) subsequently acknowledged that, they were still the best available method of determining the turbidity of the atmosphere quantitatively. Although the Linke turbidity factor has subsequently been used extensively as a parameter to compare cloudless atmospheric conditions, Louche et al(1987) found that it varied with air mass, when atmospheric conditions remained constant.

13.25 The third procedure for determining the turbidity of the atmosphere was proposed by Schüepp(1946), who based his empirical relationship on the direct spectral irradiance measured for wavelength = 0.5 μm. Schüepp's turbidity coefficient B_s is related to Ångström's coefficient by:

$$B_B = \beta\, 2^{\alpha} \log e \qquad [13.12]$$

and, for average atmospheric conditions, the Ångström value of:

$$\alpha = 1.3\,,$$

$$\textit{gives:} \quad B_B = 1.069\,\beta$$

The Ångström coefficient is therefore the most widely used of all the turbidity coefficients, and unlike the others, may be used in the calculation of spectral direct and diffuse irradiance, but as with the others, it is not considered a particularly satisfactory solution.

12.26 The scattering and absorption of solar energy by clouds has been studied by many writers. The early researchers assumed an upward and downwards flux of energy could be calculated using a scattering coefficient, which would apply throughout the cloud thickness. Hewson(1943) reviewed the early work, and computed values for the albedo of cloud, which ranged from 1.4% for very thin to 93.6% for thick clouds, and absorption ranging from 0.1% to 6.7%. There was a lack of agreement between theoretical work at that time and observations, and Neiburger(1949) used pyrheliometers mounted on a blimp to record the upward and downward flux of shortwave radiation above, within and below stratus clouds in California, and to attempt to measure the drop size and liquid water content of the clouds. Although there were problems with regard to the experimental procedure used, the Neiburger reported that as expected the albedo of cloud varied with thickness. The absorption recorded for all observations was however small, and averaged 7%. Fritz(1954, 1958) showed that there was a marked variation in the albedo of clouds in respect to solar zenith distance, especially for thin clouds, that the scattering characteristics vary at different levels within thick clouds, and that the percentage of absorption varies and depends upon the intensities of the spectral distribution of irradiance at the top of the cloud, indicating a dependence on the water vapour and scattering characteristic of the overlying atmosphere. The effect of cloud is significant. For example, it has been estimated by Rees(1990) that, at any one time, about half of the Earth is covered by cloud. Rees also reported the probability that, the LANSAT remote sensing satellite, which visits each location every sixteen days, will only obtain cloud-free readings of a particular location in the UK once per year, and readings with only one eighth(1 okta) of the sky covered by cloud only twice per year.

13.27 In terms of the overall effect of atmospheric attenuation, Houghton(1986) indicated that for a vertical column of the atmosphere, about 40% of the incident ultraviolet solar radiation is lost, whereas less than 1% is lost in the incident infrared part of the solar spectrum. Houghton also pointed out that on average, allowing for changes in solar elevation and the differing wavelengths, about 13% of incident solar radiation is Rayleigh scattered, about half of which is returned to space, and half reaches the surface of the Earth as diffuse radiation, and Lacis & Hansen(1974) provided an expression to relate the amount of Rayleigh back-scattered solar radiation to the angle of incidence.

THEORETICAL MODELS.

13.28 Following the work of: Stokes(1852) on polarisation of light; Strutt(1871,1885,1899,& 1918) on the atmospheric molecular scattering and polarisation of light; the basic equations governing Rayleigh's problem for the case of the multiple scattering concerned in the illumination and polarisation of the sunlit sky, were developed by Chandrasekhar(1950), and Chandrasekhar & Elbert(1951,1954). They gave precise solutions for the effect of perfectly conserving multiple molecular scattering on a direct beam of solar radiation in a plane parallel atmosphere.

13.29 Deirmendjian & Sekera(1954) applied Chandrasekhar's clear sky solution for the monochromatic radiative transfer problem in a plane parallel atmosphere, under the assumption according to Rayleigh's law. They derived expressions for the relative total, and diffuse radiation received on a horizontal surface, as a function of normal optical thickness and inclination of incoming parallel radiation. Corrections were also expressed to deal with ground reflection(albedo), in terms of the functions previously defined by Chandrasekhar.

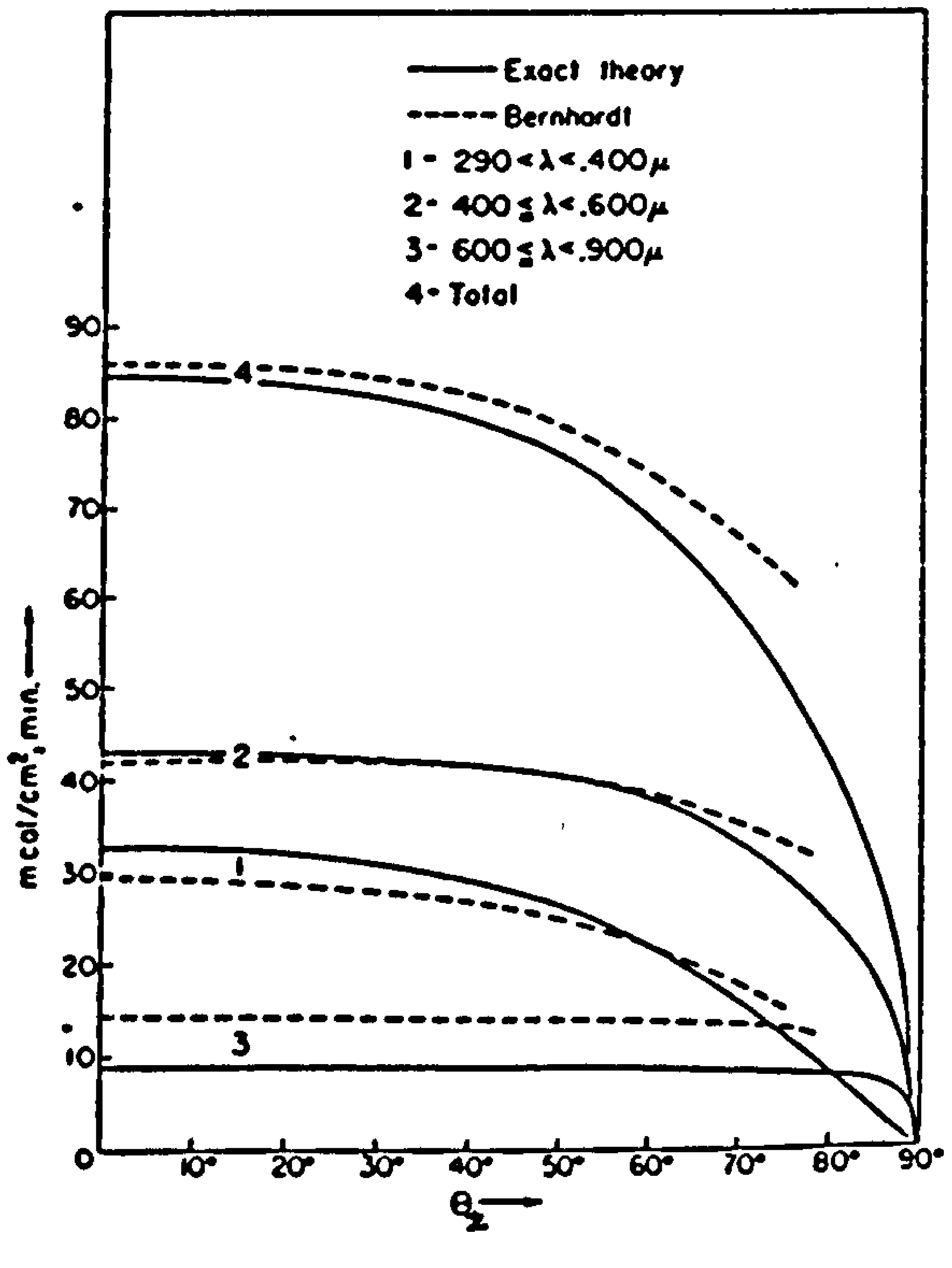

Figure 13.2 VARIATION OF MEAN SKY RADIATION FOR THE THREE SPECTRAL RANGES SHOWN, WITH SOLAR ZENITH DISTANCE.

13.30 They computed the amount of global and diffuse radiation for clear-sky conditions, as a function of wavelength and solar zenith distance (zenith angle), using the curve of Nicolet(1951a,1951b) for the spectral distribution of solar radiation outside of the atmosphere of the Earth (extraterrestrial). They also compared their theoretical results with those of Bernhardt(1952,1953), who used simplified assumptions about successive orders of scattering.(Figure 13.2)

13.31 They found that the calculation of absolute global and diffuse radiation from Chandrasekhar's procedure, integrated over the range 0.29 to 4.00 microns was in good agreement with measurements under clear-sky conditions. However, the method used involved a considerable amount of analytical and numerical processing, and did not allow for the effects of attenuation by dust and large particles(aerosol) or clouds. Sobolev(1963) gave special attention to the Earth's atmosphere, and diffuse radiation, to determine its optical properties. This method also required considerable analytical processing, and is also confined to clear-sky conditions.

13.32 The presence of clouds and aerosols introduce Mie scattering and absorption by particles, which further complicates the calculation procedures, and make it difficult to calculate, measure or predict this effect. A general framework and theoretical basis for such work was set out by Goody(1964), and Paltridge & Platt(1976). However, for practical reasons, a simplified method to estimate the direct beam, diffuse and the total amount of irradiance is also required, which can deal with all sky conditions.

EMPIRICAL MODELS.

13.33 Five main categories of empirical model can be identified for partitioning total broadband solar radiation into the direct beam and diffuse components. One concerns the modelling of clear-sky irradiance, three relate to the way in which the effects of cloud are treated as a function of the fraction of sunshine, or cloud amount, and whether total cloud, or cloud layer amounts, are considered. The fifth uses the statistical relationship between measured and computed values of irradiance for all sky conditions.

Clear-sky models.

13.34 Mosby(1936) derived an empirical, non-spectral expression for the ratio (D_{RC}) of the diffuse component to total global irradiance for a cloudless sky as a function of solar elevation:

$$\frac{I_{dc}}{I_{gc}} = D_{RC} = 0.12 + 2.4\ (\gamma) \qquad [13.13]$$

13.35 Klein(1948) observed that, although widely used, Mosby's non-spectral expression for the ratio of diffuse radiation to total radiation was known to be unsatisfactory for general use, because it was based on the assumption that scattering by water vapour and dust is constant. Klein modified the expression of Mosby to allow separate factors for scattering by air and water-vapour molecules, and the depletion of solar radiation by dust. In doing so, Klein also employed the simplification proposed by Kimball(1935), who assumed that:

(i) about half of the radiation lost from the incoming rays through scattering and diffuse radiation is finally received at the ground as diffuse radiation from the sky, and

(ii) all sky radiation is concentrated near the sun, and has the same angle of incidence as the direct beam radiation.

13.36 Klein's study used meteorological data for Blue Hill, Massachusetts, categorised for different cloud density and relative air mass to derive an empirical equation which expressed the cloudless-sky transmission for location elevations of between 300 and 8,00 metres, as a linear function of the solar zenith distance and logarithm of solar elevation.

13.37 Much later, Hottel(1976) proposed a simple method of computing the amount of beam radiation which is transmitted through a clear atmosphere. The method employed used the LOWTRAN-2 computer code of Selby & McClatchey(1972), and took account of the solar zenith distance, the site altitude, and assembled data on the absorption and scattering coefficients of the components of the 1962 American standard atmosphere(McClatchey et al 1972). The clear-day all wave-length transmittance of solar radiation to a surface was found to fit a simple mixed grey gas model with a maximum error estimated at 0.4%. The transmittance was given as:

$$\tau_b = a_o + a_1 e^{\left(-\frac{k}{\cos\theta_z}\right)} \qquad [13.14]$$

Hottel's method included correction factors, to allow for different climate types. The constants for an atmosphere with 5 km visibility were given, and those for 23 km visibility haze were:

$$\begin{aligned} a_o^* &= 0.4237 - 0.00821\,(6 - h_{km})^2 \\ a_1^* &= 0.5055 + 0.00595\,(6.5 - h_{km})^2 \\ k^* &= 0.2711 + 0.01858\,(2.5 - h_{km})^2 \end{aligned} \qquad [13.15]$$

where h_{km} = altitude of the observer in km, and the correction factors for climate type(table 13.3) have the following relationship:

$$cf_o = \frac{a_o}{a_o^*}$$

$$cf_1 = \frac{a_1}{a_1^*}$$

$$cf_k = \frac{k}{k^*} \qquad [13.16]$$

Table 13.3 Correction factors for climate type.

Climate Type	cfo	cf1	cfk
Tropical	0.95	0.98	1.02
Mid-Latitude Summer	0.97	0.99	1.02
Sub-Arctic Summer	0.99	0.99	1.01
Mid-Latitude Winter	1.03	1.01	1.00

13.38 The clear-sky beam irradiance (I_{cb}) on a horizontal surface was considered to be described by the expression:

[13.17]

$$I_{cb} = I_{on}\tau_b \cos\theta_z$$

13.39 Lui & Jordan(1960) analysed 149 solar irradiance data points of the study by Moore & Abbot(1920) of 28 clear-days at Hump Mountain, North Carolina, and found a linear relationship (figure 13.4) between the transmission coefficients for beam radiation and diffuse radiation:

$$\frac{I_d}{I_o} = \tau_d = 0.2710 - 0.2939\,\tau_b \qquad [13.18]$$

$$\text{where: } \tau_b = \frac{I_{bn}}{I_{on}} = \frac{I_b}{I_o}$$

and I_{on} = direct beam normal extraterrestrial irradiance.(W m^{-2})
I_{bn} = direct beam normal terrestrial irradiance.(W m^{-2})
I_0 = direct beam extraterrestrial irradiance on a horizontal surface.(W m^{-2})
I_b = direct beam terrestrial irradiance on a horizontal surface.(W m^{-2})
I_d = diffuse irradiance on a horizontal surface.(W m^{-2})

This expression is often used together with that of Hottel (eqn 13.17) to calculate the direct beam, diffuse and global irradiance for clear skies. Hottel's work was only tested against an empirically based quasi-physical model computer code.

13.40 The ASHRAE technique for estimating solar radiation under clear-skies was developed by Stephenson(1965,1967), based on the earlier work of Threlkeld & Jordan (1958). An even simpler method was developed, for the ASHRAE standard atmosphere, by Farber & Morrison(1977), which enabled the estimated hourly irradiance for a given day to be simply read from a graph of insolation as a function of solar zenith distance. This particular ASHRAE model was popular with heating engineers. Powell(1982, 1984) evaluated and improved the more detailed ASHRAE model, which required a clearness number to be assessed, which had caused problems. The model improvement proposed by Powell incorporated Rodger's expression for relative air mass(eqn 13.3), and the elevation correction factor given in Haltiner & Martin(1957) of:

$$p_r = \left[1 - \left(\frac{h}{44308}\right)\right]^{5.257} \qquad [13.19]$$

where p_r is the ratio of the station pressure to the standard pressure, and h is the height of the station in metres above sea level. Powell reported a significantly improved performance for his modified ASHRAE model. However, Galanis & Chatingy(1986) conducted a review of the model, which was critical of its limitations and the inconsistencies between various versions of the ASHRAE model, and made recommendations to further improve the performance in use.

13.41 A number of more detailed clear-sky models have been produced, which attempt to estimate the transmittance, absorption and scattering of the beam radiation to enable the direct beam and diffuse components to be quantified more precisely. Most are very similar, have only minor differences, and are really variations on the same theme. They use either modifications and refinements of the same or a different empirical relationship for the same atmospheric parameter. Some use either a single broad-band, a narrow-band, or two bands of the solar spectral range to compute certain transmittance values. Iqbal(1983) categorised the work on this type of quasi-physical model into three representative model types: A, B, and C. Gueymard(1993) reviewed their performance, and added a two-band variant of his own, which is referred to here as type D(See Appendix B). It is useful to comment on these, before considering other types of model.

Clear-sky attenuation of direct beam normal irradiance: detailed model types A to D.

13.42 Model type A was based on the work of Davies et al(1975) and Paltridge & Platt(1976), with developments by Suckling & Hay(1976), Davies & Hay(1978), Davies(1980) and Mächler(1983), and was given by:

$$I_{bn} = I_{sc} \; (\tau_o \tau_r - \alpha_w) \; \tau_a \qquad [13.20]$$

where I_{sc} is the solar constant, and absorption by water vapour was defined as:

$$\alpha_w = 1 - \tau_w \qquad [13.21]$$

and based on a correlation by Lacis & Hansen(1974) to fit the curve of Yamamoto(1962). The absorption by ozone was also based on a correlation of Lacis & Hansen(1974) for:

$$\alpha_o = \alpha_{o\,(vis)} + \alpha_{o\,(uv)} \qquad [13.22]$$

The attenuation by Rayleigh scattering was quantified, using the correlation of Davies et al(1975), and the transmittance coefficient used for aerosol attenuation was that obtained from Mächler(1983), which incorporated the turbidity coefficient of Ångström.

13.43 Model type B related to the work of Katayama(1966), Sasamori et al(1972) and Hoyt(1978,1979), in which separate values were formulated for the transmittances or absorptances for precipitable water, carbon dioxide, oxygen, ozone, Rayleigh scattering, and the scattering and absorption by aerosols. As in model type A, absorption by water vapour was based on the work of Yamamoto(1962). In this model two separate expressions were presented for absorption by carbon dioxide and oxygen, which combine to give the absorption by a uniformly mixed gas. Absorption by ozone was calculated using the method described in Manabe & Strickler(1964). To calculate the effect of Rayleigh scattering, a spectrally integrated function, $f(m_r)$, of the air mass, was tabulated. The values of $f(m_r)$ vary from 1 to 0.937, to represent the initial depletion of shorter-wavelength radiation, and the correspondingly reduced fraction of scattering per unit air mass for the longer path lengths from $m_r = 0$ to 4. Iqbal(1983) incorporated a formula by Mächler(1983) to provide values of $f(m_a)$ to within 0.2% of the tabled values. The treatment of the effect of aerosol attenuation in model type B also relied upon the use of the Ångström turbidity coefficient, but it was dealt with in two parts, representing scattering and absorption.

13.44 Model type C evolved from the work of Bird & Hulstrom(1980), who compared a number of direct insolation models with a model called SOLTRAN by Selby & McClatchey(1975), and Selby et al(1978), in order to develop the LOWTRAN computer code for atmospheric transmission of solar radiation. They introduced some new expressions for the transmittances(Bird & Hulstrom 1981), but kept the form of their model more or less the same as the model types A & B. However, SOLTRAN was only concerned with the spectral interval 0.3 to 3.0 microns, and the NASA value of 1353 W m^{-1} was used for the solar constant. The direct normal irradiance was therefore given as:

$$I_{bn} = 0.9662\, I_{sc}\, \tau_r\, \tau_o\, \tau_{gas}\, \tau_w\, \tau_a \qquad [13.23]$$

Iqbal(1983) introduced two changes. The first adjusted the factor 0.9662 in equation 13.23 to 0.9751 to allow for the revised value of 1367 W m^{-1} for the WMO solar constant. The second was the use of an absolute pressure corrected air mass for the calculation of precipitable water.

13.45 The Model type D by Gueymard(1989), follows the work of Lacis & Hansen(1974) & Paulin(1980) on the absorption of solar radiation. In this model the UV-visible and Infrared bands of the solar spectrum are considered separately in respect of molecular scattering, and water vapour and mixed gas absorptions respectively. The direct normal irradiance for each band is given as in eqn 13.23, but with an appropriate factor to adjust the solar constant as appropriate for each waveband. As with model C, This model is largely based on LOWTRAN. The transmittance in the infrared band due to water-vapour was taken from Leckner(1978), but the relative air mass used in the model was calculated from the approximate formula of Kasten(1966), which was derived for the broadband solar spectrum and is therefore not strictly applicable to this model. The model also relied upon the use of the Ångström turbidity coefficient in calculating the effect of aerosols.

Comparison of the method of calculating the clear-sky diffuse irradiance: model types A-D

13.46 In all four models, the Diffuse irradiance is given by:

$$I_d = I_{dr} + I_{da} + I_{dm} \qquad [13.24]$$

where: I_{dr} is the diffuse irradiance due to Rayleigh scattering, and is calculated more or less in the same way for all four models; I_{da} is due to scattering by aerosols, which is virtually the same for models A & B; and I_{dm} represents the diffuse irradiance from multiple reflections between the surface and the atmosphere, which is handled similarly for model types B & C, and model D uses the solution of model A.

Clear-sky global horizontal irradiance: model types A to D.

13.47 For model types A to D, the global horizontal irradiance is computed from:

$$I_g = I_{bn} \cos \theta_z + I_d \qquad [13.25]$$

where I_g = global horizontal irradiance.

Performance evaluation: detailed clear-sky models.

13.48 Iqbal(1983) compared the results of the three detailed clear-sky model types A, B, and C, based on a standard set of assumptions for a particular location. The results obtained for solar noon are given in the following table, but these results were not validated against observed values, and simply emphasise the commonality of the development lineage of the models.

Table 13.4 Irradiance in Watts per square metre.(Iqbal 1983)

	Irradiance in W / m^2 for clear-sky model types		
	A	B	C
I_{on}	888.48	851.92	896.44
I_b	450.90	432.35	454.90
I_{dr}	47.67	38.55	33.66
I_{da}	38.47	41.49	39.85
I_{dm}	9.08	6.13	8.59
I_d	95.22	86.17	81.80
I_g	546.12	518.50	536.80

13.49 Iqbal's results also indicated that there was hardly any difference in the performance of the models for the calculation of direct beam normal irradiance for all zenith distances, but there were significant differences in the values of diffuse and therefore global irradiances predicted by each model type. The degree to which the model outputs varied depended on the assessment of atmospheric turbidity.

13.50 Louch et al(1988) re-examined the performance of the clear-sky model types A, B & C. They compared the predicted results with data for Carpentras in Southern France. A value of 0.95 was assumed for the single scattering albedo of aerosols. They calculated the relative mean bias error and root mean square error, from the following expressions:

$$MBE = \frac{\left[\frac{calculated - measured}{measured}\right]}{total\ number\ of\ data\ points} \qquad [13.26]$$

and

$$RSME = \left[\frac{\left(\frac{calculated - measured}{measured}\right)^2}{total\ number\ of\ data\ points}\right]^{0.5} \qquad [13.27]$$

Louch et al concluded that the amendment of Iqbal(1983) to the factor of 0.9662 to 0.9751 in Equation 13.23 was justified by improved accuracy of prediction. All the models were considered to be in need of further improvement. Their overall conclusions on comparative model performance are listed in table 13.5.

Table 13.5 Comparable accuracy of clear-sky models

Model A	Worst prediction of diffuse & global.
Model B	Worst prediction of direct beam normal. Best prediction of Diffuse and global.
Model C	Best prediction of direct beam normal.

This was an interesting result, suggesting that a hybrid model, which combined the best features of these models might be an appropriate development.

13.51 Gueymard(1993) evaluated the performance of eleven clear-sky models (table 13.6), and compared the predicted beam, diffuse and global irradiances with measured data from a total of seven sites located in Belgium, Canada, France, India, Switzerland and the USA. Gueymard concluded that:

(i) type D, C, EEC, & the PSI 1-band model performed best, having a RMS error below 6% for global irradiance, and below 9% for beam irradiance;

(ii) many of the models suffer from various input limitations(MAC, JOS, & ASHRAE), and some flaws in certain conditions(IQA, JOS, & C);

(iii) POW is not an improvement for the ASHRAE model, although claimed to be;

(iv) atmospheric effects were not always modelled correctly, and

(v) accuracy is mainly dependent on the modelling of water vapour absorption, and more importantly that of aerosol extinction.

13.52 These clear-sky procedures to calculate irradiance were all somewhat complex. They required a number of measured atmospheric parameters, and were dependent on assumptions about other atmospheric parameters. They were developed for very good reasons, but being dependent on empirical relationships based on the statistical analysis of measurements at particular locations, may thereby have introduced latitude dependence, and degrees of uncertainty.

All-sky condition models:

13.53 Models, which are required to deal with all sky conditions must take into consideration the effect of clouds in the atmosphere at a given time and location. There are an enormous number of papers published in which an empirical model is proposed to deal with the prediction of either the total global horizontal, or the components of solar radiation for all-sky conditions. Most of these fall into one or other of the following four categories of model:

(i) those which rely on sunshine records to determine the cloudiness of the sky;
(ii) models which require a record of the extent of cloud cover;
(iii) models involving calculations based on the records of the layers, heights and types of cloud, and
(iv) statistical models, based on an analysis of the relationship and characteristic distribution of the components of irradiance.

Table 13.6 Clear-sky models considered (Gueymard(1993b)

Ref	Model Type	Model development.
MAC	A	Davies et al(1975), Paltridge & Platt(1976), Suckling & Hay(1976), Davies & Hay(1978), Davies(1980), Davies & McKay(1982, 1989).
IQA		Iqbal(1983).
JOS		Joseffson quoted in Davies et al(1988).
IQB	B	Katayama A(1966), Sasamori et al(1972), Hoyt(1978.1979), Iqbal(1983).
IQC	C	Bird & Hulstrom(1980), Iqbal(1983).
M&I		Mächler & Iqbal(1985).
ASHRAE	ASHRAE	Anon(1976), Galanis & Chatigny(1986).
POW		Powell(1982).
EEC	EEC	Page(1986).
CPCR2	D	Gueymard C(1989).
PSI	1 band	Gueymard C(1993a).

Sunshine:

13.54 Angstrom(1924) was the first to suggest a linear relationship between total daily global radiation and sunshine duration, calculated using the ratio of the recorded number of sunshine hours to the maximum number of sunshine hours possible on the day and place in question. His expression depended on the assessment of a value for the global radiation for a perfectly clear sky, which has to be interpolated, and a transmission coefficient for shortwave radiation through a cloud cover of average thickness.

$$H_g = H_{cg}\left(a' + b'\frac{n_s}{N_s}\right) \qquad [13.28]$$

Prescott(1940) modified the Angstrom formula, replacing the clear sky irradiance, H_{cg} by the known shortwave radiation received at the top of the atmosphere, H_0 known as the Angot value. This gave the well known and widely used formula:

$$H_g = H_o\left(a + b\frac{n_s}{N_s}\right) \qquad [13.29]$$

where the coefficients a and b,respectively, are the fractions of radiation received at the surface of the Earth, and absorbed by the clouds on a completely cloud covered day.

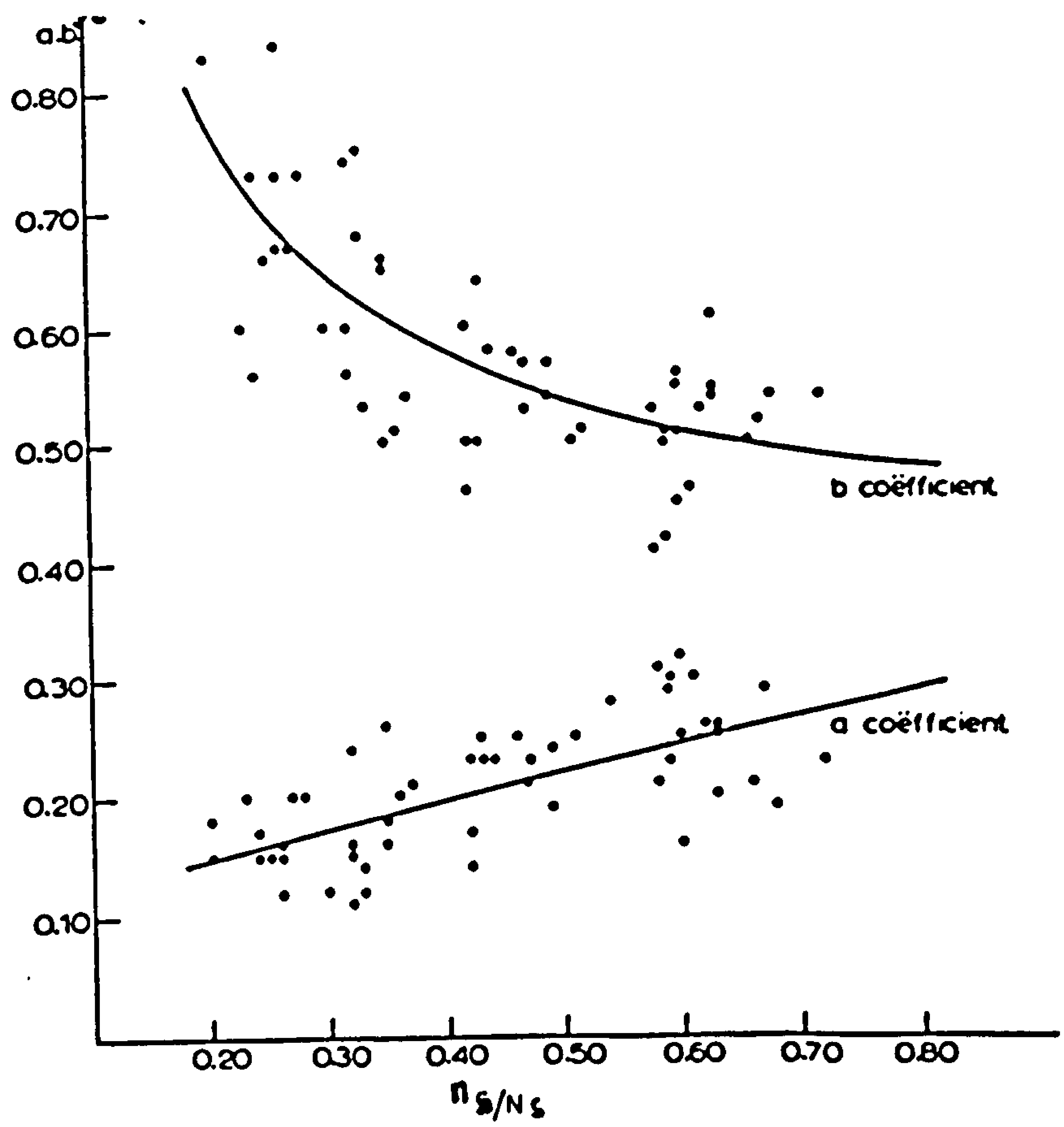

Figure 13.3 DEPENDENCE OF a AND b COEFFICIENTS ON RELATIVE SUNSHINE DURATION.

13.55 Three methods have been proposed to measure the coefficients a and b, as follows:

(i) Black(1954) calculated the average value for the coefficients from assessments of them at thirty two stations worldwide(between 35^{o}S & 65^{o}N), and assumed that this average, giving a = 0.23, and b = 0.48, would be an acceptable approximation for latitudes in this range.

(ii) Penman(1956) calculated the coefficients from observations in England and Ghana, and found, for both locations, that a=0.18 and b=0.55 and suggested that these values could have general application.

(iii) Reitveld(1978) found that 'a' is related linearly, and 'b' is related hyperbolically, to the appropriate mean value of n /N , as shown in figure 13.3, but acknowledged that there was not enough data available to support that this conclusion was of general validity.

Amount of cloud:

3.56 Kimball(1919) noted the relationship between insolation and the extent of total cloud cover in the sky hemisphere and proposed a linear correlation of the form:

$$\frac{\overline{H_g}}{\overline{H_o}} = a_2 - b_2 C \qquad [13.30]$$

where C = the monthly average fraction of the daytime sky obscured by clouds.

13.57 Black(1956) then analysed data from various stations around the globe, and proposed the following relationship:

$$\frac{\overline{H_g}}{\overline{H_o}} = 0.803 - 0.340\, C - 0.458\, C^2 \quad with\ C \le 0.8 \qquad [13.31]$$

13.58 The weakness of these methods relates to the inherent observational difficulty of estimating cloud cover, the variable effect which similar values of general cloud cover can have on recorded values of insolation, attributable to which part of the sky is cloudy, and the type, height, and layer effect of the clouds. Kasten & Czeplak(1980) concluded that transmissivity for high clouds is about three times greater than that for low clouds. Cloud layer models consider this variation by defining cloud field transmissivity as:

$$\tau_c = \prod_{i=1-n}^{nc} (1 - \tau_{i(c)} C_i) \quad [13.32]$$

where:

C_i = cloud amount, corrected for overlap effects as per Davies et al(1975).

$\tau_{i(c)}$ = transmissivity of an individual cloud layer.

nc = number of cloud layers observed

13.59 Models have been developed to estimate the total global horizontal irradiance, which require an assessment to be made of the transmissivity of the cloud field, the transmission through blue sky, and the effect of multiple reflections between cloud layers, and the clouds and the ground(Davies & McKay 1982). They have the form:

$$H_g = H_{cg} \prod_{i=1-n}^{nc} \frac{(1 - \tau_{i(c)} C_i)}{1 - \rho_g \rho_o} \quad [13.33]$$

where:

ρ_g = ground albedo.
ρ_o = atmospheric reflectivity for surface reflected solar radiation.
H_{cg} = theoretical cloudless-sky global irradiance.

13.60 The problem with this expression, as with that of the unmodified Ångström equation 13.28, is the reliance upon a theoretical assessment of the clear-sky total daily global horizontal irradiance (H_{cg}) in this procedure.

13.61 The amount of water vapour in the atmosphere is a measure of what is available to become cloud. The amount has been correlated to the surface dewpoint temperature T_{dp}. Bolsenga(1965) proposed the following expression for the natural logarithm of the precipitable water vapour w(in centimetres of water equivalent) in the atmosphere, in terms of the surface dew point temperature, using data for North Hampshire.

$$\ln w = 0.077\, T_{dp} + 0.12 \quad [13.34]$$

However, the coefficient of correlation stated was only 0.85.

13.62 The link between the surface dewpoint and the water content of the atmosphere suggests a similar relationship between surface conditions and the occurrence of cloud. However, Linacre(1992) tested the hypothesis that afternoon cloudiness is likely to be greater when the surface temperature is nearer saturation. Linacre used data on cloudiness and on the difference between T_{max} and T_{dp}, but found a poor correlation, implying that the occurrence of cloud depends on other factors in addition.

13.63 Atwater & Ball(1976) reported differences of no more than 1% between model estimates of insolation, which use precipitable water from sounding data and model estimates using an empirical function of surface humidity. However, as Davies et al(1988) observed, this agreement did not necessarily arise because the empirical formula estimated precipitable water accurately, but that it estimated it sufficiently accurately, bearing in mind that the cloud layer model estimates of global radiation are not particularly sensitive to a substantial error in precipitable water(Davies et al 1975).

13.64 Camps & Soler(1992) used a method originally developed by Anderson(1970) for mean daily values. They assumed that the Anderson method, which consisted of subtracting the irradiances absorbed and scattered by the atmosphere from extraterrestrial solar radiation, would be appropriate for predicting the diffuse component from integrated values of hourly observations, when modified to isolate the effects of atmospheric turbidity separately from: absorption by water vapour and ozone; clouds; and attenuation by Rayleigh scattering. They intended the model to be used for all-sky conditions, but only presented the case for cloudless skies, due to the high percentage of error found in predicting diffuse irradiance for other sky conditions. Their conclusion was that it was difficult to accept a single solution for clear and cloudy sky conditions.

13.65 Satterlund & Means(1978) presented a model for estimating daily total solar radiation by taking account of scattered radiation from clear-skies and reflected and transmitted radiation from clouds. The model failed to yield any reasonable estimate of measured mean daily solar radiation, which indicated that something was wrong either with the model or the cloud cover data. Their solution was to modify the cloud cover data to conform with sunshine records, after Thompson(1976). The results were then considered more acceptable, suggesting either that the general cloud cover data was unreliable, or there was a need to model cloud layers separately. Kamada & Flocchini(1984) investigated the detailed modelling and treatment of clouds to determine radiant transfer above and below the cloud layers, and consider cloud height effects. They found that there was too large a margin of error in assessing cloud cover, which adversely affects the validity of this type of model.

Statistical models:

13.66 Kimball(1919) found the ratio of the direct component of sunlight on a horizontal surface, to the total global horizontal radiation, to be a function of the solar zenith distance.

13.67 Fritz (1951) gives the results of Kimball(1919) for the relationship between the solar zenith distance, and the ratio of direct radiation on a horizontal surface to the global horizontal, illustrated in table 13.7 Fritz noted that similar values were reported by Linke(1943), who used measurements made using narrow spectral band instruments, to show, as one might expect, that the ratio of the diffuse component to the global horizontal increased when the atmospheric turbidity was high. Fritz observed that it would have been desirable to measure the ratio for non-spectral radiation with varying atmospheric transmissions, or turbidity factors, to establish the statistical relationship.

Table 13.7 I_b/I_g as a function of solar zenith distance.

θ^z degrees	30.0	48.3	60.0	66.5	70.7	73.6	75.7	77.4	78.7	79.8
Ib / Ig	0.84	0.84	0.80	0.78	0.76	0.72	0.69	0.67	0.65	0.63

13.68 Lui and Jordan analysed the daily mean solar radiation clear-sky data for Blue Hill, Massachusetts(Lui & Jordan 1960), and proposed a linear relationship between the following:

(i) transmission coefficient for instantaneous diffuse radiation defined as the ratio of the diffuse radiation received on a horizontal to the extraterrestrial irradiance on a horizontal surface,

$$\tau_d = \frac{I_d}{I_o} \qquad [13.35]$$

and

(ii) the equivalent transmission coefficient for instantaneous beam radiation defined as the ratio of the direct beam component to the extraterrestrial irradiance for either a horizontal surface or normal to the angle of incidence.

$$\tau_b = \frac{I_b}{I_o} = \frac{I_{bn}}{I_{on}} \qquad [13.36]$$

They obtained a linear best fit to their data by the least squares method(figure 13.4), and proposed that the resultant expression, with an estimated probable error of 0.0052, would be applicable to all locations, having similar atmospheric dust content and surface albedo to Blue Hill, Massachusetts($42^{0}13'N$).

$$\tau_d = 0.2710 - 0.2939\ \tau_b \qquad [13.37]$$

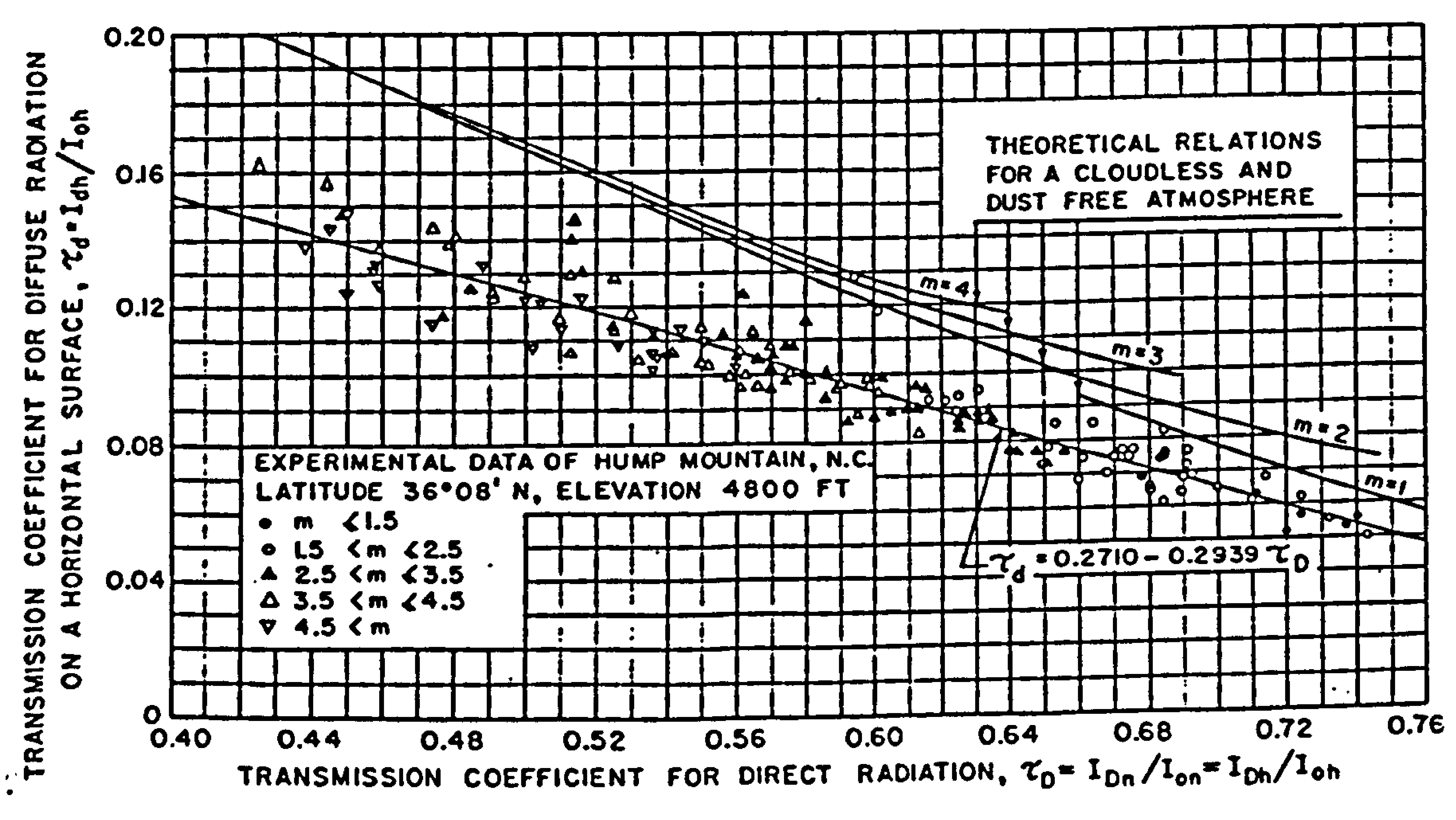

Figure 13.4 THEORETICAL & EXPERIMENTAL RELATIONS BETWEEN THE INTENSITIES OF DIRECT & DIFFUSE RADIATION ON A HORIZONTAL SURFACE FOR A CLOUDLESS ATMOSPHERE AT 1463 METRES ELEVATION. (Lui & Jordan 1960).

KEY: m = relative air mass.

They also considered the relationship between daily diffuse and daily total radiation on clear and cloudy days, and monthly average daily total and diffuse radiation, and developed relationships based on a diffuse ratio(D_R), and cloudiness index(K_T) for the sky where:

$$D_R = \frac{H_d}{H_g}, \qquad K_T = \frac{H_g}{H_o} \qquad [13.38]$$

They analysed the insolation measurements taken at Blue Hill, Massachusetts during 1947-1956 to identify the days in a particular month, on which the average daily total radiation was within a small interval of values. Approximately ten such values were obtained for each month from the ten year data set. They used a solar constant value of 2.0 ly min^{-1}, and calculated the atmospheric transmission coefficients for the global horizontal irradiance, which they called the cloudiness index KT (clearness index). They plotted this against the Mosby(1936) ratio of diffuse to global horizontal irradiance(figure 13.5), and suggested that this would be applicable to all locations with similar atmospheric dust content and surface albedo.

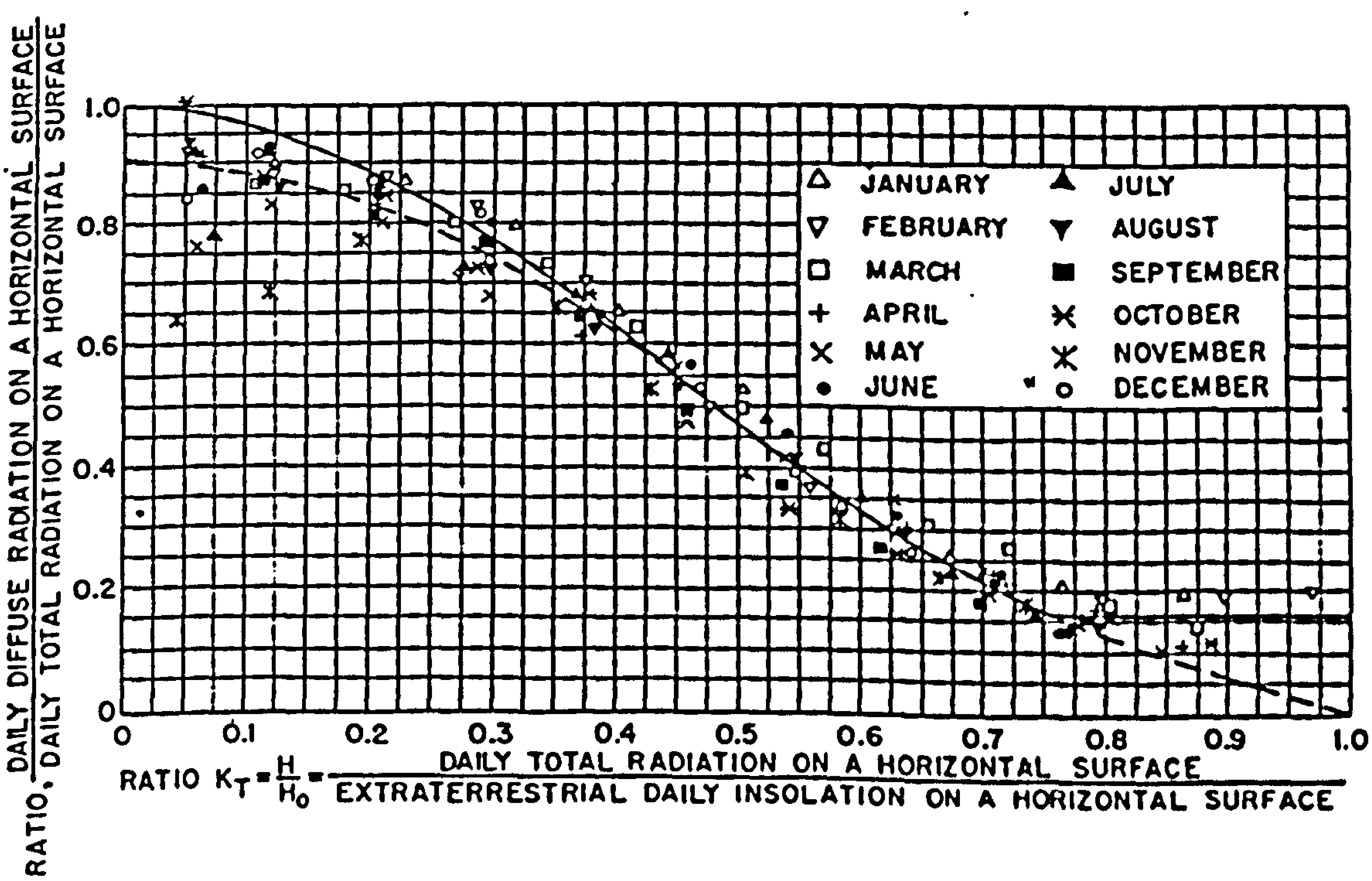

Figure 13.5 The ratio of the daily diffuse radiation to the daily total radiation as a function of the cloudiness index K_T.

13.69 Choudhury tested this procedure, using mid-latitude weather data for New Delhi, and reported generally good agreement(Choudhury 1963), although the diffuse ratio was higher than predicted by the Lui and Jordan method(Figure 13.6).

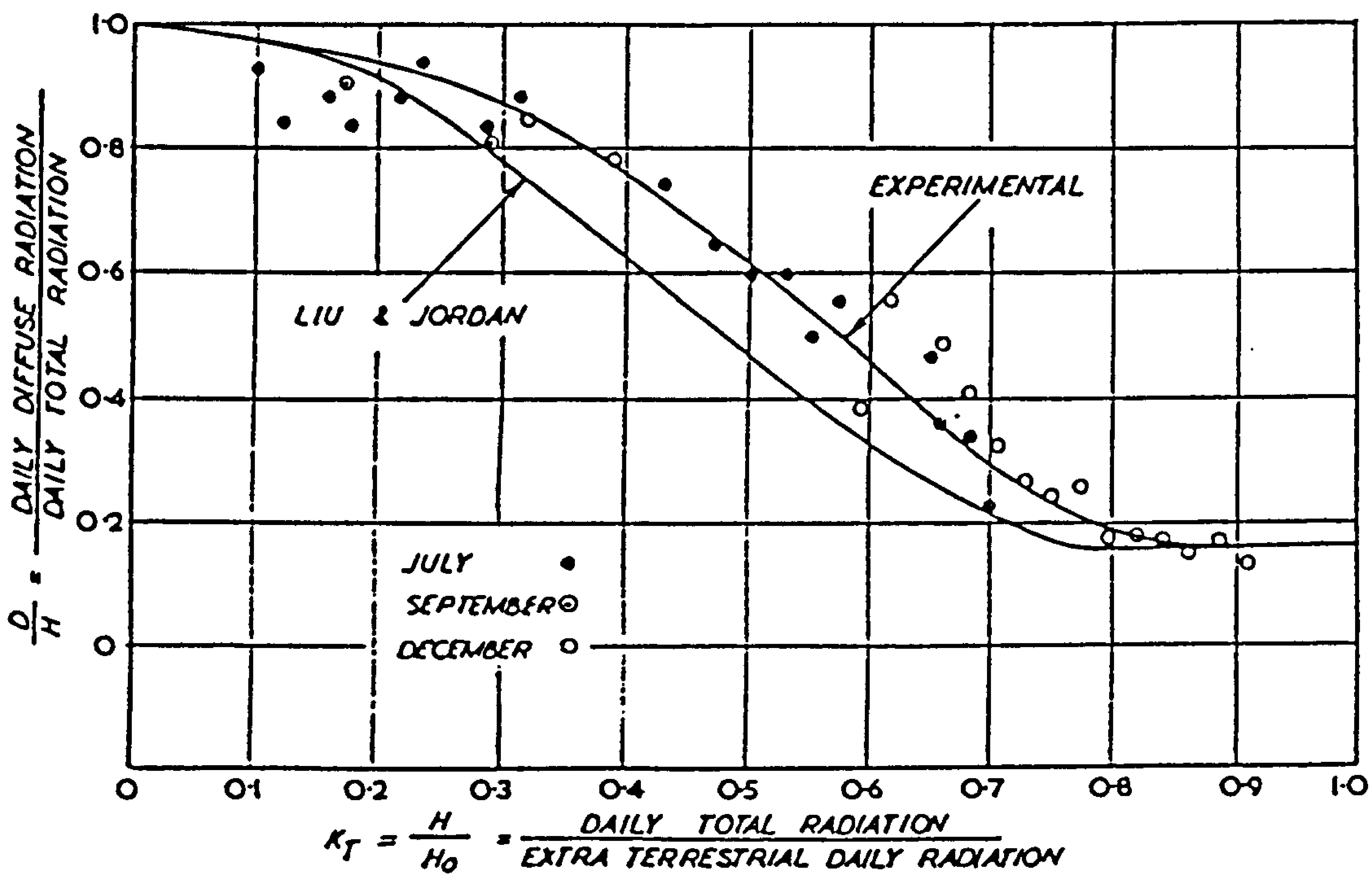

Figure 13.6 STATISTICAL RELATIONSHIP BETWEEN DIFFUSED AND DAILY TOTAL RADIATION.(Choudhury 1963)

13.70 Ruth & Chant tested the Lui & Jordan method, which used the mid day of the month to calculate the extraterrestrial daily total irradiance, using Canadian data, but found undesirable scatter. They revised the procedure to calculate the daily value of H_0, which improved the correlation accuracy, using data for Toronto(43°48'N), Montreal(45°30'N), Goose Bay(53°18'N), and Resolute Bay (74°43'N), and found the results for Toronto and Montreal were almost identical, those for Goose Bay were scattered around them, and Resolute Bay results were far above the others(Ruth & Chant 1976). They concluded that, although the Lui & Jordan method produced excellent correlations, it was not universally applicable, and showed a latitude dependence, contrary to the views of Lui & Jordan(1960). They recommended the use of locally determined correlations, and produced the following correlation for use if this was not available, but did not publish their coefficients, which are however given in Iqbal (1979).

$$D_R = \frac{H_d}{H_g} = 0.98 \qquad for\, K_T <= 0.1$$

$$D_R = \frac{H_d}{H_g} = 0.910 - 1.154\, K_T - 4.936\, K_T^2 + 2.848\, K_T^3,$$

$$for\; 0.1 \le K_T \le 0.7 \qquad [13.39]$$

where

$$\frac{\overline{H_g}}{H_o} = K_T \qquad [13.40]$$

13.71 Using a revised value of the solar constant of 1.94 ly min^{-1}, Klein(1977) calculated the correlation coefficients for the Lui & Jordan curve as:

$$\frac{\overline{H_d}}{\overline{H_g}} = 1.390 - 4.027\, K_T + 5.531\, K_T^2 - 3.108\, K_T^3 \qquad [13.41]$$

13.72 Collares-Pereira & Rabl(1979) used data from five stations in the USA, and obtained the following correlation:

$$\frac{\overline{H_d}}{\overline{H_g}} = 0.99 \qquad for\ K_T \leq 0.17$$

$$\frac{\overline{H_d}}{\overline{H_g}} = 1.88 - 2.272 + 9.473\, K_T^2 - 21,856\, K_T^3 + 14.648\, K_T^4$$

$$for\ 0.17 \leq K_T \leq 0.8 \qquad [13.42]$$

They compared their results(figure 13.7) with the correlations of both Lui & Jordan(1960), and Ruth & Chant(1976). Although their study was based on a very limited sample of data, their result was almost identical to that of Ruth & Chant. They reported that although the diffuse measurements taken at the Blue Hill observatory had not been adjusted to allow for the effect of the shade-band used, and Lui & Jordan(1960) had not allowed for the need to make any compensatory adjustment, the validity of the Lui & Jordan method was confirmed.

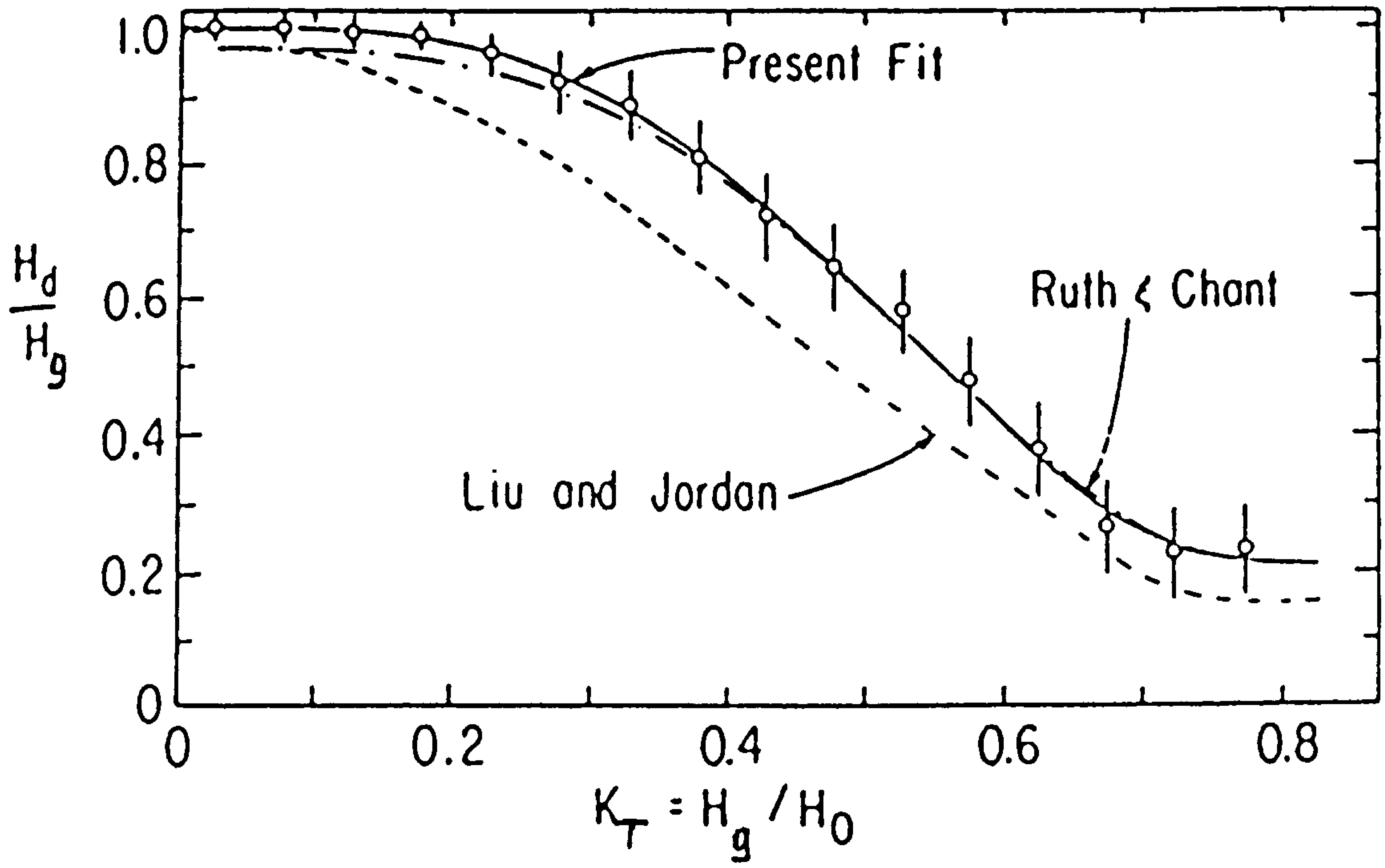

Figure 13.7 Variation of the ratio between daily total diffuse radiation and the clearness index.

13.73 The Lui & Jordan correlation was based on daily rather than the more useful hourly values of insolation. Orgill & Hollands(1977) adapted the Lui & Jordan procedure for use with hourly values ,using measured data for Toronto to produce the following correlation:

$$\frac{I_d}{I_g} = 1.0 - 0.249\,K_t \ldots\ldots\ldots\ldots\ldots \mathit{for}\ K_t < 0.35$$

$$\frac{I_d}{I_g} = 1.557 - 1.84\,K_t \ldots\ldots\ldots \mathit{for}\ 0.35 < K_t < 0.75 \qquad [13.43]$$

$$\frac{I_d}{I_g} = 0.177 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{for}\ K_t > 0.75$$

where:

$$\frac{I_g}{I_o} = K_t \qquad [13.44]$$

They used 12,704 hourly values for this data fit, and noted that:

(i) only 5.6% of the data was for relatively clear periods with some cloud cover(K_t > 0.75), and assumed that there were errors in this set of the data;

(ii) 32.4% of the data was for extremely overcast days(0 <= K_t < 0.35) with over 90% of the total insolation being diffuse, and they assumed that these values were affected by instrument sensitivity(figure 13.8).

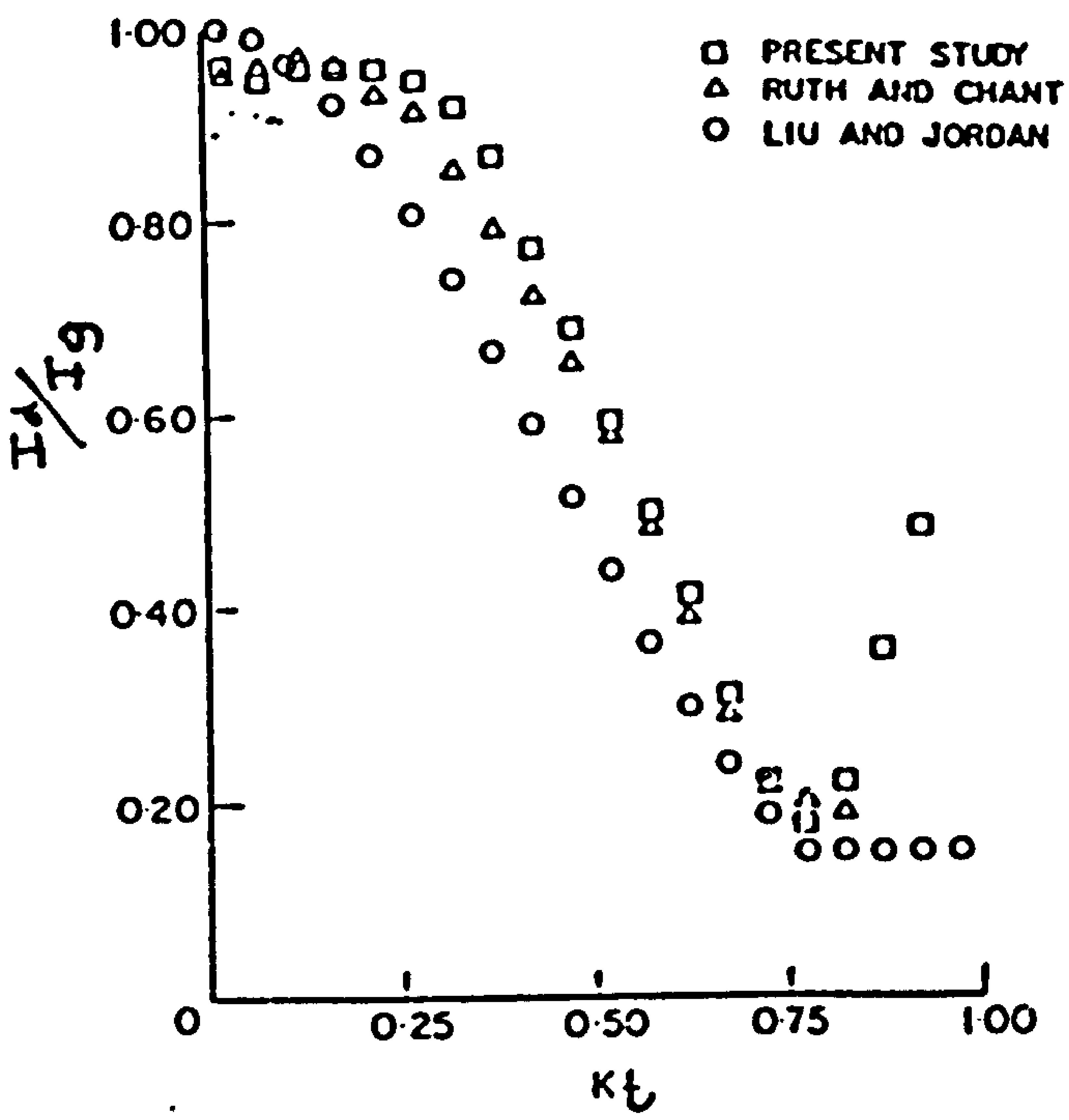

FIGURE 13.8 COMPARISON OF ORGILL & HOLLANDS CORRELARION WITH THAT OF LUI & JORDAN AND OF RUTH & CHANT. (Orgill & Hollands 1977)

They concluded that their correlation accurately represented the diffuse irradiance between latitude 43° North and 54° North, and recommended an hourly mid point value for extraterrestrial radiation to reduce computing time.

