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CRANFIELD INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

PhD THESIS

Academic Year 1989-1990

Box 3

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PASSIVE SOLAR SPACE
AND WATER HEATING SYSTEMS

Long-term performances
in the U.K. climate.

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June 1990

This thesis is submitted for the degree of
Doctor of Philosophy

ABSTRACT

The performance of three types of passive solar feature has been studied; fifteen Roof-Space Collectors on an estate of low energy houses at the Milton Keynes Energy Park, 101m² of Thermosyphoning Air Panels at a county primary school in Nazeing, Essex, and three Thermosyphon Solar Water Heaters installed on a group of three terraced cottages at Cranfield, Bedfordshire. Each of these passive solar features was monitored intensively for at least one heating season using dedicated data-acquisition systems. The maximum specific annual solar contributions to the auxiliary space/water heating systems were 128 kWh/m², 78 kWh/m², and 104 kWh/m² respectively. The corresponding payback periods were 25, 37 & 21 years respectively, on replication.

ACKNOWLEDGEMENTS

Without the generous funding of the Commission of the European Communities these three demonstration projects would not have been possible.

I am indebted to all the academic, research and technical staff at Cranfield who have, at various stages, offered advice and assistance, in particular; Dave Whittington, Dr Philip Hobson, Billy Constant, and Dr R. A. Hobday.

I would also like to thank;

Neil Cutland, Alan Horton and Steve Fuller of the National Energy Foundation for their help with the monitoring and installation of the RSC houses at Shenley Lodge 5,

John Miller of Llewellyn Construction for his advice and guidance during the construction phase at Shenley Lodge 5,

Colin Deal of Essex County Council for his endless patience and diligence while installing sensors at Nazeing County Primary school,

Mrs Voss, the headmistress, and Trishia, the caretaker, at Nazeing County Primary school for their assistance with "reading-the-meter", and

Roger Stern and Joan Knock, of the Statistical Services Centre at the University of Reading, for solving all of my statistical problems.

I would like to give special thanks to Prof. "Brain" Norton, University of Ulster for "supervision well beyond the call of duty".

Finally, I wood like two thank Alllison for all her help and support, not only for proof reading my thesis, but for being there when I needed her most.

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A_c	Area of TSSWH collector panel	(m^2)
A_e	Area of the external building envelope	(m^2)
C	Capital cost of installed system	(£)
C_{swh}	Cost of energy supplied by solar energy water heaters	(£/GJ)
C_{aso}	Cost of energy from auxiliary store	(£/GJ)
C_a	Specific heat capacity of air at a reference value	(J/kg/K)
C_p	Specific heat capacity of circulating fluid,	(J/kg/K)
D	Mean draw-off weighted time	(secs)
E	Auxiliary energy costs	(p/MJ)
f	Solar fraction applied to water heating	
F_{av}	TSSWH collector efficiency factor evaluated at the mean collector fluid temperature	
f_h	Solar Heating Fraction applied to space heating	
F_R	Heat removal factor for collector	
g	Acceleration due to gravity	(m/s^2)
h	Height of roof-space collector	(m)
H	Total daily solar radiation falling on plane of TSSWH collector	(J/m^2)
i	Discount rate	(%)
I	Instantaneous solar radiation flux	(W/m^2)
$I_{max}A$	Rate of input of solar energy through glazing area, A, for highest expected insolation, I_{max}	(W/m^2).
K	'Minor' loss coefficient for single eaves ventilator	
m	Maintenance costs	(£)
$\dot{m}$	Volume flow rate of air	(m^3/sec)
M	Mass of fluid	(kg)
n	System lifetime	(years)
P	Discounted payback period	(years)
Q	Space/Water Heating load	
t	Instantaneous time	(secs)
Δt	Period over which analysis is considered; day/months for RSC's & insolation period for TSSWH's	
T	Fluid temperature	($^{\circ}C$)
$\bar{T}_a$	Mean ambient temperature	($^{\circ}C$)
T_{min}	Temperature difference between 'fully-open' vent temperature and highest expected ambient temperature	($^{\circ}C$)
$\bar{T}_r$	Mean room temperature	($^{\circ}C$)
U	Thermal transmittance of construction	($W/m^2/K$)
U_{ann}	Average annual heat loss per unit temperature difference defined by equation 2.1.1.	
U_L	Overall heat loss coefficient from TSSWH collector plate to the ambient environment	($W/m^2/C$)
$\dot{v}$	Ventilation flow rate	(m^3/sec)
v_1	Velocity of air through an eaves ventilator	(m/s)
X	Dimensionless group derived in text	
Y	Dimensionless group derived in text	

Z	Dimensionless group derived in text	
β	Difference between mean daily store and mean daily collector temperatures	($^{\circ}\text{C}$)
α	Mean Absorptance of the surfaces within RSC /TSSWH	
ϵ	Efficacy (TSSWH)	
η	System efficiency (RSC)	
η_c	Annual TSSWH collector efficiency	
η_s	Annual TSSWH system efficiency	
ρ	Air density	(kg/m^3)
ρ_o	Density of air at an appropriate reference value	
ρ_w	Water density	(kg/m^3)
$\Delta\rho$	Difference in air density between loft and external ambient	
θ	Difference between mean store and ambient temperatures	($^{\circ}\text{C}$)
τ	Transmittance of the glazing material.	
$(\tau\alpha)_c$	Effective transmittance-absorption product for the collector	

Subscripts

o	initial/reference value
a	refers to the ambient environment
A	refers to auxiliary heated hot water
c	refers to the collector panel
d	refers to total daily
e	refers to the external building envelope
ev	refers to each draw-off event
L	refers to solar heated water withdrawn from the store
m	refers to the cold mains water supply
s	refers to the solar heated water store
sb	refers to mean temperature of solar store at beginning of the day or period of analysis
se	refers to mean temperature of solar store at end of the day or period of analysis
sw	refers to the solar heated water that is withdrawn
tk	refers to the solar heated water store

ABBREVIATIONS USED

ADC	- Analogue to Digital Converter
BOI	- Beneficial Operation Index
BIU	- Building Interface Unit
CJC	- Cold Junction Compensator
CMO	- Central Monitoring Office
Disc	- Floppy Disc
EVENT	- Event counter
IEEE	- International Electrical and Electronic Engineers
FEP	- Flourinated Ethane Propylene
HRU	- Heat Recovery Unit
MAPS	- Multi-Application Peripheral System
NBS	- National Building Standards
NPV	- Net Present Value
OPT	- Option
PRT	- Platinum Resistance Thermometer
RSC	- Roof-Space Collector
SHF	- Solar Heating Fraction
SLR	- Solar Load Ratio
SSF	- Solar Savings Fraction
TAP	- Thermosyphoning-Air-Panel
TSSWH	- Thermosyphon Solar Water Heater
u.v.	- Ultra-violet
WAHS	- Warm-Air Heating System

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CHAPTER ONE
INTRODUCTION

1.1 Passive Solar Space & Water Heating

Solely by means of its design and form, a building may use solar energy to reduce its auxiliary heating, ventilating and/or lighting energy loads. In an "active solar" building, this is accomplished by means of additional specialised mechanical components which are not required in a "passive solar" building. Passive features with "active" elements, e.g. fans, are termed "hybrid". However, many features which transport energy to the point of use via *small* fans or motors are regarded commonly as "passive" systems. In summary, the systems considered here are;

i) Fifteen Roof-Space Solar Energy Collectors

Cockerell Grove is a housing estate, which includes fifteen dwellings with integral hybrid roof-space solar energy collectors, located in Shenley Lodge, Milton Keynes, U.K. The roof-space collectors pre-heat ambient air before it is conveyed to an auxiliary gas-fired "warm-air" space heating system.

The fifteen dwellings, together with a further six "reference" houses of "conventional" design, were orientated so that the roof-space collectors and nearly all windows faced due south. The arrangement of houses on the estate was planned in order that there were no obstructions to the collection of solar energy even during the winter months at low sun-angles.

Each house was instrumented to allow it to be monitored remotely and non-invasively from a central monitoring office. Intermediate levels of monitoring in 20 houses combined with intensive high-level monitoring of the remaining house permitted the auxiliary energy consumption of each dwelling, the solar fraction, and the solar energy collection efficiency of each roof-space collector to be determined.

ii) 36 Thermosyphoning Air Panels at Nazeing County Primary School

101 m² of Thermosyphoning Air Panels (TAP) were retro-fitted to Nazeing County Primary School, in Essex in September 1988. The TAP's were installed as part of an on-going building refurbishment programme being undertaken by Essex County Council. These units contribute convective heat gains to the space heating requirements during autumn and spring whilst providing a degree of ventilative cooling during the summer months. Their high level of thermal insulation also significantly reduces heat losses through the fabric of the building. Such solar walls were particularly appropriate for institutional buildings, which were only significantly occupied during the day, as they delivered the collected solar heat into the room with minimal delay. Reverse circulation was prevented by locating a Tedlar film damper at the collector's inlet. A manually operated actuator was used to initiate ventilation of the absorber plate to the external environment when required, (primarily to avoid overheating during the summer months).

The school was monitored using two stand-alone data-loggers which sampled data from 79 temperature sensors, 5 solarimeters, and two heat meters, all at 10 minute intervals. The average hourly data was then transferred to floppy disks at the end of each month.

iii) Three Thermosyphon Solar-Energy Water Heaters

The long-term performance of three thermosyphon solar-energy water heaters, retro-fitted to a terrace of three dwellings in the village of Wharley End, Bedfordshire in eastern England, was determined. Thermosyphonic systems were chosen for their inherent mechanical simplicity, ease and economy of installation, and potentially-greater reliability. The objectives were to;

- a) demonstrate on three inhabited dwellings the contribution that a thermosyphon solar-energy water heater can provide to satisfy domestic hot-water requirements.
- b) determine the effect of different hot-water consumption patterns on the long-term solar-energy contribution to the hot-water demand.
- c) assess the reliability and effectiveness of three different methods of frost-protection.
- d) provide a realistic data base upon which a detailed economic analysis could be undertaken, and also to determine criteria for selecting heating systems established according to locality.

An automated monitoring procedure was developed and implemented to quantify the long-term performance of solar-energy domestic hot water systems. Individual system performance was monitored using a micro-computer based data-acquisition system. The daily hot water usage patterns of each house were studied, and the installation time for one particular system recorded.

The solar fraction for the indirect thermosyphon solar-energy water heater after thirteen months was 0.17 (17%) with a monthly maximum of 0.34 (34%) in July 1986. Comparing the total monthly solar fractions for all three houses during August 1986 gave solar fractions of 0.28 (28%), 0.29 (29%), & 0.42 (42%) for the third-tap with heating element, the indirect third-tap, and the pre-heated automatic draindown systems respectively. During the following month, houses Nos 7 & 9 were unoccupied, so the withdrawn volumes of solar heated water were controlled. This facilitated increases in the solar fractions of the

third-tap with heating element, and the pre-heat auto-draindown systems of 0.47 (47%) & 0.40 (40%) respectively.

When using controlled solar heated water consumption patterns, simple payback periods of between 35 and 39 years may have been expected optimistically for these three particular thermosyphon solar water heating systems. Long-term performance correlations were developed and validated via comparison with the data obtained. These may be used to simplify the design of this type of solar-energy water heater and thus encourage its replication.

1.2 Structure and Format of Thesis

Each chapter deals with a separate phase or aspect, (e.g. installation, monitoring), of the research. Common themes of each of the three installations studied are thus combined together. References cited are listed at the end of each chapter. A single nomenclature convention is employed throughout.

CHAPTER TWO
REVIEW OF PREVIOUS WORK

2.1. Demographic and Planning Constraints on the Adoption of Solar Energy in Dwellings in Europe

i) Introduction

An ideal "passive solar" urban layout would allow all buildings to face south. As can be seen from Fig. 2.1.1 this is not a new idea, and indeed, has either been proposed (see Fig. 2.1.1 (2.1.1)), or adopted, e.g. La Chaux-de-Fonds (see Figs. 2.1.2 & 2.1.3). However, most urban areas are not planned so favourably; this directly restricts the potential market for retrofit passive solar measures and also introduces site constraints on new buildings that inhibit the adoption of passive solar design.

ii) Urban layout constraints on the potential for passive solar retrofits

If passive solar design is to reduce significantly the consumption of fossil fuels in Europe, it is essential that they should be applied both to new and existing buildings. The extent to which this can be done depends upon aspects of layout, form and construction. New construction brings about a gradual transformation of the building stock. More dwellings are added to meet the needs of expanding populations and to replace existing structures which have become obsolete. The rate of construction depends upon demographic, political and economic pressures. Even at times of high economic growth, new construction may represent typically only between 1% and 2% of the total in any year. This means that for passive heating to make any significant impact on total energy demand in the short term it must be incorporated into suitable existing buildings in addition to new dwellings.

Approximately 50% of existing dwellings in the U.K. have a facade orientated within 45° of south (2.1.2). More importantly, only 5% of these favourably orientated dwellings lose more than 50% of the available solar radiation as result of any obstructions. Also in the U.K. it was found that over 33% of all roofs were of a form and orientation could, if suitably modified, act as effective passive solar collectors (2.1.2). The total national savings ensuant are shown in Figure 2.1.4. Such observations illustrate the, wholly fortuitous, benefits in terms of passive solar retrofit potential, of the less

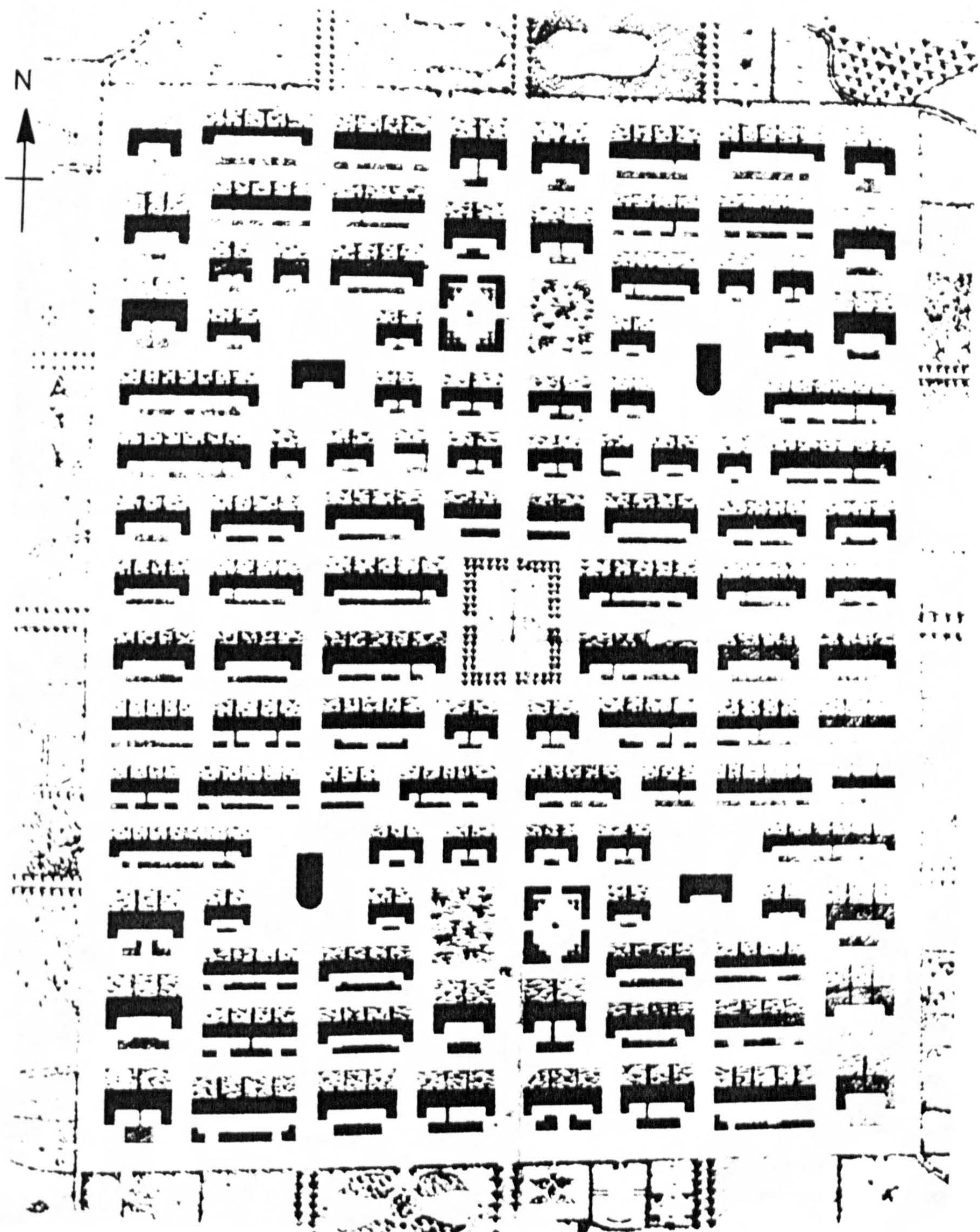
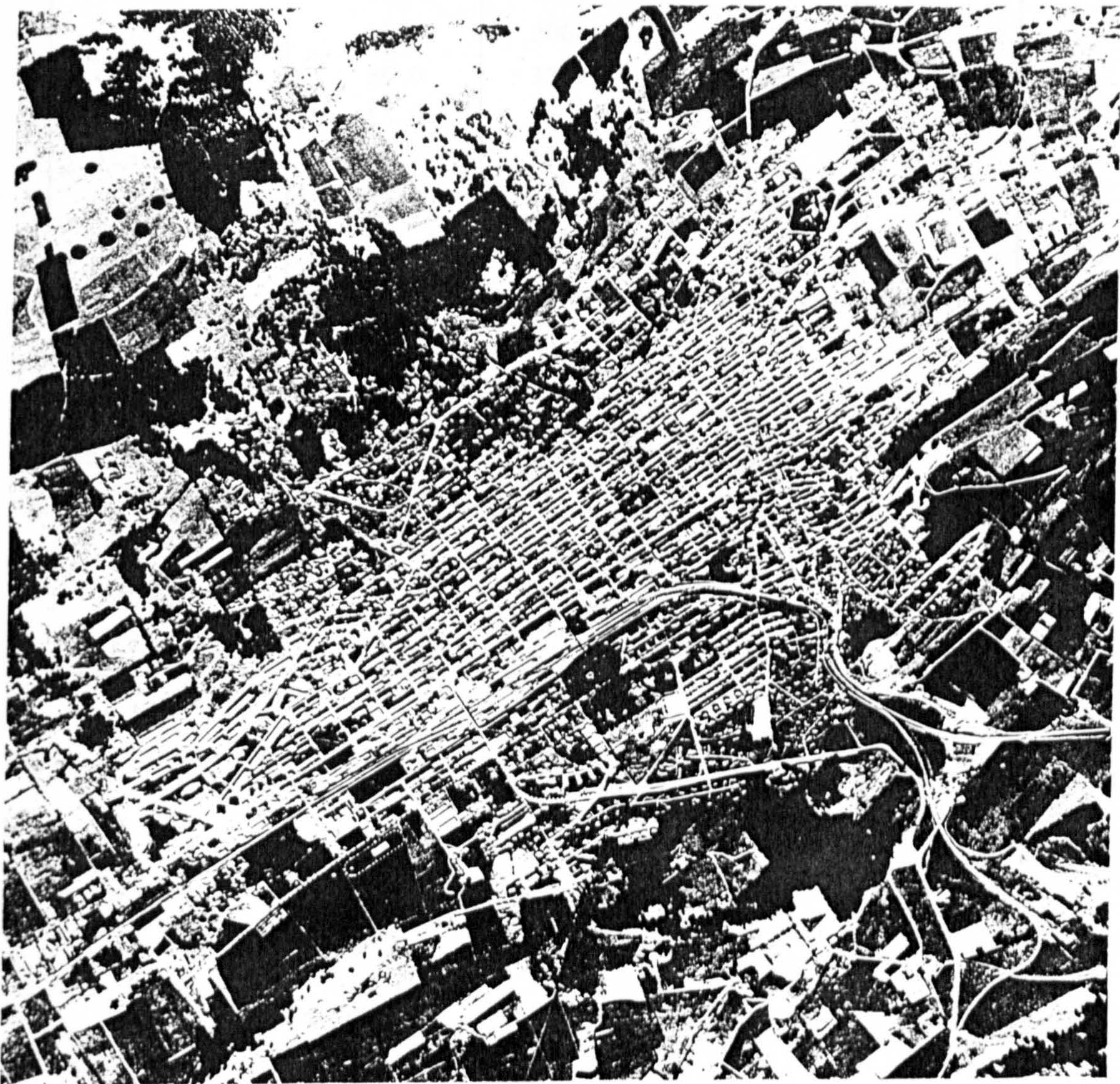


Figure 2.1.1 Plan of an "Ideal City" 1824 Germany. Inscribed "Zur Sonne nach Mittag sollen die Menschen leben" (People should live toward the Sun, toward the South).



Figure 2.1.2 La Chaux-de-Fonds, Canton of Neuchatel, Switzerland.
Rebuilt after destruction by fire in 1794. All buildings face the sun
and, as can be seen, are spaced to avoid overshadowing.

Figure 2.1.3 La Chaux-de-Fonds, an aerial view. All buildings are on a slope facing south.



Country	Primary Energy			
	Joules ($\times 10^{15}$)		mtoe	
Year	2000	2020	2000	2020
Belgium	25.1	34.3	0.6	0.82
Denmark	12.1	14.7	0.29	0.35
France	159.9	225.7	3.82	5.39
Germany	158.7	206.0	3.79	4.92
Greece	26.0	33.9	0.62	0.81
Ireland	13.0	18.8	0.31	0.45
Italy	96.7	123.9	2.31	2.96
Netherlands	35.2	47.7	0.84	1.14
U.K.	168.7	226.1	4.03	5.40

Figure 2.1.4 Estimated passive solar contribution in European domestic sector (2.1.3)

dense urban forms found commonly at the more northern latitudes.

77.4% of the total U.K housing stock are single-family houses. In Belgium and Holland, where 71.4% and 80.0% respectively of householders live in houses, it may be correct to infer that a similar result would be obtained to that for the U.K. where the climatic influences on urban form are similar. Elsewhere in Europe, the housing demography is different, with France and Germany having approximately 50% houses and 50% apartments, and Italy having only 30% of its households accommodated in single-family houses. The higher density building lay-outs further south in Europe are likely to be less favourable for passive solar heating, though they provide inherent shading, thus reducing cooling loads in summer. It has been estimated that 35% - 45% of all existing dwellings, and 65% - 75% of all new dwellings in Europe could be effectively adapted to make use of some form of passive solar space heating (2.1.3). These results were obtained by extrapolating conclusions which apply in the U.K. to the circumstances which apply elsewhere in Europe.

In modern Europe there is quite a wide variation in the proportion of houses to apartments between one country and another. Figure 2.1.5 presents basic data for the number of dwellings in each country in the European Community and Fig. 2.1.6 shows the ratio of single family dwellings to apartments in each European country. Apartments may differ markedly from houses with respect to their orientation for passive solar purposes. An important influence upon apartment block layout throughout Europe was the concern for "light, space and air" of 1920's and 1930's "modern movement" architects (2.1.4). Thus many "modern" apartment blocks may prove to be orientated and spaced so as to benefit from retrofit passive solar heating. Older tenement blocks exhibited greater site densities and may be less promising, but even in these cases there is potential for roof-based collection.

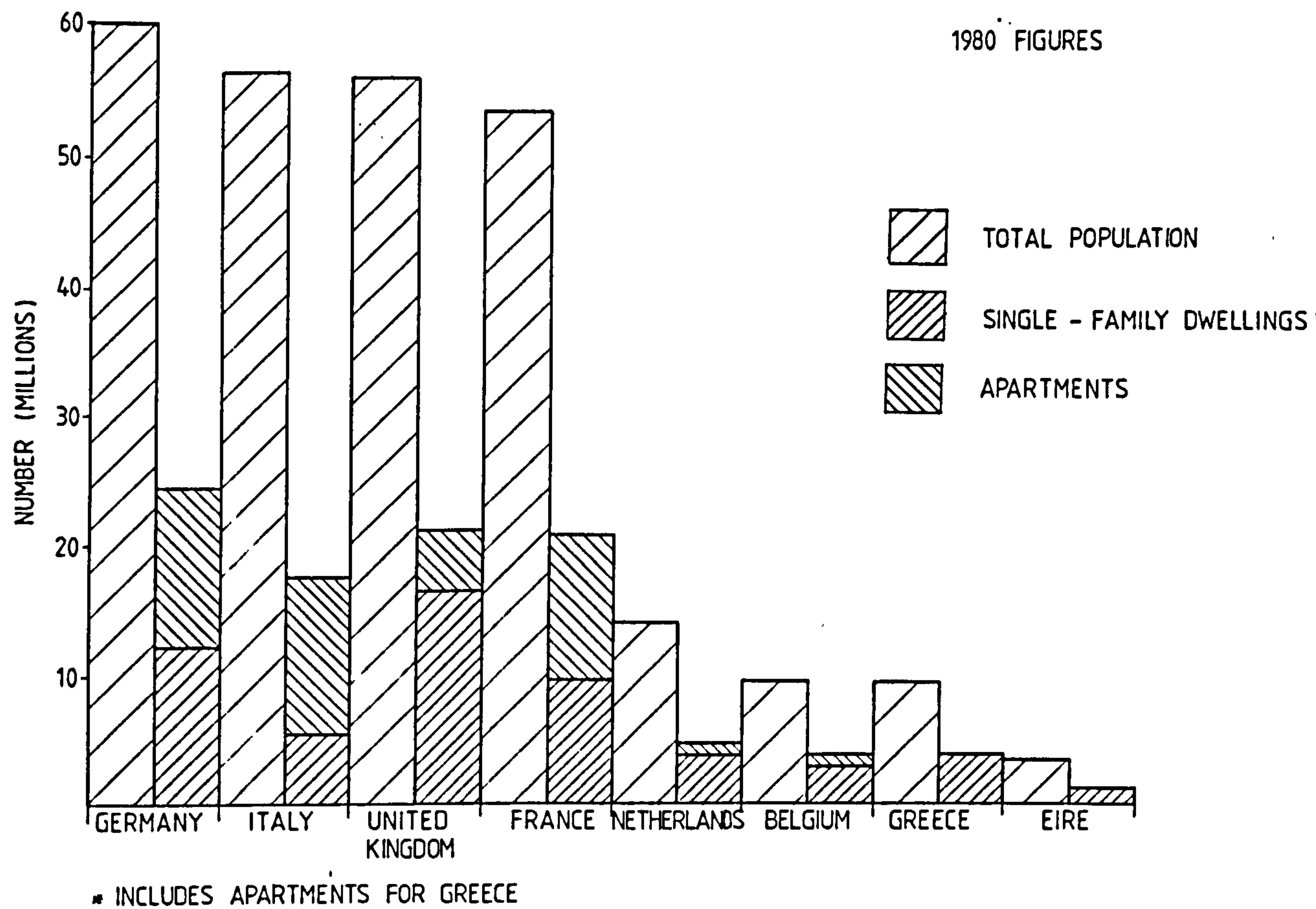


FIG 2.1.5 THE EUROPEAN STOCK OF DWELLINGS

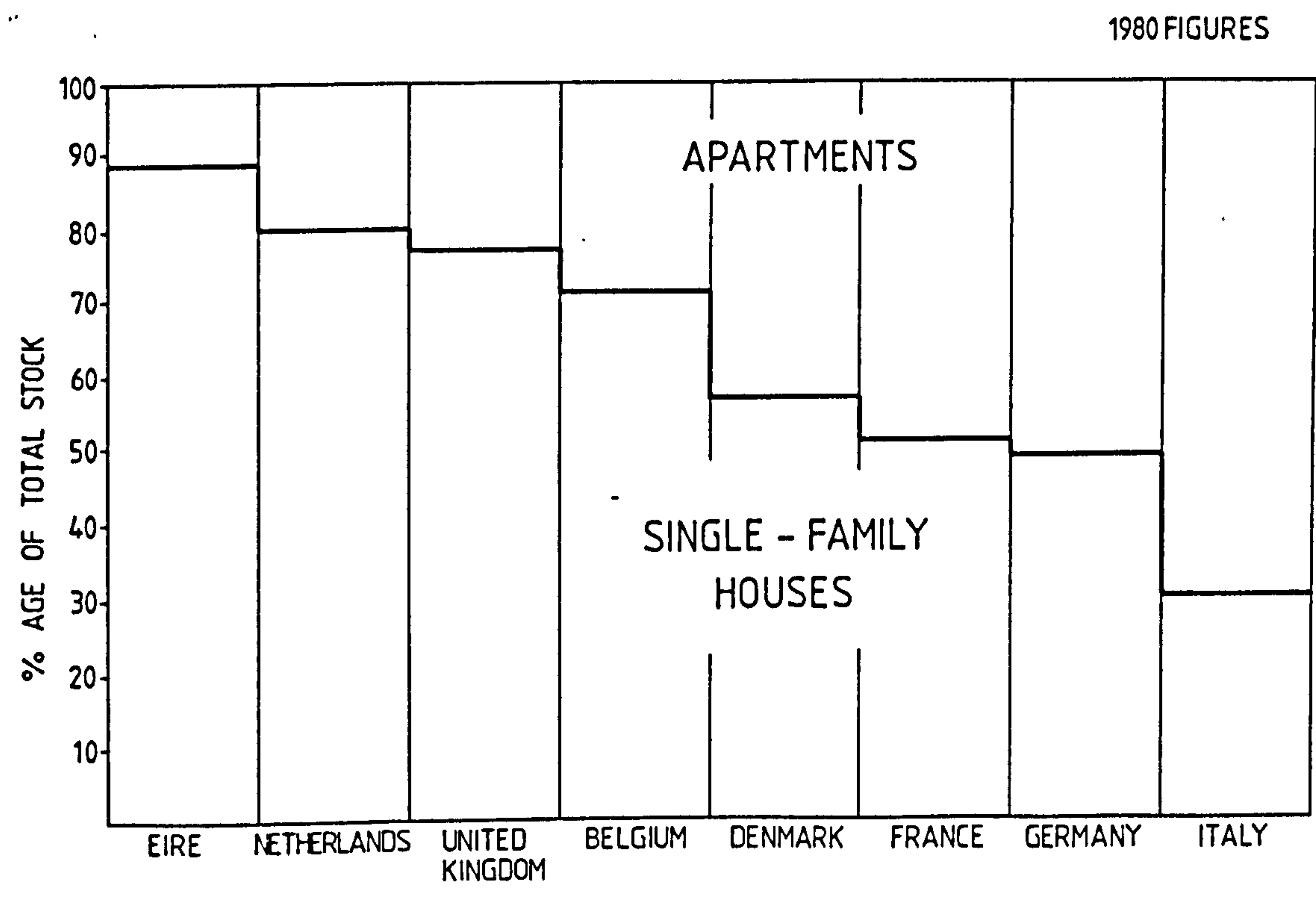


FIG 2.1.6 DWELLING TYPE PREDOMINANCE IN EUROPE

iii) Urban layout constraints on new build passive solar

Practical and economic considerations prevent many new housing developments being planned with all the dwellings orientated favourably. However, the experience of the Pennylands housing estate (2.1.5) and the Giffard Park estate (2.1.6), both at Milton Keynes, in the United Kingdom, has illustrated successfully how passive solar design considerations can be reconciled with unyielding cost constraints without undue difficulties.

Figure 2.1.7. illustrates solar site planning in relation to modestly-sized apartment blocks. This particular project, in Chambéry in eastern France, (2.1.7) was the outcome of a French national competition, (Fig. 2.1.8). Each of the fifty-three dwellings used active solar collectors, inclined for maximum winter collection, and passive direct gain (via vertical south-facing windows and glass doors).

iv) Building Standards and passive solar potential

The magnitude of the contribution which passive solar heating may make to a dwelling depends on its heating requirement. This in turn depends on occupancy, size, form, construction and the difference between the internal comfort and external ambient temperatures. All of this may be expressed succinctly by a basic steady-state heat loss equation.

$$Q = U_{ann} (\bar{T}_i - \bar{T}_a) \quad \text{equation 2.1.1}$$

where $U_{ann} = \sum UA_{ev} + \dot{v} C_p$

From this it can be seen that the large variety of dwelling types and variability in the climate throughout Europe will result in a wide range of heating requirements. An indication of this variation may be obtained from the data on average heat loss for dwellings in certain European countries shown in Figure 2.1.9. (2.1.8). These data are presented in terms of loss per unit temperature difference. This temperature eliminates the effect of climate and allows us to identify the combined effects of better standards of thermal insulation, which are required by legislation in Denmark and Germany and of the higher proportions of apartments, when compared with practice in Ireland and the United Kingdom.

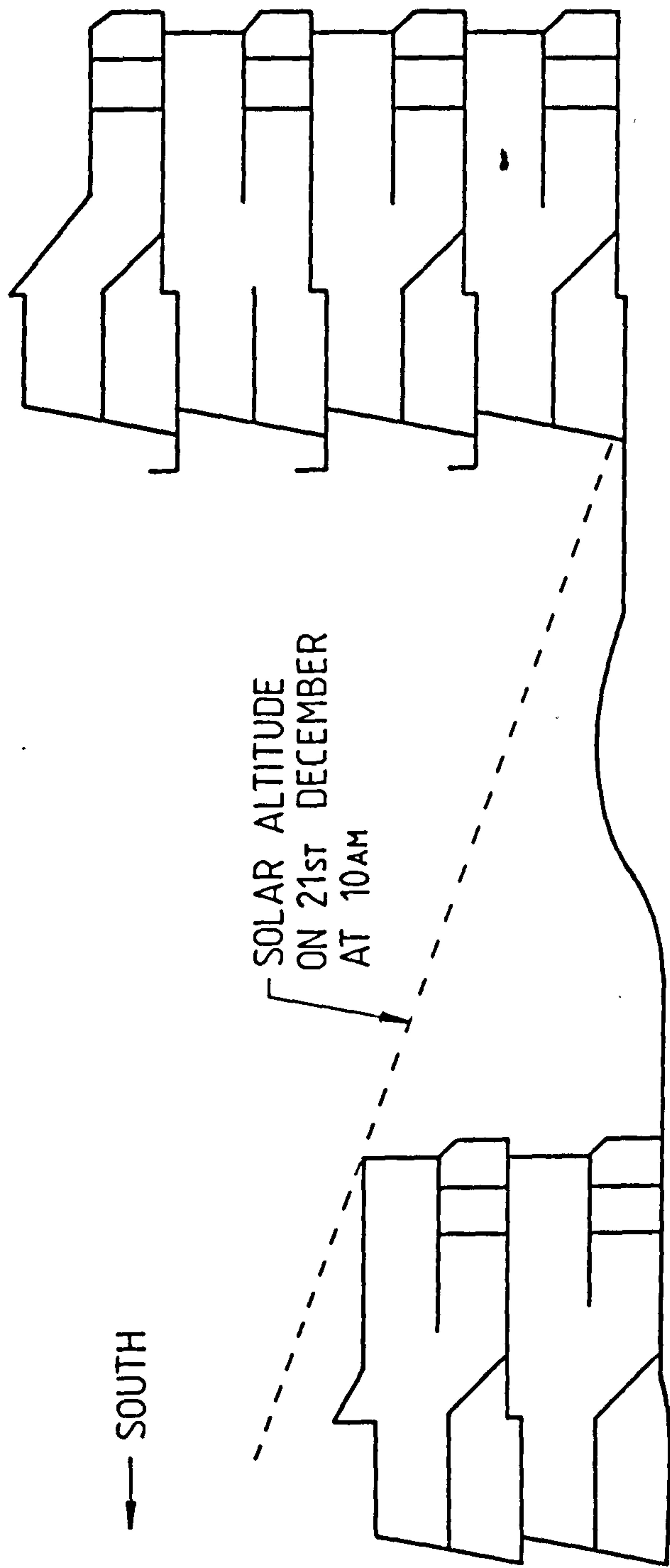


FIG 21.7 CROSS - SECTION THROUGH AN APARTMENT DEVELOPMENT IN
CHAMBERY , EASTERN FRANCE

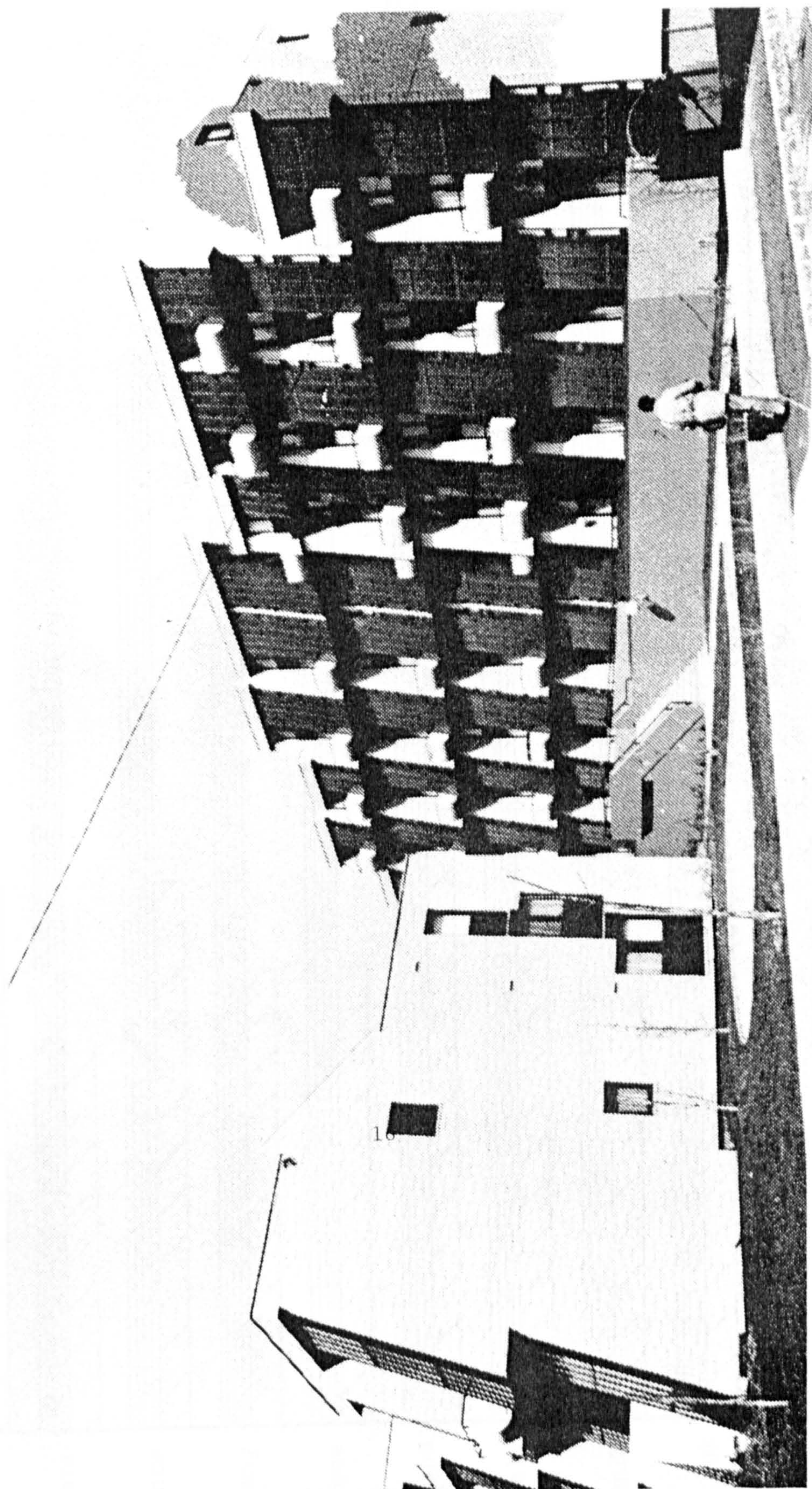


Figure 2.1.1.8 Inter-relationship between apartment blocks at Chambery

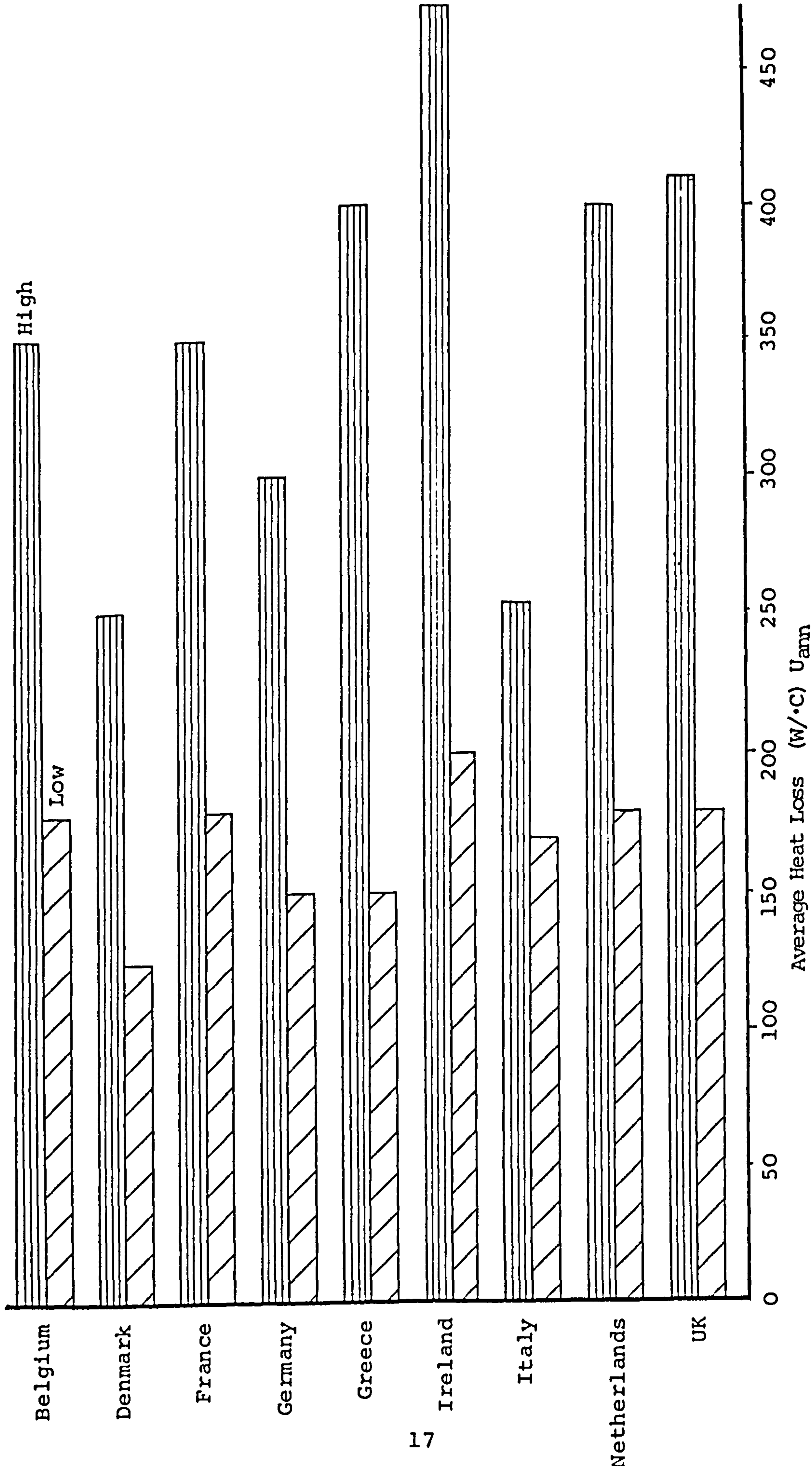


Fig.2.1.1.9 Approximations of average heat loss from dwellings in Europe

v) Conclusions

It may be seen that there are few major urban layout constraints which apply generally to the adoption of passive solar features in new buildings. However, on certain specific sites (e.g. urban renewal), and in the context of refurbishment and/or remodelling, care must be taken both with the selection of the appropriate passive solar feature and its position on the building. These constraints tend to favour roof-based solutions.

2.2 Roof-space Solar Energy Collectors.

i) Introduction

A roof-space solar-energy (RSC) collector as shown in Fig. 2.2.1. is essentially a pitched-roof which is partially or fully-glazed on its southerly aspects. The attic space is frequently painted matt black internally to enhance the collection of solar energy, thus the system is sometimes referred to, somewhat inelegantly, as a "black attic". Solar-heated air from the roof-space collector is conveyed by an automatically-controlled fan via a duct either directly into the living space or as a pre-heated supply to a warm-air space-heating system. The roof-space collector is replenished with air either from within the dwelling or from the outside ambient environment. The fan and associated ductwork, through which the warmed air is conveyed from the roof-space collector, are existing parts of a space-heating system. When the air from the roof-space solar-energy collector is at a lower temperature than the set level of the room thermostat, the air-stream emerging from the roof-space collector is a pre-heated supply to the gas-fired auxiliary space-heating system. A single fully-integrated wall-mounted control unit actuates both the gas-fired auxiliary warm-air heating system and the roof-space collector.

ii) Modes of Operation of a Roof-Space Collector

A roof-space collector involves the passive collection and active distribution of solar heated air and may thus be termed generically as a "hybrid" solar-energy system. "Warmth" may be stored within the structural elements of the roof-space collector at night. Ventilation is employed to prevent overheating in high summer. Five principal modes of operation of a roof-space collector can be identified, these are;

- a) During daytime conditions when the temperature of the roof-space collector is above that of the building, a thermostatically-controlled fan continually takes air from the building. This air is passed through the roof-space collector, is warmed and returned to the building. This mode is suitable for a dwelling that is occupied during the day.

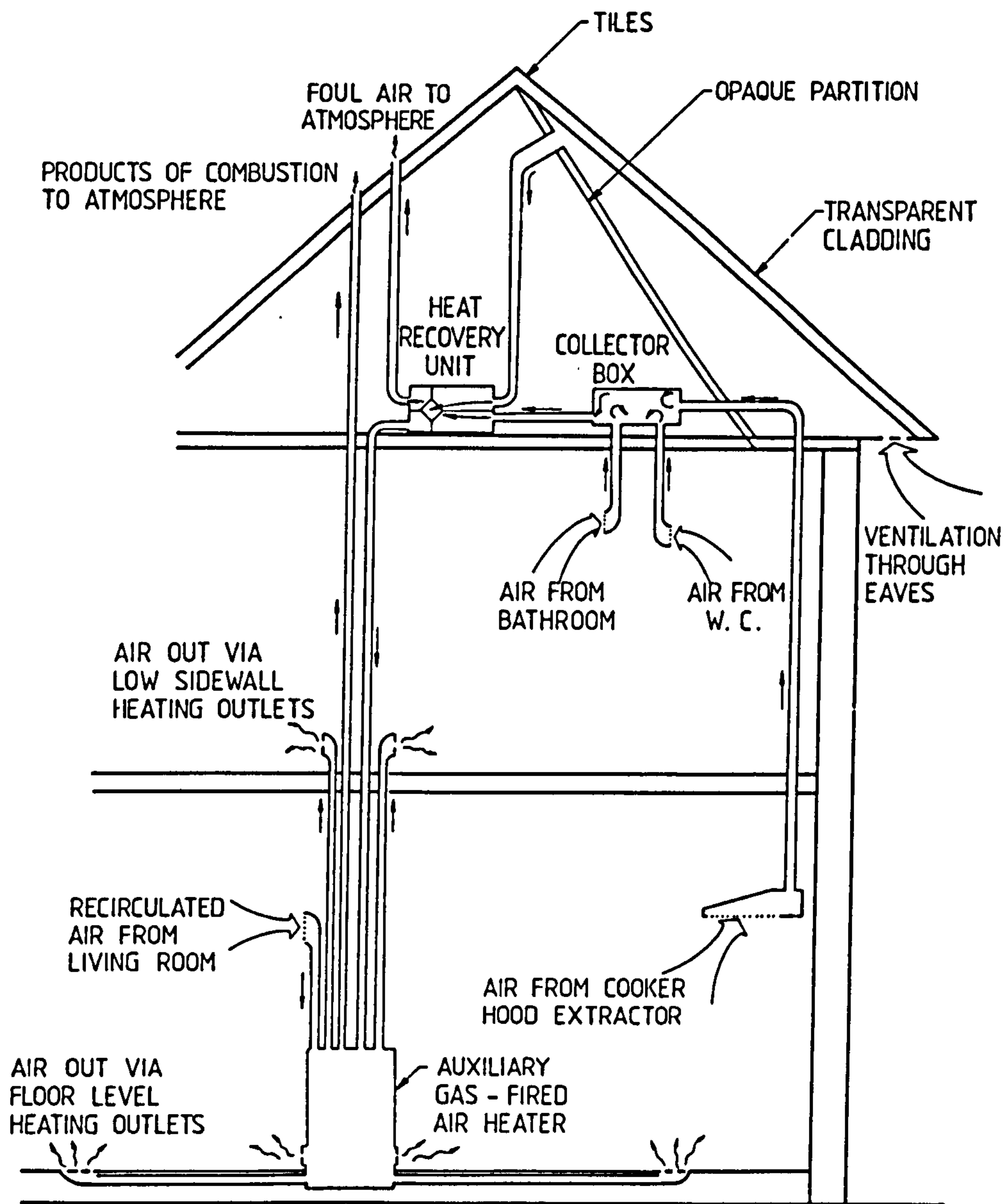


Figure 2.2.1 A Roof-Space Solar Energy Collector

- b) During the day the roof-space collector rises in temperature as solar energy is collected and no forced circulation of air occurs through the system. In the late afternoon the stored heat is harnessed when warm air is conveyed from the roof-space collector by a fan. The replenishing air to the attic may be supplied from either inside or outside the building. This mode is the most appropriate when the building is unoccupied during the day.
- c) Air is heated as it passes, under the action of the fan, from the outside via the roof-space collector into the heated building. The volumetric flow rate through the fan will be less than that used for mode (b) operation. If this air forms a large proportion of the total ventilation, then this mode provides pre-heating of the ventilation air. Unlike modes (a) and (b), the roof-space collector does not have to be at a temperature above that of the building to provide a beneficial effect, since any warming of the air as it passes through the attic-space will provide some reduction of the ventilation heat load. As buildings become better insulated, so the proportion of energy used to heat ventilation air will become greater. Roof-space collectors operating in this mode are thus compatible with, and compliment, the use of other energy conservation measures in buildings.
- d) Heat is transmitted by conduction through the floor of the roof-space collector. This will frequently be a small effect as the floor of a roof-space collector is well insulated. Good floor insulation within the roof-space is recommended, otherwise it is likely that the total diurnal losses would exceed gains, except perhaps if the roof-space collector were double-glazed and fitted with an insulating night blind. (Overheating during the summer months would also become a serious problem with this latter solution). In this mode, the roof-space collector acts as a buffer space between the ceiling of the uppermost storey and the outdoor environment, thereby reducing the heat losses from the roof of the building.
- e) Buoyancy-driven flow occurs which draws air into the roof-space collector from the building and thence outside. The replenishing flow of air into the building is from the ambient external environment. In this mode, essentially the roof-space collector is providing ventilative cooling.

iii) Advantages of Roof-space Collectors

The system has a low initial capital cost as the physical construction of a roof-space collector does not differ greatly from that of a conventional pitched roof. When roof-space solar-energy collectors form an integral part of *newly-built* dwellings (as in this demonstration project), the ensuent benefits are;

- a) more efficient performance via optimal design which is not possible within the constraints of a retrofit installation,
- b) the reduction in initial cost arising from the employment of components already present in the auxiliary heating system, and
- c) the reduced cost of installation in newly-built dwellings, when compared with an equivalent retro-fit dwelling.

The site planning of the RSC's should ensure that they are unshaded at all times. Passive solar features on buildings are frequently at ground floor level and in urban locations exhibiting high housing densities, a dwelling may often experience levels of overshadowing at lower sun angles by neighbouring buildings such that ground-floor passive solar elements are rendered ineffective. Amidst such housing arrangements the performance of a roof-space collector would not be compromised in this way. Roof-space solar energy collectors also do not cause loss of privacy as can be the case with the large glazed areas associated with direct gain systems.

iv) Introduction to individual RSC systems.