13.74 Erbs et al(1982) developed a correlation from a relatively small data base comprising the combined data from four locations. They used the Orgill & Hollands method, but they included an hourly percent of possible sunshine as a parameter in their correlation expression to reduce the standard deviation of the hourly diffuse fractions from the predicted values which would otherwise occur, without this adjustment. They found (figure 13.9) that, their results were essentially the same as those of Orgill & Hollands(1977). They also used Australian data to test for global application, and reported that the Australian data agreed to within a few percent(figure 13.10).

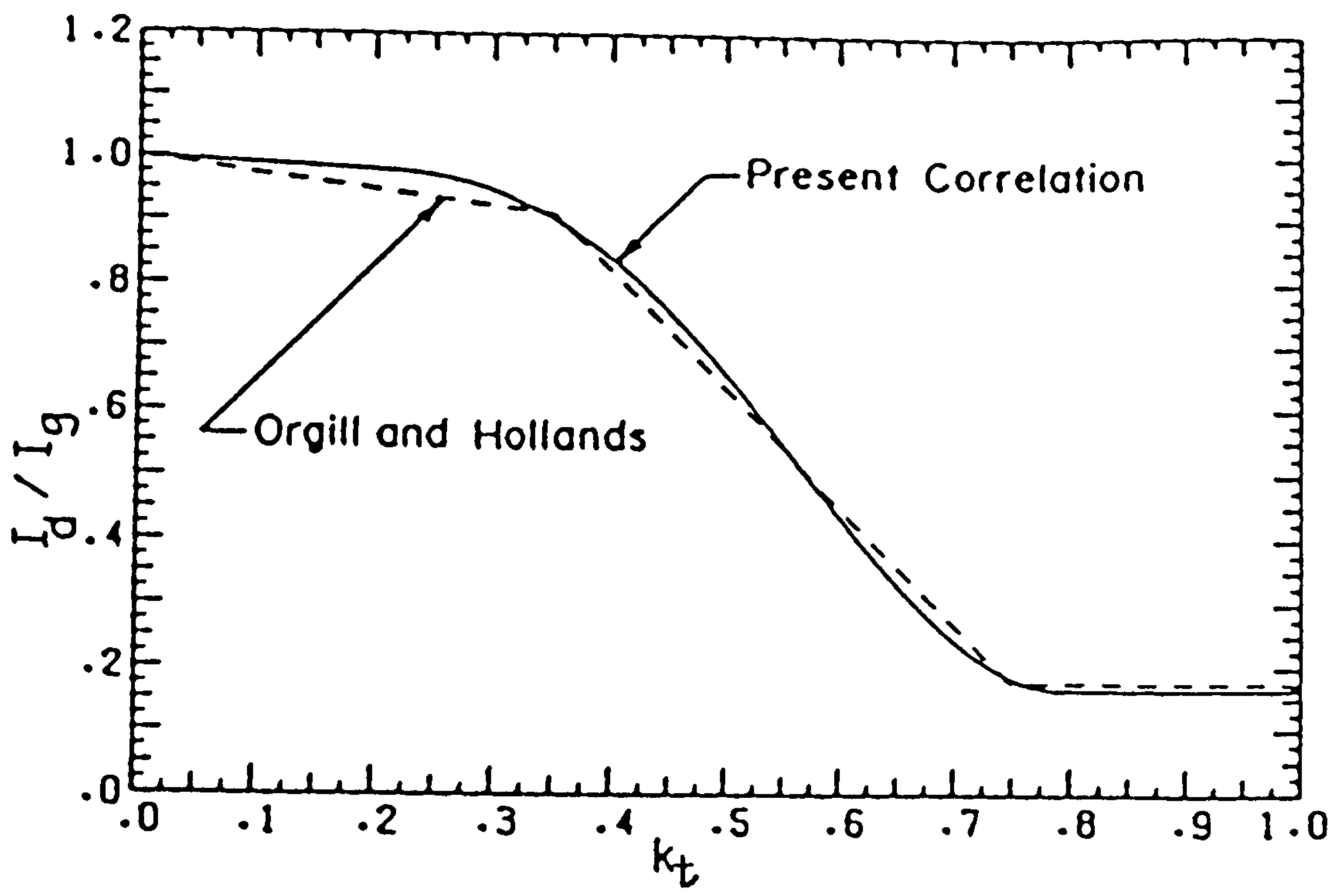

Figure 13.9 Comparison with the correlations for k_T of Erbs et al(1982) and Orgill & Hollands(1977).

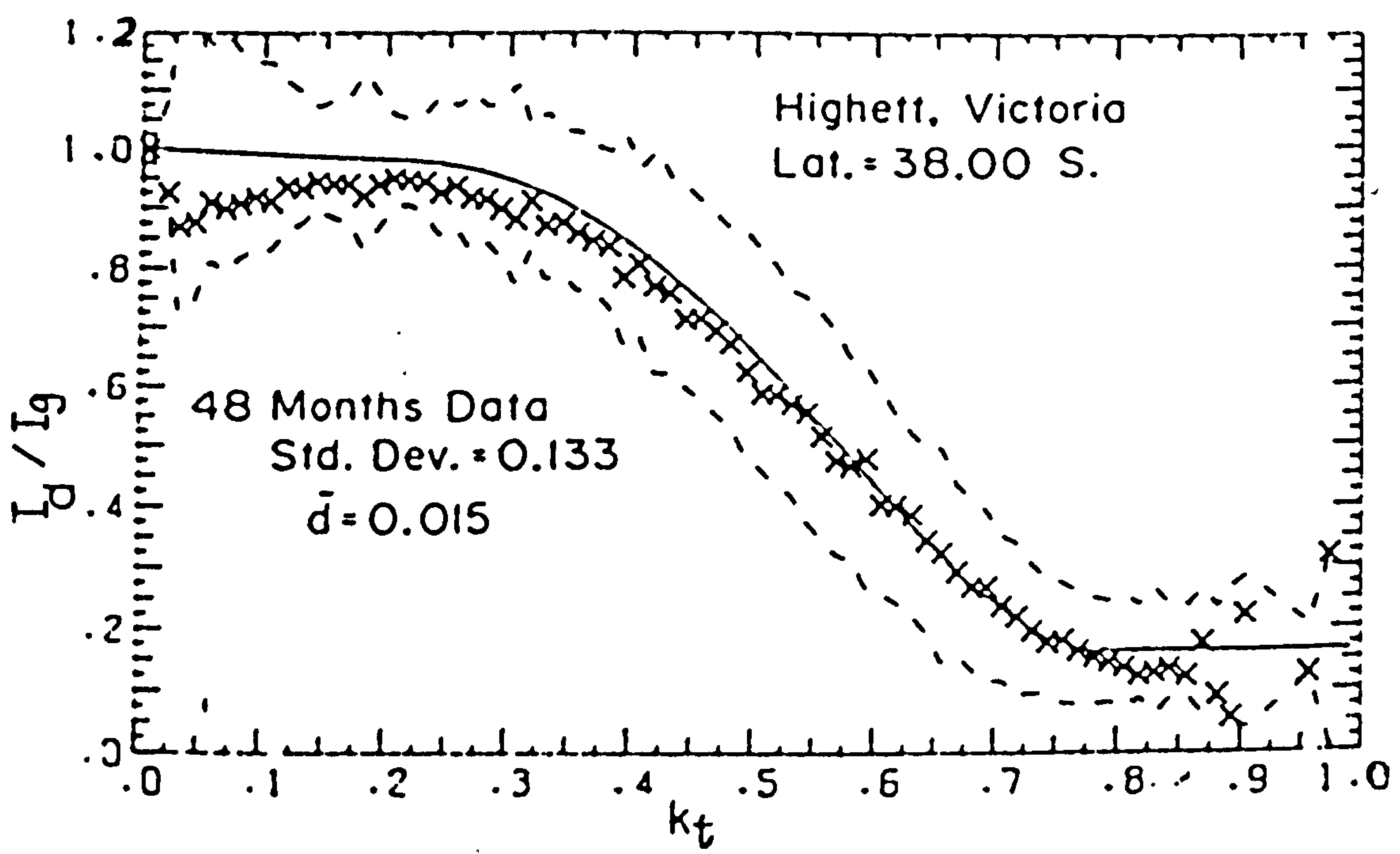

Figure 13.10 Comparison of the correlation of Erbs et al (1982) with the hourly data for Highett, Australia.

13.75 They concluded that:

(i) while the uncertainty in the estimated diffuse fraction for an hour period is significant, they considered that their correlation accurately predicted the long term average hourly diffuse irradiance, and

(ii) only the long term relationship between the diffuse ratio and the clearness index, and not the random nature of individual hourly values appeared to be important.

However such a conclusion pre-supposes that accurate individual hourly values are unimportant, and that their hourly prediction method is limited to predicting monthly mean values. Perhaps this is an inevitable consequence of using such a curve fitting procedure on data with wide variations in hourly values.

13.76 Muneer & Saluja(1986) used the Orgill & Hollands hourly procedure to produce a new correlation between the clearness index and diffuse index using UK data:

$$\frac{I_d}{I_g} = a_1 + (a_2 K_t) + (a_3 K_t^2) + (a_4 K_t^3) \ldots for\, K_t > 0.2 \qquad [13.45]$$

where the coefficients a_1-a_4 vary according to location. They provided a correlation with an estimated error of +/- 5% for Easthampstead(51°23'N), which is close to the sites of both the atrium schools studied in part one of this thesis. The data for this is illustrated in figure 13.11.

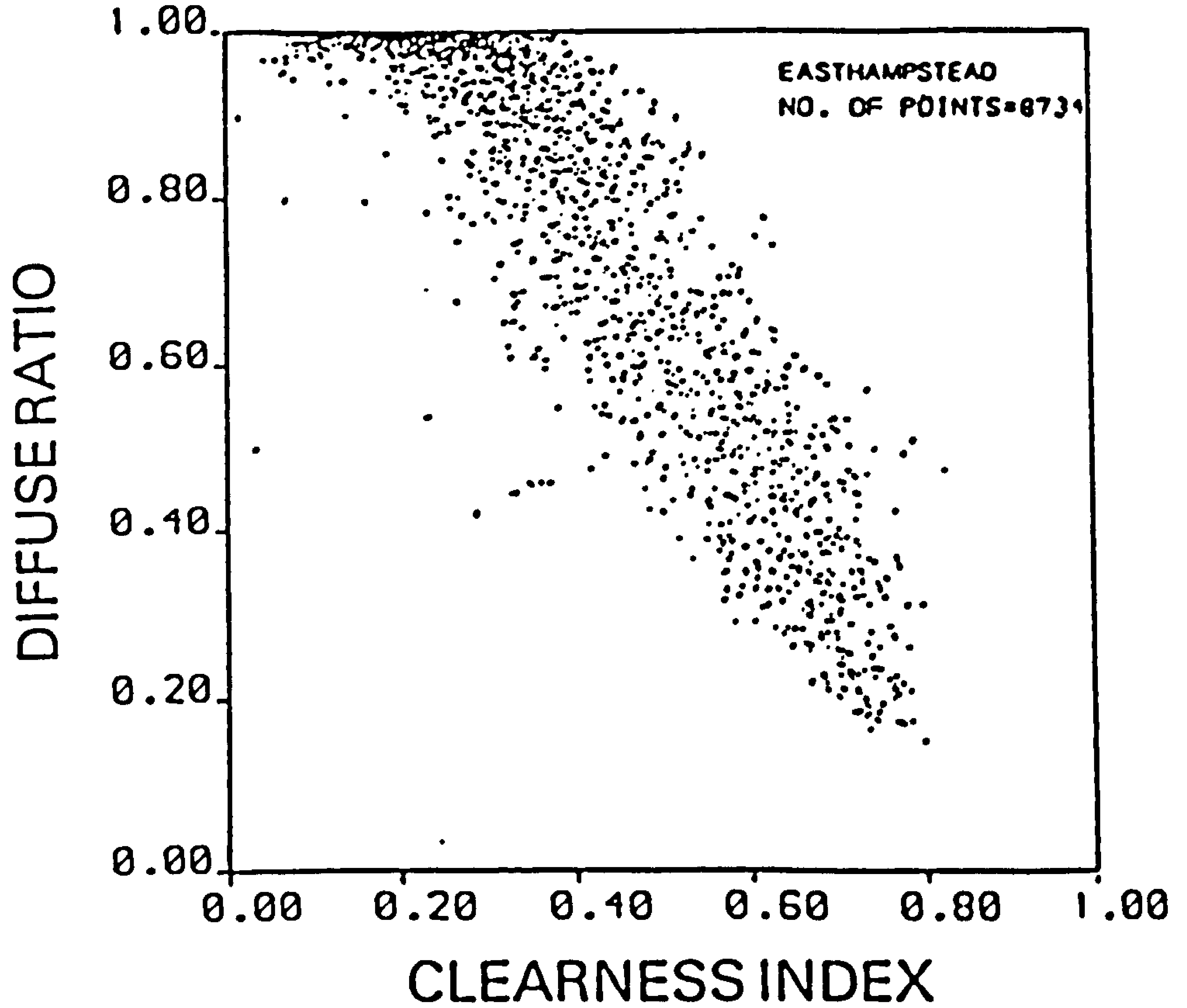

Figure 13.11 HOURLY DIFFUSE RATIO(D_t) VERSUS HOURLY CLEARNESS INDEX(K_t).(MUNEER & SALUJA 1986)

The correlation had the form:

$$\frac{I_d}{I_g} = 0.784 + 2.420\,K_t + (-7.999\,K_t^2) + 5.110\,K_t^3; \quad for\ K_t > 0.2$$

[13.46]

They adapted it for use with inclined surfaces, and to take account of ground albedo(Saluja & Muneer 1987,88). Muneer(1987,1990a) then extended and revised the study to include additional UK locations, and (Muneer 1990b)amended it further in the developing a model for applications in Europe.

13.77 Overall, there have been a considerable number of attempts to apply the Lui & Jordan daily mean method and correlation, and the Orgill & Hollands adaptation of it for hourly irradiance, using observations recorded at various locations throughout the World. Most researchers have proposed new correlation equations, because of the lack of a satisfactory fit to their data. This suggests that the Lui & Jordan method, and the Orgill & Hollands adaptation of it, are not universally applicable as often considered.

Evaluation of all sky condition models:

13.78 Davies et al(1988) assessed the suitability of each of the four categories of empirical model intended to deal with all sky conditions, for the International Energy Agency. They used ten basic models(Table 13.8), and meteorological data from fifteen locations from Australia, Europe and the United States of America. They found that:

(i) the procedure of Reitveld(1978), for estimating variable values of the a and b parameters in the Angstrom equation for sunshine duration models, did not improve upon the radiation estimates based on that of Page(1961), who used fixed parameter values;

(ii) there was little to recommend such sunshine-based models, even though the Angstrom equation can be fitted to local climate data by regression analysis, since this did not ensure reasonable accuracy of prediction for another place, or time within the same locality;

(iii) cloud layer models were superior to general cloud models, and should be used for estimating total global irradiance, preferably for periods longer than a day to provide acceptable results;

(iv) cloud model rankings for estimating hourly or daily global radiation were the same;

(v) statistically based models were best for estimating direct beam and diffuse components, and the difference in uncertainty between them and cloud layer models for daily estimates is about 25%, however they cannot have general applicability, because they are statistically based;

(vi) monthly estimates from the cloud layer and statistically based types of model have comparable accuracy;

(vii) generally the performance of all the models tested was not good, which, they concluded, may indicate that the present models are close to the limit of prediction, and

(viii) guidelines are therefore required concerning the permissable level of accuracy of radiation estimates.

13.79 The examination of these models by Davies et al concluded that statistically based models were best for estimating direct beam and diffuse components. However it is worth noting the results of Iqbal(1983), who used meteorological data for Montreal to determine the accuracy of predictions of hourly diffuse radiation, based on the statistical model correlations of Orgill & Hollands(1977), Erbs et al(1982), and Spencer(1982), which did not distinguish between different values of solar altitude, and those of Boes et al(1977), and Iqbal(1980), which allowed separately for the effect of low sun angles.

13.80 Iqbal's comparison demonstrated the difficulty inherent in predicting the diffuse component from global radiation measurements for individual hours,(Table 13.9) and established, that none of the correlations were satisfactory, except under completely overcast conditions, when most yielded good results. Iqbal concluded that considerable work and a completely different approach is required to solve this problem.

TABLE 13.8 LIST OF MODELS ASSESSED.

No	Model	Type
1	Page(1961)	Sunshine hours.
2	Reitveld(1978)	
3	Barbaro et al(1979)	
4	Monteith(1962)	Total cloud.
5	Kasten(1983)	
6	Davies & McKay(1982)	Cloud layer.
7	Josefsson(1985)	
8	Orgill & Hollands(1977) /	Statistical.
9	Collares-Pereira & Rabl(1979)	
10	Erbs et al(1982) /	

KEY: / = both hourly & daily versions.

Table 13.9 ACCURACY OF HOURLY PREDICTION OF DIFFUSE IRRADIANCE BY 5 STATISTICAL MODELS.(Iqbal 1983)

Date 1976	Hour end	Measured Montreal $kJ\,m^{-2}\,h^{-1}$		Percentage difference from correlation of:				
June		I_g	I_d	a	b	c	d	e
7	07.00	711	401	-39.9	-43.6	-48.2	-59.9	-45.6
10	16.00	2176	607	0.0	- 9.4	-16.9	-28.7	0.0
11	07.00	335	329	- 4.8	- 1.8	-15.2	0.0	- 1.5

KEY:
a = Orgill & Hollands (1977)
b = Erbs et al (1982)
c = Spencer (1982)
d = Boes et al (1977)
e = Iqbal (1980)

13.81 It was evident from the literature that, problems have been found in relation to all the types of insolation model considered. The theoretical models are very detailed, and work well for clear-sky conditions, but are inappropriate for general application or for all sky conditions. All of the empirical models, though developed for good reasons, have been found to be in need of improvement, somewhat inaccurate for hourly predictions, and generally unsuitable for global application. There does therefore seem to be a need for a new, simpler method, and one which is preferably physically based.

DAYLIGHT.

13.82 In view of the lack of general availability of photometric data, two aspects of the work on solar radiation and daylight are of particular interest. These concern the conversion of solar radiation measurements into photoptic measurements, and the distribution of light in the sky hemisphere.

Converting radiation measurements.

13.83 A large number of researchers have studied the relationship between solar radiation and the equivalent amount of available light(the luminous efficacy of sunlight). The luminous efficacy K is the quotient of the luminous flux by the radiant flux in lumens per Watt. Experimental values of K have been obtained by simultaneous measurements on a specified plane, for either the whole sky hemisphere, or specific parts of the sky, and for the global, or the direct and diffuse components.

13.84 As a design aid, Moon(1940) produced empirical spectral distribution curves for sunlight, which indicated an almost constant luminous efficacy of about 117 lm W^{-1} for solar altitudes greater than 25^0, decreasing to 90 lm W^{-1} at a solar altitude of 7.5^0. Whereas Pleijel(1954) analysed data for Stockholm, and reported that, the luminous efficacy of clear and overcast skies vary very little with solar altitude, but there was a marked decrease in the luminous efficacy of direct sunlight for solar altitudes less than 30 degrees. However at the same time, Blackwell(1954) used measurements for Kew to show that, for global horizontal radiation under clear-sky, average-skies, and overcast conditions, the luminous efficacies were 119 +/- 2, 116 +/- 7, and 120 +/- 5 lumens per Watt respectively (after deducting 5% for instrument calibration error). For average skies, the minimum value for this study was 105 lm W^{-1} in March to around 128 lm W^{-1} in September. Kimball had previously suggested(List 1951) a luminous efficacy variation from 100-112 lm W^{-1} with solar altitude of $15\text{-}65^0$, which was larger than that recorded by Blackwell for Kew.

13.85 Drummond(1959) recorded natural illumination and insolation data at Pretoria(latitude 25^0 45' S) for one year in 1955, and compared the results for four individual months to demonstrate a seasonal variation in luminous efficacy for different sky conditions(table 13.10) with those reported for Kew(Blackwell 1954, Blackwell & Powell 1956), Vienna(Sauberer 1956), Tashkent(Lopukhin 1953), and Washington (Jones & Condit 1948). Drummond only published mean monthly values for both clear and overcast sky conditions.

Table 13.10 Seasonal variation of luminous efficacy of daylight at selected places(Drummond 1959).

		Luminous efficacy lm / W				
Location	Sky condition	Mar	June	Sept	Dec	Mean
Pretoria 25o 45′ S	clear	106	99	103	108	104
	overcast	106	102	105	110	106
Washington 38^0 56′ N	average cloud	101	106	116	95	105
Kew 51o 28′ N	clear	112	122	129	106	117
Vienna 48o 15′ N	average cloud	122	128	122	111	121

He did however propose(figure 13.12) that, for clear-sky conditions, the higher values of luminous efficacy occurred, when the air was relatively moist and absorption of infrared radiation would have been higher. He did not however explain fully the experimental procedure used, the relationship between the insolation and daylight measurements and precipitable water soundings taken, or the method used to obtain the values plotted. Although the results for monthly means from the northern hemisphere are compared directly with those for identical calendar months at Pretoria in the southern hemisphere, no assessment was made of the effect of latitude. He attributed the relatively higher values for Kew(Blackwell 1954)in figure 13.12, to the likelihood of there being a much higher aerosol content for the atmosphere at Kew, compared to that at Pretoria, but it is unclear what the basis was for this argument.

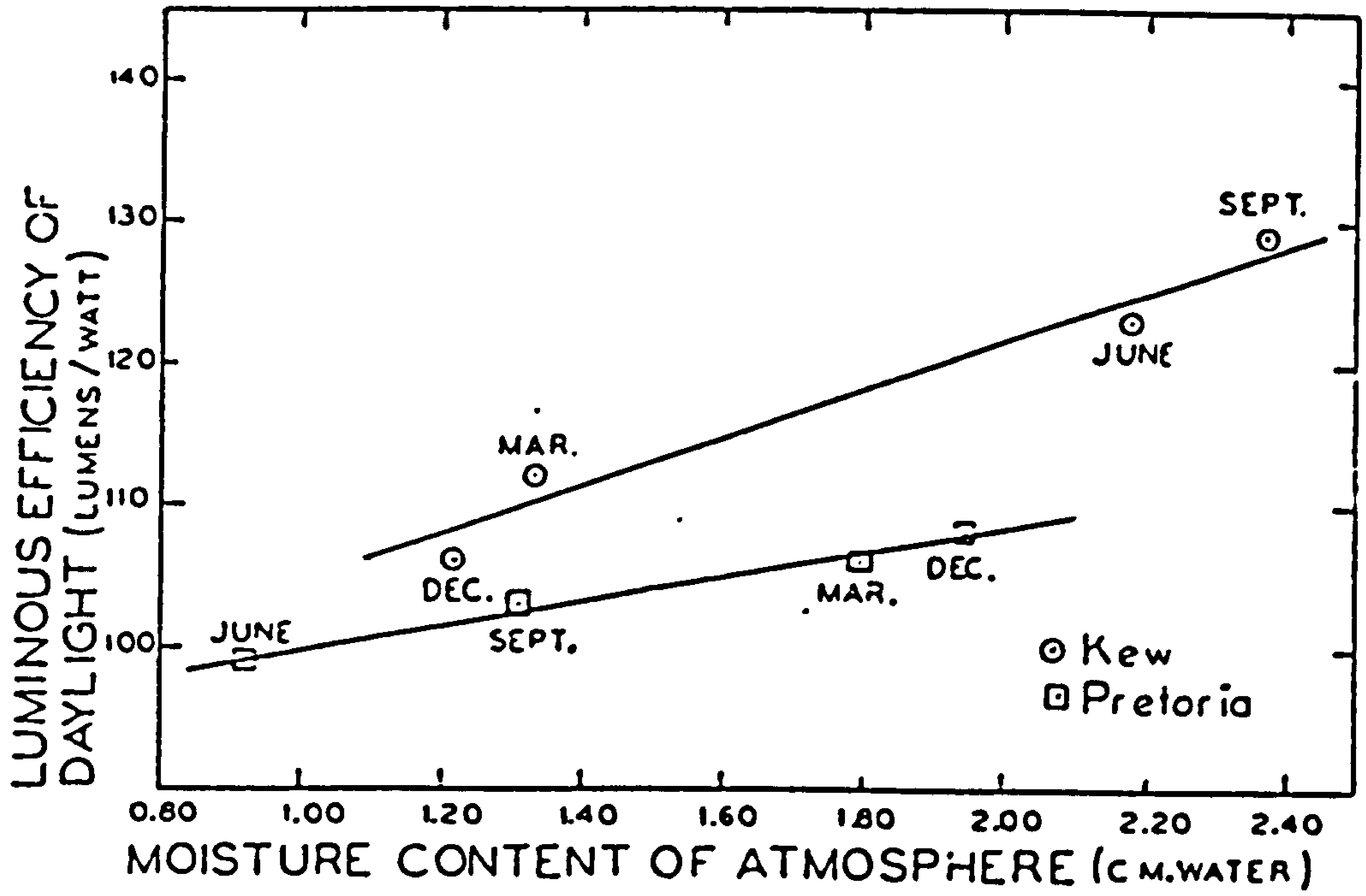

Figure 13.12 Relationship between luminous efficacy in lumens per Watt, and the atmospheric moisture content in cm of precipitable water, obtained from radio soundings(Drummond 1959).

13.86 By the early 1960's, there was renewed interest by design professionals in the assessment of daylight in buildings, and the report of the Illuminating Engineering Society (Anon 1962) contained the following luminous efficacy values:

Table 13.11 Luminous efficacy of daylight.

source of observation	lumens per Watt
Direct sunlight(solar altitude 7.5 degrees)	90
(solar altitude > 25.0 degrees)	117
(suggested mean efficacy)	100
	150
Diffuse (clear-sky)	125
(average sky)	
	115
Global horizontal	

13.87 Bennet(1962) reviewed the work of Boyd(1958) and Drummond(1959) on the relationship between daylight and solar irradiance. Commenting on the analysis of Boyd, who proposed a linear relationship between daily total global illuminance and irradiance, Bennet noted that, the data for Washington DC(figure 13.13) was the only data for which coincident radiometric and photometric readings had been taken, and that the wider study by Boyd was therefore weakened. With regard to the work by Drummond(1959), Bennet noted the use of monthly mean values, and lack of any statistical, day by day evaluation under all sky conditions, and concluded that, this work was of limited usefulness.

Table 13.12 List & type of luminous efficacy research reviewed by Littlefair(1985).

Type	By	Location
1	Anon(1984)	-
3,4	Arumi-Noe(1981)	Golden, USA
2,3,4	Ayindli(1981)	-
1	Ayindli(1984)	-
3,4,5,6	Barteneva & Poljakova(1968)	Repeteke
6	Bennet(1962)	USA
3,4,5,6	Blackwell(1966)	Kew, UK
2,3	Chandra(1980)	Roorkee, India
4	Chroscicki(1971)	Warsaw & Stockholm
2	Dognioux(1960)	Uccle, Belgium
5	Dognioux & Lemoine(1976)	-
1	Dovan & Krochman(1974)	-
3,4,5	Drummond(1958)	Pretoria, S Africa
2,3,4,5	Evnevich & Nikol'skaya(1976)	Moscow, Russia
2	Gillette & Traedo(1984)	Gaithersburg, USA
6	Goldberg & Savikoskij(1968)	Minsk, Pinsk & Vasilevici
6	Hasdemir(1984)	Ankara, Turkey
3,5	Krochman(1964)	USA
2,4	Krochman(1970)	-
2,3,4	Kuhn(1973)	Antarctic
2,3,4	Liebelt(1978)	Karlsruhe, Germany
4,5	Lofberg(1976)	Stockholm, Sweden
2,3	McCluney(1984)	-
2	Navvab et al(1983)	San Francisco, USA
5	Page(1984)	-
1,3	Page & Thompson(1982)	-
2,3,4,5	Petersen(1982)	Vaerlose, Denmark
4,5	Rattunde(1980)	Berlin, Germany
2,6	Saito et al(1983)	-
2,6	Shukuya & Kimura(1980)	Tokyo, Japan
2,4	Schultze(1970)	-

KEY: 1 = extraterrestrial; 2 = direct sunlight(clear-sky); 3 = diffuse sunlight(clear-sky); 4 = global sunlight(clear-sky); 5 = overcast sky conditions, & 6 = average.

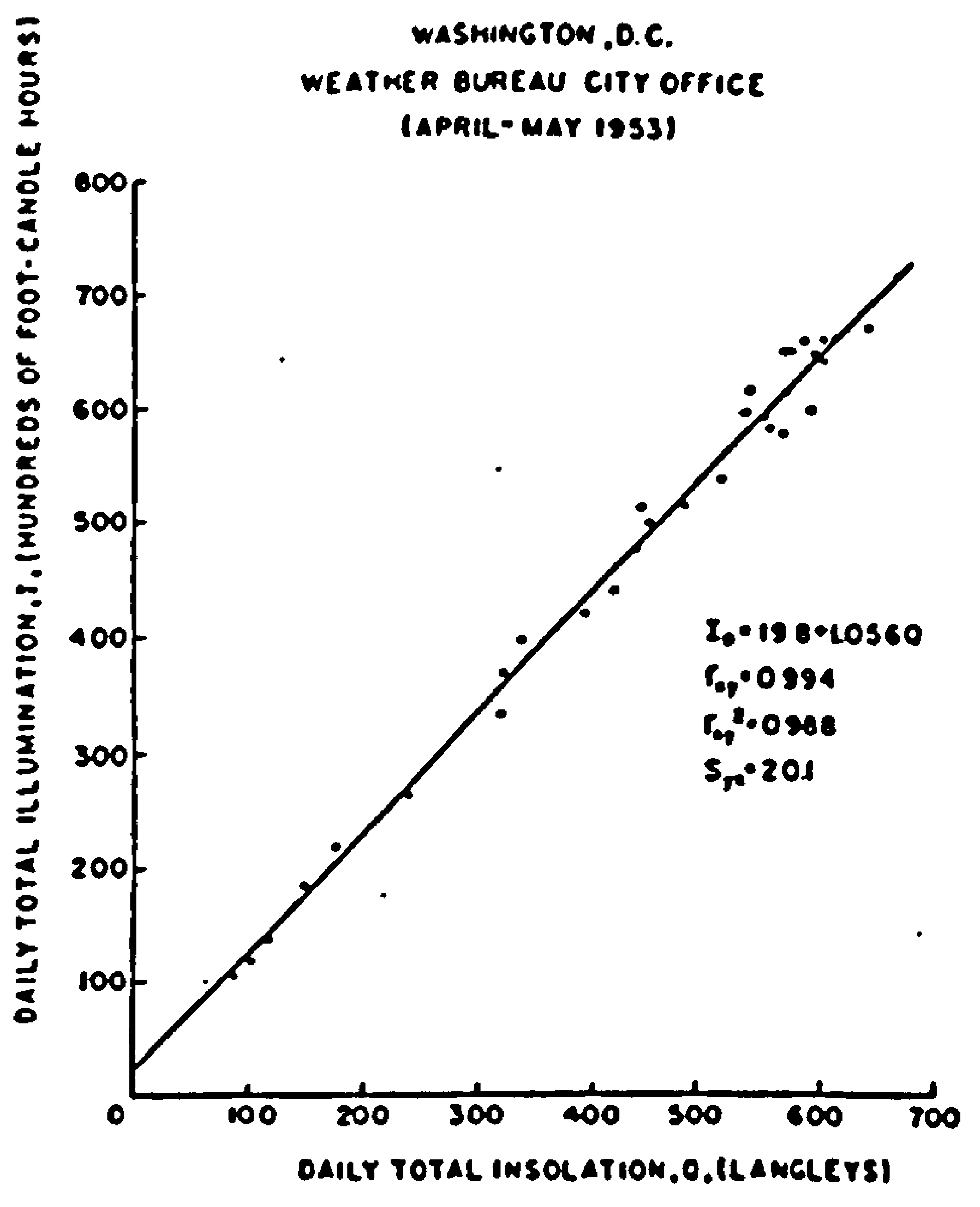

Figure 13.13 Insolation vs illumination for Washington DC.(Bennet 1962, from Boyd 1958)

13.88 Later, Littlefair(1985) reviewed the work of the various researchers on the luminous efficacy of daylight listed in Table 13.12, noting that a standard deviation error of +/- 5 to 10% would be a reasonable assumption for the global efficacy measurements reviewed. Table 13.13 lists the values for the luminous efficacy of extraterrestrial solar radiation presented by a number of researchers.

Table 13.13 Luminous efficacy of extraterrestrial radiation in lumens per Watt.

Author	reported value	correct value
Schulze(1970)	98.0	98.0
Dovan & Krochmann(1974)	87.7 *	92.7
Page & Thompson(1982)	96.8	96.8
Anon(1984), IES, North America.	94.2	94.2
Ayinli(1984)	79.8 *	97.8

KEY: * Incorrectly quoted in original paper.

13.89 With regard to the work on terrestrial values, Littlefair reported his overall conclusions that the efficacies measured varied with solar altitude. For direct sunlight, luminous efficacy increased noticeably with solar altitude(70-105 lm W^{-1}), and for diffuse skylight, the average luminous efficacies range from around 130 lm W^{-1} for clear-skies to about 110 lm W^{-1} during overcast sky conditions. Whereas global efficacies were approximately 105 lm W^{-1} for both clear-sky and average cloud conditions.

13.90 Unfortunately, although this is a very useful review paper, Littlefair does not disclose how the above figures were arrived at, and it is difficult to see how these conclusions were reached, in view of the large differences within and between the measurements of the authors of the papers reviewed in each category(table 13.14).

Table 13.14 Luminous efficacies in lumens per Watt.

	Luminous efficacy lm / W		
Source	Range reported (Table 13.12)		Littlefair (1985)
Clear-sky Direct	21-109		
Clear-sky Diffuse	84-146	+/- 14	130
Clear-sky Global	77-119	+/- 2	105
Overcast-sky	60-121	+/- 7	110
Average cloud Global	90-126		105
Average cloud Diffuse	98-129		

13.91 Littlefair's main conclusions were that:

(i) the luminous efficacy of direct sunlight exhibited the greatest variation, and increased with solar altitude, typically from 55-90 lm W^{-1} at 10^0, to 100-110 lm W^{-1} at 60^0, and should also increase with atmospheric water content, but decrease with aerosol content;

(ii) the efficacy for clear-sky diffuse light was generally higher than that of direct solar radiation, usually around 120-140 lm W^{-1}, and usually there was no obvious dependency on other atmospheric parameters, except perhaps a slight decrease with increasing solar altitude;

(iii) the efficacy for global radiation under clear-skies followed the same trend as for direct solar radiation, but with a much less marked variation, typically 95-115 lm W^{-1};

(iv) overcast skies have luminous efficacies of around 105-120 lm W^{-1}, with little or no variation with solar altitude;

(v) under partly cloudy conditions, luminous efficacy might be expected to be between the values for overcast and clear skies, and have a linear relationship with cloud ratio, and

(vi) average values of luminous efficacy lie in the range 100-115 lm W^{-1}(global), and 105-120 lm W^{-1} (diffuse), depending on climatic conditions.

13.92 More recently, Littlefair(1988)presented the results of measurements of the luminous efficacy of daylight, taken over one year at Garston, in the UK, and reported that the Garston study contained large experimental errors in respect of direct sunlight efficacies. Littlefair considered that these might mask any variation there might have been with atmospheric aerosol or water-vapour content. The errors for the efficacies measured for global horizontal sunlight at Garston were assessed as RMSE = 8%. Figure 13.14 illustrates the variation of the measured luminous efficacy of direct sunlight with solar altitude.

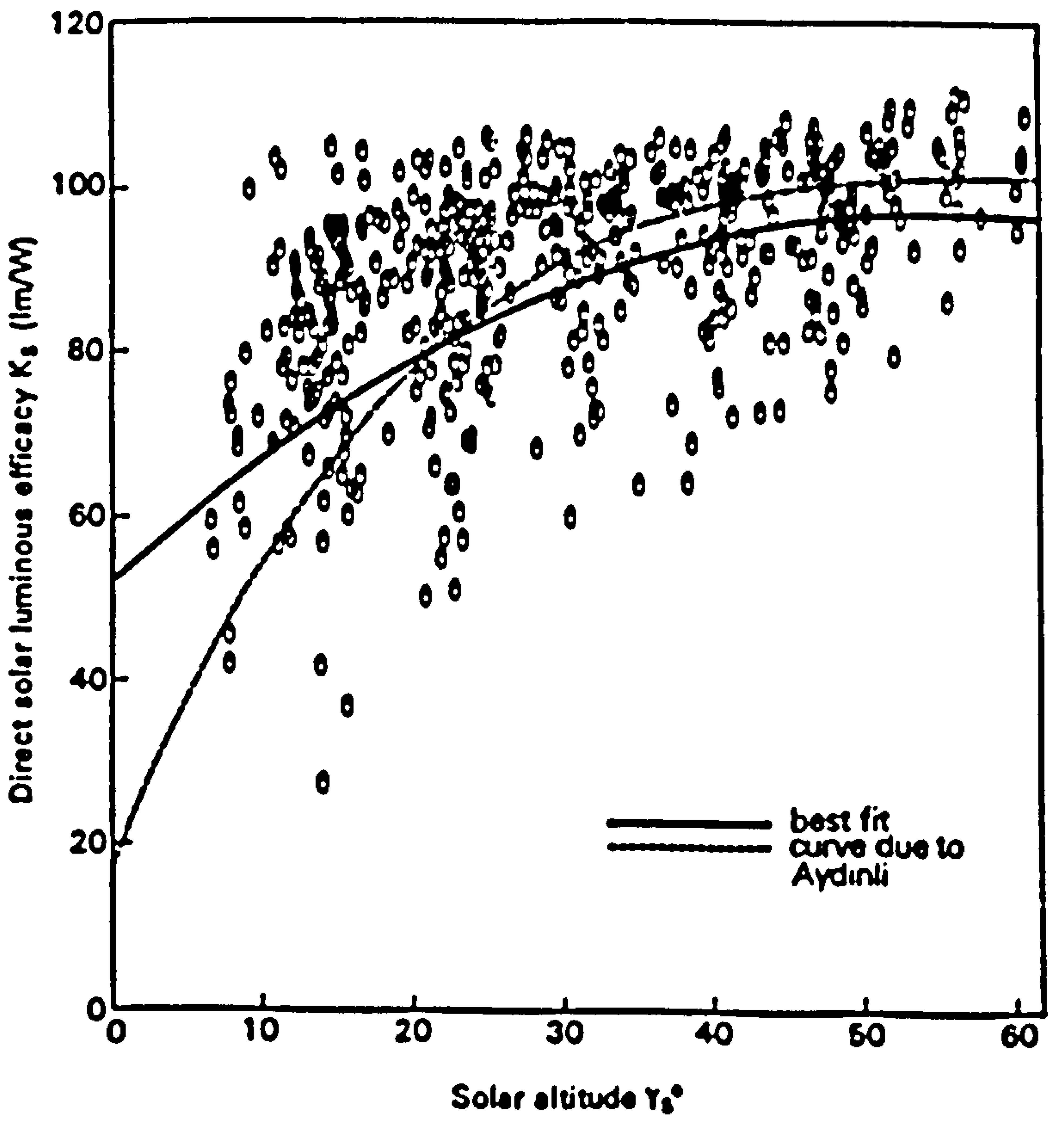

Figure 13.14 Direct solar luminous efficacies measured at Garston plotted against solar altitude.(Littlefair 1988)

The overall conclusions of Littlefair's review have been compared(table 13.15) with his more recent UK study.

TABLE 13.15 Luminous Efficacy of Daylight in lumens per Watt.

Luminous efficacy of daylight lm / W		
observation	1985 review	1988 UK study
direct sunlight with solar altitude	70-105	
direct(solar altitude of 10^{0} - 60^{0})		70-95
diffuse sunlight for clear-skies	130	144
diffuse sunlight for overcast skies	110	115
global sunlight for clear-skies	105	107
global sunlight for average-skies	105	109

13.93 Although a number of studies of luminous efficacy at various locations around the globe were reviewed, it was apparent that there does not yet seem to be a standard solution to this problem. It seems clear that the results on the assessment of extraterrestrial luminous efficacy are reasonably consistent, whereas the terrestrial results are inconsistent, and recorded values are known to vary with season, sky condition and with the hour of day, to a variable extent, depending on sky condition. This particular research into terrestrial values of the luminous efficacy of sunlight has concentrated on the analysis of empirical data, and not on the development of a suitable physical model.

Sky luminance models.

13.94 On the question of the variation in the luminance of the sky hemisphere, measurements have of course been taken since the early part of the century(Kimball & Hand 1921), and as Hopkinson(1966) pointed out, the measurements taken up to the early 1960's in this type of study confirmed the accuracy of the formula of Pokrowski(1929) for the prediction on cloudless days of the relative illuminance distribution of the clear-sky. Pokrowski obtained an approximate solution, by applying the principles of Rayleigh scattering of light, and allowing for secondary scattering by larger particles such as atmospheric dust. His formula gives:

$$E_\gamma \propto E_z\left(1 - e^{\left(-\frac{\rho_1}{\sin\gamma}\right)}\right)\left[\frac{1 + \cos^2\theta}{1 - \cos\theta} + \rho_2\right] \qquad [13.47]$$

where:

E_γ = *luminance at elevation above horizon. lux*
E_z = *luminance at the zenith. lux*
θ = *angular distance of point: sun.*
ρ_1 = *primary scattering coefficient* = 0.32.
ρ_2 = *secondary scattering coefficient (varies: dust content)*

Measurements taken indicated values of p2 in the range 0 to 5. Hopkinson(1954) compared the measured clear-sky values for Stockholm with the prediction using Pokrowski's formula(figure 13.15) and reported good agreement. Kittler(1965) amended Pokowski's formula to give an improved diffusion indicatrix:

$$E_\gamma \propto E_z\left(1 - e^{\left(\frac{-\rho}{\sin\gamma}\right)}\right)(0.91 + 10e^{(-3\theta)} + 0.45\cos^2\theta) \qquad [13.48]$$

and this resulted in a more accurate prediction of the luminance distribution of the bright aura in the vicinity of the sun, and formed the basis of the CIE clear-sky luminance model.

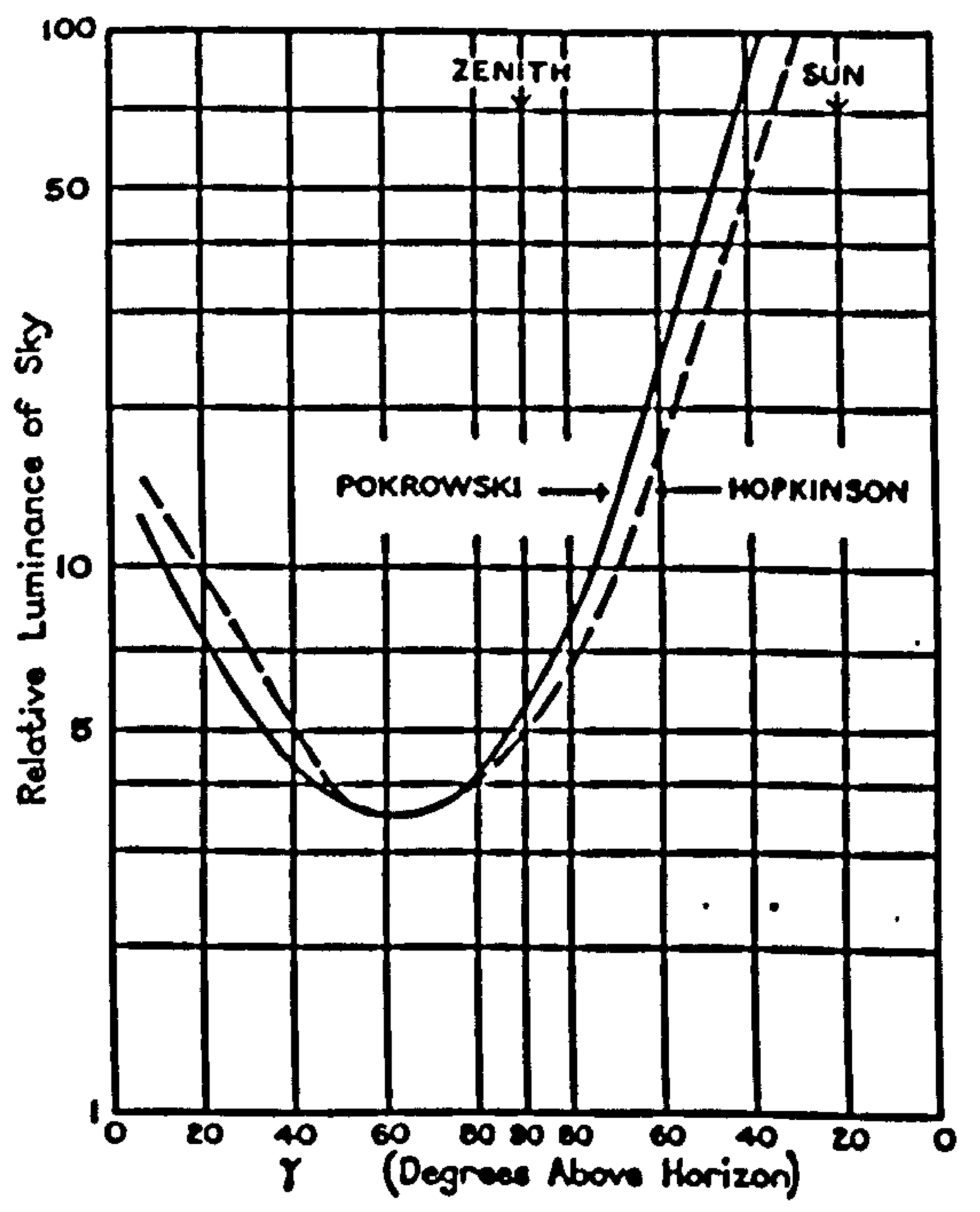

Figure 13.15 Comparison of the blue-sky luminance measured at Stockholm along a great circle through the zenith and sun with that predicted by the Pokrowski formula.

13.95 The measurements made around the globe under a fully overcast sky demonstrated that the luminance distribution for this sky-condition also conformed to a pattern. The brightest part of the sky was at the zenith, and the luminance decreased to the horizon, where the level recorded was about one third of that at the zenith. Moon & Spencer(1942) proposed a formula to determine the sky luminance at any angle of elevation:

$$E_\gamma = E_z\left(\frac{1 + 2\sin\gamma}{3}\right) \qquad [13.49]$$

where:

E_γ = *luminance at the ∠ of elevation* lux
E_z = *luminance at the zenith* lux
γ = *∠ of elevation*

13.96 Their formula lacked any allowance for the effect of ground albedo, the need for which was later clearly demonstrated by Fritz(1955), and confirmed empirically by Petherbridge(1955). However the Commission Internationale de l'eclairage (CIE), adopted it, unamended, as the standard overcast sky(Anon 1955), which was then used in the method of assessment of daylight in buildings, which was fully described by Walsh(1961), and Hopkinson et al(1966).

Table 13.16 Models reviewed(Littlefair 1993)

No	Model	Reference/note
1	CIE clear-sky model	Kittler(1967), Anon(1973b)
2	CIE overcast-sky	Hopkinson et al(1966)
3	Gusev clear & CIE overcast	Anon(1973b)
4	Quasi clear & quasi overcast	Littlefair(1993)
5	ASRC/ CIE	Perez et al(1990),(1992) [combines 1, 2, 3 with that of Nakamura et al(1986)]
6	Perez all-weather sky	Perez et al(1990),(1993)

13.97 Littlefair(1993) used measured data to evaluate six models, by the authors listed in Table 13.16, which were designed to predict the hourly variation of sky luminance distribution. He found that the sunny skies in the UK appeared to be more anisotropic than the standard CIE clear-sky model, and models 3, 4, and 5 performed best. There were substantial predictive errors found in many of the models tested, and Littlefair suggests that the results of the current CIE sky luminance measurement programme should enable luminance models to be further developed and tested.

Conclusions arising from this review of the literature.

13.98 Overall, it appears from the literature that:

(i) there are satisfactory methods of calculating the solar position, and the optical path length of the atmosphere for solar radiation;

(ii) empirical methods of measuring atmospheric attenuation due to water-vapour, clouds and aerosol involve a large degree of uncertainty;

(iii) although very complex, the physical models of monochromatic solar beam radiation transfer in a Rayleigh clear-sky atmosphere work well, but the problem has not been solved in this way for all sky conditions;

(iv) empirical insolation models abound for both clear-sky and all-sky conditions, and of these the statistically based models have been found to be the most accurate, but they have a marked latitude dependence and an unacceptable degree of error in terms of hourly predictions;

(v) there is no satisfactory, simple, physically based model, which has universal application, to enable the solar global horizontal irradiance, and its direct beam and diffuse components to be predicted with reasonable accuracy on an hourly basis;

(vi) although there is no agreed international standard for the luminous efficacy of solar radiation, the studies on extraterrestrial solar radiation have provided reasonably consistent results;

(vii) the studies of the luminous efficacy of sunlight at the Earth's surface have resulted in a wide range of results;

(viii) a number of sky luminance distribution models are available for various sky conditions, and the CIE is currently engaged on a detailed programme of sky luminance measurement in an effort to provide better information, and improved modelling, since the present information and models are not yet considered entirely satisfactory, and

(ix) there is as yet no satisfactory method available to enable reasonably accurate predictions to be made of the level of daylight to be obtained from broadband measurements of solar irradiance, for any location, season, and time of day.

13.99 Consequently research has been undertaken in the present study to ascertain the viability of developing a fundamental, but simple, theoretically based approach to predict both the components of global horizontal solar irradiance and the amount of daylight available for clear-sky conditions, and to examine the possibility of using global horizontal irradiance measurements to determine the diffuse and direct beam components of irradiance for other sky conditions.

14.0 THEORY.

Variation of extraterrestrial solar radiation.

14.1 From the review of the literature it was clear that, the amount of solar radiation, which reaches the atmosphere of the Earth in the course of one orbit of the Sun, is known to vary sinusoidally during the year, as a function of the geometry of the Earth's orbit around it. There is also a diurnal variation, which is a function of the rate of rotation of the Earth, the latitude of the location, and the continuously changing orbital declination. This local variation can be represented as a function of the cosine of the zenith distance, which varies with time. The three factors which cause the variation relative to a particular location on Earth are therefore: latitude; orbital geometry, and the zenith distance for the time on a particular day.

Atmospheric attenuation.

14.2 The amount of extraterrestrial solar radiation is reduced by the effects of the atmosphere of the Earth. For clear sky conditions, the extinction is caused by the scattering of incoming radiation by air molecules and aerosol particles(haze and dust), the effects of reflection(albedo), and selective absorption. During other weather conditions, depletion of the solar radiation also occurs due to the effects of water vapour, and cloud.

Models required.

14.3 Since the effect of location, orbital geometry and time can already be modelled to a range of accuracies to suit most applications, the problems, which have still to be resolved are:

(i) how to model the clear-sky attenuation of direct beam solar radiation by the atmosphere in a simple way, which has a physical basis and permits the components of insolation to be quantified;

(ii) how, for other sky-conditions, to extend the scope of the model to one which only depends on the need to measure global horizontal irradiance to allow an approximate prediction of the diffuse and direct beam components of irradiance , and

(iii) how to determine the amount of daylight available using such a model.

Considerations for a simple physical model.

14.4 Consider a unit of thickness of the atmosphere. If the fraction of radiation transmitted through one unit is τ, then the fraction transmitted through an atmosphere of two units thickness is represented by τ^2, and four units of thickness by τ^4. Therefore, the variation of transmissivity with optical path length is exponential in character. The fact that the Earth is roughly spherical, and spins on an axis which is tilted in relation to the plane of the Earth's orbit around the Sun, results in a significant variation in the geometric thickness of the atmosphere during the course of a day, and from season to season, in relation to the angle of incidence of sunlight. In terms of the atmosphere of the Earth therefore, the path length is usually defined relative to the thickness of the atmosphere at the zenith. This atmosphere thickness depends on latitude, making this parameter of great significance for the development of a universal model. The effect of latitude and orbital geometry on relative optical air mass is illustrated in Appendix C. The effects of the curvature of the Earth and refraction also become increasingly significant in determining the path length of the solar radiation, according to whether the sun is close to the position directly overhead(zenith), or on the horizon. The clear-sky atmospheric attenuation, or extinction of solar radiation for any specific location, should therefore be directly in proportion to the changes in the path length through the atmosphere, which occur throughout each day, and from season to season, as a result of the rotation of the Earth and the combined effect of spherical and orbital geometry. The overall effect of atmospheric attenuation can actually be ascertained by comparing surface measurements with the calculated incident extraterrestrial irradiance.

14.5 In reality the atmosphere is not of course homogeneous. It is however common for it to be modelled as a plane parallel atmosphere with layers of different density and infinite lateral extent, because the depth of the atmosphere is relatively small compared to the radius of the Earth. It is also usual to assume that the incident radiation is a parallel beam, since the Earth is such a great distance from the Sun. These assumptions greatly simplify calculations. Now suppose that the layers of such an atmosphere have the characteristics of a grey gas in terms of radiative transfer, and consider the intensity of a monochromatic beam of radiation incident on a layer of the plane parallel grey gas atmosphere of thickness dx(Figure 14.1). Then it might be reasonable to define the decrease in intensity of the radiation transmitted through the layer by an extinction coefficient due to absorption by the gas layer. Assuming that the gas layer was uniformly absorbing throughout its thickness, this could be written as:

$$dI_\lambda = -k_\lambda I_\lambda \, dx \qquad [14.1]$$

where:

k_λ = *the monochromatic absorption coefficient.*

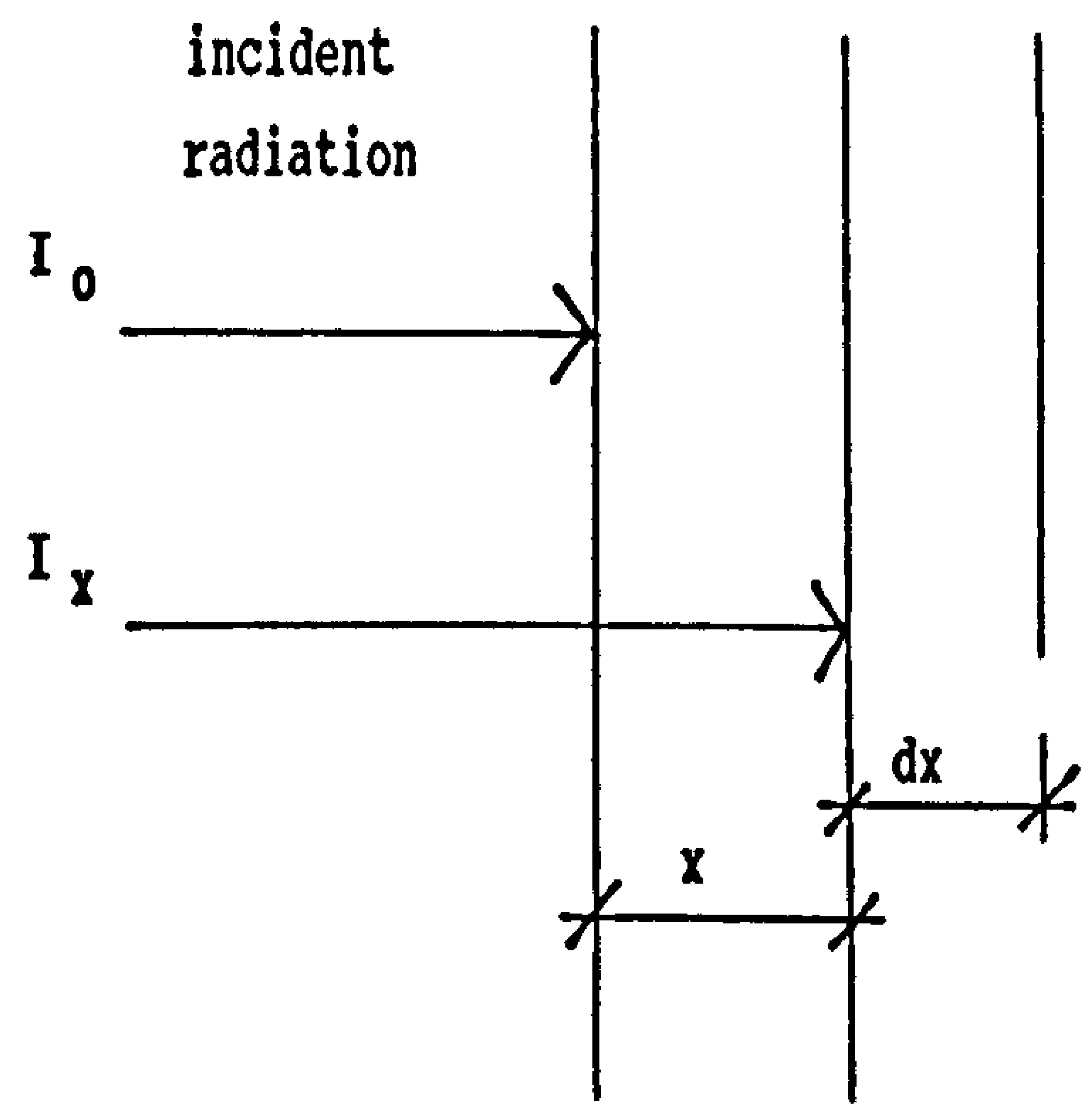

Figure 14.1 Absorption of radiation by grey gas layer.

14.6 It might also be reasonable to assume that the equation could be integrated between the distance limits o and x to give:

$$\int_{I_{\lambda o}}^{I_{\lambda x}} \frac{d I_\lambda}{I_\lambda} = \int_o^x - k_\lambda \, dx \qquad [14.2]$$

and therefore

$$\frac{I_{\lambda x}}{I_{\lambda o}} = e^{-k_\lambda dx} \qquad [14.3]$$

with

$$I_{\lambda x} = I_{\lambda o} \, e^{-k_\lambda dx} \qquad [14.4]$$

and, since the transmittance of a medium is defined as the ratio of energy transmitted to that incident upon it, the transmittance is given by:

$$\tau_\lambda = e^{-k_\lambda dx}$$ [14.5]

14.7 Clearly, for the Earth's atmosphere, the thickness of the gas layer relative to the equivalent thickness at the zenith will directly affect the amount of radiation transmitted, so equation 14.5 is written as:

$$\tau_\lambda = e^{-k_\lambda m_r}$$ [14.6]

14.8 In considering a grey gas application, it is usual to assume that the radiation, which is not transmitted is absorbed by the medium, so that

$$\alpha_\lambda = 1 - \tau_\lambda$$ [14.7]

14.9 the following problems occur in relation to equation 14.7 if applied to this application:

(i) Equations 14.6 and 14.7 are simply an application of the Beer-Bouguet-Lambert's law, which is appropriate for a condition where absorption takes place, but not scattering, and

(ii) whilst these expressions are for monochromatic radiation, and might reasonably also apply to radiation in a waveband over which the extinction coefficient k is constant, or for the case of single scattering, because the concentration of scattering centres is so small that a quantum is unlikely to be intercepted more than once, they do not apply either to the broadband of the solar constant spectrum, or in the case of multiple scattering.

14.10 In considering the transmittance of the atmosphere of the Earth, there is a need to address the probability that, the condition of multiple scattering will occur and should be accounted for, and that extinction coefficient (k) is unlikely to remain constant. However the treatment of multiple scattering is very complex, because an allowance must be made for scattering in all directions, backwards as well as in the forward direction of the beam irradiance, and if k depends on the beam direction, then the angular distribution and polarisation of the scattering must also be taken into account. This very intricate problem was solved by Chandrasekhar(1950), with the angular distribution of scattering being defined in terms of the Stokes parameters. Such detail is inappropriate in a simple model, and an alternative way of considering the effect of multiple scattering is required.

14.11 Consider a very much simplified case for multiple scattering, where k is independent of the beam direction, and the attenuation coefficient is therefore expressed as a function of a scattering-reflection coefficient (ρ), to represent the probability of an intercepted quantum being reflected, and the extent of the resultant back-scatter, assuming that half of the intensity of the incident radiation will be reflected backwards, and half forwards(Kimball 1935). Then the probable absorption after the first scatter could be expressed as:

$$\alpha_\lambda = (1 - 2\rho) - e^{-k_\lambda m_r} \qquad [14.8]$$

and after N orders of scattering as:

$$\alpha_\lambda = (1 - 2\rho)^N - e^{-k_\lambda m_r} \qquad [14.9]$$

In such a case of multiple scattering, the transmittance of the incident beam becomes:

$$\tau_{\lambda b} = e^{-k m_r} = (1 - 2\rho)^N - \alpha \qquad [14.10]$$

the scattered diffuse transmittance is given by:

$$\tau_{\lambda d} = (\rho)^N - \alpha_d \qquad [14.11]$$

and global horizontal transmittance is then given by:

$$\tau_g = \tau_b + \tau_d \qquad [14.12]$$

14.12 In the context of assessing this approach to modelling it may be possible to use a simplistic check. On the assumption that the experimental results for normal incidence reported by Feynman(1985) on the probability of the reflection of a photon of light by molecules are applicable to this case, suppose that when solar radiation is incident on a layer of atmosphere of unit thickness that, on average, the probability of broadband Rayleigh scattering was between 3 and 4% at normal incidence. Since the effect of very high orders of scattering are less significant, assume that the multiple scattering which occurs can be represented to say up to four orders of scattering, and that about one half of the Rayleigh scattered radiation is directed out to space, and the remainder is available to be received on Earth as diffuse radiation or partly absorbed, and that equations 14.10, and 14.11, have been integrated for all wavelengths. On the basis of these assumptions, the estimated clear-sky transmittances given by equations 14.10 to 14.12 would of the order of:

$$\begin{aligned} \tau_b &= 0.867 - \alpha_b \\ \tau_d &= 0.068 - \alpha_d \\ \tau_g &= 0.935 - (\alpha_b + \alpha_d) \end{aligned} \qquad [14.13]$$

The emissivity of long wave radiation by the atmosphere due to absorption of radiation is ignored in this model for shortwave radiation. On the stated assumptions therefore, about 6.8% of the incident shortwave radiation would be expected to be reflected out to space as a direct result of Rayleigh scattering, which is not dissimilar to the 6.9% reported by Coulson(1959), or after allowing fully for absorption, the 6.22% mean broadband value integrated over all the angles of incidence reported by Lacis & Hansen(1974), and the 6.5% reported by Houghton(1986) with a resultant 13% attenuation of the beam radiation for the atmosphere of unit thickness. This suggests that the basic assumption of the method about the separate allowance made for scattering and absorption, and the simple approximation used here might be reasonable.

14.13 For a Rayleigh clear-sky, the absorption effect is mainly confined to the ultraviolet end of the spectrum, which though important and involving high energy quanta, contains only a relatively small proportion(8.03%) of the total energy of the extraterrestrial solar spectrum. Absorption is relatively slight(1%) in the infrared part of the spectrum, under these assumptions about the atmosphere, but it can be significant, because almost half(46.4%) of the total energy of the solar constant value is represented in this part of the spectrum. The broadband integrated value of the absorption coefficient appropriate in the assumed circumstances is therefore likely to be small(3.7%), and equation 14.13 would give global transmittance as 0.898 and thus an extinction coefficient (-k) of -0.102 since:

$$k = 1 - \tau_g \qquad [14.14]$$

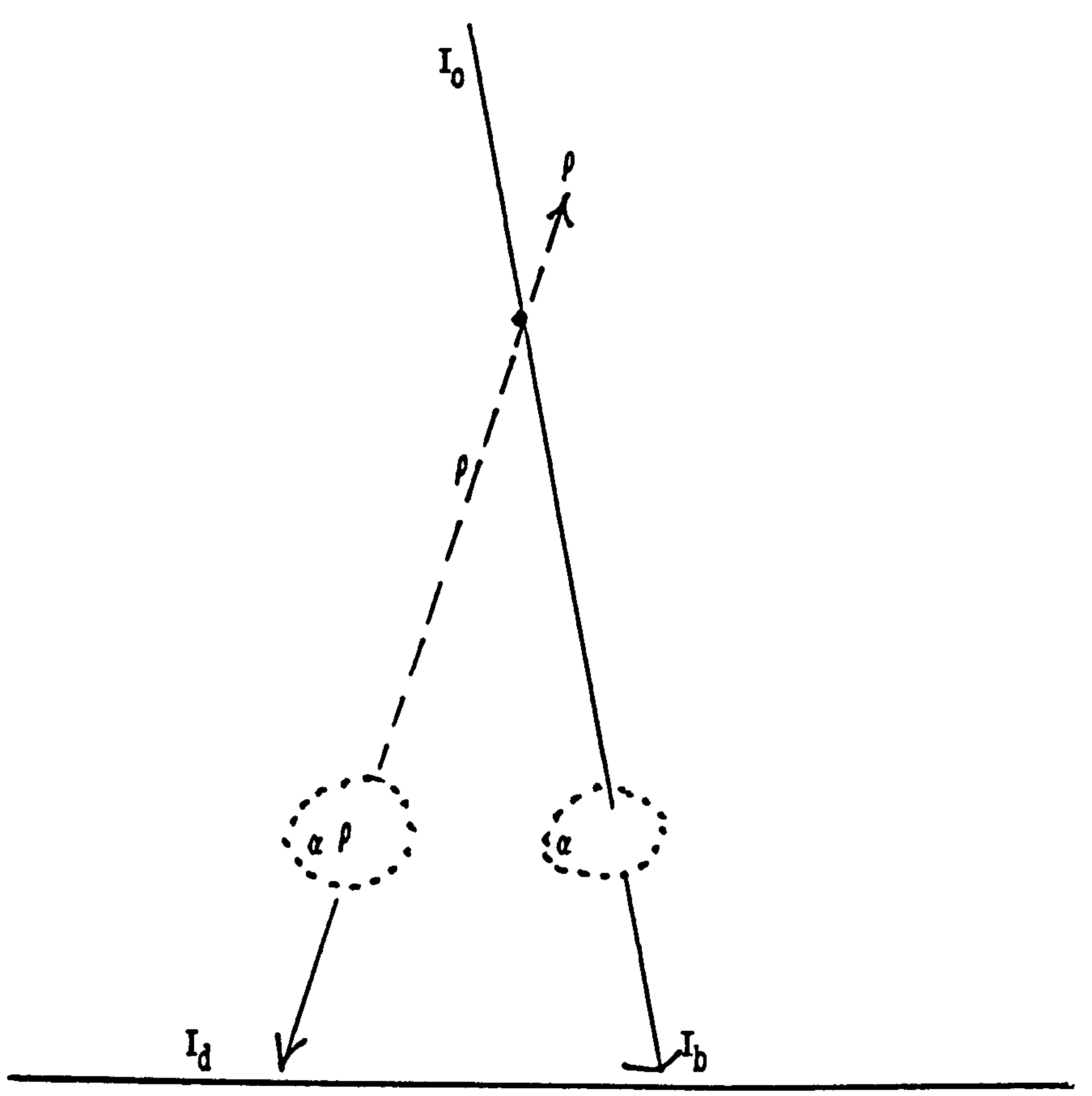

Figure 14.2 Diagram of a simple model of clear-sky atmospheric scattering, absorption and transmittance.

14.14 The obvious problems here are, the assumption concerning a broadband assessment of the probability of scatter, the simplistic treatment of the limiting case of Rayleigh scattering using a fixed reflection coefficient, which is neither properly related to the angle of incidence, nor representative of normal sky conditions, and the need to establish the broadband absorption coefficient for the appropriate sky condition at the time in question. The scope of such a model therefore needs to be extended in order to deal effectively with broadband scattering and absorption for all forms of scattering and sky conditions. In the literature such models have tended to employ empirical relationships for separate atmospheric processes. The difficulties created by that approach have resulted in the introduction of large degrees of uncertainty, and the development of overly-complex, quasi-physical models, which appear to display a degree of latitude dependence. Alternative statistical relationships have been studied and correlations produced, which were found to outperform other types of model, but nonetheless have significant inaccuracy and latitude dependence, as confirmed by the validation study of Davies et al(1988).

14.15 For clear-sky conditions, the expression of Lacis & Hansen(1974) provides a correlation relating to a geometrically based method of calculating the atmospheric albedo for solar radiation in relation to the angle of incidence as follows:

$$\rho = \frac{0.28}{(1 + 6.43\cos\theta_z)} \qquad [14.15]$$

14.16 This approach may possibly overcome the problem of determining the variable value of the scattering-reflection coefficient in relation to the angle of incidence, but the effect of increased path length would also need to be taken into account. Cloudy conditions would be much more difficult to model, but the broadband transmittance of the atmosphere under all conditions of scattering and weather can be readily calculated from the ratio of global horizontal irradiance observations to the predicted equivalent extraterrestrial irradiance. It is probably reasonable to assume that the boundary conditions are likely to be represented by the clear-sky and the overcast-sky. In view of the general availability of global horizontal irradiance measurements, it may be an advantage if this physically based approach to simple modelling for clear-sky conditions could be modified to take account of apparently clear-sky conditions and the available global horizontal irradiance observations for both cloudy and overcast conditions. The clearness index (Kt), given by Ig/Io is an indication of the transmittance of the atmosphere. It is presumably reasonable to assume that the diffuse transmittance during overcast-sky conditions is represented by Kt, when Kt < 0.5, and therefore that under these conditions the diffuse ratio would be approximately equal the clearness index, giving:

$$K_t = \frac{I_g}{I_o} \approx \frac{I_d}{I_o} \qquad for\ K_t \le 0.5 \tag{14.16}$$

The questions to consider, arising from this assumption, are whether equation 14.16 can be shown to be reasonably correct for an overcast-sky, and also to provide an approximate prediction of the diffuse ratio within this range of the clearness index under cloudy conditions. Similarly, one might assume that if the clear-sky condition represents the upper boundary condition, then for more normal sky conditions, the value of Kt might be incorporated into an equation based on apparently clear-sky conditions in order to obtain an approximate value of the diffuse ratio.

Proposed simple model.

14.17 Suppose therefore a possible simple broadband model having the relationship of the form:

$$\tau_{gm} = A\,e^{-k\,m_r} \tag{14.17}$$

where:

$$\tau_{gm} = \frac{I_g}{I_o} \quad for\ varying\ optical\ path\ length\ m_r \tag{14.18}$$

and the coefficient A is a scaling factor, based on the transmittance of radiation in a clean dry Rayleigh atmosphere with an air mass of unity. The extinction coefficient (k) relates to the total depletion of the incident radiation from scattering and absorption for the same atmosphere. The value of the scaling factor A would be expected to vary from the combined effects of changing angle of incidence and absorption due to the varying path-length. Similarly the extinction coefficient k should vary in relation to both the effect of scattering and absorption. The coefficients A and k of Equation 14.17 could therefore be defined as:

$$A = 1 - \rho - (\alpha_b + \alpha_d)\,m_r \tag{14.19}$$

$$k = \rho + \alpha_b + \alpha_d \tag{14.20}$$

On the stated assumption that the atmospheric albedo due to back-scattering of shortwave solar radiation for clear-sky conditions is equal to that scattered in the forward direction and included in global horizontal irradiance, then:

$$I_o = I_g + I_d + \alpha_d + \alpha_b \qquad [14.21]$$

and under these assumption the diffuse fraction of the global clear-sky irradiance might reasonably be estimated by:

$$\tau_{dm} = 1 - B - \tau_{gm} \qquad [14.22]$$

$$\text{where:} \quad B = \alpha_b + \alpha_d \approx \alpha_b + \alpha_b\rho$$

14.18 The value of the coefficients A and k in equation 14.17 can be calculated from equations 14.19 and 14.20 respectively, using the assessment of absorption given in paragraph 14.13, which was derived from the published data on the solar constant(Fröhlich & Brusa 1981, Iqbal 1983). This should give the predicted clear-sky conditions for global transmittance, with that for diffuse irradiance being obtained from equation 14.22. It would however be rare for the normal sky condition to be truly clear, due to increased absorption and scattering arising from the presence of water-vapour in the atmosphere, even when it appears to be clear. This is difficult to quantify, but coefficient A might then give a more realistic prediction of apparently clear-sky conditions having Kt <= 0.8, if it were based on the clear sky transmittance of beam irradiance from equation 14.13 as follows:

$$\tau_{gm} = (\tau_{bm} - \rho - (\alpha_b + \alpha_b \cdot \rho) \cdot m_r) \cdot e^{(-(\rho + \alpha_b) \cdot m_r)} \qquad [14.23]$$

14.19 To be more generally applicable, the model must also be able to deal with cloudy and overcast sky conditions. If continuous observations of global horizontal irradiance are available it might be preferable to use the relationship in equation 14.16 for Kt <= 0.5, and a scaling coefficient for equation 14.17 obtained from the mean of the calculated coefficient A for apparently clear-skies [eqn 14.23] and the clearness index, to allow in part for the measured effect of increased absorption and scattering by clouds, so that for 0.7 => Kt => 0.5, equation 14.23 becomes:

$$\tau_{gm} = \left(\frac{\frac{I_g}{I_o} + (\tau_{bm} - \rho - (\alpha_b + \alpha . \rho) . m_r)}{2} \right) . e . ^{(-(\rho + \alpha_b) . m_r)} \qquad [14.24]$$

Sometimes, observation sequences are not continuous. In such circumstances it should be possible to use the following curve fitting procedure to estimate the global and diffuse transmittance actual sky conditions. The values of A and k may be found by calculating the value of τ_{gm} for two different relative optical path lengths, using observed values of I_g. Then since:

$$\ln \tau_{gm} = \ln A - k m_r \qquad [14.25]$$

and for two different values of m_r : m_{r1} m_{r2}

$$\ln \tau_{gm_1} = \ln A - k m_{r_1}$$
$$\ln \tau_{gm_2} = \ln A - k m_{r_2} \qquad [14.26]$$

the value of k can be found by eliminating ln A so that:

$$\ln \left(\frac{\tau_{gm_1}}{\tau_{gm_2}} \right) = -k \, (m_{r_1} - m_{r_2}) \qquad [14.27]$$

and then ascribing values of τ_{gmr1} and τ_{gmr2}, at two relative optical air masses. It would be best if one value of τ_{gm} could calculated from the value of K_t measured for the m_r with a value in the range $m_r = 2$ to $m_r = 4$, and if this could be used for the calculation of the coefficient A, since this is the optimum range for calculating atmospheric extinction suggested by Young(1974). The other can be taken for the relative air mass at solar noon. The value of A is then obtained by substituting the resultant value of B into equation 14.17.

14.20 This clear-sky irradiance model has the physical and geometric basis necessary to represent the changing transmittance of the atmosphere during the day for any season and location. However, since no allowance has been made for the curvature of the Earth, it should only be possible to use the model universally with reasonable confidence for zenith distances up to 60 degrees or possibly 70 degrees for clear-sky conditions, and for other sky conditions, providing global horizontal irradiance observations are available. The diffuse transmittance for the curve fitted global transmittance is then given by:

$$\tau_{dm} = A - k - \rho - \tau_{gm} \qquad [14.28]$$

14.21 The expressions developed for the diffuse fraction enable approximate values of the components of the global irradiance on a horizontal surface to be obtained for any sky condition from:

$$\frac{I_g}{I_o} = \frac{I_d}{I_o} + \frac{I_b}{I_o} \qquad [14.29]$$

14.22 The amount of daylight available can be similarly ascertained in Watts m^{-2} or in lux, using appropriate photoptic meters for the visible wave-range, and equivalent values for the extraterrestrial intensity constant for the mean Sun-Earth distance. In the absence of such instrumentation, the luminous efficacy of daylight would need to be used, and it would be helpful if this could be established on an internationally agreed basis. There should be a linear relationship between the values of τ_{gm} for the broadband and $\tau_{gm\,(vis)}$ for the visible spectrum.

Hypotheses.

14.23 The hypotheses to be tested therefore are that:

(a) the characteristic diurnal distribution of the fraction of the solar radiation available outside the atmosphere, which is received at the surface of the Earth, under clear-sky conditions should be expressed as an exponential curve, having the form $\tau_{gm} = A.e^{-k.m_r}$;

(b) the fraction of the total irradiance received at the surface of the Earth which is diffuse radiation, might reasonably be approximated as $\tau_{dm} = 1 - B\,m_r - \tau_{gm}$;

(c) the diffuse transmittance should be approximately equal to the global transmittance under fully overcast-sky conditions, and

(d) the relationship between the fraction of total solar radiation r_{gm} and the equivalent fraction received in the visible spectrum should be linear.

Timing considerations for the empirical test of the hypotheses.

14.24 The proposed model is required for use with hourly weather data. Hourly values of solar irradiance are usually based on either the mean or the integrated value of measurements recorded at five minute intervals of time. In order to test the validity and feasibility of using such a simple physical model, it was considered necessary to employ instantaneous rather than integrated or mean values of irradiance, and to take measurements in relatively short time-steps in order to record the true dynamics of the atmosphere. For an observation sequence using one minute intervals of measurement, timing is clearly very significant. Two problems associated with using observations recorded at intervals of time of one minute duration considered were:

(i) the feasible order of accuracy for determining the solar position and time relative to the location, and

(ii) the order of accuracy of the time keeping device used to initiate and maintain the observation sequence for the experiment.

Various time scales are used in the literature concerning the calculation of the solar position and time in relation to a location on Earth.

Time scales.

14.25 The internationally agreed standard time, which provides a uniform and precise timescale for scientific purposes, is known as the International Atomic Time(TAI). For everyday activity, it is obviously more convenient to use a system of time that corresponds to night and day, and the unit of time, which is based solely on the rotation of the Earth is known as Universal Time(UT). However, as the rate of rotation of the Earth is not uniform, the difference between TAI and UT is increasing irregularly by about one second every eighteen months or so. The standard, which is therefore universally accepted for civil time, relates to time on the prime meridian, and is now known as Co-ordinated Universal Time(UTC). UTC is an atomic timescale, used for most broadcast time signals, which is kept in close agreement with UT(less than one second), by the introduction of leap seconds to UTC. This usually occurs at the end of June or December. The difference between UTC and TAI is thereby always arranged to be at an integral number of seconds. The time used in this study for the local mean time at the prime meridian(Greenwich) was UTC.

14.26 It is necessary to take account of the relativity effect for work relating to the solar system dynamics in astronomy, because time is used as an independent variable in the high-precision equations of the motion of the bodies of the solar system, depending on the co-ordinate system to which the equations refer. Terrestrial Dynamical Time(TDT) is used in the Astronomical Almanac(Anon 1992) as the timescale on which the apparent positions are given of the Sun in relation to the centre of the Earth(Geocentric). TDT differs from TAI by a constant offset. In 1991, the International Astronomical Union(IAU) adopted timescales, which all have units of measurement consistent with the SI second. Terrestrial time(TT) is the new scale, which replaced TDT, but can be considered to be equivalent to TDT. The tabulated values and expressions in the astronomical almanacs used in this study relate to TDT and UT.

14.27 There is also a difference between the standard local mean time and solar time, which varies throughout the year in a smooth, periodic, fashion, mainly due to the eccentricity of the Earth's orbit around the sun and the obliquity of the plane of orbit to the plane of the equator of the Earth. The magnitude of this difference ranges from plus sixteen minutes and nineteen seconds to minus fourteen minutes and fourteen seconds(Figure 14.1). As was evident from the literature review, for observations recorded at one minute intervals of time, it is necessary to use the approximate formulae and information tabled in the astronomical almanac to determine the solar position and time in order to attain an appropriate standard of accuracy.

Table 14.1 Summary of time scales defined.

REF	Summary
TAI	International Atomic Time, in SI seconds.
UT	Universal time from midnight, mean solar day, based on the rotation of the Earth.
UTC	Co-ordinated Universal Time (civil time) at the prime meridian, and related to TAI by an integral number of seconds.
TDT	Terrestrial dynamical time, as used in the astronomical almanac ephemerides for observations from the surface of the Earth.

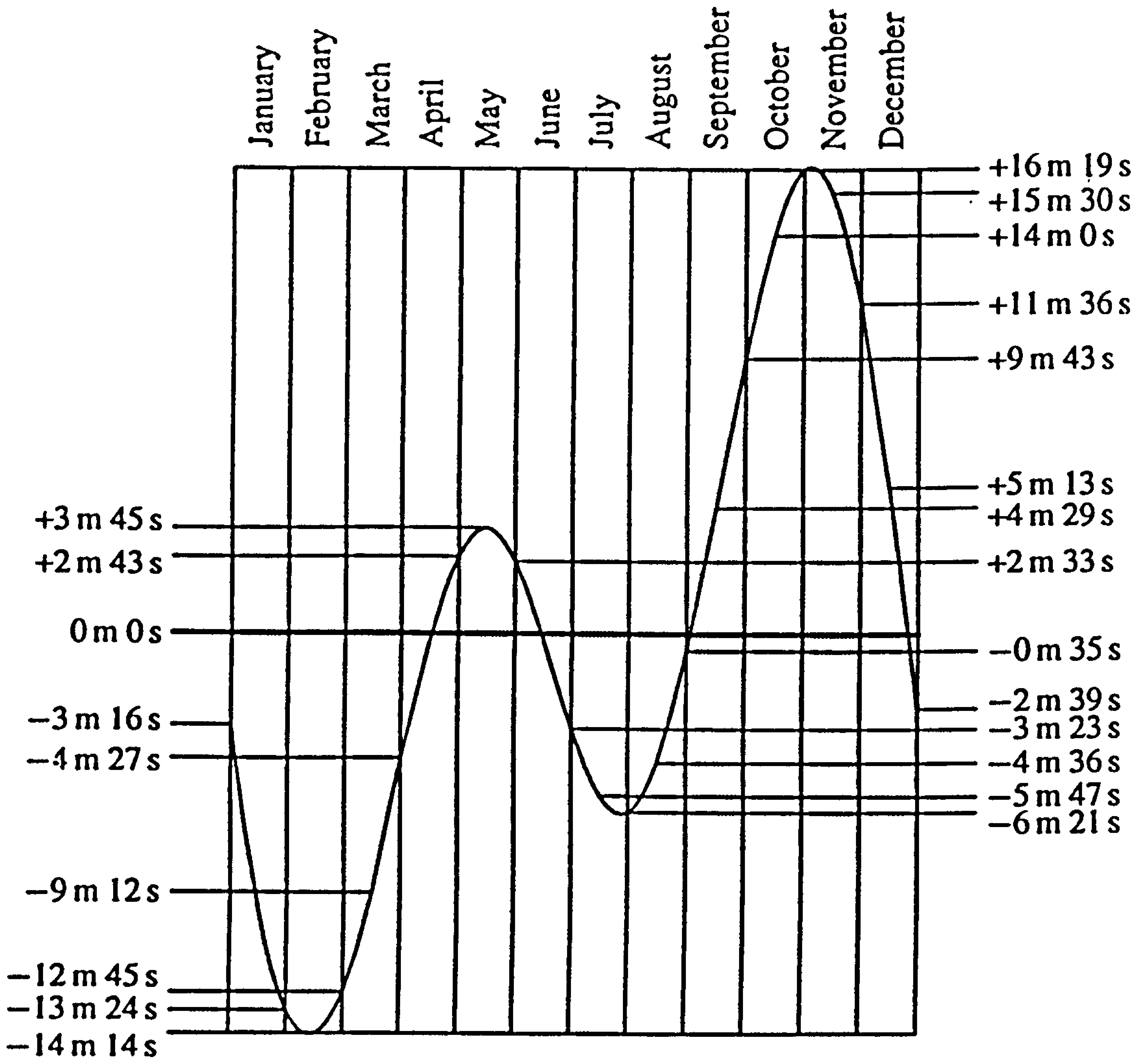

Figure 14.3 Variation in the equation of time through the year. (Seidelmann 1992)

15.0 METHOD AND RESULTS.

Measurement procedure.

15.1 Measurements of diffuse and global horizontal insolation were recorded at one minute intervals, during the period May 1992 to February 1994, at a rural location, 52.116 degrees North, and 0.083 degrees East, near Cambridge in the United Kingdom.

15.2 Four new Kipp and Zonen CM11 pyranometers to the secondary standard of the World Meteorological Organisation (Anon 1983)were used for the experiment. These instruments were chosen for their performance specification, having a 99% response time of 24 seconds, and 63% response time of four seconds. Two of the instruments were fitted with Kipp and Zonen CM11/121 shadow-rings. The instruments were mounted on top of a tower scaffold to avoid overshadowing by perimeter features and hedgerows, the mounting structure itself, or other instruments(Plate 15.1). The shade-band instruments were located to the North of the global horizontal instruments, and within an arc +/-30 degrees from due North of them. This was to ensure that the shade-bands themselves could not obstruct the direct beam irradiance component of the global horizontal measurements at any time of day or season. Although these pyranometers lack any dependence on inclination, the level of the installation, and the latitude tilt of the shade-band mounting, was checked using a digital level meter, having a measurement accuracy of < 0.5 degree over the total range +120 to -120 degrees. The shade band position was adjusted in accordance with the manufacturer's recommendations(Appendix D), and correction factors were applied to the diffuse measurements recorded, which allowed for the loss of diffuse irradiance from the sky hemisphere obscured by the shade-band. The corrected readings were checked and a further adjustment was made, if required, to ensure that the diffuse ratio did not exceed 1.

15.3 Photodiode sensors were also used to measure global horizontal irradiance in Watts per m^2 for ultraviolet irradiance(+/- 7.5% NBS USA) in the UVB spectral range 290 to 340 nm and UVA spectral range 340 to 400 nm, and also the visible spectrum 400 to 700 nm(+/- 5% NBS USA). In addition the visible spectrum was also measured in lux, and mmol per m^2 per second. All cables connecting instruments to the recording device were routed and positioned under the supporting structure, so as to be screened as far as was possible, from direct insolation, and protected from accidental damage. An altimeter was used to relate the height of the instruments to the local ordinance survey reference point to ascertain the elevation of the instrument mounting height above mean sea level.

15.4 The commencement of observation sequences was timed using a digital timing device, which was automatically controlled by the radio time signal(UTC) from Rugby. Routine checks were made on the accuracy of the internal timing device of the data logger, using this regulated timing device, in an endeavour to ensure that the logger readings were taken within +/- 3 seconds of the intended time, being within the limit of accuracy of the algorithms adopted for determining solar time.

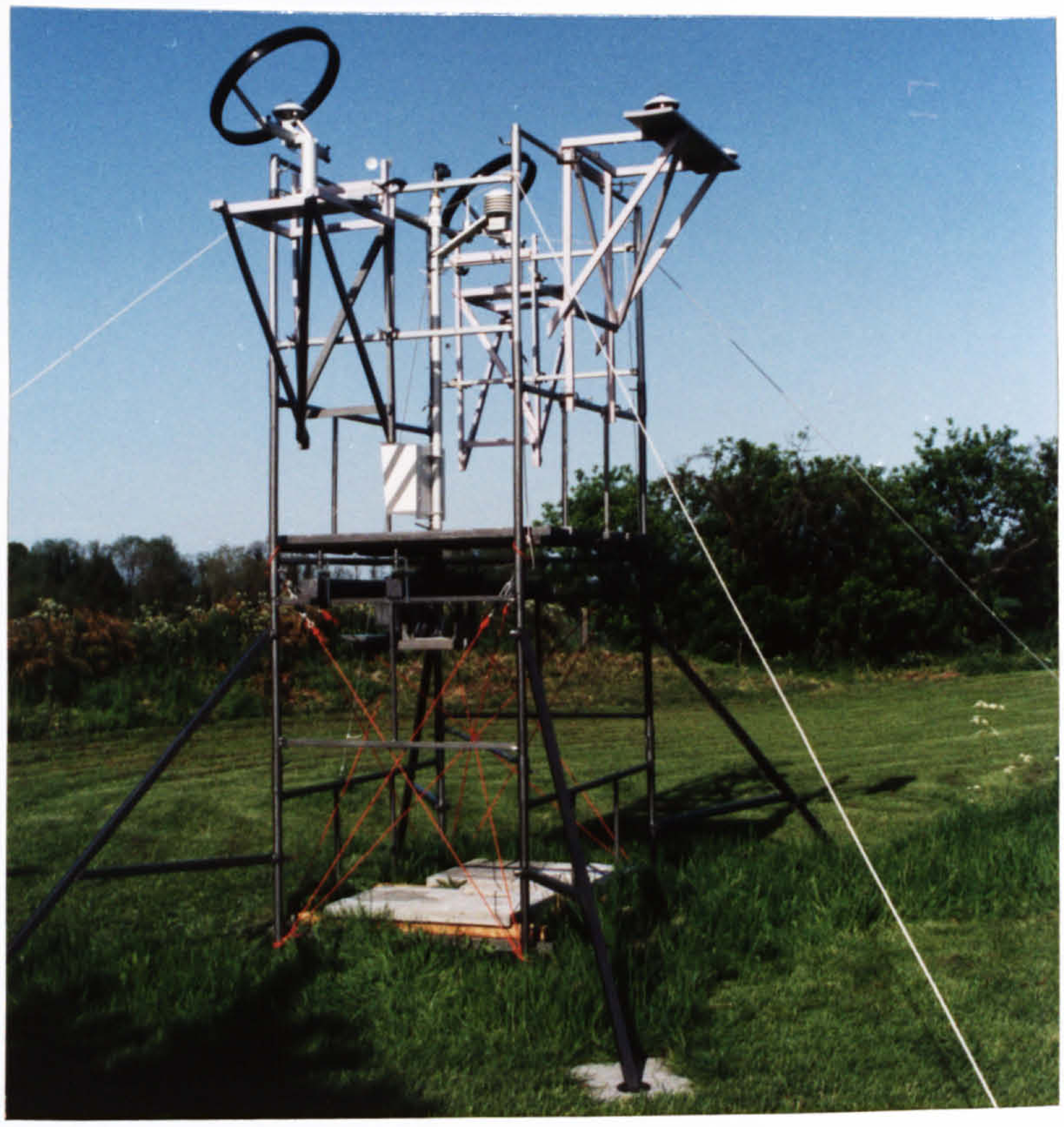

Plate 15.1 Experimental rig.

15.5 The observations were recorded using a data logger by Delta T Devices, programmed to read the irradiance sensor channels at one minute intervals, and configured to measure three wire differential voltage readings to minimise signal noise. The logger was powered using rechargeable batteries, which were maintained by regular monitoring at 75% to 100% of their fully charged state. The internal clock of the logger was set to universal co-ordinated time (UTC). No adjustment was made during the summer period to accommodate daylight saving time(British summer time), in order to maintain a constant time base throughout the experiment. An additional insulated housing was provided for the normally weather proofed data logger housing, which was also shielded from direct insolation, to reduce the effect of diurnal temperature swings on the internal timing device of the logger. All the sensors used were new instruments.

15.6 Duplicate instruments were used to record global horizontal and diffuse irradiance to detect and minimise error. At an early stage in the observation sequence, the four Kipp & Zonen CM11 pyranometers used were tested in situ, measuring global horizontal irradiance alongside a fifth new reference instrument, supplied by the manufacturer specifically for the purpose of checking the performance and calibration of the instruments supplied for this experiment(Figure 15.1). Consistent results were obtained during this test.

15.7 The data was stored in binary format in the memory of the logger and down-loaded every four or five days directly to an IBM compatible portable computer, using the RS232 communications port. Arrangements were also made to record observations for relative humidity, ambient air temperature, ground temperature, wind speed and direction, barometric pressure, and rainfall. Unfortunately, the sensor for barometric pressure required to make pressure corrected calculations of some of the atmospheric parameters was not purchased at the commencement of the experiment.

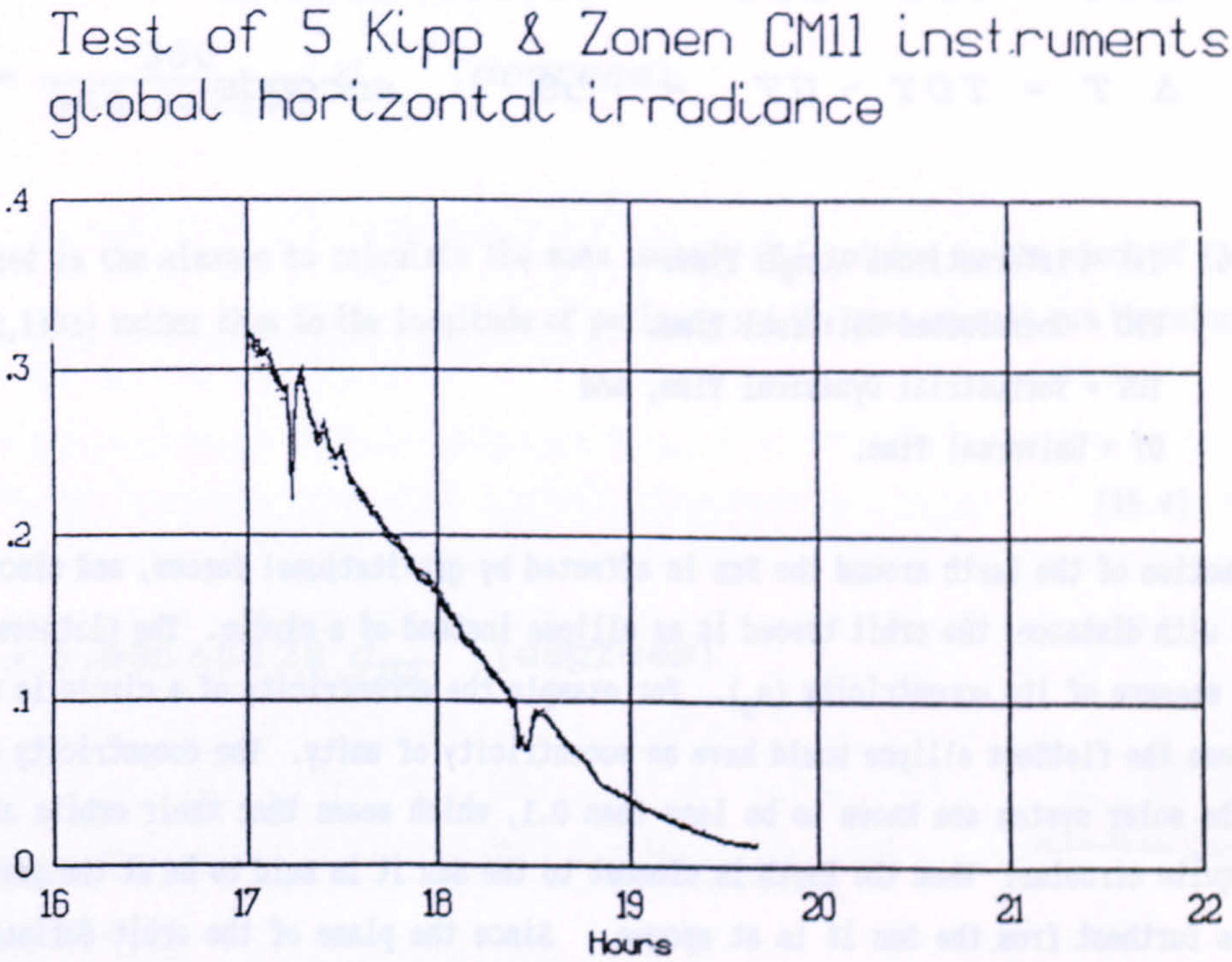

Figure 15.1 Test readings with five CM11 pyranometers.

CALCULATION PROCEDURE.

Solar position and time.

15.8 Although the Earth moves in an orbit around the Sun, it appears as though the Sun moves around the Earth. It is convenient to regard this apparent orbit of the Sun as if it were the case, when calculating the position of the Sun in relation to a location on Earth. The solar position and time were therefore calculated from the following procedures, which are mainly based on the approximate expressions contained in the astronomical almanac:

The almanac uses the time argument d as the interval of days from January 0 at 0 hours. The day numbers d_{UT}, d_{UTC}, and d_{TDT}, defined as the interval in days, hrs, and minutes expressed as the day plus the fraction of a day from January 0, 0^h, with January 1st, 0^h equal to 1, were determined for the UT, UTC, and TDT timescales respectively. For the 1992/1993 period of observation, the inter-relationship between TAI and the various timescales relating to the expressions used to calculate the solar position and time relative to the location and time of observation was determined as follows from information given in the almanac :

$$\Delta AT = TAI - UTC = +27 \quad seconds$$
$$\Delta TT = TDT - UTC = +32.184 \quad seconds \qquad [15.1]$$
$$\Delta T = TDT - UT = +58 \quad seconds$$

where: TAI = International Atomic Time.
UTC = Coordinated Universal Time.
TDT = Terrestrial Dynamical Time, and
UT = Universal Time.

The motion of the Earth around the Sun is affected by gravitational forces, and since these forces vary with distance, the orbit traced is an ellipse instead of a circle. The flatness of an ellipse is a measure of its eccentricity (e_s). For example the eccentricity of a circle is equal to zero, whereas the flattest ellipse would have an eccentricity of unity. The eccentricity of the planets in the solar system are known to be less than 0.1, which means that their orbits are almost, but not quite circular. When the Earth is closest to the Sun it is said to be at the perigee, and when it is furthest from the Sun it is at apogee. Since the plane of the orbit defines the ellipse, the position of the Sun is found by calculating the ecliptic longitude of the Sun. The method used for this involved calculating the imaginary position of the Sun relative to a fixed point on the orbit, by first assuming that the orbit was circular, and then making a correction to allow for the eccentricity of the orbit, using an approximation for Kepler's equation of the centre to calculate the solar position on the elliptical orbit and thence to determine the geocentric longitude of the Sun(figure 15.2) as follows:

The mean longitude of perigee (L_p) in degrees was obtained(Anon 1992,1993) by:

[15.2]

$$L_p = s_1 + 0.000\,047\,07\ d_{TDT} \qquad (degrees)$$

where

$$s_1 = 282^o.800\,722 \quad for\ 1992$$
$$s_1 = 282^o.817\,951 \quad for\ 1993$$

The position which the Sun would have, as seen from the Earth, if the apparent orbit of the Sun about the Earth was circular is known as the mean anomaly (M_a). It has the following form, when considering how far the Sun would have travelled in the number of days (d_p) from perigee:

[15.3]

$$M_a = \frac{360}{365.242191} d_p \quad (degrees)$$

The expression used in the almanac to calculate the mean anomaly (M_a) relates to the epoch of the Almanac(Anon 1992,1993) rather than to the longitude of perigee, and the mean anomaly was therefore obtained from:

[15.4]

$$M_a = s_2 + 0.985\,600\,28\ d_{TDT} \quad (degrees)$$

with

$$s_2 = 356^o.125\,295 \ for \ 1992$$
$$s_2 = 356^o.854\,999 \ for \ 1993$$

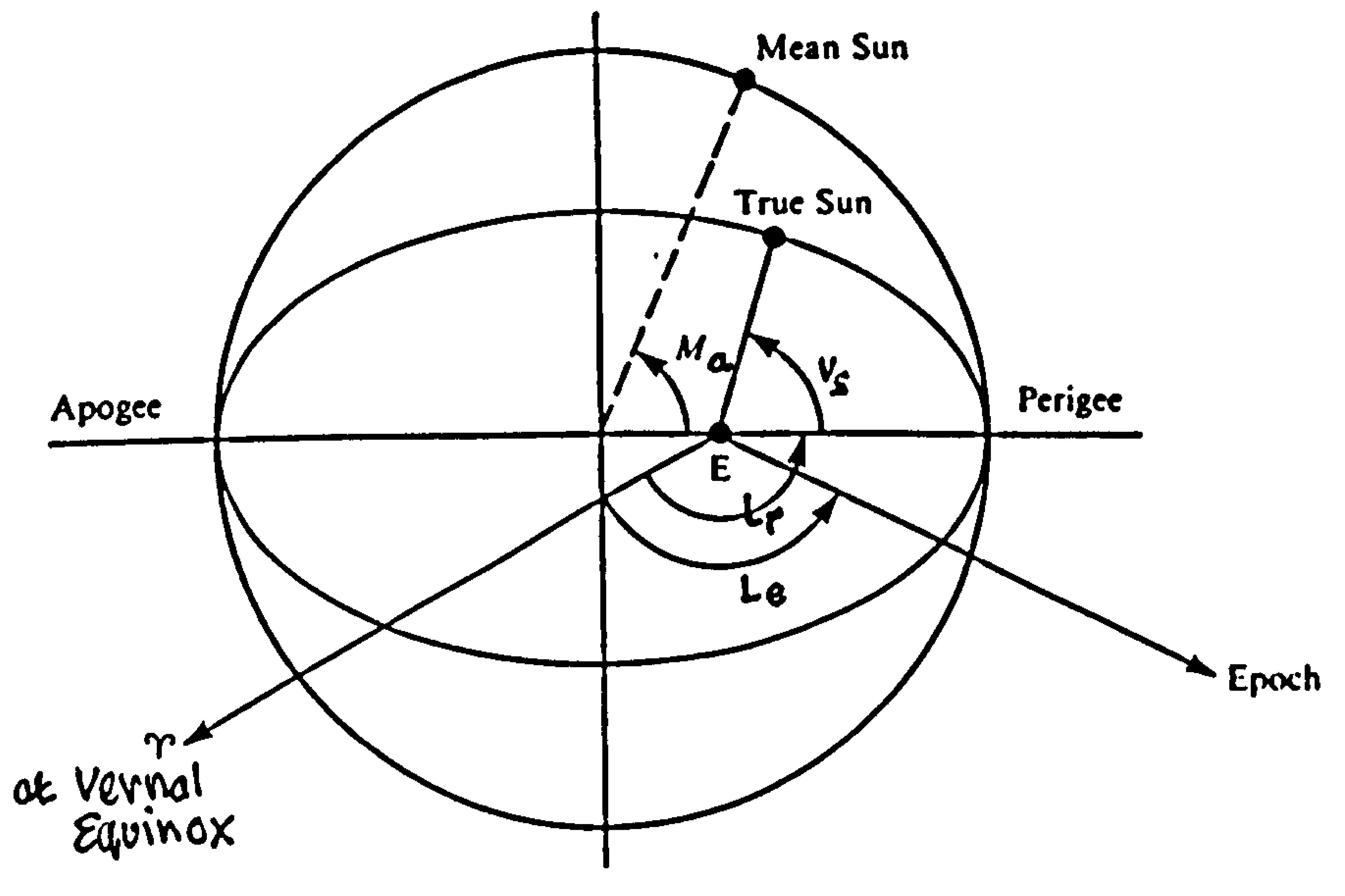

Figure 15.2 Apparent orbit of the Sun(Duffet-Smith 1988)

The value of the eccentricity (e_s) was obtained from the expression given in the almanac as:

$$e_s = s_3 - 0.000\,000\,0012\ d_{TDT} \qquad [15.5]$$

where

$$s_3 = 0.016\,711\,70 \quad for \quad 1992$$
$$s_3 = 0.016\,711\,28 \quad for \quad 1993$$

The value of the mean anomaly from equation 15.4 was used, together with the value of the eccentricity obtained from equation 15.5, in an expression which allowed for the effect of the elliptical orbit by applying an approximate solution to Kepler's equation of the centre given by Duffet-Smith(1979). The resulting value relates to the true motion of the Sun on its apparent ecliptic orbit as seen from Earth. This is known as the true anomaly (v_s) and was obtained from:

$$v_s = M_s + \frac{360}{\pi} \,.\, e_s \,.\, \sin . M_s \quad (degrees) \qquad [15.6]$$

The geocentric longitude of the Sun (L_s) was then calculated from the following:

$$L_s = L_p + v_s \qquad (degrees) \qquad [15.8]$$

and the result was adjusted to be 360 degrees or less by the deduction of multiples of 360 degrees as required. The equation of time (E_t) to a precision of 3 seconds was then obtained from the following expression given in the astronomical almanac for calculations of the required adjustment to UT time in seconds:

$$E_T = -106.4 \sin L_s + 596.1 \sin 2\,L_s + 4.4 \sin 3\,L_s - 12.7 \sin 4\,L_s$$
$$- 428.9 \cos L_s - 2.1 \cos 2\,L_s + 19.3 \cos 3\,L_s \quad (seconds) \qquad [15.9]$$

Solar time (T_{SOL}) was calculated from:

$$T_{SOL} = (d_{UT} - n_d) + \left[\frac{4\ (L_{std} - L_{loc})}{60}\right] + \frac{E_T}{360} \qquad [15.10]$$

where:

L_{std} = *Longitude for standard time (prime meridian)*

L_{loc} = *Longitude of site location (degrees)*

T_{sol} = *solar time (hours, mins, secs expressed as hours, with decimal of hour)*

The accuracy of the calculation of solar noon was checked using the tabulated value of the solar transit of the Ephemeris longitude, corrected for the longitude of the site of observation. The Sun-Earth distance (r_a) was obtained from the almanac for 0^h TDT, and was assumed to vary uniformly with time between the values for consecutive days. On this basis, the value of r was obtained from:

$$r_a = r_{d_1} + \left[\frac{\Delta\, r_{d_1,d_2}}{1440}\right] (d_{TDT} - n_d) \qquad [15.11]$$

where:

Δ = *difference : two values*

r_a = *Sun-Earth distance at TDT time of observation (astronomical units)*

r_{d_1,d_2} = *Sun-Earth distance at* 0^h *TDT on consecutive days* d_1, d *(astronomical units)*

Having determined the position of the Sun relative to the Earth, it was then necessary to calculate the angle of incidence for irradiance on a horizontal surface at the location of observation(Figure 15.3)

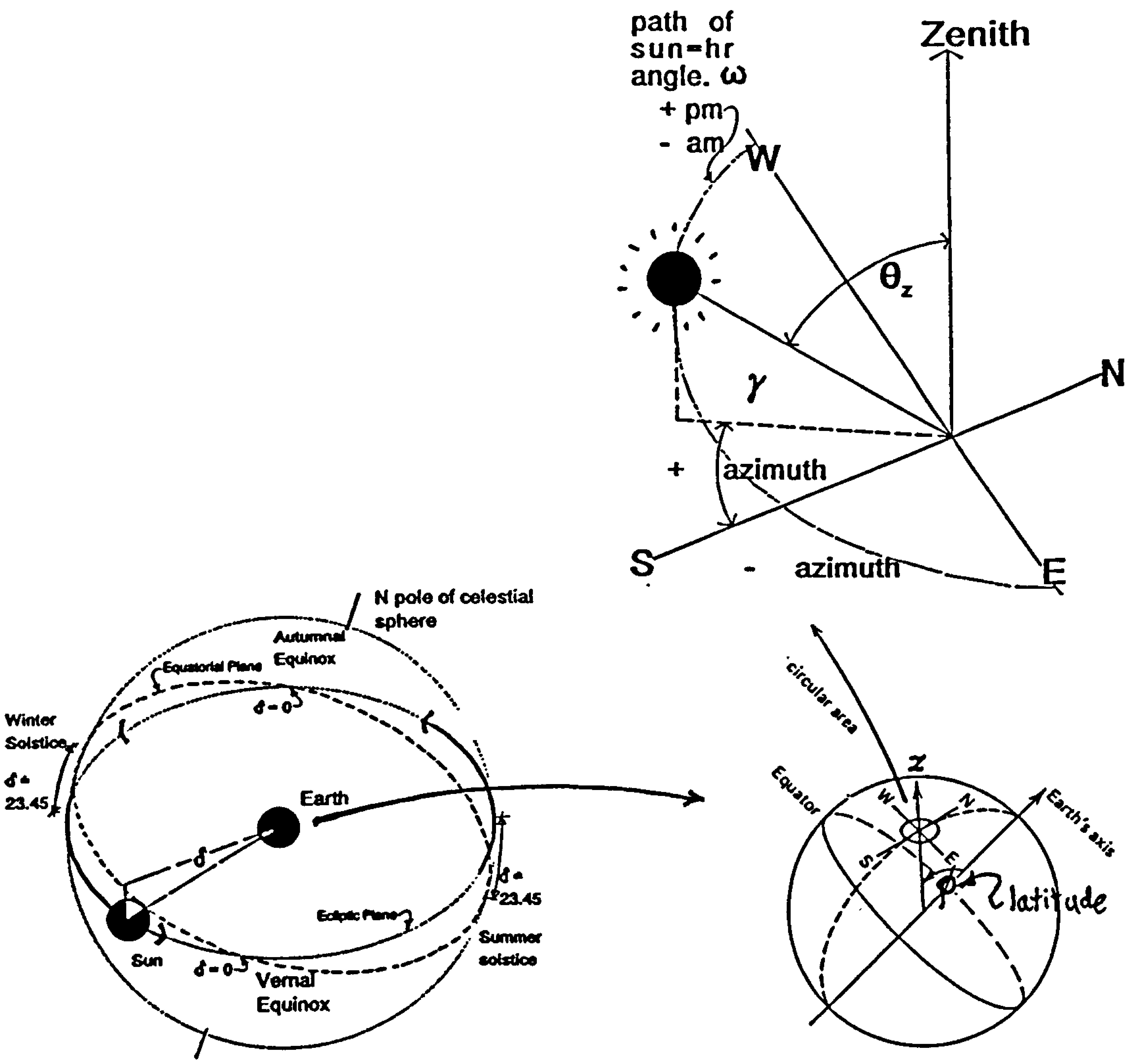

Figure 15.3 Angles to determine the incidence of solar radiation on a horizontal surface.

The Declination was taken from the tabulated value of the almanac for 0^h TDT on the appropriate day, and was assumed to vary uniformly with time between the value for consecutive days. On this assumption the declination was calculated corresponding to each consecutive observation at one minute intervals from:

$$\delta = \delta_{d_1} + \left[\frac{\Delta\,\delta_{d_1,d_2}}{1440}\right](d_{TDT} - n_d) \qquad [15.12]$$

where:

δ = *declination at TDT time of observation* (*degrees*)

δ_{d_1,d_2} = *declination at* 0^h *on consecutive days* d_1, d_2 (*degrees*)

n_d = *day number* (*integer, Jan 1st* = 1)

d_{TDT} = *day, hr, min expressed as* n_d *plus fraction of day*

The cosine of the solar zenith distance for a horizontal surface was obtained from:

$$\cos\theta_z = \sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega \qquad [15.13]$$

where:

$\cos\theta_z$ = *solar zenith angular distance,* (*beam radiation on horizontal surface*).

δ = *angular position of the Sun with equator North positive* ($-23.45 \le \delta \le 23.45$ *degrees*)

ϕ = *latitude, angular location North / South of equator* (*degrees*)

ω = *hour* $\angle$, *angular position of Sun East / West of local meridian, morning negative, afternoon positive* (*degrees*)

Extraterrestrial solar irradiance.

15.9 Having calculated the solar position and angle of incidence, the value of the extraterrestrial solar irradiance on a horizontal plane at the site of observation was then obtained for the both the broadband solar and the visual spectrum from:

[15.14]

$$I_o = I_{SC}\left[\frac{1}{I_a}\right]^2 \cos\theta_z \qquad Wm^{-1}$$

where I_{SC} is the solar constant, having the following values:

Clearness indices and diffuse ratios.

$$I_{SC} = 1367.0\ Wm^{-1}\ (broadband\ solar\ spectrum)$$

$$556.0\ Wm^{-1}\ (visible\ spectrum\ 0.392\ \mu m - 0.710\ \mu m)$$

15.10 The global horizontal and diffuse measurements before sunrise were examined and an appropriate daily correction was made to compensate for negative offset. As previously described, a correction factor was also applied to compensate for the effect of the shade-band on the diffuse values recorded. The broadband clearness irradiance index K_t and diffuse ratio D_R were calculated for each instrument, and for the mean measurements for two instruments from:

[15.15]

$$K_t = \frac{I_g}{I_o}$$

[15.16]

$$D_R = \frac{I_d}{I_g}$$

and the equivalent clearness indices were calculated for the visible spectrum from:

$$K_{t\,vis} = \frac{I_{g\,vis}}{I_{o\,vis}} \qquad (dimensionless) \qquad [15.17]$$

$$E_R = \frac{E_g}{E_o} \qquad (dimensionless) \qquad [15.18]$$

Relative optical air mass.

15.11 The relative optical air mass was determined from the approximate empirical formula of Kasten(1966) for the equation of Bemporad(1906), using the revised constants calculated by Kasten and Young(1989.) for both the full solar spectrum, and those appropriate to the work of Bemporad, which only related to the visible spectrum(Table 13.1).

$$m_{r(\gamma_{obs})} = [\sin\gamma_{obs} + a\,(\gamma_{obs} + b)^{-c}]^{-1} \qquad [13.2]$$

where:

γ_{obs} = *observed (refracted) solar altitude*

Atmospheric refraction.

15.12 The use of Kasten's approximate expression[eqn 13.2] for Bemporad's equation [eqn 13.1] required that the solar altitude be adjusted to allow for refraction, when calculating the optical air mass for zenith distances to 70^0, and that an allowance be made for the curvature of the Earth for larger zenith distances(Young 1974). Atmospheric pressure and ambient temperatures are required for such corrections, and the measurement scheme was designed with this in mind. However, there was a delay of approximately 12 months from the commencement of the experiment before a sensor for recording barometric pressure was purchased. Most of the important clear-sky data had by then been recorded, and the appropriate adjustment to the solar elevation could not be calculated for use with this data to determine the optical air path with precision for all zenith distances, and weather conditions. Although refraction was unlikely to have a major effect on the analysis proposed for zenith distances less than 60^0, the observed solar zenith distance was obtained approximately, by allowing for refraction calculated from Snell's law for the known refractive index of the atmosphere at the standard pressure for mean sea level. Such a correction is based on the assumption of a plane parallel atmosphere. It should therefore only be valid for zenith distances of less then 45^0, but might be expected to provide a fairly good approximation for zenith distances up to 60^0 or 70^0, beyond which it would be necessary to allow for the curvature of the Earth. The procedure used to obtain the value of the observed solar altitude from Snell's law was:

$$\frac{n_h}{n_o} = \frac{\sin\theta_{z\,obs}}{\sin\theta_z} \qquad [15.19]$$

and therefore:

$$n_h \sin\theta_z = n_o \sin\theta_{z\,obs} \qquad [15.20]$$

Although the refraction varies with the density and temperature of the atmosphere at various heights, it was assumed that. since the significant refraction to be allowed for was that between vacuo($n_h = 1$), and the atmosphere layer at the surface of the Earth(n_0), then:

$$\frac{\sin\theta_z}{n_o} = \sin\theta_{z\,obs} \qquad [15.21]$$

giving

$$\sin \theta_z = n_o \sin \theta_{z\,obs} \qquad [15.22]$$

with

$$\gamma_{obs} = 90^o - \theta_{z\,obs} \qquad [15.23]$$

and atmospheric refraction defined as

$$R_a = \theta_z - \theta_{z\,obs} \qquad [15.24]$$

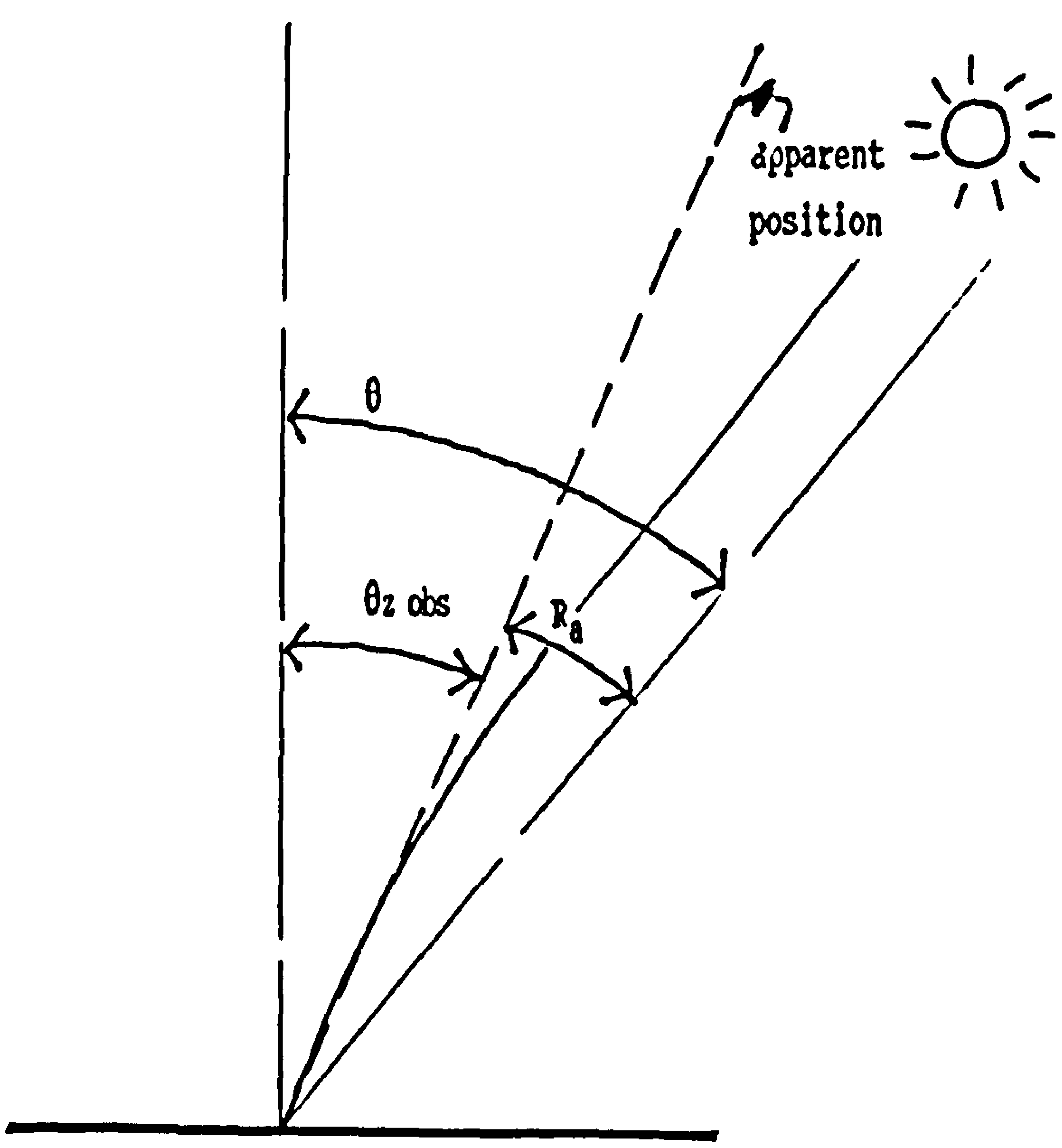

Figure 15.4 Atmospheric refraction.

Since the observed altitude of the sun is greater than the calculated altitude, the angle R_a is added to the calculated solar altitude position, when using Kasten and Young's re-calculation of the constants in Kasten's approximate formula[eqn 13.2] for Bemporad's expression[eqn 13.1] of relative optical path length. The advantage of equation 15.21 is that refraction is accounted for in terms of the calculated zenith distance and the surface refractive index of air, and gives directly the required observed zenith distance, whereas the expressions, which are usually quoted in the literature were developed for astronomical calculations, and therefore relate to known observed angles. The refraction calculated by this approximation derived from Snell's law were checked against those predicted using the following approximate expression from Green(1985), which uses two constants of refraction used in astronomical work, which allow for the effects of refraction and the curvature of the Earth:

$$R_a = 60''.29 \tan\theta_{z\,obs} - 0''.06688 \tan\theta^3_{z\,obs} \qquad [15.25]$$

For this comparison, it was assumed that n_0 had the value of 1.0002927 for the wavelength 0.7 microns, appropriate for broadband studies, and an atmospheric surface pressure of 1013.25 mbar in equation 15.11, which was the same as the assumption made by both Kasten & Young, and in the development of the expression of Green. The predicted values of the refraction for zenith angles in 5^0 steps from 0^0 to 90^0, using equation 15.12, were found to be the same as the empirical expression given by Green[eqn 15.15] to: four decimal places for zenith distances from 0^0 to 50^0; three decimal places from 55^0 to 70^0; two decimal places for 75^0 and 80^0; only one decimal place for 85^0. There was a significant difference for the refraction calculated for the solar zenith distance of 90^0. On the basis of that analysis, and because zenith distances greater than 80^0 were not considered particularly vital to this experiment, the approximate expression[eqn 15.12] was used for this study, in conjunction with Kasten's empirical formula[eqn 13.2] for calculating the relative optical air mass. The coefficients used were obtained from Kasten & Young(1989) in table 13.2, for the broadband, and the visible spectrum(Bemporad). The refractive index of air for light at the wavelength 0.54 microns with n_0 = 1.000293 was used for the optical air mass of the visible spectrum with the coefficients for Bemporad's formula.