The roof-space solar collector was first proposed by Watson in 1978 (2.2.1). Both new and retrofit installations now exist. Some roof-space collectors are included as part of a package of passive solar measures whilst others stand alone. The modes of operating and means of distribution are described, as are the performance and economics.

a) Kalwall "Solar Attic" System

The American manufacturers of this system, shown in Fig. 2.2.2, described it as "combining the normally wasted hot attic space of a building with proven passive solar fundamentals", (2.2.2). A low-powered fan was incorporated to permit controlled heat distribution for space heating. Transparent water tubes were included in the roof space for storage.

The domestic hot water supply was preheated in two or more water tanks painted black and placed at the base of the water tubes in the roof-space. The combination of direct solar radiation and convection from the trapped hot air heated the water tanks. The first prototype dwelling was a single-storey house constructed in Manchester, New Hampshire, USA.

b) Saunders Passive Solar House

This design used water as the thermal storage medium in the roof-space collector, and a rock store beneath the house (2.2.3). An example of this system was built in Shrewsbury, Massachusetts, USA. A number of different objectives led to the formation of the final design. These were, i) uniformity of temperature across north and south-facing rooms and those on the first and second floor, ii) freedom from Trombe-Michel walls, water-filled containers or any other heat storage devices in all rooms, iii) the provision of adequate daylighting in all rooms, and, iv) glare control. Necessary user interaction was kept intentionally to a minimum.

c) "Skytherm-North" System

In the Skytherm-North house, illustrated in figure 2.2.3, a "roof pond" had a pitched roof placed over it, glazed on the south-face and insulated on the north-face. The pond allowed the insulated collection of direct gain solar radiation, and forced convective cooling could be employed as necessary. Skytherm-North, was intended for the climate of the northern USA. Freedom of architectural design was retained without the constraints imposed by south-wall solar energy collection.

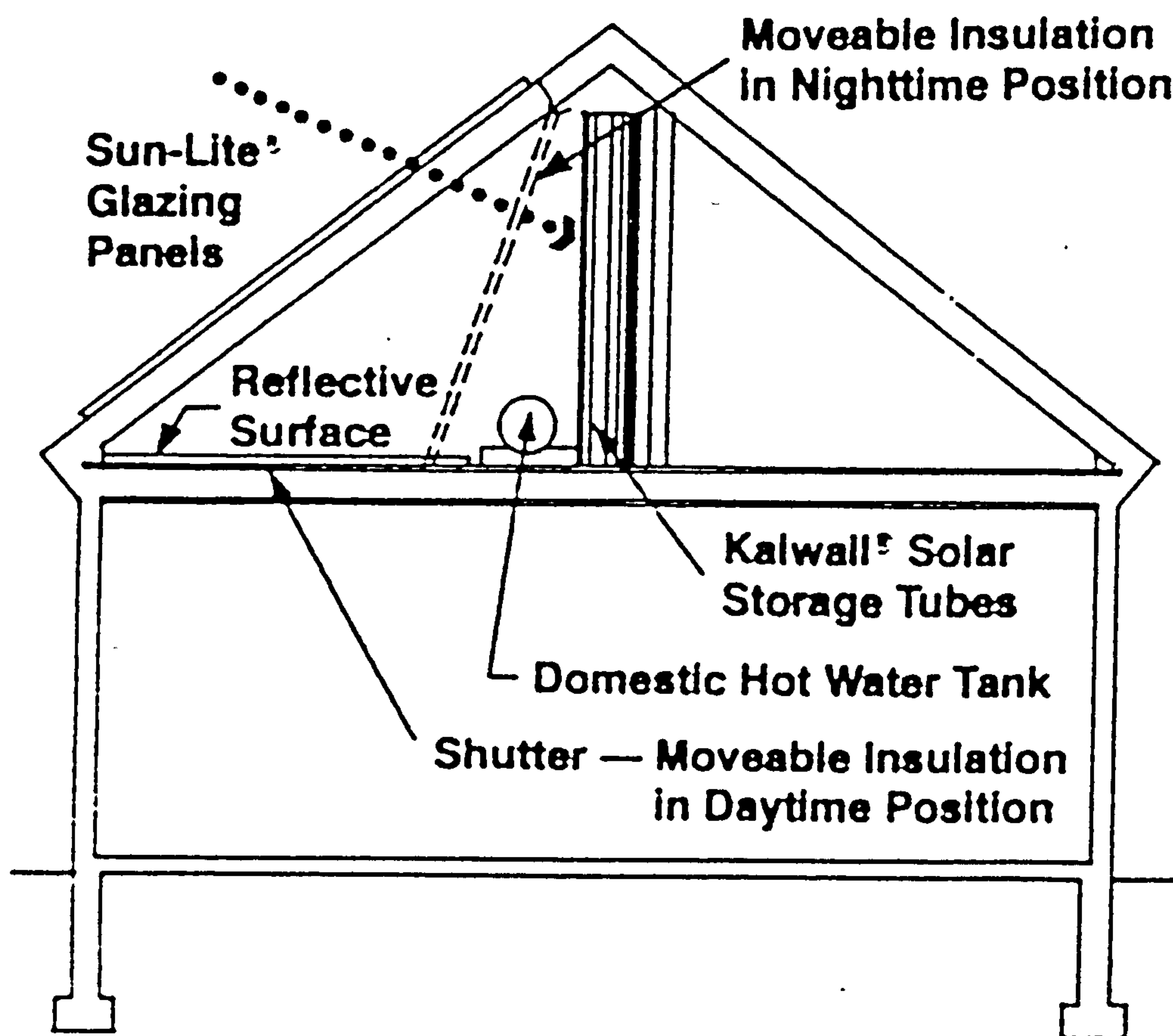


Figure 2.2.2 Kalwall "Solar Attic" System

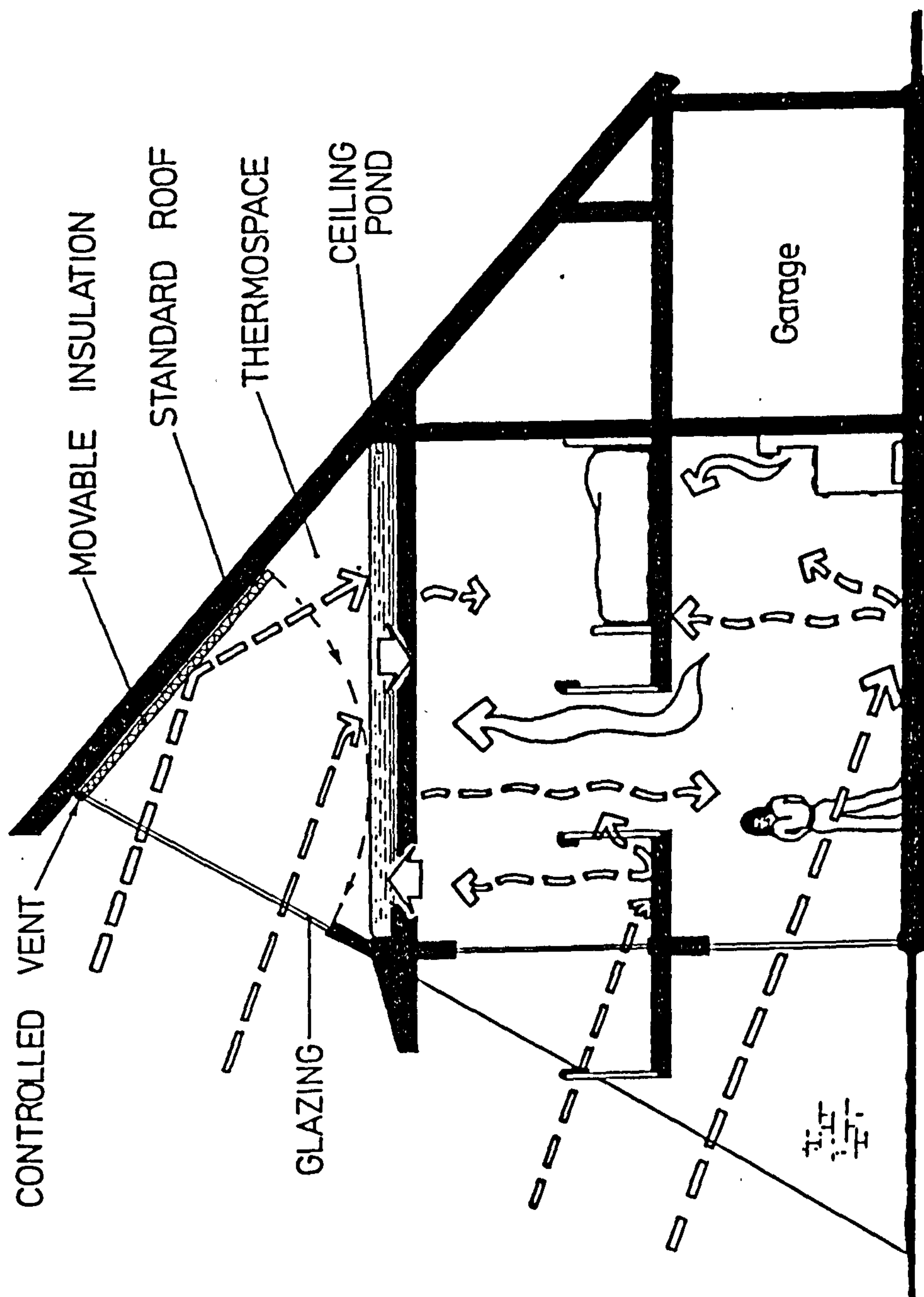


Figure 2.2.3 "Skytherm-North" System

d) "Sundance 1"

Sundance 1, was designed, constructed and occupied by Roberts (2.2.4), in Reston, Virginia, USA. It comprised a three-storey passive-solar hybrid dwelling utilising a 62 square metre single glazed Trombe wall with automated moveable insulation, and a third floor 9.1 square metre single glazed roof-space collector. Warm air from the roof-space collector was fed by a fan to an air-core storage system.

e) "Double Box" Sunspace

The Double Box Sunspace (2.2.5) was a three storey dwelling in which a greenhouse enclosed an inner thermally comfortable zone. In this American design, twenty-three tons of insulated thermal mass was placed inside the first floor. In spring and autumn two fans circulated hot air down from the third floor spaces, via the mass storage, exhausting it through the north side earth/air heat exchanger. Hence, in certain modes, the outer box was acting as a roof-space solar collector.

f) Sheffield "Housing Experiment"

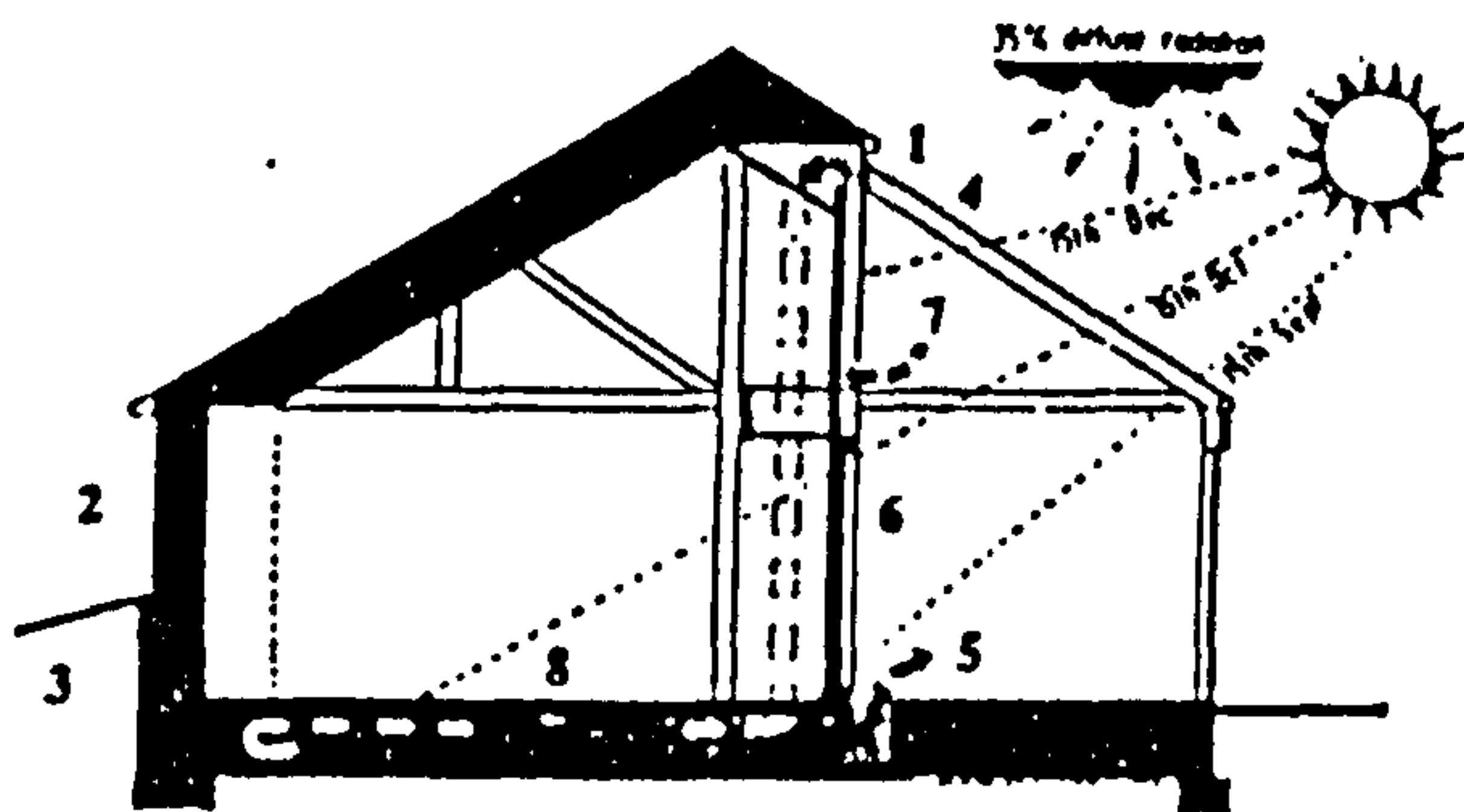
In August 1983, work began on four "self-build" passive solar houses in Sheffield, UK (2.2.6). Their design featured a large integrated conservatory, see figure 2.2.4. In summer, repositioning the insulating panels changed the design from one featuring a large conservatory with a sloping roof, to an open extension of the living space and a roof-space solar collector. The insulated panel formed the base of the roof-space collector and avoided overheating of the living space.

g) Stornoway Housing Scheme

This scheme in Stornoway in the Outer Hebrides successfully demonstrated the potential for passive solar systems within the climate of Scotland (2.2.7), where high diffuse components of insolation and low levels of winter sunshine were prevalent. Twenty-two single-person flats were built in two and three-storey blocks. A "wall and roof-space collector" was formed by double glazing the south-facing surfaces of the stairwell. The glazed stairwell formed a convective loop with a roof-space solar collector. The purpose of this was to charge a short-term rock store below the first half-landing, thereby reducing the daytime gains wasted.

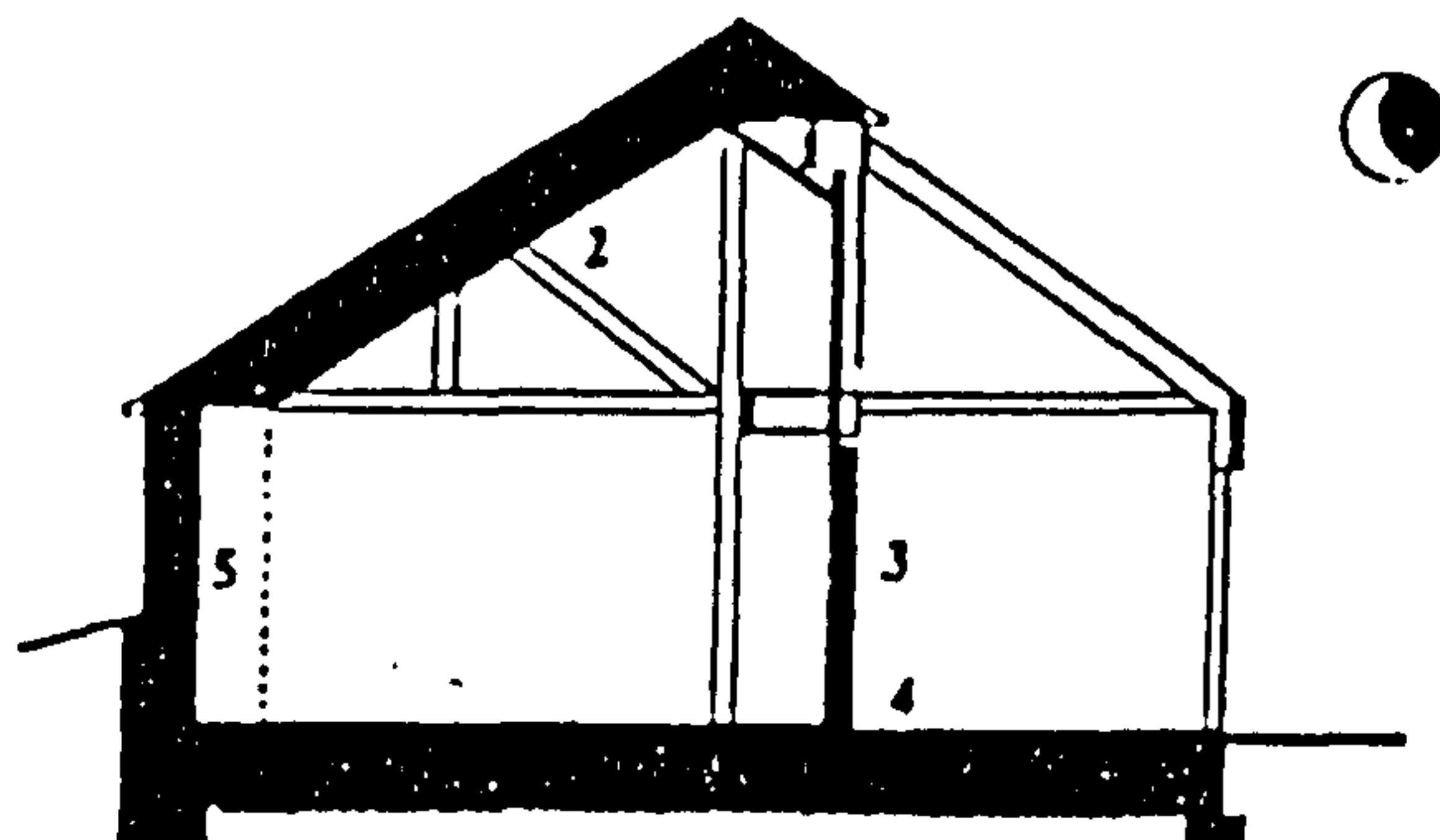
1 Winter Day

- 1 Air duct to carry warm air from collector to hypocaust; connected to vertical duct.
- 2 Small windows placed in north wall, minimum size of window to reduce heat loss.
- 3 Additional insulation (Styrofoam) against north walls with tanking and earth bermed up against it.
- 4 Single glazed conservatory roof at 32 degree pitch.
- 5 Returned air to conservatory.
- 6 Glazed doors admitting direct gain.
- 7 Solar collector of single glazing 100mm air gap collector panel painted matt black and 100mm rigid insulation. Collector connected to duct at top.
- 8 Solid thermal mass in floor slab with hypocaust cavity forming channel for warm air drawn by fan in vertical duct.



2 Winter Night

- 1 Air duct to carry warm air from collector to hypocaust.
- 2 Heavily insulated roof structure.
- 3 Insulated sliding night shutters over glazed doors.
- 4 Grills in conservatory floor for return warm air from hypocaust.
- 5 Possible shallow storage cupboards along north wall to increase insulation.



3 Summer Day

- 1 Insulated sliding night shutters hinged to form conservatory ceiling, shading room and reflecting summer radiation away or onto passive solar collector.
- 2 Single vertical glazing to conservatory with glazed hinged double doors out to court.

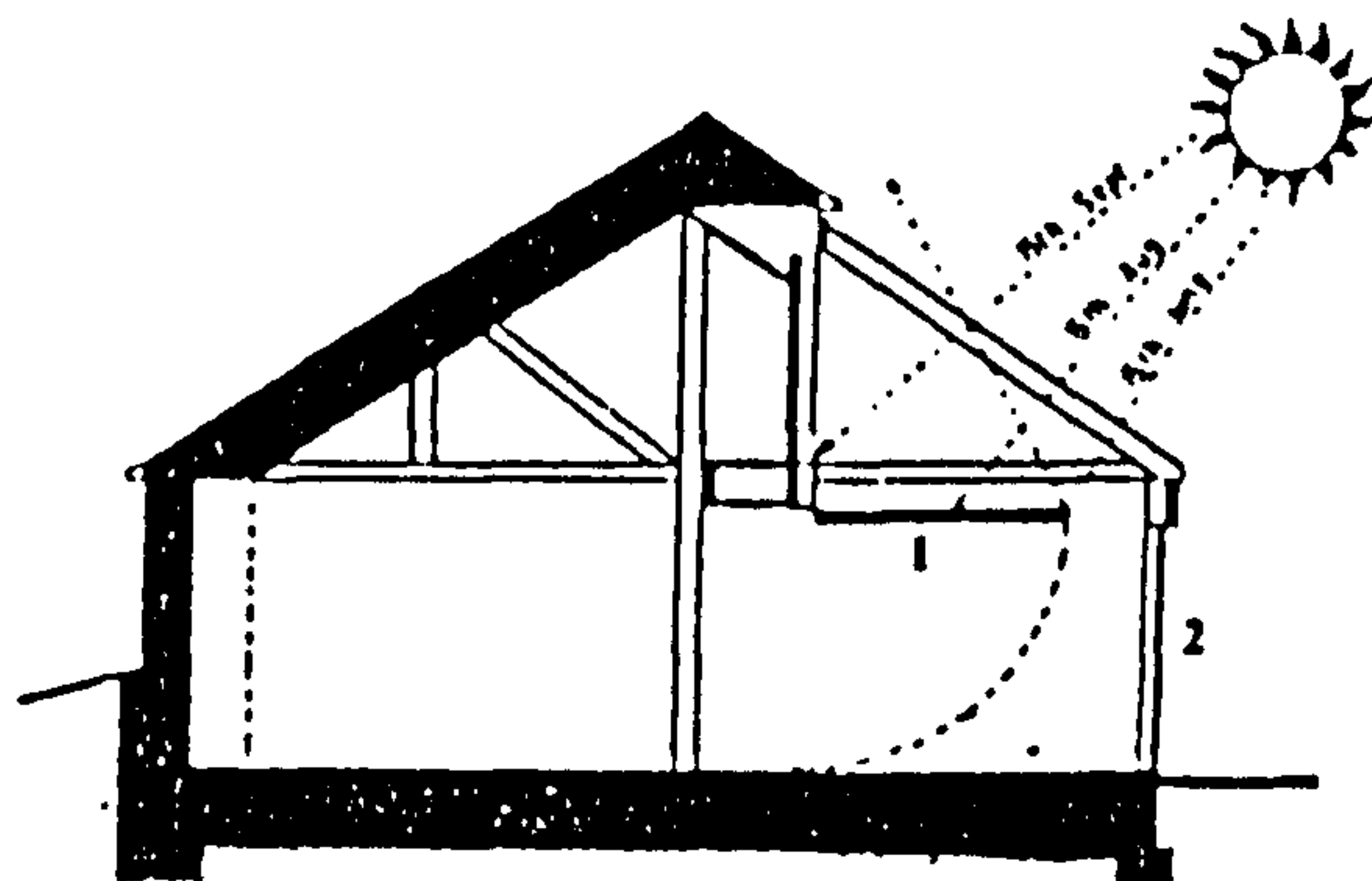


Figure 2.2.4 Sheffield Housing Experiment

h) Cambridge Roof-Space Collector

A roof-space collector was retro-fitted to a two-family, turn-of-the-century house in Cambridge, Massachusetts, USA (2.2.8). Although a contractor and an assistant were employed to remove the old roof and install the glazing, the bulk of the building work was done by volunteers over one weekend. The performance of the house was monitored in February and March 1984. The roof-space solar collector, formed by glazing part of the south-facing roof slope, was the only passive solar feature incorporated. The roof was due to be repaired and so an attic fan was already in place for summer venting.

i) Woodbridge Cottage

Woodbridge Cottage near Bristol, UK, was the first roof-space solar collector retrofit in the UK, (2.2.9). Monitoring took place between October 1983 and July 1984. One of the conclusions was that, in retrospect, the building had been far from ideal as an example of the potential of roof-space solar collectors in the UK. The high levels of insulation and low air change rates meant the heating season was wholly in the "worst" months of the year for solar contributions. More suitable candidates would have been the large number of older terraced houses; where a roof-space collector was an alternative to the costly insulation of external walls.

j) Newham Refurbishment Scheme

In the UK, the Building Design Partnership, in conjunction with A5 Architects, CAP Scientific Ltd., and Davis, Belfield and Everest, prepared a design study of a roof-space solar collector for an existing private terrace (2.2.10). Following this study, six roof-space collectors were included when ninety, two and three bedroomed terraced houses in Newham, east London, UK, were refurbished (2.2.11). The roof-space system had been designed to be as simple and comprehensible as possible, user-interaction involved only the operation of a single switch.

k) Urban Roof Top Solar Greenhouse

The Urban Roof Top Solar Greenhouse consisted of a 104 square-metre greenhouse to be built, again by a self-help group, on top of a six

storey apartment building in New York City USA, (2.2.12). Its primary role was to provide tenants with vegetables, but in addition, there would be a significant contribution to the building from excess heat produced in the greenhouse during the heating season. The greenhouse heating set point was kept to 13°C to avoid crop damage. Simulation studies indicated that the very modest net heat gains from ducting excess greenhouse heat to the building, were unfortunately offset by the cost of running the recirculating fans.

1) Solar Mobile Home

A system which had a solar collection aperture above the dwelling yet was considered not to be a roof-space solar collector, was a passive solar mobile home (2.1.13). The reason for this was the manner of heat distribution. A thermally conductive ceiling was the passive manner in which heat would be distributed. The attic was, however, specifically designed for passive solar heating. The roof-space was chosen as the position for the main solar aperture since the glazing could then be placed on the main structure facing either of the two long sides, depending on which was closest to south-facing. Potential problems with transportation imposed limits on the roof height, and on the weight of any storage materials included in the roof-space.

Whilst radiant heating due to passive distribution of solar gains meant that the room air could be several degrees cooler for the same level of thermal comfort, and no fans or controllers were necessary, the heat storage surface had to be a significant proportion of the living space's surface area, and the ceiling material had to be highly conductive. Control of excess solar gains may be a problem.

m) Fulmer Solar Roof

Studies undertaken in an experimental solar roof at the Fulmer Institute, west of London, UK, evaluated the performance of glazed roof-spaces of varying pitches (2.2.14). The aims were to (i) evaluate the total usable energy gain using a glazed roof-space collector, (ii) evaluate the system with a phase change material (PCM) store and an automated blind, (iii) perform the same evaluation with a PCM store but no blind, and (iv) examine the effect of roof pitch on the above three variations.

v) Glazing Materials for a Roof-Space Solar Collector

In the roof-space collectors incorporated during the refurbishment scheme at Newham a twin-wall polycarbonate was chosen to cover the south-facing slope instead of glass. The same material was used at Woodbridge Cottage. Its long-life, rigidity, spanning capabilities, resistance to breakage and high transmittance make it ideal for roof-space solar collectors. The specially treated twin-wall polycarbonate at Woodbridge had a solar transmittance of 0.77, and was expected to degrade by 5% over twenty years.

Another reason for the choice of twin-wall polycarbonate at Newham was its fire resistance. Substantial effort was required before the local authority were satisfied with the level of fire protection afforded by the glazed aperture. The "fire grading" is satisfactory when it is regarded as a "cladding material", but difficulties may occur if it is classed as some form of "rooflight" where more stringent fire regulations apply.

In the Cambridge, Massachusetts system twin-wall polycarbonate was also chosen. Great stress was placed on the need for careful detailing to prevent water penetration. Sundance I utilised 9.1 square metres of Plexiglass, whilst "Sun-Life" two-layer glazing panels formed both the glazing aperture of the roof-space collector and the cover for the storage wall of the Kalwall Solar Attic System. These panels also have a solar transmittance of 0.77 at normal incidence.

vi) Thermal Storage in Roof-Space Collectors

The decision on whether or not to include thermal storage depends on a number of issues and constraints. The US examples incorporate vast quantities of thermal mass in order to achieve high passive/hybrid solar heating fractions. Sundance I had a 32045 kg Trombe wall, a central core mass of 68649 kg of concrete, and 50270 kg of air-core storage wall. The hot store in the Saunders' design held 10 tonnes of water in twenty 110 ltr containers, directly above the upper storey ceiling! In European Maritime temperature climates such high levels of thermal mass in passive solar buildings are not required. Occupancy patterns have a strong influence on the amount of thermal mass to be incorporated; ideally a system should remain flexible enough to permit a change of occupancy without a serious deterioration in its

performance. With regard to roof-space collector design, intermittent occupancy implies a choice, "store" or "ignore". In the latter case, when there is no longer a direct solar input, the roof-space is isolated from the rest of the dwelling, and only the auxiliary system is used. If the decision to store has been made, then thermal mass will be necessary, either within the attic or the house. A greater solar fraction may be achieved in the latter case, because the solar gains displace more fossil fuel energy, but there is an added cost associated with the provision of thermal storage.

Stress on simplicity and low cost has meant the Newham collectors have no added thermal mass, and gains to the dwellings cease shortly after sunset. The retrofit at Cambridge was sized to provide most of the space heating requirements of the second and third floors of the house during a typical sunny winter day. Hence, it too did not include thermal storage. At Woodbridge Cottage, no storage was added to the collector, since it was assumed that the heavyweight masonry partitions and floors of the house beneath would be sufficient. In the UK, solar energy is available during the heating season in such limited quantities that it is not economical to introduce a complex and expensive storage system.

If the situation "demands" thermal storage, then which medium should be chosen to provide it? At Stornoway, the wall and roof collector charged a short-term rock-bed store, with the aim of optimising the useful solar contribution; storing daytime surplus gains for use at night. Although the main passive solar feature was an integrated sunspace the ability to make use of daytime gains in the evening, particularly in a location with an extended heating season, justified the inclusion of the collector and store combination. The experimental houses in Sheffield used two storage zones, a water tank and a perforated hypocaust, above and below the living areas respectively. Air directed over and around the two volumes either deposited excess heat from the conservatory or collected and distributed it to the space and water heating systems.

The glazed roof pond of the Skytherm-North house provided the means of heat transfer to the rest of the house, through a conductive ceiling. In another mode, the water provided evaporative cooling when necessary, but a fan was required to promote evaporation. Water was also the storage medium chosen for the Kalwall Solar Attic System. Fifteen

vertical, water-filled tubes (0.36 m diameter x 2.4 m high) provided the storage within the attic, and a further four tubes together with glazing panels constituted a solar storage wall.

Twenty six tubes (each of 0.039 m diameter x 3.05 m long) with a total mass of 115 kg, were arranged on the floor and the rear baffle board of each test cell during experiments carried out at the Fulmer Institute. The tubes contained a phase-change energy storage material, (PCM), with the melting temperature of 31°C. The cells using PCM without blinds gave very similar results to "standard" cells without either PCM or blinds; the PCM serving only to smooth out the peaks and troughs in the demand and supply of energy. During the day, demand would normally be low and the supply high. The PCM absorbed energy, leaving little available should there be a demand, whilst the standard cells produced a greater contribution if demand and supply were in phase. At night, there was no energy supply from the standard cells, but the PCM slowly released heat. Unfortunately, in the absence of a blind, some of this energy was lost through the glass cover, thereby failing to contribute to the space heating load. One possible improvement suggested was a PCM with a lower transformation temperature.

vii) Should Blinds Be Included On Roof-Space Collectors ?

The Fulmer Institute study showed the benefits of including a blind. Two reasons exist for the incorporation of blinds, either they are intended to reduce heat losses during periods of no solar collection, or to prevent summer overheating. In the former case, they are usually employed in conjunction with thermal storage.

The Saunders' house made the exclusion of all forms of thermal shutter a deliberate policy, the designer wanted nothing which the occupants had to operate daily. Similarly, the reason for their omission at Newham was the desire for a system which was simple to operate and cheap to install.

Internally-mounted, motorised moveable insulation was used in the Skytherm-North design. The associated electricity consumption was reported to be minimal. In the Kalwall system, the fixed and moveable reflectors performed a number of functions. Located on the floor and gable ends of the attic, they were intended to (i) augment the winter solar heat gain by reflecting heat onto the storage tubes, (ii) reduce

storage losses at night or on cloudy days, (iii) provide an air flow passage for controlled heat extraction, and (iv) reject excess summer heat. The moveable insulation, made from reinforced foam, was controlled by a simple differential thermostat. In its night-time position, it did not actually cover the glazing but protected the hot water tanks and the storage tubes and reduced the volume of the roof-space considerably. When in this position it provided a reflective surface to heat losses from the storage elements.

In the Sheffield housing experiment the wall between the living space and the conservatory had three different functions. These are clearly illustrated in figure 2.2.4. On winter nights, it acted as an insulator with double skin shutters, whilst on winter days, without the shutters, light and direct gain solar radiation were able to filter through the glazed doors. It was on summer days, when the insulator was swung into a horizontal position and became a reflector, that the roofspace solar collector was formed. This provided an extended living area beneath and some gains in the upper part of the conservatory. The Double Box Sunspace used only greenhouse shading cloth over the south-facing glass to regulate the heat gains in summer. At the other extreme, Sundance I had a seasonally-adjusted exterior slat to reduce summer gains. Fixed overhangs were chosen for the passive solar mobile home, to reduce the summer cooling load in a climate where cooling is usual. They were chosen because they were inexpensive, maintenance free, and no occupant participation was necessary. An optimal degree of overhang existed, since an increase in overhang length led to an increased heat load and a decreased cooling load. Although moveable shading devices control unwanted heat gains more effectively, and minimise heat losses during cold nights, they require occupant intervention for daily and seasonal operation. In addition, they can be expensive.

At Woodbridge Cottage, nine roller blinds were required to cover all the interior surface of the polycarbonate. They were made from aluminised polyester to reflect transmitted solar radiation in summer. They were intended to be operated on a seasonal basis, drawn in July and probably raised in late August.

viii) Prevention of Overheating in Roof-Space Collectors

Before the reflective blinds were installed at Woodbridge Cottage, attic temperatures were controlled by both passive and active venting

systems. When the collector temperature exceeded 40°C, heat-actuated controls vented the roof to the outside, supplemented by a thermostatically-controlled fan. As the fan was frequently used, the blinds were installed, considerably reducing its period of operation. Another, very simple method used to control the temperatures within the roof-space was lining the insulated floor with foil-faced building paper to reflect solar radiation at high angles of incidence.

To safeguard the materials in the attic, an automatic roof-space cooling system had been included in the Newham houses. An 80W auxiliary fan ensured that roof-space temperatures did not exceed 60°C. A similar system was employed in the retrofitted collector at Cambridge, Massachusetts. A pre-existing attic fan conveyed air through several open gable vents. The Double Box Sunspace also had an attic fan to provide back-up cooling.

In certain regions in the US, with a more pronounced cooling load than in the UK, extensive measures are required. The mobile home required forced night-time ventilation of the attic, in addition to the fixed overhangs, to provide sufficient cooling. The thermal mass had to be sufficiently cooled to enable it to provide a heat sink for the living space. Hence, although a fan was rejected as a means of distributing desired heat gains, it was necessary for cooling purposes. The roof pond of the Skytherm-North house, also a heat sink for the living areas, occasionally required forced connective cooling.

The purpose of the thermal store in the Saunders' scheme was to allow a large direct gain solar contribution in winter whilst preventing overheating caused by the large solar apertures in summer. The pathway of the air outlet for the thermal store was such that any transfer of hot air to the store would produce a flow of cool air into the living region.

ix) Partitioning the Attic.

Two out of the three retrofit schemes considered had a partition constructed in the roof-space. At Cambridge, Massachusetts, the vertical internal wall dividing the attic into north and south partitions was insulated and enclosed in a black plastic air/vapour barrier. It was also beneficial to cover the plastic with a protective material such as gypsum board, also painted black. This was because

when the collector stagnated for a few days, the rising temperatures caused some stretching of the plastic. Extensive caulking had reduced cold air infiltration into the south/collector part of the attic. The reason for the construction of a partition in the design of the Newham collector was to preserve some space for domestic storage and to separate the cold water supply tanks from the solar energy collecting area.

x) Types of Auxiliary Heating System for use with Roof-Space Collectors.

The Saunders' house, like the Skytherm-North design did not include any form of auxiliary heating. In the Double Box Sunspace the only form of back up heating was a wood-burning stove located on the first floor. Sundance I employed wood burning only occasionally, the main auxiliary heat supply was electric. Immersion-type electric resistance heaters were located at the base of the south-wall vertical storage tubes of the Kalwall system. These were supplemented by portable electric heaters. The entire auxiliary system was designed to be operated during low-cost "off-peak" hours. During September 1978, and March to May 1979, 100% solar space heating was reportedly achieved by the Manchester prototype.

At Stornoway there was a conflict of need between the desire to provide thermal capacity to store solar gains, and a wish for the building to have a rapid response time to the intermittent electrical heating appliances. The living spaces were lined with light-weight finishes to favour a quick response to any sudden demands, with a heavy-weight back-up from the internal structural elements and the externally insulated elements. The rock-bed store provided additional thermal mass.

The problems of utilising auxiliary electric night storage radiators with a solar heating system became all too apparent at Woodbridge Cottage. As the heating system discharged uncontrollably during the day, it displaced potentially useful solar gains. The availability of "off-peak" lower-cost electricity meant that night storage radiators were the cheapest form of electric heating. However, they did not allow the maximum use to be made of a solar heating system.

xi) Means of Distribution of Heat Gains From Roof-Space Collectors

For Sundance I, the masonry of a hollow-block rear wall was a hybrid sub-system which was charged by the operation of small fans. Passively-collected solar-heated air was forced down through the wall, thereby giving up its heat to the mass. The Kalwall system employed two low-power fans to direct air over the water-filled tubes in the attic. The warmed air was then distributed to the spaces requiring heat. The two stores in the Saunders' house were served by low-power variable-speed fans governed by thermostats. Overheating was prevented by an additional fan operating during the coolest part of the night driving cool outdoor air through the thermal store. A high degree of thermal stratification existed in the hot store, and the solar energy inputs and energy extracts were designed to enhance this stratification. In Cambridge, Massachusetts, a fan conveyed solar-heated air to five rooms in the house, and returned cool air to the attic, whenever the roof-space collector temperature exceeded 22°C. Natural-convection in the Double-Box sunspace was augmented by two thermostatically-controlled fans.

At Woodbridge Cottage, the air-handling system was designed to provide a positive pressure within the house and a negative pressure within the collector, to ensure that any leakage entered the roof space first and was hence pre-heated. The 20% of air delivered to the house that was entrained from outside had very little effect on the efficiency of the collector but allowed the necessary ventilation air to be preheated. A 75W, 350 mm diameter axial fan distributed heat via a 400 mm duct to the dining room, living room and utility rooms, whilst another fan returned air to the attic.

A duct system with a grille in the ceiling of the lounge was chosen in preference to utilising the chimneys as the conduits for the ductwork in the Newham retrofits. The reason was that the chimneys would require smaller ducts and therefore an increase in velocity and possible noise problems. In addition, it was not possible to supply bedrooms via the chimney, whereas the main ducts supplied side ducts to two bedrooms. After circulation throughout the house, air returned to the roof-space via the stairwell, with the kitchen and bathroom isolated due to the high relative humidity of the air in these rooms.

xii) Control Systems for roof-space collectors

An automatic control system was employed within the Newham houses in accordance with the desire for operational simplicity. At Stornoway, ventilation control was achieved by a combination of active and passive means. Fans were activated by humidistats to ventilate the kitchens and bathrooms, whilst a plenum over the internal lobby vented all of the rooms and stores to the attic. A differential thermostat switched the fan between the roof-space collector and rock-bed store.

Since the Kalwall Solar Attic system was designed for intermittent occupancy, the room thermostat was set at 20°C between 6 am and 9 am, and 4 pm and 10 pm, and 14.4°C at all other times. The fans were controlled by a differential thermostat in series with the room air thermostat. The blind was also operated by a differential thermostat.

xiii) Performance of Previous Roof-Space Collectors.

Sundance I was monitored in 1982, with ninety temperature measurement sensors placed throughout the structure to characterise its energy balance. The reported results were 52% passive solar heating, 36% internal heat generation, and only the remaining 12% of the total heat load had to be met by the auxiliary back-up system. The performance figures were for the combination of Trombe wall and third-floor sunspace roof-space collector.

As mentioned previously, the first Kalwall prototype was monitored for a year from September 1978. The annual measured space-heating solar fraction from the system was reported to be 72%, whilst the solar contribution to the annual domestic hot-water requirement was 66%. The mean daily domestic hot water consumption was 151 litres per day at a delivered temperature of 49°C. The building was a single storey structure with a heated floor area of 37m². It was believed that the system would in future achieve closer to an 80-85% space heating solar fraction because the moveable shutter and four tube water-wall had not been in place for the full heating season.

The Shrewsbury, Massachusetts house, the first example of the Saunders' design, reportedly achieved 100% of the heating load by a combination of casual gains and solar energy, despite levels of casual gain somewhat lower than usual. It was a two storey, 230m² floor-area house.

The living room temperature remained within a few degrees of 21°C throughout winter and nearly always below 25.5°C in summer.

An unoccupied prototype of the Skytherm-North system was monitored. The two storey house was reported to have an 85% solar-heating fraction in that particular climate. This was despite no added insulation, no curtains, and no incidental gains. Hence with occupancy and controlled window insulation, it was believed that an auxiliary energy supply would only be required during prolonged overcast periods, or the coldest weather.

The retrofitted roof-space solar collector at Cambridge, Massachusetts, was monitored for one and a half months from February 1984. During the monitoring period, the roof-space collector operated on average 5.9 hours per day, and supplied on average 3.5 kW per monitoring hour. The roof-space collector temperature was generally 8°C above room temperature, itself usually around 17°C.

The conclusion from the experiments at the Fulmer institute was that cells containing the PCM and fitted with a solar blind gave superior performance to the other two cells.

Woodbridge Cottage was monitored between October 1983 and July 1984 and the results have been reported elsewhere (2.2.11) as have the final results of the roof-space collectors at Newham (2.2.15).

xiv) Economics of Roof-Space Collectors

Care must be taken to examine the assumptions on which calculation of payback periods are based. For example, the Kalwall Solar Attic System was claimed to have a payback period of 8-12 years, when evaluated on the basis of oil for space heating and the replacement of electricity for water heating. This assumed a 15% annual increase in fossil fuels costs, a scenario which clearly favoured a system employing a renewable form of energy. A figure for the annual fuel price inflation rate is always the hardest to allocate with any accuracy, but this particular percentage seemed unnecessarily high. A better indication of its economics was that its cost was only 30-50% of that for an active flat-plate solar water heating system of equal performance.

The Cambridge, USA, roof-space collector was built largely by

volunteers, resulting in a cost in autumn 1983 of only \$134/m² of glazing. The estimated cost if the job had been entirely undertaken by professionals, was \$328/m² of glazing. When the seasonal efficiency of the roof-space collector, 29%, was taken into account with a 65% assumed seasonal efficiency for the back-up system, and an estimated saving of 17 GJ of natural gas each year, the simple payback period was 4.8 years. This was for a system built with one weekend of volunteer labour, and a contractor and assistant employed for one week. In addition, both federal tax credits of 40% and Massachusetts tax credits of 21% were included in the calculation. Without any tax benefits, and for a system built with entirely contractual labour, the payback period would be extended to 30.2 years!

A discounted cash flow method was used to assess the package of passive solar measures at Stornoway. The 36% energy saving gave rise to an annual saving of £55.00 at that time. A 5% real discount rate, the same as that chosen by the UK Government's Treasury, and a 4% long-term predicted real rate of increase in fuel prices combined to produce a net present value over 10 years of £520. As the predicted extra cost associated with solar heating was £400, this resulted in a payback period of 8 years.

xv) Conclusion

Higher site densities of passive solar buildings can be achieved with roof-space collectors than would be the case with ground floor conservatories or direct gain. They also have considerable retrofit potential. This means that both new and existing buildings can be beneficial candidates for the inclusion of roof-space collectors. A study of the potential for passive solar retrofit of existing dwellings in the United Kingdom (2.2.16) found that over 13% of those houses were suitable from roof-space collectors. A number of housing developments and refurbishments are planned currently which will incorporate roof-space collectors.

2.3. THERMOSYPHONING AIR PANELS

2.3.1. History

A Thermosyphoning Air Panel (TAP) is an example of an "isolated gain" passive solar feature, i.e., it can be decoupled thermally from the building. This is accomplished via an insulated separating wall, as in a TAP, or by location above the building, as in roof space solar-energy collectors (2.3.1). A more controllable heat gain combined with - if well designed - an avoidance of summer overheating, is the primary advantage of isolated gain. With new materials becoming available it may be possible to design either a TAP as a cladding collector or a roofspace collector, at low or even zero additional cost to the basic building, and these in conjunction with solar pre-heating of the ventilation air would be attractive economically. For isolated gain passive solar systems the provision of thermal storage should concentrate on convective linking with the external walls and ceiling rather than to provide further thermal capacity. Isolated indirect elements should not adopt storage unless it is insulated during periods of non-collection, or is remote, with a controlled convective link. That is, the definition of isolated indirect features is strictly adhered to, otherwise a net heat loss will ensue.

Isolated gain collectors such as the Thermosyphoning Air Panel, patented in 1881 (2.3.2) in the form shown in figure 2.3.1, overcome some of the disadvantages of indirect gain collectors by dispensing with heat storage and relying totally on convective heat gain. Heat input is almost instantaneous whilst heat losses during non-gain periods when the collector is isolated from the heated space, are low. This design is ideally suited to the task of providing daytime heat in cool or cold climates. A TAP operates in the same manner as the natural convection mode of a Trombe-Michel Wall. However, the absorber is often made of metal, usually aluminium or steel, (in contrast to the masonry of a Trombe-Michel wall) and the unit is insulated to prevent heat loss to, or from, the building. The problem most associated with passive solar energy systems generally is control of any unwanted heat output. This is not the case for a TAP as all that is required is for an inlet or outlet vent to be closed and the thermosyphoning process ceases. There has been comparatively little commercial development of the TAP to date, but it has proved to be popular with some homeowners in the U.S.A. (2.3.3) as it allows the introduction of solar heating on a

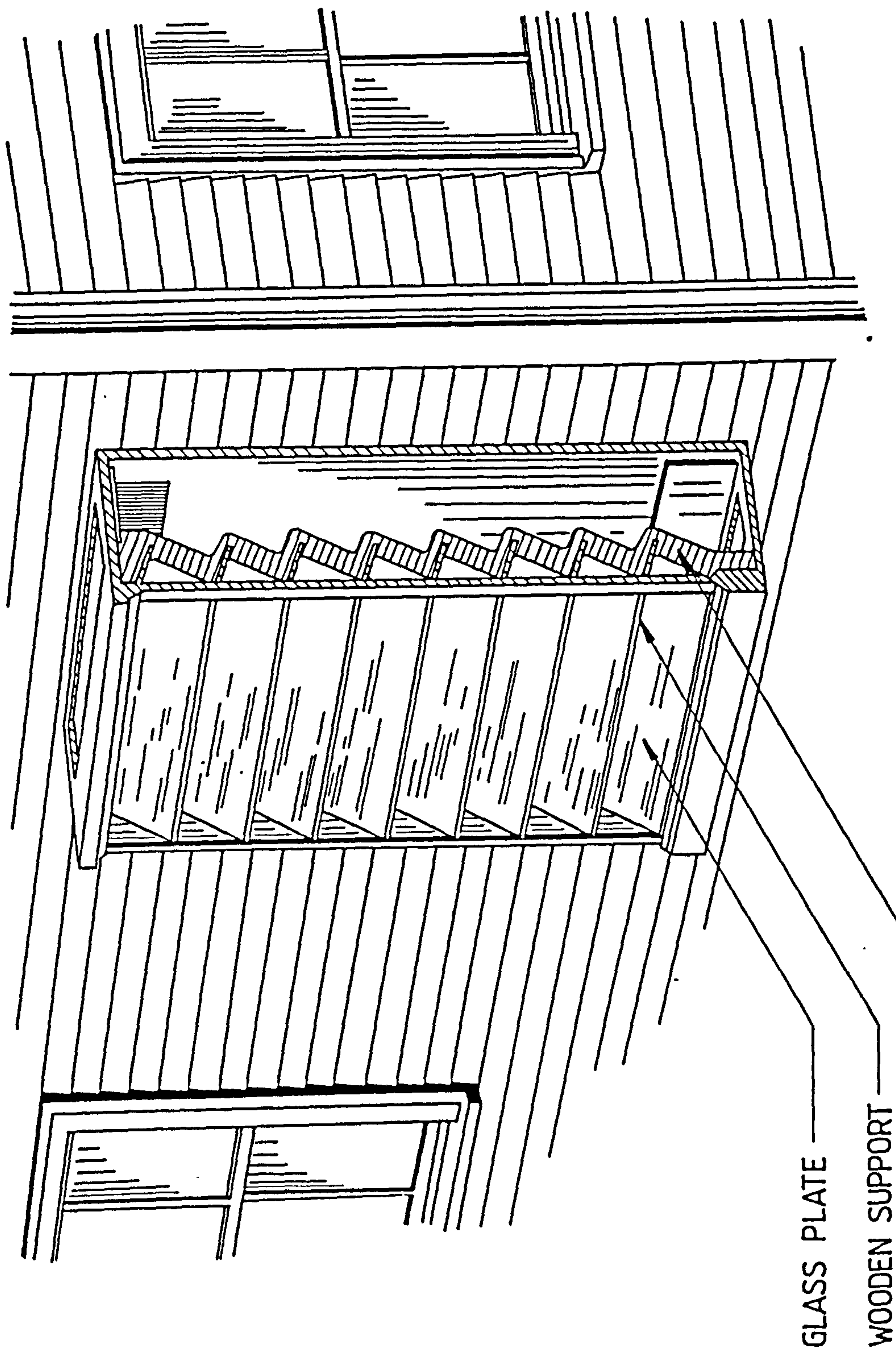


Figure 2.3.1 The Morse Passive-Solar Air-Heating
& Ventilating Unit Patented in 1881

small scale with the minimum of cost and inconvenience.

The relative merits of the single glazing and double-glazing of TAP's are reviewed in Table 2.3.1.

2.3.2 TAP Configurations

Four configurations of TAP may be identified;

a) Front-Pass Collectors

The most simple solar-energy air-heaters have the absorber plate attached to the rear panel of the collector so that the air passes between the glazing and the absorber, figure 2.3.2a. The disadvantage of this configuration is that air convects over the glazing and heat is lost to the exterior, whilst a dust and smoke film may gradually form on the inner surface of the glass. This reduces the transmittance of the cover and detracts from the appearance of the system. The amount of dust which accumulates will depend on the room air, and the amount of condensation which forms on the inner surface of the glazing.

b) Back-Pass Collectors

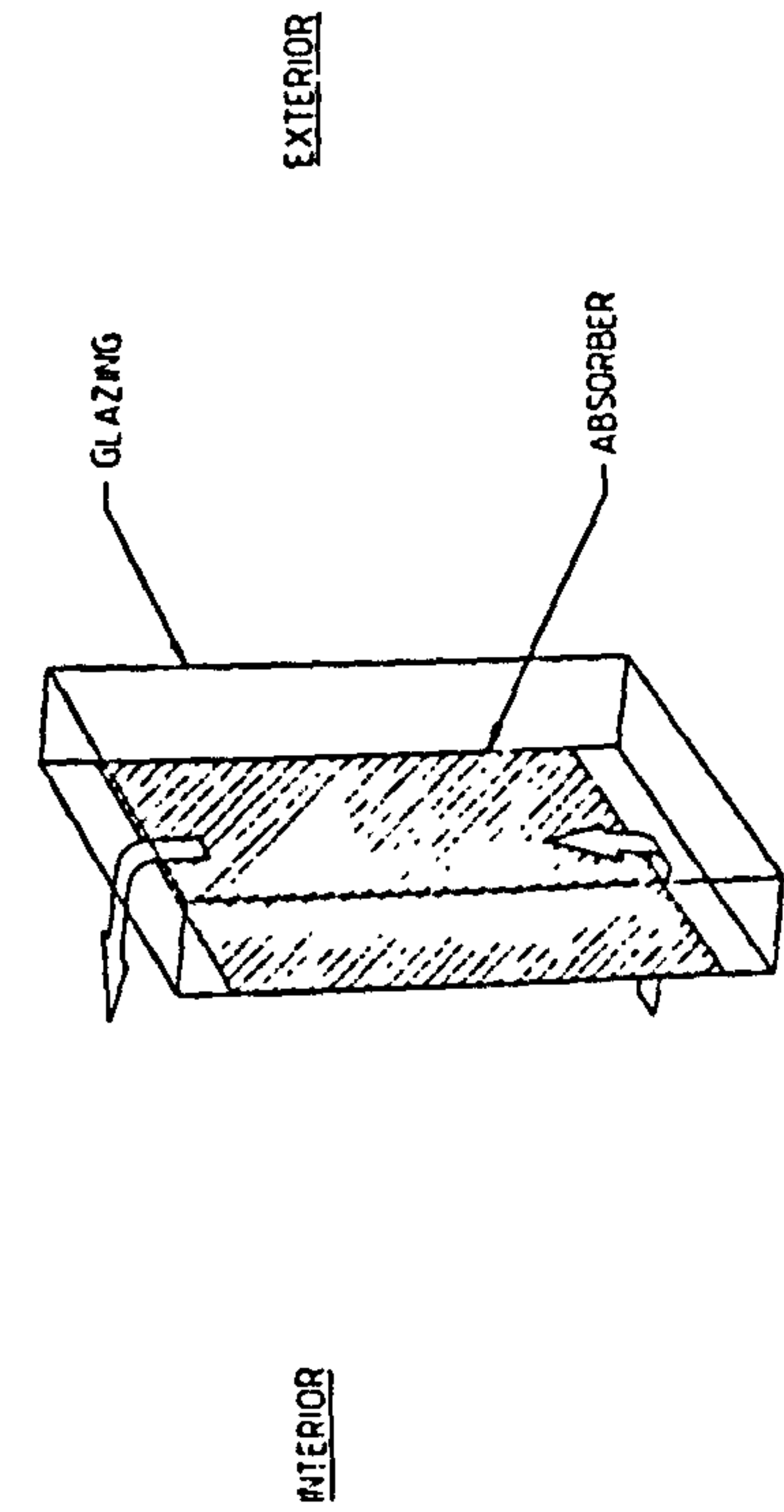
One advantage of the Back-Pass design is that the moving air stream is isolated from the glazing, as shown in figure 2.3.2b. The layer of air contained between the absorber panel and the glazing provides insulation, whilst the inner surface of the cover is kept free from dust. In the Back-Pass configuration the air-tightness of the cover is not crucial to the performance of the collector. A collector which has the Back-Pass arrangement, and is well sealed, is potentially maintenance-free. However, the air space between the glazing and the absorber makes the collector deeper than other designs and this may prove to be a disadvantage in certain applications. Insulants and sealants which may give off fumes and leave deposits on the cover should be avoided.

c) Dual-Pass Collectors

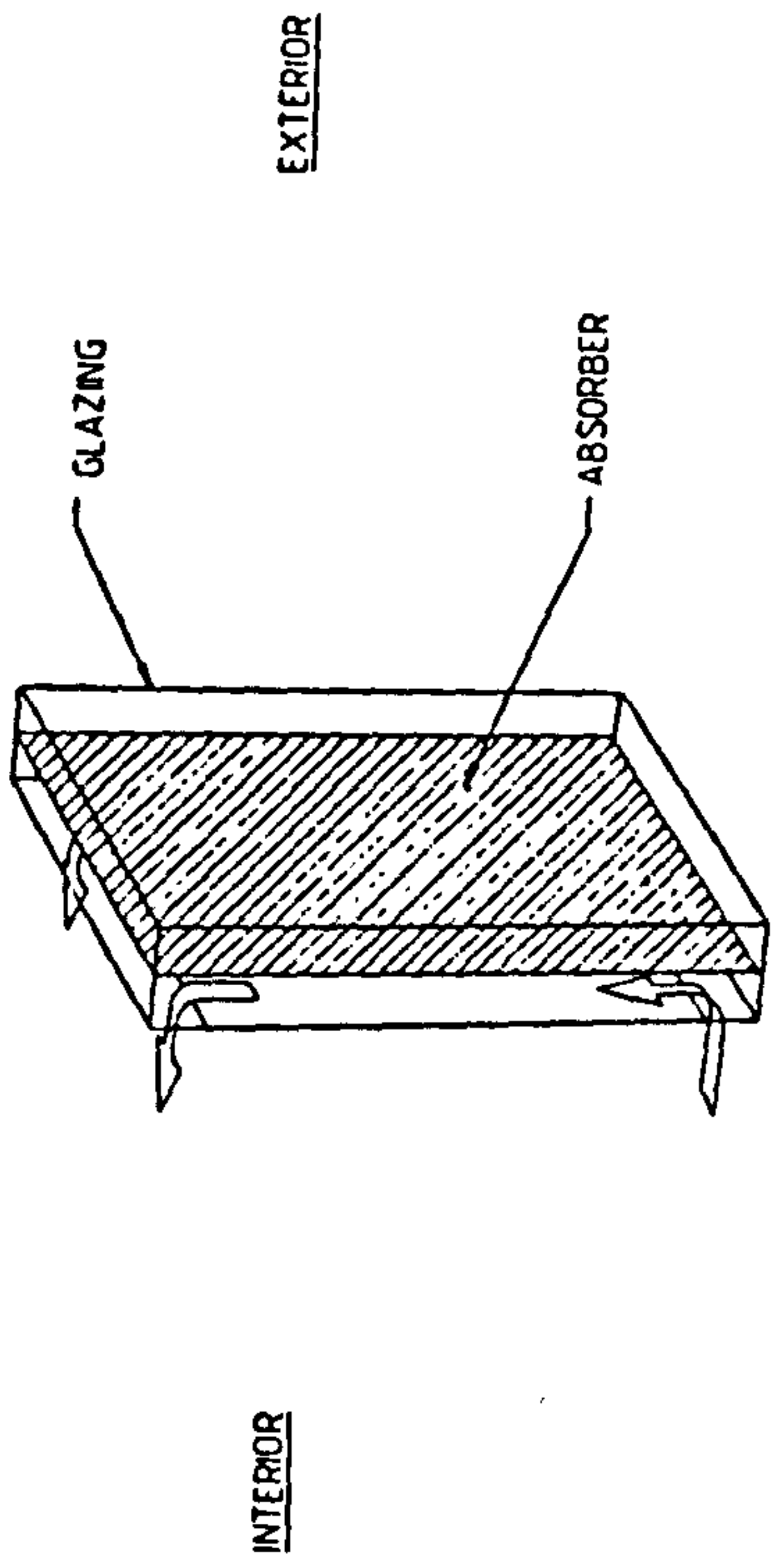
In a Dual-Pass collector air passes on both sides of the absorber, providing twice the heat transfer area of the previous designs, (figure 2.3.2c). Some heat from the front air-flow is lost to the glass with

	Advantages	Disadvantages
Single - Glazing	<ul style="list-style-type: none"> . Low cost . High transmittance . Single-glazed collector not subject to high stagnation temperatures . Light weight 	<ul style="list-style-type: none"> . Heat losses via the glazing are significant reducing collector efficiency . Reverse thermocirculation will take place at night therefore an effective form of back-draught damper is required . Condensation
Double - Glazing	<ul style="list-style-type: none"> . Reduced heat losses from the collector . Less nocturnal reverse thermocirculation . Backdraught damper does not have to be as effective . Reduced condensation 	<ul style="list-style-type: none"> . High cost . Lower transmittance . Heavy weight if glass is used . High stagnation temperatures . May require venting or shading mechanism

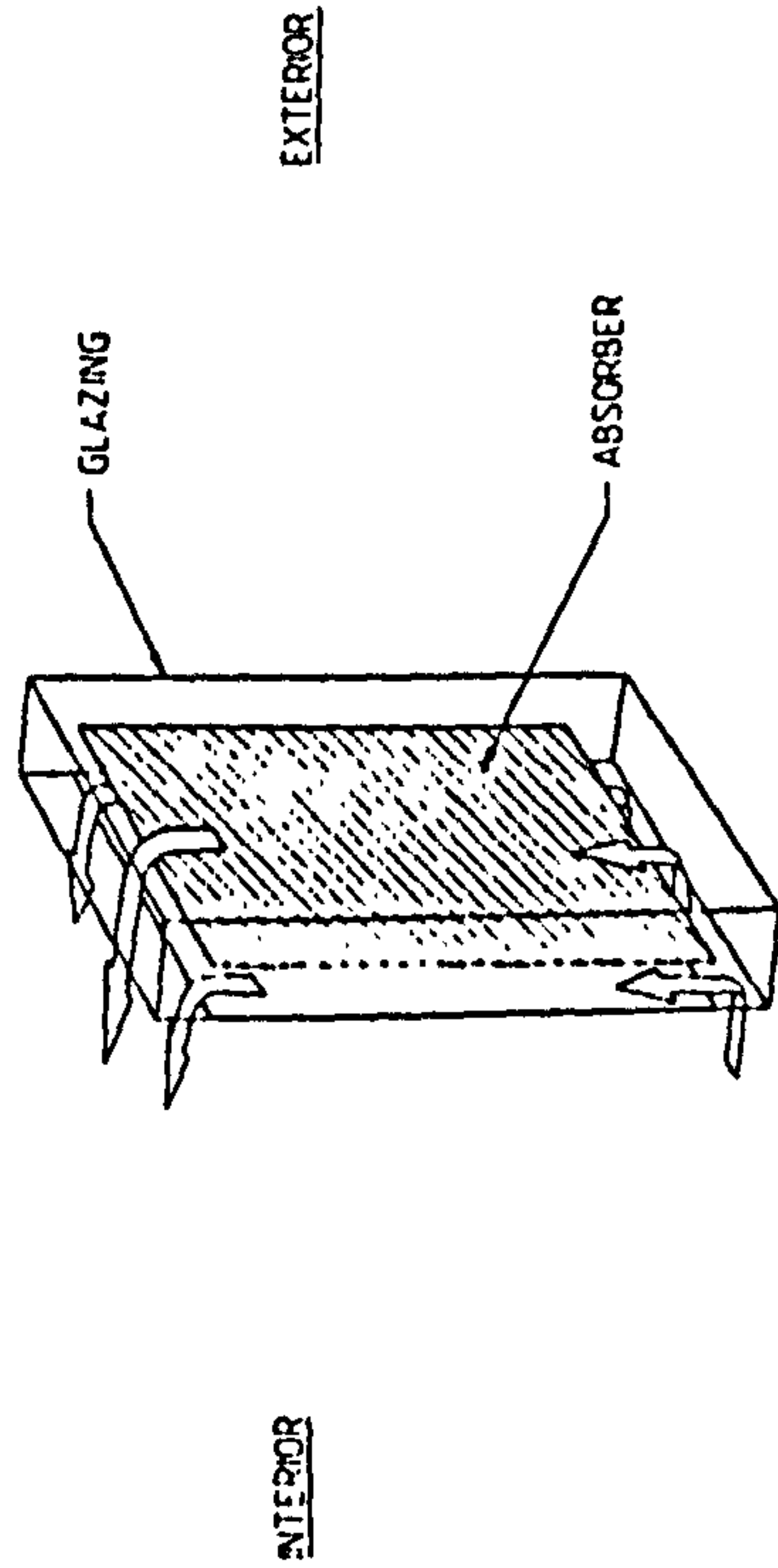
Table 2.3.1 The Relative merits of single & double-glazing thermosyphoning air panels



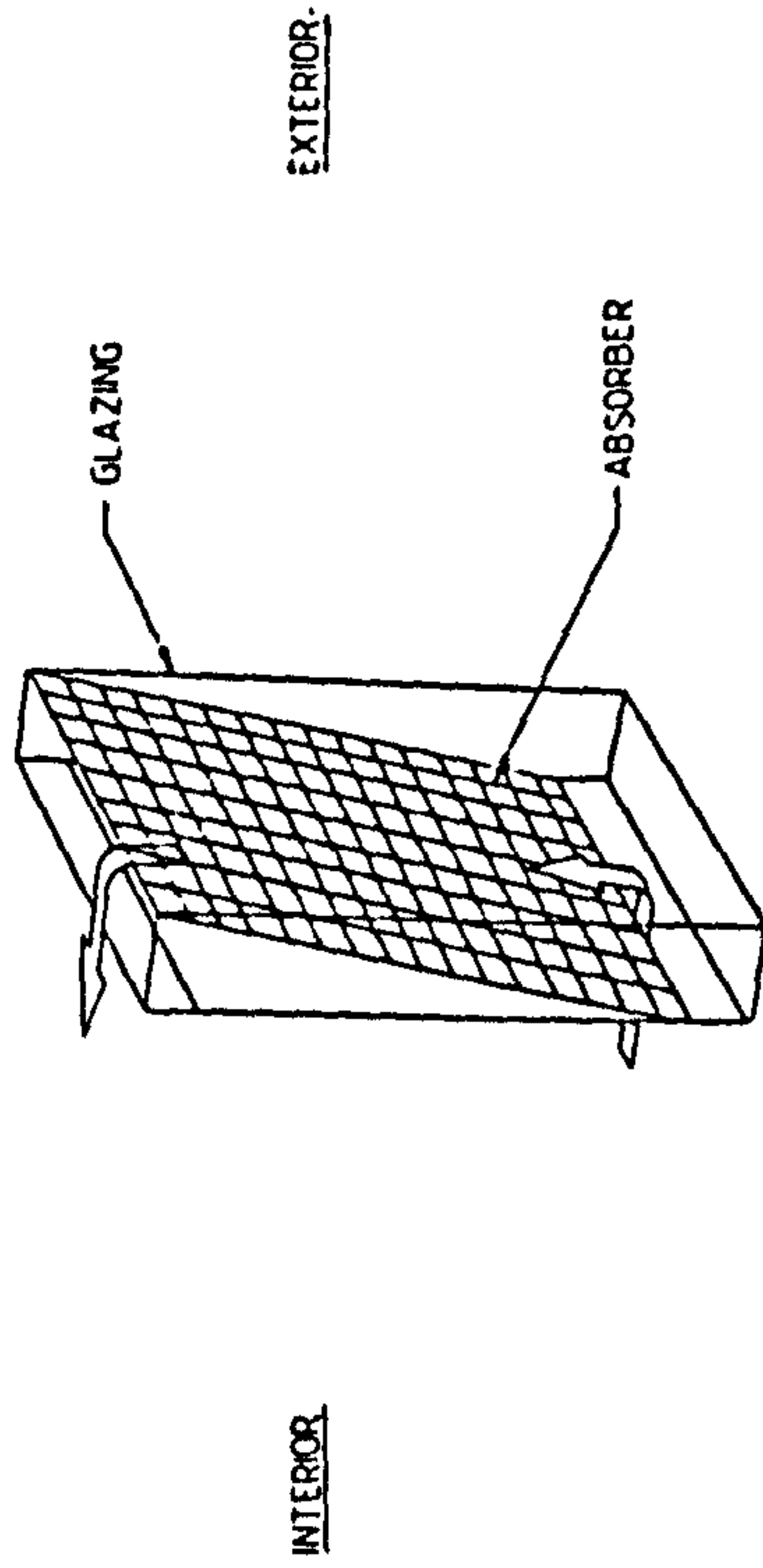
a) Front-pass collector



b) Back-pass collector



c) Dual-pass collector



d) Matrix collector

Figure 2.3.2 Four "standard" Thermosyphonic Air-heating Solar-Energy Collectors

this arrangement and it shares the drawbacks of the Front-Pass design whilst being more difficult to construct.

d) Matrix Collectors

The Matrix absorbers advocated by Baer (2.3.4) and Morris (2.3.5, & 2.3.6) consist of a metal lath placed diagonally within the collector, creating a mesh through which the air passes, as shown in figure 2.3.2d. An attractive feature of this design is that the incoming air passes over the glazing before being heated by the mesh, so less heat is lost than with Front-Pass or Dual-Pass collectors. However, Morris (2.3.5) observed that a mesh was effective only if there was sufficient air-flow to maintain a slight pressure drop at the mesh itself. Low velocity flows allowed mixing of the hot and cold air on the glazing side, increasing losses and decreasing efficiencies. A solution was to increase the flow velocity by decreasing the area of the flow channel or by using a slightly less permeable mesh, but this would produce a collector which is better suited to high levels of insolation (2.3.6).

2.3.3 Retrofit options & TAP selection

Three methods of retrofitting passive solar energy air heating collectors to institutional buildings, and one method for industrial buildings, are summarised in Table 2.3.2. A cladding collector was adopted at Nazeing County Primary School because a full refurbishment programme was already being implemented by the local education authority. The manufacturers of the insulating panels were able to produce a TAP, which did not compromise the performance of the conventional cladding units.

	Definition	Advantages	Disadvantages
CLADDING COLLECTOR	Unit which acts as cladding and solar collector. Replaces conventional cladding panel as part of a refurbishment programme.	<ul style="list-style-type: none"> • No more difficult to install than conventional recladding unit. 	<ul style="list-style-type: none"> • Cost of construction. • Depth of collector limited by depth of conventional unit. • May require development of totally new cladding system.
OVER-CLADDING COLLECTOR	Unit which fits between overcladding and existing building envelope during refurbishment programme.	<ul style="list-style-type: none"> • Depth of collector only limited by space between overcladding and existing building envelope. • Collector does not require extensive weatherproofing. 	<ul style="list-style-type: none"> • May be expensive. • Inlet and outlet openings must be made in building envelope. • Moving parts within collectors, such as dampers, may not be readily accessible for repair.
GLAZING COLLECTOR	Panel designed to fit behind existing glazing to provide insulation and a convective heat input.	<ul style="list-style-type: none"> • Inexpensive. • Easy to install. • Does not have to form part of a refurbishment programme. 	<ul style="list-style-type: none"> • Occupies interior space. • Depends on integrity of existing glazing framework. • Glazing area must be reduced.
METAL BUILDING COLLECTOR	Part of the existing south-facing metal cladding is glazed and thus forms the absorber for a retrofit TAP.	<ul style="list-style-type: none"> • Cost effective. • Straightforward installation. • Uses existing building components. 	<ul style="list-style-type: none"> • Large area of building has to be glazed. • Cannot be implemented on a small scale. • May only be suitable for new buildings.

Table 2.3.2 The relative merits of four options for the retrofitting of Thermosyphoning Air Panels (TAP's)

2.3.4 Operating Regimes of Thermosyphoning Air Panels

The detail drawings of the construction of the TAP's installed at Nazeing County Primary School are documented in Appendix A. There were two different modes of collector operation which were intended to be activated manually by the teachers.

In the heating season, during any periods of insolation, the air from the classroom was drawn-in through a low level grille, circulated between the absorber plate and the insulated back-panel, and expelled via a high level outlet grille back into the classroom. The flow rate of the solar-heated air was dependent upon the solar radiation incident upon the collector panel, the external ambient temperature and the internal classroom temperature.

During the summer months when the contribution from the TAP's was no longer necessary, the high level grille was closed and the solar heated air was exhausted out to the ambient environment. This also reduced the risk of overheating which could damage the absorber surface and/or the glazing.

2.4 THERMOSYPHON SOLAR WATER HEATING SYSTEMS

2.4.1 System Classification

There are three criteria by which solar water heating system types are classified:

- a) the means by which the fluid in the collector loop is circulated;
- b) the means by which the heat is transferred from the collector loop to potable hot water; and
- c) the means of freeze protection.

2.4.2 Collector Loop Circulation

There are two primary means of circulation within the collector loop; natural (or passive, via thermosyphonic action), and forced (or active, using a pump). A comparison of forced and natural circulation solar-energy water heaters is given in Table 2.4.1.

Thermosyphon solar water heaters which must be designed carefully to ensure a minimum resistance to flow are self regulating: "switching themselves on and off" as dictated by the insolation. Their advantages include lower initial costs (i.e. little hardware involved), high mechanical reliability (i.e. no moving parts, no electronic control systems), and lower operating costs (i.e. no power is necessary for fluid circulation). These thermosyphon solar-energy water heaters can be categorised into three types, namely close-coupled, same-level, and distributed. The pertinent differences between these system types are outlined in Table 2.4.2.

A direct open-loop system is by far the easiest method of transferring heat from the collector to the store where the collection fluid and the potable hot water are one and the same. This approach minimizes hardware requirements and eliminates the inefficiencies of the intermediate heat transfer stage.

TABLE 2.4.1 THE ADVANTAGES/DISADVANTAGES OF THERMOSYPHON AND
FORCED CIRCULATION SOLAR WATER HEATING SYSTEMS

	Forced Circulation	Natural Circulation
Mode of circulation	Requires a pump and associated control equipment	No pump required - self regulating, i.e. dependent on insolation
Complexity of system	Greater number of components involves increased installation time and costs	Reduced cost due to lower installation times are not always significant when compared to the total system cost.
Reliability	Greater number of components reduces reliability	Increased potential reliability of a more simple system configuration
Physical Requirements	Not restricted by shallow roof pitches	Requires sufficient headroom to enable the installation of the tank above level of collector

TABLE 2.4.2 GENERIC CLASSIFICATION OF NATURAL-CIRCULATION
SOLAR-ENERGY WATER HEATERS.

	Close-coupled	Same-level	Distributed
Position of hot-water store :- i) relative to collector,	Directly above	At the same level	More than 0.5m above
ii) relative to loftspace.	Outside	Outside	Inside, outside, or contained in "solar chimney"
Orientation of hot-water store	Horizontal	Vertical	Vertical
Fabrication	Installed as a complete unit	Installed as a complete unit	Assembled from component parts during installation.
Primary method of preventing nocturnal reverse circulation	Height difference between collector and the store	Non-return valve or pipe-work arrangement	Height difference between collector and the store

There are, however, two cases where it is ill-advised to allow potable water to flow through the collectors ;

- a) where the local water is high in mineral content (resultant scaling obstructs the collector passages), or
- b) where a toxic non-freezing fluid is circulated through the collector loop as a means of freeze protection, e.g. propylene-glycol.

In both these situations the collector loop must be isolated from the potable water and the heat transfer must be accomplished via a heat exchanger. These systems are referred to as indirect (or closed loop). Potential scaling is eliminated and freeze problems are avoided. The disadvantages are, additional hardware and increased heat exchanger inefficiencies, (especially where double-walled heat exchangers are used with the more toxic collector fluids, e.g. ethylene-glycol).

2.4.3 Freeze protection of thermosyphon solar water heaters

Unless a solar water heating system is designed specifically only for use in the summer, the collector will be functioning through the winter. Almost every location in the world, outside the tropics, will experience freezing temperatures at one time or another. It is essential that fluid in the collector pipes does not freeze, as extreme damage may result.

Several approaches to freeze protection may be adopted. These include; i) re-circulation or draindown type systems, ii) electrical heating elements, iii) the use of non-freezing fluids in the collector, or iv) the use of extra insulation. More often than not the method of freeze protection defines the type of system employed.

i) Draindown

Freeze protection can be achieved by simple draindown. The collector is isolated from both incoming, and stored water, by means of valves. The water contained within the collector is then discarded. This can of course be automated at the expense of extra hardware, control equipment, and potentially lower system reliability.

ii) Trace heating

An alternative method of protection involves using a small heating element to heat the system. This uses additional electricity and consequently would provide little protection during a power failure.

iii) Non-freezing heat transfer fluid

This method of freeze protection, is, broadly speaking failsafe, though a major decision concerning the design of an indirect system is the choice of the heat transfer fluid. Due to the increased viscosity of the fluids involved, at very high temperatures (i.e. up to 150°C in the summer), the antifreeze employed eventually breaks down to form glycolic acid. This would cause severe corrosion to any associated pipework. An ethylene-glycol solution is frequently selected as it is readily available and cheap. Unfortunately this fluid is very toxic and must satisfy the safety regulations of the water authorities. The installation of a double-walled heat exchanger is also necessary at the expense of reduced overall efficiency.

Non-aqueous heat transfer liquids such as silicone fluids (2.4.1) and synthetic hydrocarbon fluids (2.4.2), have low or moderate toxicities. However, their use in an indirect thermosyphon solar water heater would severely impair the system's efficiency as they have lower specific heats and thermal conductivities combined with much higher viscosities than aqueous solutions. Current regulatory trends indicate that the use of an aqueous anti-freeze solution with a single-walled heat exchanger will probably be permitted if the solution is "practically non-toxic and chemically stable over the operating range of the system" (2.4.3). It has been demonstrated (2.4.4, & 2.4.5) that propylene glycol solutions containing the necessary inhibitors can satisfy these requirements.

2.4.4 Previous Studies of Thermosyphon Solar-Energy Water Heaters

1) Experimental Investigations

The earliest (c 1935) relevant experimental study was undertaken by Brooks in California (2.4.6, & 2.4.7). The first results recorded for the U.K. climate were reported by Heywood (2.4.8, & 2.4.9) with a direct system installed in a dwelling in south-east London, U.K. During the mid to late 1950's several general performance evaluations were undertaken in the U.S.A. (2.4.10, & 2.4.11), Australia (2.4.12), Japan (2.4.13), South Africa (2.4.14) and New Zealand (2.4.15).

The behaviour of a heavily-instrumented natural-circulation solar-energy water heater in Israel was studied, which was considered to be representative of those in common use throughout Israel (2.4.16). The water within the storage tank experienced little mixing and was well-stratified thermally.

A thermosyphon solar water heating system, with electric auxiliary heating, was installed in a house in New Zealand and monitored for over four months (2.4.17). The system operated satisfactorily, but was too small for the patterns of hot-water consumption encountered, and so the solar fraction was disappointingly low.

At high altitudes thermosyphon solar water heaters have been used for both water and space heating (2.4.18 - 2.4.20): A study (2.4.21) was undertaken for a region in northern India, (at an altitude of 3.5 km above sea level). Although extremely cold, (experiencing temperatures down to -20°C at night), this area benefitted from relatively intense insulations of 1250 W/m^2 on clear days in January, and showed solar space heating to be feasible in such environments. Space heating at high altitudes could be achieved more economically using a Trombe wall (2.4.22). Nevertheless, in these inclement conditions, a thermosyphon system (with a heat exchanger immersed in a tank of water replacing the normal storage tank), would find a ready application as an indirect domestic water heater.

In the temperate climate of the Pacific North-West U.S.A., a thermosyphon solar-energy water-heater was monitored, during non-freezing periods for a year from August 1979 and the overall system productivity was a linear function of insolation (2.4.23).

The largest installation reported supplied a four-storey block of flats in Honolulu, Hawaii, U.S.A. (2.4.24). Three systems were installed, each of 75m² collector area and 4.66m³ storage tank capacity. One of these, which delivered hot water to six flats (occupied by twelve adults and seven children) as well as a communal laundry, had been extensively monitored (2.4.25). A comparison of the recorded behaviour with that for a similarly sized, pumped-circulation system operating under identical conditions showed that, when the pumping energy of the active system was taken into account, the thermosyphon unit exhibited a marginally better performance.

The maximum density of water occurs at 3.98°C, and water between 0°C and 3°C will rise above slightly warmer water (c 4.5°C); although the ensuent pressure head is small. This effect ensured that one particular system remained undamaged even when the ambient environmental temperature was as low as -5.5°C (2.4.26).

The diurnal pattern of hot water withdrawal has a large influence on system behaviour (2.4.8, 2.4.27 - 2.4.32). The thermosyphon circulation rate is dependent on the prevailing meteorological conditions and also the temperature of the hot water in the store. If there is no day-time withdrawal of solar-heated water in a system with low fluid resistance and consequently a large thermosyphon flow rate, then the high temperature of the store in the afternoon causes a significant reduction in the flow rate during that period.

For domestic installations, the use of a "third tap", (an additional faucet on a bath or sink), has been suggested which would permit hot water to be drawn directly from the store (2.4.33 - 2.4.35). However, oscillations may develop in the thermosyphon flow at high rates of utilization of solar heated water (2.4.36, 2.4.37) which may destratify the hot water store. To prevent the degradation of the thermally-stratified store when cooler water enters via the top of the tank, the fitting at the top of the hot water storage tank of a floating inlet has been recommended (2.4.38, 2.4.39). In addition, Legionnaires Disease can present a problem when using third taps (2.4.40).

ii) Indirect thermosyphon solar water heaters

Alternative approaches to freeze protection have included collectors where flow channels expand to accommodate the freezing water (2.4.41 - 2.4.43), the use of an indirect system circulating an aqueous anti-freeze solution, and manual draining. The latter is not a reliable day-to-day long-term solution though may be appropriate on a seasonal basis.

Direct units have been found to be more efficient than indirect systems (2.4.44); the expected effect of incorporating a heat exchanger in the system (2.4.45). Nevertheless, the use of a heat exchanger, together with an anti-freeze solution as the working fluid in the collector flow circuit, is a convenient method for the prevention of freezing. Therefore it is important to assess carefully and thus minimise the reduced efficiency of indirect thermosyphon solar water heaters. A particular indirect system was shown to be 9% less efficient than a comparable direct system (2.4.46). This was attributed principally to the reduced thermosyphonic flow rate in the indirect system due to the higher viscosity of the ethylene-glycol solution heat transfer fluid and additional flow resistance of the heat exchanger. The heat transfer losses in the heat exchanger and the lower specific heat capacity of the antifreeze solution (in comparison with water) were considered to be only small contributory factors to the overall reduction in the system's efficiency. Simulation of indirect thermosyphon solar water-heaters containing propylene-glycol (2.4.3, 2.4.47) have indicated system efficiencies of the order of 10% less than those of comparable direct systems.

A thermosyphon system was developed (2.4.48, & 2.4.49) in which water containing a corrosion inhibitor flowed in a closed circuit, comprising a solar collector and a shell-and-tube heat exchanger. The water to be heated also passed through this heat exchanger from a header-tank under the action of gravity. Indirect thermosyphon solar water heaters have been manufactured (2.4.50) which use concentric tanks for the heat exchanger or involved the use of a black heat transfer fluid in a gap between the collector plate and the glazing (2.4.51). It has also been suggested (2.4.52) that visco-elastic fluids be used as the heat transfer fluid in indirect systems.

iii) Comparison with other types of solar water heater

Both the performances (2.4.25, 2.4.53 - 2.4.56) and the economic viability (2.4.57, & 2.4.58) of thermosyphon systems have been shown to compare favourably with those of solar water heaters employing pumps.

Six types of solar water heaters were monitored by the United States National Bureau of Standards over the year from July 1978 to June 1979 (2.4.44, 2.4.59 - 2.4.62); the relevant comparative data for the systems are shown in Table 2.4.3. As can be seen from Fig. 2.4.1. the best performance was obtained from a thermosyphon unit. The effectiveness of the two indirect units monitored was enhanced by the provision of a greater thickness of thermal insulation around the hot water store.

The NBS studies also showed that system efficiency decreased with the addition of a second storage tank, because the storage and piping losses then exceeded the decrease in collector losses. This experimental conclusion differs from the computer prediction of a simulation study for one or two tanks, and pumped or thermosyphon systems (2.4.55). In the latter study, comparisons were made of the annual solar energy harnessed of the two thermosyphon (one or two tanks) and two pumped (also one or two tank) systems. Analytical results were presented for two different thermal load profiles, one in which the day-time use of hot water predominated, and the other in which most of the hot water was used during the evenings. For both demand patterns, the theoretical results indicated that a larger solar fraction was provided by the two-tank units and thus such systems were considered to be economically more favourable (2.4.63). However, the validity of this conclusion applies only for the particular one- and two-tank systems investigated, and then only under the meteorological conditions which prevailed in California.

During the period from March 1979 to March 1980 (2.4.64) the performances of nine thermosyphonic, two pumped, and two breadbox systems, (i.e. hot water tanks in glazed insulated collector boxes), were monitored in New Zealand. There were wide variations in the collector areas and this made direct comparisons of performances difficult. Another comparison of the performances of thermosyphon, pumped and breadbox solar water heaters in Florida was made during the six months after August 1980 (2.4.65). Two direct pumped, a direct

Fluid Circulation	Description of System	Gross Collector Area (m ³)	Hot-Water Store						Controller Differential Temperature Setting (°C)		Method of Freeze Damage Protection
			Capacity (m ³)		Insulant Thickness (m)						
					Pre-heat tank	Auxiliary tank	Pre-heat tank	Auxiliary tank	On	Off	
	Single tank; direct; liquid	3.34	0.37	-	0.051	-	0.051	8.8	16.1	Drain-down	
	Double tank; direct; liquid	5.02	0.37	0.19	0.051	0.051	0.051	8.8	16.1	Drain-down	
Pumped	Single tank; indirect; liquid	5.02	0.37	-	0.076	-	0.076	7.8	16.1	Anti-freeze	
	Double tank; indirect; liquid	5.02	0.37	0.19	0.076	0.051	0.076	7.8	16.1	Anti-freeze	
	Double tank; indirect; air	7.25	0.37	0.19	0.051	0.051	0.051	4.44	6.7	Air	
Thermosyphon	Single tank; liquid	5.00	0.30	-	0.051	-	0.051	-	-	Drain-down	

Table 2.4.3 Characteristics of six types of solar water heater

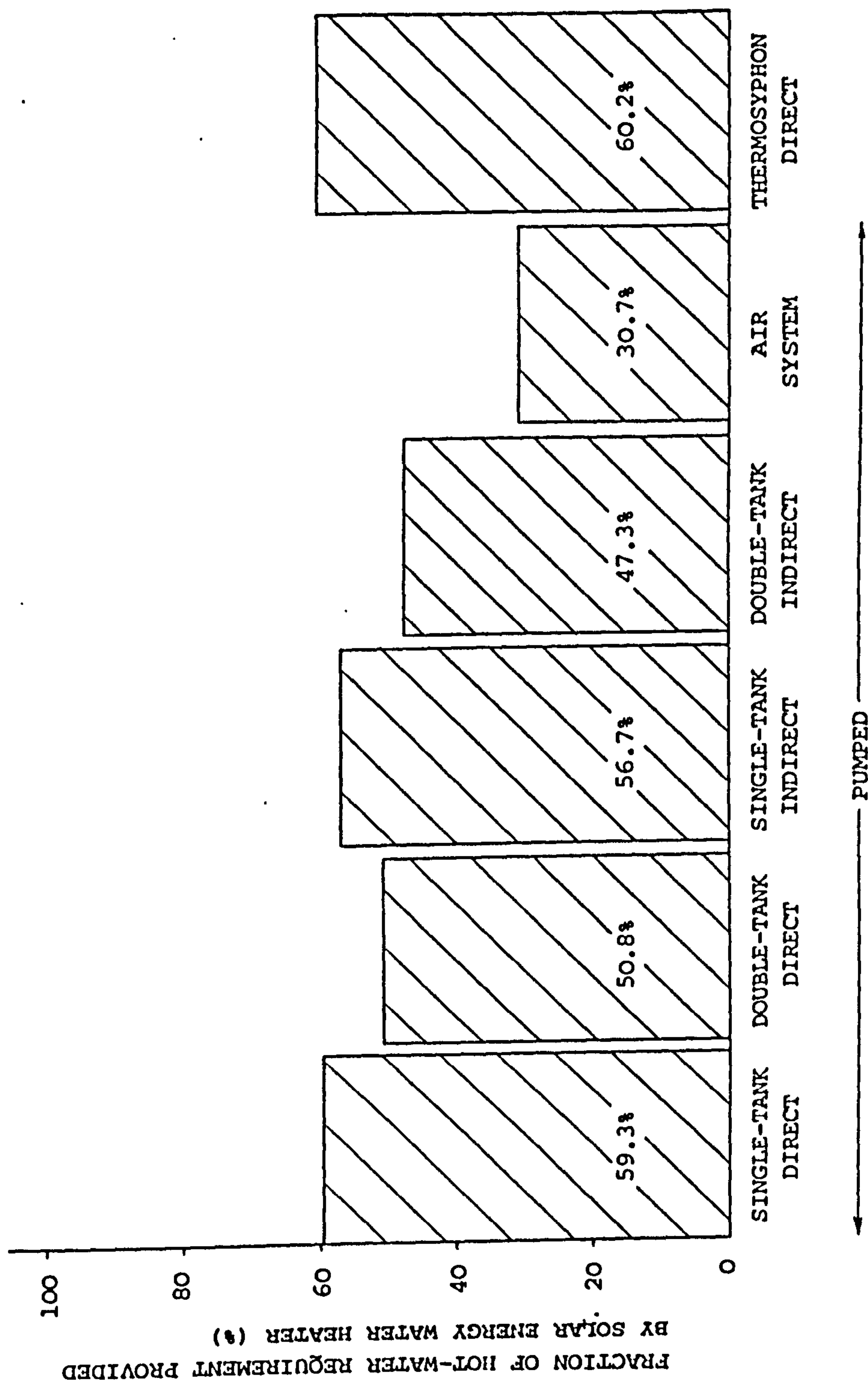


Figure 2.4.1 Performance of six types of solar water heater

thermosyphon and a breadbox unit, were monitored. In this study, the thermosyphon system was installed completely "outdoors", whereas the tanks of the pumped units were within a building. This resulted in greater thermal losses from the tank of the natural circulation unit, and so it achieved a lower overall efficiency than the pumped unit. However, despite this, the economic comparison favoured the thermosyphon unit even relative to the breadbox system. This was because the thermosyphon system efficiency approached that of the pumped unit, yet consumed no external power to produce the circulation. Furthermore it incurred approximately the same low cost to install as the breadbox unit.

The Public Housing Corporation of Japan monitored, from November 1979 to August 1980, two town houses installed with equipment to harness solar energy (2.4.66 - 2.4.67). One house incorporated a direct thermosyphon domestic hot-water system: in the other an indirect pumped system provided domestic hot water and hydronic space heating. In both houses, "gas" was used as the auxiliary heating fuel. The systems were found to satisfy equally well a given portion of the actual hot water demand patterns of the occupants.

The performances of three pumped and two thermosyphon indirect solar water heaters operating in the conditions of the Pacific North-West of the U.S.A. were compared (2.4.68). Each was subjected to the demand pattern typical of a two-person household. The indirect thermosyphons achieved the highest solar fractions during the monitoring period.

An indirect thermosyphon system for solar-energy hot-water supply in a three to five person household in West Germany was monitored from 1979 to 1981 (2.4.69). The results were compared with those of two independently-monitored pumped systems. It was concluded that with an optimised configuration an indirect thermosyphon solar water heater can be as efficient as an indirect pumped unit under the climatic conditions of Central Europe. Also in West Germany, proprietary pressurised (i.e. the cold water which replenished the tank came directly from the mains supply) and non-pressurised (i.e. the cold water entering the tank passed through a pressure reduction valve) units were tested side-by-side under identical conditions (2.4.70, 2.4.71). The systems differed in the physical and geometric characteristics of both their collectors and the associated components, nevertheless, the overall performances achieved were similar.

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CHAPTER THREE

INSTALLATION OF
SYSTEMS MONITORED

3.1 Installation of Fifteen Roof-Space Solar-Energy Collectors

1) Project location

The estate of twenty-one demonstration houses, fifteen of which incorporate roof-space collectors, on Cockerell Grove and Livesey Hill, are situated within the Milton Keynes "Energy Park" (see fig. 3.1.1). Milton Keynes, is located at a latitude of 54°N and a longitude of 0° 48'W, 65 km NNE of London, The site is 102m above mean sea level and is subject to a Northern Maritime Climate.

Roof-space solar-energy collectors (RSC's), each facing due south, were installed on fifteen of the twenty-one dwellings as shown in Fig. 3.1.2. with the remaining six dwellings used as control houses. The three different house types which incorporated roof-space solar-energy collectors are summarised in Table 3.1.1.

House Type	Number off	Floor Area m ²	Number of Bedrooms	Location of Bedrooms	RSC Area m ²	Effective* RSC Area m ²
5A	7	69.12	3	1st Floor	16.04	14.43
5B	3	73.11	3	1st Floor	13.12	11.81
5C	5	77.40	3	Grd Floor	14.17	12.75

* Glazing bars constitute 10% of the RSC area.

TABLE 3.1.1 Summary of house-types with Roof-Space Collectors

The 21 demonstration houses fell into three different house types, types 5A, 5B & 5C, (Figs 3.1.3 - 3.1.5). There were nine detached 3-bedroom type 5A houses on the estate, of which seven had 16m² of roof-space collectors. In addition to roof-top collection of solar energy these dwellings also incorporated full height "direct gain lobbies" as shown in figure 3.1.6. Of the five type 5B houses three had roof-space collectors of 13m² total area, (Fig. 3.1.7). Five of the remaining seven type 5C dwellings incorporated 14m² of roof-space

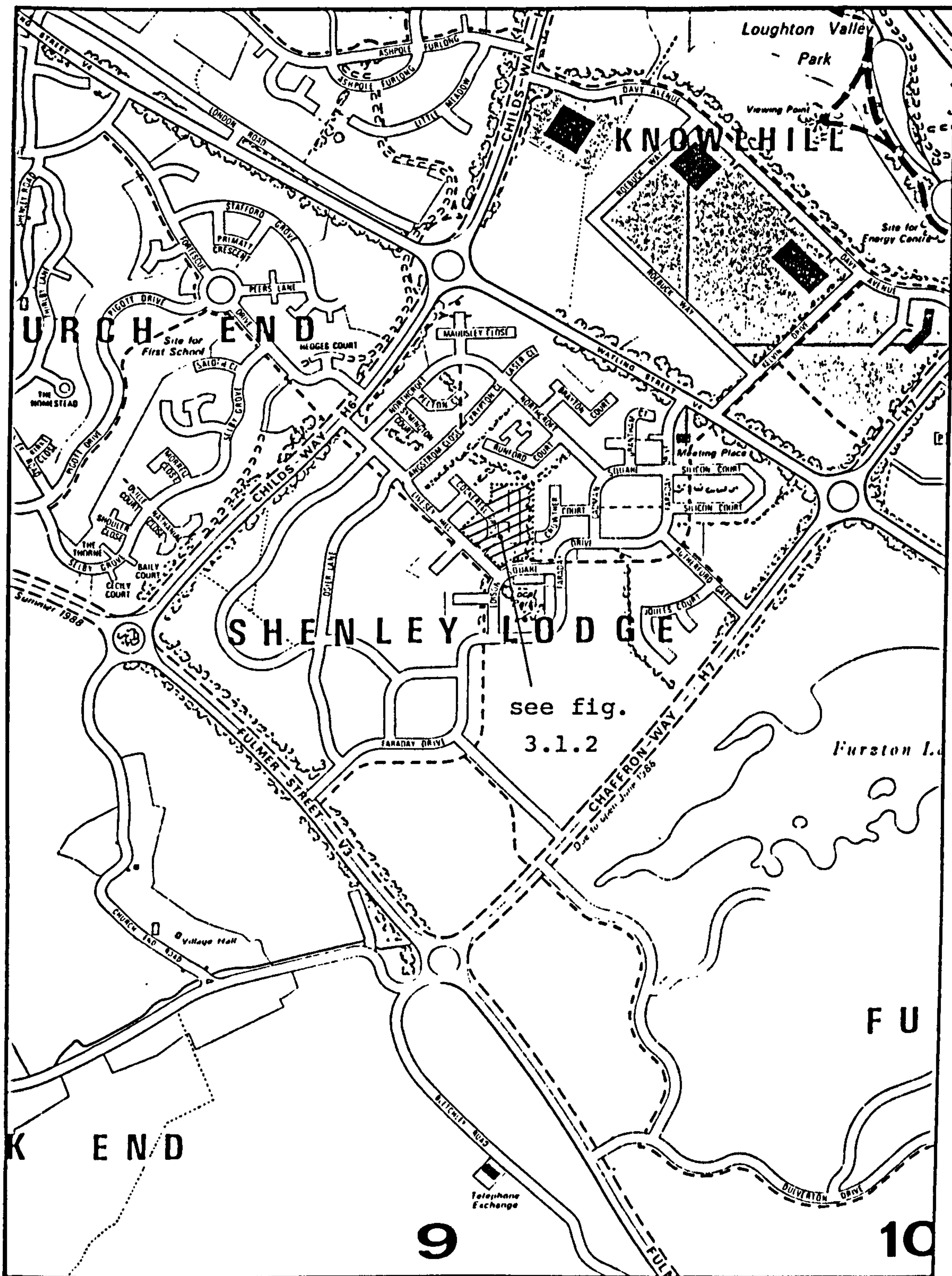
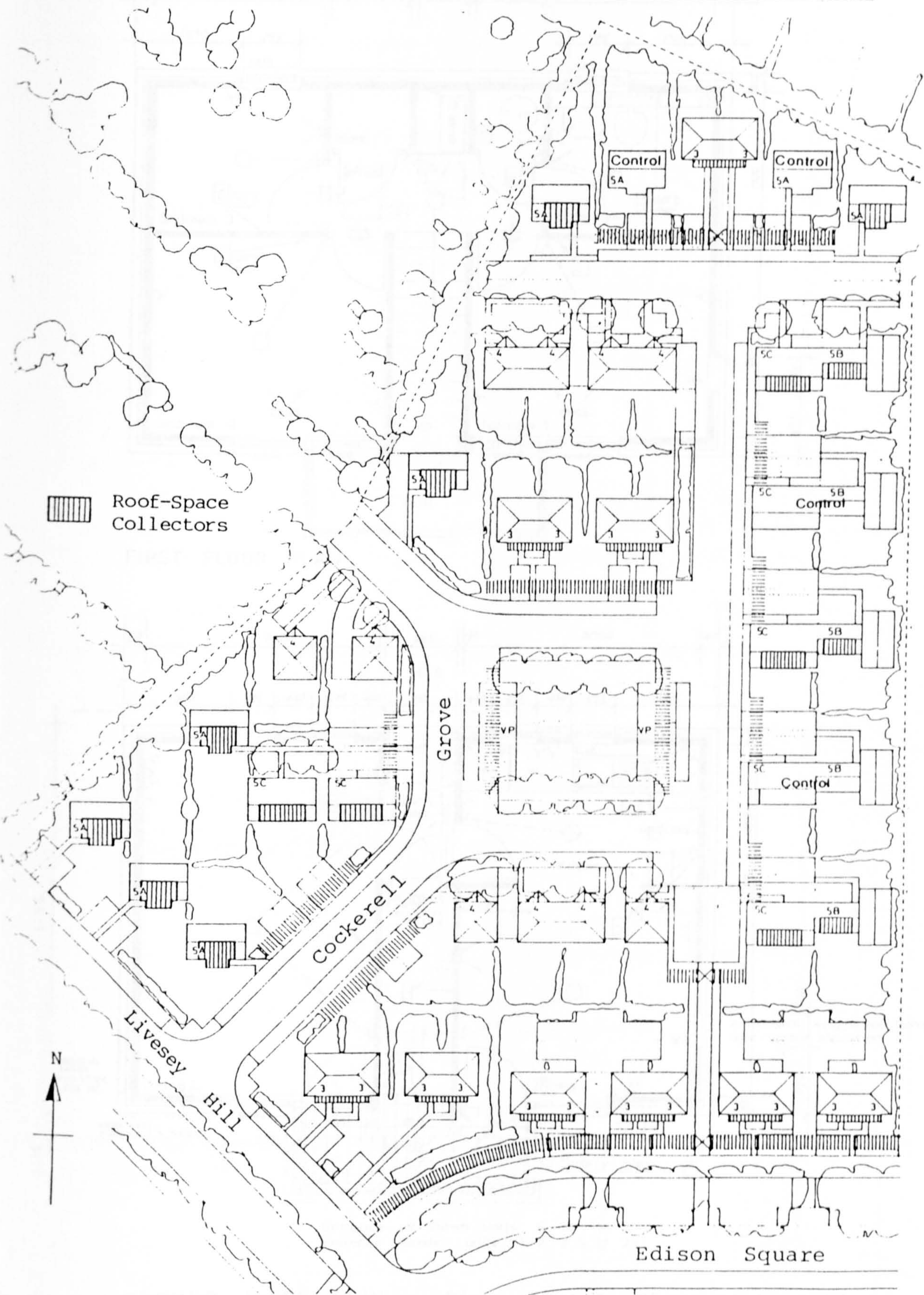
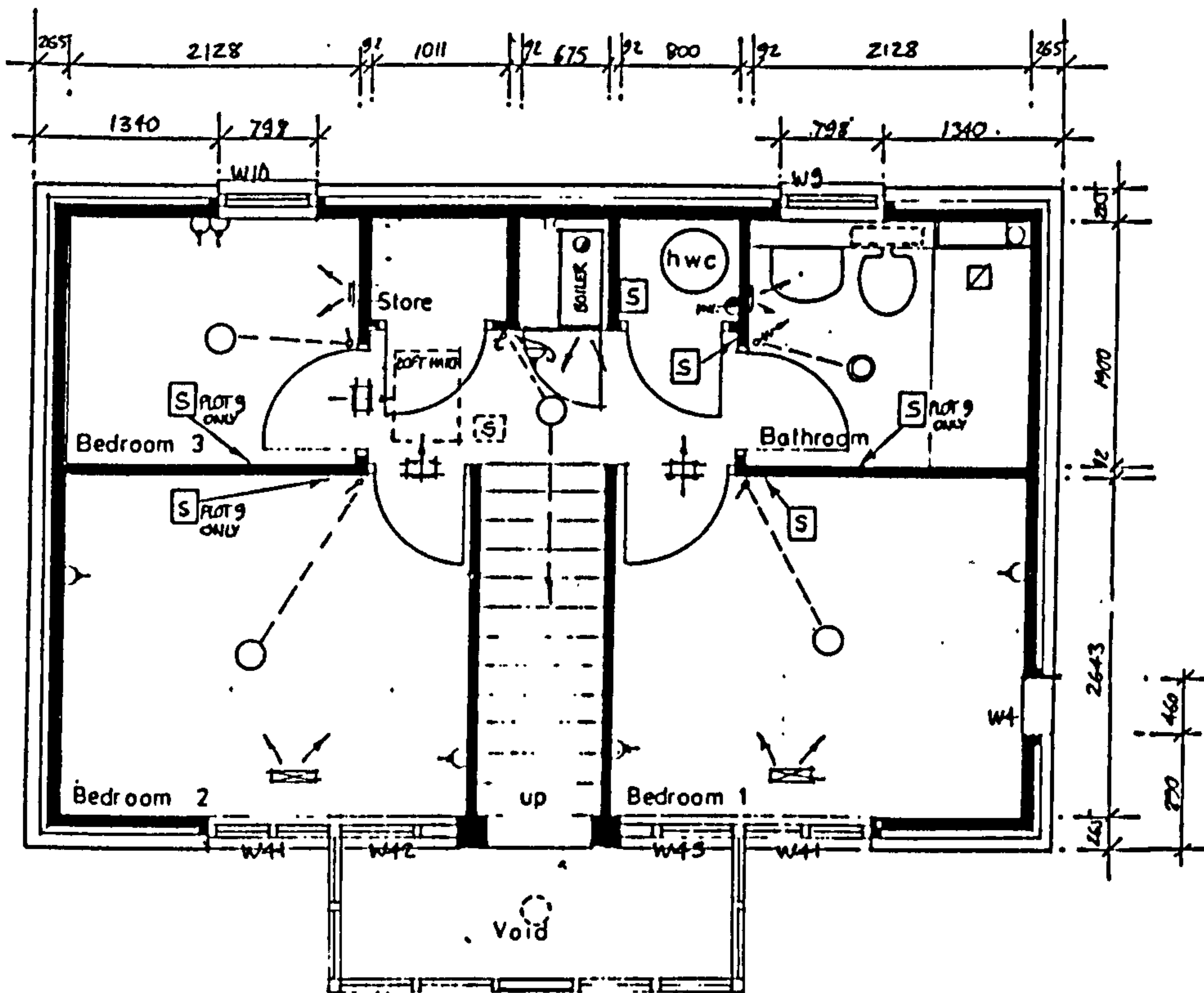


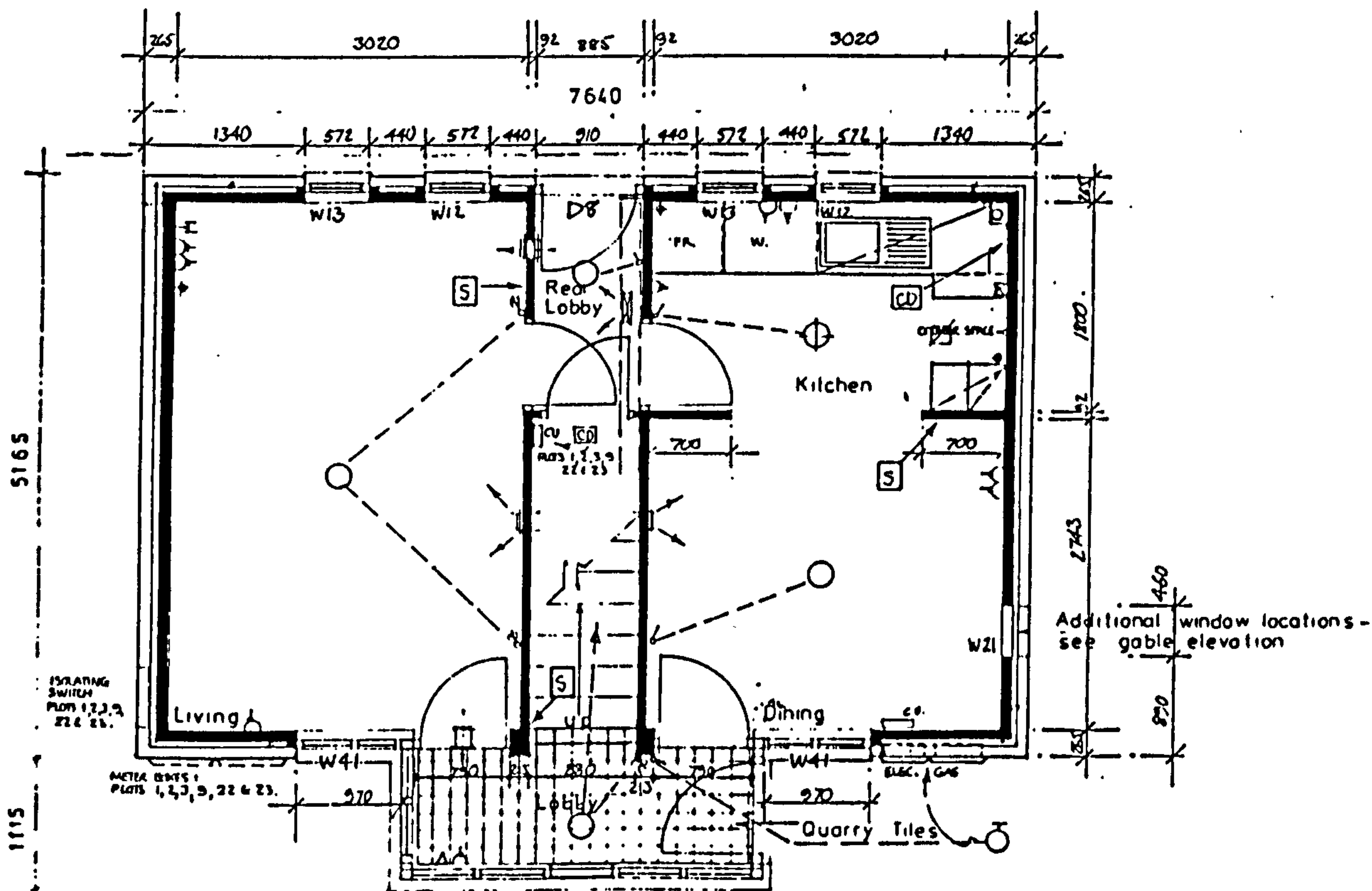
Figure 3.1.1 Location of Cockerell Grove & Livesey Hill within Shenley Lodge 5, Milton Keynes.