Table 15.1 Comparison of angles of refraction obtained using equations 15.22 & 15.25.

angle of incidence	true solar altitude	refraction from Snell's Law	observed solar altitude Snell's Law	refraction from eq15.25	observed solar altitude eq15.25
0	90	0	90	0	90
5	85	.0014668	85.00147	.0014647	85
10	80	.0029562	80.00296	.002952	80
15	75	.0044923	75.00449	.0044856	75.00001
20	70	.006102	70.0061	.0060926	70.00001
25	65	.0078177	65.00782	.0078047	65.00001
30	60	.0096791	60.00968	.0096617	60.00002
35	55	.0117385	55.01174	.011715	55.00002
40	50	.0140665	50.01407	.0140346	50.00003
45	45	.0167631	45.01676	.0167189	45.00004
50	40	.0199763	40.01998	.0199131	40.00006
55	35	.0239366	35.02394	.0238423	35.00009
60	30	.0290261	30.02903	.0288769	30.00015
65	25	.0359297	25.03593	.0356735	25.00026
70	20	.0460123	20.04601	.0455155	20.0005
75	15	.062443	15.06244	.061277	15.00117
80	10	.094639	10.09464	.090777	10.00386
85	5	.1881024	5.188102	.1596272	5.028475

TEST PROCEDURE.

Test of the Lui & Jordan method.

15.13 The Lui & Jordan(1960) method was developed to enable the ratio of diffuse radiation to the global radiation received on a horizontal to be determined from the value of the clearness index(K_T). The clearness index is the ratio of global horizontal irradiance to that available outside of the atmosphere(extraterrestrial). Four of the main assumptions of authors were that: there was a linear relationship between the global and diffuse transmittances of the atmosphere to solar radiation; a high clearness index would be representative of conditions with a high solar altitude; a low clearness index would be associated with a high diffuse ratio, which would mainly occur at very low solar altitudes, and the irregular values of the clearness index from one measurement to the next were less important than the long term mean value. The diffuse ratio obtained from observations recorded at one minute intervals was therefore plotted as a function of the clearness index, in order to check how the results compared to those of Lui & Jordan(1960) and Orgill & Hollands(1977), and to verify the basic assumptions of the method relating to solar altitude, when compared with instantaneous measurements. The following five figures give some indication of the variety of distributions found for individual days.

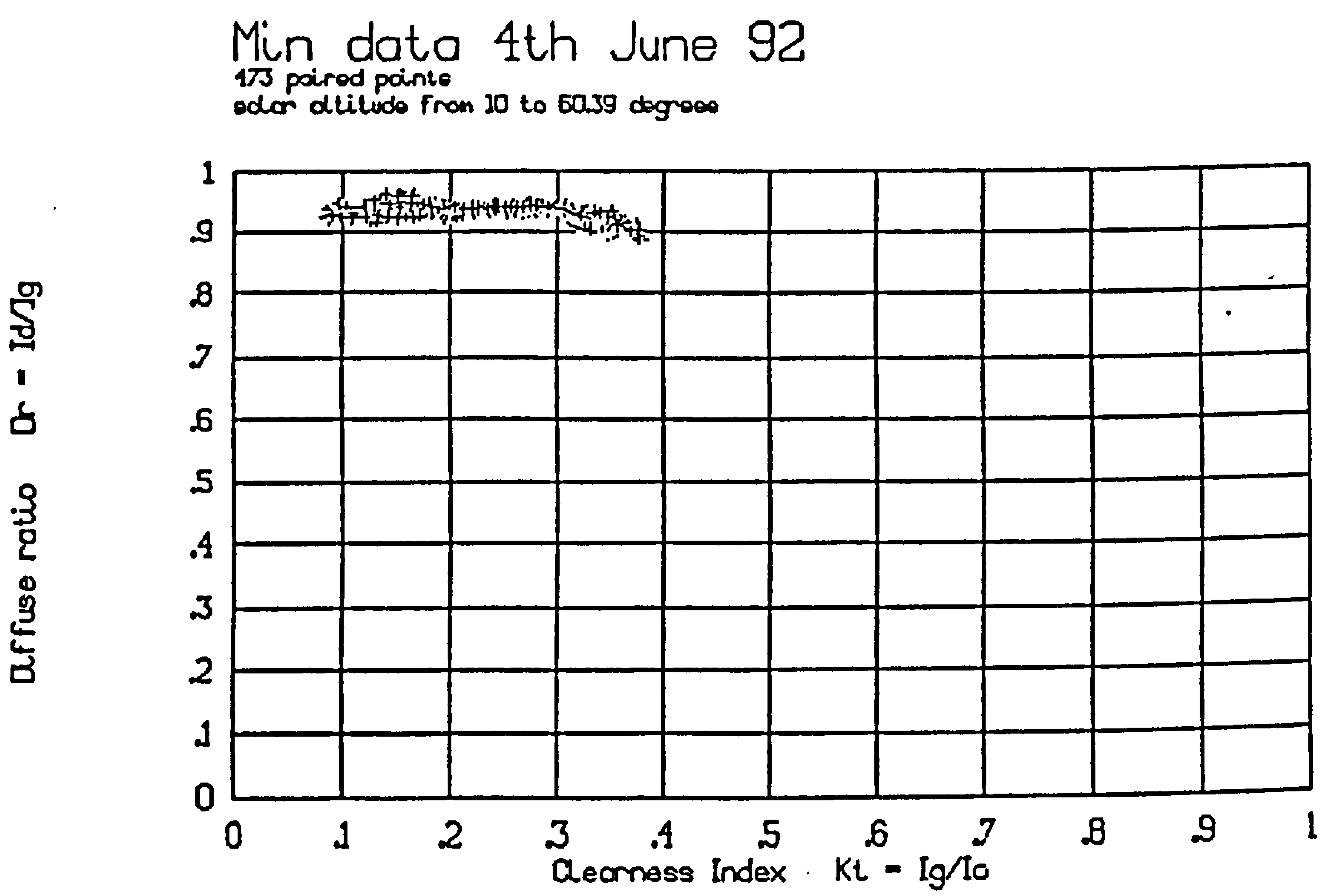

Figure 15.5 Overcast day. (Low and high solar altitudes with high diffuse ratio)

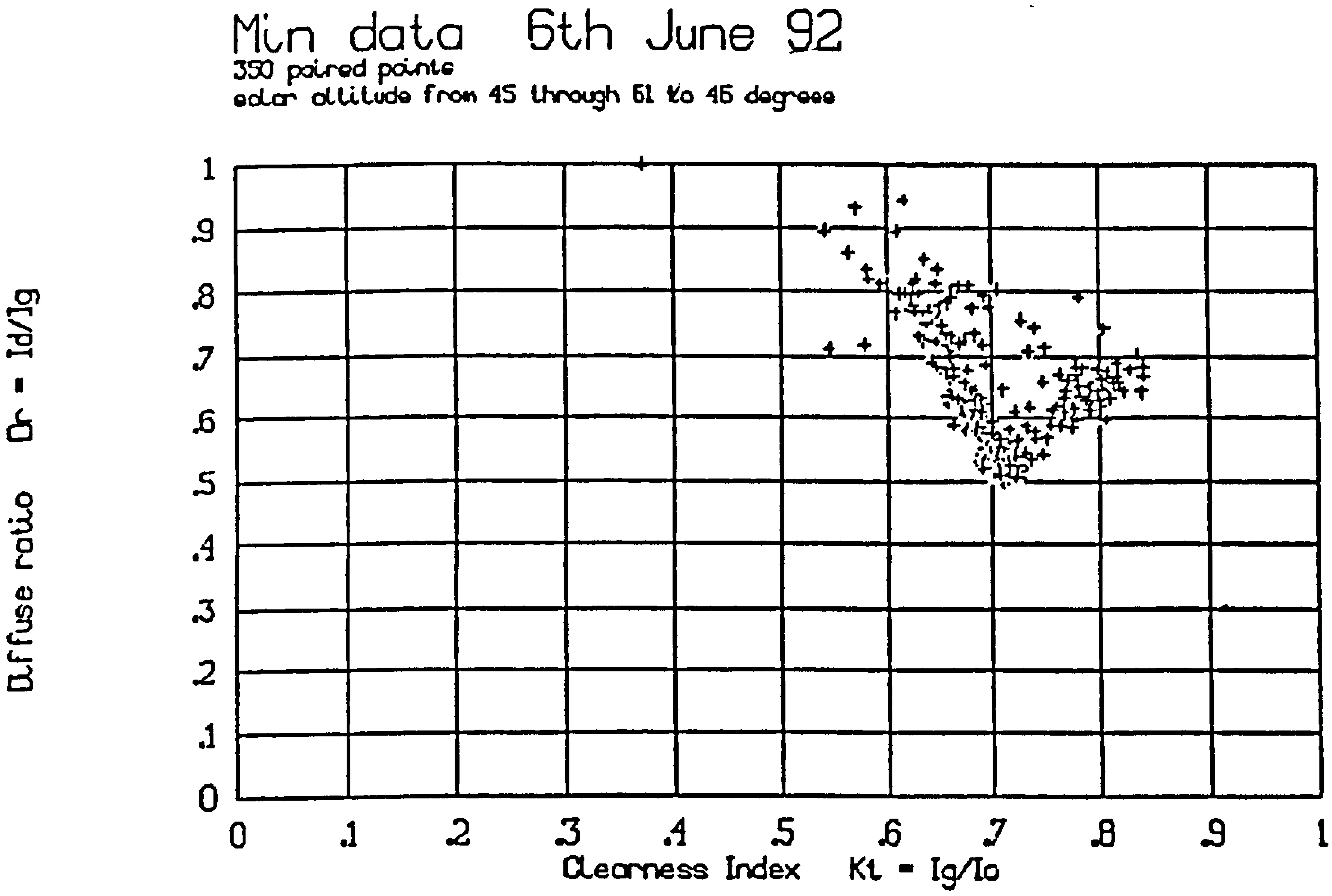

Figure 15.6 Cloudy. (High solar altitude, and high clearness index with high diffuse ratio)

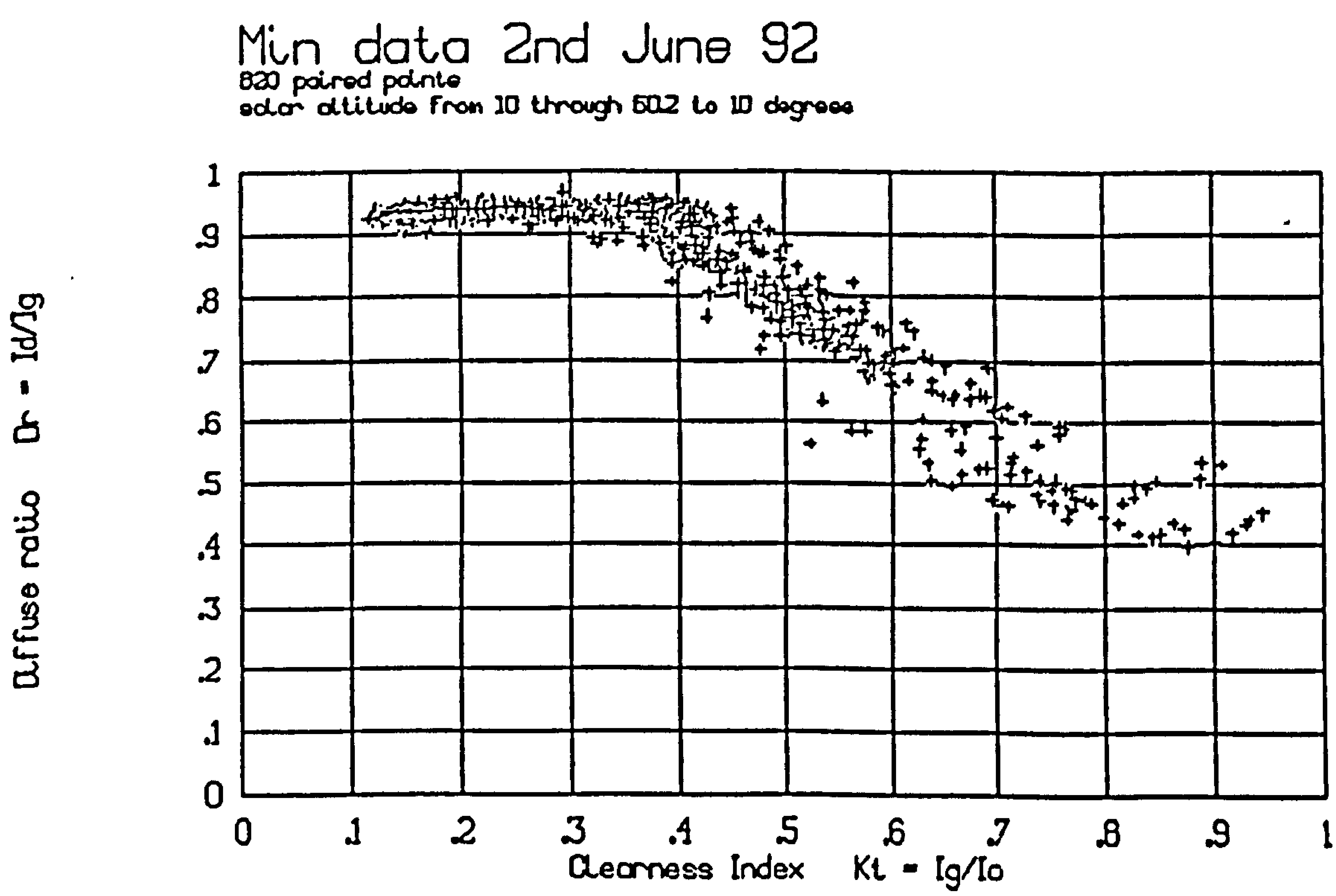

Figure 15.7 Sunny with cloud (low and high solar altitudes).

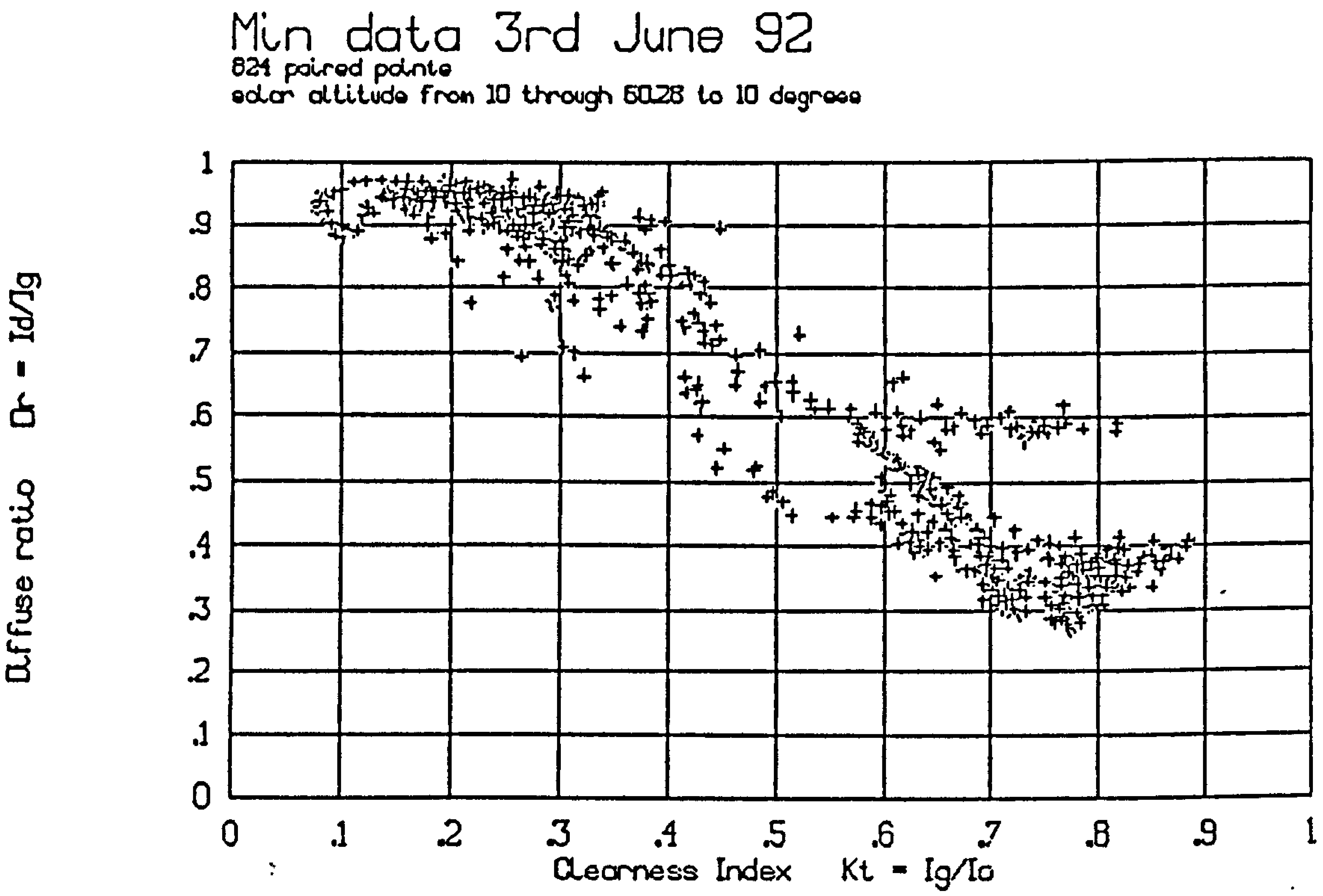

Figure 15.8 Sunny.(low and high solar altitudes: range of diffuse ratio for given clearness index)

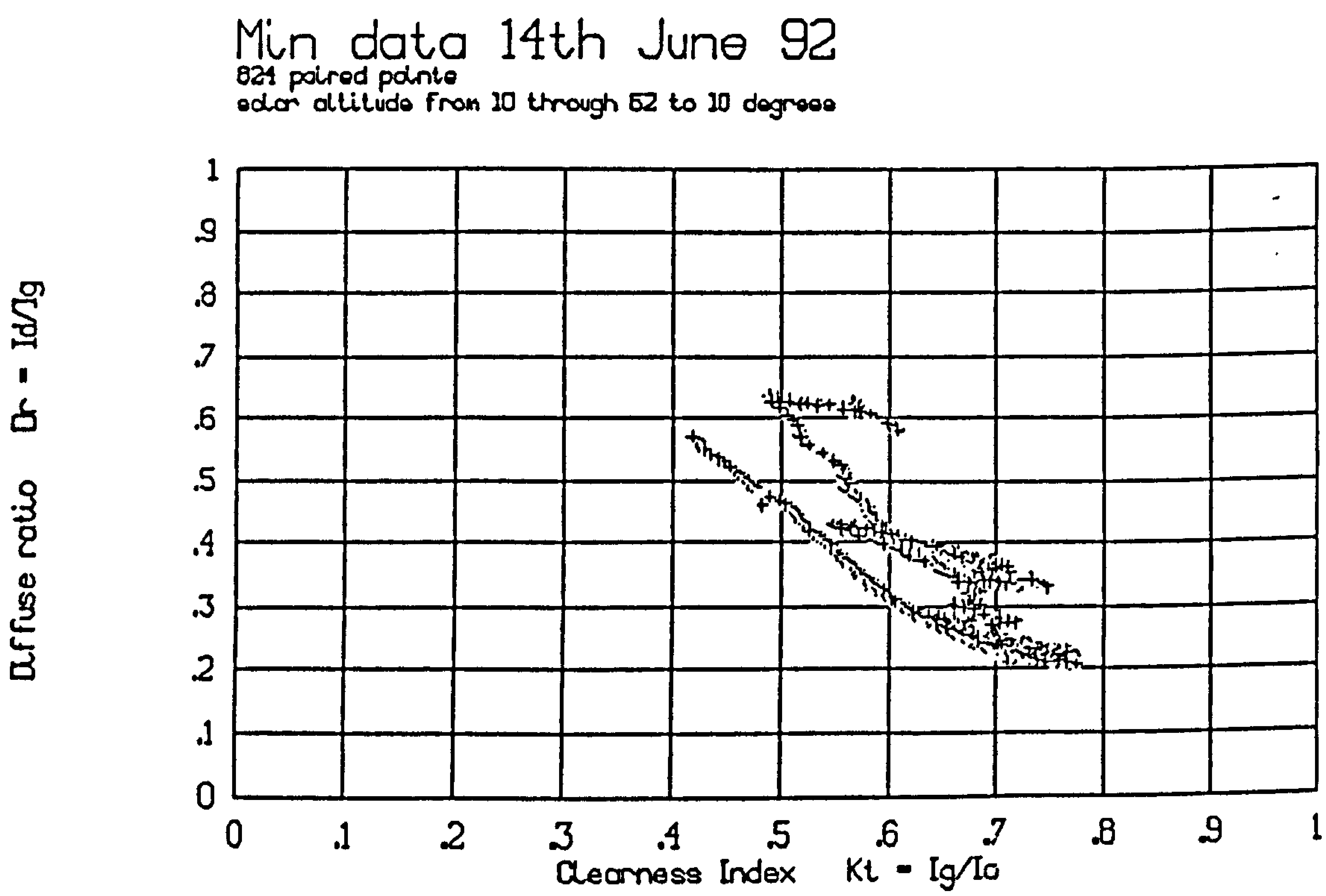

Figure 15.9 Clear sky. (low and high solar altitudes)

15.14 As can be seen from the figures for individual days, there was considerable scatter of the data evident on a typical day with sunshine and cloud(figs 15.7 & 15.8), and a wide range of possible configurations were found to exist for other sky conditions. These results did not support the authors' assumptions concerning solar altitude. For example the data for both low and high solar altitudes is plotted in figures 15.7 and also in 15.9, indicating that such assumptions were an over-simplification.

15.15 The results using one minute data collected over a twenty-two month period, indicated that there was a significantly larger margin of error possible in predictions of the diffuse ratio based on this method, than was suggested by the original authors. There is far too much data in the study to illustrate this graphically, but the point can be demonstrated by simply plotting the combined data for the above five sample days(figure 15.10). This shows quite clearly that there is a wide range of possible diffuse ratios for a single clearness index, which indicates that this method is fallible.

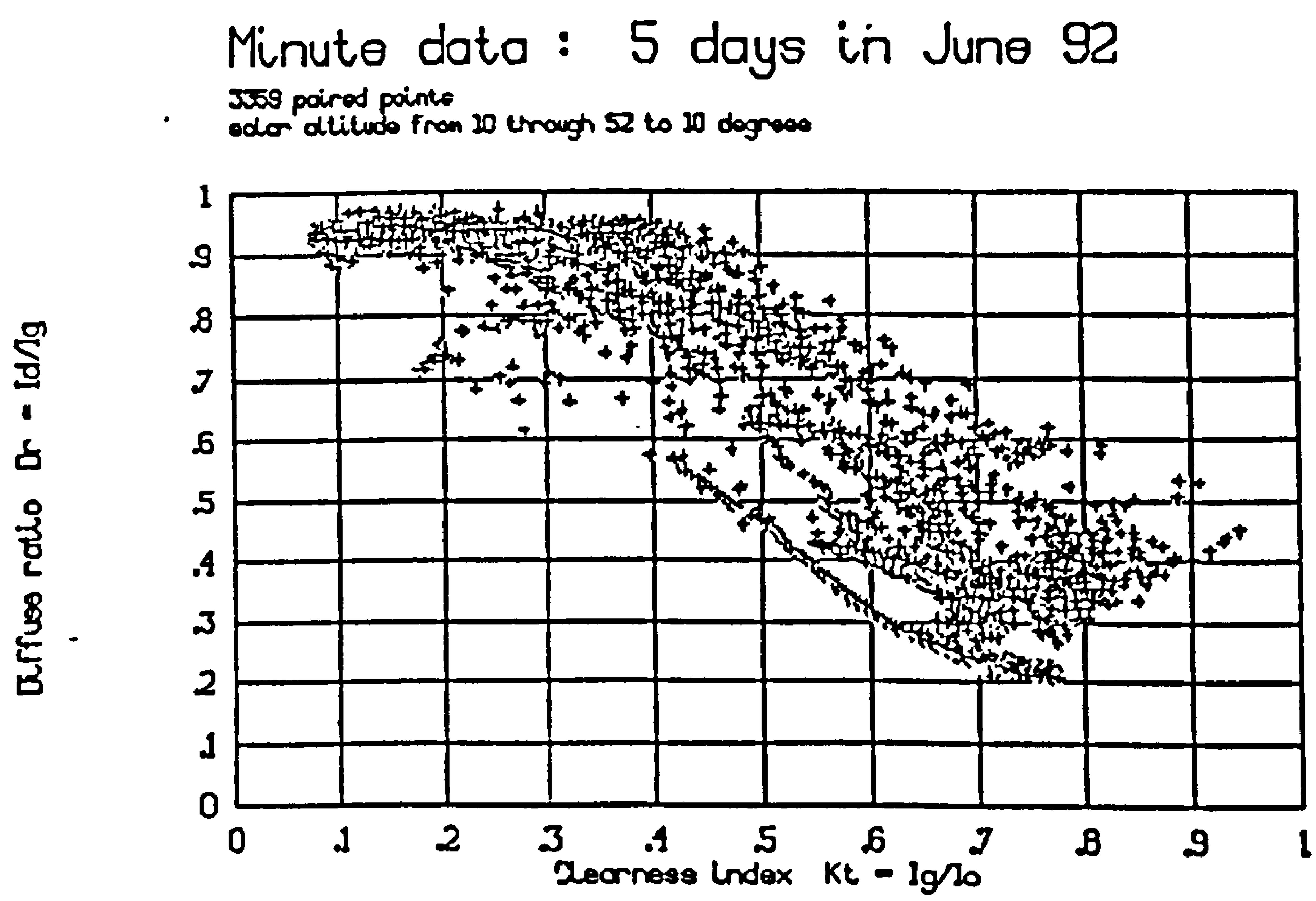

Figure 15.10 5 days of data: note the range of possible diffuse ratios for a given clearness index

15.16 It is appreciated that the original method was developed for daily mean values, and relied upon the averaging and smoothing of data to enable a statistically significant correlation being obtained from long time scale data(ten years). However the number of data points available for only one day of the present study, greatly exceeds the total amount of data available for each monthly mean daily result of the original study, which used data for only ten days on average per month from the ten year data base.

15.17 The Lui & Jordan model produced significant errors in relation to this study, when used to predict either instantaneous or hourly mean values of the diffuse ratio.

Test of the hypotheses.

15.18 The data for the whole of the observation period was examined and each day was classified into clear-sky, clear-sky plus some cloud, sunny and cloudy, mainly diffuse, wholly diffuse, and overcast conditions. For apparently clear-sky conditions, the fraction of the calculated extraterrestrial irradiance on a horizontal surface, which was received as global horizontal irradiance was plotted against time of day, and compared to that predicted by the hypothesis $\tau_{mg} = A.e^{-k.mr}$. Two theoretical and one curve fitting comparisons were made with the observed data. In the first theoretical test, the scaling coefficient A was calculated using equation 14.19 to establish the predicted boundary conditions for global horizontal clear-sky transmittance, and the equivalent diffuse transmittance for a clean, dry atmosphere from equation 14.22. Figures 15.11 to 15.16 illustrate some typical results obtained.

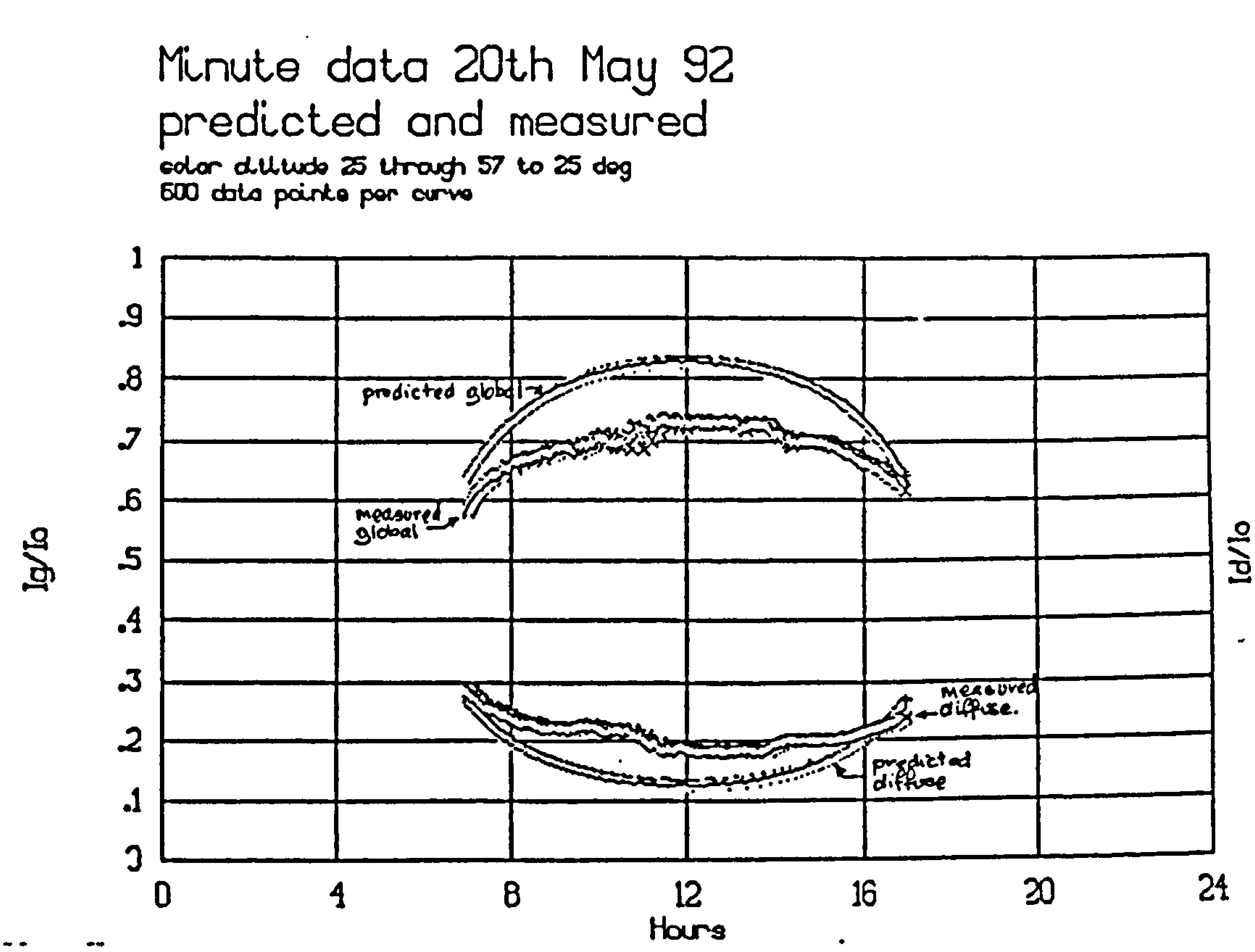

Figure 15.11 Measured global &d diffuse transmittances with those predicted for clear-skies.

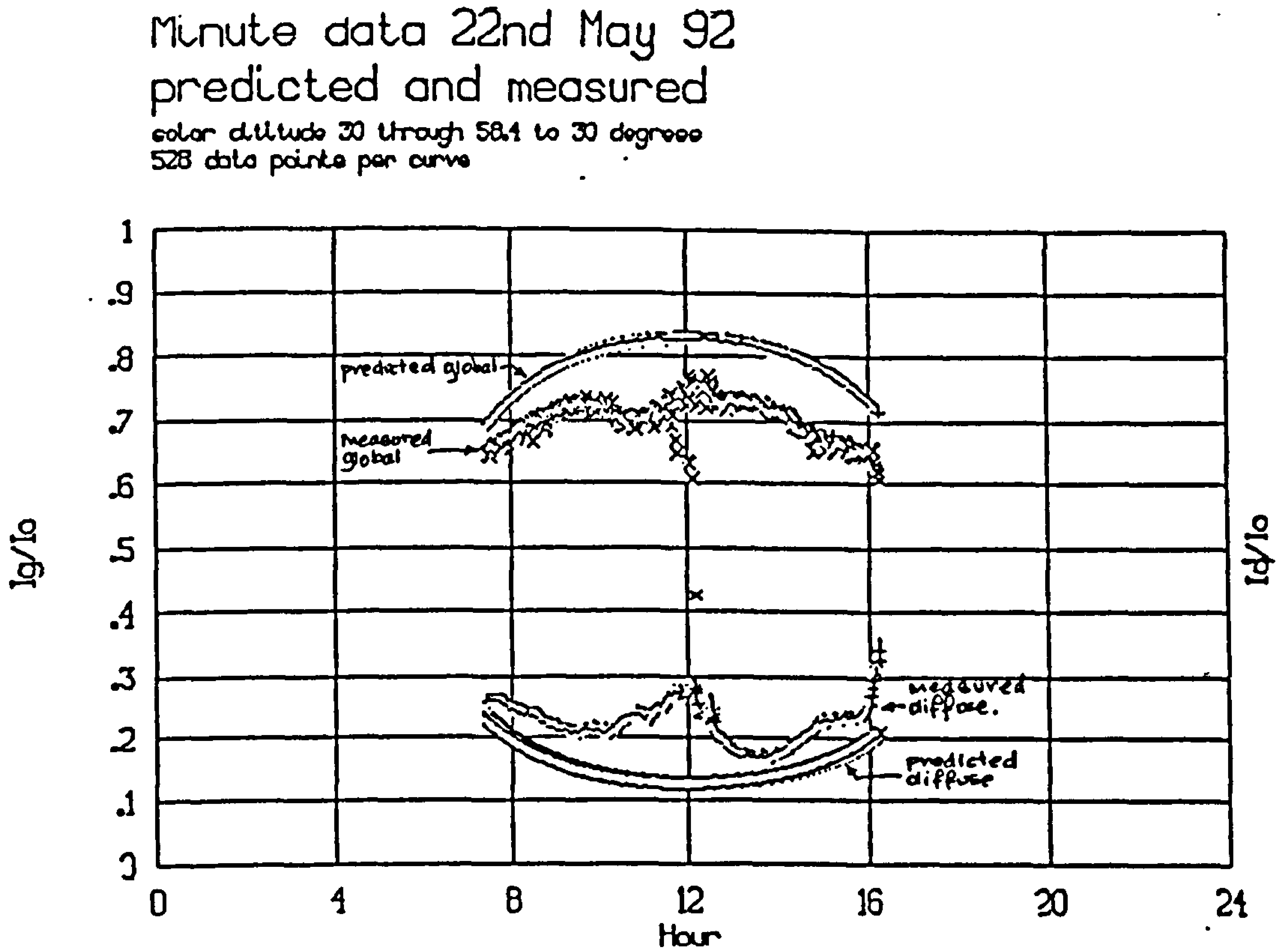

Figure 15.12 Measured global & diffuse transmittances with those predicted for clear-skies.

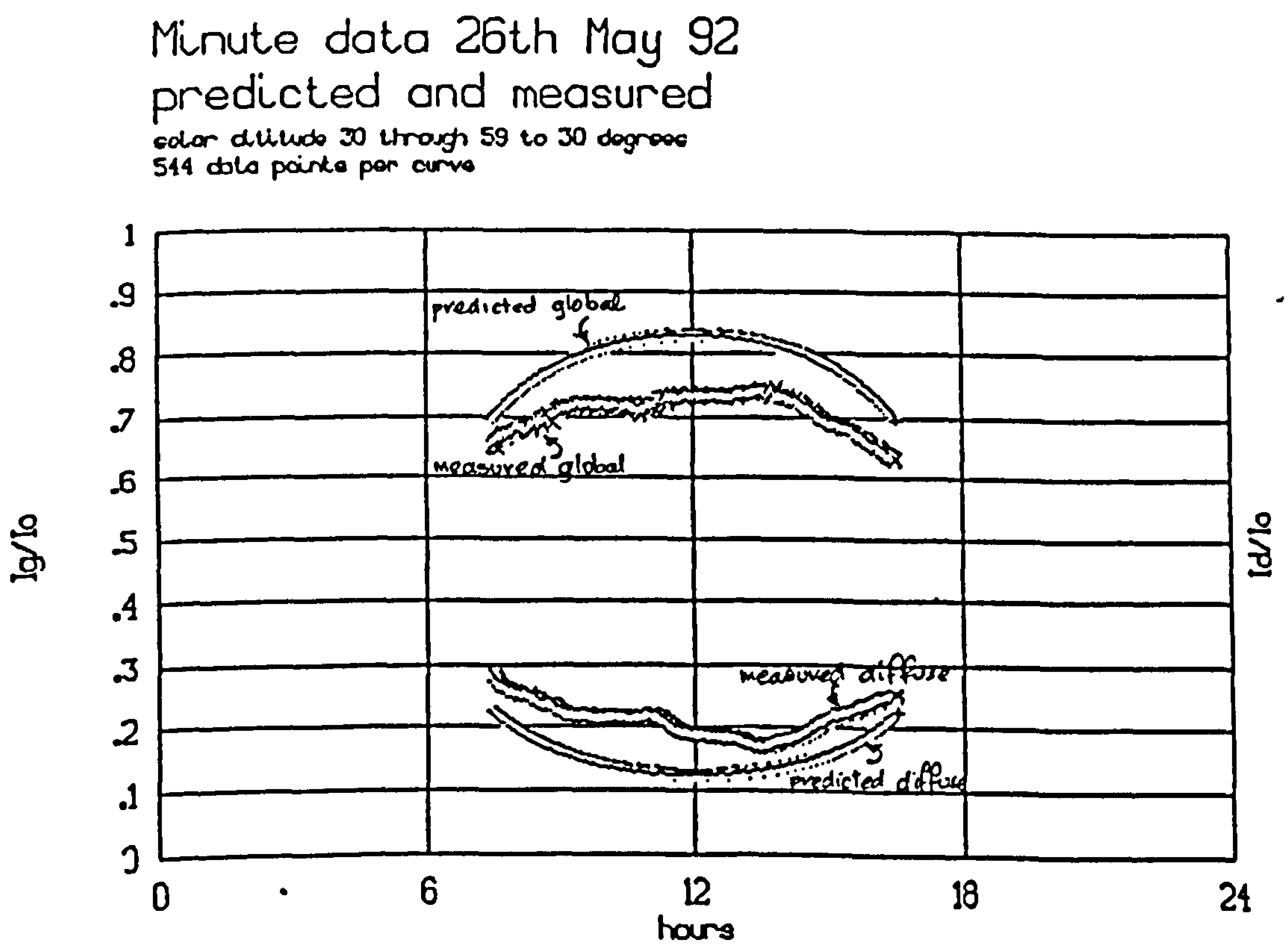

Figure 15.13 Measured global and diffuse transmittances with those predicted for clear-sky conditions.

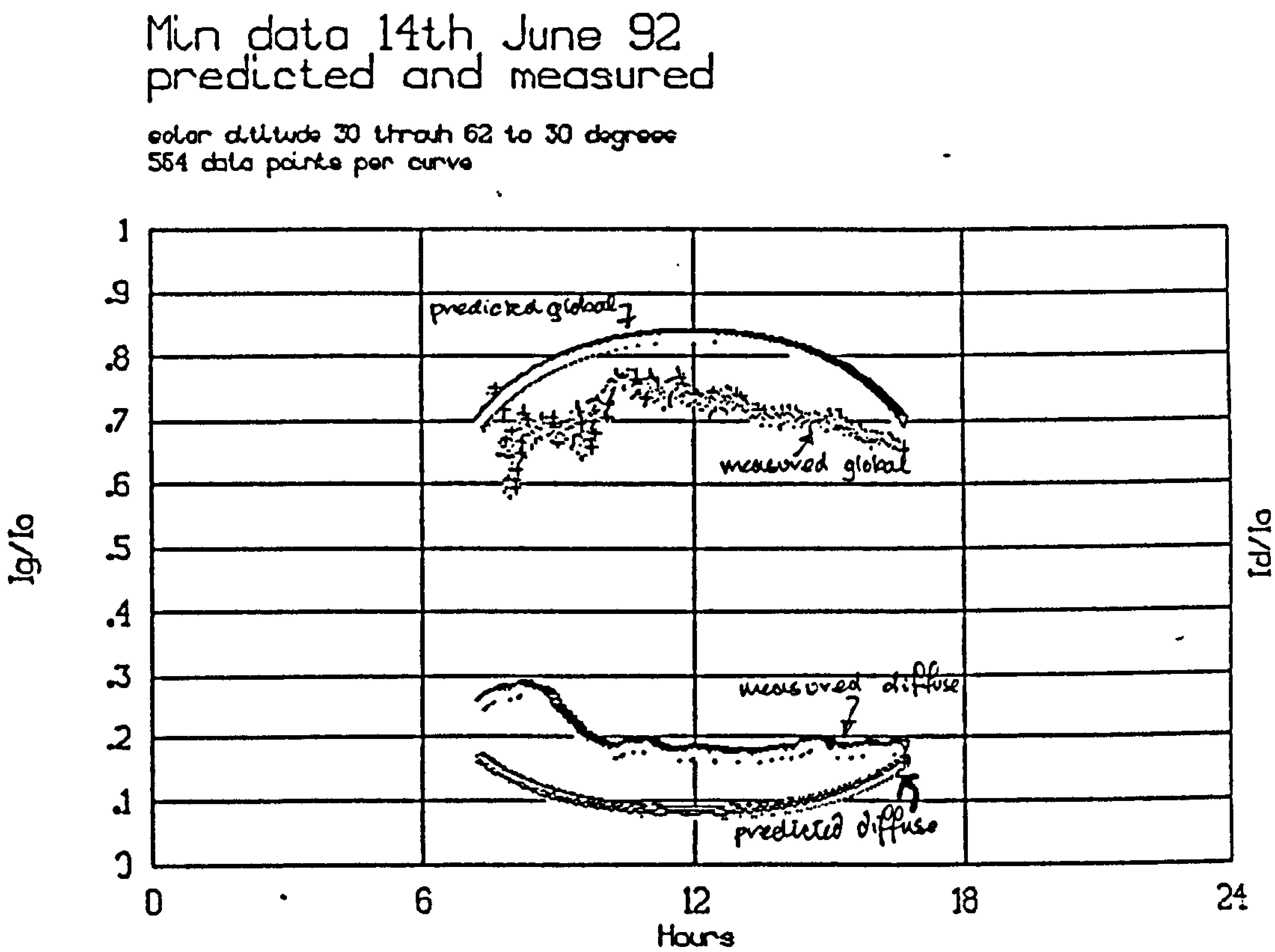

Figure 15.14 Measured global and diffuse transmittances with those predicted for clear-sky conditions.

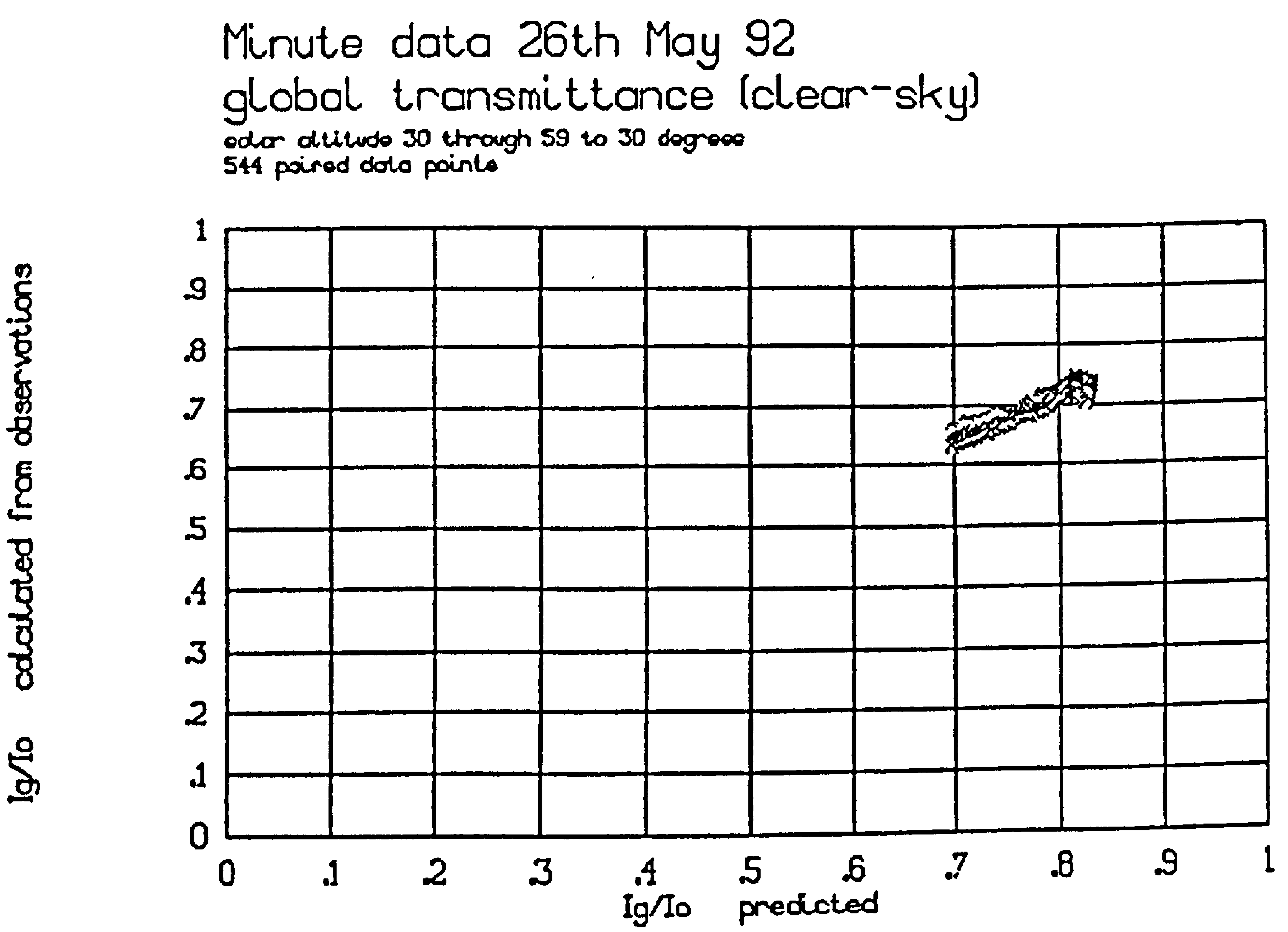

Figure 15.15 Measured and predicted global transmittance for clear-sky conditions.

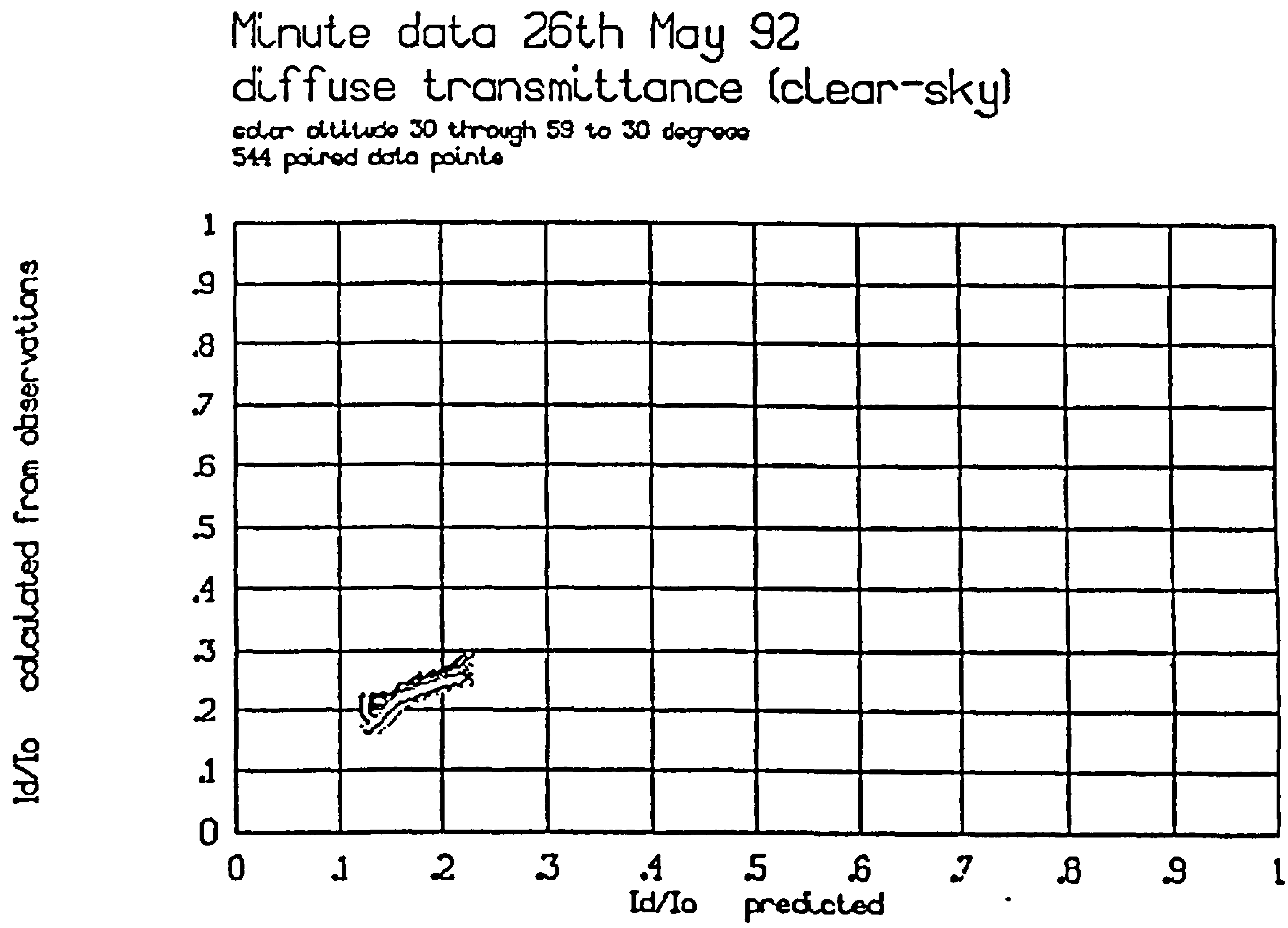

Figure 15.16 Measured and predicted diffuse transmittance for clear-sky conditions.

15.19 In the second test, the coefficient A was based on the value of the beam transmittance obtained from equation 14.13 with the scattering and absorption alowances as in equation 14.23 to permit an approximate prediction of the global and diffuse transmittances for apparently clear-skies relating to a more normal atmosphere from equations 14.22 and 14.23. Some typical results are shown in figures 15.17 to 15.22 inclusive, suggesting that this was a reasonable approximation.

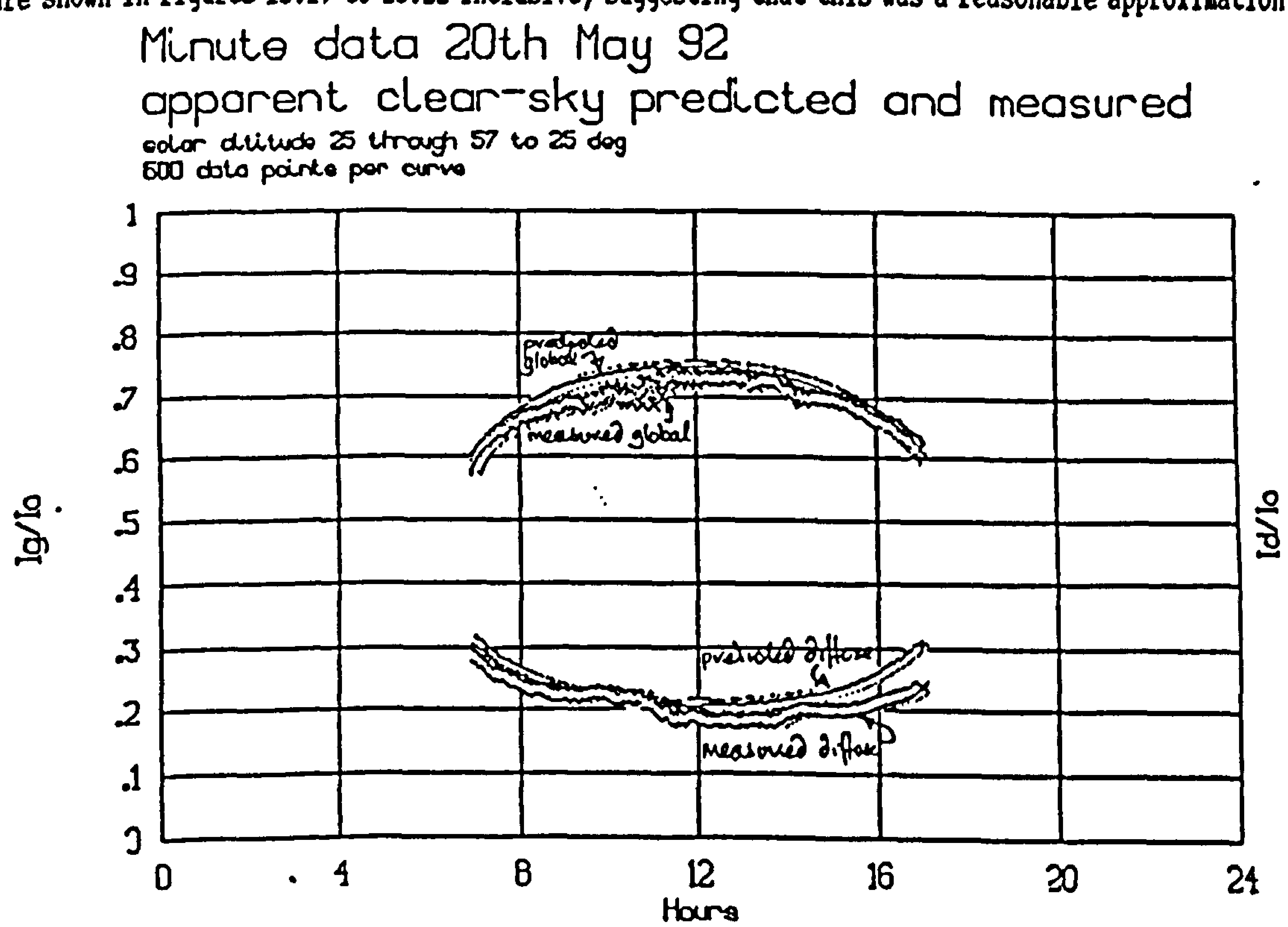

Figure 15.17 Measured and predicted global and diffuse transmittances.(apparently clear-sky)

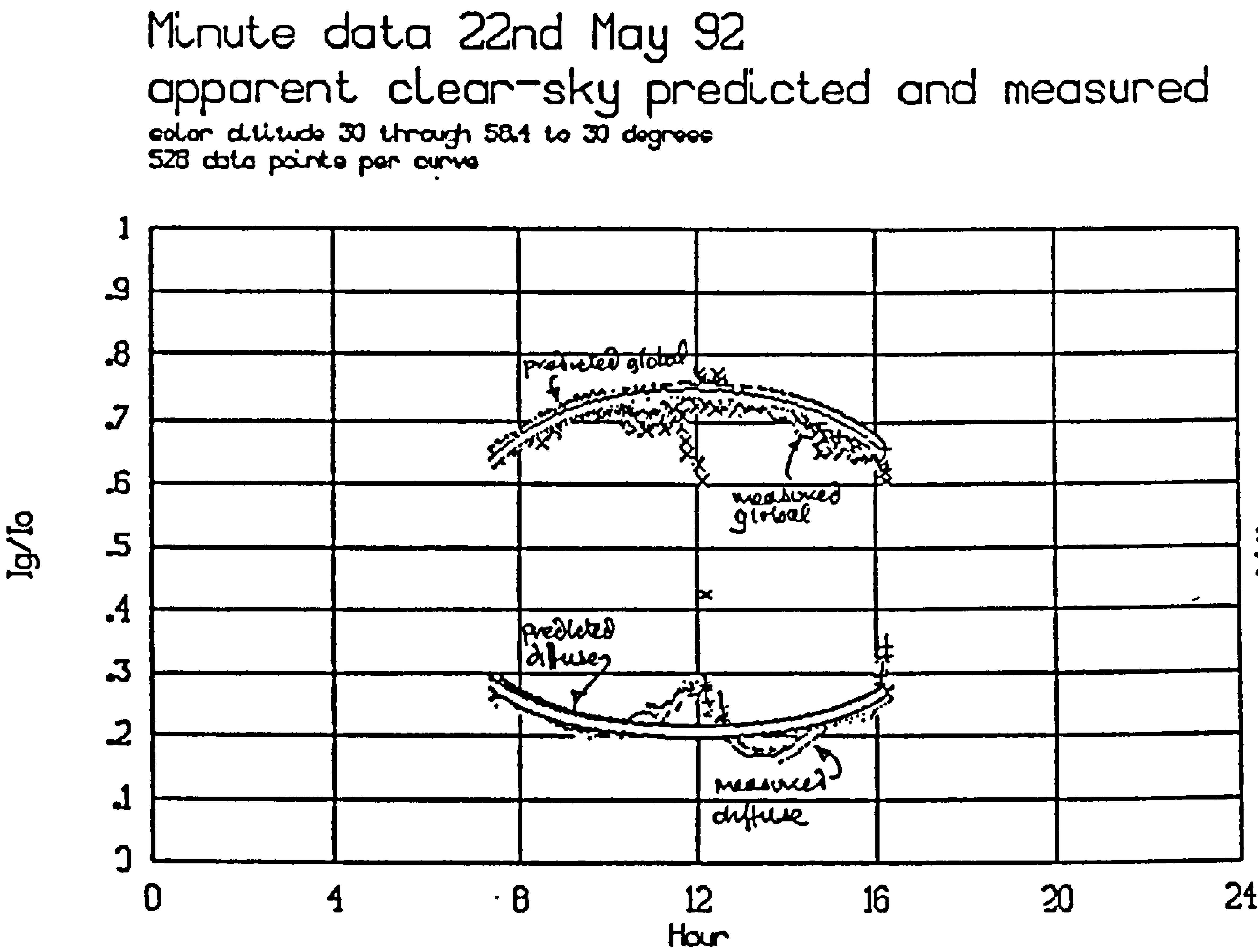

Figure 15.18 Measured and predicted global and diffuse transmittances.(apparently clear-sky)