Figure 3.1.2 Distribution of 15 Roof-Space Collectors
Installed on 21 Dwellings at Shenley Lodge 5





FIRST FLOOR PLAN



Entrance as shown units 6, 18, 19
Entrance handed units 1, 2, 3, 9, 22, 23

GROUND FLOOR PLAN

Figure 3.1.3 Plans of type 5A dwellings

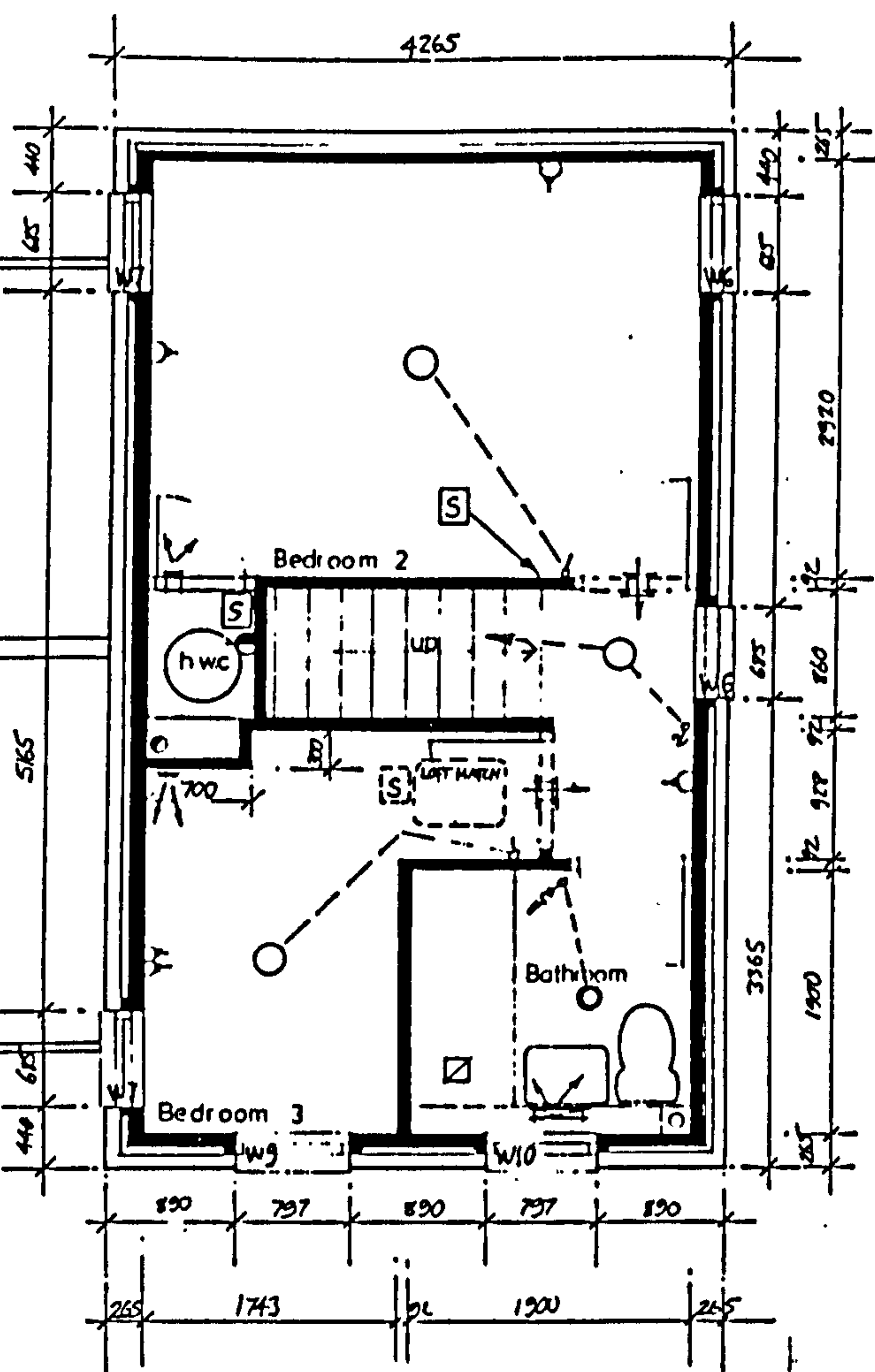
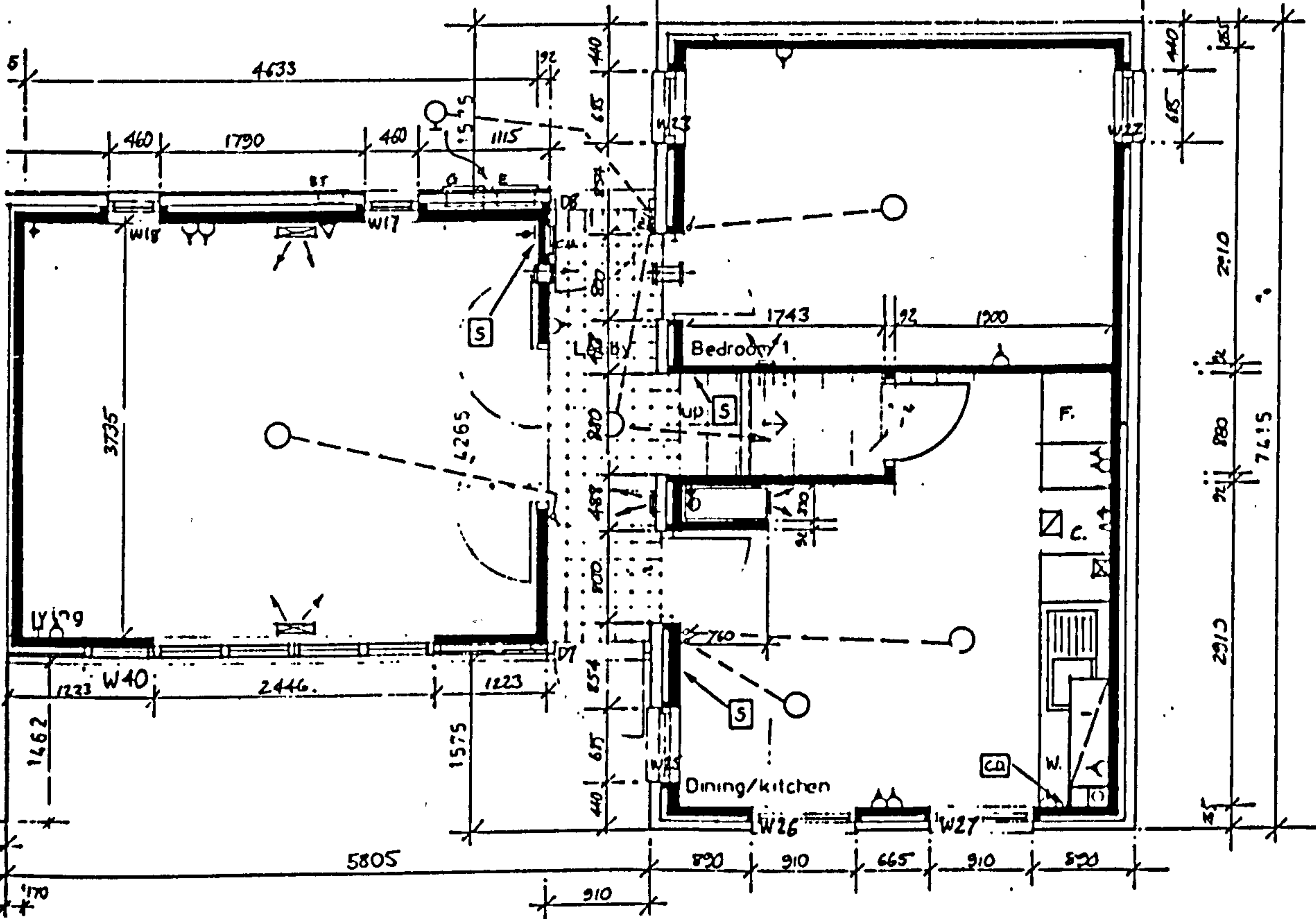
Figure 3.1.4 Plans of
type 5B dwellings

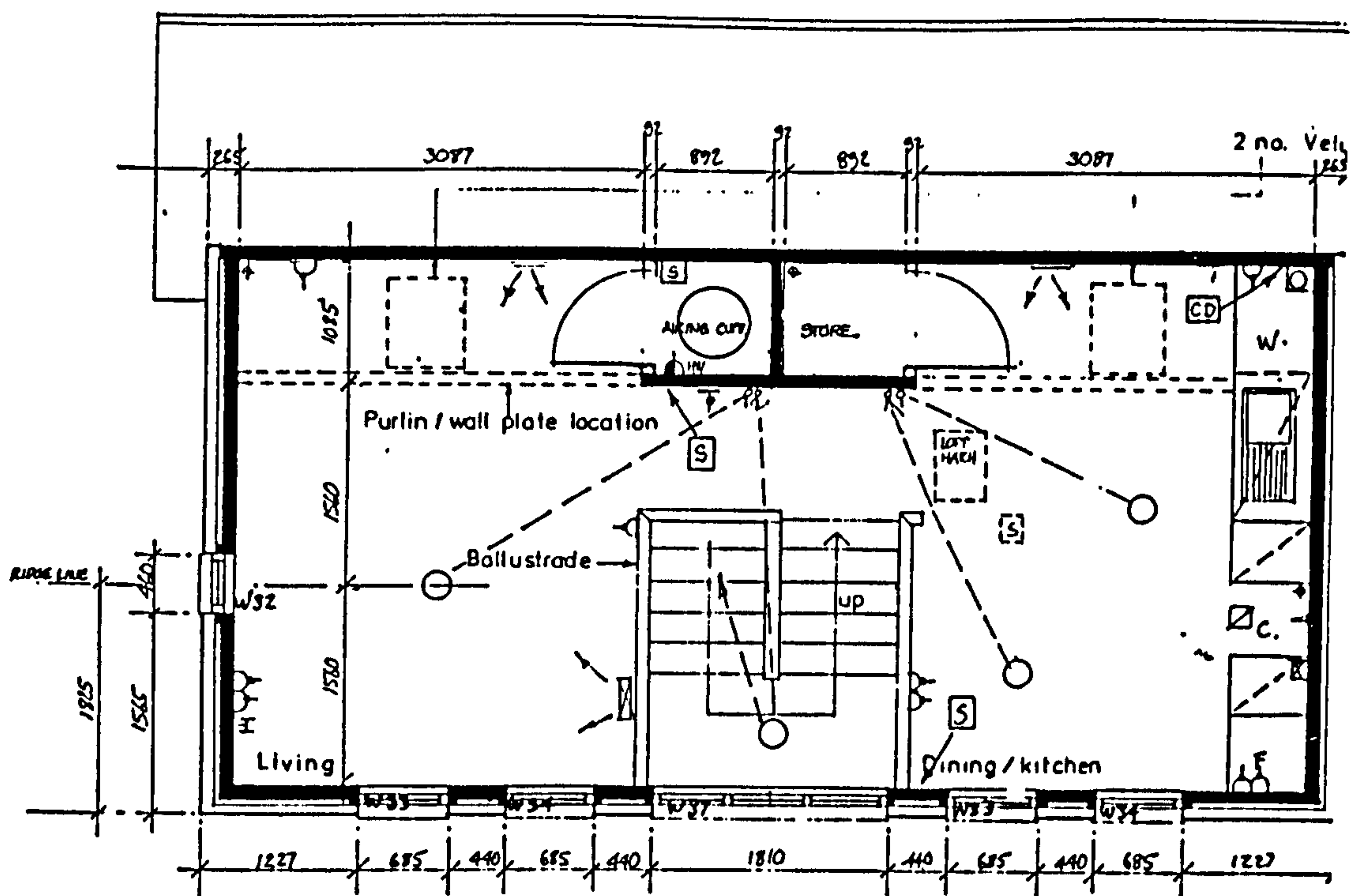
ix windows

VENTING RIDGE TILES : SOLAR ROOF ONLY.

SOLAR COLLECTOR : PLOTS 25 . 29 & 33

HOUSE TYPE 5B





HOUSE TYPE 5C

Figure 3.1.5 Plans of
type 5C dwellings

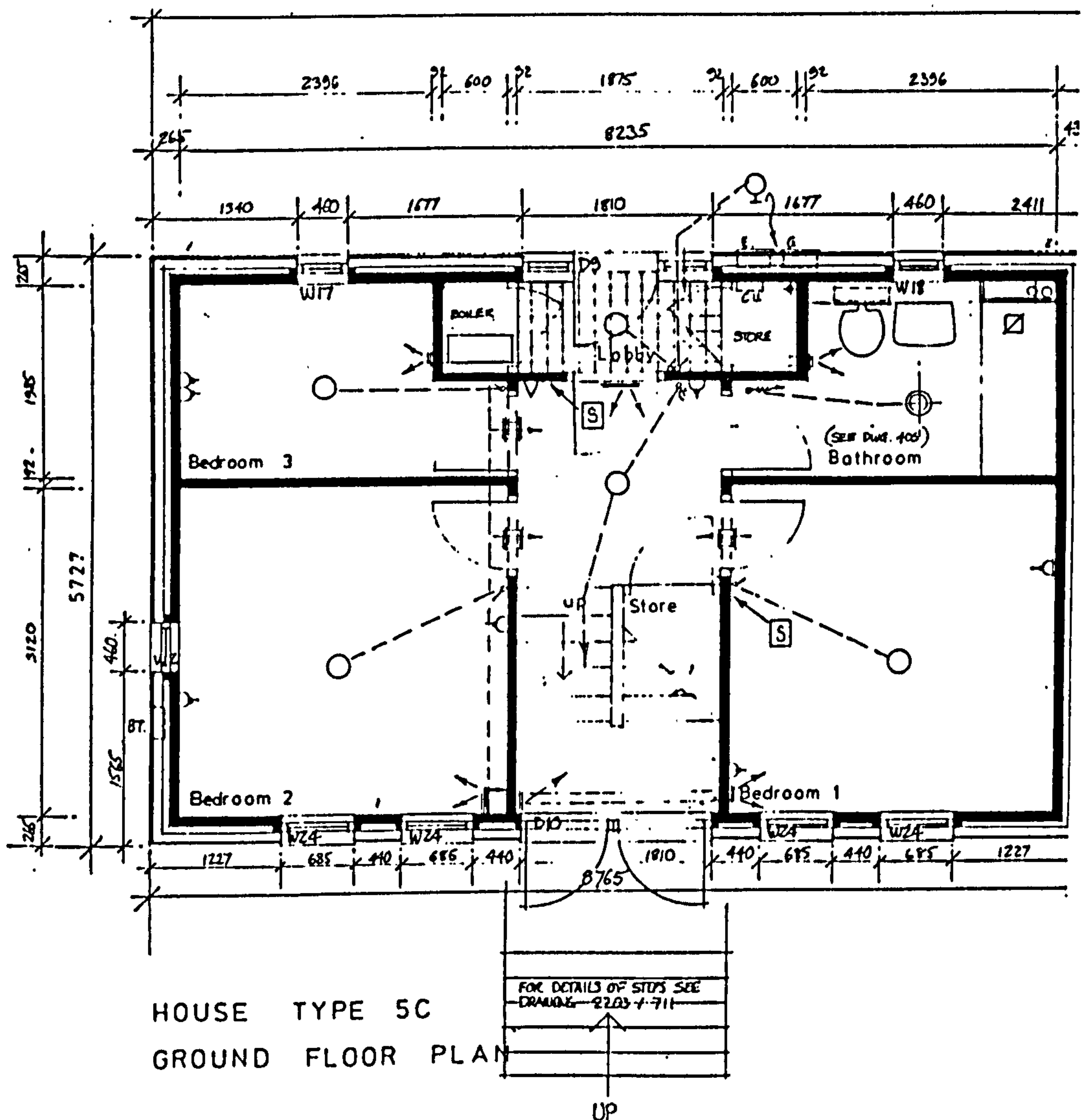


Figure 3.1.6.

Three type 5A dwellings
Livesey Hill, Shenley Lodge 5, M.K.



Figure 3.1.7.

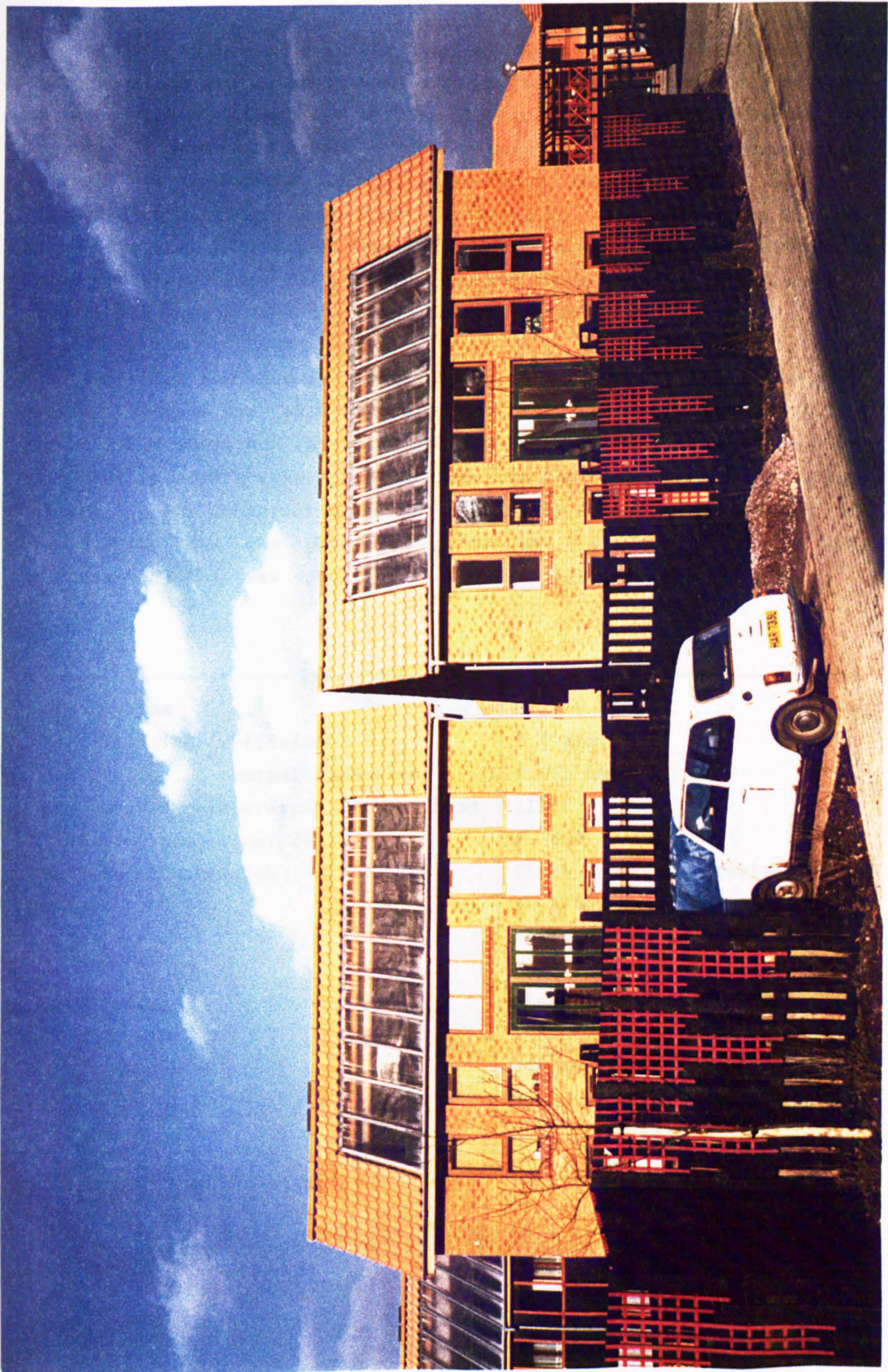
Type 5B & type 5C dwellings
Cockerell Grove, Shenley Lodge 5, M.K.



Figure 3.1.8.

Two type 5C dwellings

Cockerell Grove, Shenley Lodge 5, M.K.



collectors, (Fig. 3.1.8). This latter house type differed from the 5A's and the 5B's by having all the "living" spaces on the first floor. The three bedrooms and bathroom were situated on the ground floor and the entrance lobby was mid-way between the two floor levels as shown in Fig. 3.1.7. These are known as "upside-down" houses. They were designed to keep all household odours, generated by the first floor open-plan kitchen/diner/ lounge, away from the sleeping areas. The ground floor areas were also cooler and remained a more comfortable environment in which to sleep, especially during the hot summer months. Unfortunately privacy may have become a problem for the ground floor bedrooms.

All twenty-one houses were heated by proprietary gas-fired "warm air" heating systems each with an additional heat recovery unit (3.1.1). Figure 3.1.9 shows how this standard commercial warm-air heating system with heat recovery was incorporated into the roof-space solar-energy collectors. The construction of the roof-space collector is detailed in Fig 3.1.10, and the physical properties of the twin walled polycarbonate that was specified is shown in Table 3.1.2, (3.1.2).

Area weight	c. 2.0 kg/m ²
Heat Transfer Coefficient	3.1 W/m ² K
Coefficient of thermal expansion	0.065 mm/m°C
Max. service temperature without load	115°C
Transmittance (Clear 281)	c. 80%
Ball impact strength	Class A safety material to BS 6206. Ball impact-resistant as per DIN 18032, Part 3 (incl. hockey balls)
Fire rating	Class 1 to BS 476, Part 7: 1971, Section 2. Class 0 surface according to the Building Regulations 1976 E 15 (i) e (ii).

Table 3.1.2. Physical properties of 10mm twin-walled polycarbonate

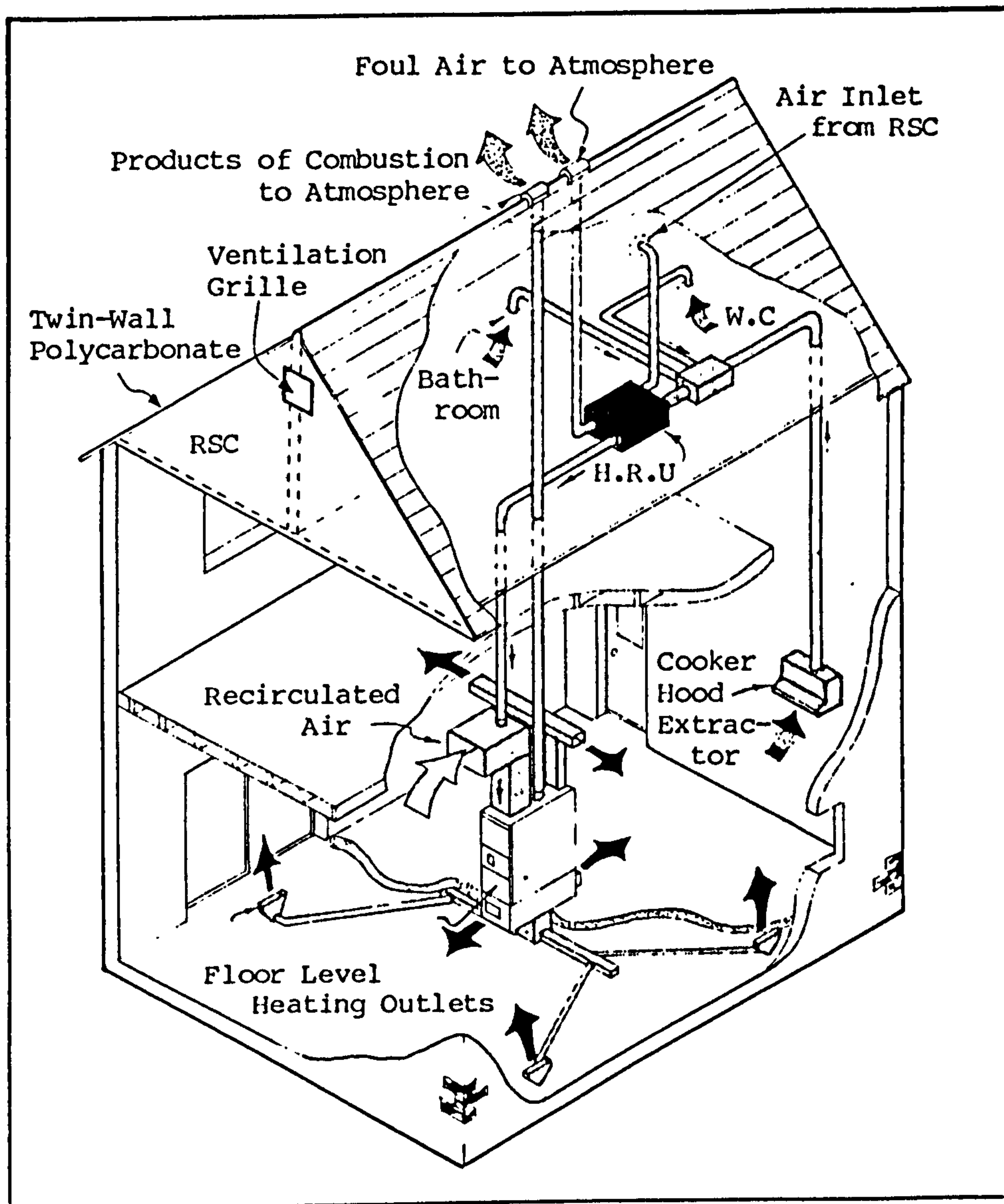


Figure 3.1.9 Configuration of warm-air heating system and heat recovery unit (HRU)

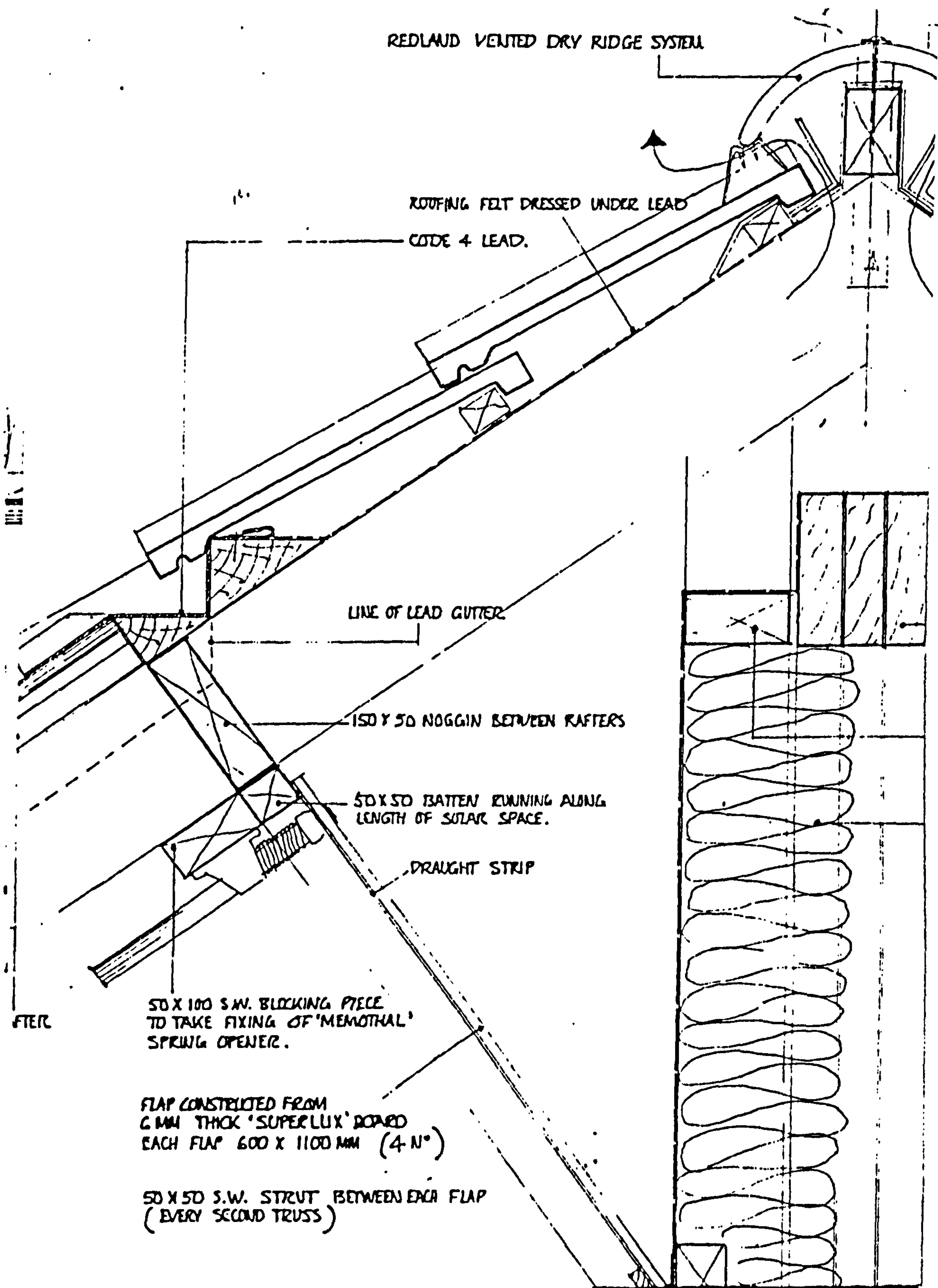


Figure 3.1.10 Detail of Roof-Space Collector construction

ii) Aesthetic Considerations

The external appearance of "direct-gain" passive solar houses is distinguished generally by;

- a) extensively-glazed south facades,
- b) windowless north facades,
- c) site planning which avoids overshadowing of the southerly aspects,
- d) orientation towards the south.

These elements can lead to monotony and a feeling of "facelessness" to the visitor and a lack of individual identity and privacy for the occupants. The design the Cockerell Grove development, (an aerial photograph is shown in figure 3.1.11), sought to address these challenges as follows;

- a) The fifteen "RSC houses" and six reference houses consisted of one of three different detached and semi-detached house types. This diversity allowed greater scope for adventurous site planning. This would not have been possible readily with, for example, a terrace of identical passive solar dwellings.
- b) The living spaces on the semi-detached type 5C houses (which had the entrance on the north side) were on the first floor, above. In addition the garden area immediately beyond the south facade, (where the bedrooms were located), was enclosed by timber fencing and a masonry wall. This is illustrated in figure 3.1.12.
- c) The north-side of the type 5C houses was only single-storey in order not to overlook the adjacent dwellings, as shown in figure 3.1.13. The proximity of their adjacent car port also reinforced the location of the entrance to the dwelling which was on the north side.
- d) The detached type 5A houses which face the main road have entrances *through* the south-facing passive solar facade as shown in figure 3.1.14.

Figure 3.1.11.

Aerial view of Cockerell Grove development

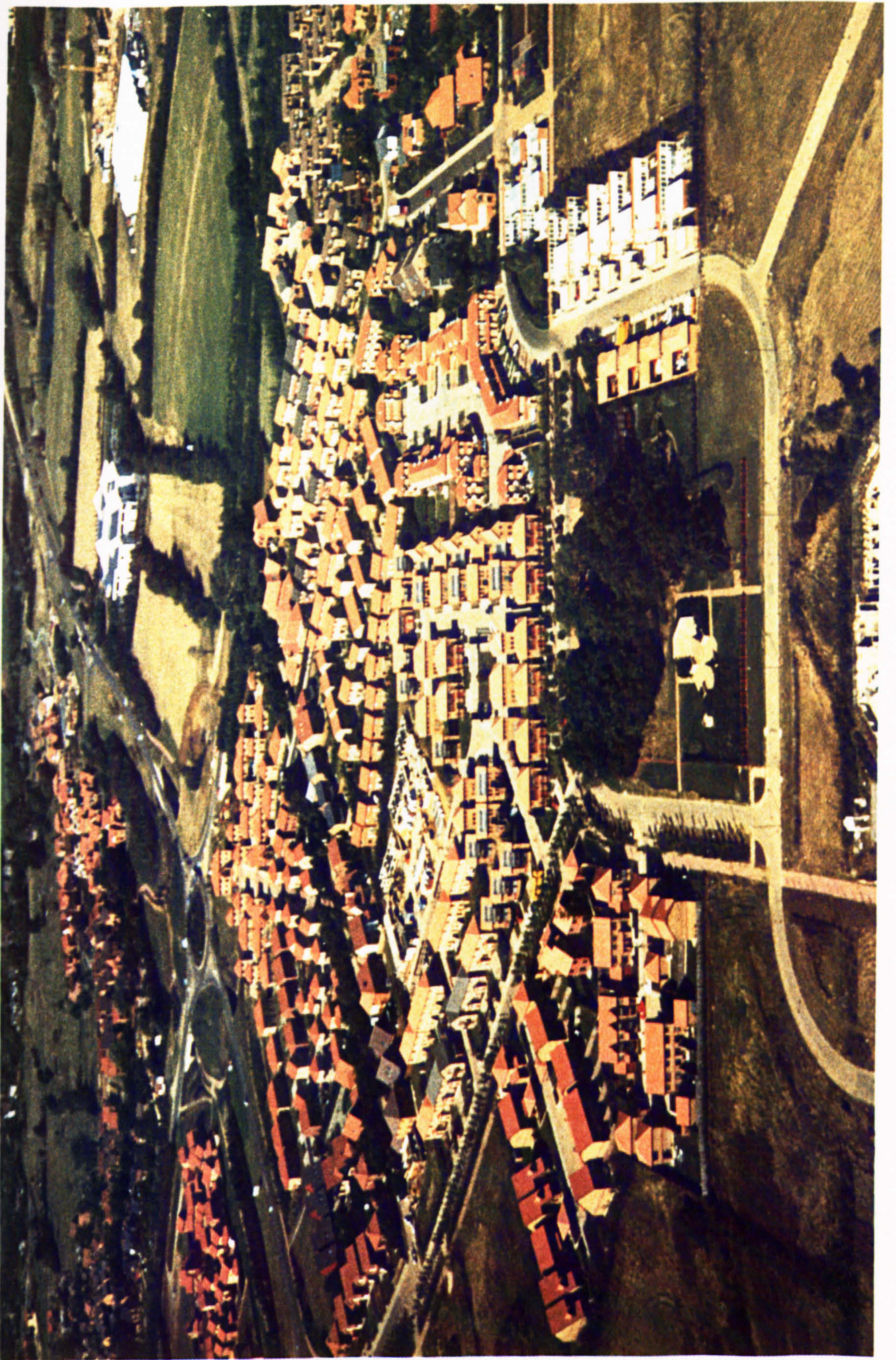


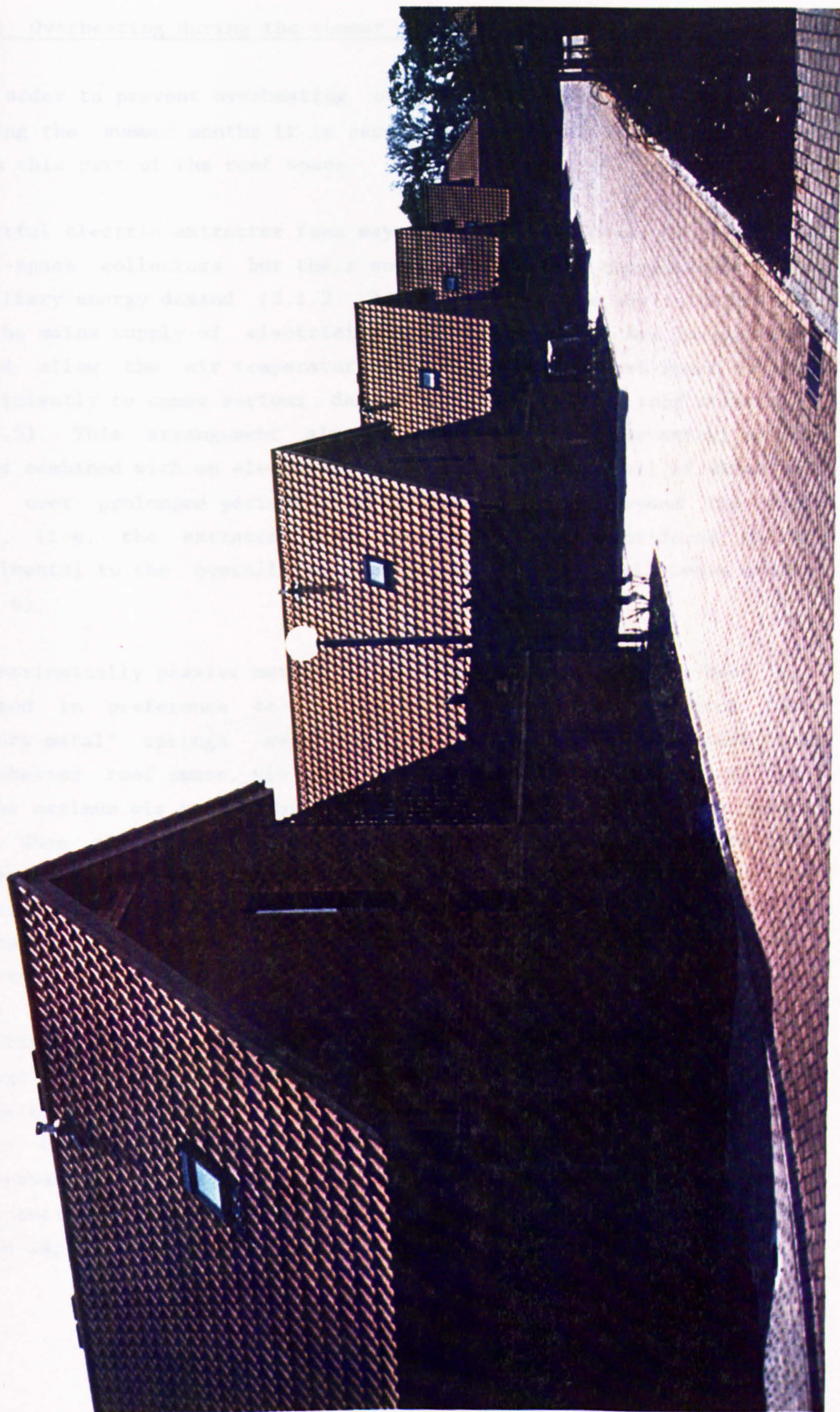
Figure 3.1.12.

Enclosed gardens of type 5C houses
at Cockerell Grove



Figure 3.1.13.

North facade of type 5C houses
at Cockerell Grove



iii) Overheating during the summer months

In order to prevent overheating of the roof-space solar collector during the summer months it is necessary to exhaust the excess hot air from this part of the roof space.

Powerful electric extractor fans may have been employed to ventilate roof-space collectors but their energy consumption contributes to the auxiliary energy demand (3.1.3, 3.1.4). Furthermore any interruptions to the mains supply of electricity while the fans are in operation would allow the air temperature within the heated roof-space to rise sufficiently to cause serious damage to the timber roof structure, (3.1.5). This arrangement also incorporates many mechanical moving parts combined with an electronic control mechanism, all of which may fail over prolonged periods of use. Protruberances beyond the roof line, (i.e. the extractor fan cowlings), were considered to be detrimental to the overall appearance of the Cockerell Grove estate (3.1.6).

An intrinsically passive method of extracting this excess heat was adopted in preference to an electrically powered extractor fan. "Memory-metal" springs were used to automatically ventilate the over-heated roof space, via ridge & gable ventilation grilles, as soon as the maximum air temperature within the roof-space collector exceeded 60°C. When the alloy spring was cold (i.e. below its start-to-open temperature) and the spring was fully contracted, the micro structure was martensitic and the material was rather soft. As the temperature is increased, the material gradually transformed into an austenitic structure which was more rigid and caused extensive elongation. The phase transition also created a relative movement of the atoms resulting in spring expansion (3.1.7). The physical properties of these springs is shown in Table 3.1.3 and Figure 3.1.15. Figure 3.1.16 illustrates how the spring activated the ventilator damper to allow the air to exhaust via the gable end grilles. As an additional precaution to prevent excess temperatures, the floors within the roof-space collectors were painted gloss-white, which sacrificed performance, but should improve overall reliability.

Figure 3.1.14.

South facade of type 5A houses
at Cockerell Grove



Material:	Brass (Cu, Zn, Al)
Possible shear elongation achieved through thermal memory:	2.5%
Normal tolerance of start-to-open temperature T_z :	+7°C
Motion hysteresis:	Max. 20°C for unloaded spring Min. 2°C for heavily loaded spring
Electrical resistivity:	$8-18 \times 10^{-8}$ Ohm metres
Density:	7.9 g/cm ³
Corrosion:	There is a risk that water will cause dezincification and that contact with nitric gases will result in stress corrosion. This presents the need for protective surfaces in some situations.
Life expectancy:	Dependent upon application, but normally 10^4 thermal cycles can be obtained without difficulty.
Max. spring force:	$F_{max} = 80 \times (d^3/D) \quad (N)$
Max. useable spring force:	$0.5 \times F_{max}$
Max. expansion:	$(D^2 \times n)/12d$ (unloaded spring) n = Number of active spring turns d = Wire diameter D = Coil Diameter

Table 3.1.3 Material characteristics of memory-metal spring

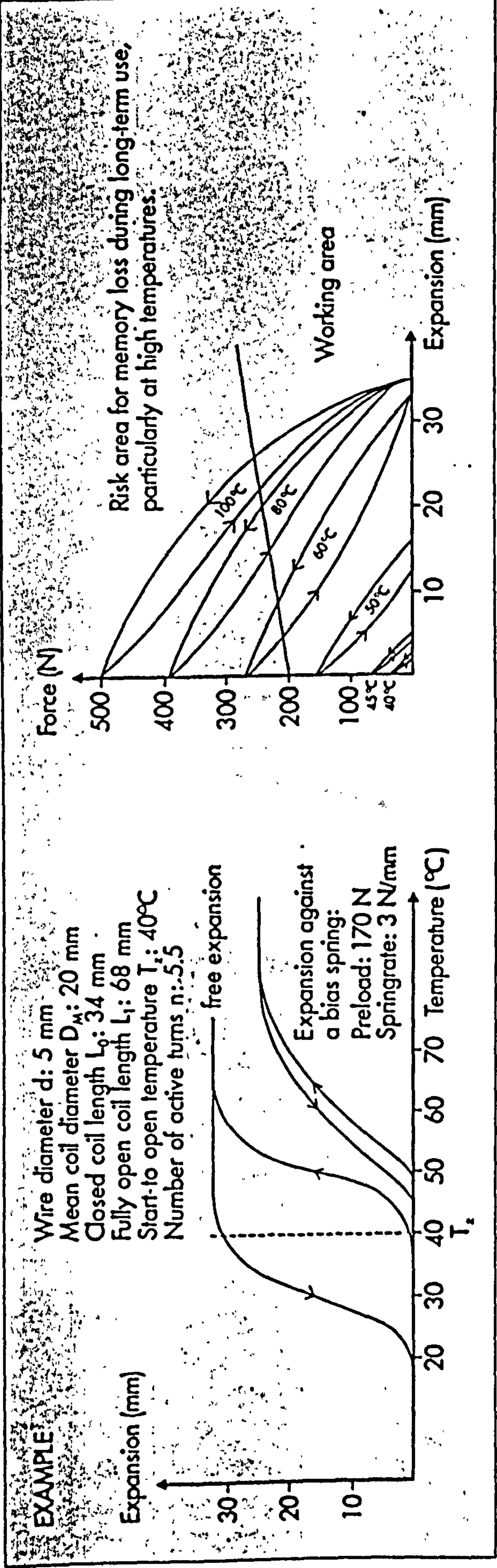


Figure 3.1.15 Mechanical properties of memory-metal springs

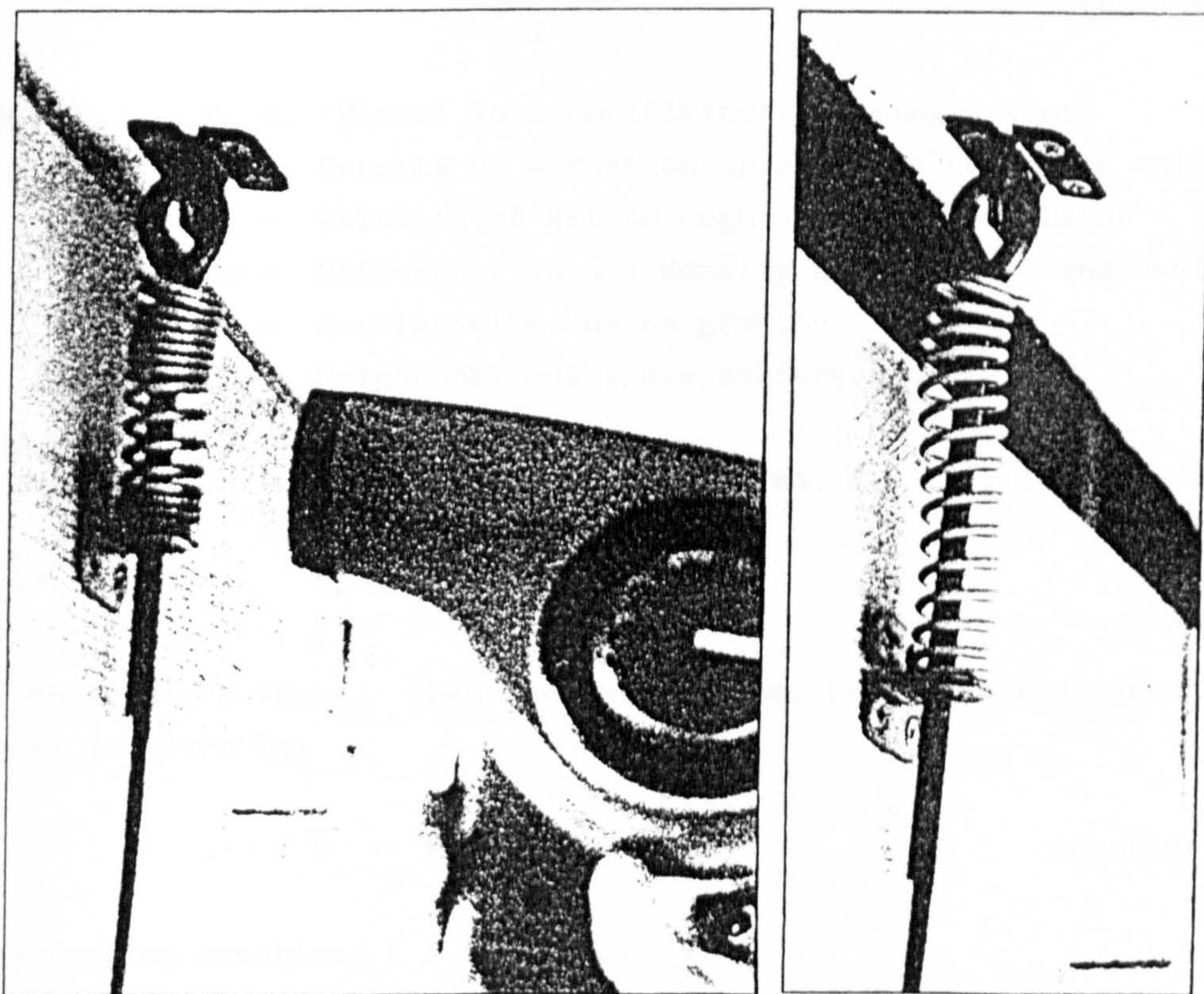


Figure 3.1.16 Behaviour of memory-metal springs
when heated

iv) Calculation of the number of eaves ventilators required to prevent overheating within a Roof-Space Collector

If it is assumed that there is an equal pressure drop across each ventilator, then they will each experience a pressure differential equivalent to the buoyant head established by the heated air within the RSC. Thus from an individual vent, a simple steady-state momentum balance gives;

$$\text{Buoyant Head} = \text{Frictional Loss}$$

$$\Delta\rho gh = \frac{K\rho_o(v_1)^2}{2} \quad \text{equation 3.1.1}$$

Where: K = 'Minor' loss coefficient for single vent.
 ρ_o = Density of air at an appropriate reference value
 v_1 = Velocity of air through an eaves ventilator
 $\Delta\rho$ = Difference in air density between loft and ambient
 g = Acceleration due to gravity
 h = Height of roof-space collector space

Volume flow rate, V_1 , through a vent of area, A_1 , is given by;

$$V_1 = A_1 v_1$$

If there are N vents, then the total volume flow rate through the roof space is given by;

$$V = NA_1 v_1 \quad \text{equation 3.1.2}$$

Rearranging equations 1 & 2 gives;

$$\Delta\rho gh = \frac{K\rho_o V^2}{2(NA_1)^2} \quad \text{equation 3.1.3}$$

The required total volume flow rate through the loft is obtained from an energy balance on the air in this space. Assuming that the energy loss from the roof-space is predominantly by venting rather than via the fabric of the roof structure or due to re-radiation to the sky, then;

$$\tau\alpha I_{max}A = \rho_o V C_o \Delta T_{min} \quad \text{equation 3.1.4}$$

Where:-

τ = Transmittance of the glazing material.