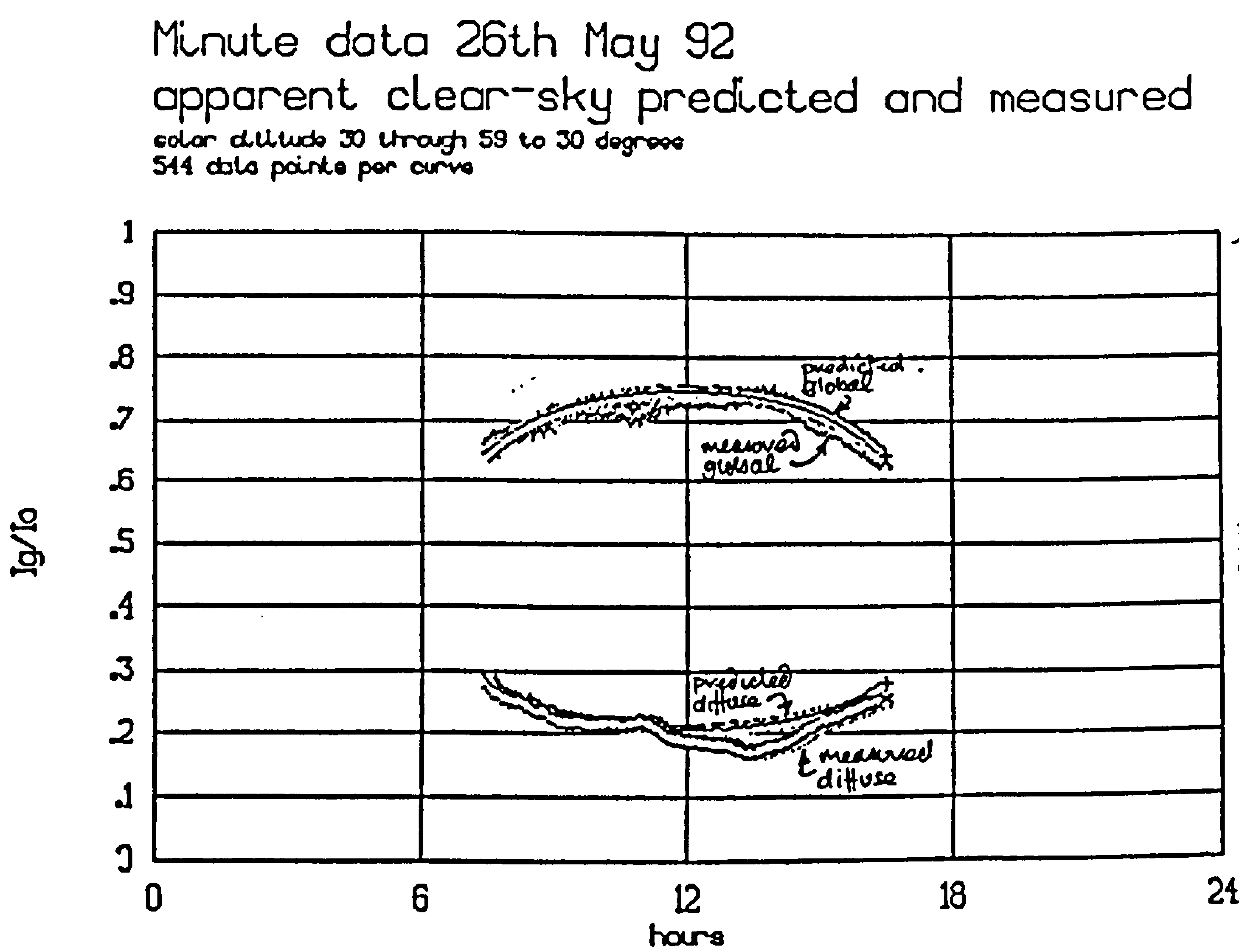

Figure 15.19 Measured and predicted global and diffuse transmittances.(apparently clear-sky)

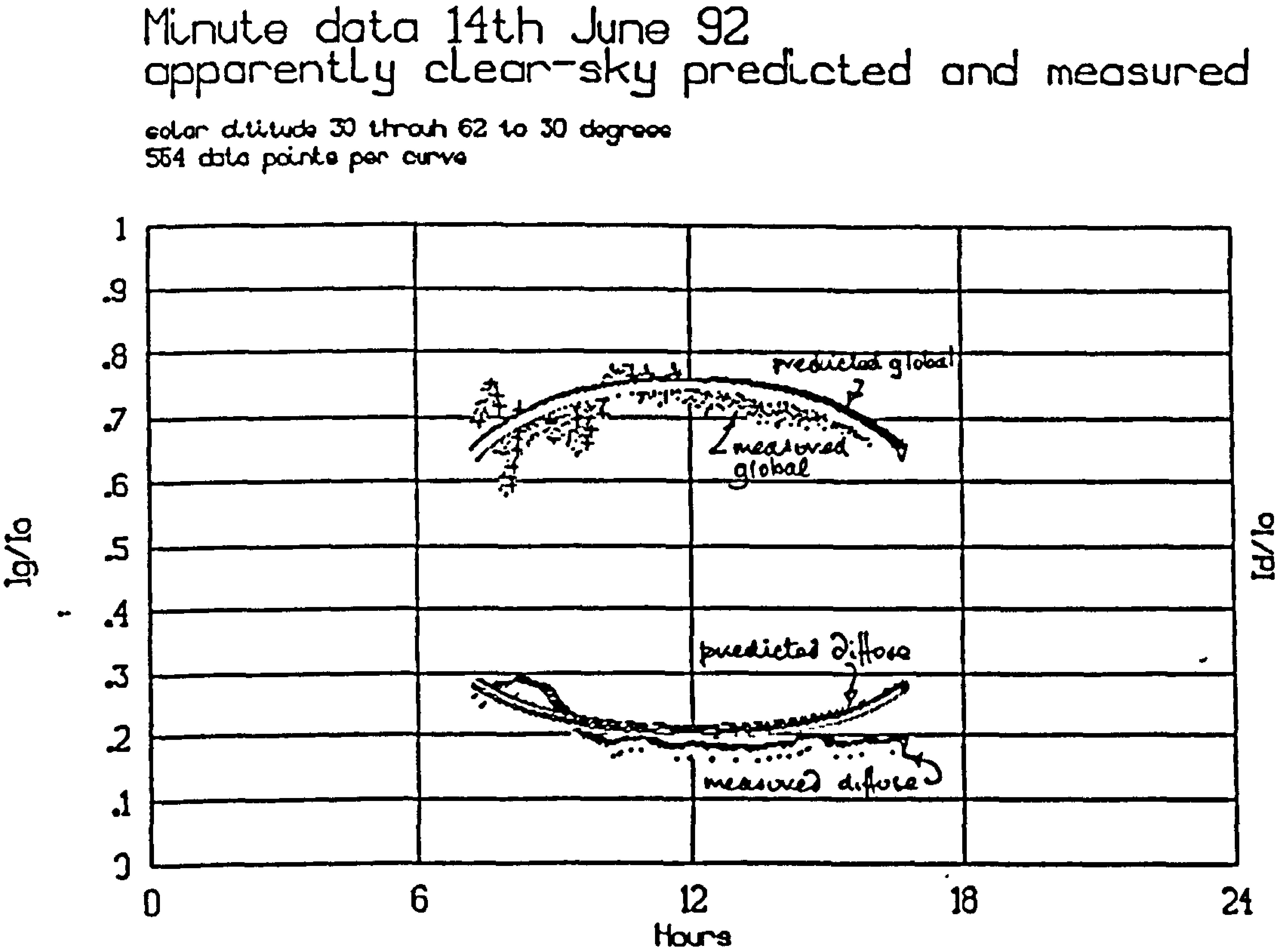

Figure 15.20 Measured and predicted global and diffuse transmittances.(apparently clear-sky)

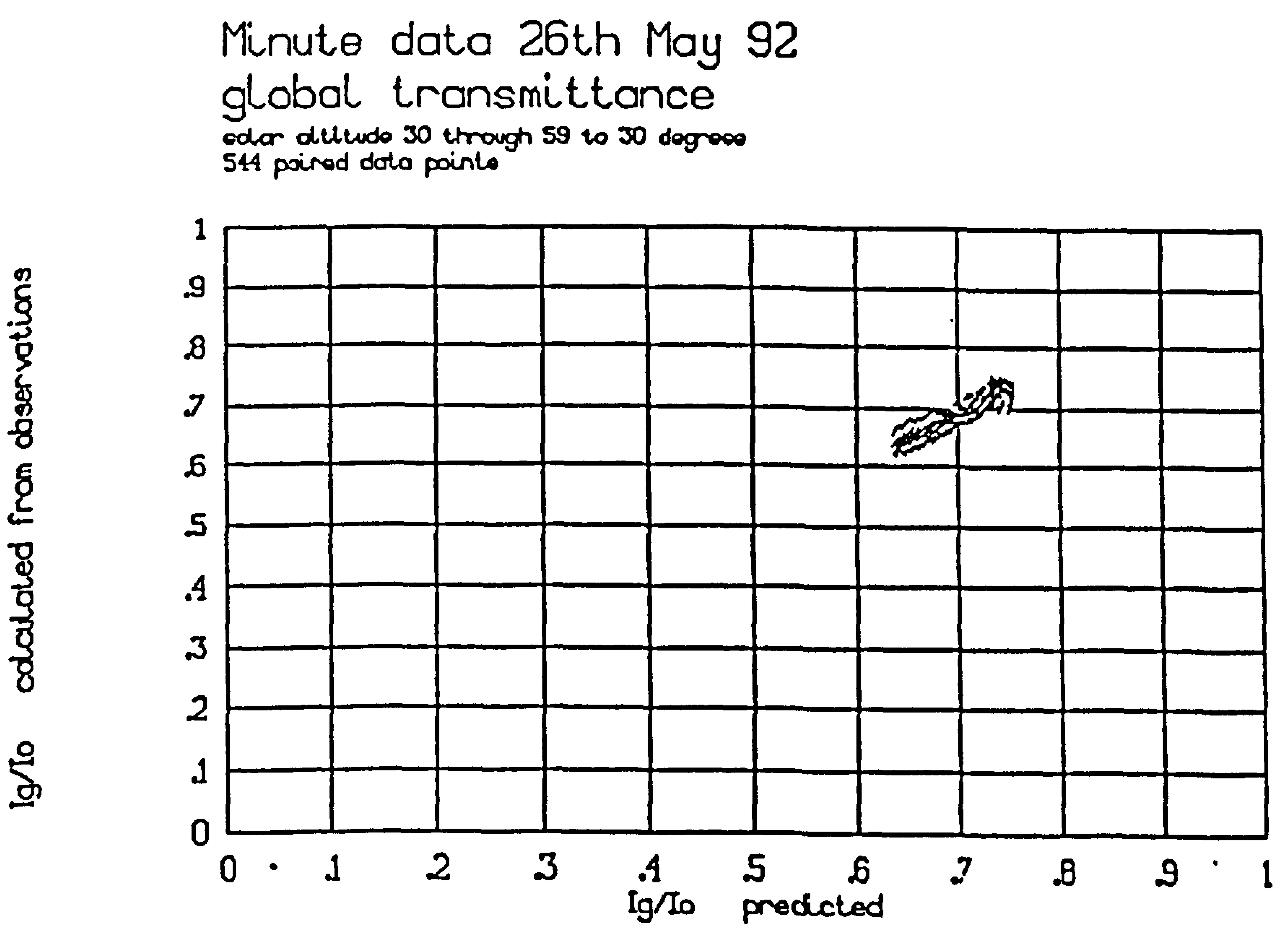

Figure 15.21 Measured and predicted global transmittance for an apparently clear-sky.

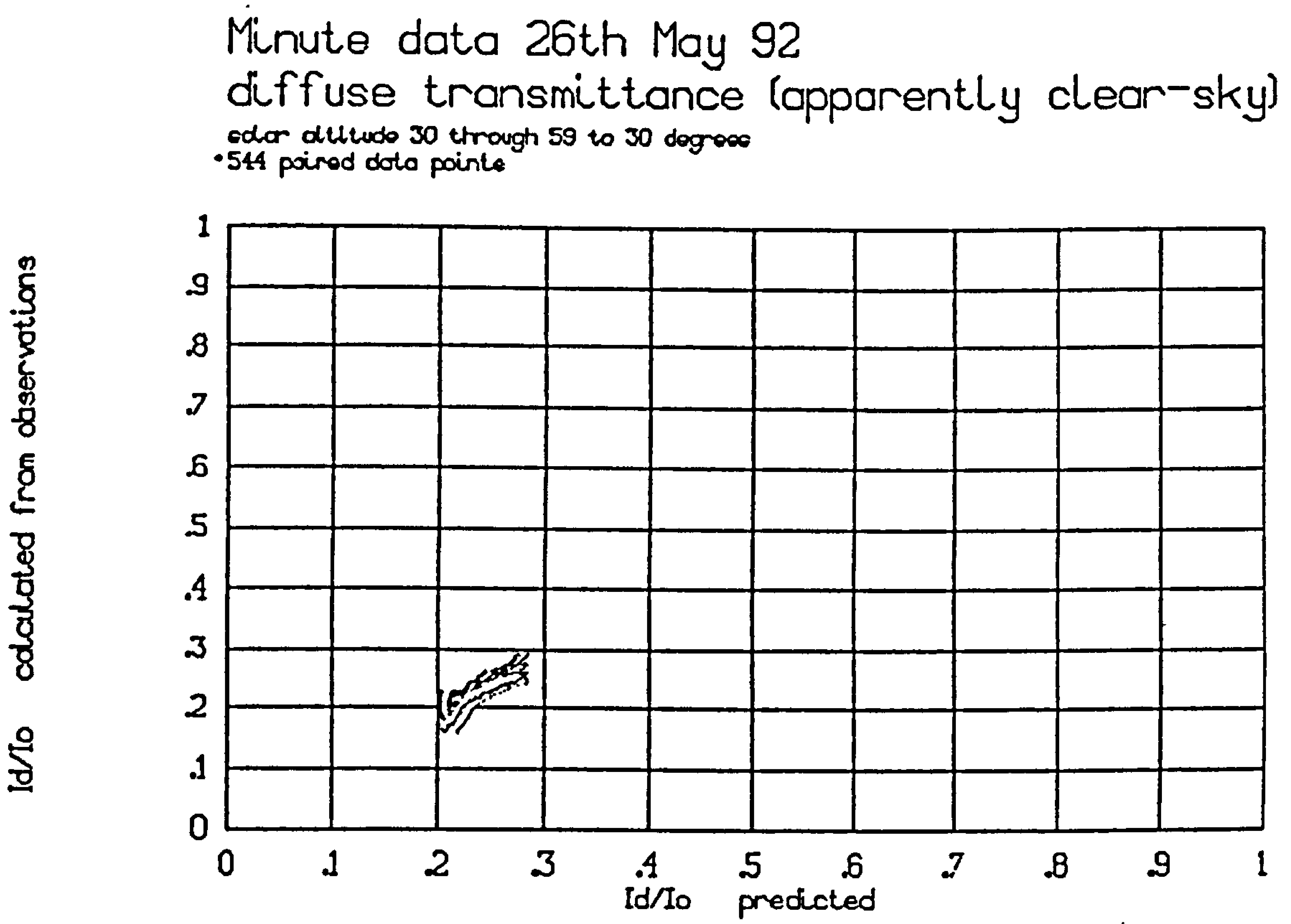

Figure 15.22 Measured and predicted diffuse transmittance for an apparently clear-sky.

15.20 As can be seen from figures 15.11 to 15.16, good correlations were evident between the hypothesis prediction of both the global horizontal transmittance and the diffuse transmittance on a minute by minute basis, and those obtained using the measured irradiance data. Table 15.2 lists the results of an error analysis using equations 13.26 and 13.27. The MBE and RMSE result of 0.02 and 0.05% respectively for the clear-sky predictions of global transmittance, and 0.05 and 0.1% for diffuse transmittance suggest that this method might reasonably be used to provide clear-sky irradiance estimates when no observation data is available. However, it should be noted that the spectral sensitivity of the sensors used can give rise to a measurement uncertainty of +/- 2%, to which must be added an estimated +/- 5% uncertainty in the observed diffuse transmittance determined using instruments fitted with shade-bands. The modified form for predicting apparently clear-sky transmittances(figures 15.17 to 15.22) resulted in even lower MBE and RMSE results. These results compare favourably with the RMSE of less than 6% and 9% reported by Gueymard(1993) for the global and direct-beam transmittances respectively of the best current clear-sky irradiance models.

15.21 The third test involved predictions using the curve fitting procedure described.[eqns 14.25 to 14.28] The curve fitted predictions for apparently clear-skies(figures 15.23 to 15.28) were also very accurate, which suggest that this method would be useful for predicting transmittances when only intermittent global horizontal irradiance observations are available, or possibly for predicting the diffuse transmittance under cloudy skies.

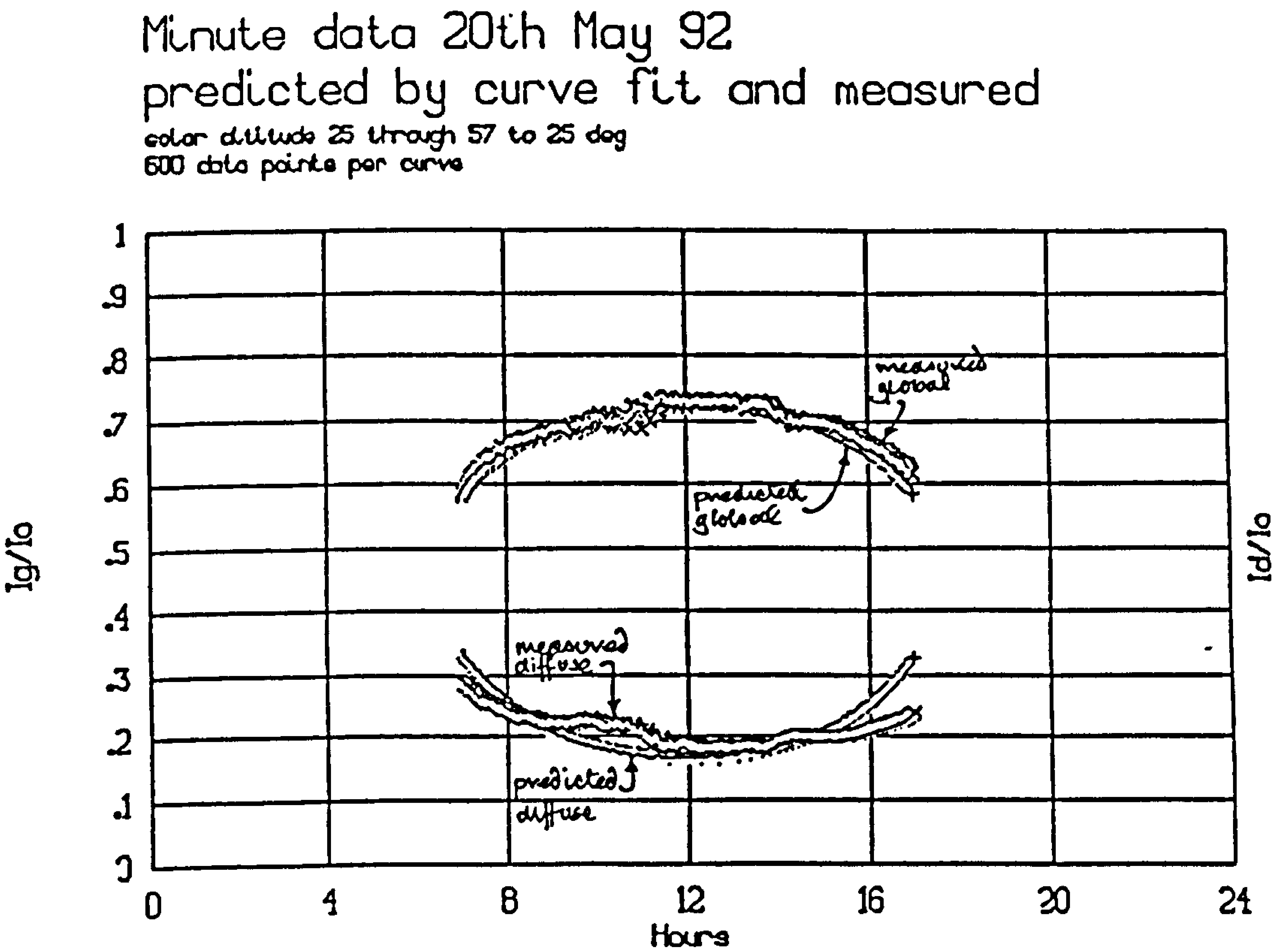

Figure 15.23 Measured & predicted transmittances: apparently clear-sky. (curve fitting procedure)

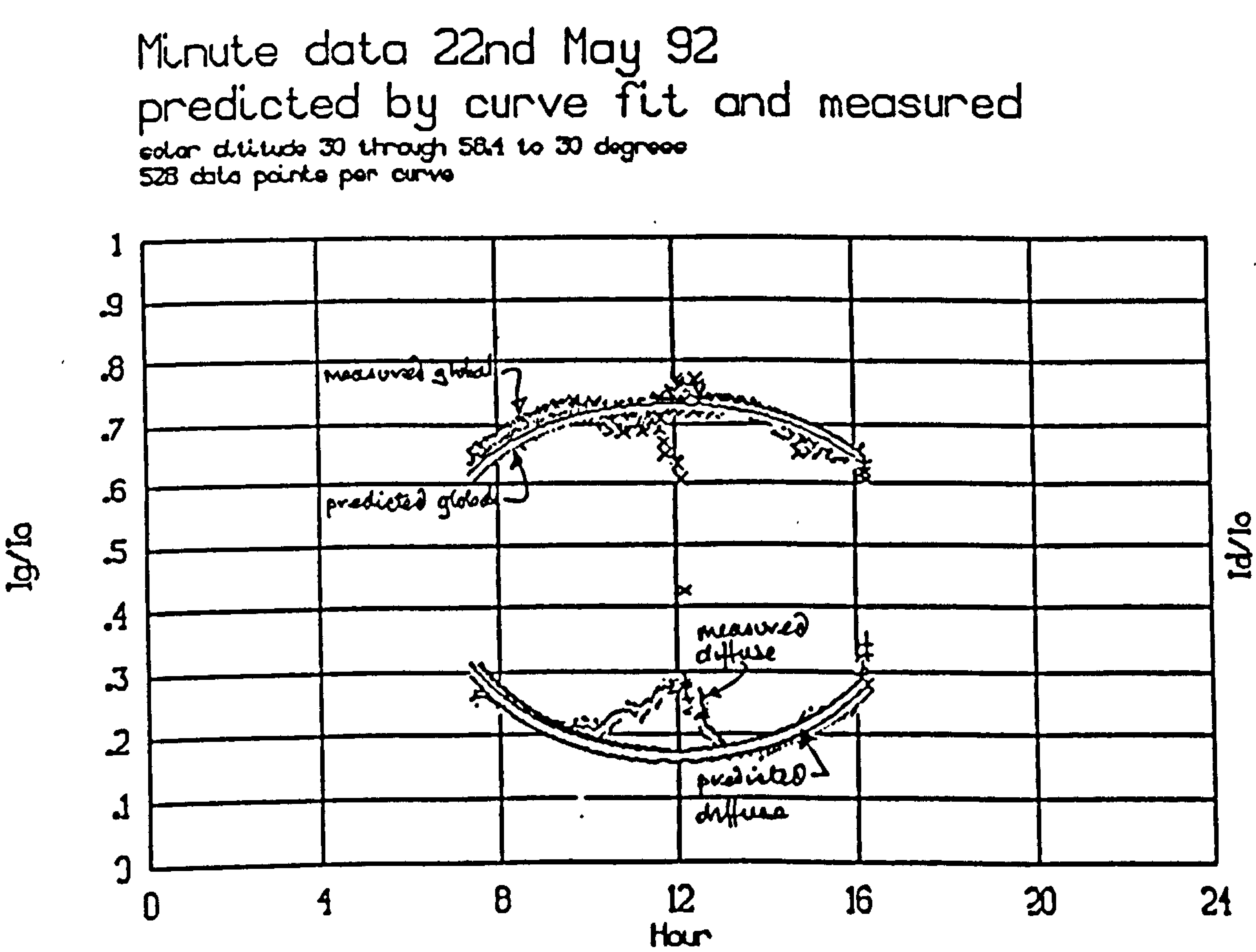

Figure 15.24 Measured & predicted transmittances: apparently clear-sky.(curve fitting procedure)

Table 15.2 Error analysis: transmittance predictions.

Results of Mean Bias Error and Root Mean Square Error calculations [equations 13.26 & 13.27]

Data	transmittance of global irradiance		transmittance of diffuse irradiance	
figure (date)	MBE	RMSE	MBE	RMSE
15.11 (20-05)	0.000 261 5	0.005 939 2	-0.000 510 6	0.011 600 0 (clear)
15.12 (22-05)	0.000 254 6	0.005 849 2	-0.000 610 0	0.014 019 9 (clear)
15.13 (26-05)	0.000 221 0	0.005 154 9	-0.000 519 0	0.012 108 3 (clear)
15.14 (14-06)	0.000 219 5	0.005 211 8	-0.000 427 0	0.010 148 5 (clear)
15.17 (20-05)	0.000 063 0	0.001 437 0	0.000 162 7	0.003 696 9 (app clr)
15.18 (22-05)	0.000 054 7	0.001 256 9	0.000 011 6	0.000 266 6 (app clr)
15.19 (26-05)	0.000 029 5	0.000 687 2	0.000 119 0	0.002 775 0 (app clr)
15.20 (14-06)	0.000 033 1	0.000 786 7	0.000 239 6	0.005 689 5 (app clr)
15.21 (26-05)	0.000 029 5	0.000 687 2	--- --- -	--- --- - (app clr)
15.22 (26-05)	--- --- -	--- --- -	0.000 119 0	0.002 775 0 (app clr)
15.23 (20-05)	-0.000 019 0	0.000 422 9	-0.000 088 0	0.002 008 5 (fit)
15.24 (22-05)	0.000 005 6	0.000 128 4	-0.000 189 0	0.004 339 5 (fit)
15.25 (26-05)	0.000 006 8	0.000 158 9	-0.000 103 0	0.002 412 5 (fit)
15.26 (14-06)	0.000 241 0	0.000 572 0	0.000 121 9	0.002 894 9 (fit)
15.31 (06-09)	--- --- -	--- --- -	0.000 111 4	0.002 171 8 (o'cast)
15.35 (06-07)	--- --- -	--- --- -	0.000 156 9	0.003 709 7 (cloudy)
15.36 (13-10)	0.000 031 6	0.000 632 4	0.000 200 7	0.004 018 6 (fit)
15.36 (13-10)	--- --- -	--- --- -	0.001 539 8	0.030 834 8 (clear)
15.38 (05-09)	--- --- -	--- --- -	0.000 111 4	0.002 171 8 (vis)
15.39 (06-07)	--- --- -	--- --- -	0.000 156 9	0.003 709 7 (vis)

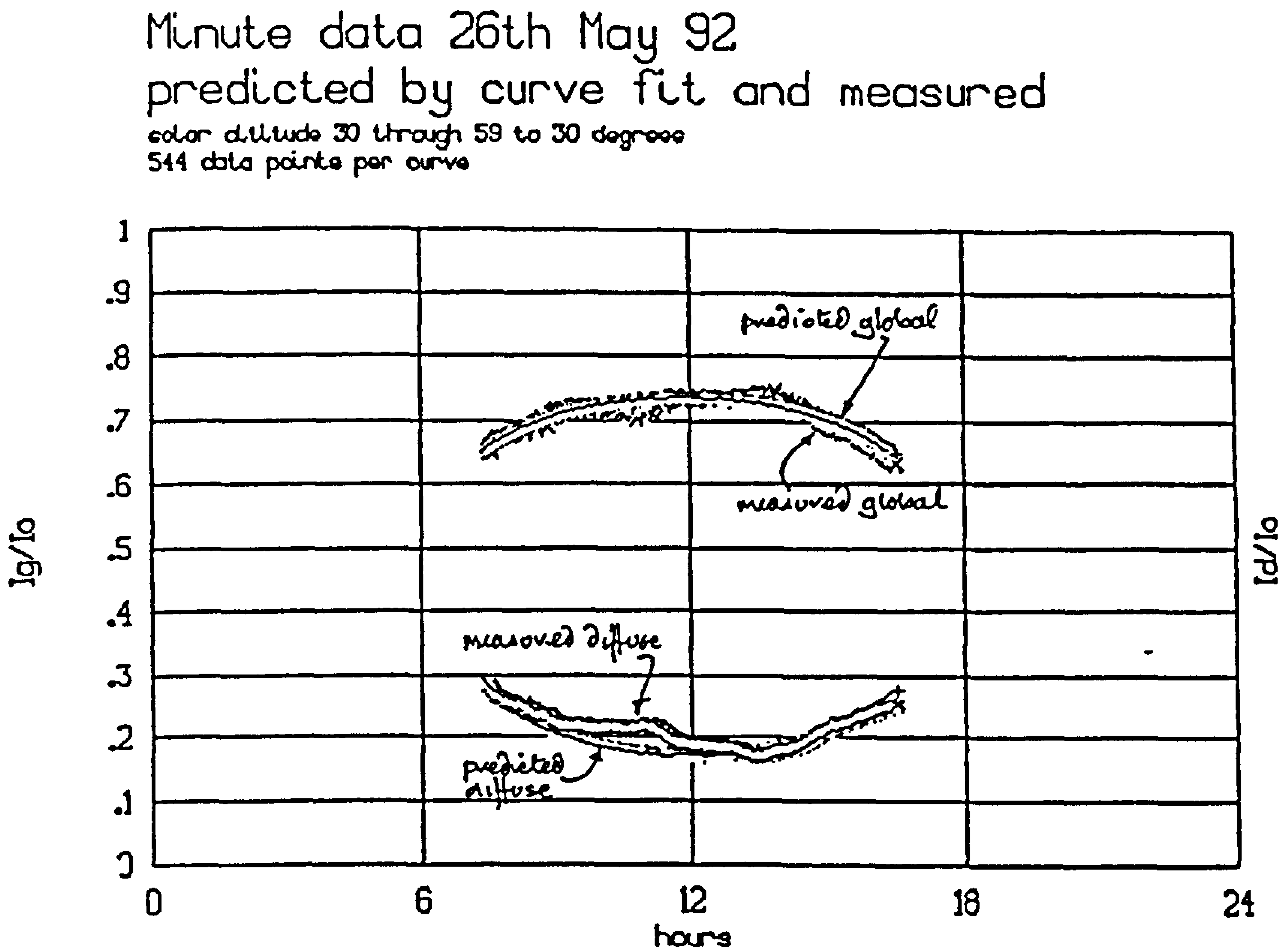

Figure 15.25 Measured and predicted global and diffuse transmittances for an apparently clear-sky.(curve fitting procedure)

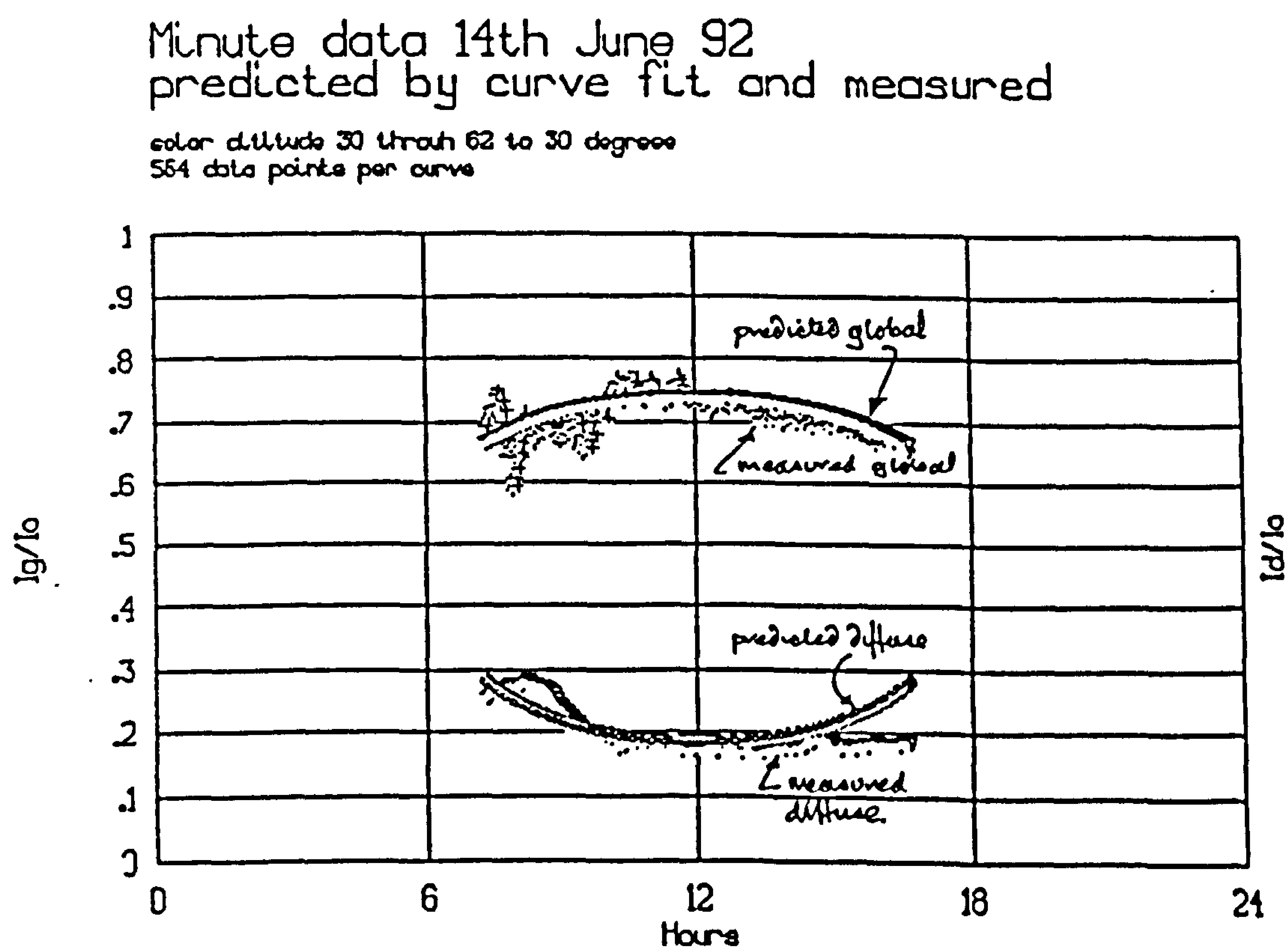

Figure 15.26 Measured and predicted global and diffuse transmittances for an apparently clear-sky.(curve fitting procedure)

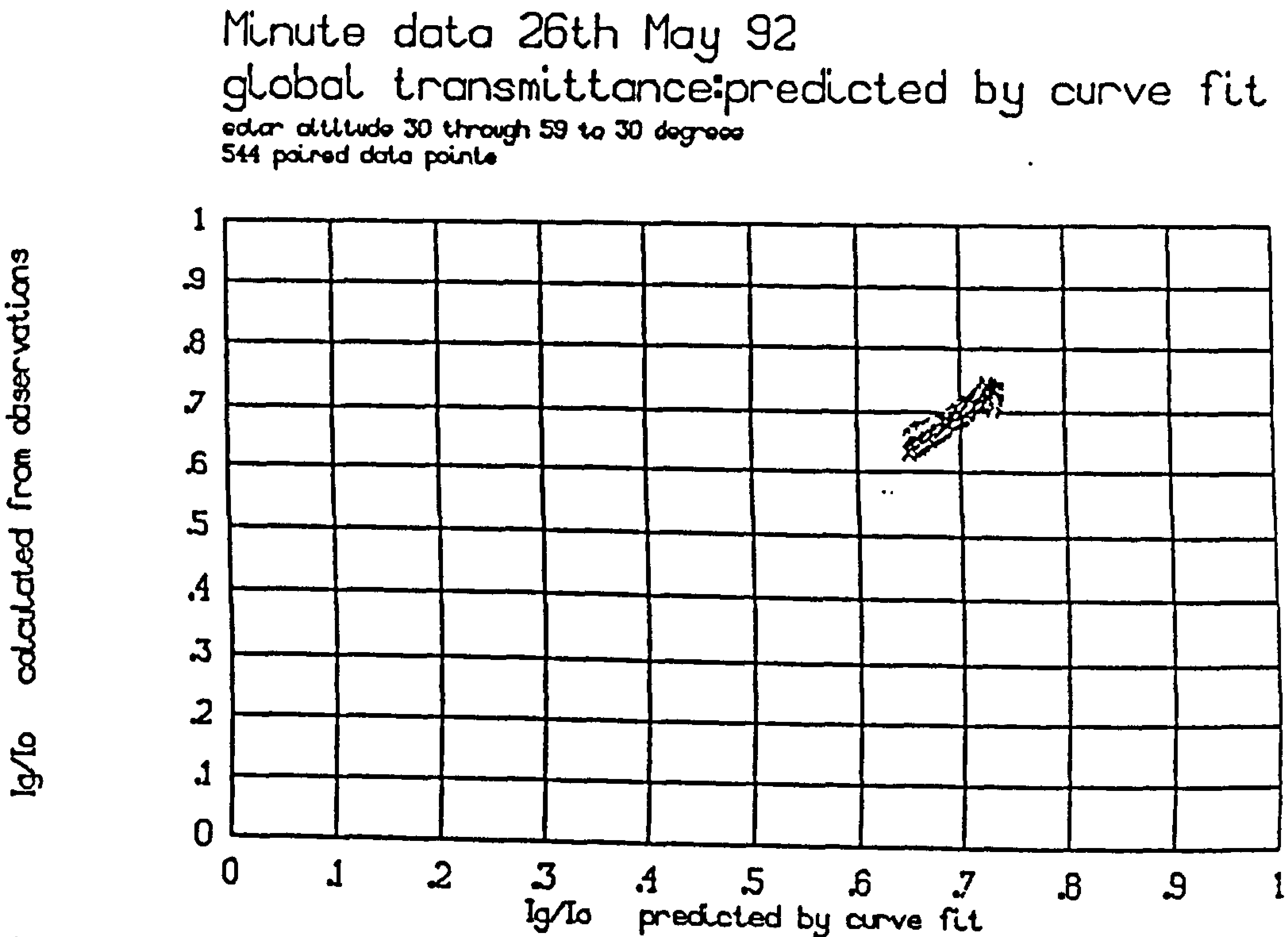

Figure 15.27 Measured & predicted global transmittance: apparently clear-sky.(curve fit procedure)

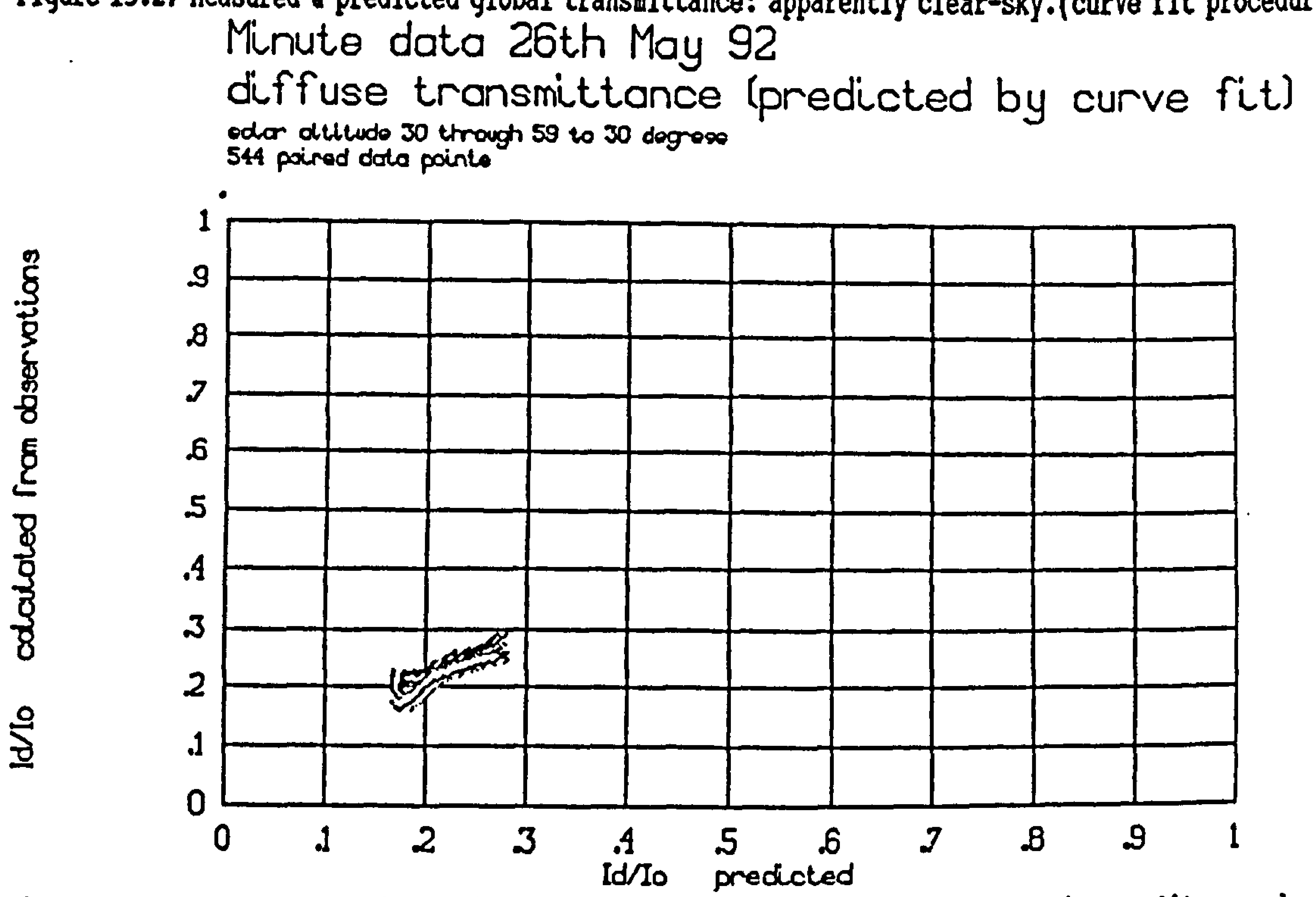

Figure 15.28 Measured & predicted diffuse transmittance: apparently clear-sky.(curve fit procedure)

15.22 Appendix D contains an example of a correlation result for a larger range of solar altitudes. The model was not expected to be satisfactory over a larger range of zenith distances. (plane parallel assumption and lack of allowance for the curvature of the Earth). The procedure used to test the hypotheses for cloudy days was carried out in two stages. The first dealt with overcast days, of which the data illustrated in figures 15.29 to 15.31 was fairly typical.

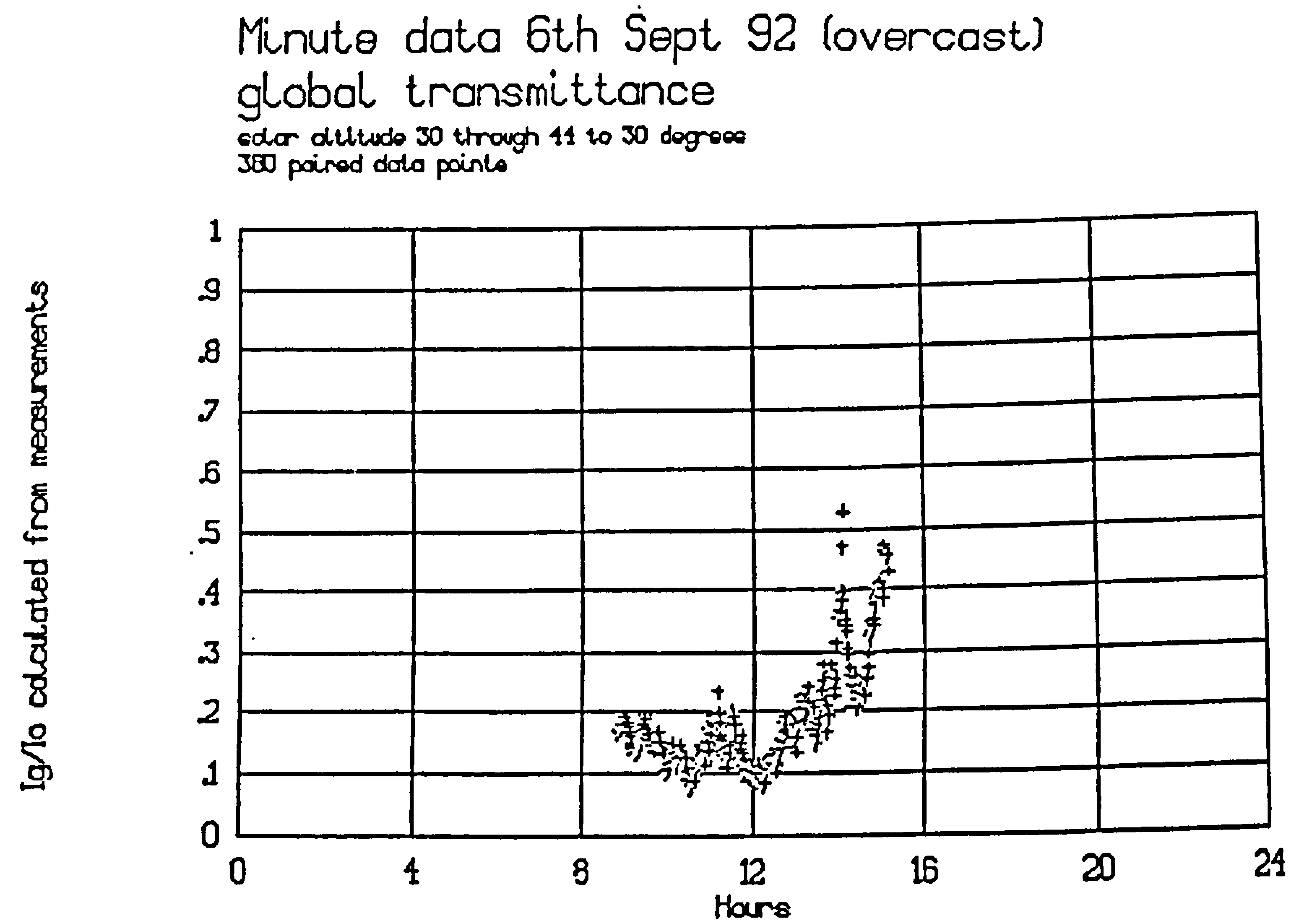

Figure 15.29 Measured Global horizontal transmittances on an overcast day.

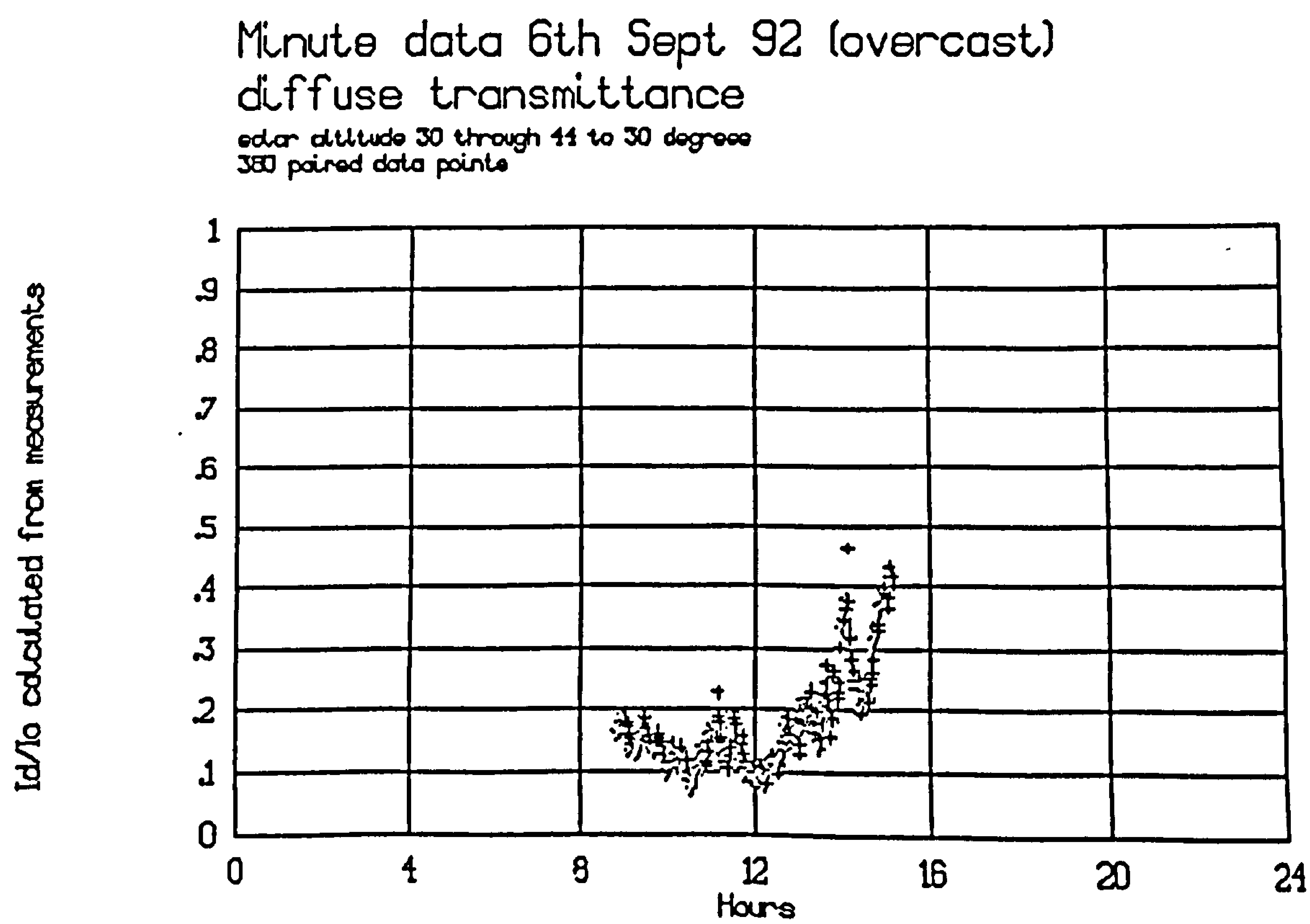

Figure 15.30 Measured diffuse transmittances on an overcast day.

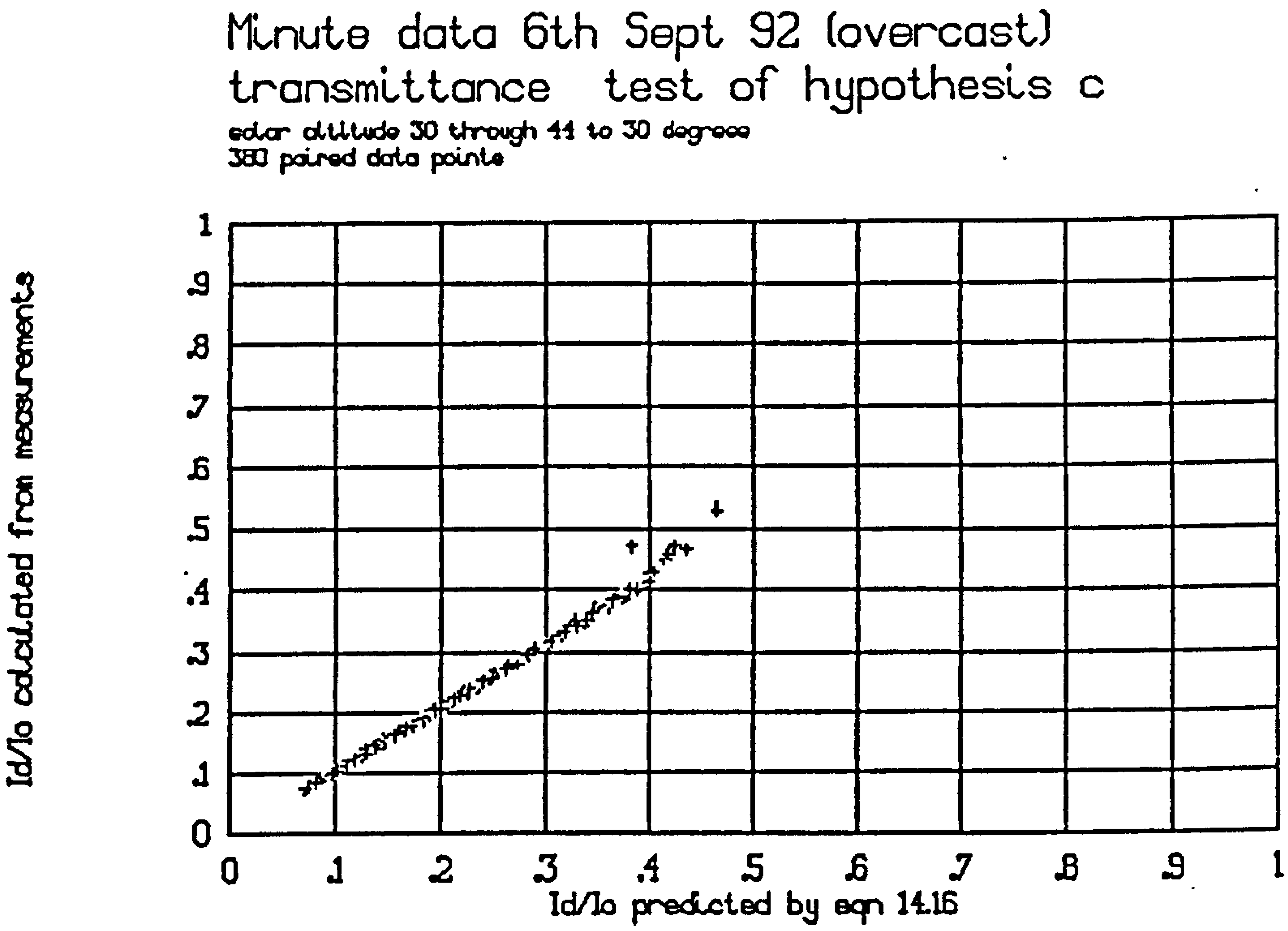

Figure 15.31 Measured to predicted[eqn 14.16] diffuse transmittances : overcast day.

15.23 This result was replicated, and supports the hypothesis,[eqn 14.16] suggesting that it might be possible to combine this expression with that for the clear-sky and clearness index[eqn 14.24] to predict the approximate diffuse transmittance for cloudy sky conditions as shown in the following results:

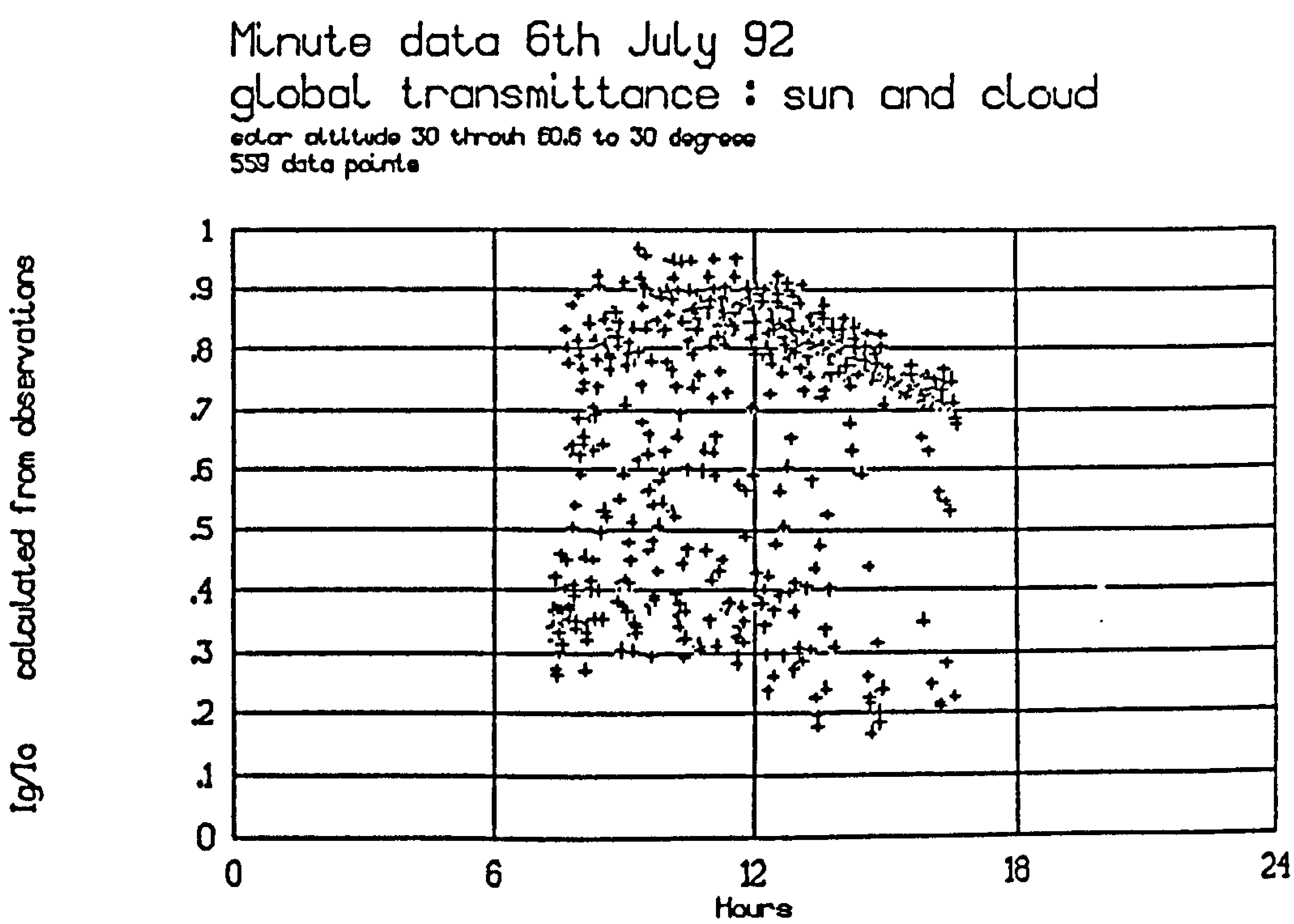

Figure 15.32 Transmittance of global irradiance. (cloudy day with sunshine)

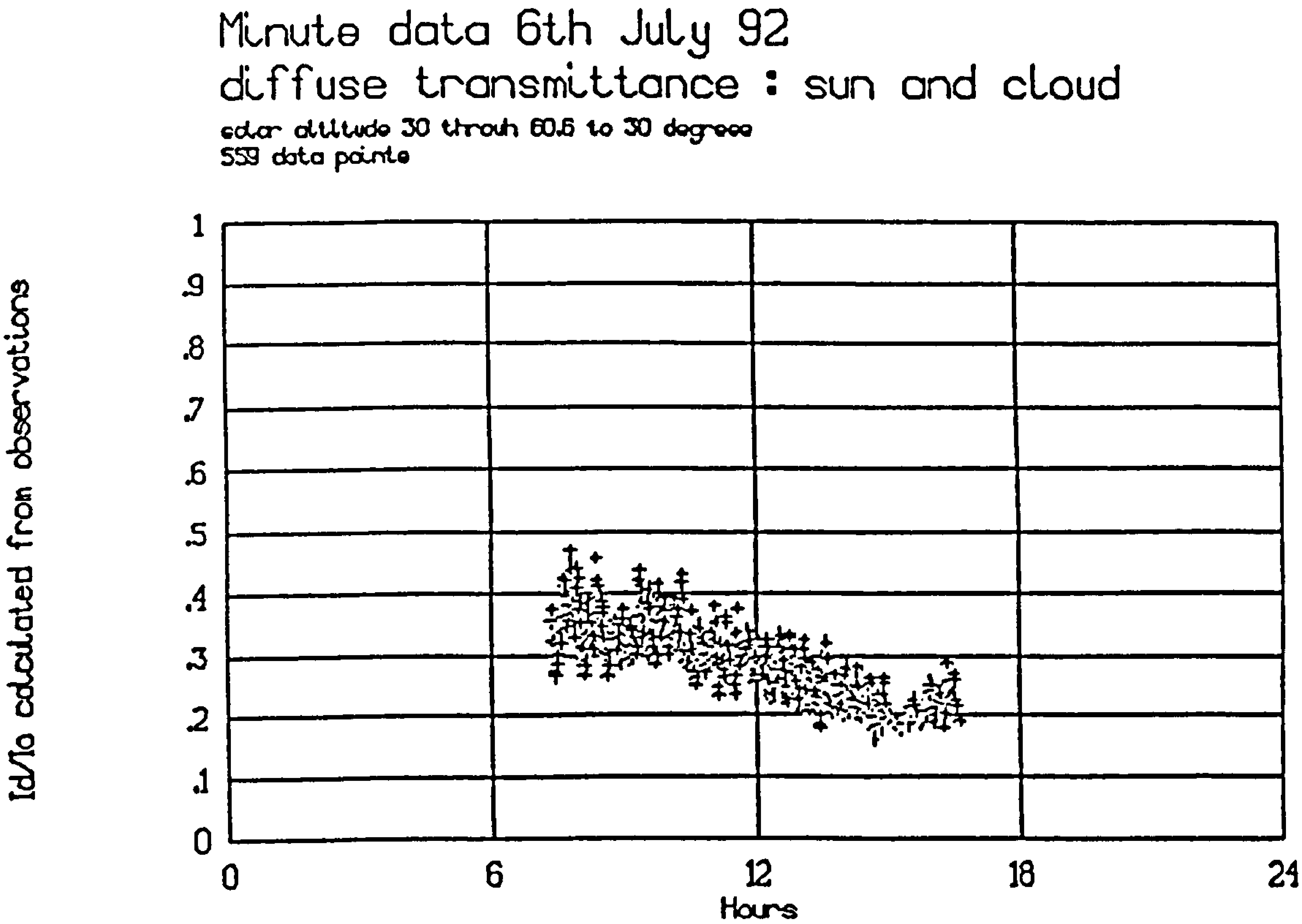

Figure 15.33 Transmittance of diffuse irradiance. (cloudy day with sunshine)

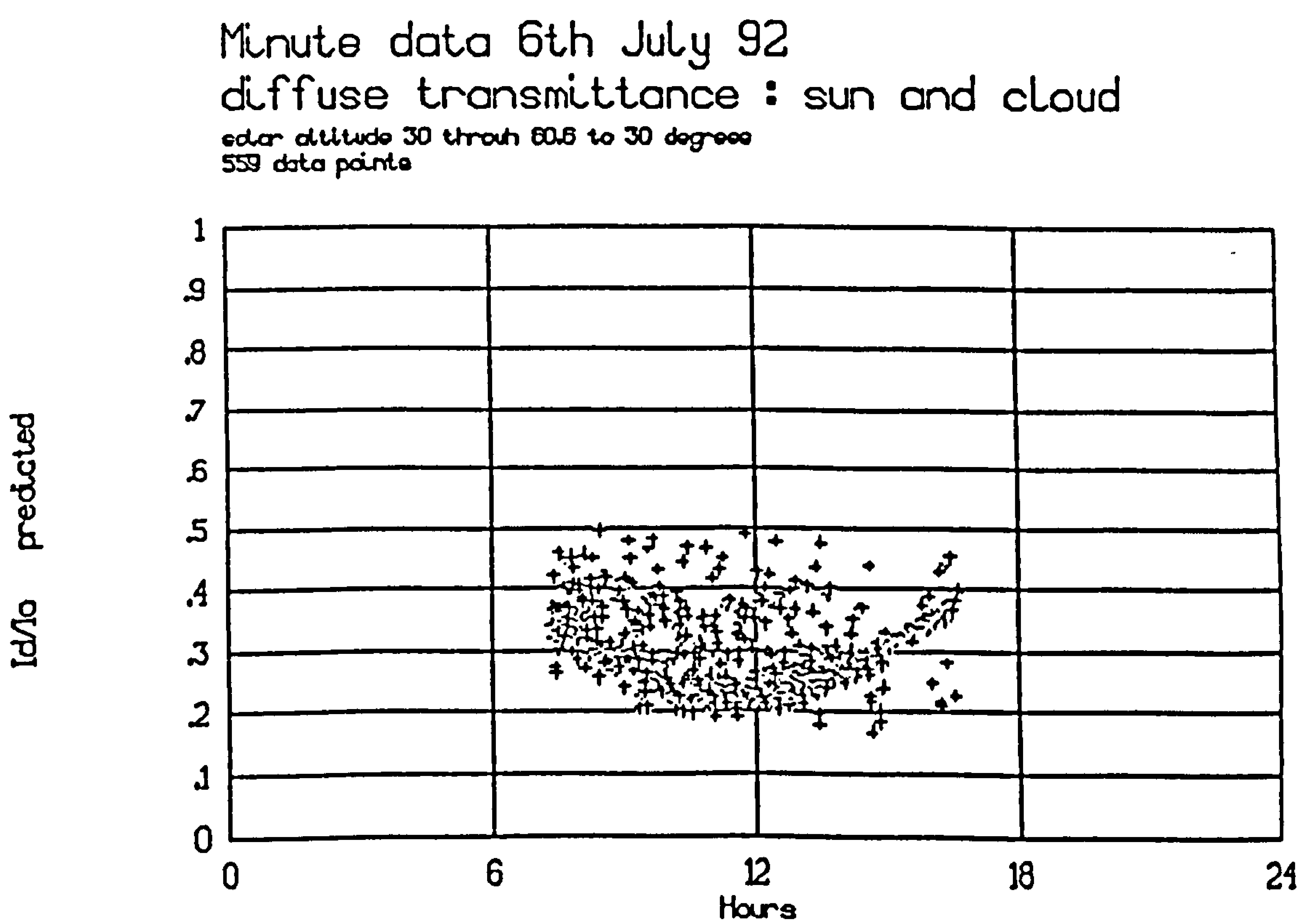

Figure 15.34 Predicted transmittance of diffuse irradiance. (cloudy day with sunshine)

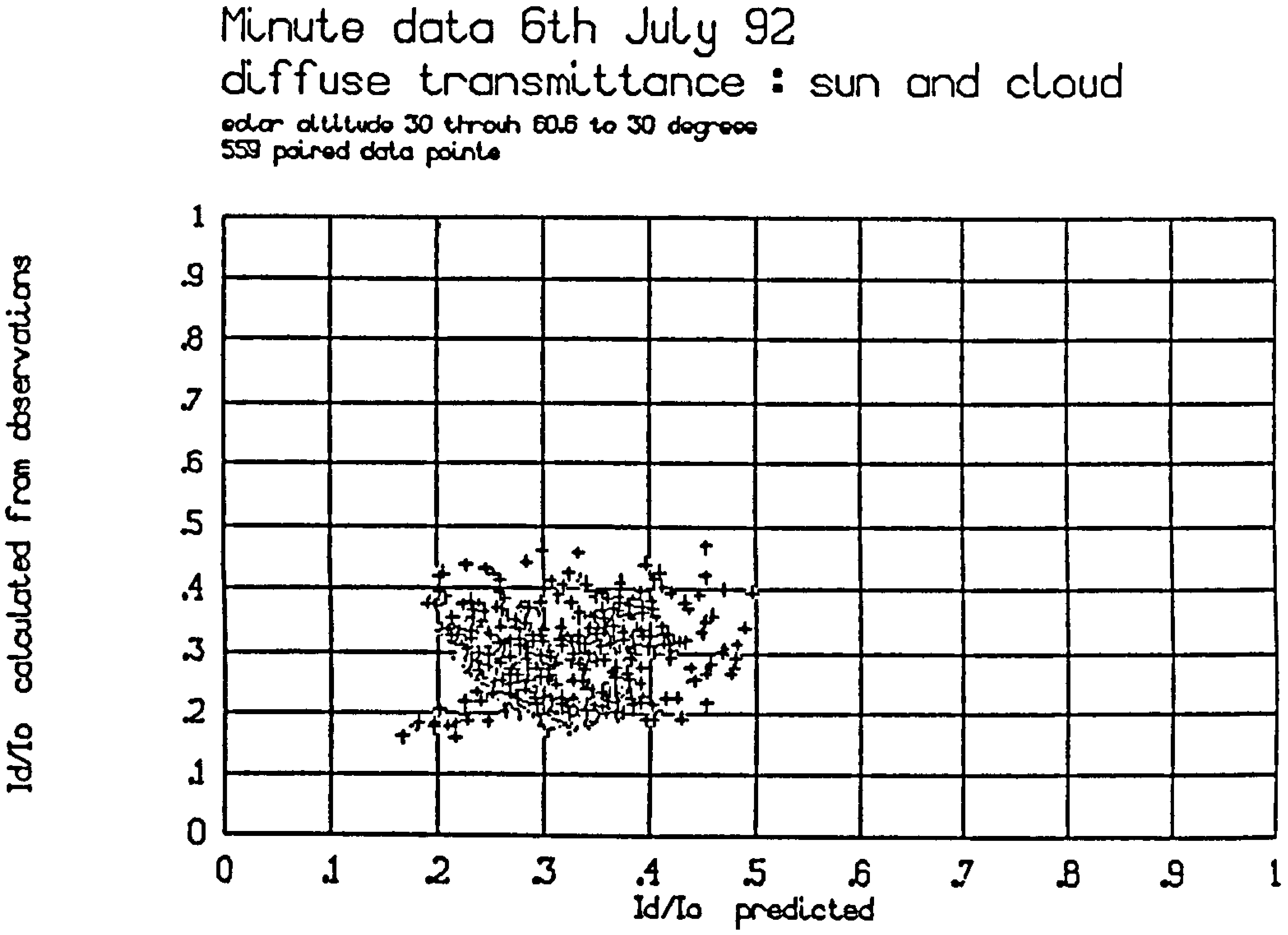

Figure 15.35 Measured and predicted diffuse transmittance. (cloudy day with sunshine) [eqns 14.16 & 14.24]

15.24 However, from a visual assessment of the observations recorded, it was evident that the overcast sky assumption was not always appropriate for values of Kt <= 0.5 under other sky conditions. An example of this can be demonstrated as follows(figure 15.36) for a sunny, and hazy October day with significant attenuation, but little scatter evident in the recorded data.