α = Mean Absorptance of the surfaces within the RSC.

$I_{\max}A$ = Rate of input of solar energy through glazing area, A, for highest expected insolation, $I_{\max}$.

C_o = Specific heat capacity of air at a reference value.

$\Delta T_{\min}$ = Temperature difference between 'fully-open' vent temperature and highest expected ambient temperature.

So the volume flow rate from equation 4 is;

$$V = \frac{\tau \alpha I_{\max} A}{\rho_o C_o \Delta T_{\min}} \quad \text{equation 3.1.5}$$

Substituting 5 into 3 gives, from the momentum balance;

$$\Delta \rho g h = \frac{K \rho_o}{2(N A_1)^2} \left(\frac{\tau \alpha I_{\max} A}{\rho_o C_o \Delta T_{\min}} \right)^2 \quad \text{equation 3.1.6}$$

Rearranging 6 to obtain the number of vents required to ventilate the roof-space collector gives;

$$N = \frac{\tau \alpha I_{\max} A}{C_o \Delta T_{\min} A_1} \sqrt{\frac{K}{2 \rho_o \Delta \rho g h}} \quad \text{equation 3.1.7}$$

The difference in density, between the interior and exterior given a temperature difference of $T_{\min}$ can be approximated by;

$$\Delta \rho = \rho_o \beta_o \Delta T_{\min} \quad \text{equation 3.1.8}$$

where; β_o = Coefficient of volumetric expansion for air at some reference temperature (T_o). For an ideal gas, $\beta_o = 1/T_o$.

Substituting 8 into 7 and rearranging,

$$N = \frac{\tau \alpha I_{\max} A}{C_o \rho_o A_1} \sqrt{\frac{K}{2 \beta_o g h \Delta T_{\min}^3}} \quad \text{equation 3.1.9}$$

N.B. A suitable value of T_o at which fluid properties are evaluated would be;

$$T_o = \frac{T_{\text{setting}} + T_{\max, \text{ambient}}}{2}$$

The values for the parameters that relate to the materials used in this demonstration project which are required to solve equation 9 are outlined below:

- $\tau = 0.8$ This value would apply only to a clean sample of the 10mm thick twin-walled, u-v stabilized polycarbonate (3.1.2) that was used for this RSC. In practice this value will be reduced by as much as 5% - 10% as a result of either dust deposits, staining from the lead flashing used to waterproof the RSC, mild condensation within the two layers of polycarbonate, or through degradation over time. Thus, a transmittance of 0.8 represents a worst case for this particular scenario.
- $\alpha = 0.6$ The absorptance of the surfaces within the RSC may be taken as the mean absorptance of the timber partition and the white gloss painted loft RSC floor (3.1.8).
- $I_{\max} = 900\text{W/m}^2$ It was estimated that the maximum global radiation in the plane of the RSC that can be reasonably expected in the UK is 900 W/m².
- $A = 14.43\text{m}^2$ This area corresponds to that of the largest RSC on the site at Cockerell Grove excluding the area of the glazing bars.
- $C_o=1006.3\text{J/kgK}$ The maximum temperature reached in the RSC to date was 75°C (348 K) and the maximum corresponding external ambient temperature was 28°C (301 K). The specific heat capacity was derived from the arithmetic mean of these two temperatures i.e. 52°C (325 K).
- $\rho_o=1.086\text{kg/m}^3$ The specific density was calculated in the same manner as the specific heat capacity.
- $A_1=0.012\text{m}^2$ Ventilation of all the loft spaces was provided by a continuous 25mm wide slotted ventilator which was installed along the complete length of the eaves with an effective area of 0.06m².

$K = 0.85$ (3.1.9) As air is drawn through the ventilator by the buoyancy forces within the RSC there will be a corresponding drop in pressure which can be quantified as a loss coefficient K .

$h = 2.5\text{m}$ This value represented the height through which the air must rise before it reached the ridge/gable ventilators

$\Delta T_{\text{min}} = 47\text{K}$ Temperature difference between the maximum temperature within the RSC with all ventilators fully open (75°C), and the maximum external ambient temperature (28°C) on 20th June 1989.

When all of these values were substituted into equation 3.1.9, 3.5 ventilators are required. The actual number of installed ventilators was five, so the assumptions made in the analysis may be viewed as within the correct order of magnitude. (In this particular RSC the ventilator slot was 5m in length.) If this is repeated for a maximum desired temperature of 60°C the required number of ventilators increases to 7.4 (i.e. 111% greater than that required at 75°C). Thus, additional soffit/eaves ventilators with a total area of at least 0.067m^2 should have been sufficient to restrict the maximum temperature in the RSC to this level.

iv) Delays to the Original Schedule

There were circumstances which, although not entirely unexpected, delayed the completion of the dwellings beyond the scheduled stages of construction. In the majority of cases these minor oversights resulted from inappropriate on-site supervision due to the lack of communication between the builders and the on-site contractors. For example, the roofing contractor merely completed each stage of the glazing construction as and when instructed by the main contractor. Due to the roofing contractors' inexperience with such an unconventional roofing arrangement three days were required to complete the first fully glazed roof. Once he had fabricated ten such roofs consecutively the average construction time was reduced to a single working day. The employment of a roofing contractor who had a certain degree of experience in such methods of construction would have reduced the risk of such problems occurring, but the innovative nature of the design prevented this.

When prospective buyers were viewing the completed properties the majority of them were not fully-informed of the innovative nature of the house design and the way in which it differed from a conventional dwelling. Further confusion arose when ownership of the houses was transferred to the current owners; very little documentation regarding the operation of the warm air heating system was left with the new owners. Any information which was given did not pertain to the particular heating systems that were installed!

The contractors rarely appreciated the significance of the original RSC design and the function of all its constituents. The following problems occurred as a result of such misunderstandings:

- a) During the construction of a conventional loft space the required carpentry that is undertaken generally leaves the space very untidy and dusty. Though this is of little significance in a conventional roof, in a roof-space-collector such dust would be drawn automatically into the warm-air-heating system, and distributed throughout the dwelling! Attempts were made to keep the glazed portion of each RSC as dust-free as possible but the desired level of cleanliness was rarely achieved and each RSC had to be vacuum cleaned after the dwellings had been occupied.

- b) To achieve the air change rate in a conventional loft space that is required by the Building Regulations, a ventilation grille must normally be installed in the underside of the overhanging eaves of the roof. Any minor obstructions to the air flow path would not significantly impair their performance in a conventional loft-space. However, it was essential that this grille be kept as free from obstructions as possible to allow the RSC to expell any excess hot air which would prevent overheating of the roof-space. Unfortunately when the roof-space was lined with building paper, (to reduce the levels of dust), the paper was often completely obstructing the eaves ventilators, as shown in figure 3.1.17. In addition, the total area of the eaves ventilators was below the calculated requirement necessary for adequate control of overheating and the roof-space reached a maximum of 76°C on a particularly sunny day in June!
- c) As part of the contractual obligations between the electricians and the main contractor, the monitoring cables were to be left in the loft to allow simple and quick termination with temperature sensors. In many instances they were left underneath the rockwool loft insulation which required a lengthy search to locate each hidden cable.

It was essential for all of the building contractors to have a full understanding of the mechanics of the RSC and its interaction with the warm-air heating system and the occupants, to enable the contractors to exercise the appropriate attention to detail during all the stages of construction.

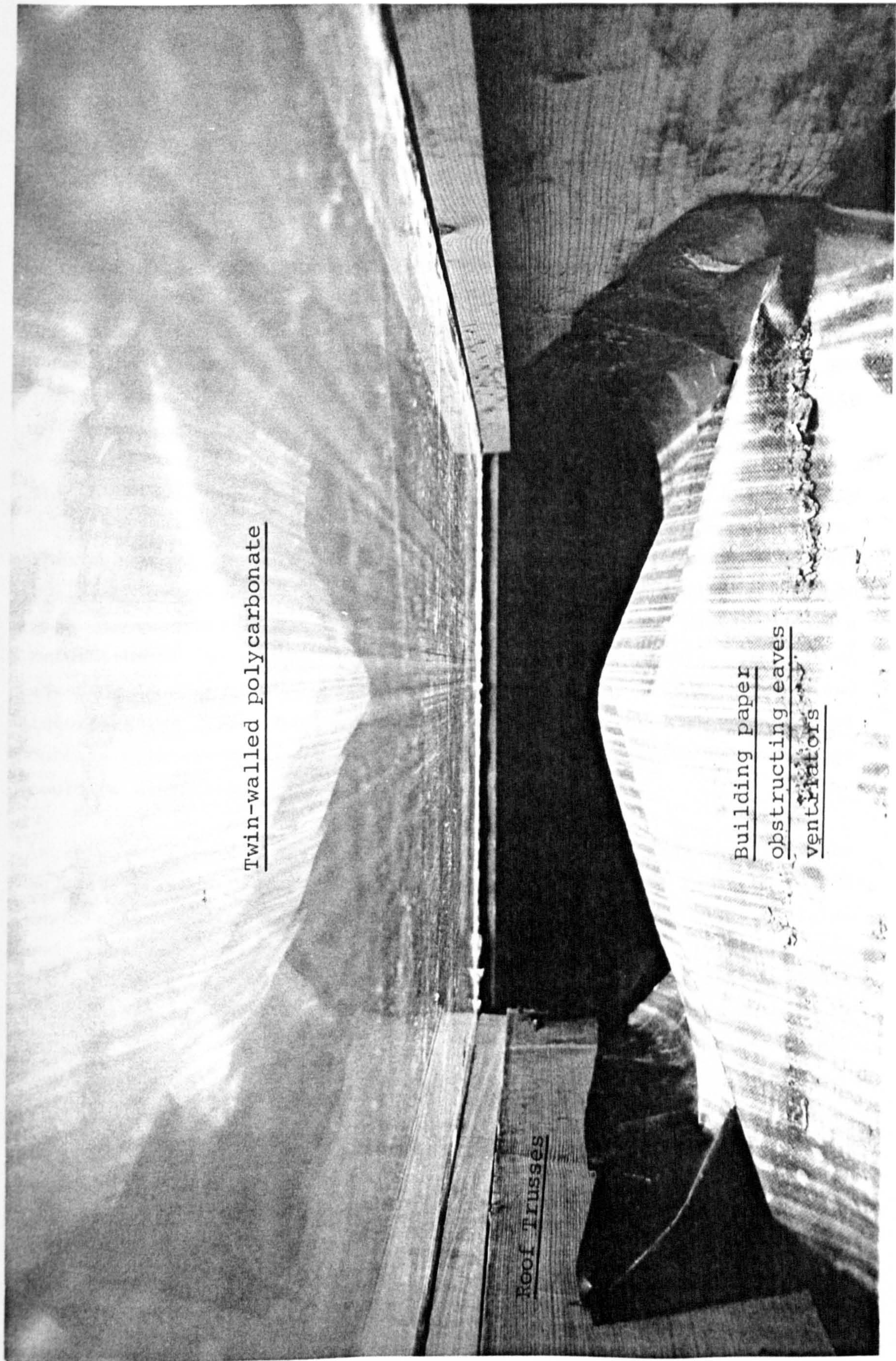


Figure 3.1.17 Interior detail of obstructed eaves ventilators

3.2 Installation of Thermosyphoning Air Panels

1) Description of project site

Nazeing County Primary School is owned by Essex County Council. The school has 181 pupils, aged between 5 and 12 years old, who are taught by 11 teachers. The building occupies 1631 m² and is heated via an automatically-controlled gas-fired central heating system. Nine of the ten classrooms are heated by fan convector heaters, fuelled by a gas-fired water-circulating "central" heating system, with the remaining classroom being heated by two electric convector heaters. The periods of occupation are from 8-00 am until 3-30 pm Monday-Friday with occasional use during the evenings and weekends.

The school was built in 1958 and represented a typical Essex County Council "post-war" lightweight timber-framed curtain-walled structure. This rendered it both simple, economic and quick to build, but such buildings deteriorated rapidly. Thus Essex County Council, in common with many other local authorities in the United Kingdom, had a refurbishment programme for all such similar schools. By taking advantage of the opportunity presented by refurbishment and incorporating the thermosyphoning air panels into a conventional curtain-wall cladding system the over-cost of the passive solar feature could be minimised.

As shown in figure 3.2.1 this school was oriented East-West with the majority of classrooms having south-facing glazing. The East, South and West facades of the building overlooked playgrounds and playing fields and remained free from any obstructions which may have impinged upon the collection of solar energy. The project location lies at a latitude of 51° 44'N and a longitude of 0° 01'E. The village of Lower Nazeing is situated 26km due north of Central London, is 30m above mean sea level, and is subject to a Northern Maritime Climate.

ii) Installation of Thermosyphoning Air Panels

A total of 36 TAP's, with an area of 101 m² were installed in the classrooms and offices within the school. The effect of this refurbishment is shown in figure 3.2.2. There were 14 panels on each of the east and south facades with the remaining 8 panels on the west facade.

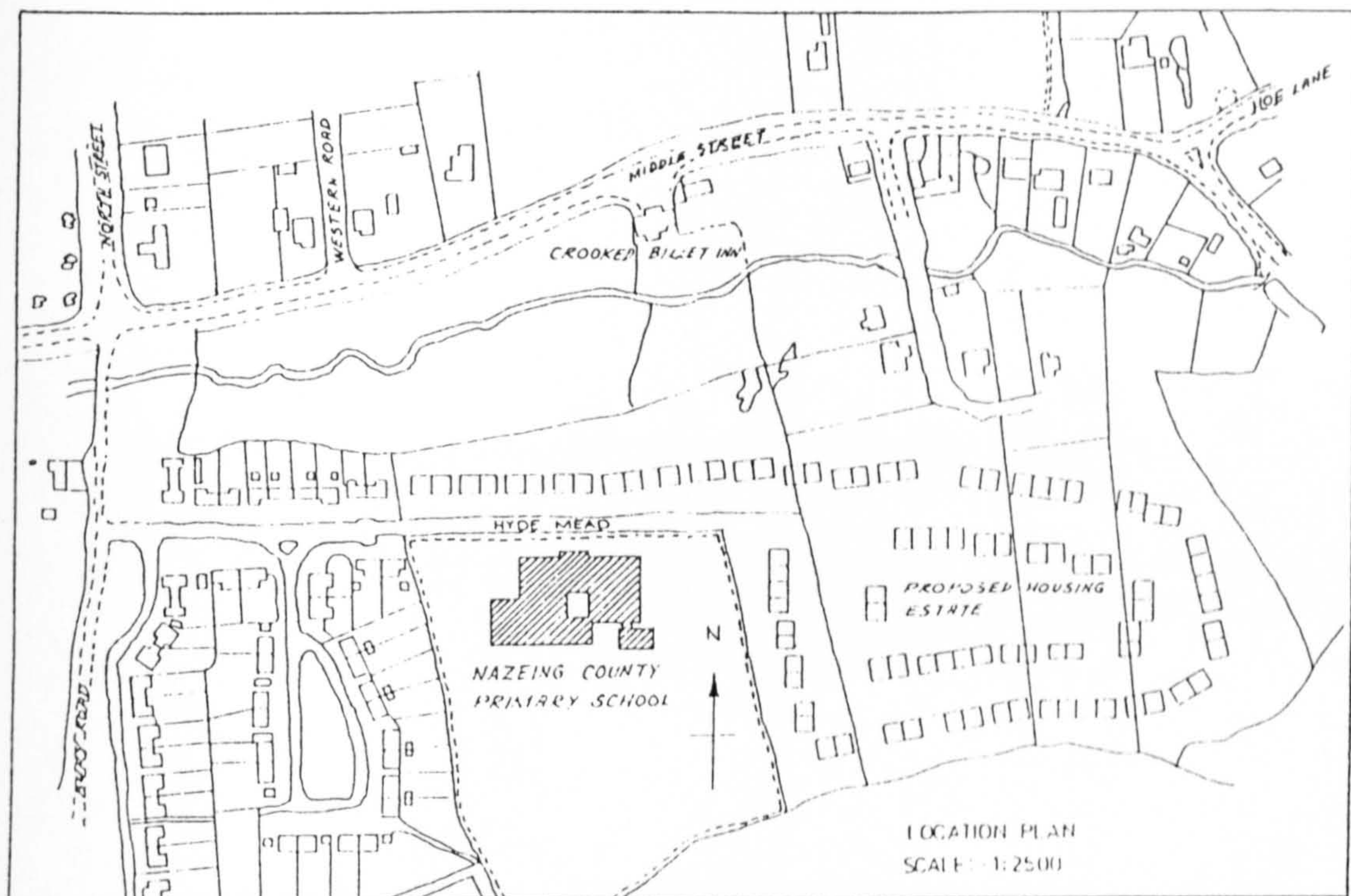


Figure 3.2.1 Orientation and location of Nazeing C.P. school



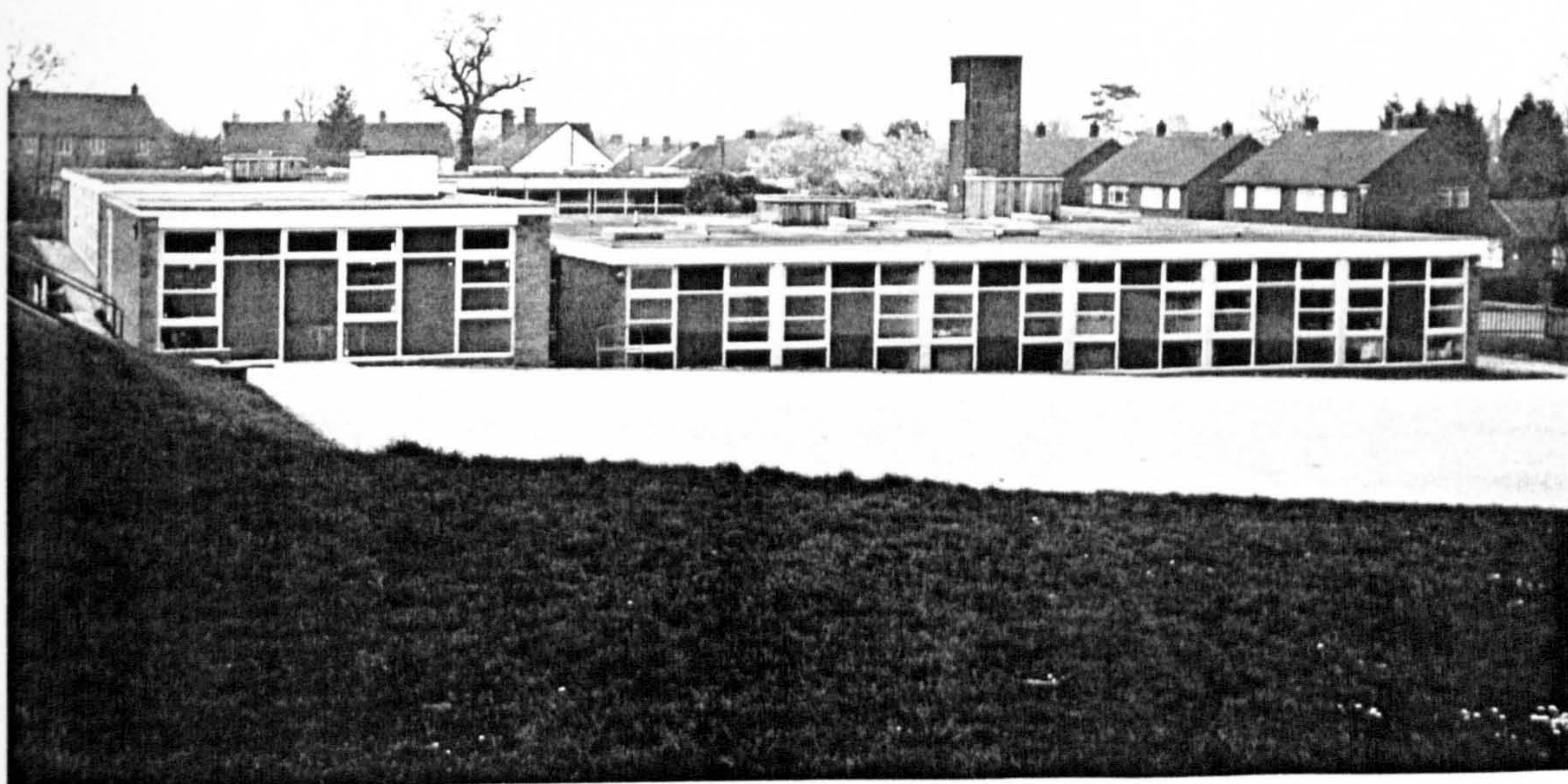
Figure 3.2.2

The East facade of Nazeing County Primary
School before & after refurbishment

Before Refurbishment



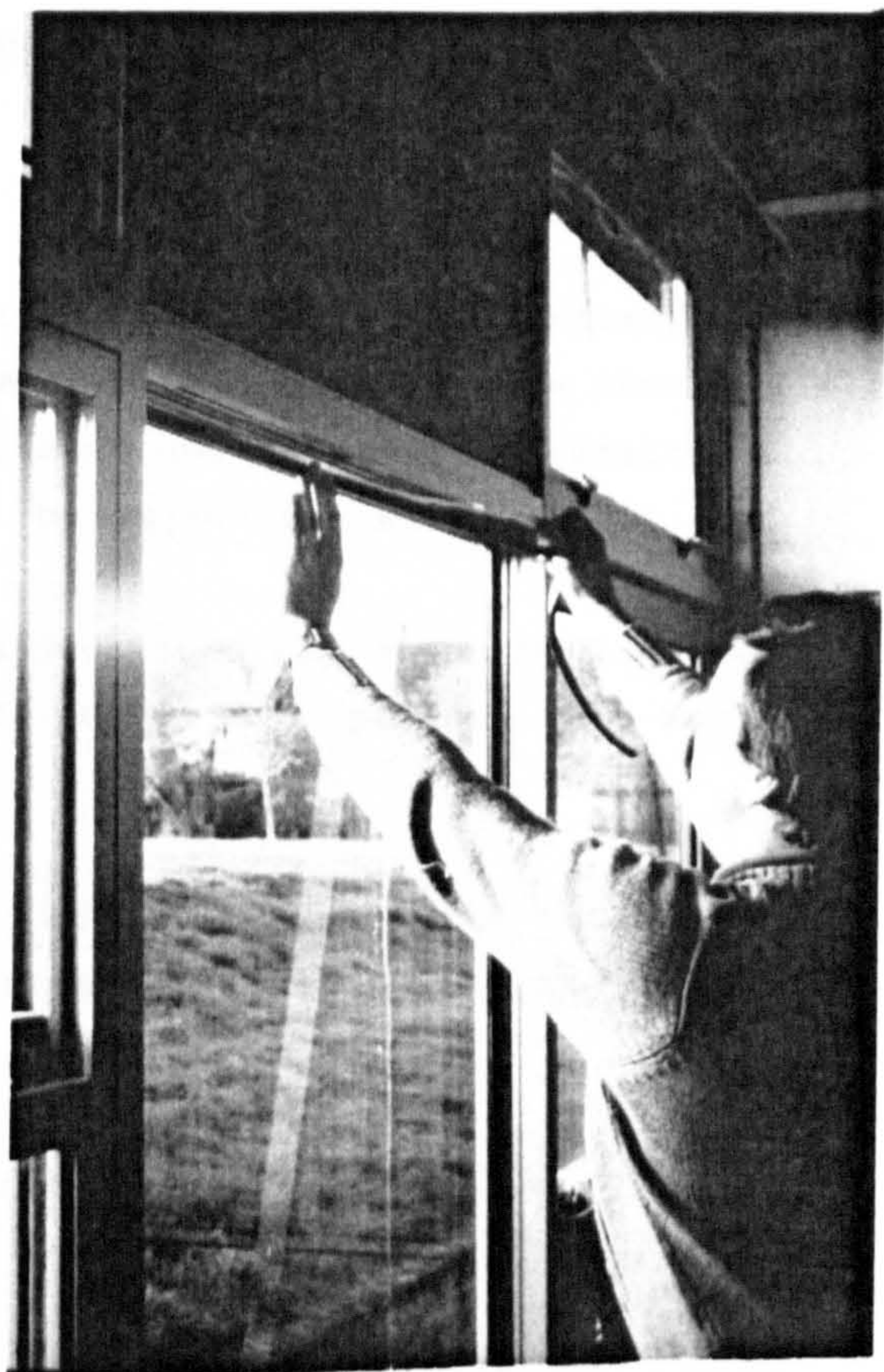
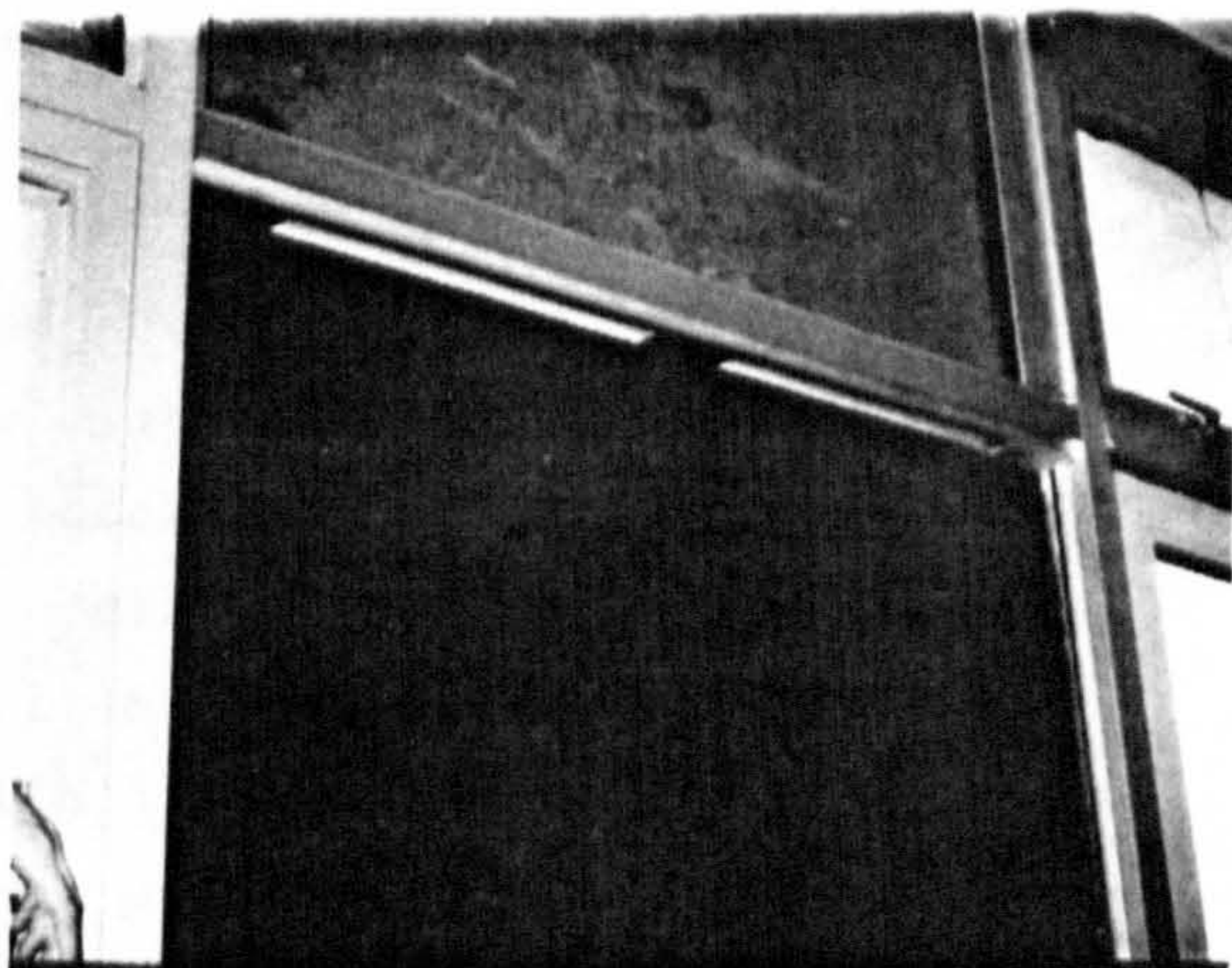
After Refurbishment



The installation sequence for the glazing and absorber plate for an individual collector panel is shown on figure 3.2.3. In the majority of cases the TAP's represented only 35% of the external glazed wall area of each classroom/office so as to minimize any increase in the lighting load over that before refurbishment.

Figure 3.2.3

Installation sequence of glazing and
absorber plate for an individual TAP



3.3 Three Thermosyphon Solar Water Heaters Installed at Wharley End

i) Introduction

Three thermosyphon solar-energy water heaters were retro-fitted to a terrace of three dwellings. Thermosyphonic systems were chosen for their inherent mechanical simplicity, ease and economy of installation, and potentially-greater reliability. The objectives were;

- To demonstrate on three inhabited dwellings the contribution that a thermosyphon solar-energy water heater can provide to satisfy domestic hot-water requirements.
- To demonstrate the effect of different hot-water consumption patterns on the long-term solar-energy contribution to the hot-water demand.
- To assess the reliability and effectiveness of three different methods of frost-protection.
- To provide a realistic data base upon which a detailed economic analysis may be undertaken, and also to determine criteria for selecting heating systems established according to locality.

ii) System description

The project was located at 7-9 East Road, Wharley End, Bedfordshire, in south-east England. Wharley End is situated 75km NNW of London, lies at a latitude and logitude of 52° 4'N, 0° 38'W, and is 111m above mean sea level. The three basically-identical thermosyphon solar-energy water heaters were retro-fitted to three adjacent occupied dwellings, (See Fig. 3.3.1). Each system comprised two single-glazed selectively-coated flat-plate copper absorbers, with a total area of four square metres. The physical construction of the collectors and their tested performance is shown in Table 3.3.1 & Figs 3.3.2 - 3.3.3. The collectors were mounted 'on tile' with 5/8" (16 mm) studs through the rafters, and linked by 25mm I/D copper pipe to a 200 litre hot water store with vent, insulated on all surfaces by a 5cm thick layer of fibrous insulant. This solar store was located at the apex of each loft space, together with a 12 litre header tank. (In house No. 8 the header tank acted as a glycol make up tank).



Figure 3.3.1 Thermosyphon Solar Water Heaters installed at three dwellings at Wharley End, Cranfield, UK.

Name of manufacturer Name of Collector: Transparent covers: Absorber Plate: Thermal insulation: Caseing material: Total weight of collector (with water): Gross dimensions of collector: Maximum temperature of operation: Maximum pressure: Acceptable heat transfer fluids:	Gull Air Ltd. Maxsun - Number: 1 - Material: Clear float glass - Effective aperture: 1.9 m ² - Material: Copper - Surface treatment: Maxorb selective foil - Manufacturing process: Fins mechanically bonded to 15mm tubes - Thickness: 100mm - Material: Glass Fibre - GRP - 63 kg - 2.015m x 1.015m x 0.11m - 100 °C - 300 psi - Water or Water/antifreeze	
	Test	Flow Rates
Test Data (3.3.1)	0.016 kg/s m2	0.003 kg/s m2
Fr()e FrUL	0.66(+0.02) -4.2(+0.5)	0.65(+0.05) -4.0(+1.0)

The performance at 0.016kg/sm2 corresponds to British Standard classification (3.3.2) Class IV, as shown in Fig. 3.3.3

Table 3.3.1 Specification of flat-plate solar collector

Figure 3.3.2 Solar simulator thermal performance test

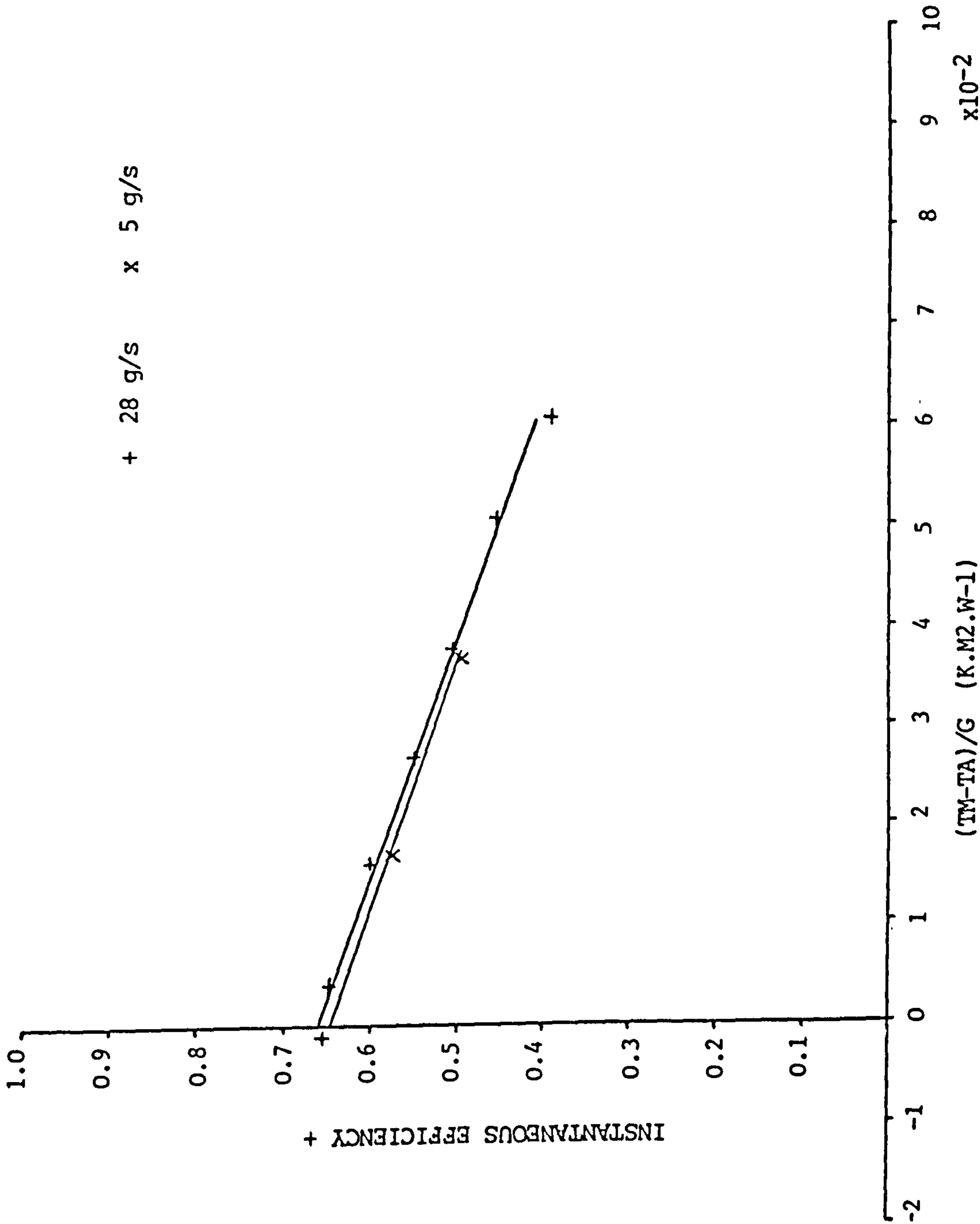
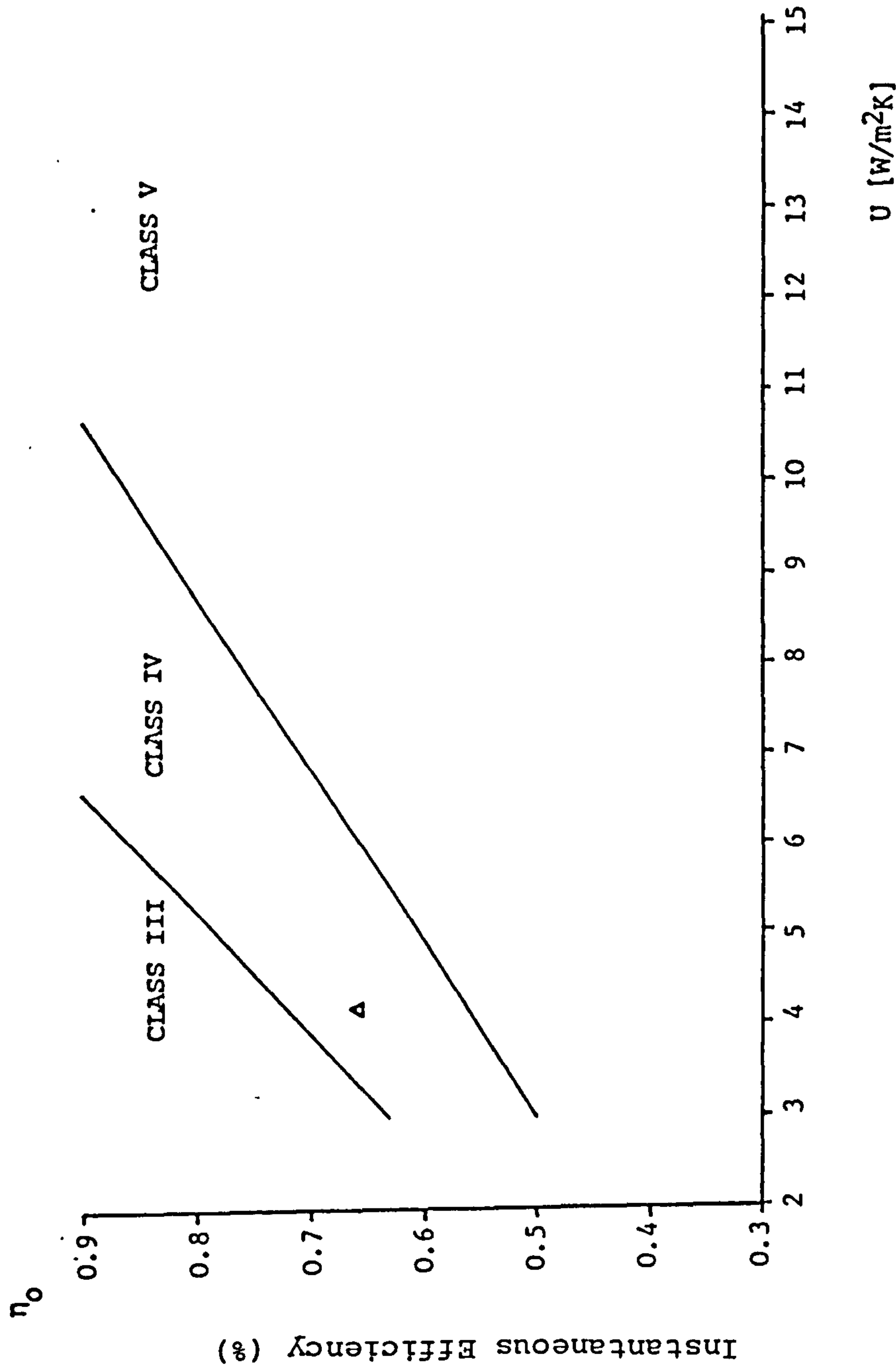


Figure 3.3.3 Class IV Gull-Air flat plate solar collector



B.S CLASSIFICATION OF COLLECTOR

All systems were manufactured from light-gauge copper. Acute pipe bends were avoided wherever possible and all pipework inclined sufficiently to prevent air-locks. A drain facility was provided at the lowest point in each of the thermosyphon flow circuits. The three systems installed combined two different modes of hot water delivery from the solar store. Houses Nos. 7 and 8 employed a third tap system whereby 'solar' water could be drawn off directly, while house No.9 used the solar heated water as a pre-heat to their existing hot water cylinder.

Each house had a completely different method of frost protection. In house No.7 an electrical heating element was wrapped around the lower header of the absorber plate, which heated the water therein when near-freezing temperatures were imminent, (Fig. 3.3.4). It was activated by an electronic 'frost-stat' sensor. House No.8 used the only indirect system (Fig. 3.3.5). An aqueous solution of with 35% propylene-glycol, whose properties (3.3.3) are shown in Table 3.3.2., flowed through a closed-circuit comprising the collector, a single-wall heat exchanger in the hot-water store, and the connecting pipes. The system in house No. 9 was of the automatic 'draindown' type, in which, when the ambient temperature approached zero, a sensor would activate valves which drained and isolated the solar collector, (Fig. 3.3.6). When the temperature rose above zero again this process was reversed and the collector was replenished with water.

Table 3.3.2 Approximate Freezing Points of
 propylene-glycol in water (3.3.3)

Concentration of propylene/ glycol	Degrees C	Gravity at 20°C
10%	-1.7	1.007
15%	-4	1.012
20%	-6	1.016
25%	-8	1.021
30%	-11	1.025
35%	-14.5	1.029
40%	-19	1.033
45%	-25	1.037

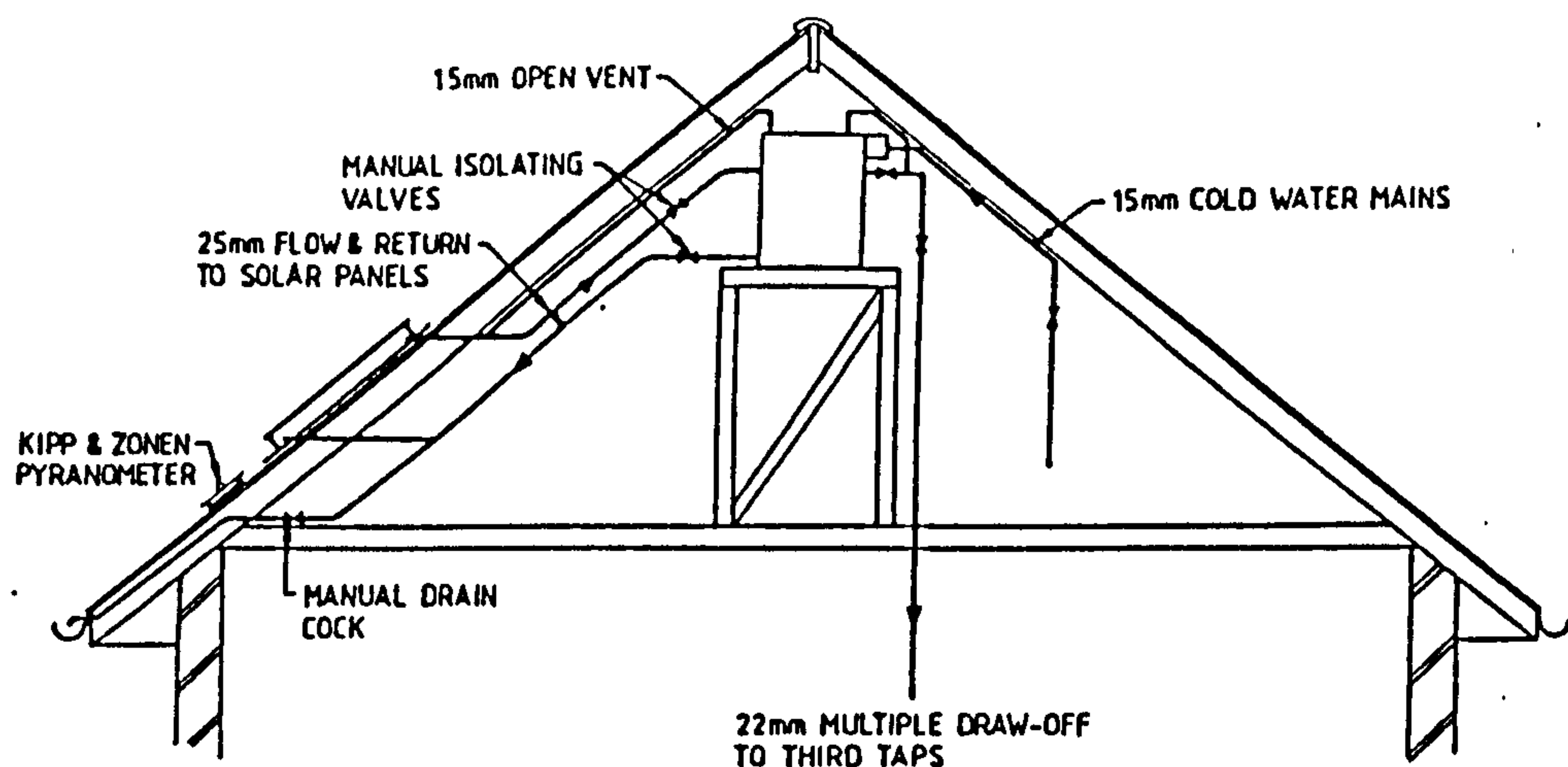


Figure 3.3.4 Cottage No.7 heating element + third tap

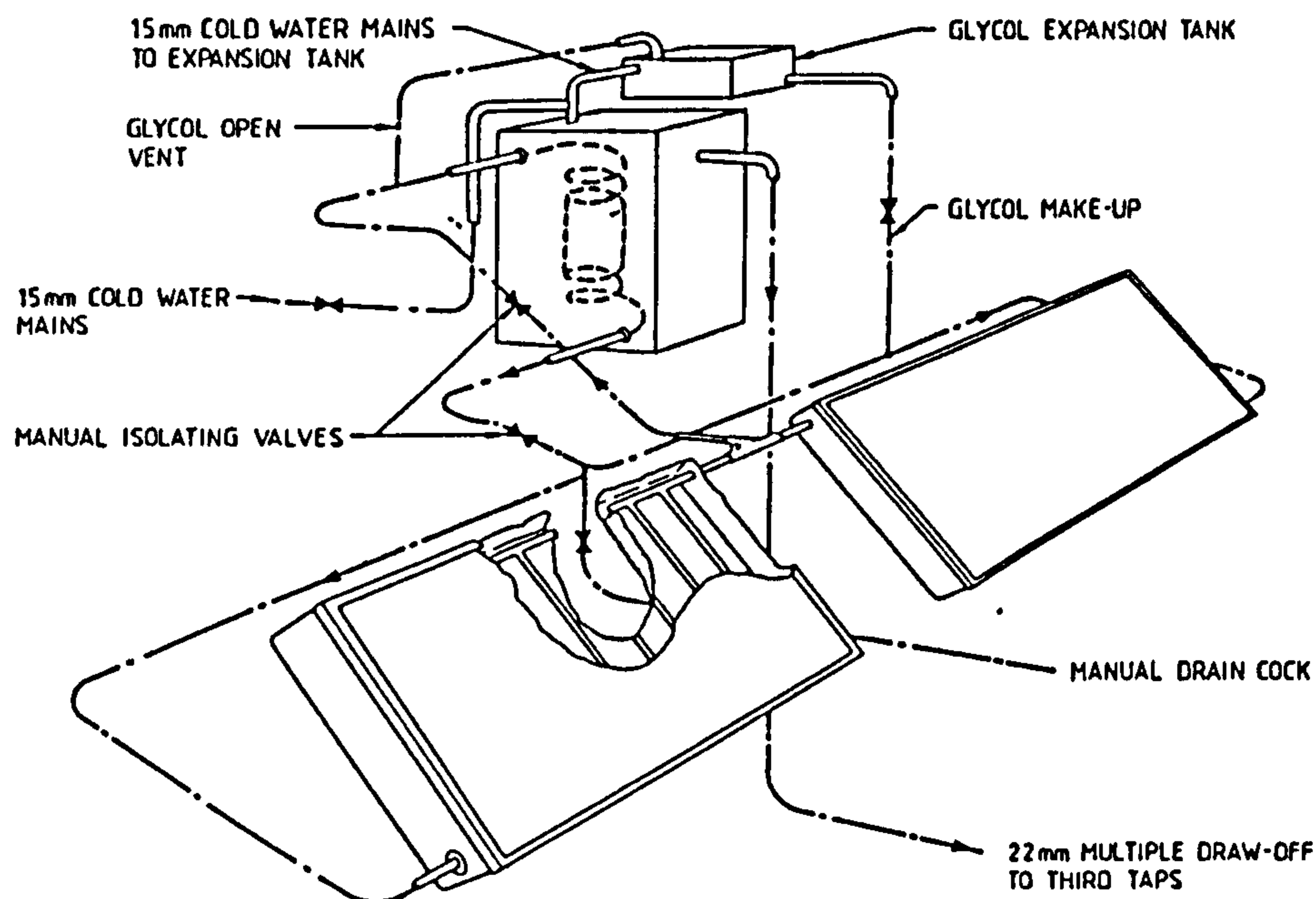


Figure 3.3.5 Cottage No.8 antifreeze system + third tap

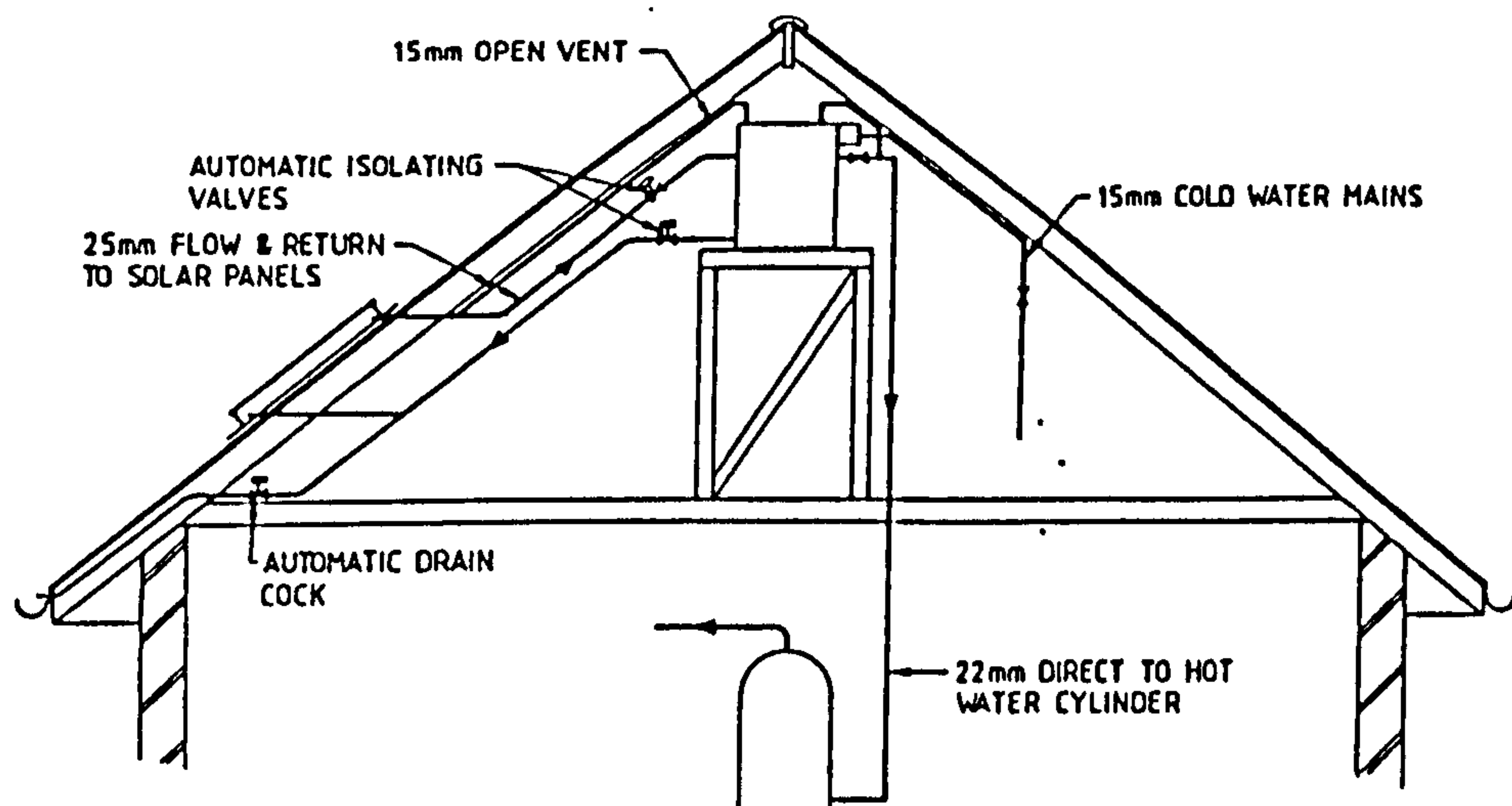


Figure 3.3.6 Cottage No.9 automatic draindown system

These houses were owned by Cranfield Institute of Technology and were occupied usually by married students with children. Many of the students undertook one-year courses of study leading to Master of Science degrees. Thus during the three year monitoring period the three houses could have been occupied by as many as nine different families. Therefore it was envisaged that the effect of up to nine patterns of hot water consumption on the systems' performance could be demonstrated cost effectively. Unfortunately, these particular dwellings were only occupied by five different families during the monitored period. These terraced houses were typical of many in rural areas of Europe in being a considerable distance away from a mains gas supply. Water heating was provided by a coal-fired back-boiler supplemented by an additional electric immersion heating element; both systems being controlled manually.