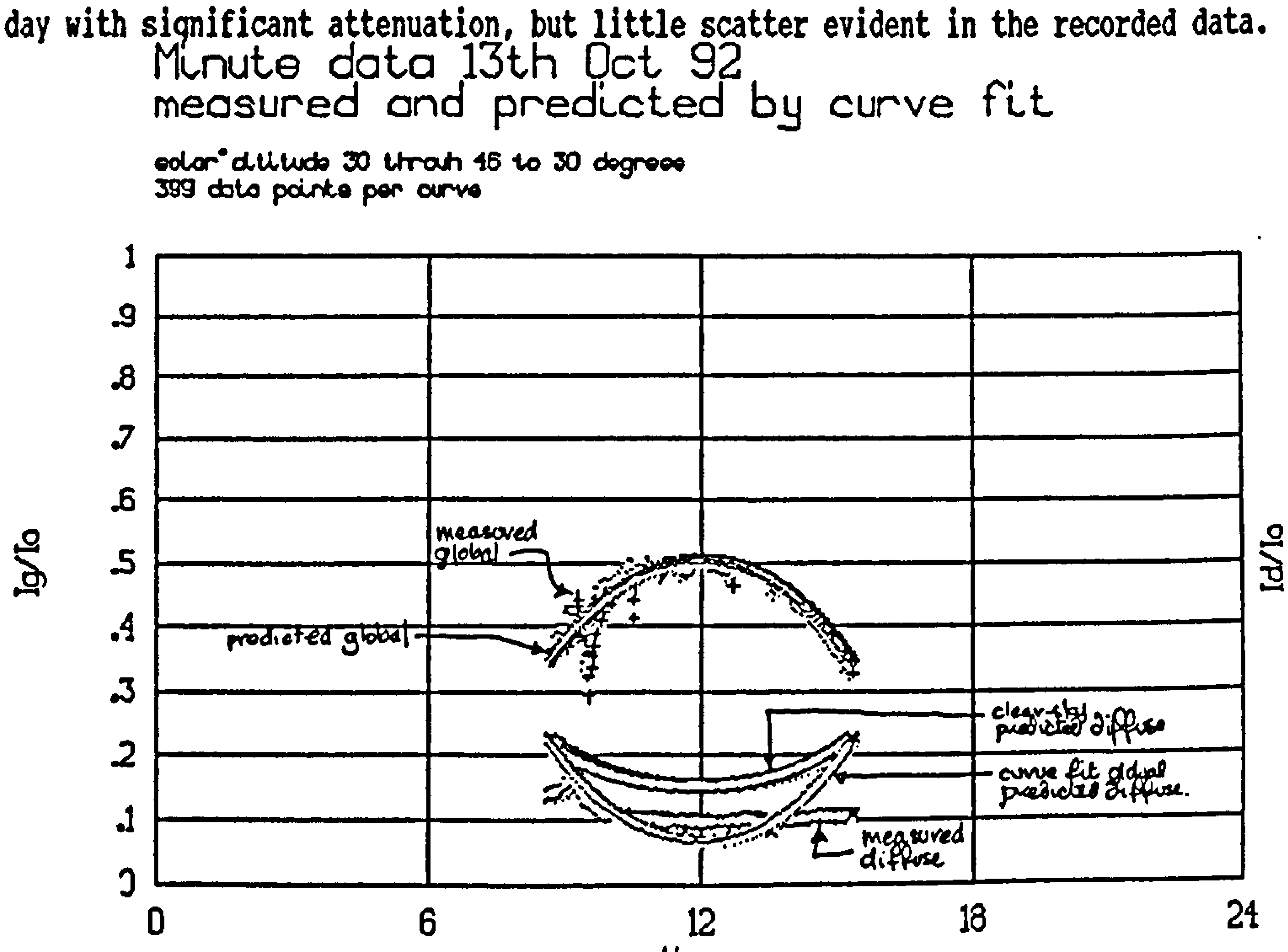

Figure 15.36 measured global transmittance compared with that predicted by the curve fitting procedure, together with diffuse transmittance measured and predicted by eqns 14.22 & 14.28.

15.25 Finally, the fraction of the broadband solar irradiance available outside the atmosphere, which was received as global horizontal irradiance was plotted against the equivalent fraction of the extraterrestrial irradiance in the visible spectrum, for clear-sky, cloudy, and overcast conditions. A linear relationship was evident, of which figures 15.38 and 15.39 are typical.

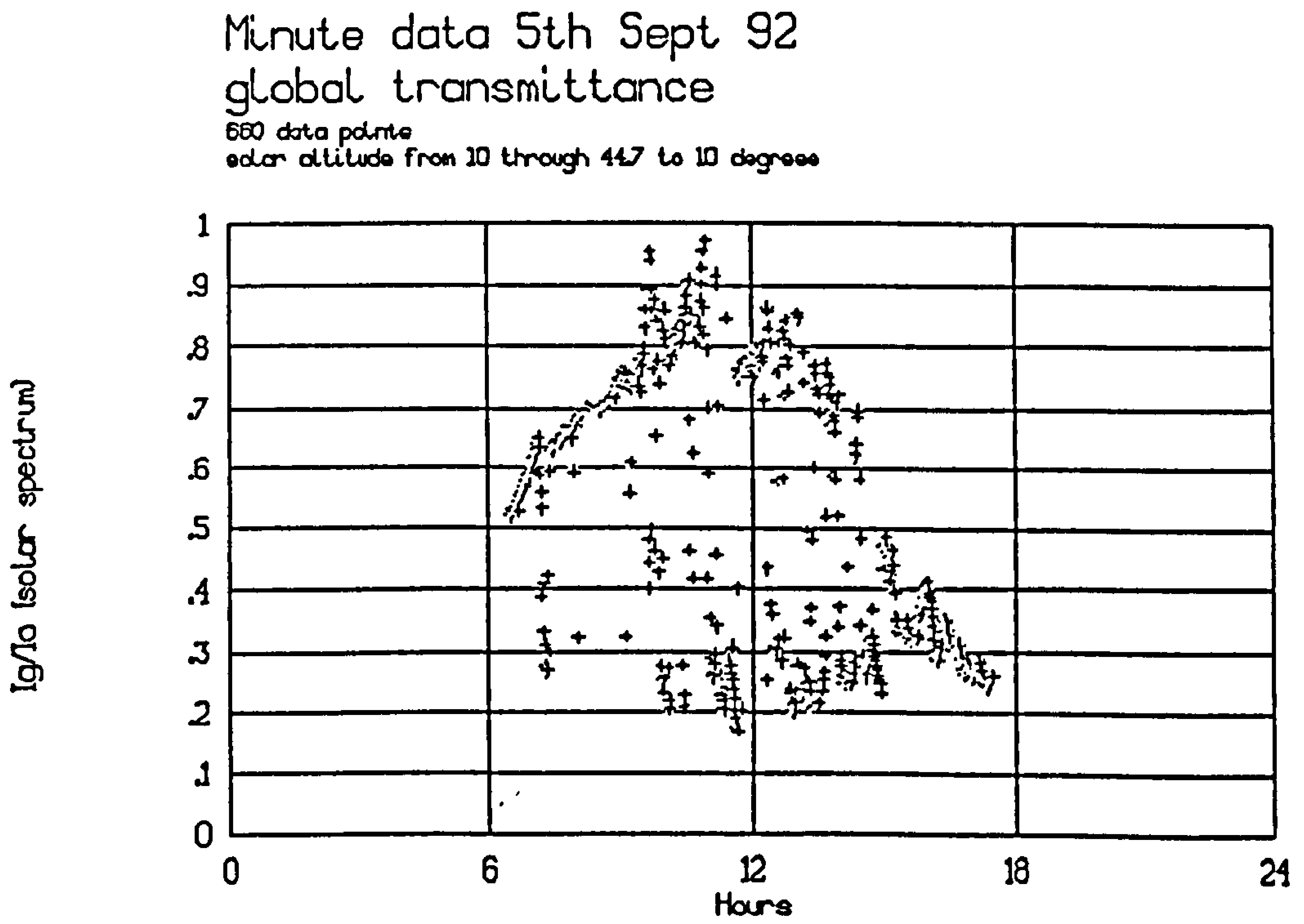

Figure 15.37 Measured global horizontal broadband solar transmittance.(sun & cloud)

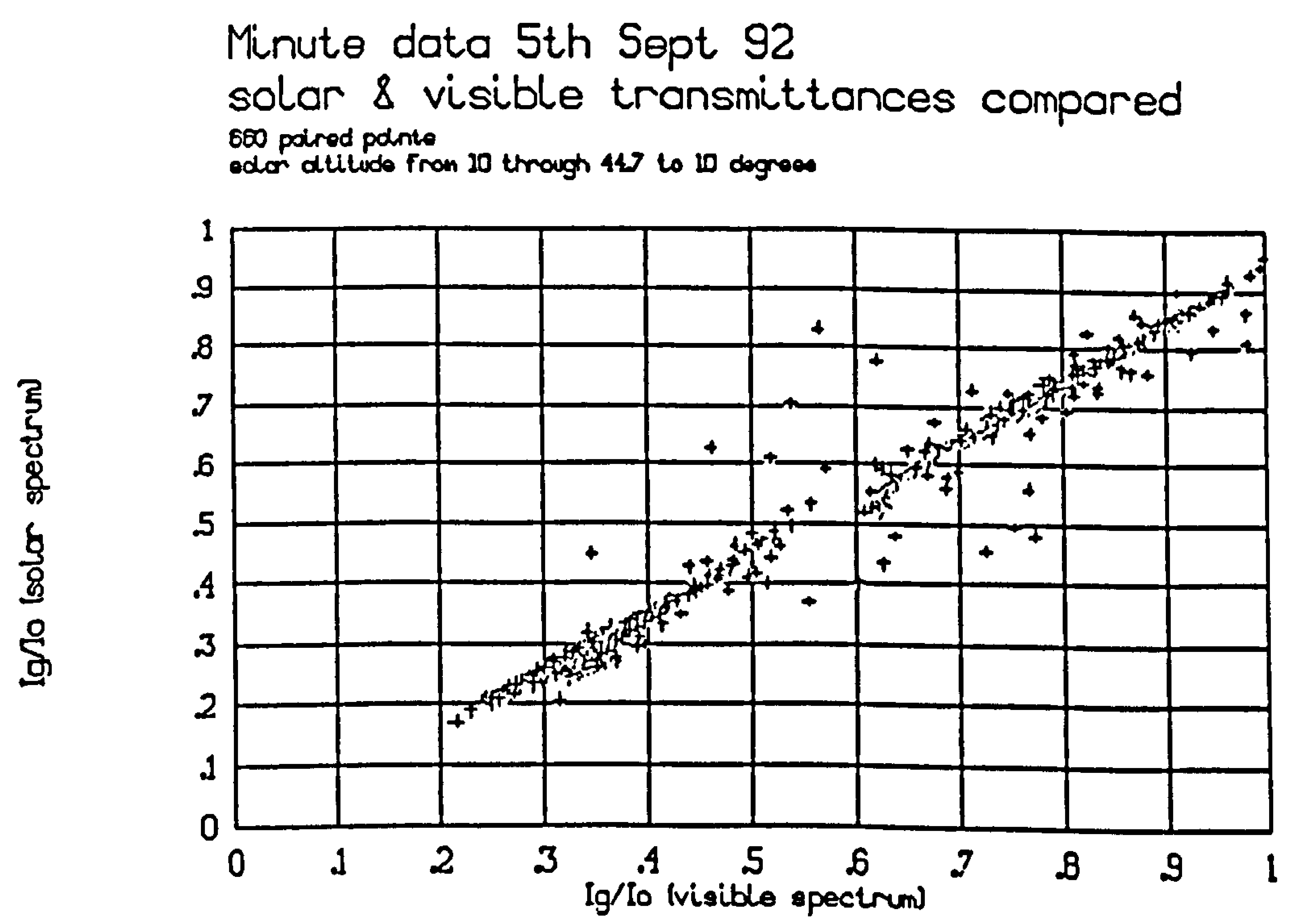

Figure 15.38 Measured global horizontal transmittances for solar & visible spectrum.(sun & cloud)

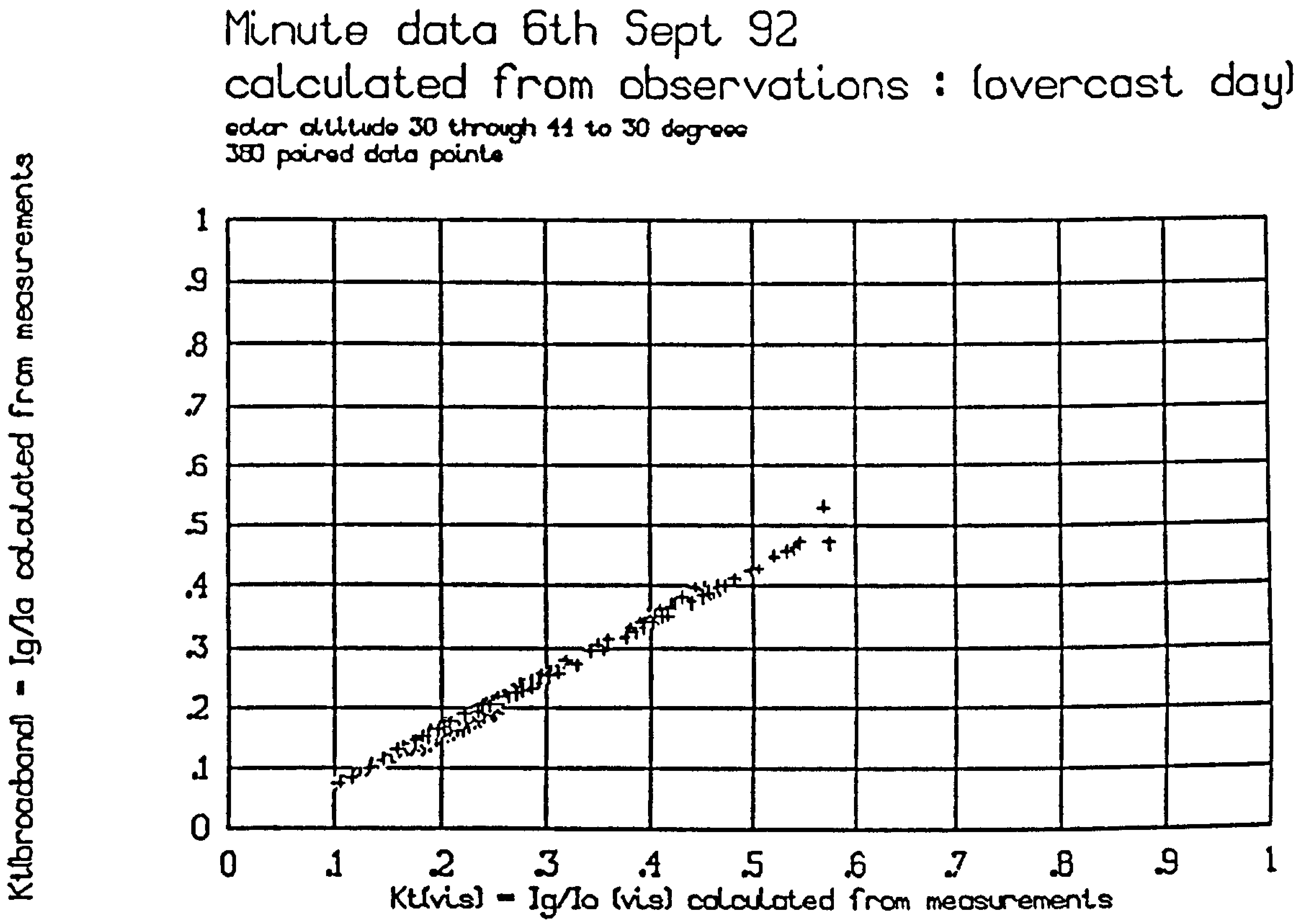

Figure 15.39 Measured and global horizontal broadband solar transmittance to transmittance in the visible spectrum. (overcast day)

CONCLUSIONS.

Lui & Jordan method.

16.1 The relationship between the transmittance of diffuse and global irradiance under clear-skies, calculated from the instantaneous measurements recorded at one minute intervals was clearly non-linear, contrary to that proposed by Lui & Jordan(1960). However, because the curve relates to that for the relative air mass, which for certain latitudes and seasons would be considered fairly flat for a large part of the day centred on solar noon, it is easy to see how one could make a linear assumption. The results of the test of the Lui & Jordan method to determine the diffuse fraction of global irradiance from values of the clearness index indicated that the diffuse ratio varied significantly compared to the clearness index during relatively short observation intervals. It was also evident that the diffuse fraction could vary from say between 0.2 and 0.6, or 0.3 to 0.75 or 0.8 for commonly occurring values of the clearness index. This represents a possible margin of error of up to 250% or thereabouts. Obviously this model, though developed for good reasons and reliant upon the statistical smoothing of data and averaging of observations, is none the less fallible. This procedure would not therefore be particularly suitable for predicting the diffuse component of global horizontal irradiance on an hourly basis.

Hypotheses.

16.2 The test of the hypotheses, using observations taken at intervals of one minute indicated that for clear-sky conditions:

(a) there was good agreement between the values of the fraction of extraterrestrial irradiance received as global horizontal irradiance, and those predicted by equations 14.17, to 14.20, indicating that hypothesis (a) is supported by the measurements taken, and

(b) the predicted approximate relationship between this fraction and the diffuse ratio obtained from observations also supported hypothesis (b).[eqn 14.22]

These clear-sky conclusions were confirmed by the results of the error analysis,[table 15.1] which also indicated that the modification proposed[eqn 14.23] as an approximation to represent the more normal, apparently clear-sky condition, worked reasonably well for the location of the observations, and appeared to have the potential to model the sunny part of cloudy days. The curve fitting procedure developed[eqns 14.25 to 14.28] permitted the use of available global horizontal irradiance measurements, and was found to provide satisfactory results. The results of the tests for cloudy-sky conditions indicated that:

(c) the diffuse transmittance was found to be approximately equal to the global transmittance on overcast days as expected, indicating that hypothesis (c)[eqn 14.16][figure 15.28] is probably a reasonable assumption to make in such circumstances.

The diffuse transmittance was also predicted reasonably well for cloudy days with sunshine, using a combination of equations 14.16 & 14.24, of which figure 15.32 is an example. This suggests that such an approach might provide acceptable hourly mean estimates of the components of global irradiance for all sky-conditions, however figure 15.34 indicated that for autumn days with haze and sunshine, hypothesis (c) was not supported. In this case of significant attenuation with little scatter of data, the global irradiance was predicted best by the curve fitting procedure, and the diffuse transmittance was reasonably close to that predicted for clear-skies. This suggests that a combination of the curve fitting procedure for global transmittance, together with the diffuse transmittance calculated by the clear-sky equation, might provide an appropriate basis for a model using global horizontal irradiance measurements.

With regard to the availability of daylight, hypothesis (a) was tested and supported by the measurements. Hypothesis (b) was not tested due to lack of instrumentation, but hypothesis (c) appeared to be supported. In addition:

(d) the linear relationship predicted by hypothesis (d) was found as expected between the broadband transmittance of solar radiation and the transmittance in the visible spectrum, for overcast, cloudy and sunny conditions, indicating that it should also be possible to predict levels of daylight using this model with global horizontal irradiance measurements.

16.3 Overall, the measurements taken indicated that all four hypotheses were supported for the stated sky conditions. Further work would be necessary to carry out more extensive tests and develop this simple model for practical application. Although the empirical test of the hypotheses used data for only one location, the basic clear-sky model was designed to be universally applicable. Whilst the assumptions on which modifications were devised to deal with other sky conditions appeared reasonable for the location and climate of the site of the observations in South-East England, they should ideally be tested for other latitudes and climates. The proposed simple model may have the potential to predict the amount of the components of solar radiation and the level of daylight availability for any location. The applications envisaged include building and engineering design, horticultural and meteorological use. The main advantages should be the minimum dependence of the model on the need for complex measurements or significant computing power, to obtain reasonable predictions of the components of irradiance and daylight from measurements of global horizontal irradiance.

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APPENDIX A

Table A.1 SURFACE HEAT TRANSFER COEFFICIENTS: HOOK & BARNES FARM SCHOOLS.

ELEMENT	INTERNAL COEFFICIENT	SOLAR COEFFICIENT	EXTERNAL COEFFICIENT	SOLAR COEFFICIENT
	W/m^2K	fraction	W/m^2K	fraction
ROOF	12.60	AREA	14.30	0.90
CEILING	6.60	AREA	10.00	AREA
GROUND FLOOR 1	6.50	0.56	0.10	AREA
GROUND FLOOR 2	6.50	0.34	0.10	AREA
PARTITION	8.13	AREA	8.13	AREA
EXTERNAL WALL 1	8.13	AREA	12.50	0.90
EXTERNAL WALL 2	8.13	AREA	12.50	0.40

Table A.2 GLAZING TYPES: BARNES FARM.

Type	U Value	Shade Coefficient	Extinction Coefficient	Index of refraction	Thickness	Panes
	$W\,m^{-2}\,K^{-1}$	fraction	m^{-1}		mm	
single4	5.4	0.98	0.0197	1.526	4.0	1
single6	5.4	0.95	0.0197	1.526	6.0	1
double4	2.8	0.87	0.0197	1.526	4.0	2
double6	2.8	0.82	0.0197	1.526	6.0	2
solar	5.4	0.76	0.0197	1.526	6.4	1
roof	3.4	0.60	0.0197	1.526	6.0	2
atrium	3.2	0.95	0.0010	1.526	3.0	2

APPENDIX A

Table A.3 CONSTRUCTION TYPES & CODES: BARNES FARM SCHOOL.

TYPE	LAYER 1	2	3	4	5	6
Gfloor1	carpet	screed	dpm	concrete	hardcore	earth
2	quarry tile	screed	dpm	concrete	hardcore	earth
3	wood1	air	dpm	concrete	hardcore	earth
Roof 1	plasterbrd	insulation	air	metal	-	-
2	plasterbrd	dpm	wood6	metal	-	-
3	plasterbrd	dpm	insulation	air	wood	felt
4	plasterbrd	dpm	insulation	air	plywood19	felt
5	metal	-	-	-	-	-
6	concrete12	roofing felt	-	-	-	-
ceiling	plasterbrd	dpm	-	-	-	-
partn 1	blockwork4	-	-	-	-	-
2	plasterbrd	blockwork4	-	-	-	-
4	brickwork9	-	-	-	-	-
5	wood	paper	air	concrete12	-	-
6	brickwork900	-	-	-	-	-
7	plasterbrd	blockwork8	-	-	-	-
8	blockwork8	plasterbrd	-	-	-	-
wall 1	blockwork7	air	blockwork	-	-	-
2	blockwork7	insulation	air	wood	-	-
3	blockwork7	air	concrete	earth	blockwork4	-
door	plywood6	air	plywood6	-	-	-

APPENDIX A

Table A.5 CONSTRUCTION TYPES & CODES: HOOK SCHOOL

TYPE	LAYER 1	2	3	4	5	6
Groundfloor 1						
2	carpet	screed	dpm	concrete	hardcore	earth
	pvc tile	screed	dpm	concrete	hardcore	earth
3	quarry tile	screed	dpm	concrete	hardcore	earth
Roof 1						
2	vapour	woodwool	screed 1	metal	insulationrf	metal
	wood	air	metal	insulationrf	metal	-
3	metal	insulationrf	metal	-	-	-
4						
	plasterbrd	insulation3	air	woodwool	screed 1	felt
5	metal	-	-	-	-	-
ceiling						
partition 1	fibreboard	insulation1	air	-	-	-
	plasterbrd	plasterbrd	air	plasterbrd	plasterbrd	-
2	plasterbrd	plasterbrd	insulation2	plywood19	-	-
3						
4	brickwork9	polystyrene	brickwork9	-	-	-
	brickwork9	-	-	-	-	-
wall 1	brickwork1	polystyrene	brickwork1	-	-	-

Table A.6 GLAZING TYPES: HOOK SCHOOL.

Type	U value $W/m^2 K$	Shading Coefficient fraction	Extinction Coefficient m^{-1}	Index of refraction	Thickness mm	Panes
single	5.4	0.98	0.0197	1.5260	6.0	1
double	2.8	0.70	0.0197	1.5260	6.0	2

APPENDIX A

Table A.4 THERMAL PROPERTIES OF MATERIALS: BARNES FARM SCHOOL.

MATERIAL code	THERMAL CONDUCTIVITY	DENSITY	SPECIFIC HEAT	THICKNESS
	$W\,m^{-1}\,K^{-1}$	$kg\,m^{-3}$	$kJ\,kg^{-1}\,K^{-1}$	m
blockwork	1.600	2300	1.050	0.100
blockwork8	0.130	1340	1.050	0.200
blockwork7	0.130	1340	1.050	0.165
blockwork4	0.130	1340	1.050	0.100
blockwork9	0.620	1800	0.840	0.210
brickwork900	0.620	1800	0.840	0.900
hardcore	1.800	2300	1.050	0.100
concrete	1.400	2500	1.050	0.150
concrete12	1.400	2500	1.050	0.300
plaster	0.500	1300	0.840	0.0125
plasterbrd	0.160	950	0.840	0.0125
screed	0.410	1200	1.050	0.050
quarry tile	1.130	2300	1.050	0.050
plywood19	0.150	700	1.420	0.019
plywood6	0.150	700	1.420	0.006
earth	1.280	1460	0.879	0.500
wood	0.130	630	2.760	0.025
wood6	0.130	630	2.760	0.150
insulation	0.037	30	0.840	0.100
carpet	0.060	160	2.500	0.006

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Table A.7 THERMAL PROPERTIES OF MATERIALS: HOOK SCHOOL.

TYPE	THERMAL CONDUCTIVITY $W\,m^{-1}\,K^{-1}$	DENSITY $kg\,m^{-3}$	SPECIFIC HEAT $kJ\,kg^{-1}\,K^{-1}$	THICKNESS m
brickwork1	0.620	1800	0.840	0.105
brickwork9	0.620	1800	0.840	0.210
hardcore	1.800	2300	0.840	0.150
concrete	1.400	2500	0.840	0.150
plasterbrd	0.160	990	1.000	0.012
screed 1	0.410	1200	0.840	0.025
screed	0.410	1200	0.840	0.050
quarry tile	1.130	2300	1.050	0.012
pvc	0.850	2000	0.837	0.004
carpet	0.060	160	2.500	0.006
plywood19	0.150	700	1.420	0.019
plywood	0.150	700	1.420	0.006
wood	0.130	630	2.760	0.025
wood5	0.130	630	2.760	0.125
fibreboard	0.030	290	2.000	0.012
insulation1	0.037	30	0.840	0.025
insulation2	0.037	30	0.840	0.050
insulation3	0.037	30	0.840	0.075
insulationrf	0.022	101	2.300	0.050
woodwool	0.120	500	1.000	0.050
polystyrene	0.030	25	1.000	0.050
earth	1.280	1460	0.879	0.500
roofing felt	0.150	700	1.420	0.010

BUILDING DESCRIPTION : NOTIONAL CLASS-BASE.

Table A.8 NOTIONAL CLASS-BASE: SERI-RES SCHEDULED VALUES.

VARIABLE	HOURS	VALUE	UNITS
INFILTRATION	00-08 08-09 09-11 11-12 12-15 15-16 16-24	0.25 1.00 0.50 1.00 0.50 1.00 0.25	air change/ hr
INT GAIN	00-08 08-11 11-12 12-15 15-24	0.25 3.50 1.00 3.50 0.25	kW
VENTILATION	00-09 09-16 16-24	45 23 45	set point oC
BLIND SET PT (shade coeff 0.3)	00-08 08-15 15-24	900 250 900	W/m^2
OCCUPATION	00-08 08-11 11-12 12-15 15-24	0 1 0 1 0	0 = NO 1 = YES

Table A.9 SURFACE HEAT TRANSFER COEFFICIENTS W/m^2 K. NOTIONAL CLASS-BASE.

ELEMENT	INTERNAL	EXTERNAL
ROOF	12.6	27.0
WALL	8.3	14.5
FLOOR	12.6	7.0 ground

Table A.10 BUILDING CONSTRUCTION: NOTIONAL CLASS-BASE.

ITEM	LAYER 1	2	3	4	5	6
Wall-1	Pinboard	Plaster	Blockwork	Woolboard	R-0.18	Brickwork
Wall-2	Plaster	Blockwork	Woolboard	R-0.18	Brickwork	-
Roof	Acoustic	Glasswool	R-0.18	Tiled	-	-
Partn-1	Pinboard	Plaster	Blockwork	Plaster	Pinboard	-
Partn-2	Plaster	Block	Plaster	-	-	-
Floor-1	Carpet	Screed	Concrete	Polycell	Hardcore	Soil
Floor-2	Pvc	Screed	Concrete	Polycell	Hardcore	Soil

APPENDIX A

Table A.11 PROPERTIES OF MATERIALS: NOTIONAL CLASS-BASE.

MATERIAL	THERMAL CODUCTIVITY	DENSITY	SPECIFIC HEAT	THICKNESS
	W/m K	kg/m^3	kJ/kg K	m
Plaster	0.420	1200.0	0.837	0.015
Blockwork	0.200	720.0	1.069	0.100
Woolboard	0.048	240.0	1.050	0.055
Brickwork	0.700	2100.0	0.920	0.105
Carpet	0.060	186.0	1.360	0.005
Screed	1.280	2100.0	1.000	0.050
DPM	0.430	1600.0	1.000	0.002
Concrete	0.870	1800.0	0.920	0.125
Polycell	0.033	32.0	1.210	0.025
Polythene	0.500	1050.0	0.837	0.0003
Hardcore	0.650	1570.0	1.057	0.150
Soil	1.400	1900.0	1.700	0.500
Pinboard	0.059	320.0	1.670	0.010
Acoustic	0.058	288.0	0.586	0.010
Glasswool	0.040	200.0	0.670	0.140
Sarkfelt	0.410	960.0	1.000	0.003
Rooftile	0.850	1900.0	0.837	0.020
Pvctile	0.500	1050.0	0.837	0.003

APPENDIX B.

Table B.1 Analysis of clear-sky models A, B, C & D.

A	B	C — Spectral Interval of SOLTRAN $\lambda = 0.3$ to $3\ \mu m$	D — 2 band spectral intervals. (UV+VIS)(IR)
$I_{bn} = I_{sc}(\tau_o \tau_r - \alpha_w)\tau_a$ where $\alpha_w = 1 - \tau_w$ $\tau_o = 1 - \alpha_o$ ← absorption effects different →	$I_{bn} = I_{sc}\left(1 - \sum_{i=1}^{i=4} \alpha_i\right)\tau_r \tau_{as}$ where α_1 = water vapour α_2 = mixed gas α_3 = ozone α_4 = aerosols ← absorption effects different → IQBAL – WORST	$I_{bn} = 0.9751 I_{sc} \tau_r \tau_o \tau_g \tau_w \tau_a$ ← same effect different bands → BEST – IQBAL (1983)	$I_{bn} = I_{on} \tau_o \tau_r \tau_{gs} \tau_{wo} \tau_a$
α_o (LACIS & HANSEN 1974) ozone layer thickness in cm α_w (LACIS & HANSEN 1974) correlation for curve of YAMAMOTO (1962) for α_w	τ_{as} = transmittance due to scatter by aerosols. $\tau_1 \tau_2 \tau_3 \tau_4 = (1-\alpha_1)(1-\alpha_2)(1-\alpha_3)(1-\alpha_4)$ $= 1 - \alpha_1 - \alpha_2 - \alpha_3 - \alpha_4$ → YAMAMOTO (1962) for α_w	$\tau_r = e\left[-0.093\, m_a^{0.84}(1 + m_a - m_r^{1.01})\right]$ τ_o $\tau_{gu} = e\left[-0.0127\, m_a^{0.26}\right]$ $\tau_w = 1 - \alpha_w$ based on $\lambda = 0.38$ & $\lambda = 0.5\mu m$ $\tau_a = e\left[-k_a^{0.873}(1 + k_a - k_a^{0.7088})\, m_a^{0.9108}\right]$	$\tau_o = e(-m_o u_o k_{ox})$ $\tau_R = e(-m_R \sigma_R \lambda)$ absolute optical air mass; Rayleigh optical thickness $m_r = (P/P_o)$ $m = [\sin h + a(h+b)^c]^{-1}$
τ_R (Davies et al 1975) regression analysis. τ_a (Houghton 1986) using Mächler (1983) regression.	2 separate expressions used for α by CO_2 & O_2 α_o (MANABE & STRICKLER 1964) τ_r (Mächler 1983)	where $k_a = 0.2758 k_{a\lambda} + 0.35 k_{a\lambda}$ (for $\lambda = 0.38$) (for $\lambda = 0.5\mu m$) aerosol thickness uses these two wavelengths readings by US Nat Weather Service	ie Kasten where $a = 0.15$ $b = 3.885°$ $c = -1.253$ but this is Broadband would be more appropriate to use Bemporad for this narrow band use

APPENDIX B.

Table B.1 contd. Analysis of clear-sky models A, B, C & D.

A	B	C	D	
$I_d = I_{dr} + I_{da} + I_{dm}$ ← Same expression different composition of parts.	$I_d = I_{dr} + I_{da} + I_{dm}$			Accuracy mainly dependent on water vapour absorption & more important - aerosol extinction
$I_{dr} = I_{sc} \cos\theta_z T_o [0.5(1-T_r)] T_a$ assumes 1/2 Rayleigh scatter lost & 1/2 reaches grnd	$I_{dr} = I_{sc} \cos\theta_z \left(1-\sum_{i=1}^{i=4} \alpha_i\right) 0.5(1-T_r)$ ditto	$I_{dr} = 0.79 I_{sc} \cos\theta_z T_o T_g T_w T_a \; 0.5(1-T_r)/(1-m_a+m_a^{1.02})$	$I_{dr} = 0.5 T_r T_g T_w T_a (1-T_r) I_o$ From Robinson (1962)	
T_w omitted because effect only seen in spectral band where $T_R \approx 1$. $I_{da} = I_{sc} \cos\theta_z (T_o T_r - \alpha_w)[F_c \omega_o (1-T_a)]$ note absorption by water vapour is deducted before aerosol scatter effect	BEST — IQBAL (1983). $I_{da} = I_{sc} \cos\theta_z \left(1-\sum_{i=1}^{i=4} \alpha_i\right) 0.75(1-T_{as})$ virtually the same effect ie average $F_c = 0.8$ with ω_o @ 0.95	$I_{da} = 0.79 I_{sc} \cos\theta_z T_o T_g T_w T_{aa} \times F_c(1-T_{as})/(1-m_a+m_a^{1.02})$ where $T_{as} = T_a / T_{aa}$	$I_{da} = B_a T_o T_g T_w T_{aa} T_R (1-T_{as}) I_o$	
I_{dm} ← all the same effect. ie $1-F_c = 0.25$ = backscatter.			Same.	
$I_g = I_{bn} \cos\theta_z + I_d$			Same	
WORST — IQBAL (1983)	BEST — IQBAL (1983)	NEXT BEST ← GUEYMARD own model based on this	BEST — own model.	

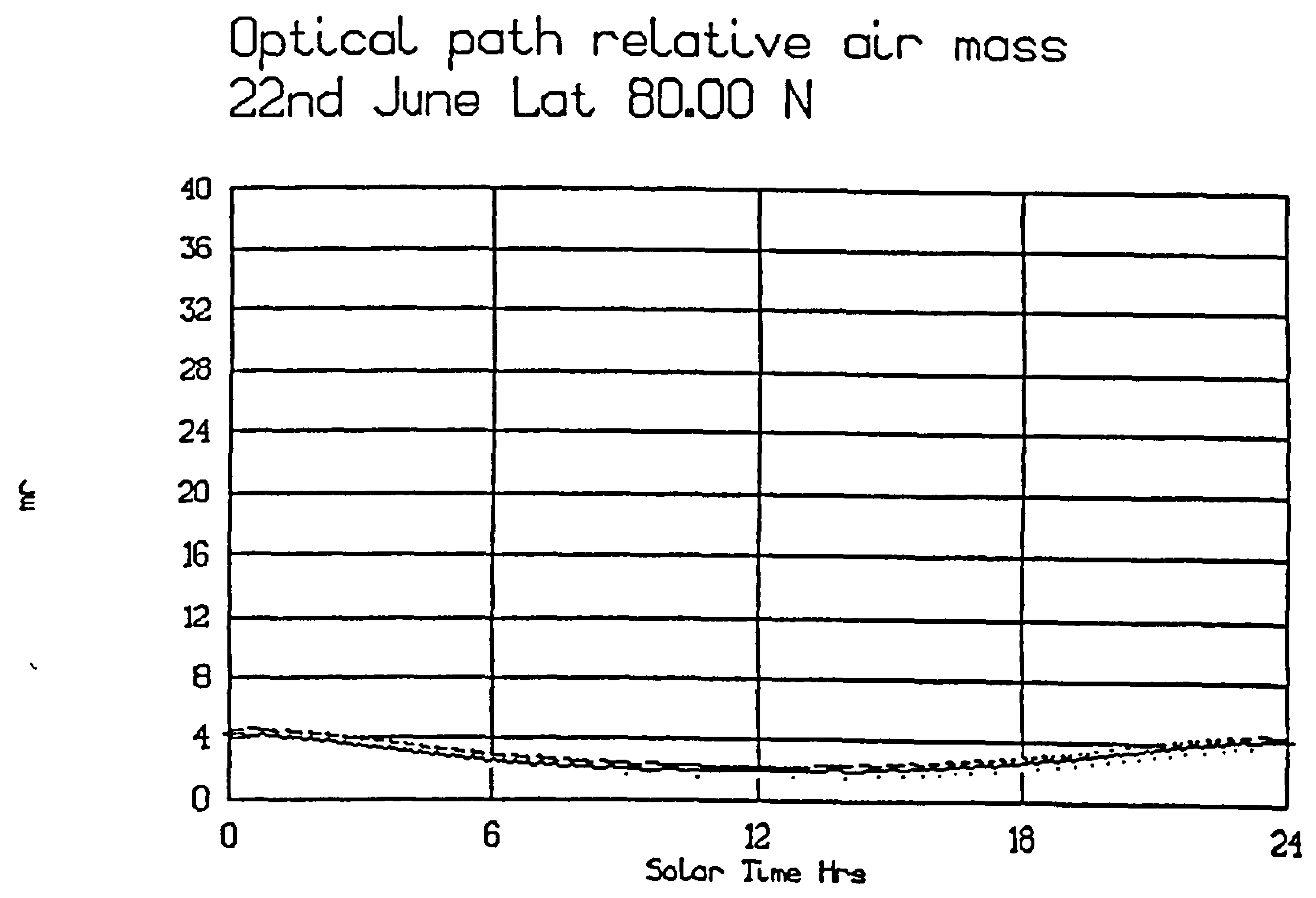


Figure C.1 Relative air mass: 22nd June , Latitude 80.0 degrees N.

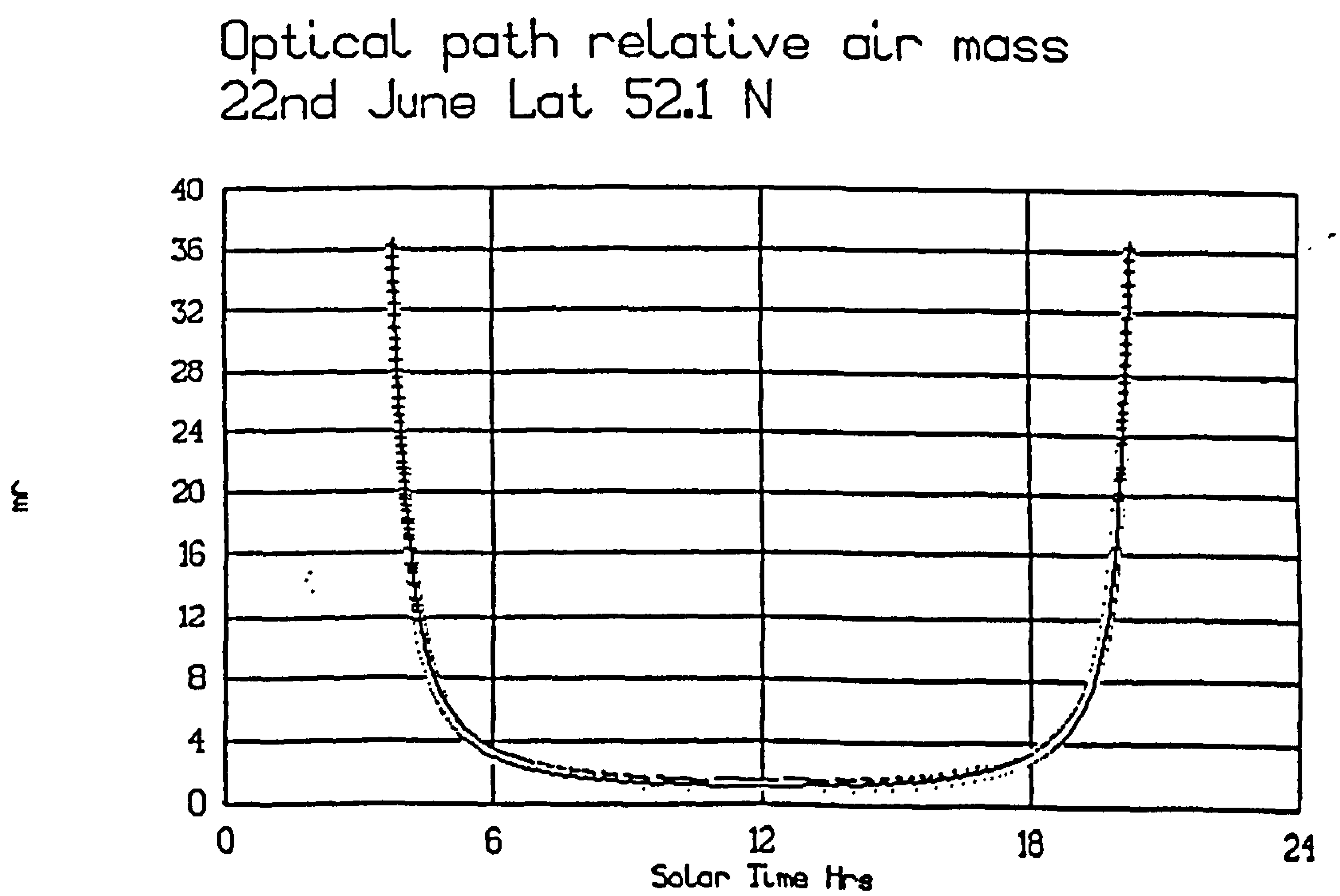


Figure C.2 Relative air mass: 22nd June , Latitude 52.1 degrees N.

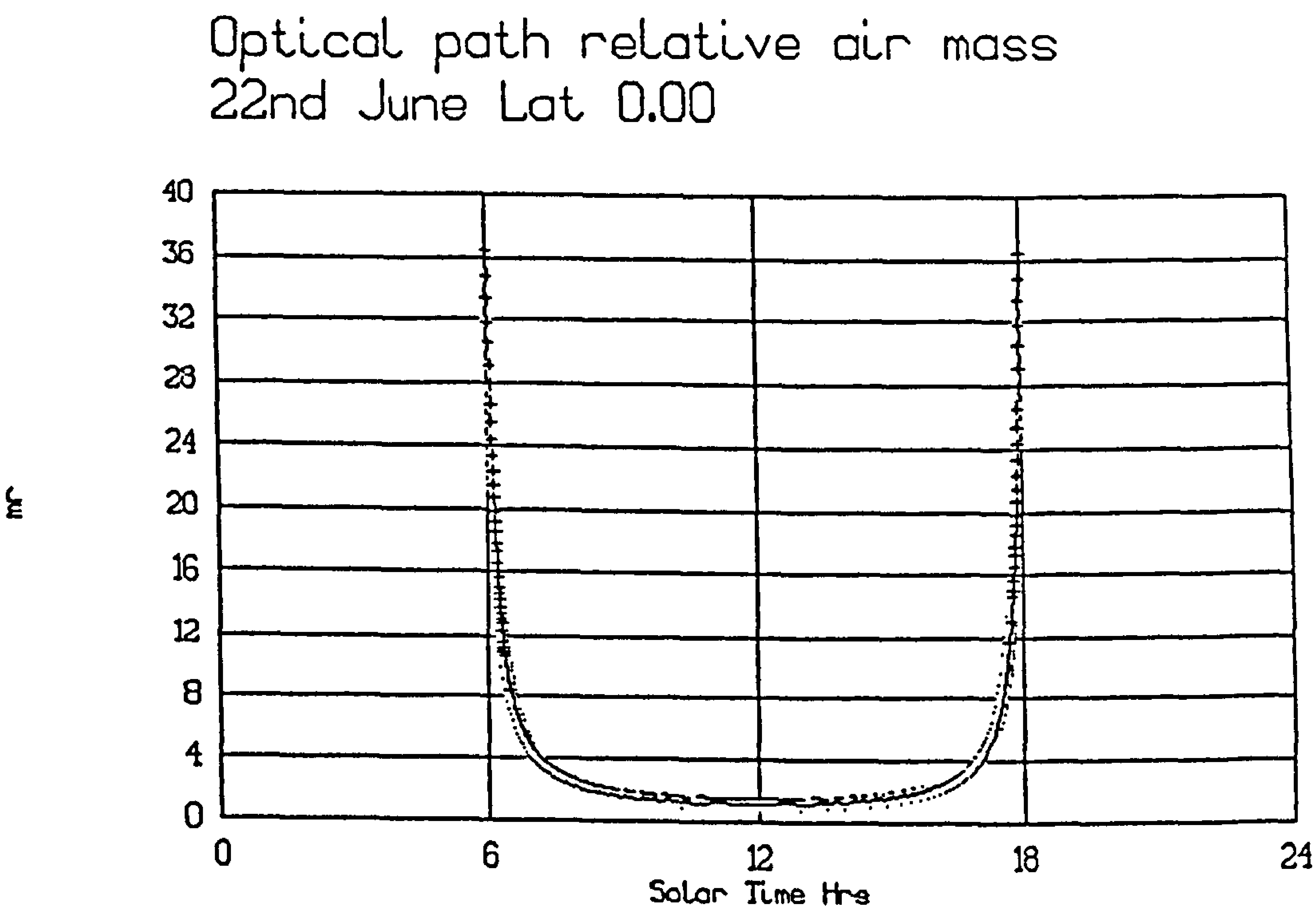


Figure C.3 Relative air mass: 22nd June , Latitude 00.0 degrees.

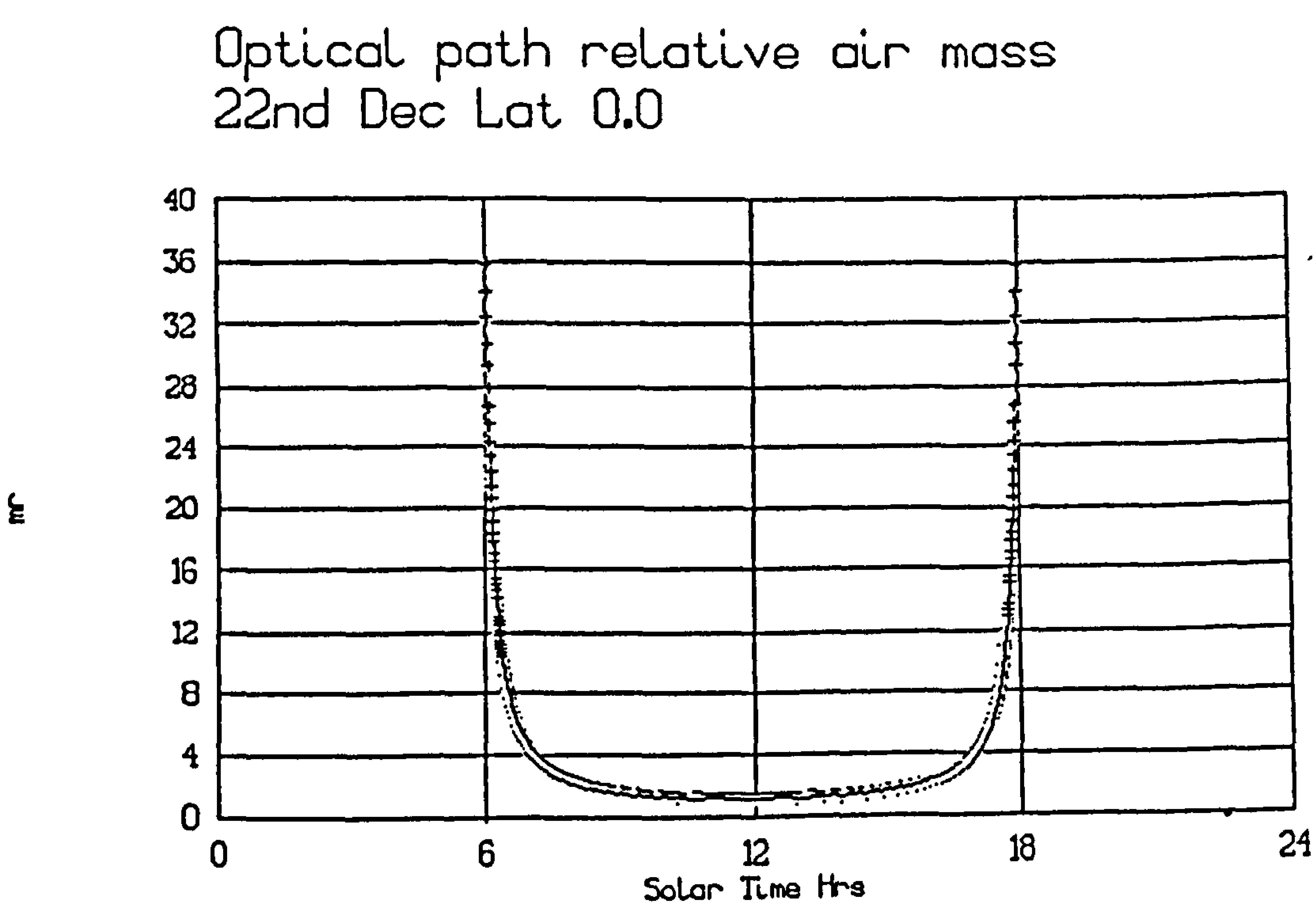


Figure C.4 Relative air mass: 22nd Dec , Latitude 0.0 degrees.

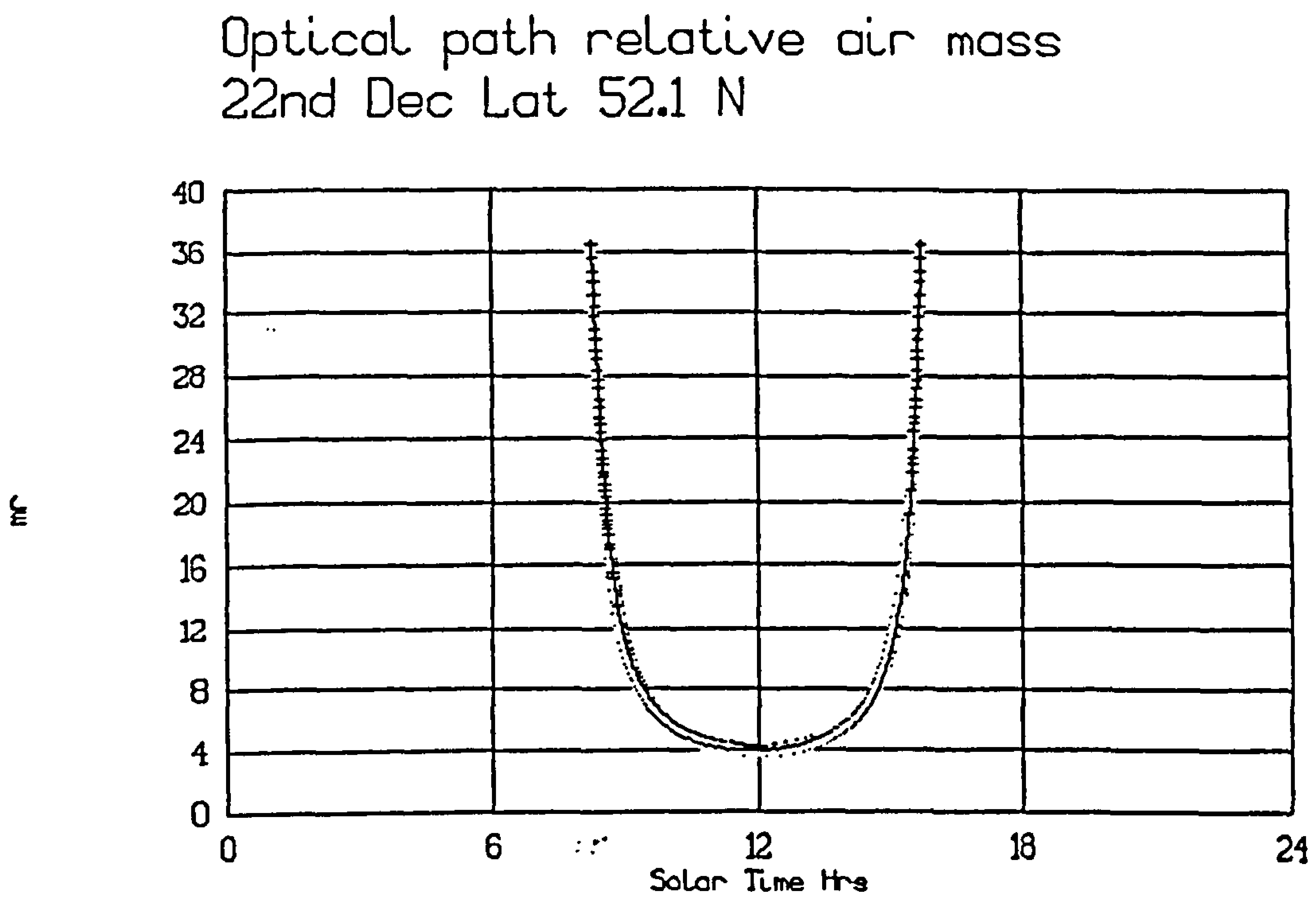


Figure C.5 Relative air mass: 22nd Dec , Latitude 52.1 degrees N.