The roofs were inclined at 40 degrees to the horizontal, faced SSE and overlooked a childrens play area, free from obstructions. The site is subject to a Northern Maritime Climate and the conclusions drawn from this project may also be applied to similar systems within Northern Temperate Climates, since both describe comparable weather patterns.

iii) Installation procedure

Installation of the third system, in house No. 7, was achieved in a total time of 19 hours 15 minutes, under the most favourable weather conditions. Considerable time had been lost during the two previous installations (houses No.s 8 & 9) due to bad weather, with additional delays while awaiting the delivery of the correct components, and the arrival of tradespersons with particular skills. The third system has been analysed in greater detail in order to determine the characteristic times required for the various stages of construction. Figure 3.3.7 shows the proportion of the total time required to complete each of these tasks.

All the various activities required to secure the collector panel and associated pipework to the roof were completed in 7 hours and 30 minutes (Fig. 3.3.8). This was longer than anticipated as, due to the brittle nature of the roof tiles, (Fig. 3.3.9), only one person, i.e. the physically lightest, could work confidently on the roof for such prolonged periods. Difficulty was also experienced in handling and positioning each collector panel, (Fig. 3.3.10), due to its considerable weight, (63 kg). Within the loft space, the pipework and hot water store installation required 9 hours 45 minutes, (Fig. 3.3.11). Included within this time, 90 minutes (15%), were spent removing and later reconstructing the loft hatch. This was due to an overall dimensioning error which resulted in the supplied tank being larger than the existing loft opening! Also an incorrectly specified flange had to be removed and replaced, taking 25 minutes (4.5%). Both of these activities would not normally have been necessary during the installation of a 'typical' system, where greater care would have minimised the risk of such problems.

The total time taken to install the third taps was 120 minutes, a breakdown of which appears as Figure 3.3.12. Figures 3.3.13 - 3.3.14 show the third taps that were installed over the kitchen sink and the bathroom hand basin. These tasks would have been unnecessary in a solar pre-heat system. Although much of the pipework required merely conventional plumbing skills, a more comprehensive understanding of the design and function of the system by the installers would have reduced the time spent on this activity. The total system installation could then be reduced to 2 man-days, (960 minutes), which corresponded well with typical installation times quoted by other installers (3.3.4).

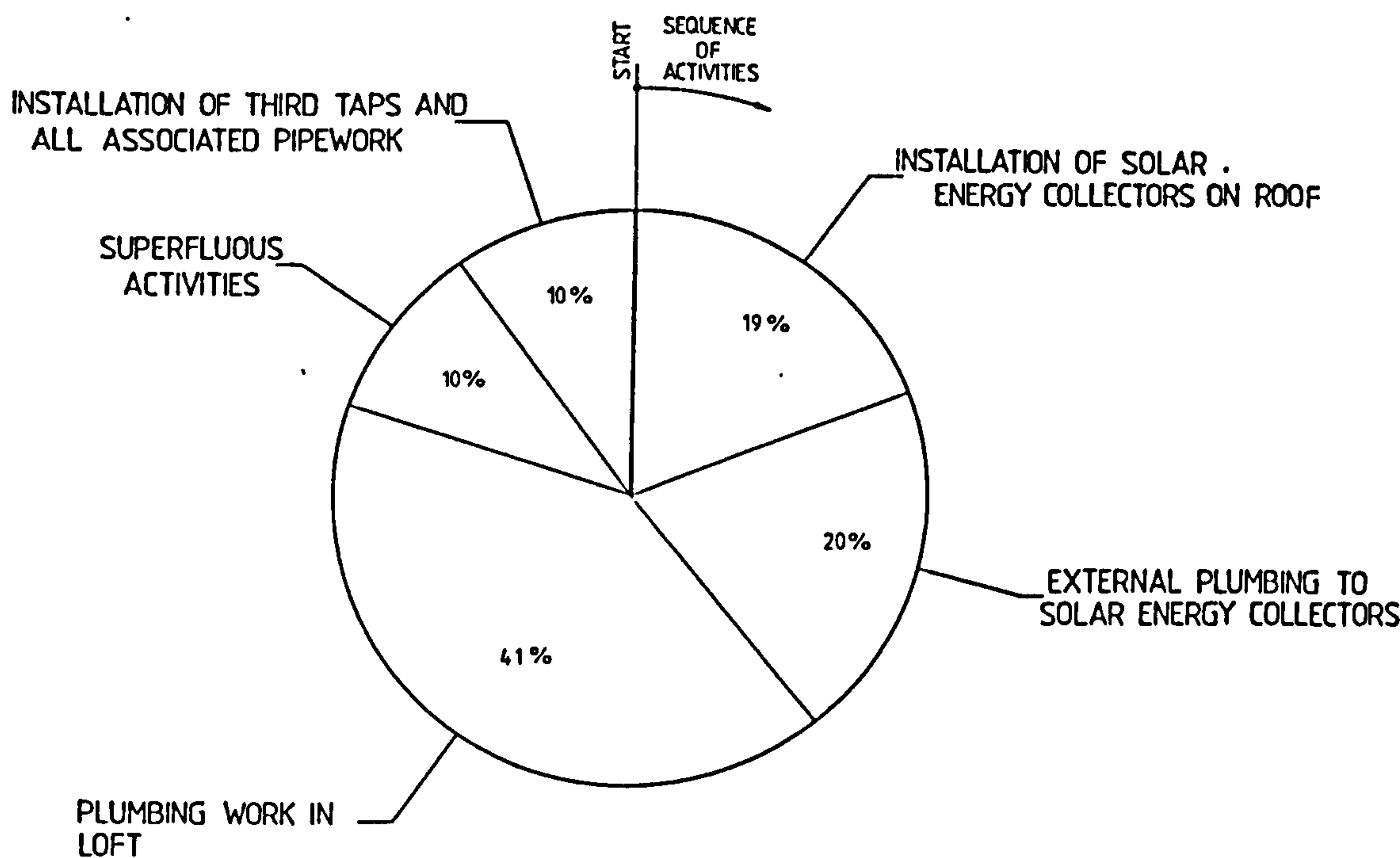


Figure 3.3.7 Total installation time for one complete system

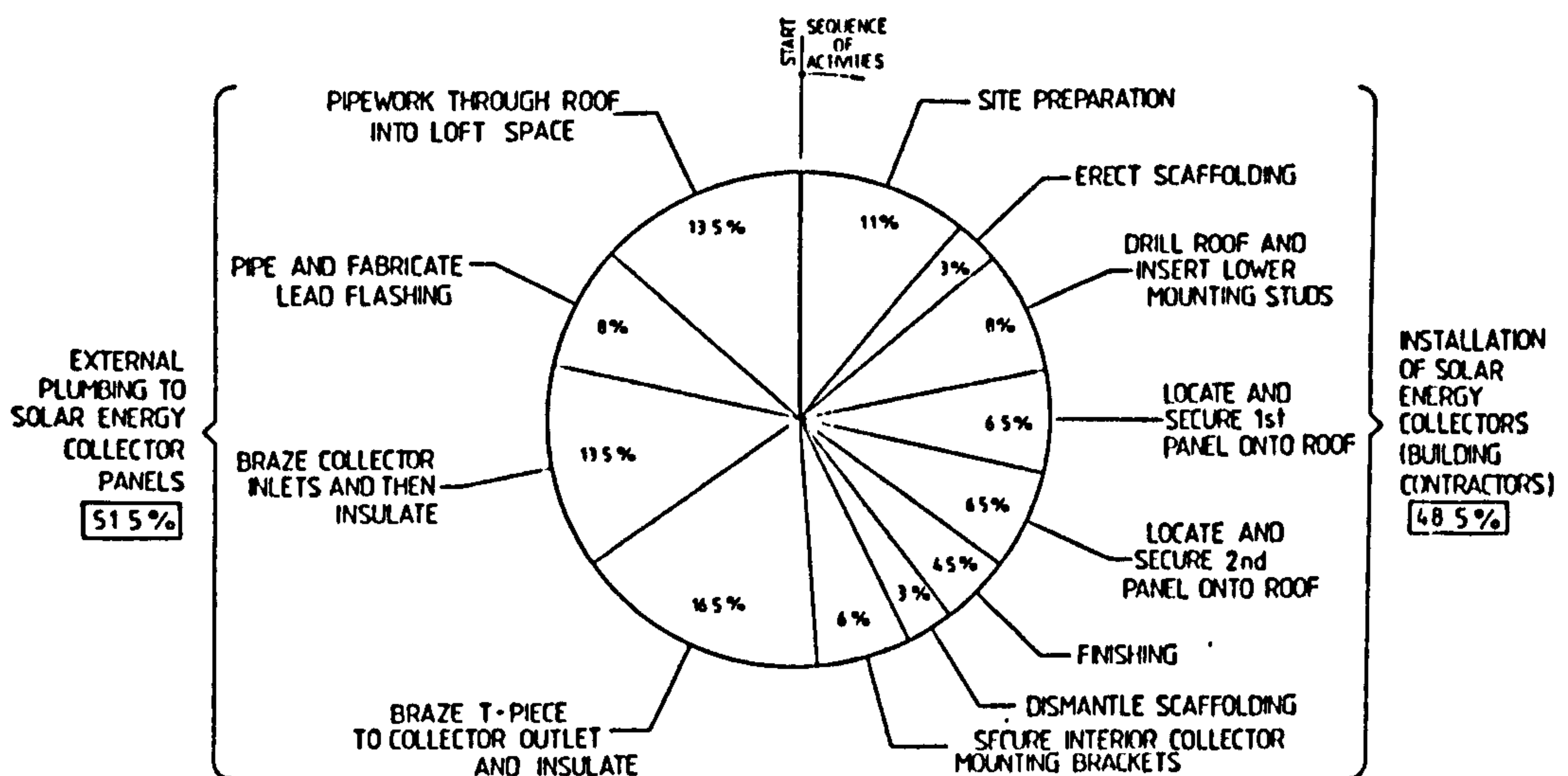


Figure 3.3.8 Installation time for collector panels

Figure 3.3.9

Cracked roof tiles due
to weight of collector boxes



Figure 3.3.10

Installation of a single collector onto roof



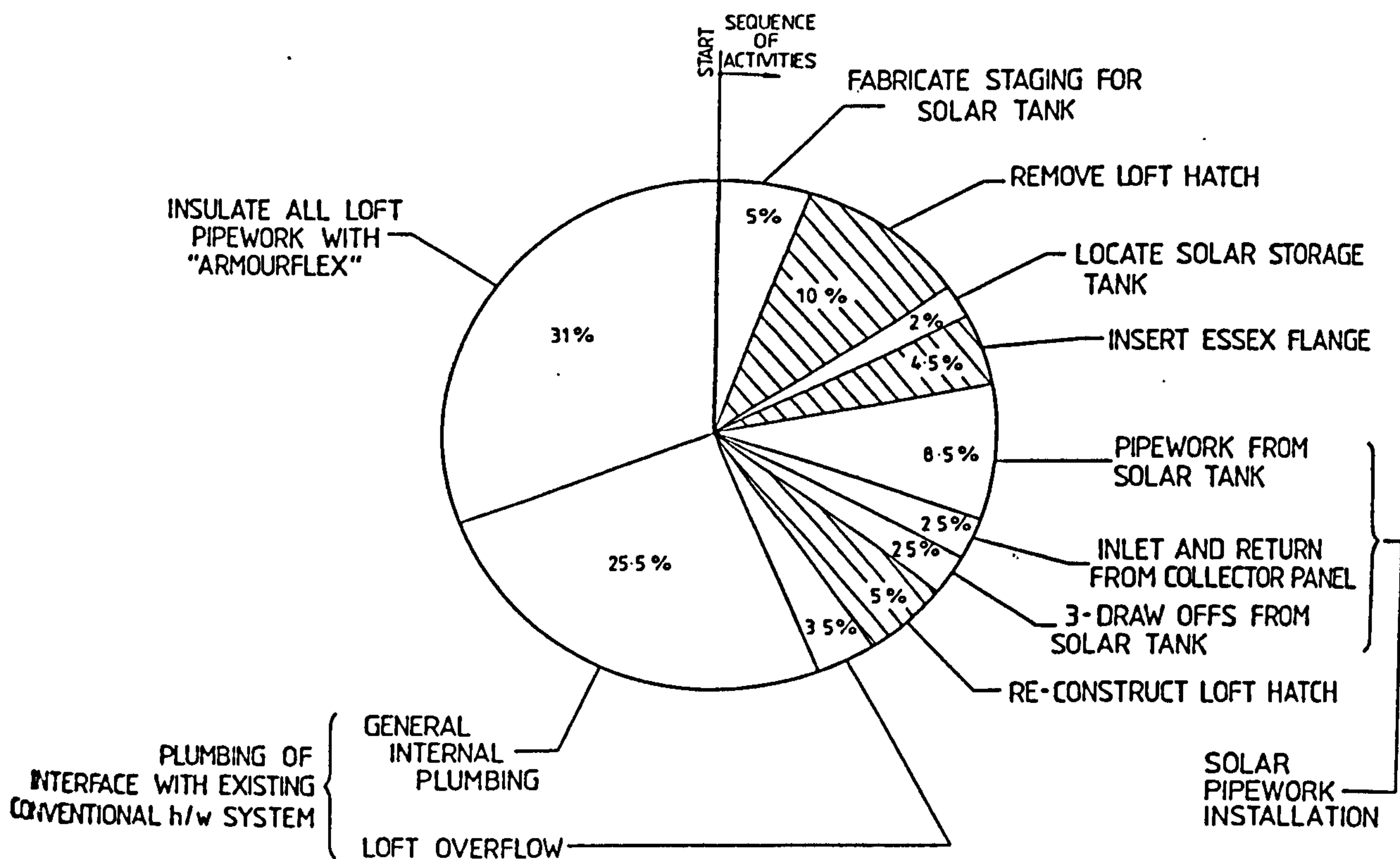


Fig.3.3.11 Time taken to install pipework + solar store in loft

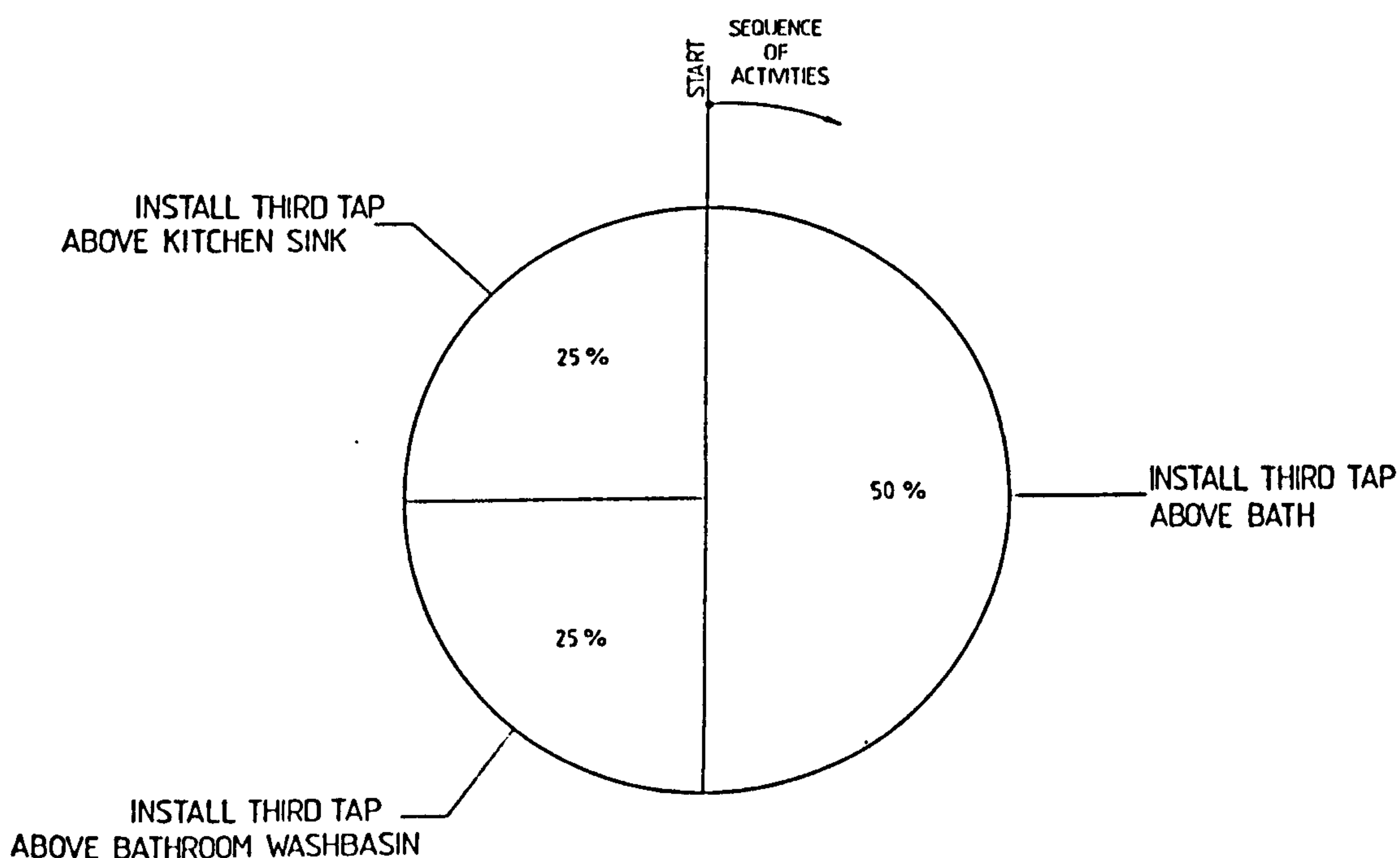


Figure 3.3.12 Installation time for third taps

Figure 3.3.13

Third tap over kitchen sink

Figure 3.3.14

Third tap for bathroom hand-basin



iv) Installation of sensors

Additional time, compared with that normally required, was needed to install the temperature and flow sensors. This work was completed in a total time of 325 minutes, (i.e. 28% of the total system installation time). The time taken to fit each sensor is shown in Table 3.3.3.

TABLE 3.3.3 Times taken for the installation of sensors

Sensor	Installation time (minutes)
Pyranometer	115
Turbine Flowmeters:-	
Cold mains	125
Solar-heated water	15
Conventional hot water	15
Magnetic Induction Flowmeter (Including calibration)	50
'Binda Plug' temperature points:-	
Collector inlet	10
Collector outlet	10
Conventional hot water	15
Cold mains	10
Five equidistant thermocouples in solar tank	20

v) Installation experiences

a) The collector

The construction of the particular collector employed in this project was not conducive to ensuring a simple and efficient installation. The glass-reinforced plastic collector box was prone to cracking at the mounting points and one of the boxes was punctured accidentally during its installation. Connecting the associated pipework to the collector inlet/outlet was also more time consuming than expected, due to the short length of pipe that was left protruding from the collector box. When soldering, the rubber grommet which sealed the header pipe to the collector box melted!

Weighing 63 kg, each of the collectors installed was of a design that, in 1984, was among the heaviest collectors available. However, perhaps surprisingly, three workmen only required five minutes to manipulate the collector onto its locating studs, as shown in Figure 3.3.10. Any significant weight reduction could have reduced this labour requirement to two people and less damage would have been done to the roof tiles. Although it should be noted that the ensuing improvement in the collector installation time would lead to a minimal reduction (less than 2.5%), of the overall installation time.

b) Contractors

Numerous problems were encountered, arising directly from poor liaison between the three different contractors; the roofing, plumbing, and electrical. There was much discussion between them as some contractors arrived at the site while others were just leaving. With the exception of the plumber, they never appeared to be fully aware of what was required of them, e.g. when asked to secure the collector panels to the roof, the building contractors did not realise that the collector outlets had to be aligned. Thus, to enable the connection of a brass 'T' piece to the outlet pipes, the plumber spent two hours re-positioning two adjacent collector panels. Close supervision was required at all times.

Once all the collectors were finally secured to the roof, three weeks elapsed before even the first pipe was soldered! Lying stagnant under levels of high insolation the absorber plates reached temperatures in

excess of 150 °C. As a result the selective coating, (3.3.5), began to wrinkle and peel, (Fig. 3.3.15) although its performance was not significantly impaired (3.3.6). In addition, the rubber grommets at the collector inlets/outlets had completely deformed.

The general lack of enthusiasm shown by the building and electrical contractors stemmed from the novelty of the installation, hence their lack of knowledge of the system, and their scepticism of the product. By contrast, the plumber was fully capable of installing whatever was asked of him with diligent haste (3.3.7).

c) Pipework

Soldered joints were preferred to 'compression' fittings by the plumber. He considered them to be more secure and permanent if installed correctly (3.3.7). Compression fittings were, however, used whenever it was necessary to allow for the insertion of flowmeters at a later date. This was accomplished by the fitting of gate valves either side of its intended position, thus allowing the flow meter to be inserted without draining down the complete system.

d) Leaks

A number of leaks occurred as a direct result of installing the temperature monitoring points. The antifreeze system in particular showed a propensity to leak from the 'Binda-plug' temperature sensor points. This may have been due, in part, to the high proportion of antifreeze, (35%), in the system as this solution can leak through smaller apertures than water. A more serious leak in the same system occurred when the occupants noticed "an unpleasant odour" from the third tap. Further inspection revealed a manufacturing fault in the heat exchanger coil which had ruptured and was contaminating the solar store.

With the onset of temperatures as low as -15 °C in mid-January the two remaining systems failed due to bad on-site supervision when they were installed. The configuration in house No. 7 was designed to prevent freezing by heating the water in the lower header of the absorber on detection of sub-zero temperatures. It failed to do so because the heating element was merely wrapped loosely around the header pipe. Insufficient conductive heat transfer between the two allowed the water

to freeze and eventually the copper pipe fractured. Within 24 hours the automatic drain down system had also failed. The end of the drain-down pipe was actually in, rather than slightly above the gutter. As a result of a minor leak from the draindown valve preceeding three consecutive days of sub-zero temperatures, successive layers of ice were formed in the gutter. Eventually the draindown pipe had been completely encased in ice, thereby preventing the system from draining down. As a result the lower header split along its seam (Fig. 3.3.16). At this point we discovered that the collector manufacturers were using 28mm seamed soft-copper and not seamless semi-hard-copper, as recommended by the plumber (3.3.7).

A secondary problem caused by the the header leaking inside the collector box was that the glass fibre insulant became completely water-logged. Unfortunately, the insulant was never allowed to dry out completely, thus vapour formed on the inside surface of the glazing thereby seriously reducing its transmittance. The excess vapour vented out over a period of 2-3 weeks.

e) Solenoid valves

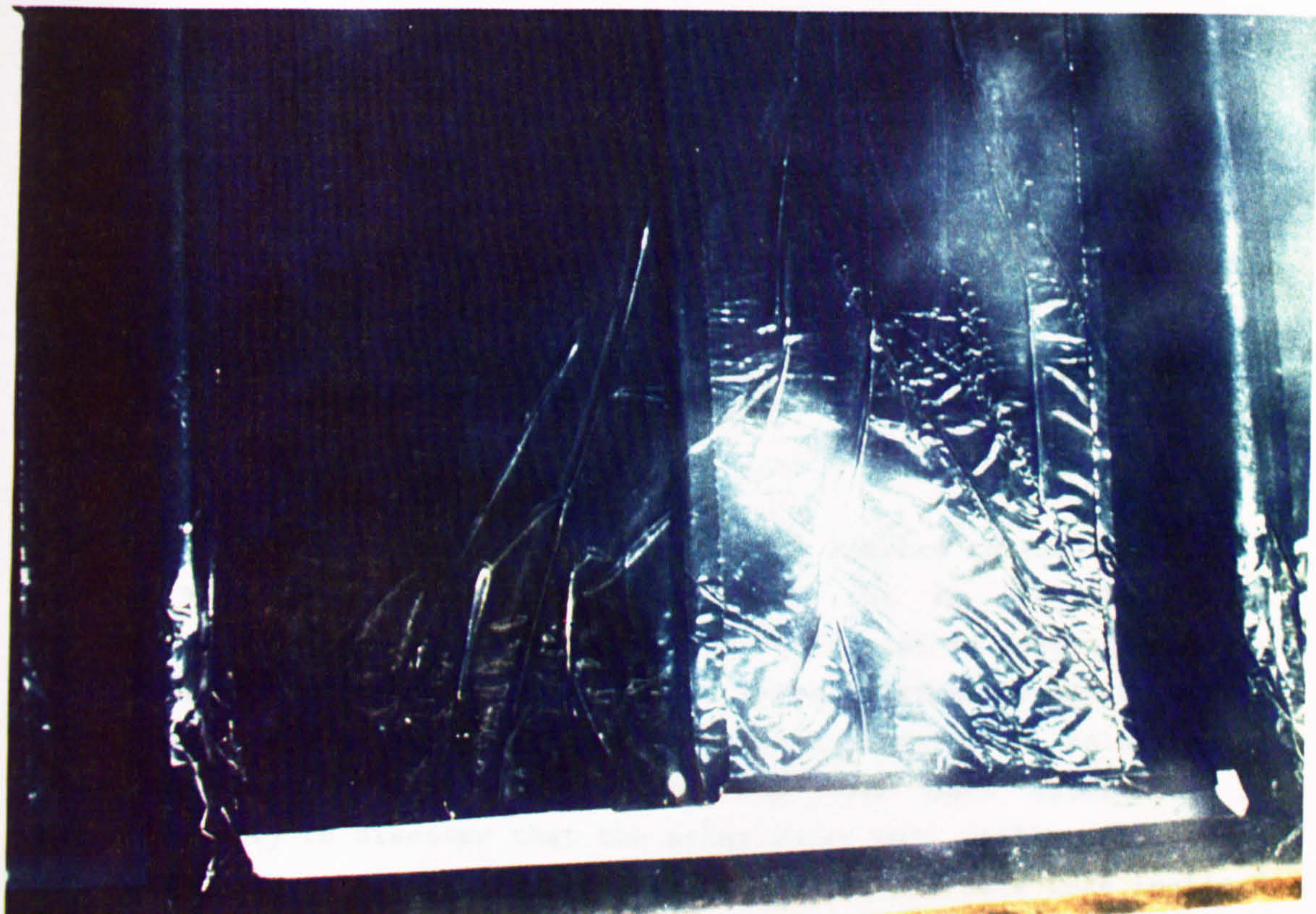
The automatic draindown system was designed to protect the pipework from freezing by isolating the collector loop and then draining down the fluid therein. This was achieved by closing off valves at the inlet and outlet to the store, and then opening a third valve below the level of the collector loop. Unfortunately the original solenoid valves installed at the inlet and outlet to the solar store had to be permanently energised in order to remain open. The valves eventually overheated through continuous use and were temporarily replaced by manual 28mm gate valves. When the two defective solenoid valves were removed it was then discovered that they were 15mm globe valves! Not only was the circulation restricted by the smaller bore of the valve but also by its obstructive flow geometry. Globe valves induce the maximum resistance to fluid flow of any valve currently available today (3.3.7). If the correct valves had been specified, (i.e devices which only closed when energised), for the inlet and outlet to the solar store, failure of the solenoid-coil could have been avoided. This configuration would, however, still be unable to prevent frost damage during periods of simultaneous sub-zero temperatures and power failure. To allow for this eventuality a separate uninterruptable power supply is necessary.

Figure 3.3.15

Deformation of selective coating

Figure 3.3.16

Fractured soft-copper header pipe



to use the third top. Water in the center must not already being depleted without making a useful contribution to the overall hot water load.

The monitoring system was the 400 series 90 series some of the



f) General comments

The effect of all these interruptions was to erode the occupants' confidence in solar water-heating systems. In particular as they were never certain if any hot water was available the householders' with third-tap systems were reluctant initially to use any solar heated water. The solar pre-heat system made a more significant 'solar' contribution because any hot water drawn off, automatically included solar heated water.

The significant length of plumbing from the kitchen to the solar store allowed water in the pipework to cool when not in use. Thus, large volumes of water were drawn off from the third taps to ascertain solely the temperature of the solar-heated water. During the winter months there was little difference between the temperature of the solar-heated water and the cold mains temperature, and even more water would be drawn off only to discover that the solar water was still cold. Some occupants grew weary of this fruitless exercise and were less inclined to use the third tap. Water in the solar tank was slowly being depleted without making a useful contribution to the domestic hot water load.

The monitoring system was the only means by which some of the aforementioned anomalies could have been detected. In practical installations a monitoring system would not be present to perform such a task.

These solar water heating systems were, to an extent, "imposed" upon the occupants of 7-9 East Road. The householders had not chosen to install them and so inevitably some occupants were less concerned with utilizing the full potential of the solar energy water-heaters than others. Constant interruptions during the course of the installation period merely served to antagonise deteriorating occupant/contractor relations. Subjectively, one may assume reasonably that someone who had spent their own money on a solar water-heater would not tolerate the failure of so many system components.

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CHAPTER FOUR

INSTRUMENTATION AND
DATA ACQUISITION

4.1 Philosophy of Long-term Performance Evaluation.

Non-invasive monitoring seeks to;

- i) minimise disturbance to occupants,
- ii) try to ensure that realistic occupant behaviour ensues (i.e., the "experiment" does not influence the measurements) and,
- iii) achieve reliable data acquisition (i.e., not relying on occupants to take measurements).

In reality these laudible objectives were difficult to achieve all of the time in each case reported here. Common problems arose with the need to repair, maintain and adjust equipment and/or systems. Additional, (i.e. spot), manual measurements could be undertaken with differing degrees of success in the context of different building types. In the school, which received many visitors and was unoccupied at weekends, this was not difficult. In marked contrast the houses were private domains into which access was, rightfully, restricted.

4.2 Testing and Measurement Phase of the RSC Houses

i) Selection of sensors

Detailed performance monitoring of the twenty-one demonstration houses at Cockerell Grove, Milton Keynes was undertaken for three years, with the first data sets becoming available in June 1989. An advanced-design computer-based system was employed to collect and store data from all the twenty-one dwellings. The stored data was held at a central monitoring office nearby, (i.e. at 51 Silicon Court, Shenley Lodge 5, Milton Keynes). A weather station was also installed at the same location. The measurements recorded included direct and diffuse insolation, ambient temperature, wind speed and direction, and rainfall. Within each house, the measurements outlined in Table 4.2.1 were recorded at intervals not exceeding fifteen minutes.

- A Intermediate level monitoring of 14 RSC houses (see Table 4.2.2)
 B Detailed level monitoring of single RSC house (see Table 4.2.3)
 C Five control dwellings
 D Sensor type used (see Table 4.2.4)

		A	B	C	D
1.	Total gas consumption (water +space heating)	*	*	*	1
2.	Space heating gas consumption	*	*	*	2
3.	Air temperature as it leaves RSC	*	*		3
4.	Air temperature at exit of HRU	*	*		3
5.	Operation time of fan in HRU	*	*		2
6.	Exhaust air from house as it enters HRU		*		3
7.	Foul air outlet temperature from HRU		*		3
8.	Loft temperature on cold side	*	*		3
9.	Five vertically equidistant temperatures in the RSC		*		4
10.	Insolation on plane of glazing		*		5
11.	Hall	*	*	Various	3
12.	Lounge	*	*	Combinations	3
13.	Kitchen	*	*	of 3 sensors	3
14.	Bathroom	*	*	from No.s 11,	3
15.	Bedroom	*	*	12, 13, 14,	3
16.	Hot water cylinder cupboard	*	*	15, & 16	3
17.	Total electricity consumption	*	*	*	6
18.	Relative humidity	*	*	*	3

Table 4.2.1. Monitoring Schedule

Table 4.2.2 Data structure for intermediate level monitored houses (4.2.1)

Ch. No.	Field Name	Description
1	Month	Month expressed in fractions of a 30-day month
2	MONTH	The actual month
3	DATE	The actual date
4	SYS-ADD	System address
5	T1_D	Lounge
6	T2_D	Kitchen
7	T3_D	Bedroom
8	HUM_D	Relative Humidity in the Lounge
9	RSCT_D	Roof Space Collector Air Temperature
10	EXTAIR_D	External Air Temperature
11	HSOL_D	Horizontal Global Solar Radiation (kWh/m ² /day)
12	SSOL_D	South Facing Global Solar Radiation "
13	WINDSPD_D	Wind Speed (m/s)
14	EXTHUM_D	External Humidity (%)
15	RAINFALL_D	mm total per day
16	TOTGAS	Total Gas consumption to date (ft ³ /day)
17	SPHGASTIME	Duration that space heating gas-valve is open (hrs)
18	FANTIME	Total daily operation time of RSC fan (mins)
19	TOTELEC	Total daily Electricity Consumption (kWh)
20	HRUT1_F	Air temperature into HRU from RSC
21	HRUT2_F	Air temperature from HRU to WAHS
22	RSCT_F	Roof Space Collector Temperature where available (default 0.01)
23	EXTAIR_F	External Air Temperature
24	HSOL_F	Horizontal Global Solar Radiation
25	SSOL_F	South Facing Global Solar Radiation
26	TRISE_RSC	Rise in air temperature resulting from gains by the RSC i.e. (T20 - T23)
27	TRISE_HRU	Rise in air temperature resulting from gains by the HRU i.e. (T21 - T20)
28	PKHRUT1_F	Max. air temperature into HRU from RSC
29	TPKHRUT1_F	Time at which max. air temperature into HRU from RSC occurred
30	PKHRUT2_F	Max. air temperature from HRU to WAHS
31	TPKHRUT2_F	Time at which max. air temperature from HRU to WAHS occurred
32	PKRSCT_F	Max. Roof Space Collector Temperature where available
33	TPKRSCT_F	Time at which Max. Roof Space Collector Temperature occurred where available
34	PKRSCT_D	Max. Roof Space Collector Temperature where available
35	TPKRSCT_D	Time at which Max. Roof Space Collector Temperature occurred where available
36	HEATING	When heating comes on and off

RSC Roof Space Collector
HRU Heat Recovery Unit
WAHS Warm-air heating system
D Denotes values averaged over a whole day
F Denotes values averaged over the total daily duration of RSC fan operation.

TABLE 4.2.3 Data Structure for detailed monitored houses (4.2.1)

Ch No.	Field Name	Description
1	Month	Month expressed in fractions of a 30-day month
2	MONTH	The actual month
3	DATE	The actual date
4	SYS-ADD	System address
5	T1_D	Lounge
6	T2_D	Kitchen
7	T3_D	Bedroom
8	HUM_D	Relative Humidity in the Lounge
9	RSCT1_D	Roof 900mm from ridge
10	RSCT2_D	Space 750mm from ridge
11	RSCT3_D	Collector 600mm from ridge
12	RSCT4_D	Air 450mm from ridge
13	RSCT5_D	Temperature 300mm from ridge
14	RSCT6_D	Sensors 150mm from ridge
15	EXTAIR_D	External Air Temperature
16	HSOL_D	Horizontal Global Solar Radiation (kWh/m ² /day)
17	SSOL_D	South Facing Global Solar Radiation "
18	WINDSPD_D	Wind Speed (m/s)
19	EXTHUM_D	External Humidity (%)
20	RAINFALL_D	mm total per day
21	TOTGAS	Total Gas consumption to date (ft ³ /day)
22	SPHGASTIME	Duration that space heating gas-valve is open (hrs)
23	FANTIME	Total daily operation time of RSC fan (mins)
24	TOTELEC	Total daily Electricity Consumption (kWh)
25	HRUT1_F	Air temperature from RSC into HRU
26	HRUT2_F	Air temperature from HRU into WAHS
27	HRUT3_F	Air temperature of Kitchen/Bathroom air into HRU
28	HRUT4_F	Air temperature from HRU to external flue
29	RSCT_F	RSC Temperature where available (default 0.01)
30	EXTAIR_F	External Air Temperature
31	HSOL_F	Horizontal Global Solar Radiation
32	SSOL_F	South Facing Global Solar Radiation
33	TRISE_RSC	Temperature rise in RSC resulting from solar gains i.e. (T20 - T23)
34	TRISE_HRU	Rise in air temperature resulting from gains by the HRU i.e. (T21 - T20)
35	PKHRUT1_F	Max. air temperature from RSC into HRU
36	TPKHRUT1_F	Time at which max. temp. from RSC into HRU occurred
37	PKHRUT2_F	Max. air temperature from HRU into WAHS
38	TPKHRUT2_F	Time at which max. temp. from HRU into WAHS occurred
39	PKHRUT3_F	Max. air temp. of Kitchen/Bathroom air into HRU
40	TPKHRUT3_F	Time at which max. air temperature from Kitchen/Bathroom air into HRU occurred
41	PKHRUT4_F	Max. air temperature from HRU to external flue
42	TPKHRUT4_F	Time at which max. air temperature from HRU to external flue occurred
43	PKRSCT_F	Max. RSC Temperature where available
44	TPKRSCT_F	Time at which Max. RSC Temp. occurred where available
45	PKRSCT_D	Max. RSC Temperature where available
46	TPKRSCT_D	Time at which Max. RSC Temp. occurred where available

The six different sensor types listed in Table 4.2.1 are described in detail in Table 4.2.4, with the emphasis on appropriate levels of required accuracy with a high degree of reliability.

No. Device	Output	General information
1. British Gas approved meter	Digital Pulse	Output sent directly to Building Interface Unit (BIU)
2. Two pole relay	On/off	RS 8-pin 230v a.c. relay Monitored operation time of heat recovery unit (HRU)
3. Vaisala Platinum Resistance Temperature/Humidity Sensor (PRT)	4 - 20 mA from -5°C to 55°C + 0.2°C	Expense of such a device was justified by their stability, reproducibility and linearity. Low responsivity suited to relatively long time-constant of rooms being measured
4. RS Negative temperature coefficient R-T curve-matched thermistor	10 kOhms at 25°C. Temperature range from -80°C — 180°C + 0.2°C	Rapid response thermistors required for fast transient temperature changes within RSC. Reliability of Vaisala PRT could not be guaranteed at such high temperatures.
5. Delta-T Silicon Diode Solar Energy Sensor type ES	10.8 mV/kWm ² for total solar radiation	Linear mV output Accuracy -+ 5% traceable to NBS standards. Fast response time c. 10 microseconds
6. Multi-rate electricity meter	Pulsed output	Specially adapted by East-Midlands Electricity to give pulsed output directly to BIU

Table 4.2.4 Description of sensor types used to monitor
15 RSC houses at Shenley Lodge 5.

ii) Central monitoring operation

a) Overall system design

The monitoring facility consisted of the following major components, as illustrated in figure 4.2.1.

- o Sensors
- o Building Interface Unit (BIU) (4.2.2)
- o Communications Network
- o Central Monitoring Office (CMO)

The system operated as follows (4.2.2):

- o Sensors, installed in buildings during construction, were connected to the BIU via cables which were installed during construction. The BIU was situated in the British Telecom Cupboard outside each dwelling.
- o The BIU sampled and conditioned the output from sensors within each building at pre-determined intervals, and stored this data in preparation for transmission back to the CMO.
- o On receiving the appropriate instruction from the CMO processor, the BIU transmitted its stored data back to the CMO via the communications network. The network itself supported two-way communications; transmission commands to the BIU from the CMO, and data transmission from the BIU to the CMO.
- o The data from all buildings received by the CMO was formatted and stored on a Winchester hard disk. This acted as an intermediate logging file from which data packages were prepared and written to floppy disks.
- o Data was backed-up on magnetic tape for long term archiving, leaving the Winchester disk available for further data acquisition.

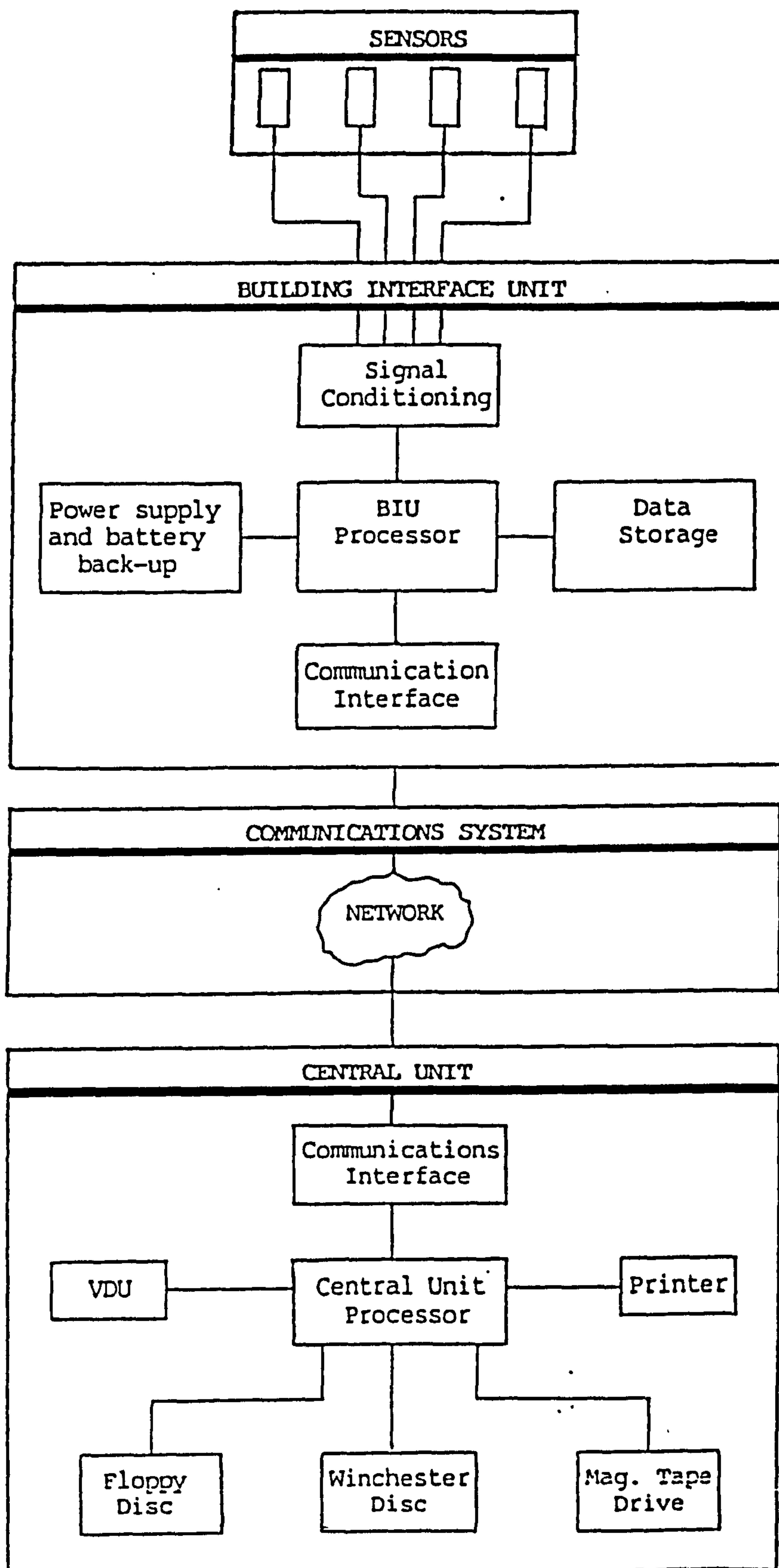


Figure 4.2.1 System design overview

The typical operating parameters of the CMO hardware were;

- 1 hour data recording intervals. This was nominal - sampling intervals as high as one recording every minute were possible, (resettable from the CMO).
- Data transmitted to the CMO once per 24 hours, at night, or more frequently according to requirements.
- Preparation and despatch of data on a monthly basis.

b) Building Interface Unit

The BIU was a compact purpose-built microcomputer whose features were as follows:

- All electronic components were contained on a single card measuring only 200mm x 200mm.
- Card to be housed in a metal box measuring 300mm x 200mm x 120mm, to ensure adequate screening.
- Designed to withstand the full range of UK temperatures and humidity conditions (thermostatically-controlled enclosure with heating incorporated).
- Battery powered; 6 - 12 months between battery changes.

c) Sensor inputs

A total of 16 inputs into each house were provided, selectable as either eight analogue, or eight digital inputs. Analogue inputs were 4-20mA current loop or 0-5V (selectable). Digital inputs were capable of status indication and pulse counting. Temperature and humidity transducers with 4-20mA current loop output were used. The temperature transducers incorporated PRT sensors to grade II, (4.2.3).

For more extensive monitoring requirements several BIU's could be linked together, increasing the available input by steps of 16 channels.

d) Operation of Building Interface Unit

Three types of software are incorporated within the BUI:

- Data acquisition system; sampled and converted analogue signals and monitored digital inputs, storing data in memory. Sampling intervals could be reset from the CMO. 8K or 16K bytes RAM for data storage (more than one day's data for even the most intensive monitoring requirements, and several days storage for typical monitoring levels).
- Communications in the BIU accommodated the interchanges of data, commands and status between the BIU and the CMO. Error detection techniques and handshake protocols were used to ensure that data was transferred to the CMO without loss or corruption. Data was not deleted from the BIU until satisfactorily stored at the CMO.
- Diagnostics system provided on-line test procedures for checking the integrity of the BIU and correct operation of the sensors. Some of these routines could be carried out automatically by software within the BIU and the results communicated to the CMO on demand. Other routines could be accomplished on-site using configuration switches, status leads and test boxes connected to the inputs (to mimic sensors).

e) Weather data

Table 4.2.5 shows which environmental parameters were measured at the weather station installed at 51 Silicon Court.

Parameter to be measured	Device	Comments
Global solar radiation on horizontal plane	Kipp & Zonen Type CM 11 Solarimeter	4-6 microvolts per W/m ² . Response time < 5 secs Accuracy to within 0.5%
GSR on a south facing vertical surface	"	"
Air temperature	Delta-T sensor type AT-1	Sealed and shielded 2K thermister Accuracy $\pm 0.1^{\circ}\text{C}$
Soil temperature	Delta-T sensor type ST-1	Stainless steel clad 2K thermister Accuracy $\pm 0.2^{\circ}\text{C}$
Relative humidity	Delta-T sensor type RH1	Cracked-chromium oxide capacitance sensor. Linearity within 2% from 0 to 95% RH.
Wind speed & Direction	Wind Vane type WD1	0.6 m/s threshold Accuracy $\pm 2\%$ if > 5 m/s
Rainfall amount and duration	Raingauge type RG1	Tipping bucket raingauge Sensitivity 0.2mm/tip

All devices formed part of a Full Delta-T weather station (4.2.4)

Table 4.2.5 Specification of weather station components

4.3 Monitoring System of TAP'S

i) Monitoring schedule

A total of 83 type-T copper/constantan thermocouple temperature sensors, five solarimeters and two heat-meters were installed at Nazeing County Primary School to monitor the performance of 36 thermosyphoning air-heating panels. Although thermocouples are fragile mechanically and are accurate only to 0.5°C (4.3.1) they were chosen for their relatively low cost and thermal durability. Three of the solarimeters, whose specification is shown in Table 4.3.1, measured the global radiation on the vertical plane of the east, south and west facades of the school, and the remaining two solarimeters measured global and diffuse radiation on the horizontal plane. A heat-meter was installed in the main plant room in order to measure the total space heating gas consumption of the school, and a more sensitive heatmeter was located in one of the south facing classrooms to record the heating requirements of two adjacent classes of children.

The signals from all of these sensors were recorded and stored by two "stand-alone" data-loggers, as specified in table 4.3.2. They were programmed to sample all of the sensors every 10 minutes and store the average of six readings every hour. A total of thirty days data could be stored before the data-loggers required "interrogation", when the data were transferred to a floppy disk for further analysis.

Spectral range	0.3 to 3.0 m
Cosine response	+ - 2% from normal to 70° from normal
Response time	17 seconds to 65% of final reading
Output	1mV/W/m ²
Voltage input	+10/-8v dc
Current consumption	Approx. 3mA
Dimensions	99mm dia. x 80mm height. 180mm dia shield.
Weight	0.53 kg
Cable length	Up to 100m
Manufacturer	Casella London Ltd.

Table 4.3.1 Specification of Solarimeter W6500

Logging

LOGGING INTERVAL AND SPEED

1, 5, 10, 30 s, 1, 5, 30 min, or 1, 2, 4, 12 or 24 hours, programmable for each channel. Readings can also be reduced to averages, maxima or minima at these intervals. Typically 10 channels/s.

INPUT CHANNELS

60 channels max., depending on input cards installed, plus 2 resident digital inputs & 2 relay outputs.

Analogue Inputs

STANDARD ANALOGUE CARD, LAC1

Each LAC 1 multiplexer card can select analogue inputs from:
Either: 15 channels of differential voltages and/or 3-wire resistances.
Or: 30 channels of single-ended voltages and/or 2-wire resistances.
Directly measures voltages up to $\pm 2V$ or resistances $< 1 M\Omega$. Voltages up to $\pm 50V$ & currents can be measured using resistors, mounted on the input screw connectors or on an LPR1 or an LPR1V.

4-WIRE CARD, LFW1

Each LFW1 card can select up to 12 bridge, potentiometric, differential voltage or 2-, 3-, or 4-wire resistance sensors. 4-wire resistance measurements virtually eliminate cable resistance. PT₁₀₀ platinum resistance thermometers, (e.g. DIN 43760/BS1904 type) are measured over -200 to $+850^{\circ}C$. In the -17 to $+57^{\circ}C$ range of logger & PT₁₀₀ temperature, $0.01^{\circ}C$ resolution, $\pm 0.2^{\circ}C$ accuracy is obtained.

VOLTAGE READINGS

12 bit + sign. 4 Ranges, user-selected or autoranged:	Range 1:	Full Scale	Resolution
	Range 2:	$\pm 4mV$	$1\mu V$
	Range 3:	$\pm 32mV$	$8\mu V$
	Range 4:	$\pm 262mV$	$64\mu V$
		$\pm 2.097V$	$0.5mV$

ACCURACY (Typical figures in brackets)

Logger Temperature	$20^{\circ}C$	-20 to $+60^{\circ}C$
Full scale error	$\pm 0.07\%$ (0.04%)	$\pm 0.2\%$ (0.1%)
Long term stability	$\pm 0.25\%$ (0.02%) over 1 year	
Differential Offset	$\pm 10\mu V$ (3 μV), $\pm 0.2\%$	$\pm 12\mu V$, $\pm 0.02\%$
Noise	(0.2 μV RMS)	
Input Impedance	$10 M\Omega$ approx.	As $20^{\circ}C$
Common Mode Range	$\pm 2V$	

RESISTANCE READINGS

Autoranging 12 bit voltage readings with programmable 2, 20, 200 or 2000 μA excitation, giving $1 M\Omega$ full-scale or $< 0.01\Omega$ resolution.

ACCURACY

As Voltage readings, with additional errors:		
Logger Temperature	$20^{\circ}C$	-20 to $+60^{\circ}C$
2 μA excitation	$\pm 0.01\%$ Full Scale	$\pm 0.3\%$
Other excitation	$\pm 0.04\%$	$\pm 0.01\%$
2-Wire LAC1 only	$\pm 20\Omega$ (6 Ω typical)	As $20^{\circ}C$

INPUT PROTECTION

Analogue inputs withstand $\pm 15V$ continuously, and much higher voltages in brief pulses. For additional protection see LPR1V below.

ATTENUATOR CARD, LPR1

For use with Standard Analogue Card only. Provides socketed positions for mounting signal conditioning resistors to 30 channels. Resistor positions may be left vacant or resistors fitted in shunt or divider configuration, for measuring currents or voltages up to $\pm 50 V$ respectively.

INPUT PROTECTION CARD, LPR1V

Connects transient-absorbing varistors to 30 Standard Analogue Card inputs, or 12 4-Wire Card inputs, for additional input protection. Also provides socketed resistor positions for signal conditioning, but only when used with LAC1 (see LPR1 above). Can cause significant inaccuracies when measuring resistances $> 100 K\Omega$.

Digital Inputs and Outputs

DIGITAL INPUTS

All Loggers have 2 resident 16-bit counter channels that continuously monitor logic levels or switch-closures, logging digital status, counts or frequency (up to 1000 Hz) or triggering special logging sequences.

COUNTER CARD, DLC1

Each DLC1 card provides up to 15 extra 16-bit counter or frequency channels. Max frequency: 500 Hz for switch closures, 50 kHz for 5V logic level signals. Every channel records up to 65,535 counts between scans.

RELAY OUTPUTS

2 SPDT relays for powering up, alarms, malfunction warning. 1A, 50V rating.

Other Specifications

PROCESSING

The Logger can convert readings into engineering units using look-up tables or a conversion factor & zero offset. User-expandable software sensor library includes Delta-T sensors, Platinum Resistance Thermometers, Thermistors (Fenwal 2K, 2K252, 10K & 100K types) & Thermocouples (types J, K & T). Cold junction temperature is measured at isothermal terminals.

DISPLAY

A 2-line LCD shows instantaneous output from any sensor (in engineering units), time, battery & memory condition, & status messages, without disturbing logging.

MEMORY

Highly reliable 2 battery-backed RAM. Expandable from 16K to 128K readings. Automatic RAM check.

DATA FORMAT

ASCII, easily loaded into many spreadsheets etc, such as Lotus 1-2-3, SuperCalc. ASCII readings are date/time stamped, labelled in engineering units with errors flagged.

Data files, created by the Delta Logger Software are comma separated. Printouts are tabulated.

INTERFACE

RS232 Serial up to 9600 baud. i.e. 10,000 readings transferred/min (without disturbing logging).

COMPUTERS

Type LCS Delta Logger Software suits IBM PC, AT, PS/2 & most compatibles. Ask about other computer types. Requires PC-DOS or MS-DOS and BASICA, GWBASIC, or equivalent.

POWER

6 internal AA alkaline cells typically provide power for 500K readings, or 24 hrs keypad/LCD or RS232 interface operation, or 12 months quiescent operation.

An external 9-15 DC supply can be used, with the alkaline batteries as backup. The internal lithium cell will retain data in memory for 2 months in the event of power supply failure.

ENVIRONMENTAL

Operating temperature: -20 to $+60^{\circ}C$. IP65 weatherproof main case with desiccant and humidity indicator.

SIZE/WEIGHT

280 x 220 x 140 mm / 2.7 kg.

Table 4.3.2 Specification of Delta-T data-logger

ii) Detailed descriptions of all data channels

Tables 4.3.3 & 4.3.4 describe, in detail, the wiring location of the 90 data channels that were being monitored by the data acquisition system, and the respective channel location within the statistical analysis package (INSTAT). The location of each sensor in each room of the school is shown in figure 4.3.1.

Table 4.3.3 Location of sensors for 60-channel logger

Channel No. in INSTAT	Wiring Location in Logger	Position within the school at Nazeing or otherwise
1		Day of the Month
2		Month
3		Hour
4		Minutes
5		Seconds
6	61	Counter on N-W logger, small heat meter
7	1	CJC thermister in Delta-Logger
		CLASSROOM 5
8	2	East facing (S-E) collector outlet
9	3	Radiant ambient temperature
10	4	South facing (S-W) collector inlet
11	5	South facing (S-W) collector outlet
		CLASSROOM 4
12	6	East wall surface temperature
13	7	South facing (S-E) collector inlet (edge)
14	8	South facing (S-E) collector inlet (centre)
15	9	South facing (S-E) collector outlet (edge)
16	10	South facing (S-E) collector outlet (centre)
17	11	South facing (S-E) collector absorber surface (edge)
18	12	South facing (S-E) collector absorber surface (centre)
19	13	Radiant ambient temperature
20	14	North wall surface temperature
21	15	South facing (S-W) collector inlet (edge)
22	16	South facing (S-W) collector inlet (centre)
23	17	South facing (S-W) collector outlet (edge)
24	18	South facing (S-W) collector outlet (centre)
25	19	West wall surface temperature
		CLASSROOM 3
26	20	South facing (S-E) collector inlet
27	21	South facing (S-E) collector outlet
28	22	North wall surface temperature
29	23	Radiant ambient temperature
30	24	South facing (SS-W) collector inlet (edge)
31	25	South facing (SS-W) collector inlet (centre)
32	26	South facing (SS-W) collector outlet (edge)
33	27	South facing (SS-W) collector outlet (centre)
34	28	South facing (SS-W) collector absorber surface (edge)
35	29	South facing (SS-W) collector absorber surface (centre)
36	30	West wall surface temperature
37	31	South facing (S-W) collector inlet
38	32	South facing (S-W) collector outlet

Table 4.3.3. Cont.

Channel No. in INSTAT	Wiring Location in Logger	Position within the school at Nazeing or otherwise
39	33	CLASSROOM 2 South facing (S-E) collector inlet
40	34	South facing (S-E) collector outlet
41	35	Radiant ambient temperature
42	36	West facing (S-W) collector inlet
43	37	West facing (S-W) collector outlet
44	38	CLASSROOM 1 West facing (S-W) collector inlet
45	39	West facing (S-W) collector outlet
46	40	Radiant ambient temperature
47	41	ASSEMBLY HALL West wall surface temperature
48	42	Radiant ambient temperature
49	43	East facing (E) collector inlet
50	44	East facing (E) collector outlet
51	45	East facing (N-E) collector inlet
52	46	East facing (N-E) collector outlet
53	47	STAFF ROOM (alias the Music Room) North wall surface temperature
54	48	West facing collector inlet
55	49	West facing collector outlet
56	50	HEADMISTRESSES'S OFFICE South wall surface temperature
57	51	West facing collector inlet
58	52	West facing collector outlet
59	53	SECRETARY'S OFFICE South wall surface temperature
60	54	West facing collector inlet
61	55	West facing collector outlet
62	56	SOLARIMETERS Total West facing radiation on vertical plane
63	57	Total horizontal global radiation
64	58	Total horizontal diffuse radiation
65	59	Total South facing radiation on vertical plane
66	60	CLASSROOM 5 East facing (S-E) collector inlet

Table 4.3.4. Location of sensors for 30-channel logger

Channel No. in INSTAT	Wiring Location in Logger	Position within the school at Nazeing or otherwise
67 68	61 1	Counter on N-E logger, large heat meter CJC thermister in Delta-Logger
69 70	2 3	CLASSROOM 9 East facing (S-E) collector inlet East facing (S-E) collector outlet
71 72 73	4 5 6	CLASSROOM 8 Radiant ambient temperature East facing (S-E) collector inlet East facing (S-E) collector outlet
74 75 76 77 78 79 80 81	7 8 9 10 11 12 13 14	CLASSROOM 6 West facing (N-W) collector inlet West facing (N-W) collector outlet South facing (S-W) collector inlet South facing (S-W) collector outlet Radiant ambient temperature East wall surface temperature South facing (S-E) collector inlet South facing (S-E) collector outlet
82 83 84	15 16 17	CLASSROOM 7 Radiant ambient temperature East facing (N-E) collector inlet East facing (N-E) collector outlet
85 86 87 88	18 19 20 21	ENTRANCE HALL North wall surface temperature External Ambient temperature East facing (E) collector inlet East facing (E) collector outlet
89 90 91	22 23 24	UTILITY ROOM East wall surface temperature South facing (S-E) collector inlet South facing (S-E) collector outlet
92	25	CLASSROOM 10 West wall surface temperature
93	26	CLASSROOM 9 Radiant ambient temperature
94 95 96	27 28 29	CLASSROOM 10 Radiant ambient temperature East facing (N-E) collector inlet East facing (N-E) collector outlet
97	30	SOLARIMETERS Total East facing radiation on vertical plane

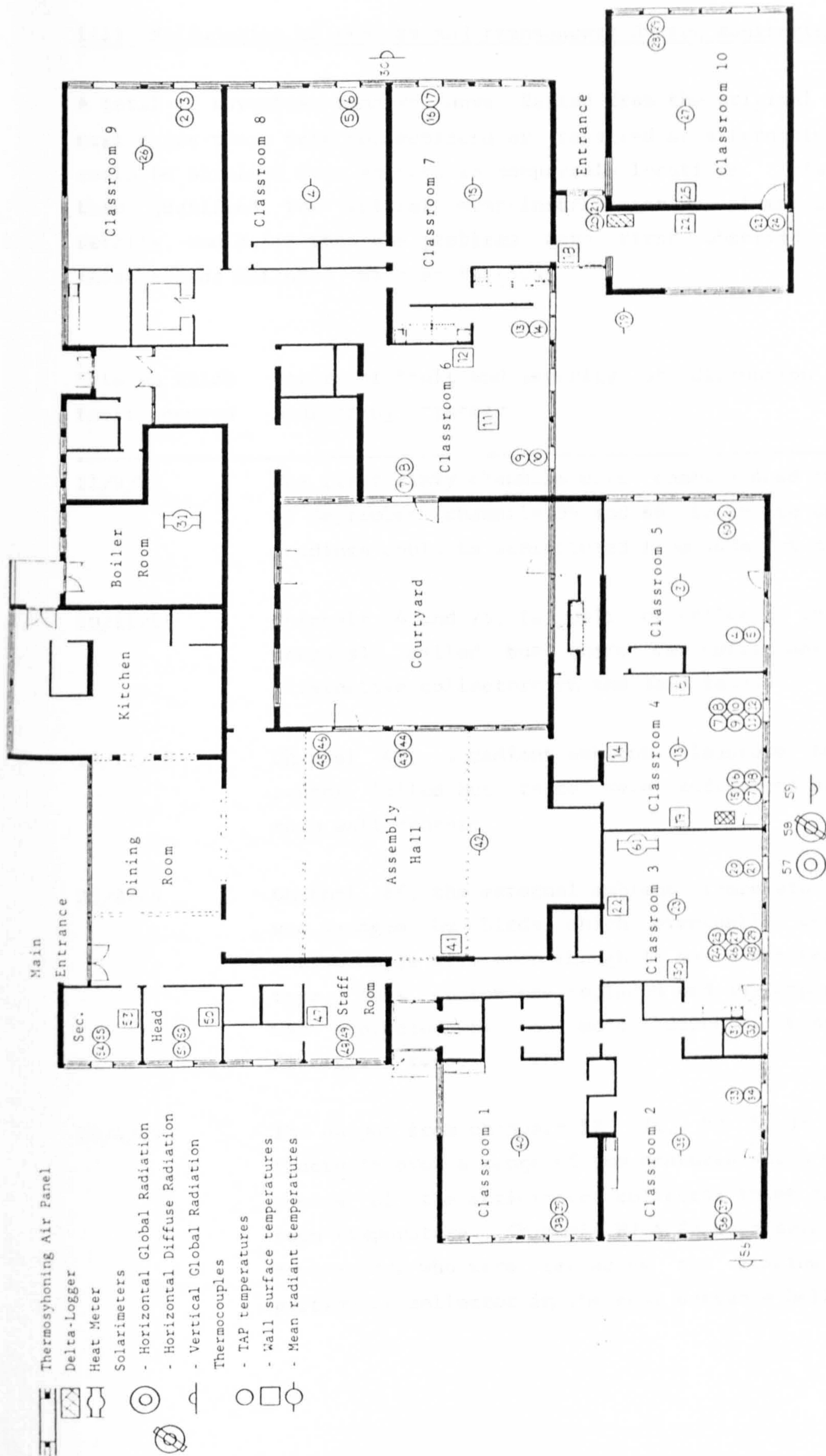


Figure 4.3.1 Plan and location of all monitoring equipment at Nazeing County Primary School.

iii) Malfunction of sensors and transducers during monitoring period

A total of seventeen sensors have failed from the original ninety. In most cases these were not replaced or repaired as alternative readings could be obtained from sensors in comparable locations. This has more than justified the initial over-instrumentation of the school. The details, and dates when the problems were first observed, of all of these sensor failures, were as follows;

Date on which fault occurred	Nature of fault and severity of disruption to overall monitoring strategy
21/9/88	The first sixty channels were commissioned on the 21st of September; channels 59 and 66 failed to operate but readings could be substituted from adjacent sensors.
10/11/88	Channels 74 and 75, (a pair of collector inlet/outlet sensors), failed but there was sufficient data from alternative collectors on the same facade.
13/12/88	Channel 48, a radiant ambient classroom temperature sensor, failed but there were sufficient alternative room wall sensors.
28/2/89	Channel 86, the external ambient temperature sensor, was damaged by birds which eventually severed the thermocouple wire even though it was protected by cloth tape. This sensor was replaced and any exposed wiring was protected by a more durable weather-proof fibreglass tape.
10/4/89	The output from channels 57, 76, 92 & 94 began to fluctuate over a range of temperatures which was far in excess of the anticipated collector inlet and ambient room temperatures. Channels 87 & 88 were severed by the contractors who were replacing the glazing on this particular collector in the east entrance hall.

- 1/5/89 Channel 19, a radiant ambient classroom temperature sensor, was "disconnected" by some of the children. The suspended thermocouple proved to be too great a temptation and the remaining wire was used as a mobile!
- 24/5/89 The solarimeters which were measuring the horizontal global and diffuse solar radiation, channels 63 & 65, failed and were sent back to the manufacturers to be calibrated and repaired.
- 29/5/89 Channel 95, a collector inlet sensor, was damaged when it became exposed at the lower inlet grille.

iv) Maladjustment of non-return damper

Due to the low flow rates involved, the original continuous Tedlar damper proved to be too obstructive to the air flow to permit optimal TAP operation. To alleviate this problem the damper was divided into a larger number of narrower 30mm wide strips to allow the air to pass around each individual section of Tedlar.

In addition to this flow restriction the damper occasionally adhered to the back of the absorber plate as a result of static charges which were generated by the Tedlar film. The air gap between the insulation and the absorber should have been 60mm but in practice this varied from 35mm - 65mm and the static charge in the damper occurred more frequently in collectors which had particularly narrow air gaps.

4.4. Monitoring of Three Thermosyphon Solar Water Heaters

i) Monitoring system hardware

The data logging was accomplished by a modular system in which an Acorn BBC Model B microcomputer was used in conjunction with a specialist instrumentation peripheral (4.4.1). Both the computer and this peripheral were equipped with an IEEE-488 instrument interface (4.4.2). As this has become the established method for interfacing laboratory-scale data-collection systems, many IEEE-488 compatible devices were available. Thus the advantage of the approach adopted was that an almost unlimited expansion and/or adaption of the system was possible by simply adding further devices to the same interface. Figure 4.4.1 shows a schematic block diagram of the complete system (4.4.3).

Early IEEE interface designs were complex and expensive so the data logging systems in which they were incorporated tended to utilise only one interface in a "master" scanner. When extra channels were required, in addition to those available from the master scanner, they were consigned to a "slave" scanner without an interface of its own. This approach had two disadvantages (4.4.1); (i) as the slave scanners could not be used independently, it was difficult to separate large systems into smaller operating units, and (ii), if the master scanner had failed, so would the whole system. These problems were avoided in the data logging system adopted because it consisted of two main-frames each with its own IEEE-488 interface. Each main-frame could accommodate up to six plug-in modules. In this instance, scanner modules, an analogue to digital converter, (A.D.C.), and a water draw-off monitoring module were required.

In Figure 4.4.1, it can be seen that four type 10E scanner modules together with the A.D.C. were resident in the type R6B rack. These four scanners were each capable of switching up to ten input pairs onto the A.D.C. for measurement. Cold junction compensation (C.J.C) for the thermocouples was required to eliminate the effects of ambient temperature variations. The C.J.C. enclosures provided an output which varied linearly with temperature. The equivalent voltage that would be generated by the chosen thermocouple type at a given temperature was evaluated. This is added to the actual voltage recorded before conversion and linearization in the software using the appropriate polynomial.

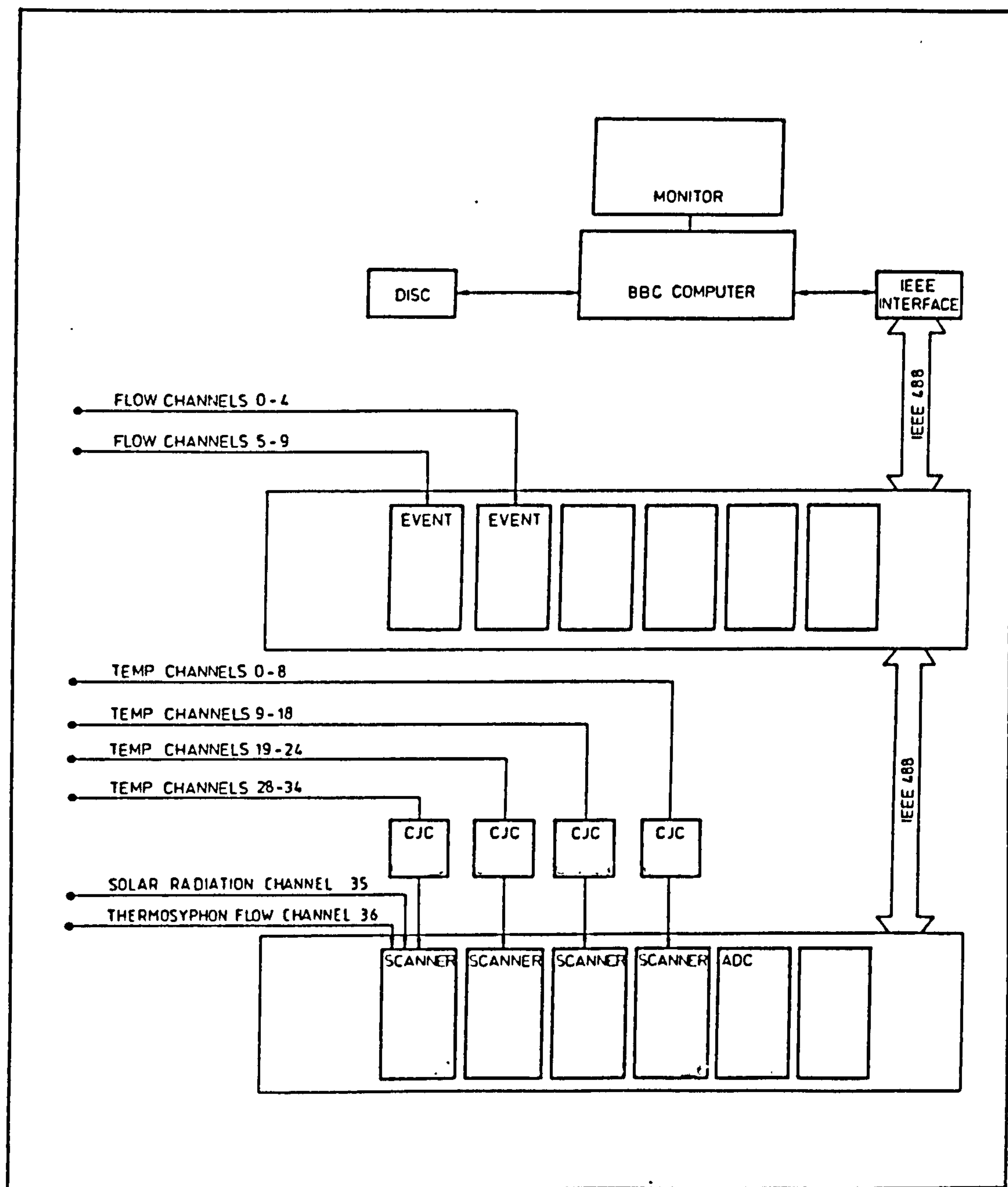


Figure 4.4.1 Schematic block diagram of instrumentation peripheral

Quantifying water consumptions constituted the other requirement. A new module was designed for this purpose: it accepted up to five inputs from pulse-type flow meters of the free contact closure type. This module was capable of informing the computer whenever each or any of the counters had been pulsed. The entire data-acquisition system could be housed in a single 48cm enclosure which provided environmental protection and ease of handling.

ii) Specification of monitoring software

The sensor readings were recorded, using the data acquisition software, at regular intervals (e.g half hourly) and at the beginning and end of any hot water draw-off, with the data then being stored on a floppy disk. A flow chart of the program appears in Figure 4.4.2 and a full listing is given in Appendix B. It consisted of the following parts;-

- a) A short opening sequence, during which the general purpose interface bus was initialised;
- b) The main working section of the programme which continuously displayed the time, the current water draw-off and the previously recorded temperatures, thermosyphon flow-rate and the magnitude of the solar radiation. The event counters were continuously scanned, each count corresponding to a water draw-off of one litre. The approximate start of a hot water draw-off (i.e. a minimum draw-off of one litre) and the end of a hot water draw-off (i.e. present draw-off equalled the previous draw-off) initiated a recording of all the sensors.
- c) The analogue channel conversion and data storage section.

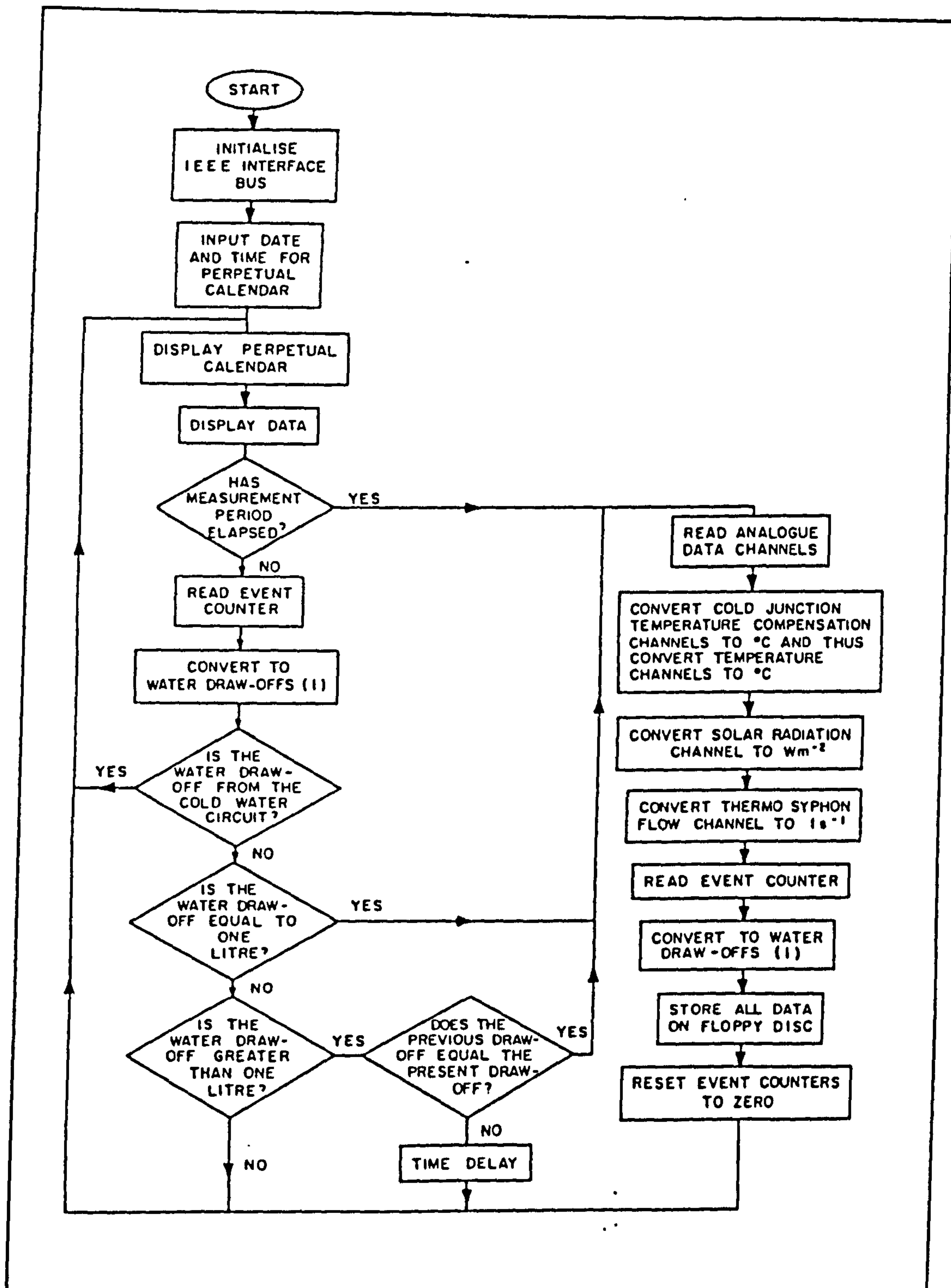


Figure 4.4.2 Flow chart of data-logging computer program

iii) Measurements

The temperatures of the following were measured at 30 minute intervals with additional recordings whenever auxiliary or solar-heated water was drawn off;

- i) the outside ambient environment,
- ii) the solar heated water at five equidistant positions along the vertical axis of the solar stores,
- iii) the inlet and outlet to the collector, and
- iv) the cold mains water.

All the temperatures were measured using copper/constantan thermojunctions. The thermosyphon flow rate of the system in house No. 7 was determined by a magnetic induction flow meter, (4.4.4), selected specially for its low fluid flow resistance. The global insolation on the plane of the collector was measured with a pyranometer appropriately inclined, (Figure 4.4.3). Each time the hot water was used, the volumes of, i) solar-energy heated water, ii) the conventional heated water, and iii) the cold water supply, consumed from each house were measured using turbine flowmeters, (Figure 4.4.4). The specification of the turbine flowmeters is shown in Table 4.4.1.

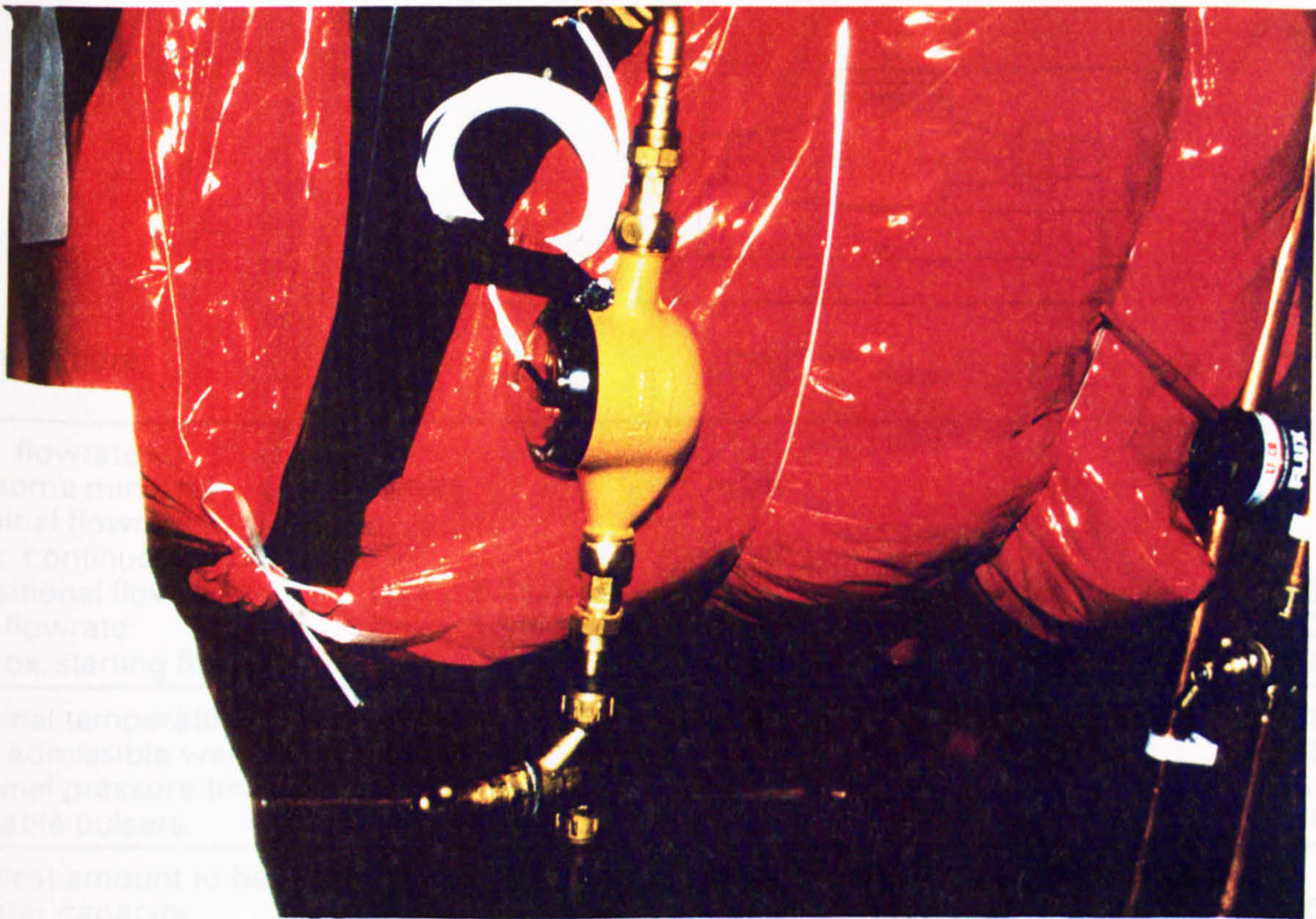
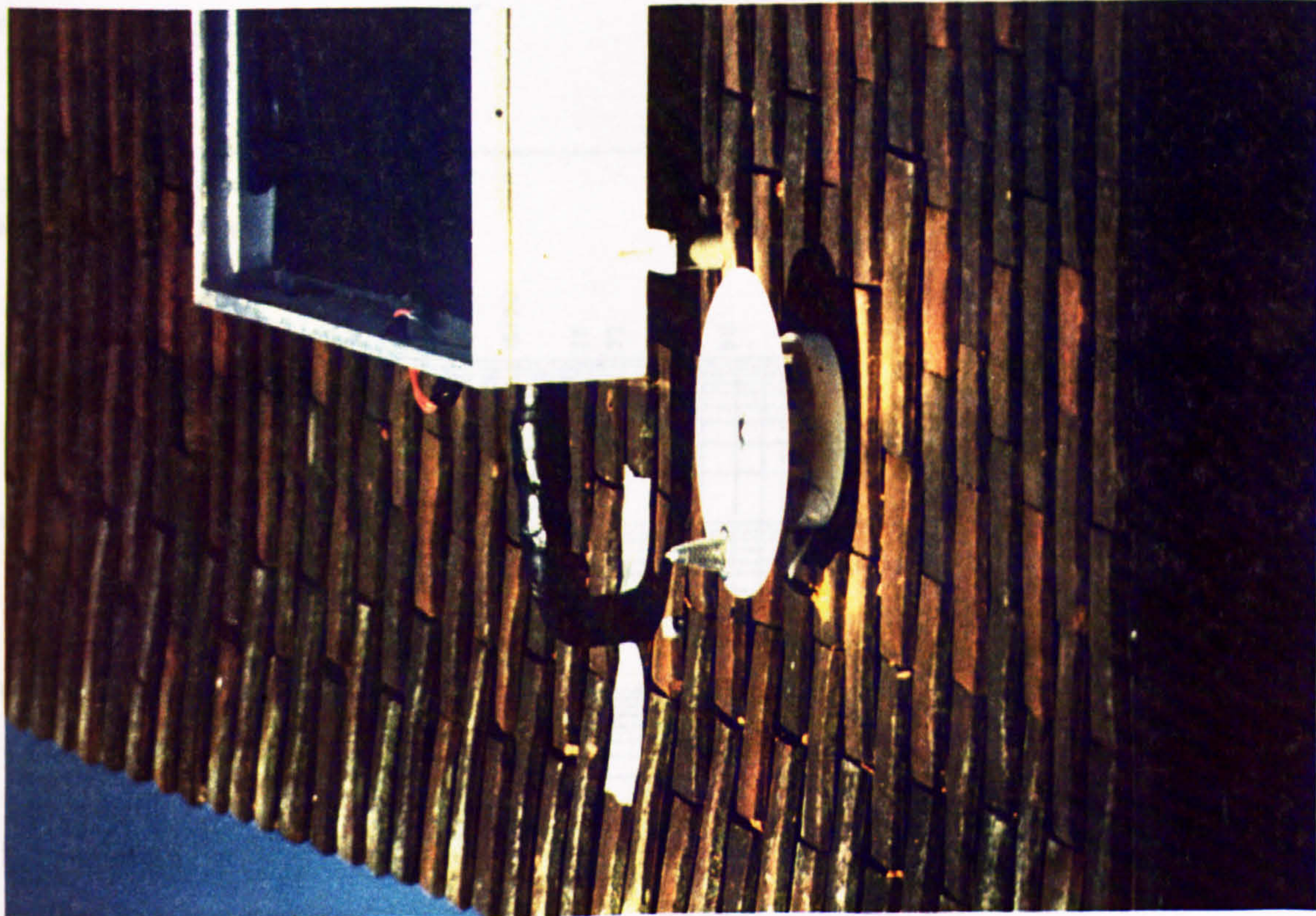
All the data was recorded by a programmable data-acquisition system, (Figure 4.4.5), located in an externally-accessed lock-up compartment (Figure 4.4.6).

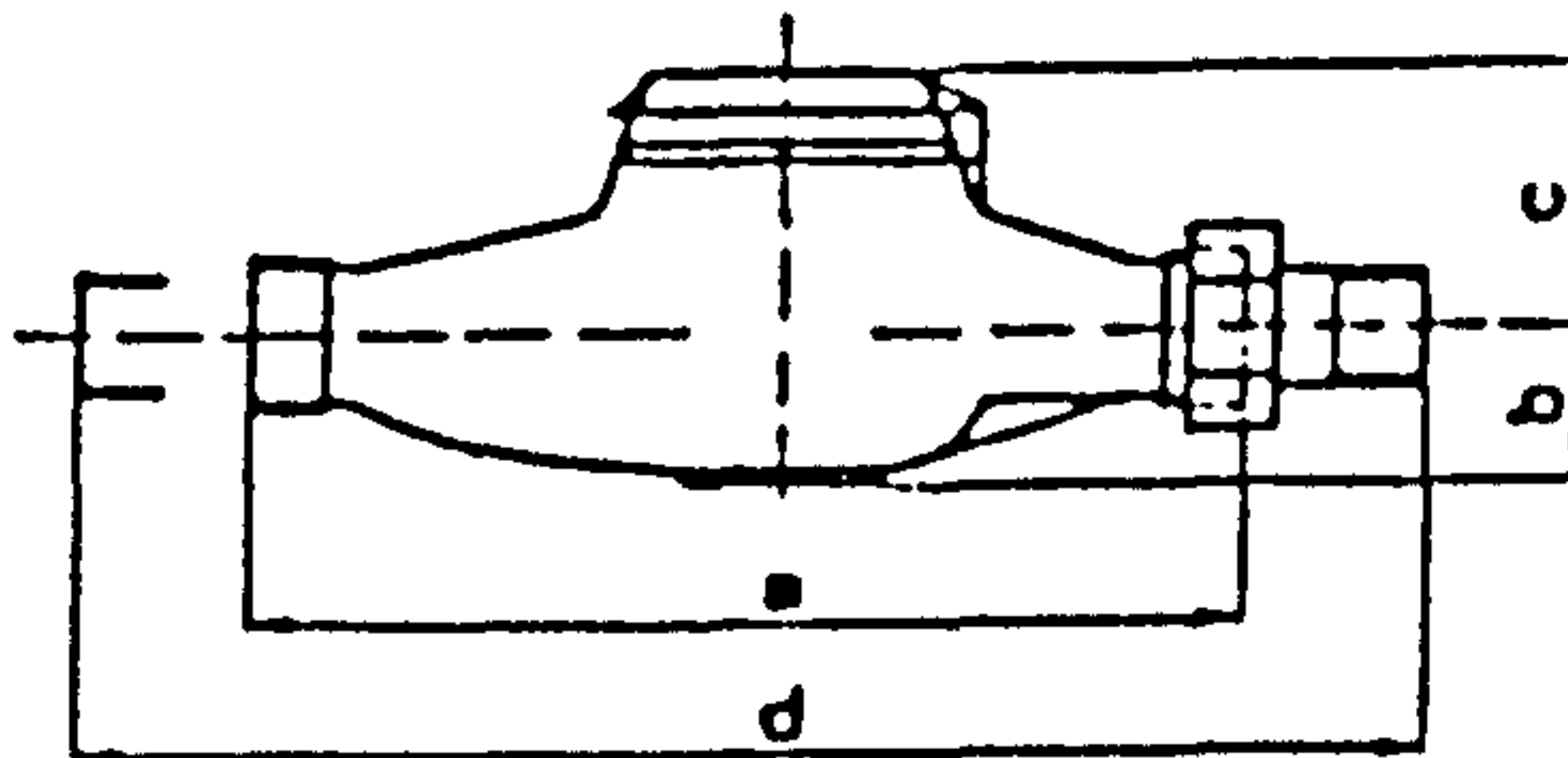
Figure 4.4.3

Pyranometer installed on roof

Figure 4.4.4

Cold water store +turbine flow meter on loft





Nominal bore	mm	25
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Max flowrate (for some minutes)	Q_{max}	m^3/h	10
Nominal flowrate (max. continuous flow)	Q_n	m^3/h	5.0
Transitional flowrate	$Q_t \pm 2\%$ from	m^3/h	0.28
Min. flowrate	$Q_{min} \pm 5\%$ from	m^3/h	0.07
Approx. starting flowrate		m^3/h	0.022

Nominal temperature	30°C
Max. admissible water temperature	60°C
Nominal pressure (max. operating press.)	16 bar
Available pulsers:	RH, NH, IH

Smallest amount to be read	litres	0.1
Register capacity	m^3	100 000

Dimensions

a) Length without couplings	mm	260
b)	mm	40
c)	mm	71.5
d) Length with couplings	mm	375

Weight without couplings	kg	2.8
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Head loss curves

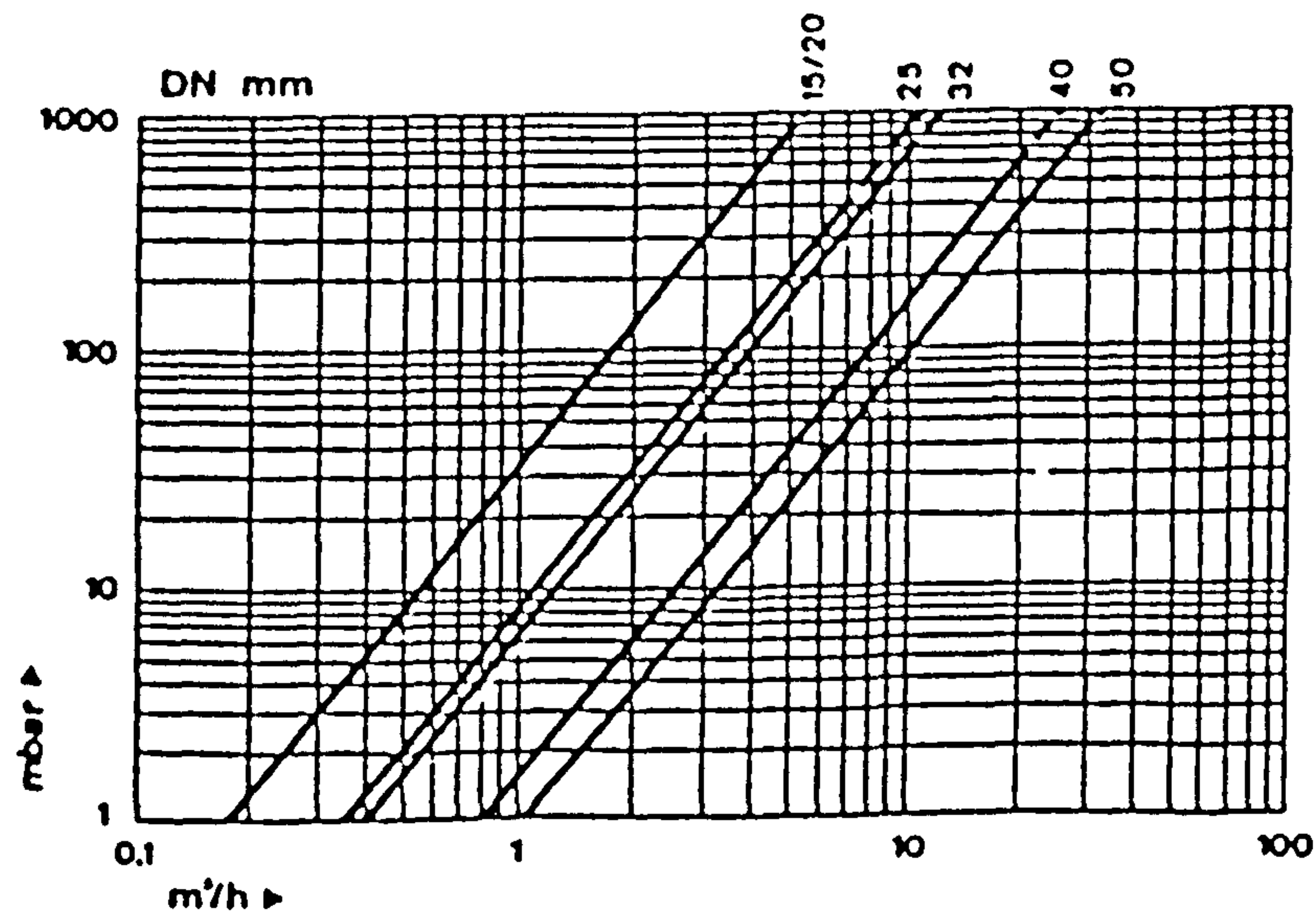


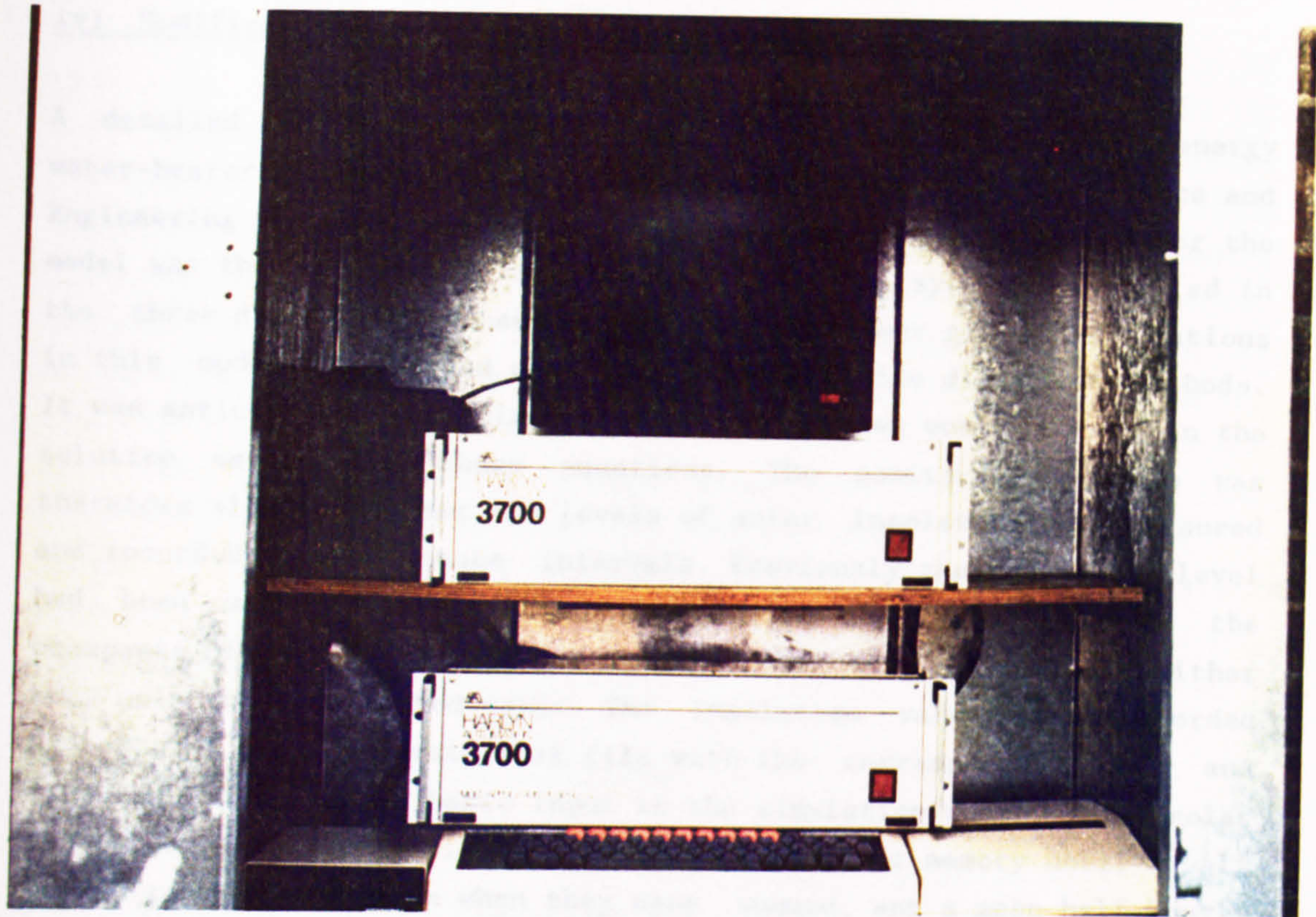
Table 4.4.1
Specification of
turbine flowmeter

Figure 4.4.5

Data-acquisition system

Figure 4.4.6

External lock-up enclosure



iv) Modifications to the monitoring software

A detailed mathematical model of a thermosyphon solar energy water-heater was being developed at Cranfield for the U.K. Science and Engineering Research Council (4.4.5). One source of validation for the model was the long-term data collected from the systems installed in the three demonstration houses. The time-dependent governing equations in this model were solved numerically using finite difference methods. It was anticipated that time steps of two minutes would be used in the solution method for these equations. The monitoring program was therefore altered so that the levels of solar insolation were measured and recorded at two minute intervals. Previously the insolation level had been measured every 30 minutes or alternatively whenever the occupants of any of the houses consumed more than one litre of either hot, cold or solar-heated water. The insolation values were recorded and stored in a separate disk file with the corresponding date and time, and used as a basic input to the simulation model. These solar insolation values were also stored in the computer memory until a half hourly reading was taken when they were summed, and a mean half hourly value recorded where previously an instantaneous value had been stored. This was considered to give a more realistic representation of the energy incident on the collector over the day.

v) Data storage

All data collected from the houses stored in disk form were transferred onto magnetic tape housed at the Cranfield Computer Centre and remained available on the Cranfield VAX 11/785 computer system. This was a permanent back-up for the data stored on disk, and also enabled the analysis and presentation of the results using the large mathematics library and graphics software available on the VAX system, if required. In addition, the data were being used to validate a high-level, VAX-based mathematical simulation model of natural-circulation solar-energy water heaters being developed for the U.K. Science and Engineering Research Council.

Transfer of the data was achieved using KERMIT, a program developed at the Columbia University, New York, USA which allowed simple and flexible transfer of data from the Acorn BBC model B microcomputer to the mainframe or indeed to another microcomputer. Simple terminal emulator programs which are available commercially for the BBC micro

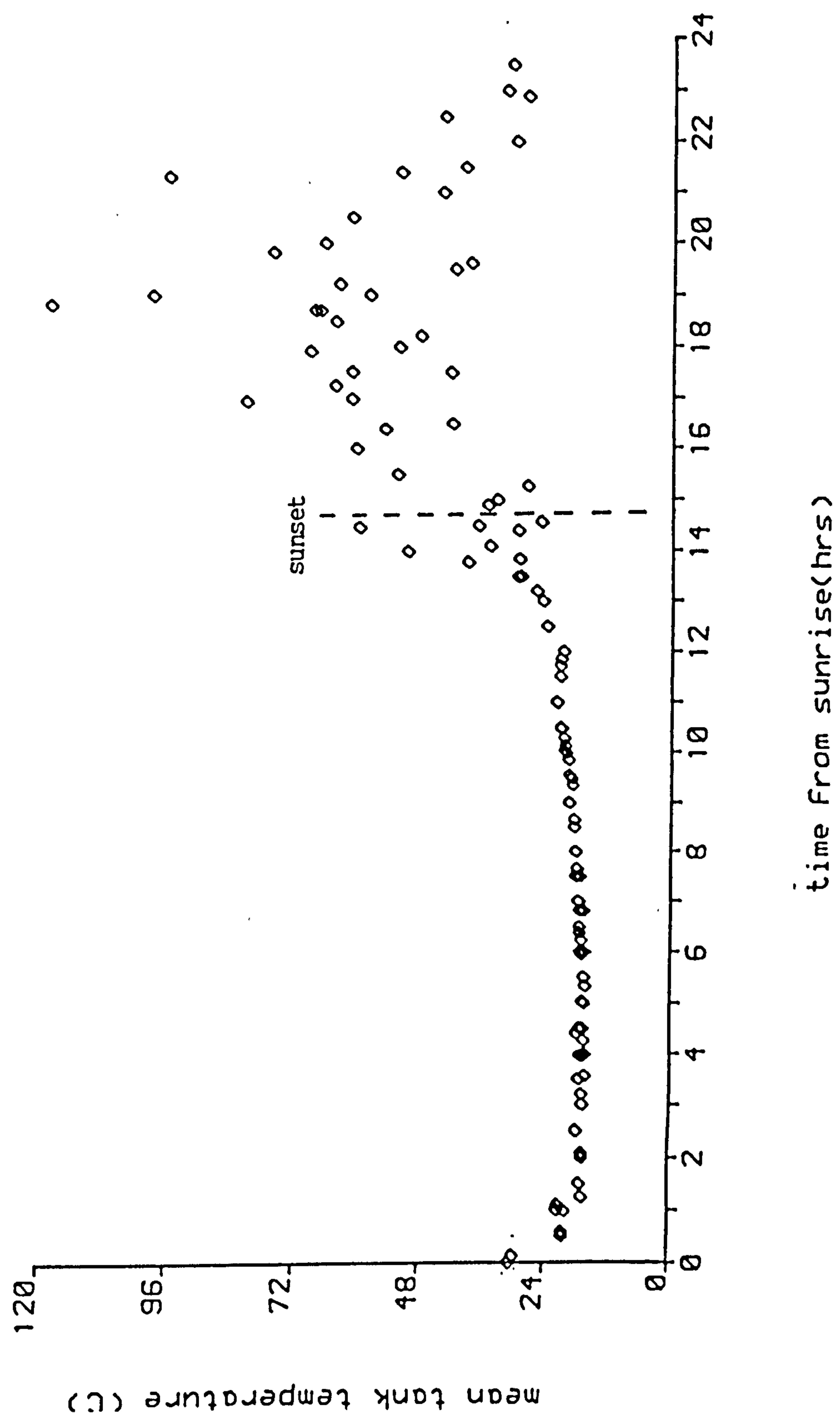
could be used to input data from a BBC disk into a mainframe file, as they were less restricted by the range of characters that could be sent. In addition, if the communication line being used was vulnerable to electrical noise, then there was nothing to prevent data being "corrupted" during transmission. The use of the KERMIT program running simultaneously both on the VAX and the BBC micro computer however, overcame these problems. The data were then sent according to an established protocol, which ensured that the data transmitted from the BBC microcomputer corresponded to the data received by the VAX mainframe computer. Any corrupted data were detected and the transmission was repeated until the correct data had been sent. A binary file was created on the VAX 11/785 system. A program, (4.4.6), converted this binary file into a form which allowed easy access to, and economical storage of, the data.

vi) The quality of the recorded data

On some days it was found that the data recorded exhibited values which were considerably higher than those which could be expected reasonably. This phenomenon was apparent particularly with the thermocouple temperature readings in the solar store, an extreme case of which is shown in figure 4.4.7. It was also found that this scatter of the results commenced approximately, either before sunrise, or after sunset. As this also corresponded to periods when many household electrical appliances were most likely to be in use, it was considered likely that the thermocouple leads were receiving stray electrical signals from these appliances. Evidence of electrical interference was also detected in the recorded solarimeter readings. The appliances that would cause electrical interference included, televisions, radios, thermostats (on cookers and immersion heaters) and also poor electrical contacts on plugs, wall sockets and light switches.