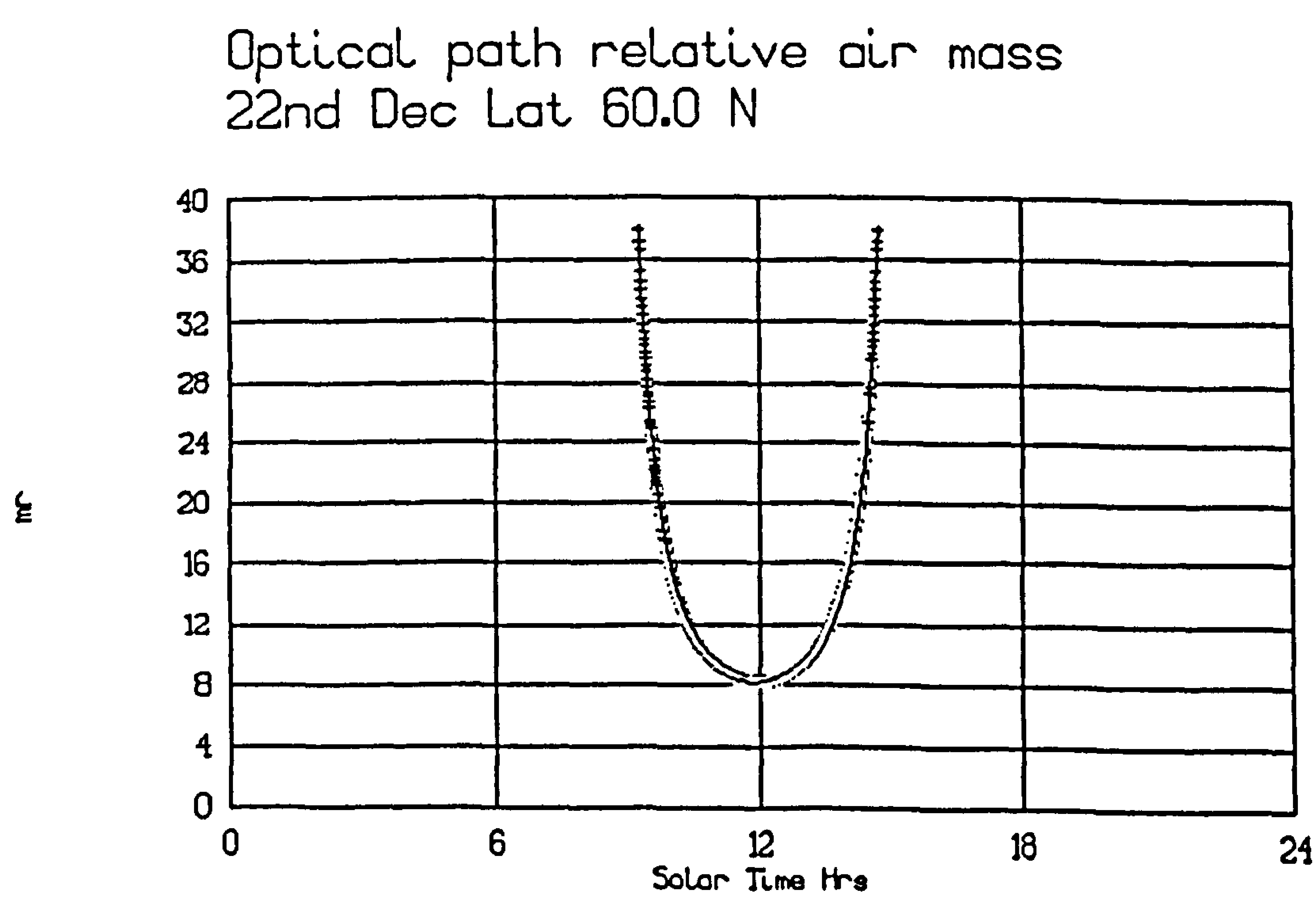


Figure C.6 Relative air mass: 22nd Dec , Latitude 60.0 degrees N.

Table D.1 Shade-band correction factors.

Kipp & Zonen CM12 shadowing correction factors for uniform sky conditions. (Viewangle 0.185 rad. = 10.6°)

DATE INTERVAL			JANUARY 1	17	26	FEBRUARY 2	8	15	21	26	MARCH 3	9	14	19	24	29	APRIL 3	8	14	19	25	MAY 2	9	16	26	JUNE 11
	90	1	1	1	1	1	1	1	1	1	1	1	1	1	1.01	1.03	1.04	1.05	1.07	1.08	1.10	1.11	1.12	1.13	1.15	1.16
	85	1	1	1	1	1	1	1	1	1	1	1	1	1.01	1.02	1.03	1.04	1.05	1.07	1.08	1.09	1.11	1.12	1.13	1.15	1.16
	80	1	1	1	1	1	1	1	1	1	1.01	1.01	1.01	1.02	1.03	1.04	1.04	1.05	1.07	1.08	1.09	1.11	1.12	1.13	1.14	1.16
	75	1	1	1	1	1	1	1	1.01	1.01	1.01	1.02	1.03	1.03	1.04	1.05	1.05	1.06	1.07	1.08	1.09	1.10	1.12	1.13	1.14	1.15
	70	1	1	1	1	1	1.01	1.01	1.01	1.02	1.02	1.03	1.04	1.04	1.05	1.06	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.13	1.14	1.15
NORTHERN LATITUDE	65	1	1	1	1.01	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.05	1.05	1.06	1.07	1.07	1.08	1.09	1.10	1.10	1.11	1.12	1.13	1.13	1.14
	60	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.06	1.06	1.07	1.08	1.08	1.09	1.10	1.10	1.11	1.12	1.12	1.13	1.14	1.14
	55	1.01	1.02	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.05	1.06	1.07	1.07	1.08	1.08	1.09	1.10	1.10	1.11	1.12	1.12	1.13	1.13	1.14	1.14
	50	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.05	1.06	1.06	1.07	1.08	1.08	1.09	1.09	1.10	1.10	1.11	1.12	1.12	1.13	1.13	1.13	1.14	1.14
	45	1.03	1.03	1.04	1.04	1.05	1.05	1.06	1.06	1.07	1.07	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.13	1.13	1.13	1.14	1.14	1.14
	40	1.04	1.04	1.05	1.05	1.06	1.06	1.07	1.07	1.08	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.13	1.13	1.13	1.14	1.14	1.14	1.14
	35	1.05	1.05	1.06	1.06	1.07	1.07	1.08	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14
	30	1.06	1.06	1.07	1.07	1.08	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14
	25	1.07	1.07	1.08	1.08	1.09	1.09	1.09	1.10	1.10	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.14	1.14
	20	1.08	1.08	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.13	1.13	1.13
	15	1.08	1.09	1.09	1.10	1.10	1.11	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
	10	1.09	1.10	1.10	1.11	1.11	1.11	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12
	5	1.10	1.11	1.11	1.11	1.12	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.12
EQUATOR	0	1.11	1.11	1.12	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.12	1.11	1.11
	5	1.12	1.12	1.12	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.12	1.11	1.11	1.11	1.10
	10	1.12	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.11	1.10	1.10	1.09
	15	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.11	1.10	1.10	1.09	1.09	1.08
	20	1.13	1.13	1.13	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.08	1.08
	25	1.14	1.14	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.10	1.10	1.09	1.09	1.09	1.08	1.08	1.07	1.07
	30	1.14	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.08	1.07	1.07	1.06	1.06
SOUTHERN LATITUDE	35	1.14	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.12	1.12	1.12	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.08	1.07	1.07	1.06	1.06	1.05	1.05
	40	1.14	1.14	1.14	1.14	1.13	1.13	1.13	1.12	1.12	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.08	1.07	1.07	1.06	1.06	1.05	1.05	1.04	1.04
	45	1.14	1.14	1.14	1.13	1.13	1.13	1.12	1.12	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.07	1.07	1.06	1.06	1.05	1.05	1.04	1.04	1.03	1.03
	50	1.14	1.14	1.13	1.13	1.13	1.12	1.12	1.11	1.10	1.10	1.09	1.09	1.08	1.08	1.07	1.06	1.06	1.05	1.05	1.04	1.04	1.03	1.03	1.02	1.02
	55	1.14	1.14	1.13	1.13	1.12	1.12	1.11	1.10	1.10	1.09	1.08	1.08	1.07	1.07	1.06	1.05	1.05	1.04	1.04	1.03	1.03	1.02	1.02	1.02	1.01
	60	1.14	1.14	1.13	1.12	1.12	1.11	1.10	1.10	1.09	1.08	1.08	1.07	1.06	1.06	1.05	1.04	1.04	1.03	1.03	1.02	1.02	1.02	1.01	1.01	1.01
	65	1.14	1.13	1.13	1.12	1.11	1.10	1.10	1.09	1.08	1.07	1.07	1.06	1.05	1.05	1.04	1.03	1.03	1.02	1.02	1.01	1.01	1.01	1	1	1
	70	1.15	1.14	1.13	1.12	1.11	1.10	1.09	1.08	1.07	1.06	1.06	1.05	1.04	1.04	1.03	1.02	1.02	1.01	1.01	1.01	1	1	1	1	1
	75	1.15	1.14	1.13	1.12	1.10	1.09	1.08	1.07	1.06	1.05	1.05	1.04	1.03	1.03	1.02	1.01	1.01	1.01	1	1	1	1	1	1	1
	80	1.16	1.14	1.13	1.12	1.11	1.09	1.08	1.07	1.05	1.04	1.04	1.03	1.02	1.01	1.01	1.01	1	1	1	1	1	1	1	1	1
	85	1.16	1.15	1.13	1.12	1.11	1.09	1.08	1.07	1.05	1.04	1.03	1.02	1.01	1	1	1	1	1	1	1	1	1	1	1	1
	90	1.16	1.15	1.13	1.12	1.11	1.10	1.08	1.07	1.05	1.04	1.03	1.01	1	1	1	1	1	1	1	1	1	1	1	1	1
DATE INTERVAL			DECEMBER 12	NOVEMBER 27	18	10	4	OCTOBER 29	23	17	12	7	1	SEPTEMBER 26	21	16	11	5	AUGUST 31	25	19	13	6	JULY 29	19	3
SUN'S DECLINATION		−24	−22	−20	−18	−16	−14	−12	−10	−8	−6	−4	−2	0	2	4	6	8	10	12	14	16	18	20	22	24
SLIDING BAR SETTING		132	120	108	97	85	74	63	52	42	31	21	10	0	10	21	31	42	52	63	74	85	97	108	120	132

APPENDIX D.

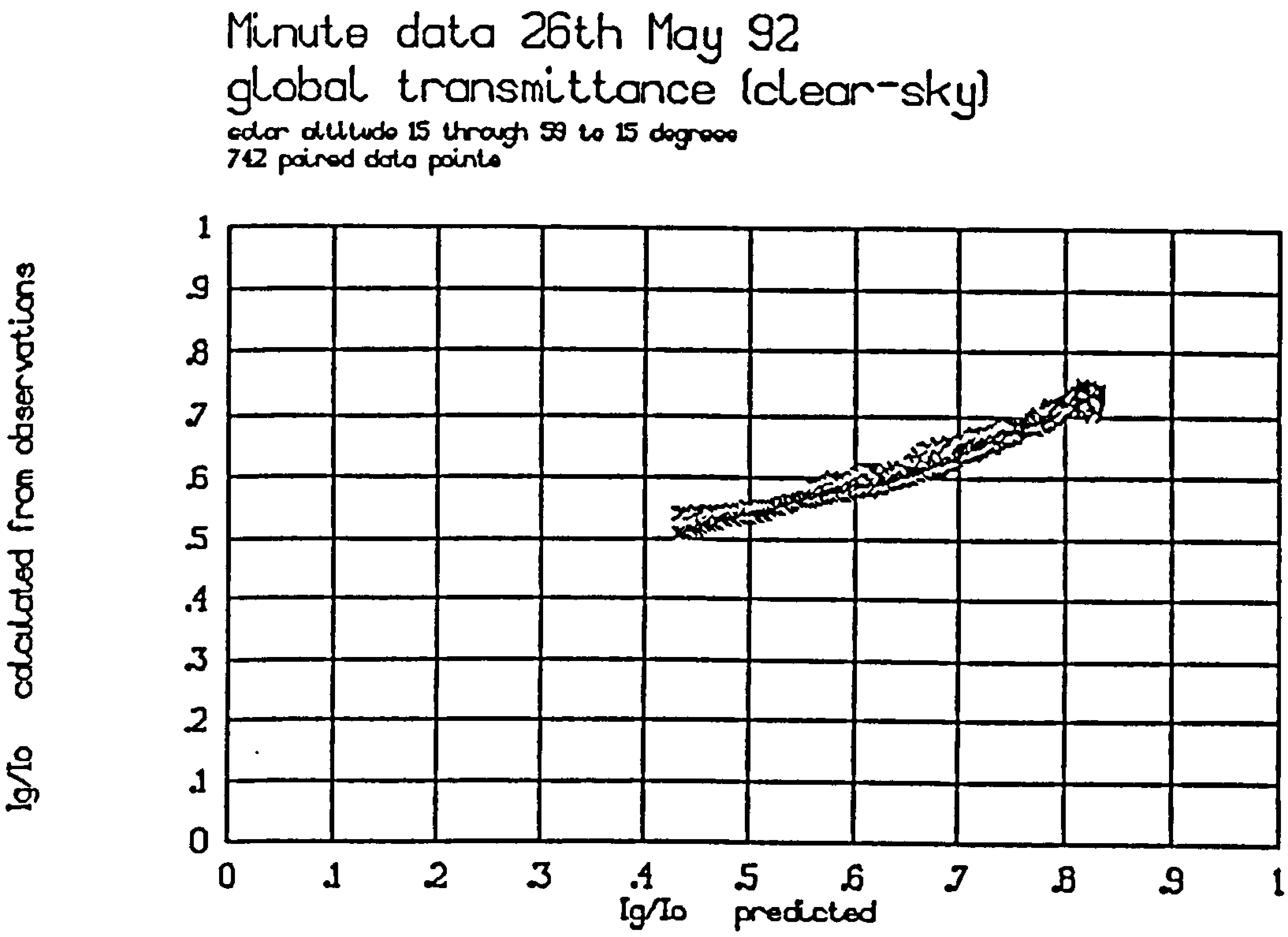


Figure D.1 Measured global transmittance vs that predicted for clear-sky.

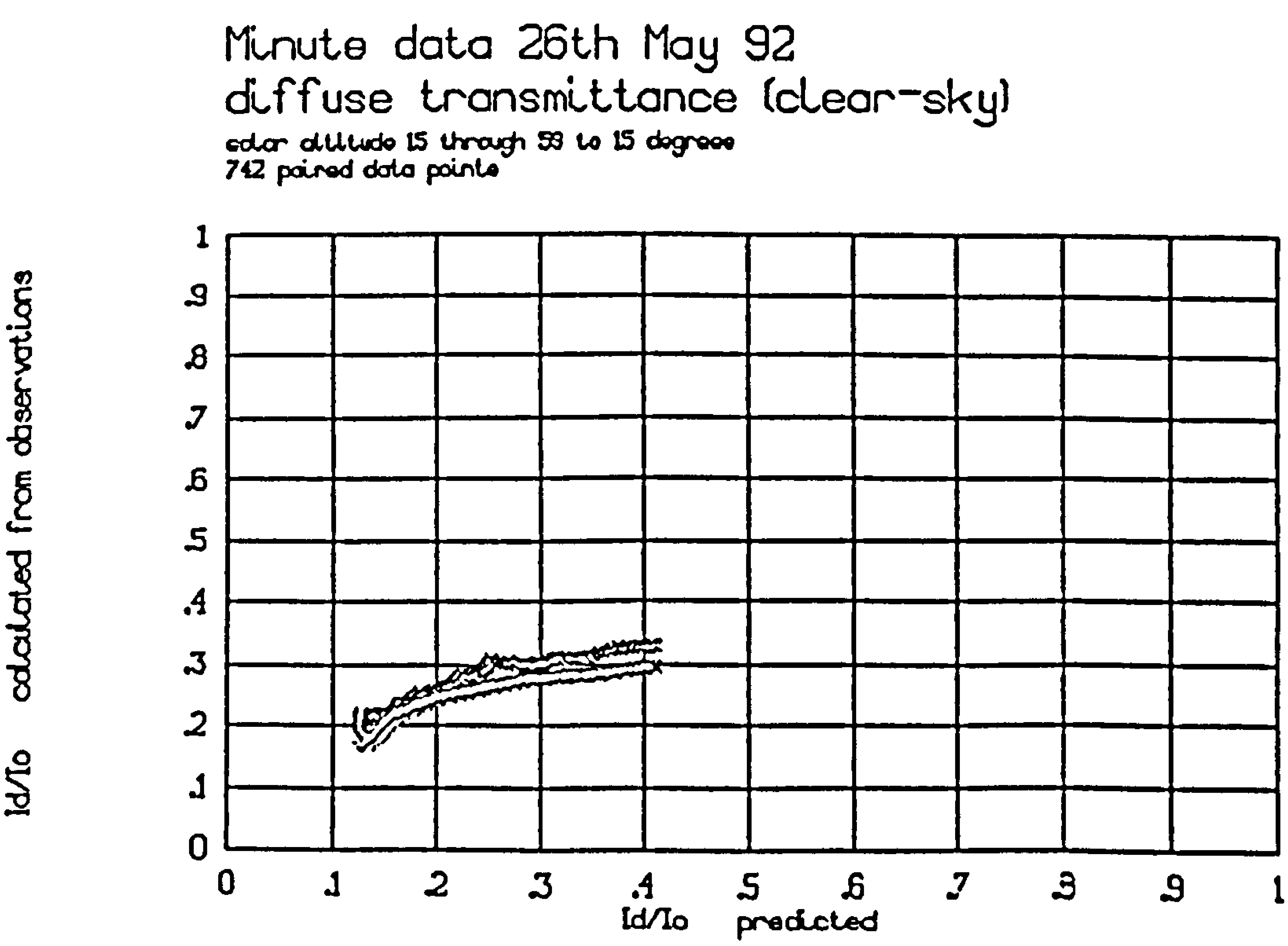


Figure D.2 Measured diffuse transmittance vs that predicted for clear-sky.

Cabot City Technology College

Location:

Woodside Road, Kingswood, Bristol. The site falls away both to the north and to the west, and for this reason the area which could be developed was severely restricted. There is a good view down across the site to the north west towards the new grass amphitheatre and existing orchard which are at the focus of the new crescent block.

Design:

An innovative low-tech design for minimum environmental impact using simple and comprehensible environmental controls, natural ventilation and daylighting of deep plan spaces. Teaching spaces are of high quality and responsive to climate.

Form:

The crescent runs roughly northeast to southwest which comprises both teaching accommodation and a circulation street. At the north end of the street is the administration, entrance atrium, main hall and dining room. At the south end of the street is the sports hall placed at the lowest point of the site. Running south east off the street are three 2-storey, deep plan classroom blocks. The layout of the building is intended to provide specific principle circulation routes and side streets and public spaces that provide many opportunities for social interaction. The circulation is designed to reinforce departmental identities. The design philosophy is similar to that of Leith *Academy (see case study).*

Construction:

There are exposed steel columns on both the wings and the crescent, providing fixings for the solar shading, structural support for the roof and acting as rainwater downpipes.The aluminium windows are double glazed, powder-coated and thermally broken.

The majority of the roofing is low profile metal decking but terne-coated stainless steel is used on the curved part of the crescent. Floors are cast-in-situ concrete slabs on reinforced strip footings under column lines. Wall finishes are either plastered or fair-faced brickwork. There is a suspended ceiling on the ground floor to allow for service runs. The acoustic lining on the upper floor follows the roof line.

Passive Features:

The exposed floor mass in the street absorbs heat from the winter sun. Extensive solar shading allows 65% of the external wall to be glazed to minimise energy use by using daylight whilst preventing summer overheating. The classroom wings are designed to maximise the use of daylight and natural ventilation.

Heating and ventilation:

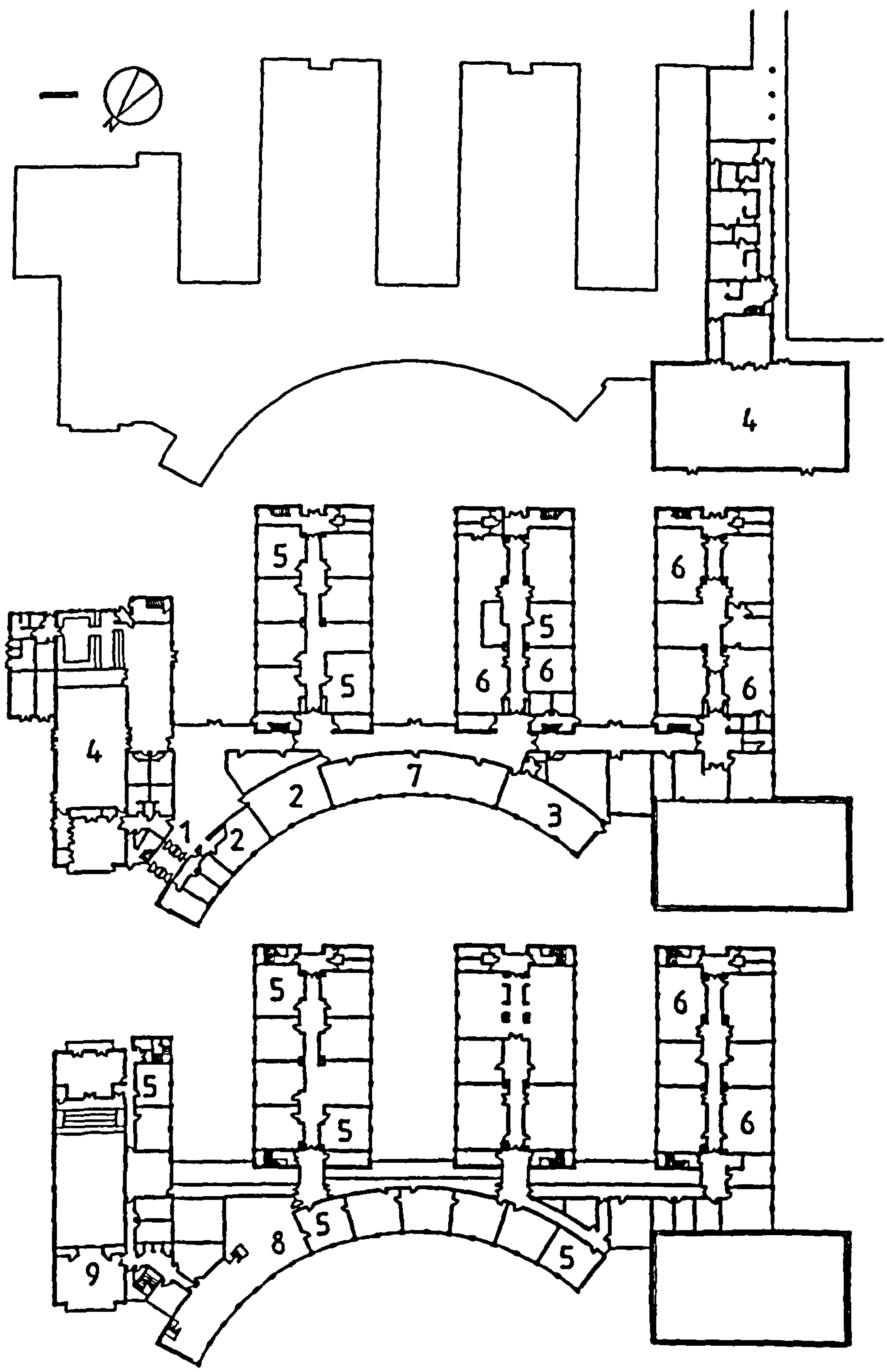
Natural ventilation inlets and outlets have been designed for all spaces. The inlets in places are combined with warm air heating and the outlets are automatically controlled.

The classroom wings have central shafts down to the ground floor providing daylighting and cross ventilation to the deep plan. Heating is extensively zoned and controlled by a Building Management System with central computer and printer. One of the three gas-fired boilers is condensing and supplies a low temperature underfloor heating system in the entrance atrium, main hall, and drama space.

Warm air heating *systems provide a fast response in the sports hall, sports changing room, kitchen and dining* room. Classroom blocks and circulation areas have radiators.

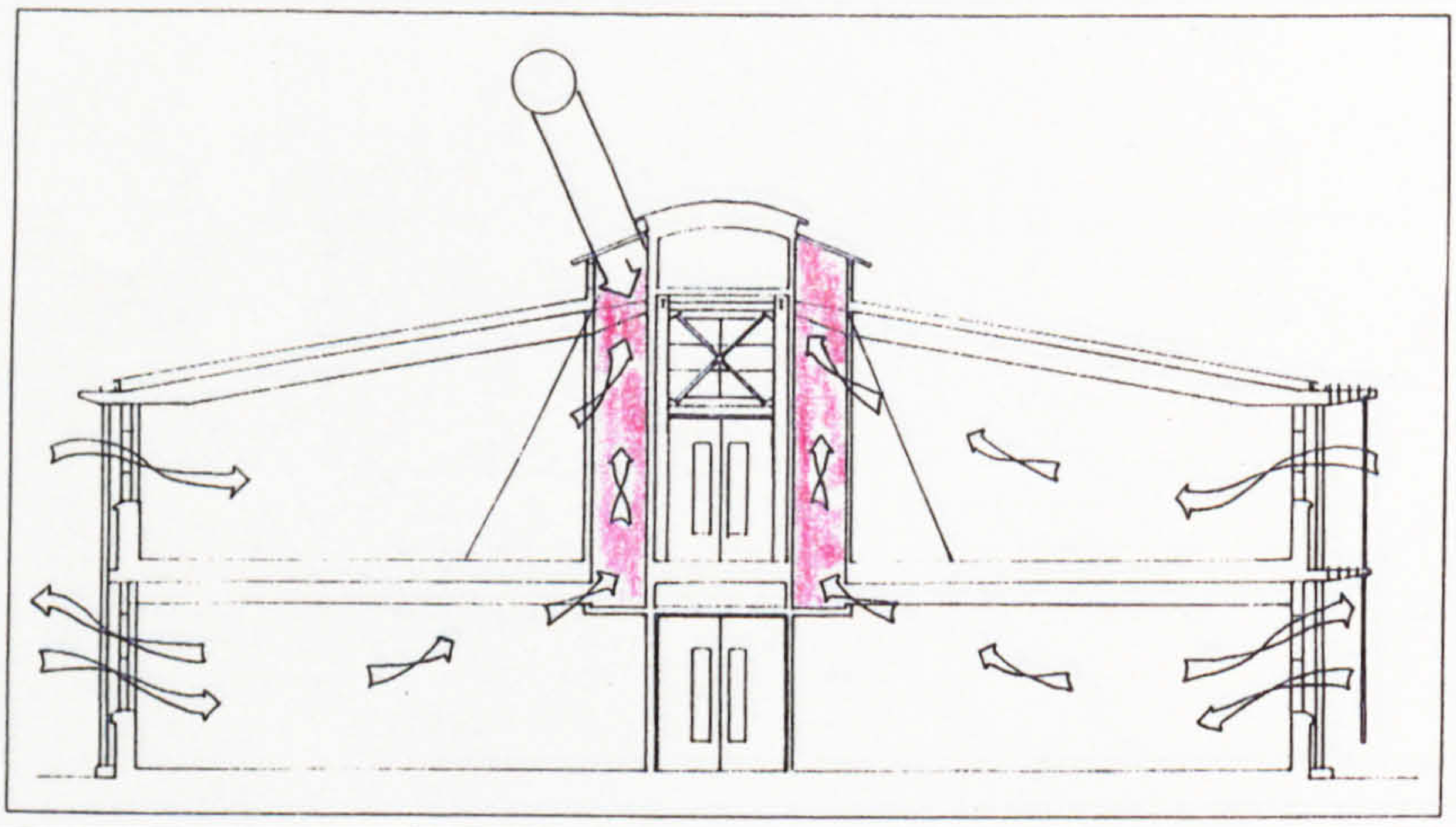
Direct gas fired storage water heaters are provided in the sports changing rooms and kitchen and point of use electric water heaters in toilets and teaching areas.

Cooling is only provided to the computer room.



1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Laboratory 7. Computer 8. Library 9. Music 10. Kitchen

Typical section through classroom block showing ventilation ducts to ground floor and daylighting of top floor



Lighting:

Recessed fluorescent fittings with high frequency control gear and louvres provide the necessary quality of light for frequent use of visual display terminals. There is external access and security lighting and floodlighting of outdoor sports areas.

First floor science laboratory showing daylighting from two sides

Model of school from the south east

Energy and Building statistics:

The design annual energy consumption in primary energy units is 173 kWh/m² compared with the 1981 Department for Education Design Note 17 maximum of 240 kWh/m².

U-values are much lower than the current Building Regulations Standards:-

U-values	Regs.	Actual	% improvement
Walls	0.45	0.32	40%
Roofs	0.45	0.30	50%
Ground slab	0.45	0.45	

Calculated Annual Energy Consumption Value in Primary Energy Units = 173kWh/m²

Gross Floor Area: 8720m² excluding unheated sports store: 50m²
Teaching Area: 4330m²
Number of pupil places: 900
Building Net Cost (BNC): £5,242,946 excluding external works
External works: £781,641
Base date 4th Quarter 1992
BNC/gross floor area: £601.26/m²
Completed in 1993

Architecture:

Fielden Clegg Design

Structural and Building Services Engineering:

Buro Happold

Conclusions:

The building is designed to be clearly legible with easily identified structure and services, eg. the central plant room is visible from the internal street. It is a low energy building making good use of daylight and natural ventilation and fits in with the landscape.

References:

'Building which explains itself', Construction study by Tim Ostler, Architects Journal, 17 March 1993.

Barnes Farm Infants School

Location:

Henniker Gate, Chelmsford, CM2 6QH, Essex, 51.6N 0.41E

There are two schools on this site: the Infants School which was occupied in January 1988, and the Junior School which is a system building, similar to Cherry Tree Primary, completed in 1980.

Design:

The Infants School is similar in design to the Newlands School in Hampshire, in that it features an unheated atrium/ greenhouse which joins two school blocks. The atrium is oriented along a north-south axis and classrooms are incorporated in both blocks. There is no significant direct gain element to this school.

Form:

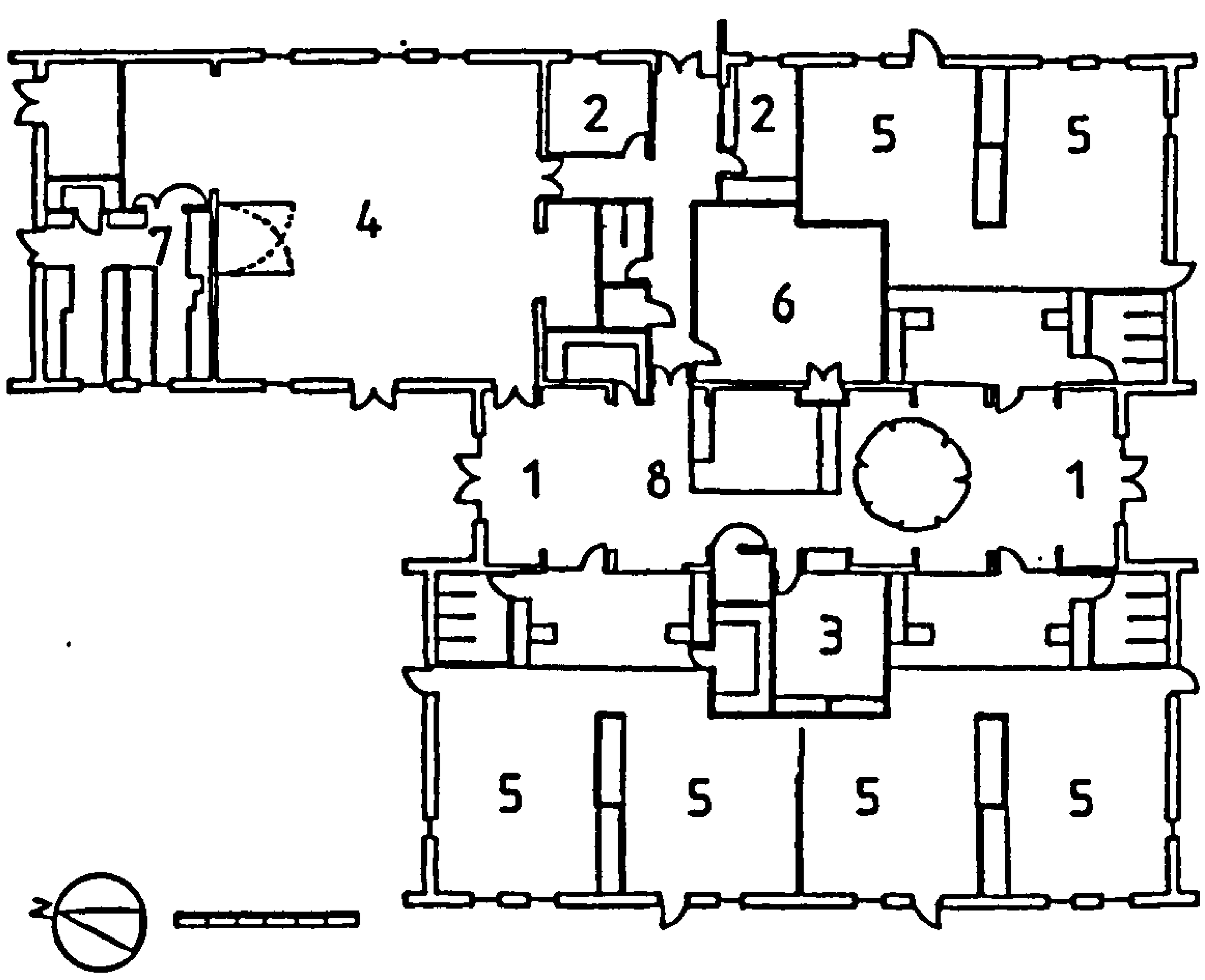
The two teaching blocks of the Infants' school are joined by a long atrium providing a low-cost additional area which functions both as a covered courtyard and covered external teaching space. This "buffer zone" has allowed the use of extensive glazing in the walls of the classrooms adjacent to it.

Construction:

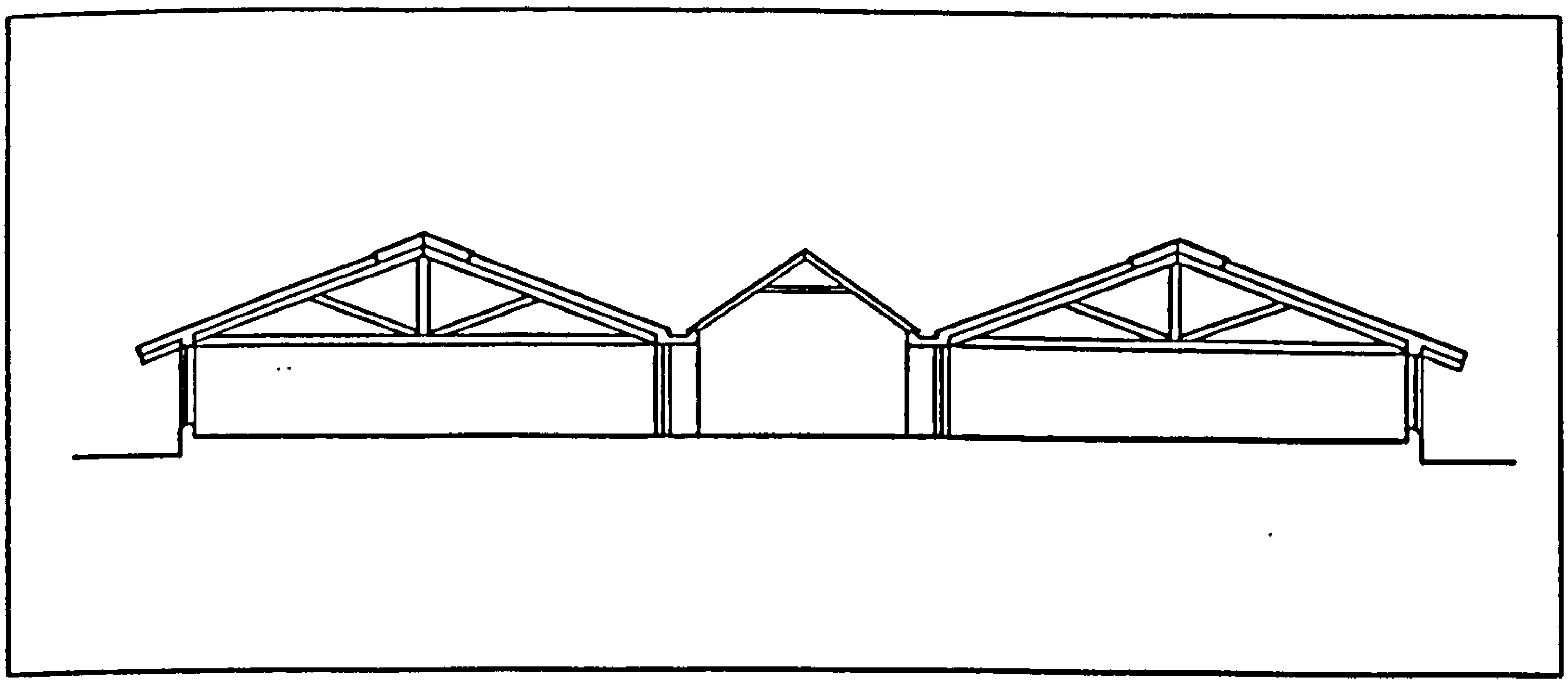
The external cavity walls have an external skin of 100mm concrete blocks, a 50mm cavity and 160mm fair-faced Lignatherm blocks internally. The walls have aluminium single glazed vertical sliding-sash windows with a polyester powder finish.

The atrium is glazed with twin-walled polycarbonate. The roof trusses in the classroom blocks are visible and those on the gable ends are glazed to provide daylight.

Plan of Barnes Farm Infants School. In clement weather the classrooms can be opened to the atrium.



1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Resource 7. Kitchen 8. Atrium



Section through the two teaching blocks and the unheated atrium which has been a popular feature of the school.

The low pitched roof is covered in cement fibre sheeting.

Passive Features:

The unheated atrium was constructed using greenhouse technology and includes motorised ridge vents for ventilation, operated by a rack and pinion mechanism. Doors at each end of the enclosure are opened to promote ventilation during warm periods. There is no heating in this atrium as it is not intended to be used as teaching space year round but as additional covered space. There have been no attempts to heat this space by leaving classroom doors open and using warm air from these areas to heat the space. The atrium may be entered from the classrooms via doors or sliding glass partitions. In clement weather the classrooms may be opened to the atrium.

Heating and ventilation:

The motorised butterfly ridge vents installed to provide summer ventilation may only be effective if sufficient low level inlet flow paths are available, i.e. it may require the end doors to be open.

Lighting:

The extensive use of glass along both classroom/atrium walls ensures good daylighting of the classrooms. The classrooms also enjoy a high level of daylighting via sun resistant double glazed roof lights and glazing in the gable ends. Artificial light is provided by uplighting of the sloping underside of the roof. There were complaints of glare from the glazing under the eaves of one classroom which faced southeast. However, the combination of uplighting and natural lighting was considered to be very restful and it was popular with staff and a welcome alternative to fluorescent lighting.

The north-south alignment of the atrium ridge facilitates good daylighting, as the low winter sun is allowed in from the south-facing gable-end windows, whilst in addition it inhibits overheating in summer.

Amenity:

The atrium is a very popular feature of the building and there were no complaints of cold air from this space entering the classrooms.

Energy and Building statistics:
Calculated annual primary energy consumption
= 296 KWh/m²

Actual average annual primary energy consumption of both schools combined (corrected from region and annual degree days to national 20 year DD average)
= 230 kWh/m²

Gross Floor Area: 704m²
Unheated atrium: 283m²
Number of pupil places: 180
Building Net Cost: Base date 2nd Quarter 1986
Building Net Cost (BNC): £378,358 excluding external works
External works: £66,269

BNC/gross floor area: £537.44/m²
Completed in 1988

Client:

Essex County Council

Architecture:

C.P.French, County Architect's Dept., Essex County Council

Conclusions

This is a good example of an unheated atrium. The atrium width of 6.2m is optimal.. The vents are effective in preventing overheating.

The south facade showing the entrance to the central atrium

Internal view of the unheated atrium

Fleet Infants School

Location:

Velmead Road, Fleet, Hampshire. On the outskirts of the small town of Fleet in Hampshire. Sheltered by a narrow belt of pine trees to the north and looking out to the south onto more woodland across a narrow tract of sandy heathland.

Design:

Nine class bases face south and look out onto paved areas. The hall/gym, music/drama room, kitchen and administration areas are on the north side of the central spine circulation route with its shared use niches. The central entrance opens onto a shared resource/library area. The administration, kitchen and toilets are in enclosed cellular pods.

Form:

The building has a low angle, pitched, profiled sheet steel roof rising to a continuous central barrel-shaped poycarbonate rooflight. It has full height double glazing on north and south facades and a concrete slab with underfloor heating.

Construction:

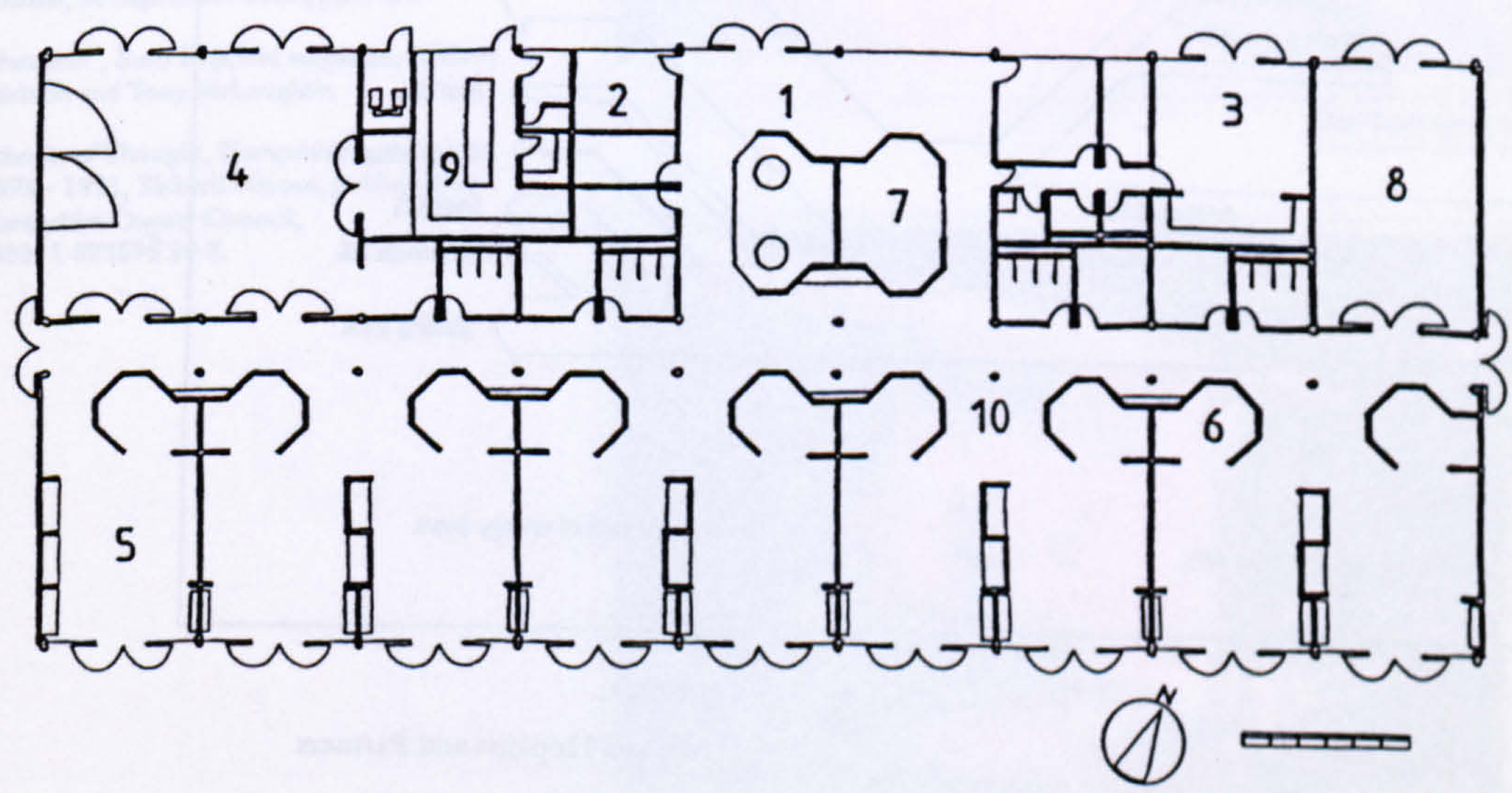
A minimal lightweight tubular steel frame supports a sandwich profiled steel sheet roof containing a mineral wool quilt with a polythene vapour barrier and a perforated ceiling on the inside giving good acoustic absorbency.

A mesh reinforced slab is locally thickened to support the columns. The north and south facades have full height double glazing.

Passive Features:

External stretched fabric awnings on the south side protect the glazing from solar gain in summer. Ridge vents in the rooflight are opened automatically by thermostat or can be opened by a switch and are intended to generate natural

Plan of Fleet Infants School. The central spine of circulation separates the classrooms to the south from the ancillary spaces on the north side of the building.



1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Class Base 7. Library 8. Music 9. Kitchen 10. Shared

ventilation for the 10 metre deep classrooms which are fitted with perimeter louvre windows at clerestory level.

Heating and ventilation:

The building has little thermal mass to store solar gains and has a polythene pipe hot water underfloor heating system which is not sufficiently responsive to accomodate such gains. Overheating has been reported in spring and autumn.

Mechanical ventilation is provided to the kitchen and toilet pods.

Lighting:

Lighting is principally by daylight from the perimeter glazing and central rooflight. The quiet areas, toilets, kitchen and other areas located in pods are dependent on electric lighting.

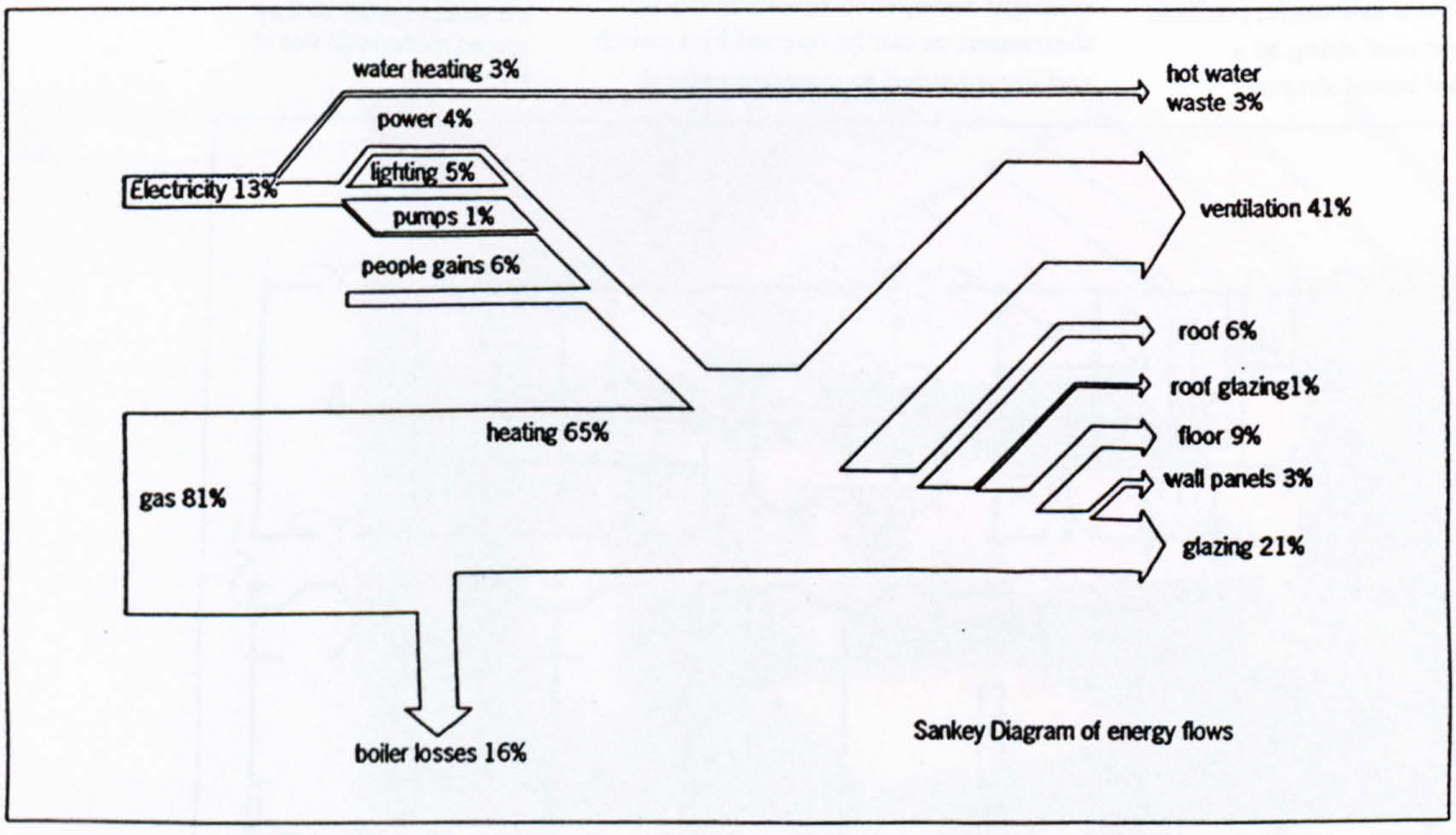
with other well known modern Hampshire designed schools. The ventilation loss accounts for 41% of the energy use as shown by the Sankey diagram. This may be due to the use of louvre type window vents which are notoriously leaky and were replaced in many London schools partly for this reason.

Energy and Building statistics:
Actual Annual Energy Consumption(corrected for regional differences but not to the 20 year Degree Day average) = 312.1 kWh/m²

Gross Floor Area: 1188m²
Number of pupil places: 315
Number on role: 220
Building Net Cost (BNC): £651,761 excluding external works
External works: £74,674

Base date 2nd Quarter 1987
BNC/gross floor area: £548.62/m²
Completed in December 1986.
Public sector tender price index: 254

Sankey Diagram showing the buildings supply and consumption of energy.



Sankey Diagram of energy flows

Energy:

The actual average primary energy consumption (corrected for regional differences but not to the 20 year Degree Day average) = 312.1 kWh/m²

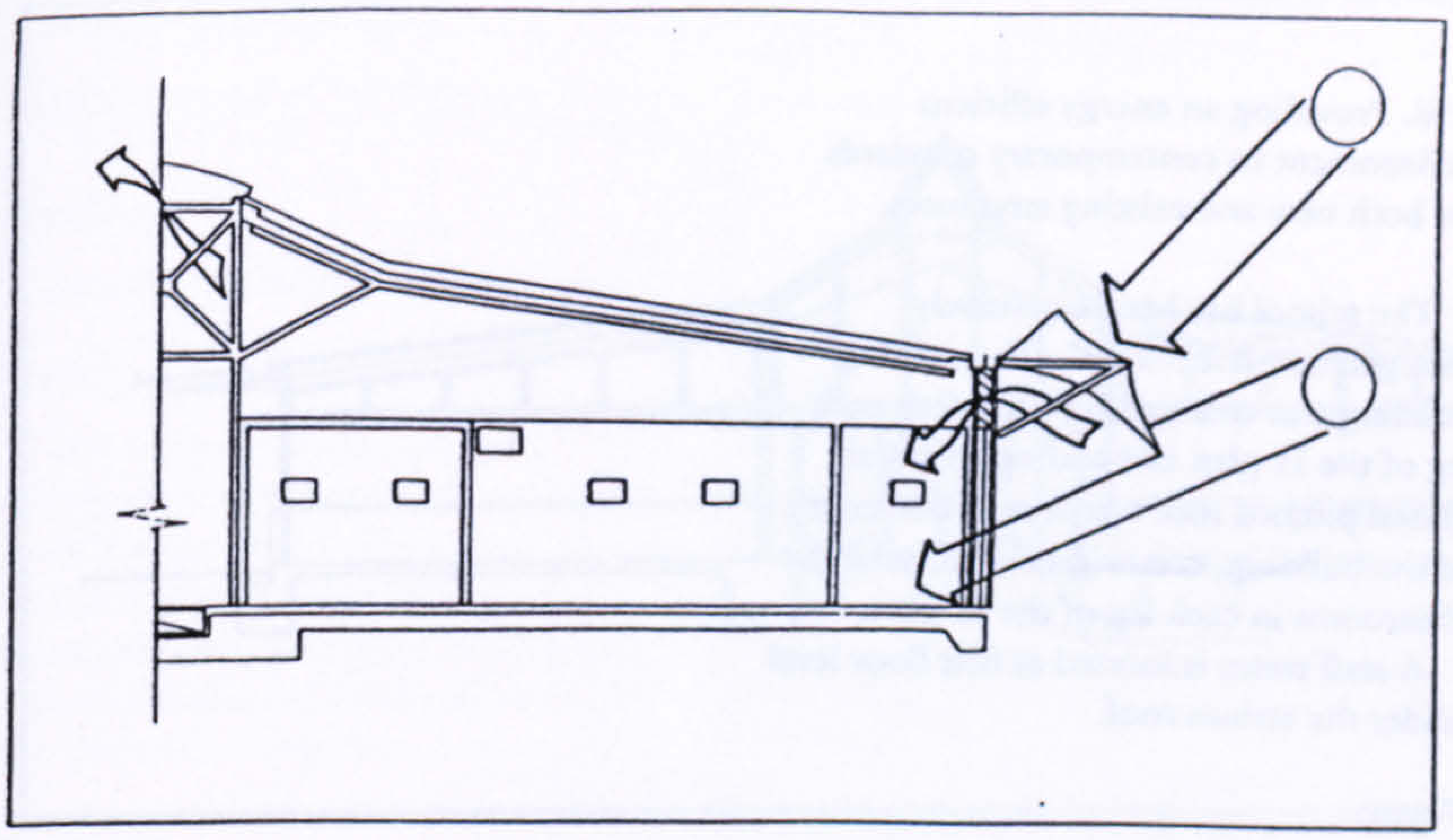
The energy use is high when compared

Architects:

Michael Hopkins and Partners

Services and Structural Engineers:

Buro Happold

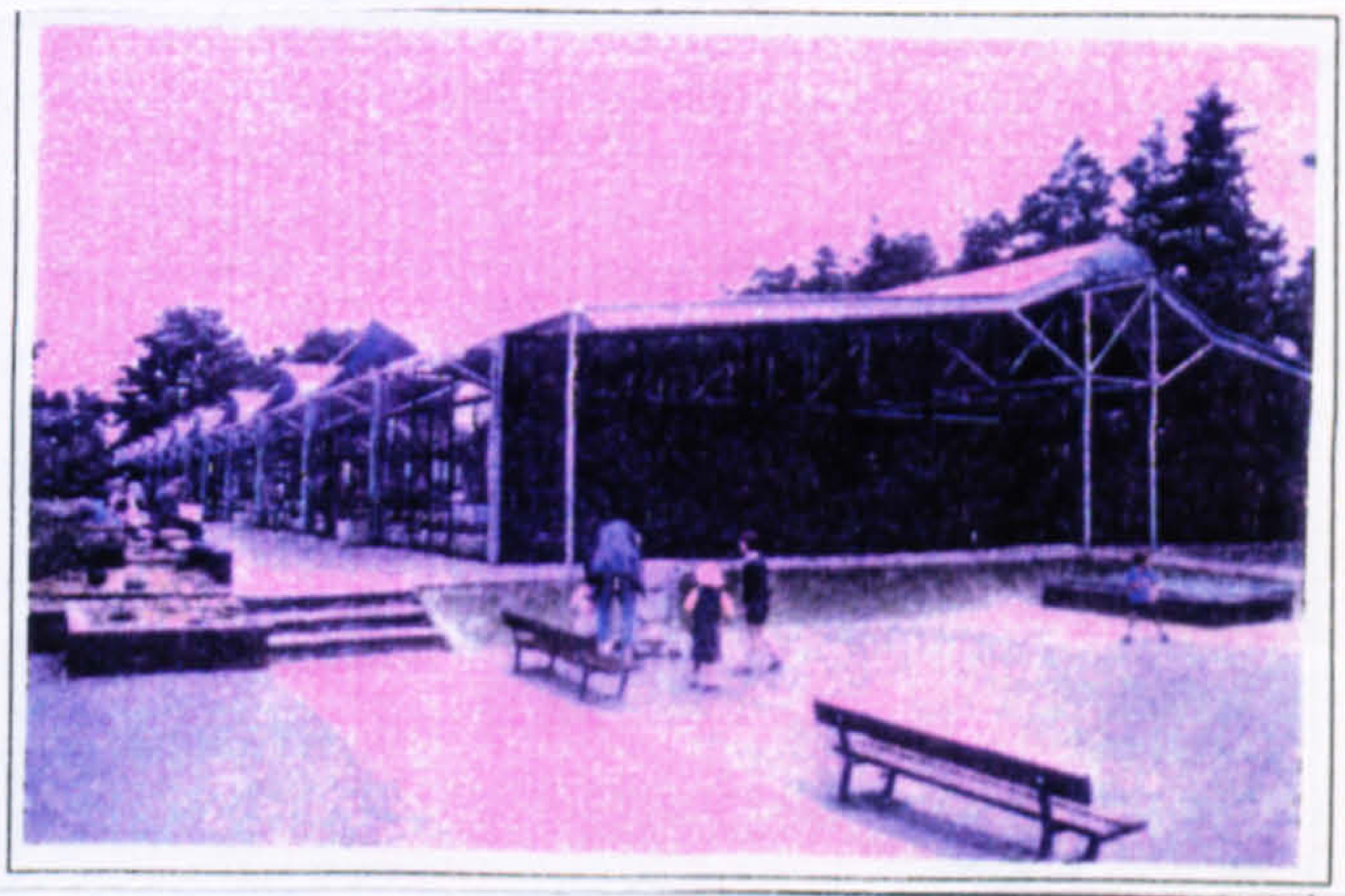


Schematic section through a classroom showing the external stretched fabric blinds which protect the glazing from summer solar gains. The ridge vents in the rooflight and the louvre windows at clerestory height help ventilate the classrooms.

Conclusions:

A very popular modern design which won RIBA national and regional awards, a British Steel Construction Award and a Civic Trust award. Environmental performance was considered in the design as can be seen from the environmental section.

The energy use is relatively high.



View from the east

References:

P.Hannay, G.Nelson & R.Barbrook, "Setting Sail at Fleet - Velmead Infants School", Architects Journal, 30 September 1987, pp37-53.

"Patterns", Buro Happold magazine, Michael Dickson and Tony McLaughlin.

Schools of Thought, Hampshire Architecture 1974 - 1991, Richard Weston, published by Hampshire County Council, ISBN 1 873595 10 7.

Interior of class base

HOOK INFANTS AND JUNIOR SCHOOL

Location:

Hook, Hampshire 51.2N 5W

Design:

The project was a prototype in its approach to the maintenance and refurbishment of SCOLA-system buildings and represents the first combined approach to building and site rationalisation by the County Architect with the aim of:-

i. Integration of two schools under one pitched roof to provide shared use of facilities on a reduced site area.

ii. Upgrading of an existing building to current teaching standards within the brief for a new school.

iii. Providing an energy efficient environment to contemporary standards for both new and existing structures.

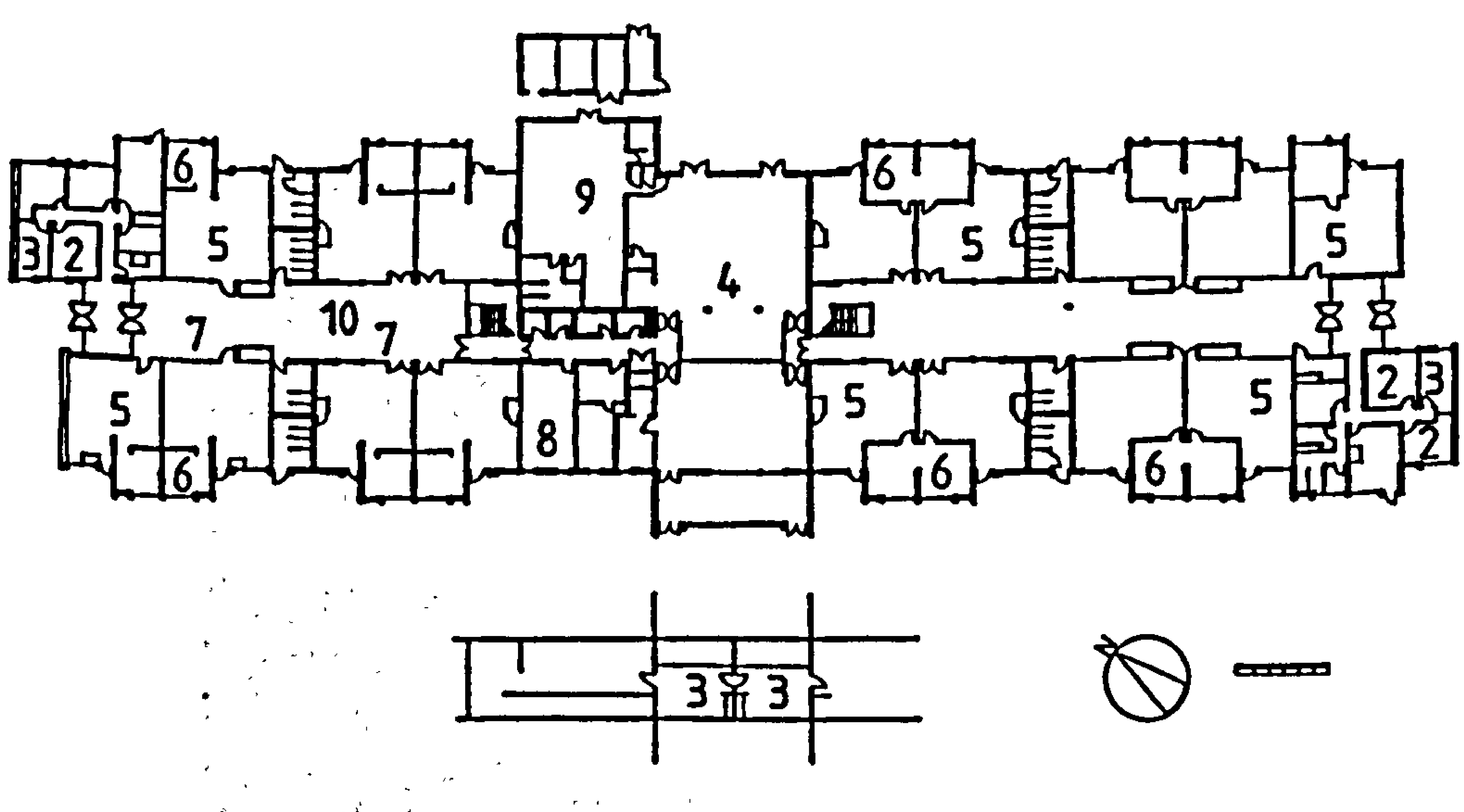
The school has been extensively enlarged and remodelled. The existing building was enlarged by extending each leg of the H-plan and adding a central glazed pitched roof which runs the length of the building, creating atria between the classrooms in each leg of the H-plan.

A staff room is located at first floor level under the atrium roof.

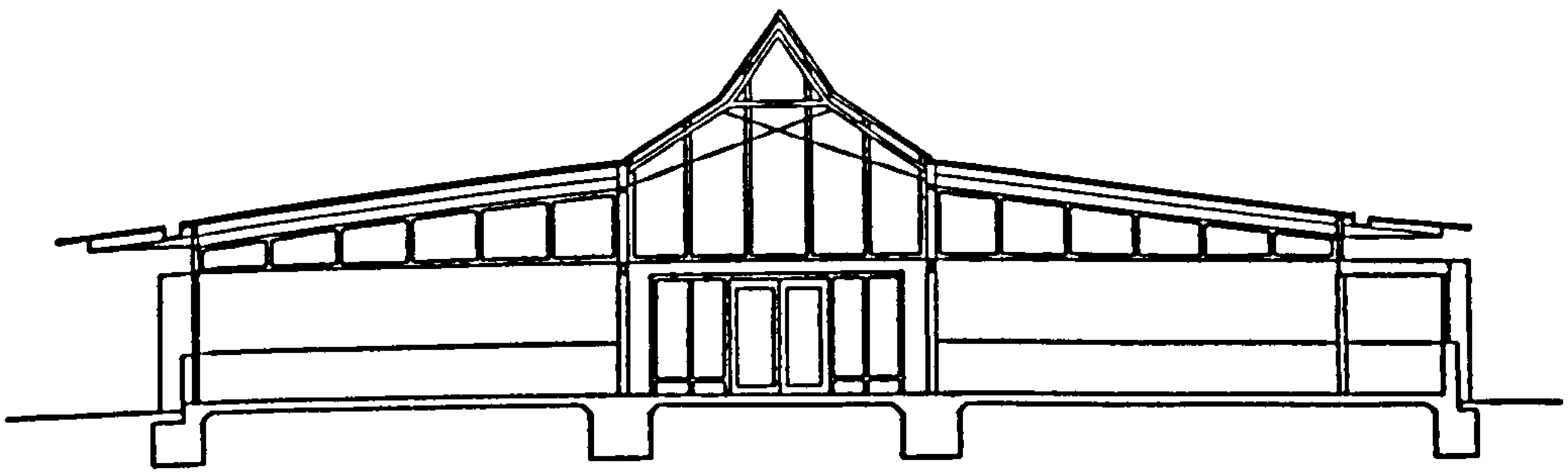
Form:

The axis of the glazed portion of the school lies in a Northwest-Southeast direction, the infants school occupying the Northwest and the juniors the Southeast. The occupants of the north end of the building consider that the atrium is often very cold in winter.

Plan of Hook Infants and Junior School. Below the ground floor plan is the first floor level where the staff room is located.



1. Reception 2. Office 3. Staff 4. Hall 5. Classroom 6. Class Base 7. Resource 8. Music 9. Kitchen 10. Atrium



Section showing the classrooms either side of the atrium. The atrium has a glazed roof with vents which can be opened manually.

Passive Features:

The atria are heated. The glazed roof may also act as a source of ventilation when both high solar gains generate sufficient buoyancy and the vents are opened. The latter require manual operation. Stale air is drawn from the classroom spaces and exhausted via the roof vents. Overheating of the central glazed area during periods of high solar gain is also controlled by these vents. Glare is prevented by an opaque composite roof sheet attached to part of the south facing section of the pitched, glazed roof.

Heating and ventilation:

The school is heated by gas-fired central heating, and no provision has been made for the warm air generated under the glazed roof to be conveyed for heating of classrooms.

Lighting:

Daylighting from the central areas is intended to illuminate the adjacent classrooms. Between the atria and the new classrooms there is clerestory glazing giving better daylighting than in the existing classrooms. The level of daylighting provided in the original classrooms, in contrast to the atria areas, is not considered to be satisfactory by the occupants, and artificial lighting is used at all times.

Energy:

The school has been well insulated and incorporates energy saving features, for example automatic lighting controls which switch off the electric lighting every twenty minutes.

Amenity:

The atria are heated and carpeted, and used extensively as additional teaching space, as well as providing circulation between the classrooms.

Energy and Building statistics:

Calculated Annual Primary Energy Consumption:
246.3 kWh/m²

Actual Annual Primary Energy Consumption:
243.6 kWh/m² (corrected for regional 20 year DD averages)

Gross floor area of extension: 827m²
Gross floor area of whole school: 2586m²
Teaching area of extension: 606m²
Teaching area of whole school: 1433m²
Number of pupil places: 430 (original school 320)

Building Net Cost (BNC):£805,500 including external works
Base date 1st Quarter 1985
BNC/gross floor area of whole school: £311.48/m²
Remodelling & refurbishment completed by 1988

Architecture:

M.Ogden, Perkins Ogden Partnership, Winchester

Building Services Engineering:

G.Herman, King Cathery Partnership

Energy Consultant:

Prof.P.O'Sullivan, UWIST, Cardiff

North Facade

Interior of heated atrium. The opaque surface of the south facing roof prevents excessive solar gain

Leith Academy Secondary School

Location:

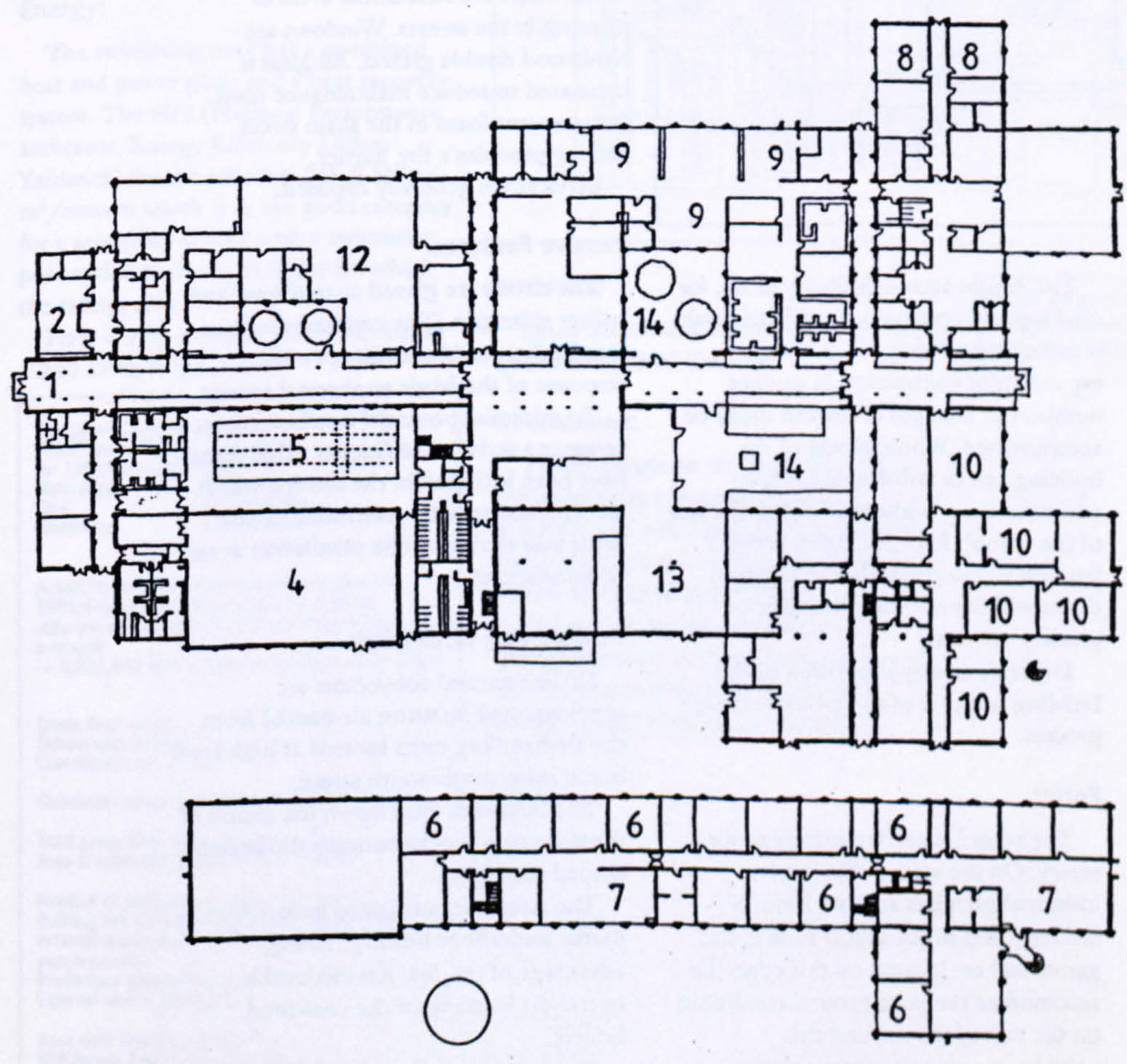
Quarryholes, Edinburgh

Design:

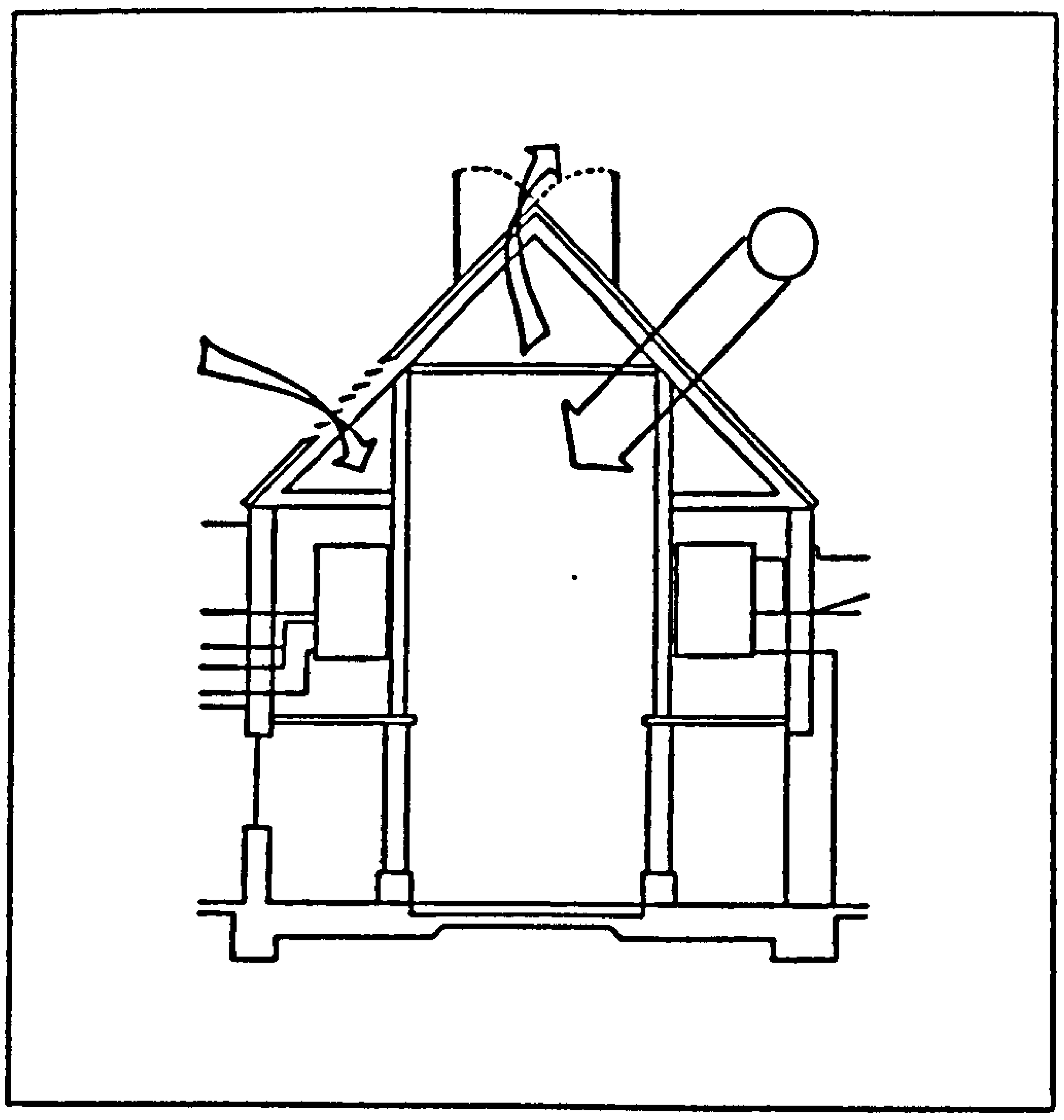
The design is planned for the management of change, with maximum flexibility and versatility and resembles a shopping centre, with a glazed main street, extensive planting, seats, a street cafe, and displays and banners identifying the subjects on offer. There are extensive community facilities. There is a swimming pool used by both school and community.

The secondary streets, also glazed, are at right angles to the main street to give access to any department without having to go through another one. The blocks of accomodation between the streets have a clear span of 16.8 metres, giving two bays of 7.2 metres each side of a 2.4 metre circulation/services distribution zone, also glazed. Sometimes this zone is incorporated within a room and sometimes it is "corridor" but nevertheless wide and full of light.

Plan of Leith Academy. The glazed main and secondary streets provid provide independent access to all departments within the academy.



1. Reception 2. Office 3. Staff 4. Hall 5. Pool 6. Classroom 7. Resource 8. Music 9. Art 10. Laboratory 11. Computer 12. Library 13. Kitchen 14. Courtyard



Schematic section of a street showing the glazing at roof level with ridge vents which help control potential overheating and enable smoke ventilation in the event of fire.

The design allows flexibility of use for teaching and community use of the main accomodation blocks. In this way expansion or contraction in student numbers or changes of use can easily be accomodated. Whole blocks of the building can be sub-leased for non-educational use without affecting the rest of the school. Reorganisation is easier because all interior walls can be taken down without affecting structure or primary services.

Dynamic energy simulation of the building was part of the in-house design process.

Form:

The school is predominantly single storey. On the west of the site are industrial premises and the 2 storey elements and major spaces such as the games hall are located on this edge. To accomodate the poor ground conditions on the east of the site and the neighbouring single storey and semi-detached private dwellings the college is single storey along this eastern perimeter.

Construction:

The building is a steel portal frame at 3.6m centres spanning the full width of the 16.8m typical building section thus achieving the maximum unobstructed volume. The roof is of composite insulated steel panelling with a barrel vaulted spine at the apex lighting the 2.4m wide circulation zone and enabling all rooms to be daylit. External walls are cavity insulated facing brick/block construction, and internal partitions dense paint grade concrete block. The main and secondary streets have facing blockwork walls roofed with patent glazing incorporating automatic opening sky vents. There are substantial areas of planting in the streets. Windows are hardwood double glazed. All glass is laminated to reduce maintenance costs. Intumescent foam in the main street glazing provides a fire barrier.

Services are generally exposed.

Passive Features:

The streets are glazed at roof level and collect solar gain. The exposed medium weight thermal blocks dampen the response of the fabric to thermal swings.

To minimise potential overheating in summer a series of additional ridge vents have been included in the streets, which are thermostatically controlled. These vents also enable smoke ventilation at no additional cost.

Heating and ventilation:

Sill line natural convectors are supplemented by warm air ducted from the air-handling units located at high level in the main north-south street.

The ductwork runs down the centre of the deep plan blocks beneath the barrel-shaped rooflights.

The streets are unheated except for partial underfloor heating, taking advantage of residual heat from the overnight kindling of the coal-fired boilers.

The heating and ventilating is controlled by a central BMS system linked to the Central Council Offices. Fresh air supply rates can be minimised in the haeting season. Fresh air can be used for free cooling in summer using the supply air fans. Local air-conditioning is not needed except for in small areas with high casual gains due to information technology etc.

Lighting:

By the use of clerestory glazing on corridor walls, in conjunction with slatted ceilings in smaller rooms, every room in the building is able to enjoy natural light within the deep plan.

Energy:

The swimming pool has a combined heat and power plant and a heat recovery system. The NPI (National Performance Indicator, Energy Efficiency Office Yardstick) for the school is 269.8 kWh/m^2/annum which is in the good category for a secondary school with a swimming pool and community facilities for which the ratings are:-

Poor < 470, Average < 370 and Good < 280 kWh/m^2/annum.

Energy and building statistics:
Actual Annual Energy Consumption for 1991/February 1992:

Natural gas	660,903 kWh
Coal	1,550,400 kWh
Electricity	620,652 kWh

Actual Primary Annual Energy Consumption for 1991/February 1992(corrected for regional differences but not to the 20 year Degree Day average)
= 5,821,842 kWh = 626 kWh/m^2(gross floor area)

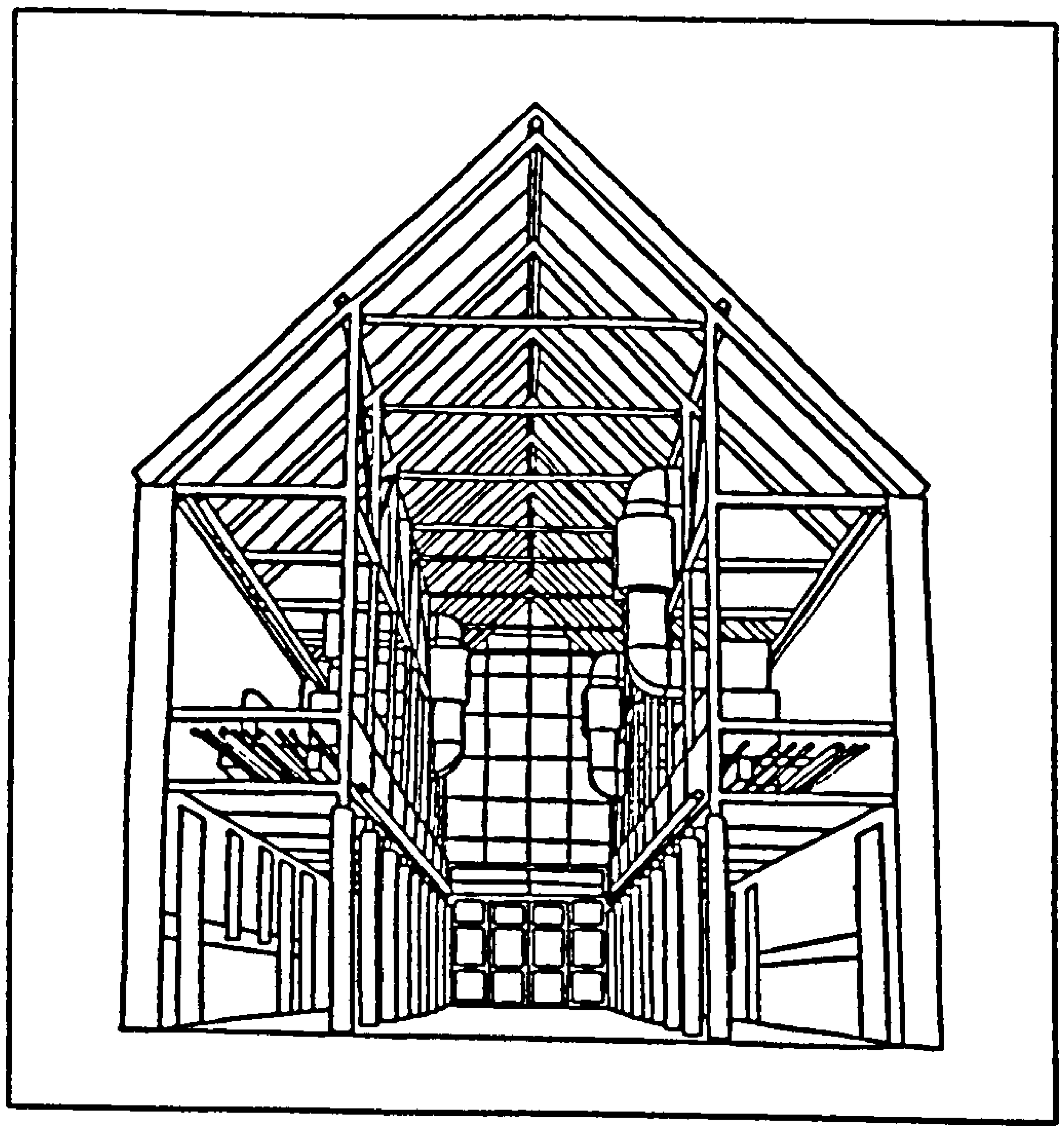
Gross floor areas:
School use: 7174m^2
Community use: 1311m^2

Circulation space for both uses: 810m^2

Total gross floor area: 9295m^2
Area of unheated glazed streets: 1,568m^2

Number of pupil places: 900 -1500 on occasion.
Building Net Cost (BNC):£6,797,293 excluding external works and preliminary ground improvements.
Preliminary ground improvements: £620,832
External works: £549,815

Base date 2nd Quarter 1988
BNC/gross floor area: £731.28/m^2
Completed in 1991.



Internal perspective of a street showing exposed ductwork and glazed roof above.

Architect:

Laura Stevenson, Architectural Services, Lothian Regional Council

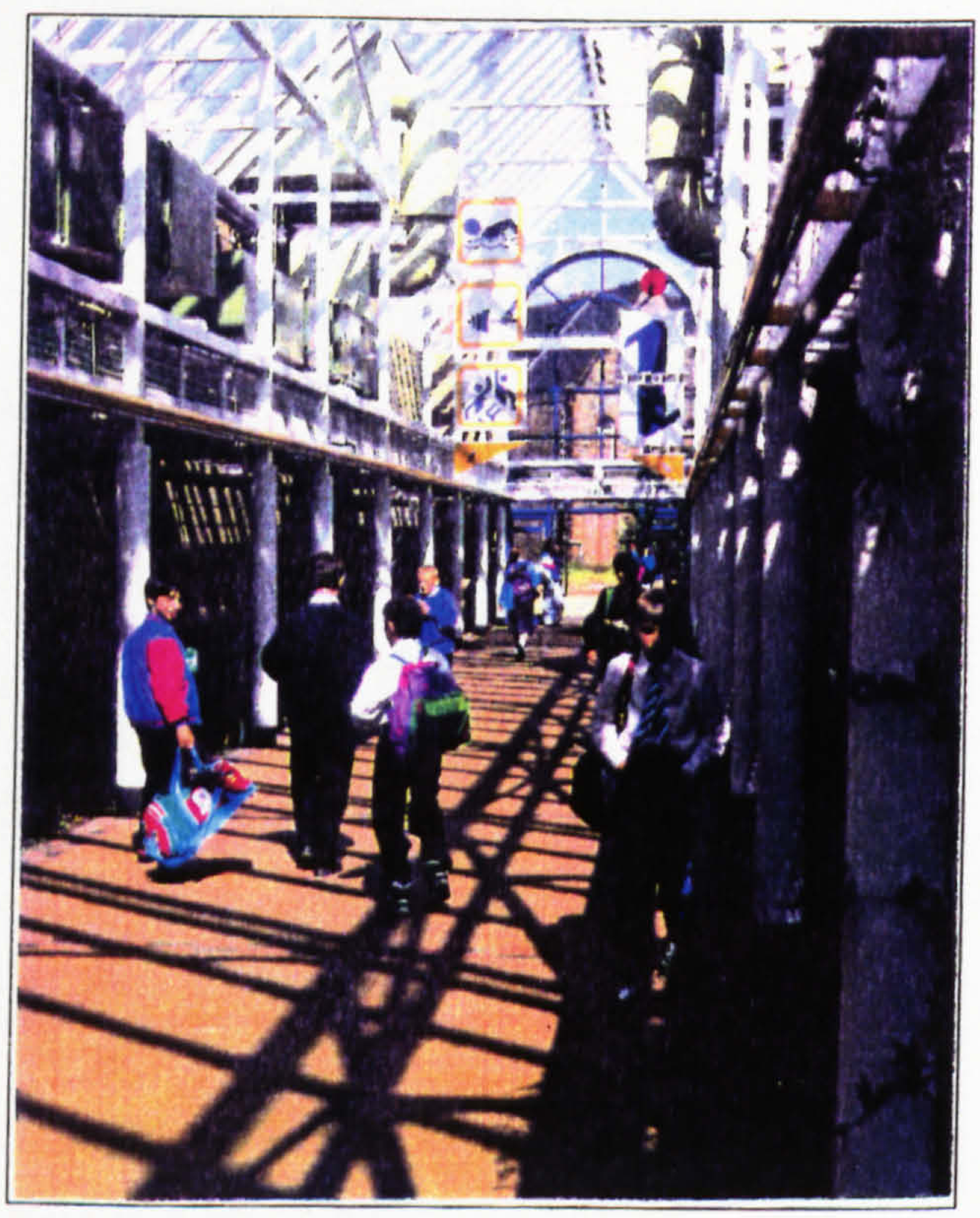
Conclusions:

The emphasis on the changing role of the building is a concern of many designers and this building demonstrates a way of providing for a range of end uses within one building envelope.

The design has received much attention, seems to work well and may be used as a model for further schemes including mixed use redevelopment.

North Facade and main entrance from street

Internal glazed street



Swanlea Secondary School

Location

Brady Street, Whitechapel, London. The school is in the east end of London. It is on the corner of two streets and is bounded on the north by a burial ground with some fine trees and on the west by an underground railway.

Design

In order to provide good communication between subject areas the school is designed around a main street with circulation by means of high level walkways, bridge links and a disabled access lift. By careful fire-engineering the stairs at each end of the mall have not been enclosed in fire compartments which eases the access beween levels.

Form

The teaching spaces are on three storeys on the north side of the mall and two storeys on the south. The south facing slope of the roof over the mall takes up the difference in levels and also maximises solar gains. The building is constructed on a module equal to the classroom width of 8.1 metres. This is expressed externally by the classroom setbacks and the repeating crest shaped slopes of the classroom roofs.

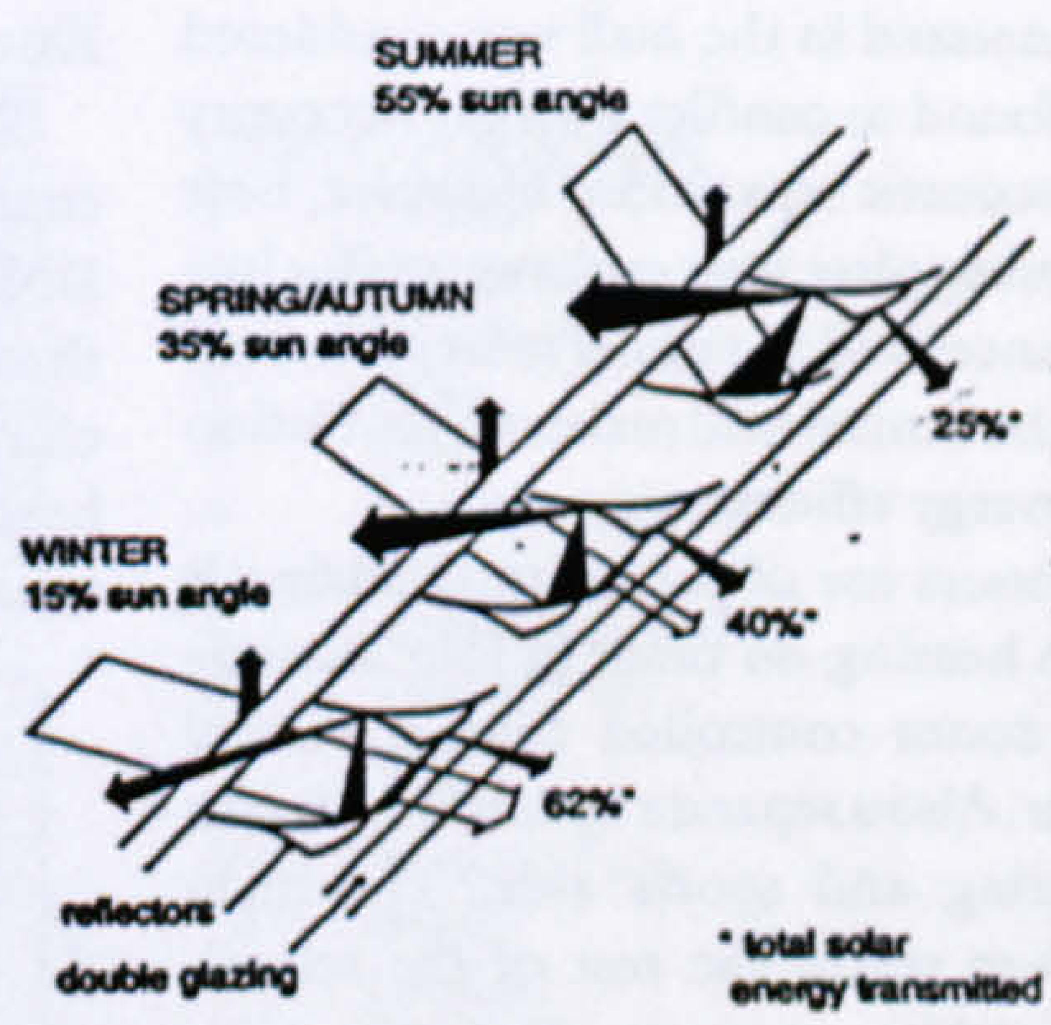
Construction

Bored cast in-situ piled foundations support a ventilated suspended ground floor slab. The walls are of loadbearing blockwork clad with bricks or cladding panels with insulated cavities. The street elevations are mainly in yellow London stock bricks, similar to existing local buildings. Internal walls are largely of plastered loadbearing blockwork with extensive glazing onto the mall. Blockwork partitions provide the robustness, fire resistance and acoustic separation needed and are an economical form of construction. Precast gutters provide fire stability to the compartment walls.

Upper floors were formed with precast shuttering with integral void formers to provide service routes and reduce weight. The curved roofs to the classrooms are built up from profiled aluminium sheet with standing seams carried on curved steel T-sections.

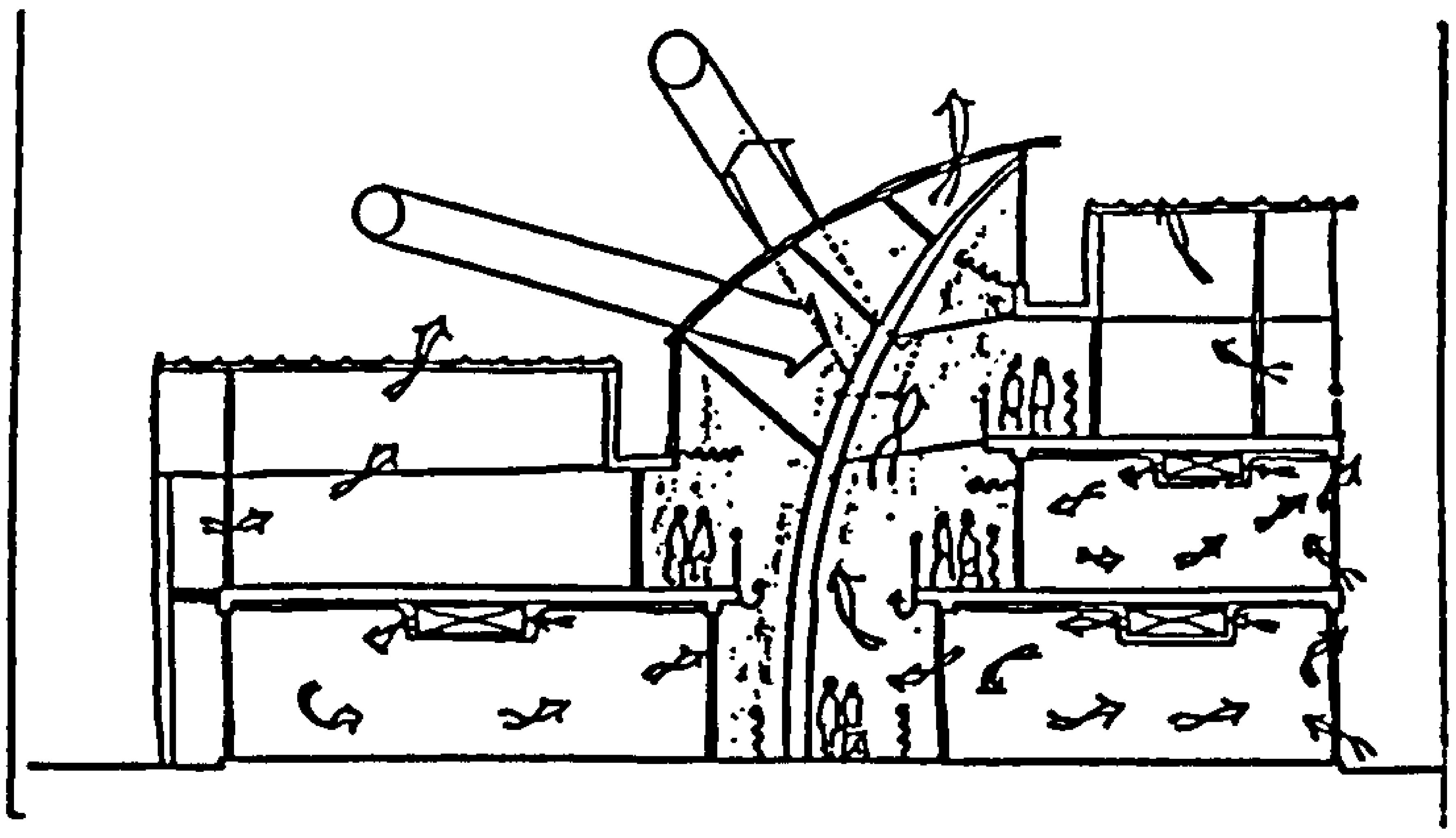
Passive features

The mall is glazed with special glass panels.These are hermetically sealed and double glazed. They incorporate purpose designed 'Okasolar' reflective glass prismatic strips set at predetermined angles. The angles of the prisms are adjusted depending on the location of the glass panel on the roof slope. This is because the slope of the roof gets steeper towards the bottom. The angle is chosen to reflect the majority of the sunshine in summer and to transmit the majority in winter.The angle depends on the altitude of the sun in summer and the angle that the glazing makes with the horizontal. The glass prisms are reflective are a form of fixed shading device. The glass is largely self-cleaning as the minimum slope is 15 degrees.



Detail section through Okasolar double glazing

The mall is unheated except for passive-solar gains and gains from the adjoining classrooms. Significantly, there have been no complaints that the mall is too hot or too cold. It therefore provides a useful thermal buffer space. The end walls are fully glazed as is the opening onto the south exhibition courtyard. In the heating



Environmental section through the central mall

season, when the temperature of the air in the mall reaches 20°C it is used as a preheated supply for the mechanical ventilation system serving the classrooms. In summer, overheating of the mall is prevented by thermostatic opening of the fire ventilators located in the top section of the sloping roof.

Heating and ventilation

Both the cavity-walls and the roof are well insulated with U-values around $0.3W/m^{2\circ}C$, much lower than required by the Building Regulations. The larger classrooms, laboratories and technology spaces are provided with mechanical ventilation. A scheme of natural ventilation using the stack effect generated in the mall was considered but was found to conflict with the necessary fire and acoustic separation. However, heat reclaim using plate heat exchangers (for low maintenance) and the use of solar preheated air from the central mall make the ventilation system energy efficient.

Out of hours use of part of the building is easy with heating-on times of four separate heating zones controlled from a central computer. Also a separate boilerhouse serves the catering and sports area. The main boilerhouse serves the rest of the school. The heating system has weather compensation, optimum start and radiators are fitted with thermostatic valves. Hot water is provided by local hot water generators except for the kitchen and shower rooms which are served from their own boiler plant.

Lighting

The maximum amount of daylight is admitted to all areas. Classrooms are lit from two sides; from the main view windows and from the clerestory glazing under the raised edges of the classroom roofs. Light is also borrowed from the central mall.

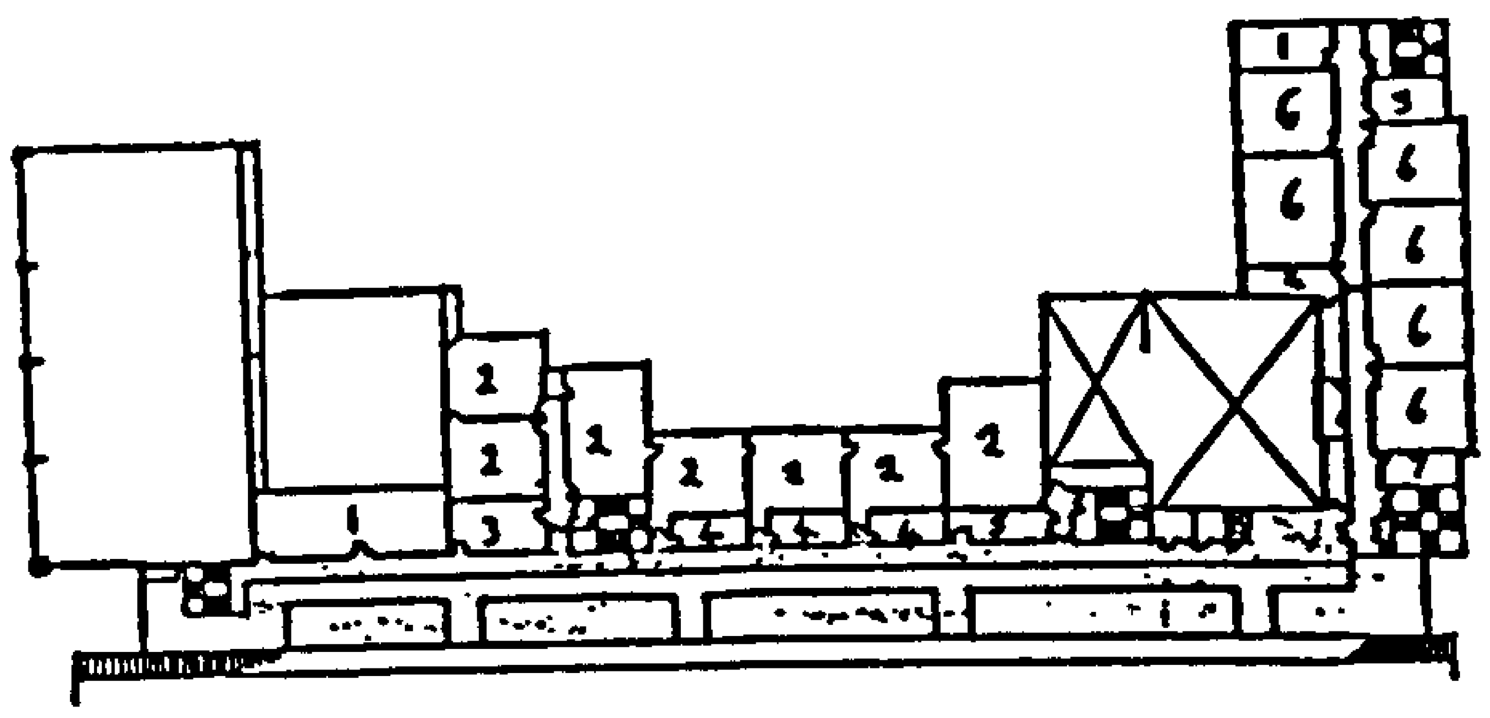
High frequency fluorescent lighting is used in most areas. In the classrooms a two stage switching arrangement controls each of 2 sets of bulbs in each luminaire so that the lighting can be adjusted to suit the level of daylight available. A central time control enables all classroom lights to be switched off at break or lunch time. This has proved cost effective in other schools.

Energy

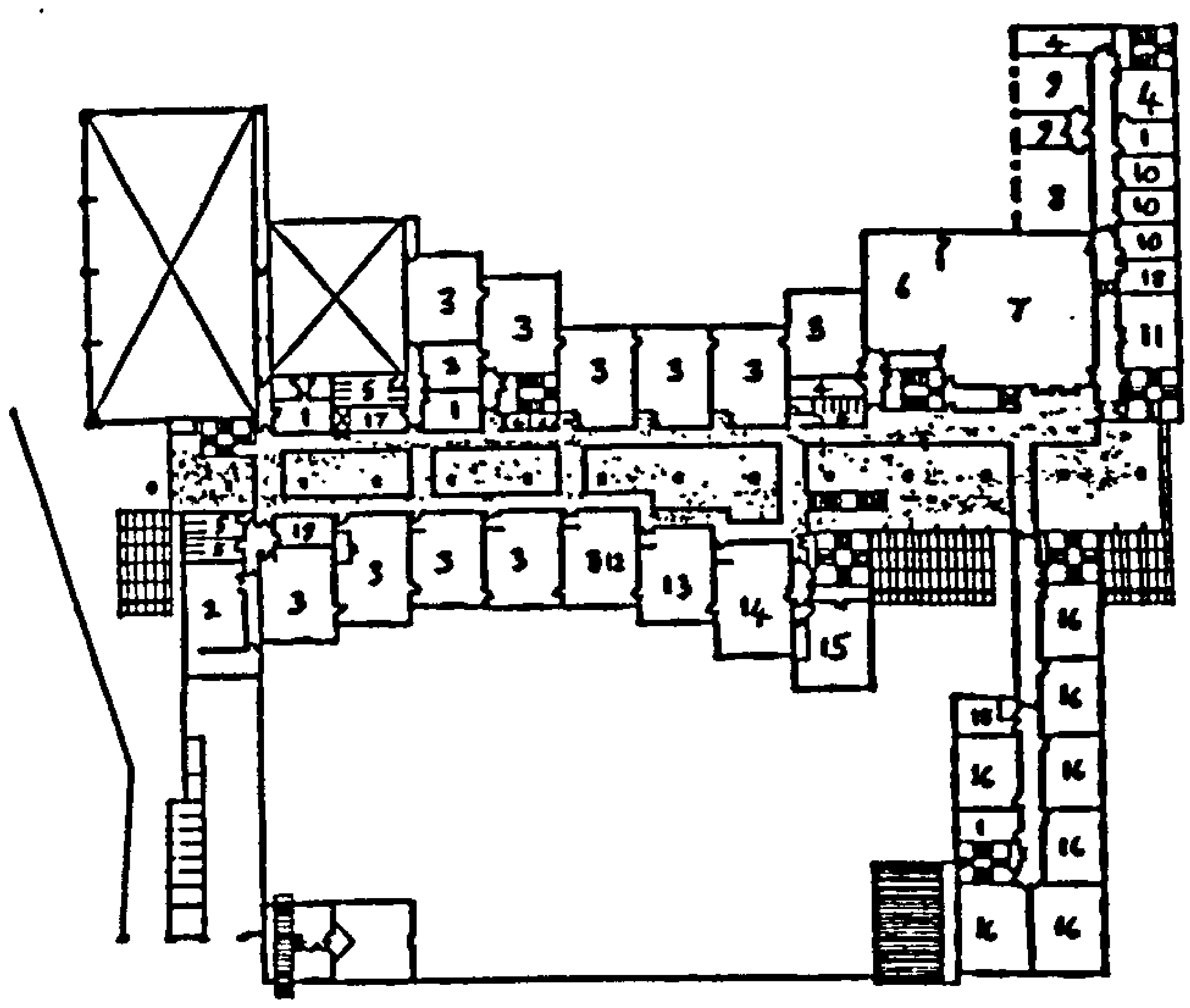
The building has predicted primary energy consumption figures based on the DN17 calculation which are much lower than the target values. The energy efficiency is due in large part to the simple heating and lighting controls aided by the unheated passive solar mall.

Energy and Building Statistics
Calculated Annual Energy Consumption in primary energy units = 148 kWh/m²
Calculated Energy Design Value in primary energy units = 96W/m² (compared to DN17 target of 120W/m²)
Teaching Area: 5092m²
Gross Floor Area(excluding the central mall): 9,023m²
Area of unheated mall: 1,486m²
Number of pupil places: 1050

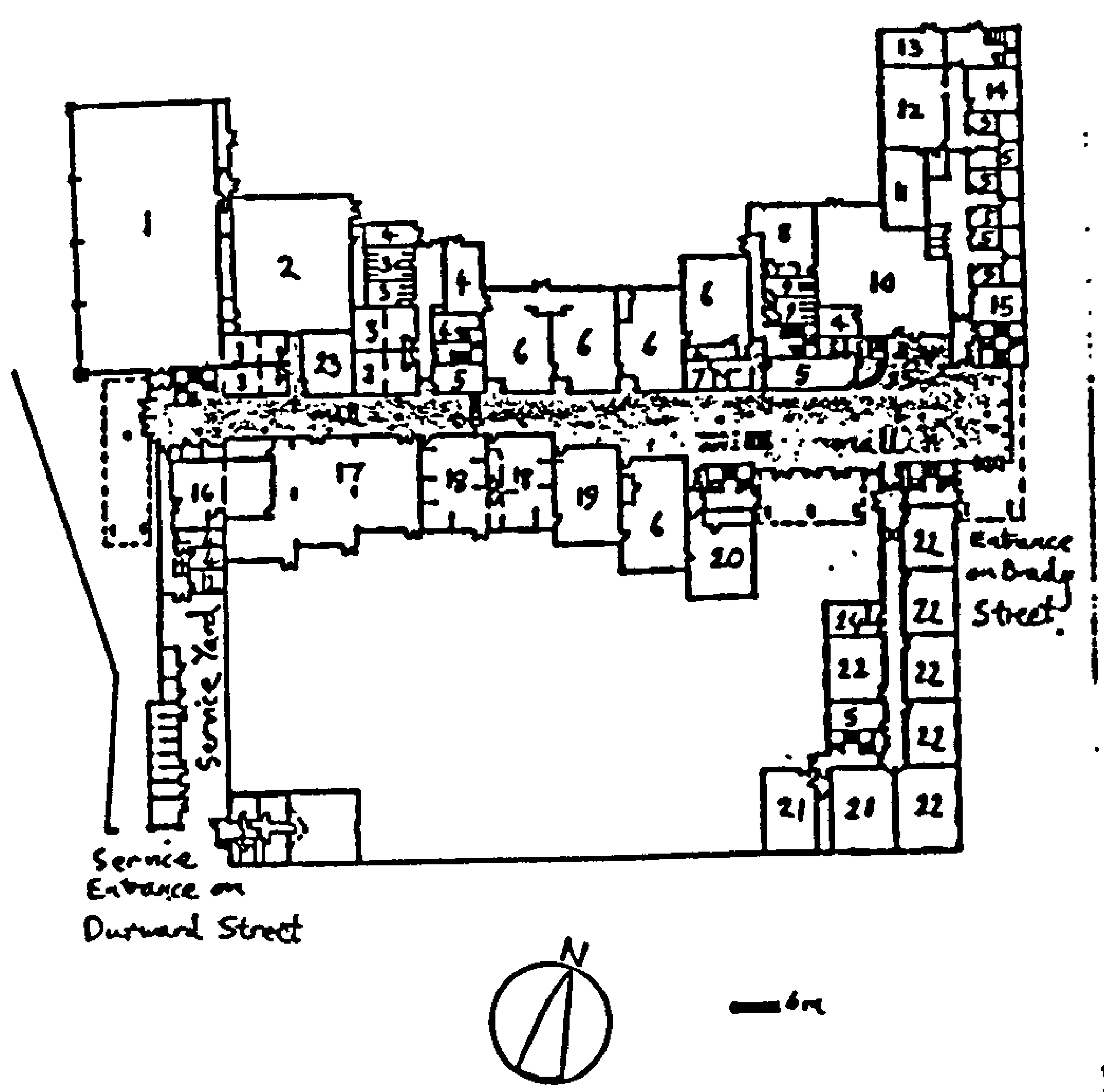
Building Net Cost (BNC): £6,981,800 excluding external works
External works: £580,000
Base date 4th Quarter 1993
BNC/gross floor area: £773.78/m²
Completed in August 1993
Public sector tender price index: 249



SECOND FLOOR
1 Plant
2 Maths
3 Office
4 Small teaching room
5 WC
6 Humanities
7 Store



FIRST FLOOR
1 Office
2 Plant
3 Science
4 Store
5 WC
6 Dance/drama
7 Assembly
8 Music
9 Studio
10 Ensemble
11 Meeting room
12 Electronics
13 Information technology
14 Office environment
15 Graphics
16 English
17 Caretaker's
18 Small teaching room



GROUND FLOOR PLAN
1 P.E.Hall
2 Gymnastics
3 Pupil change/WC
4 Store
5 Office
6 Technology/Art
7 Medical
8 Audio Visual Aids
9 Teacher's WC
10 Library
11 Study
12 Common Room
13 Boilers
14 Records
15 Headteacher
16 Kitchen
17 Restaurant
18 Food technology
19 Textiles
20 Resources
21 Community
22 Languages
23 Multi-gym
24 Small Teach
25 Reception

Amenity

Community use of the school has been considered as part of the design. The sports and catering facilities are separately zoned for heating allowing economical letting. A creche and community rooms are provided adjacent to the language department. The landscaping provides paved play areas and formal gardens. An ecological garden forms the focus of the southern courtyard and the small courtyard directly accessible from the mall is intended as an exhibition area.

Second floor classroom

Client and project management

Bethnal Green Neighbourhood Project Management, London Borough of Tower Hamlets Education Department

Architecture

The Percy Thomas Partnership

Structural Engineers

YRM Anthony Hunt Associates

Services Engineers

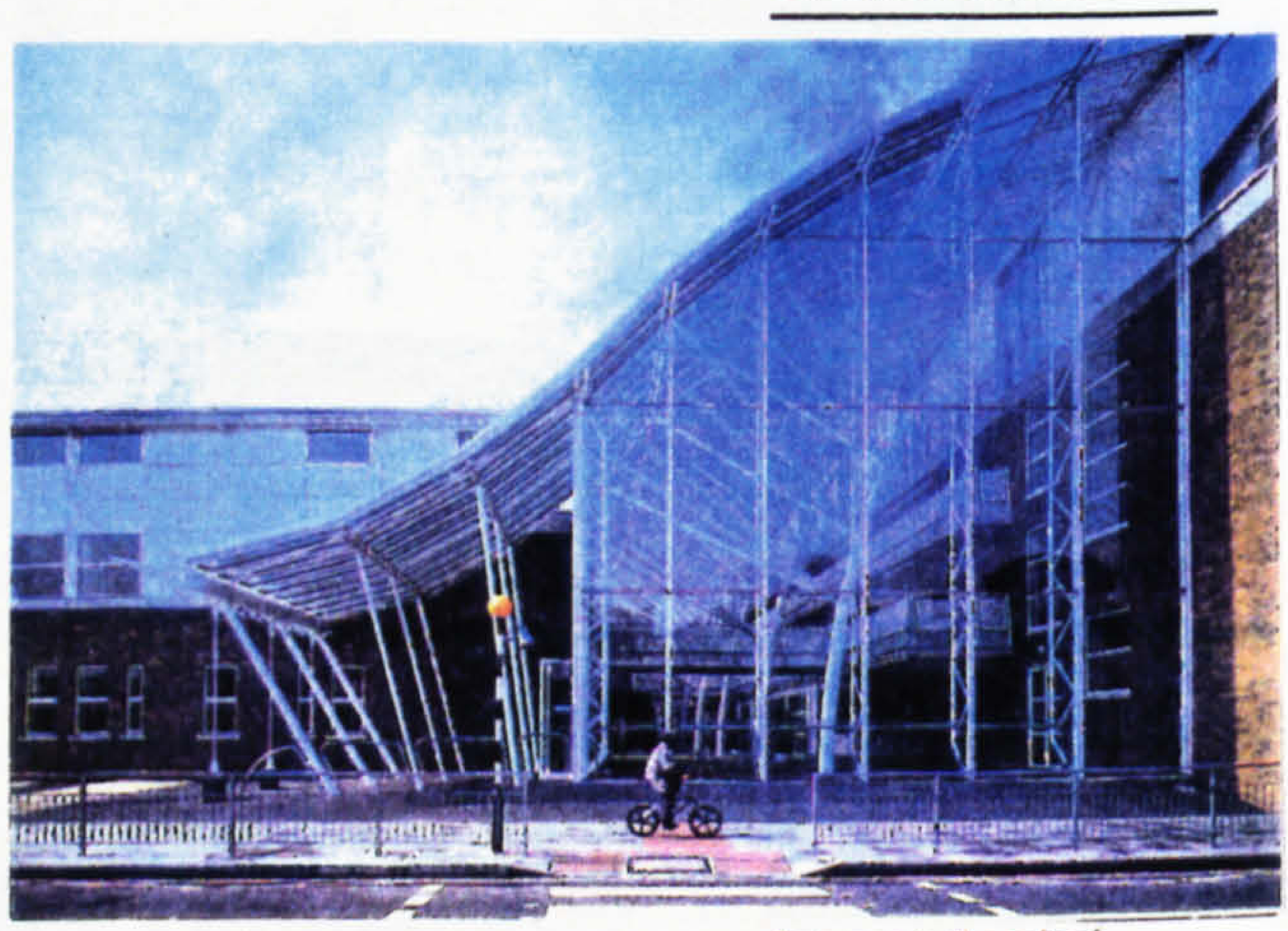
Whitby and Bird

Thermal and smoke modelling

Design Flow Solutions

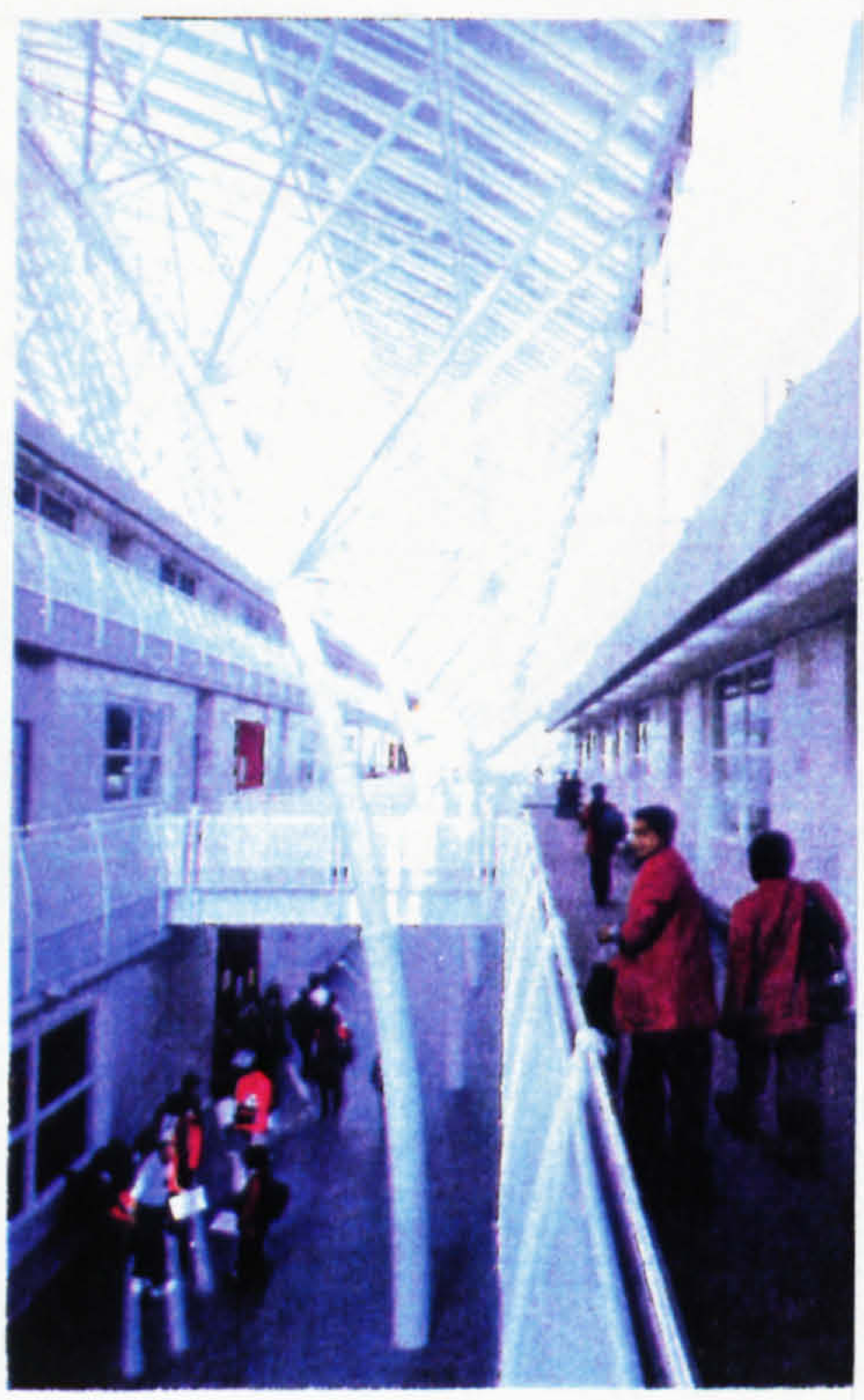
Fire Engineering

Colt International Ltd



Entrance to the school

View from the south



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The passive solar mall showing the curved tapering circular hollow section support columns and the fire ventilators at the top of the sloping roof

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