This electrical interference at the onset of the insolation period made the estimate of an initial tank temperature, (used in validating the analysis for the long-term correlation of performance), very difficult. However, since the mean tank temperature was observed to change very little during the first two hours of the insolation period, an initial value was obtained by extrapolating backwards after discarding the first ten readings.

Figure 4.4.7 Effect of signal interference on mean tank temperature readings



Sunrise and sunset were taken initially as the points in time where the measured solar radiation intensity rose above, and dropped respectively below, a value of 5% of the maximum recorded level for that day. However, it was found that extreme electrical interference on some days would give spurious high values of insolation at night resulting in a very poor estimate of the total period of insolation. The initial correlations were improved considerably when a theoretical value for the insolation period was calculated for each day based on the latitude of the installations and the time of year (4.4.7).

vii) Interruptions to data collection

The decision was taken to drain down the solar-energy water heating systems in houses 7 and 9 over the winter period from September 1985 until spring 1986. Therefore no data was collected from these two houses for this period. This was done in an attempt to improve relations with the occupants and, due to the unreliability of the automatic drain-down and the auxiliary heater frost protection mechanisms during the previous winter, was considered essential. This decision proved subsequently to have been a fortuitous one; the solenoid operated drain down valves in house 9 were found to be disconnected from the mains supply despite having been repaired supposedly since the previous failure of this system. The remaining indirectly heated system, relying for frost protection on a circulating propylene glycol antifreeze solution, continued to operate successfully throughout the winter months and the data collected was used in the validation of long-term performance correlations.'

4.5 References

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- 4.4.6 B. Highfield, Cranfield Computer Centre, Cranfield Institute of Technology, Bedford, U.K., Private Communication, 1986.

- 4.4.7 P.A. Hobson, B. Norton & S.N.G. Lo, "Demonstration of Thermosyphon Solar-Energy Water Heating in a Group of Three Dwellings", EEC Technical Report No.4, Project Number SE 034/83, April, 1986.

CHAPTER FIVE

PERFORMANCE DATA

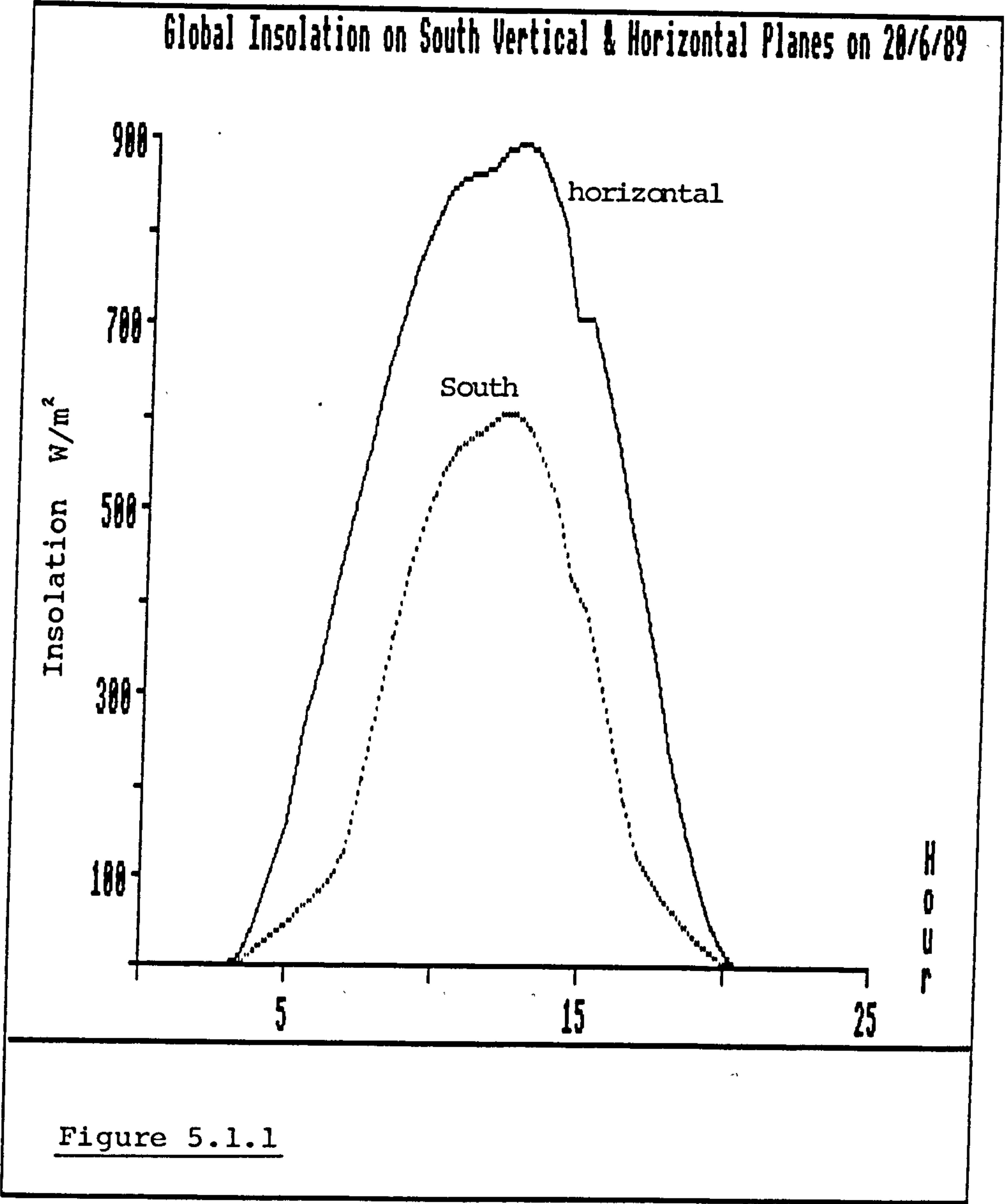
5.1 Instantaneous Performance of Roof-Space Collector Dwellings

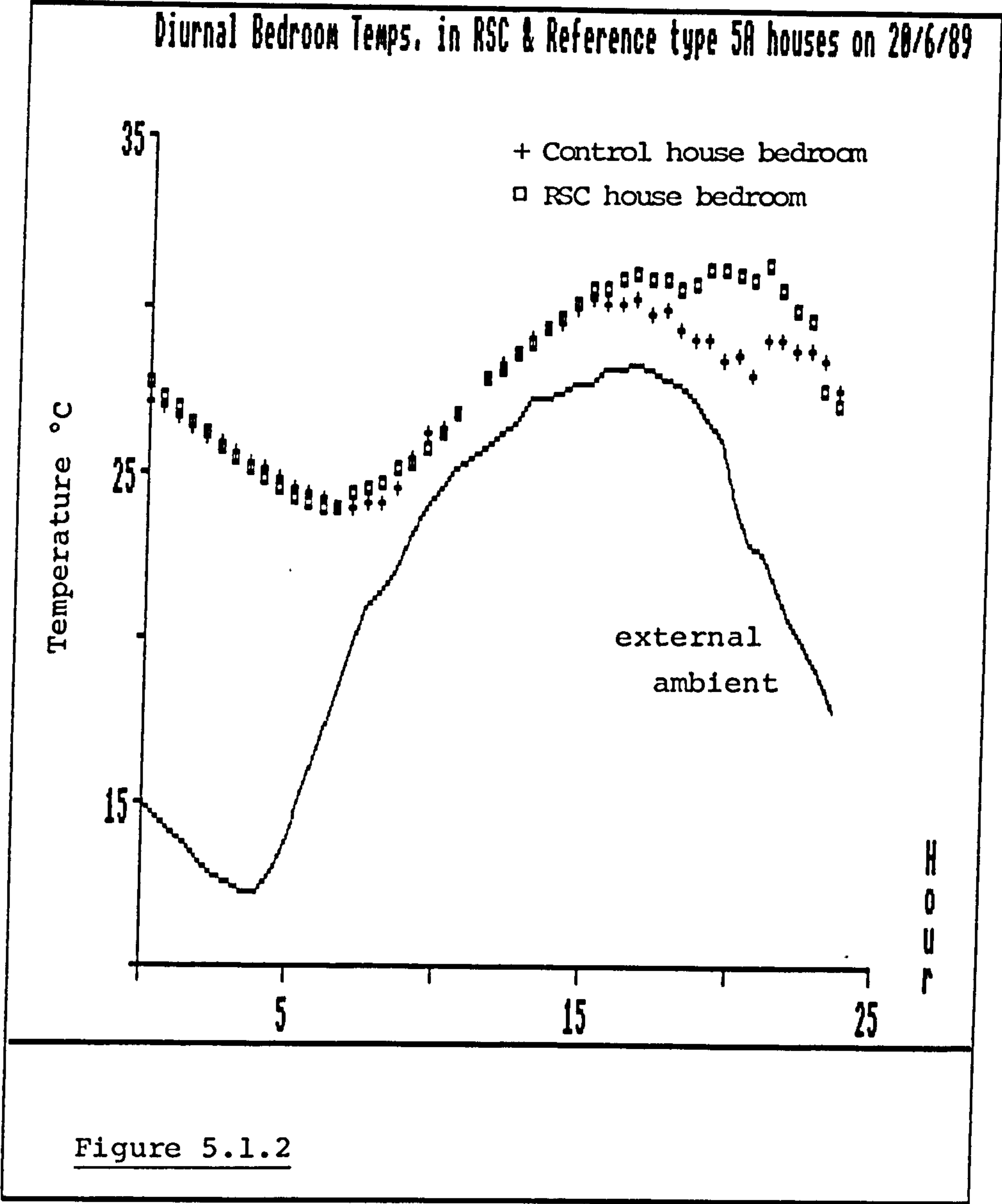
1) Comparison of RSC dwelling with control dwellings

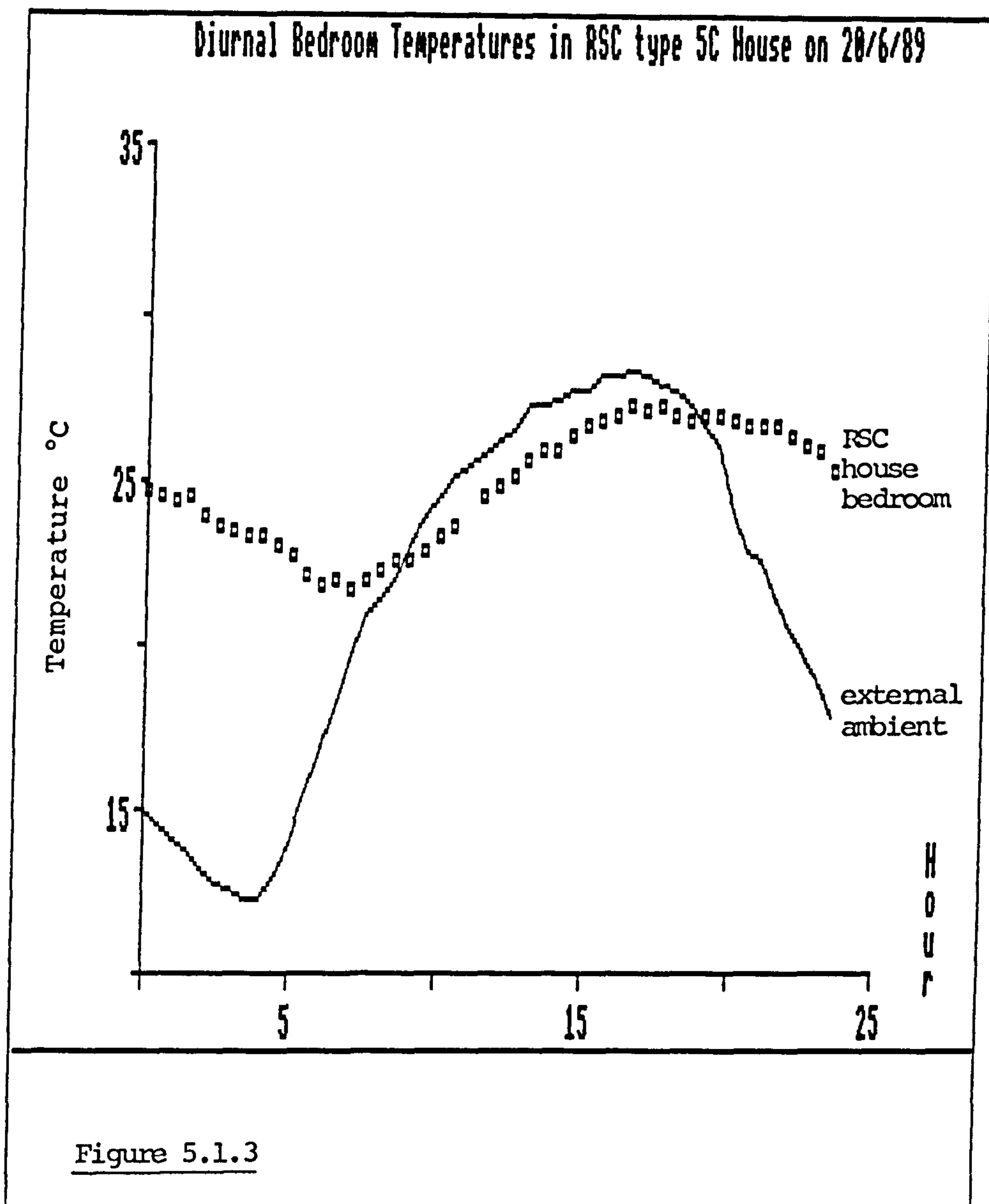
The results for one of the warmest days in June in 1989, with very high levels of global insolation on a horizontal plane, (900W/m^2 maximum), were used as an indication of the maximum temperatures that could be attained in a roof space collector during the summer months. It was also necessary to quantify the duration of such elevated temperatures to determine if any degradation of the roof trusses occurred as a result of thermal cycling. The resolution with which these transient temperature changes, (due to the constantly fluctuating levels of global insolation), could be measured was governed by the data-acquisition equipment. So, the software was programmed to sample the insolation at thirty second intervals, and recorded the arithmetic mean of these readings every 15 minutes.

On the 20th of June 1989 the insolation on a horizontal plane reached 898 W/m^2 at 12-30pm (figure 5.1.1), with a maximum ambient temperature of $28.3\text{ }^\circ\text{C}$ at 4-30pm. As can be seen from figure 5.1.2 the bedroom temperatures in an RSC house and a reference house were both greater than the ambient temperature throughout the day. As expected the bedroom temperature in the RSC house was marginally higher than the bedroom temperature in the control house during the latter periods of the day due to radiation/conduction through the floor of the RSC. The similarity of the two bedroom temperatures in these type 5A houses suggested that the overheating occurred as a result of direct gain rather than from the roof space collector. (The inclusion of high level openings within the direct gain space, to avoid overheating, was suggested well before the dwellings had been completed, but neither the architects nor the contractors regarded this as a potential problem. The overall comfort of the occupants throughout the year should, of course, never be compromised for the sake of maximising solar gains.)

The significantly lower temperatures of the ground floor bedrooms, (which exhibited a time lag of up to two hours), in the type 5C houses showed that the design could be integrated into a workable solution, figure 5.1.3. The bedroom temperature actually fell below that of ambient for almost 11 hours!



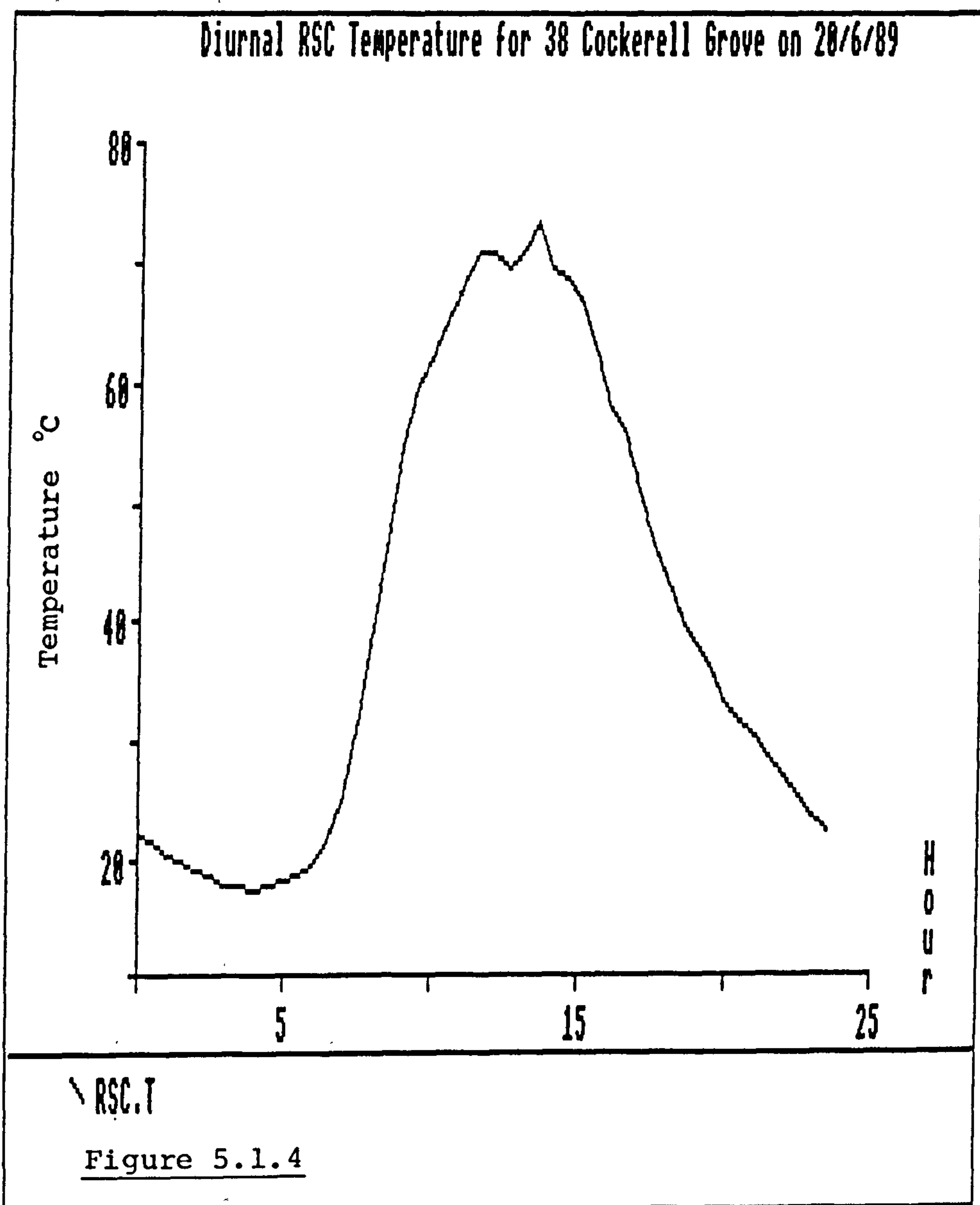


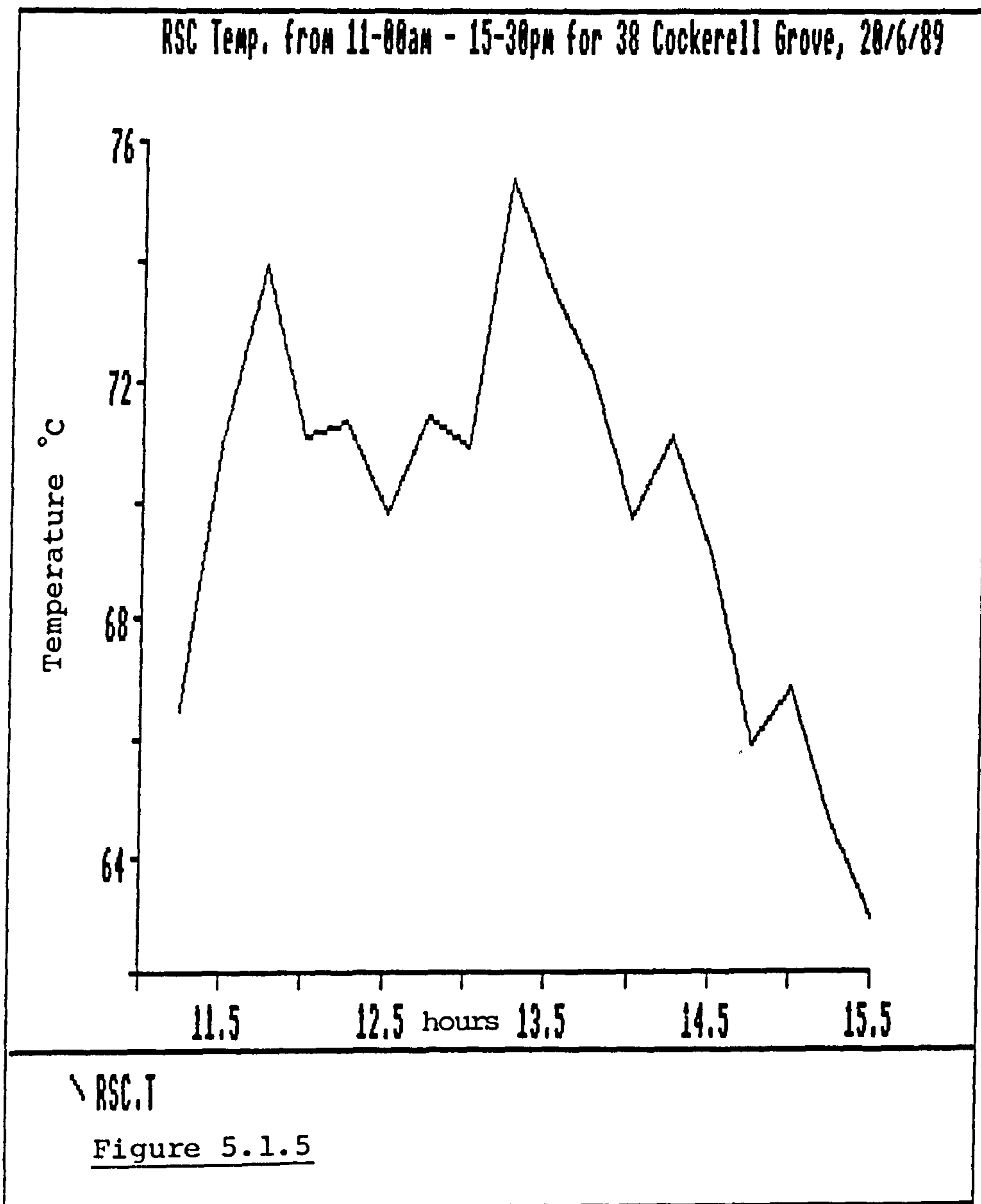


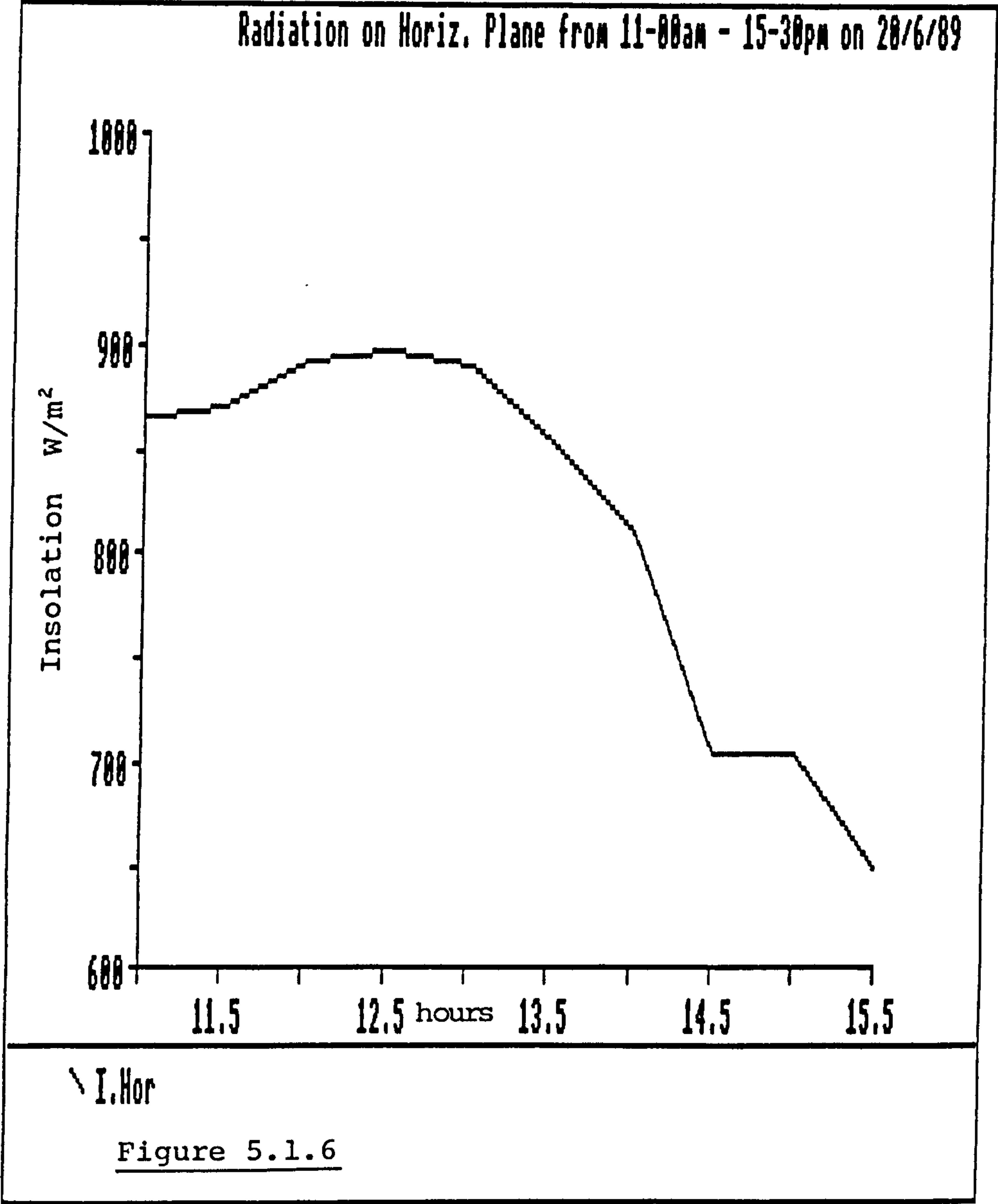
ii) Temperatures within the Roof Space Collector

The maximum temperature attained by the RSC on the 20th of June was 75.4 °C at 1-15 pm as shown in figure 5.1.4. This was no higher than expected considering that the area of the eaves ventilators was below that which was specified to ensure a sufficient air-flow rate through the RSC. The contractors did not appreciate the significance of this minimum requirement.

A closer inspection of the temperature profile in the RSC between 11-00am and 3-30pm revealed that the temperature decreased while the level of insolation remained unchanged from its normal diurnal distribution as shown in figures 5.1.5 & 5.1.6. This indicated that the memory-metal actuated ventilators were operating as intended.







5.2 Long-term performance of Roof-Space Collectors

i) Data from 1989/90 heating season

During the heating season which began in 1989 a large variety of heating patterns, (and hence occupancy patterns), were observed up to 31st January 1990. (The data for February 1st onwards is not yet available for analysis). Details of the heating regimes of each dwelling, and the number of days for which full monitoring data exists, is tabulated in Table 5.2.1.

The most important factor in achieving a significant solar contribution was a daily auxiliary heating profile which mimicked that of the daily insolation. Detailed frequency distributions of the diurnal auxiliary heating profiles for each dwelling are shown in figures 5.2.1 - 5.2.5. The incidence of the operating periods of each warm-air auxiliary heating system which occurred within the insolation period could be identified, subjectively, with ease. This was especially important with occupants who chose to have up to thirty heating regimes, e.g. RSC-32 Figure 5.2.5. Each distribution was also plotted in accordance with the three different house types in order to evaluate any significant differences in their performance.

A complete range of data was available for nine Type 5A, three type 5B and seven type 5C dwellings. The distributions of the operating periods of their heating systems showed that only six of these nineteen dwellings utilised the auxiliary heating system predominantly during the insolation period. Such a range of occupancy patterns and auxiliary heating requirements only permitted a limited number of comparisons to be made between the roof-space collector dwellings and the control dwellings of the same house type.

Table 5.2.1. Monitoring data for heating system from each house
at Shenley Lodge 5 Milton Keynes up to 31/1/90

RSC Plot No. (a)	System Address	Address at Shenley Lodge 5	Roof type	House type	Beginning of "heating season"	Number of monitored days	Number of days during which heating system is off
1	60_1	31 L H	RSC	5A	11:09:89	173	6
2	60_3	33 L H	RSC	5A	02:11:89	73	0
3	60_5	35 L H	RSC	5A	03:10:89	149	15
4	50_5	67 C G	RSC	5C	16:10:89	140	2
5	51_2	68 C G	RSC	5C	06:11:89	108	20
6	51_6	69 C G	RSC	5A	27:12:89	63	6
9(b)	51_7	38 C G	RSC	5A	01:07:89	211	17
18	48_5	47 C G	RSC	5A	15:10:89	128	6
19	48_2	48 C G	Ctrl	5A	01:10:89	169	17
22	49_1	51 C G	Ctrl	5A	09:09:89	47(c)	6
23	49_6	52 C G	RSC	5A	03:10:89	140	0
24	49_7	54 C G	RSC	5C	01:10:89	106(d)	22
25	49_2	53 C G	RSC	5B	28:08:89	188	0
26	49_4	56 C G	Ctrl	5C	30:06:89	242	0
27	49_3	55 C G	Ctrl	5B	01:06:89	240	0
28	49_5	58 C G	RSC	5C	03:10:89	146	5
29	49_8	57 C G	RSC	5B	01:06:89	285	7
30	50_1	60 C G	Ctrl	5C	03:30:89	170	1
31	50_2	59 C G	Ctrl	5B	01:06:89	245	0
32	50_3	62 C G	RSC	5C	24:10:89	124	0
33	50_4	61 C G	RSC	5B	28:09:89	165	6

C G - Cockerell Grove

L H - Livesey Hill

RSC - House incorporating Roof-Space Solar Collector

CTRL - Control dwelling

a) Plot number 1 will be denoted RSC-1

b) Highly Monitored House

c) No data from 26:10:89 to 28:02:90

d) No data from 23:01:90 to 28:02:90

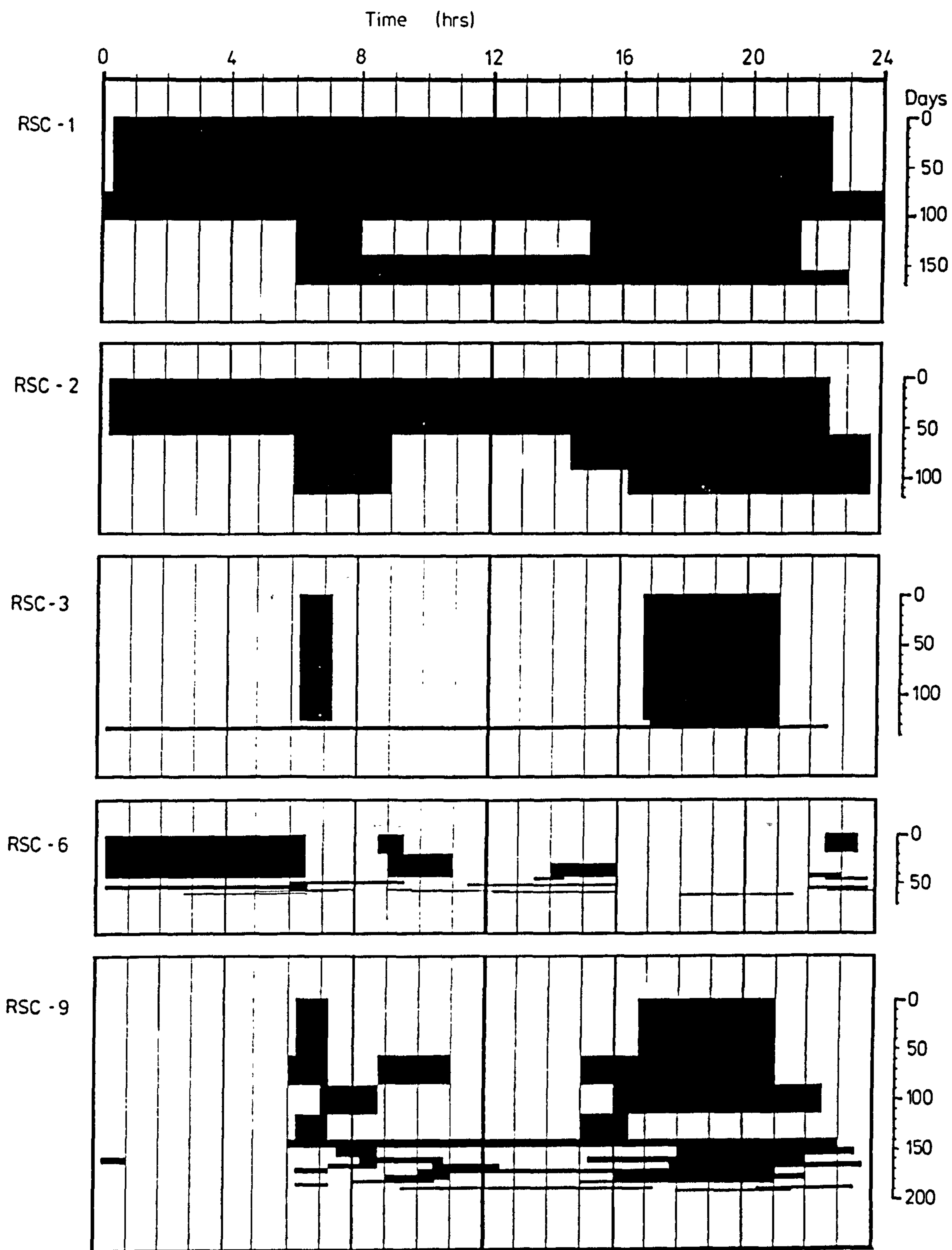


Figure 5.2.1 Frequency distribution of days during which auxiliary space-heating is operational for five type 5A dwellings

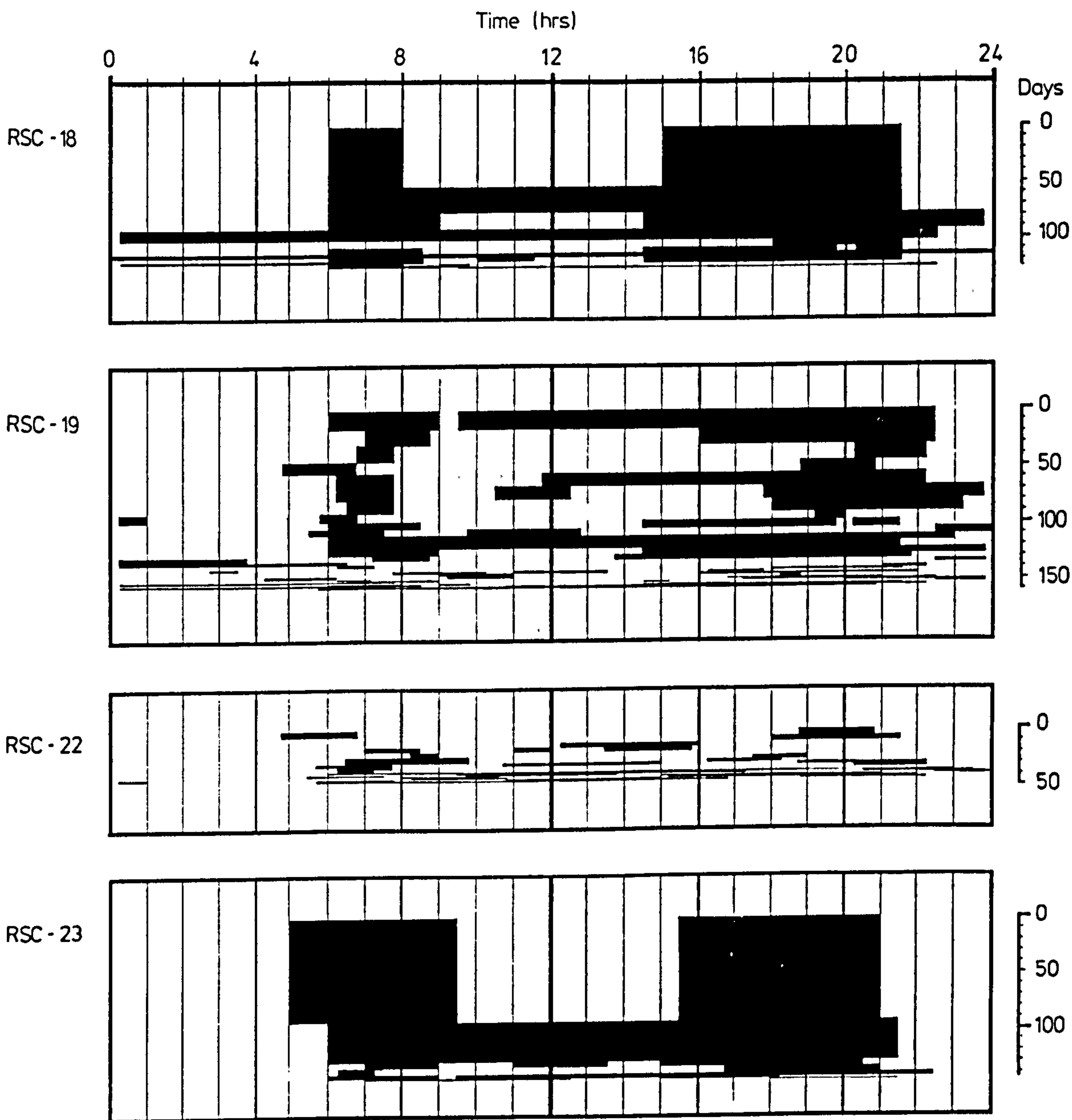


Figure 5.2.2 Frequency distribution of days during which auxiliary space-heating is operational for four type 5A dwellings

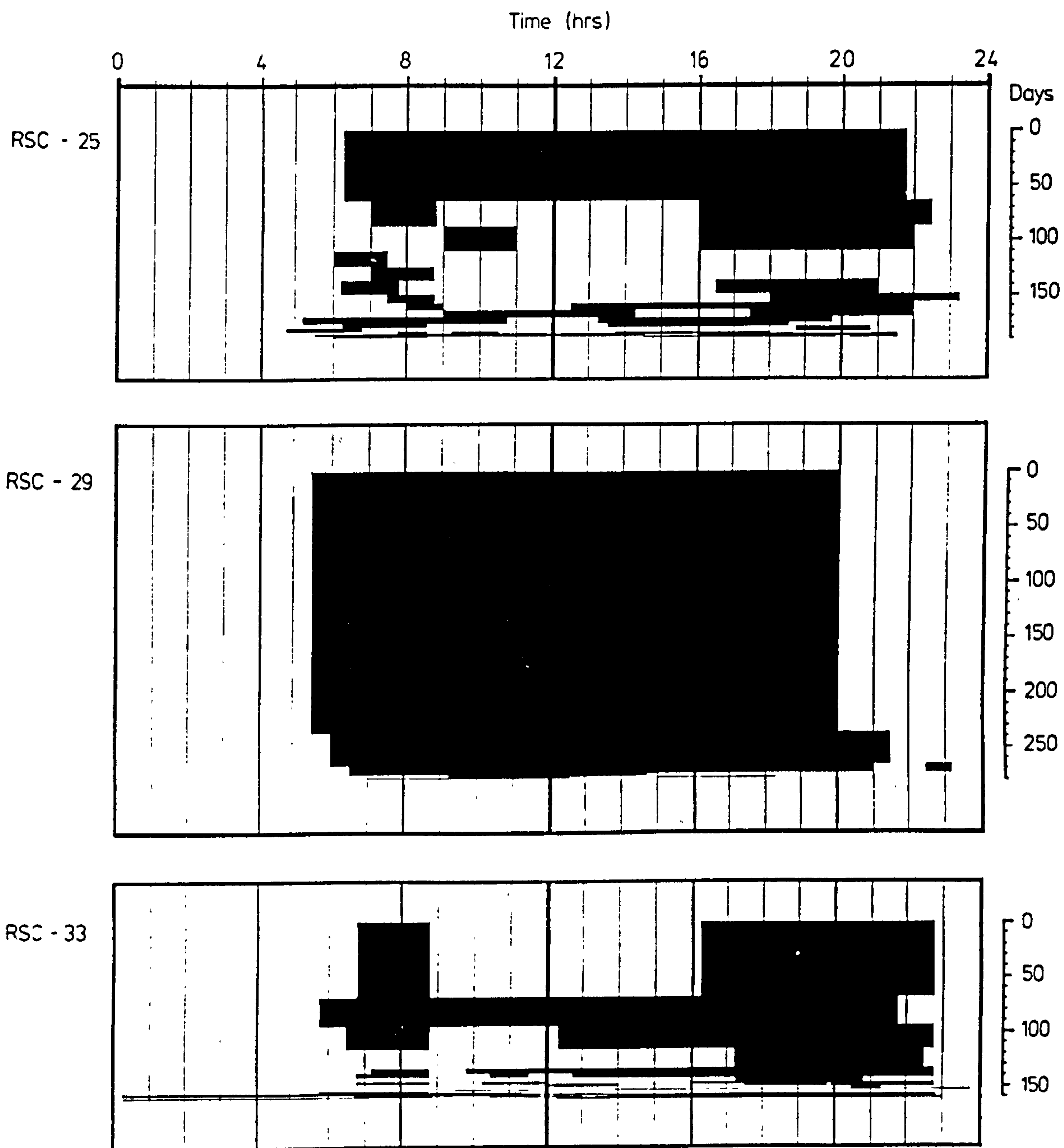


Figure 5.2.3 Frequency distribution of days during which auxiliary space-heating is operational for three type 5B dwellings

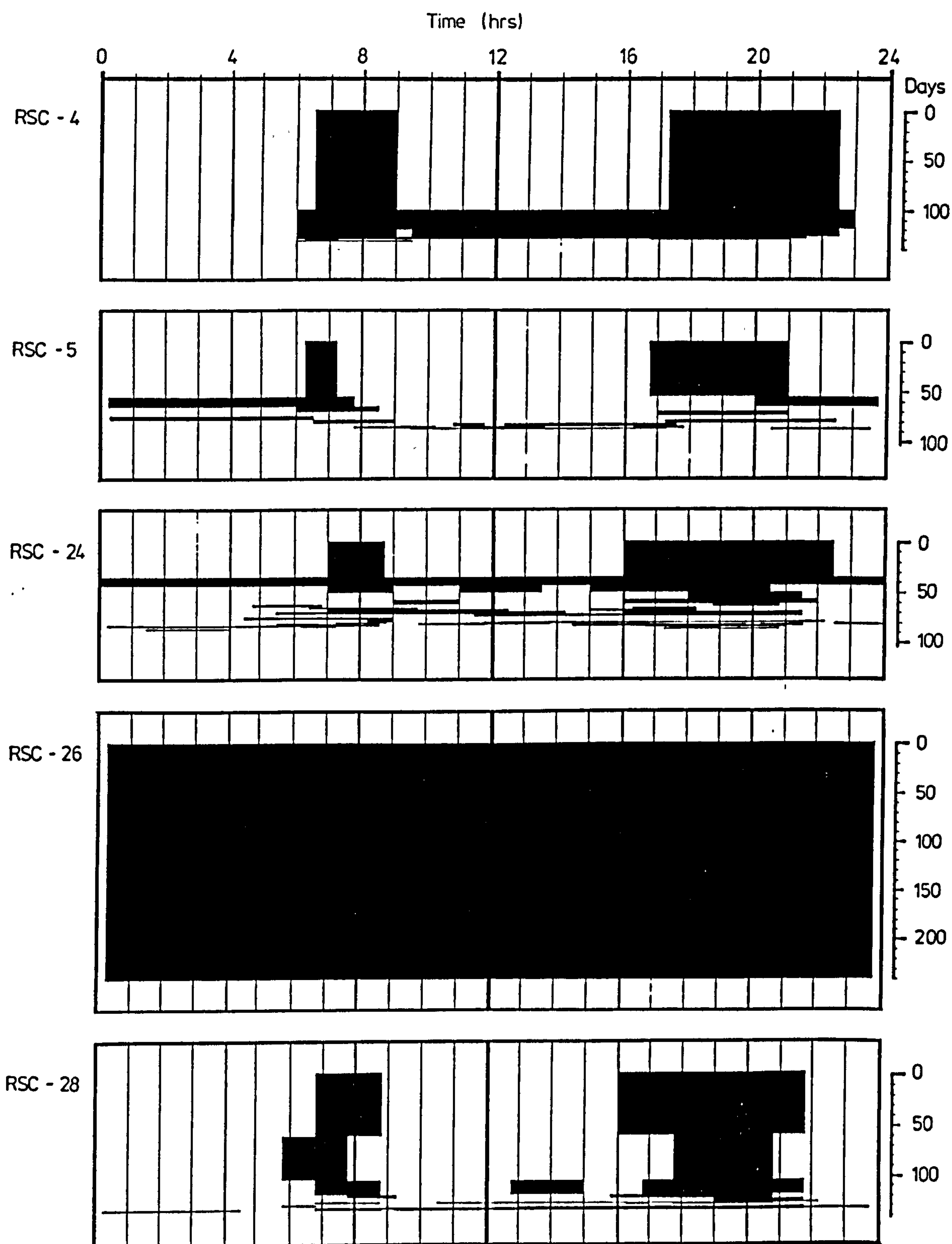


Figure 5.2.4 Frequency distribution of days during which auxiliary space-heating is operational for five type 5C dwellings

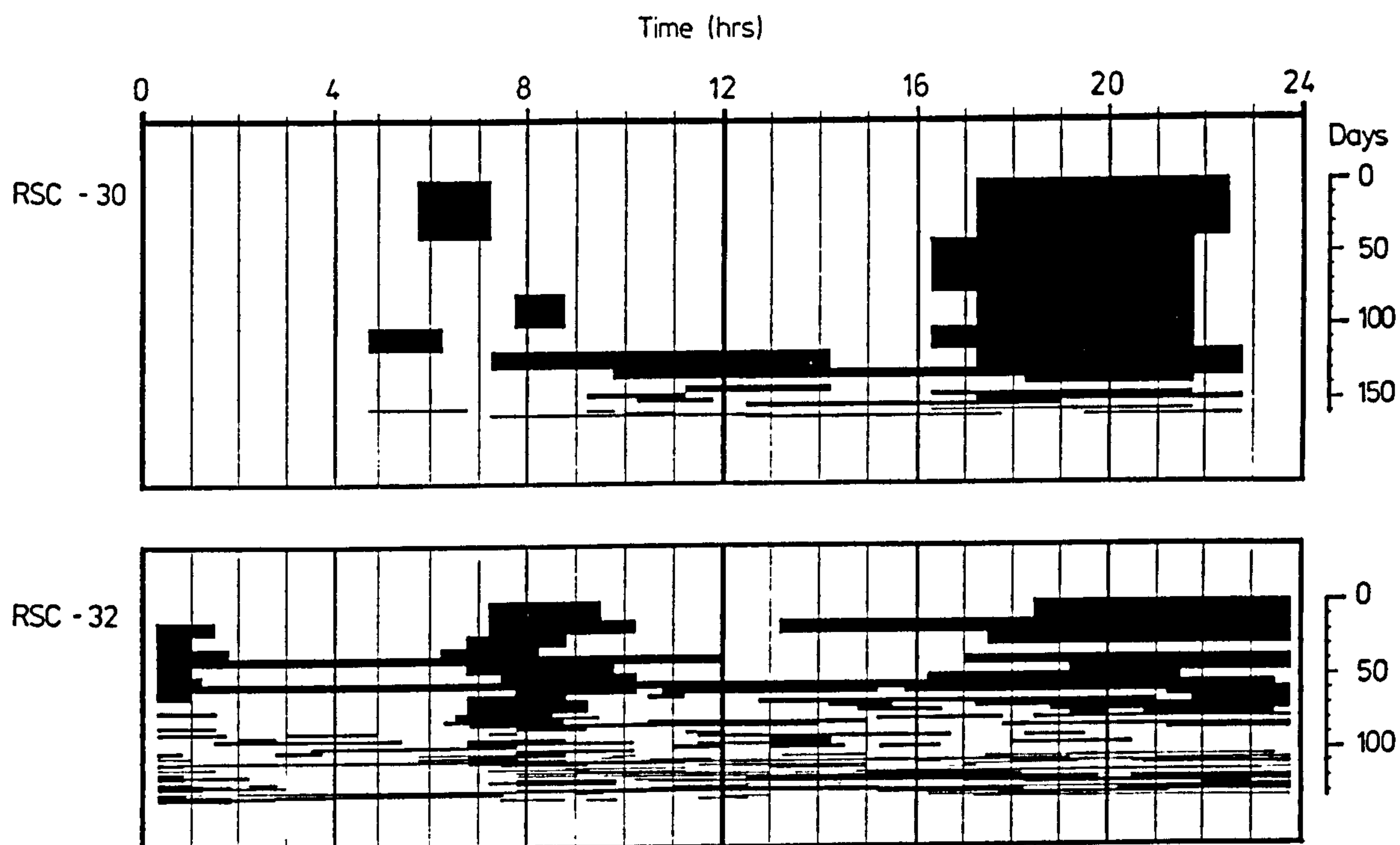


Figure 5.2.5 Frequency distribution of days during which auxiliary space-heating is operational for two type 5C dwellings

ii) Derivation of performance indices for Roof Space Solar Collectors

The Beneficial Operation Index was a relationship based entirely on the portion of time, (and not energy), within the insolation period during which the fan in the HRU delivered solar heated air to the central warm-air heating unit. This allowed the occupancy patterns, and consequently the heating patterns, of the 21 dwellings to be correlated with the useful heat gained from the RSC.

Beneficial
Operation Index (BOI) = Portion of insolation period during which
solar heating is circulated from RSC

RSC Space
Heating = $Q_{rsc} = \dot{m} C_p (T_{thru, in} - T_a) \Delta t$

Thermal
Efficiency = $\eta = \frac{Q_{rsc}}{I_{plane} A_{rsc} \Delta t}$

Solar Heating
Fraction (SHF) = $f_h = \frac{Q_{rsc}}{Q_{aux} + Q_{rsc}}$

a) Beneficial Operation Index (BOI) for RSC Houses

This performance index was calculated, on a daily basis, for all houses where sufficient data existed. This parameter did not, however, account for the time of day within the insolation period during which the HRU fan was operational, i.e. more solar radiation is utilised at midday than at sunrise and sunset. In addition, the beginning of the 1989/1990 "heating season" ranged from as early as 1st June, at 57 Cockerell Grove, to as late as 27th December at 69 Cockerell Grove. The disparate nature of the majority of heating patterns did not permit a weighted mean daily energy consumption for each dwelling to be calculated with any degree of confidence.

Despite these anomalies there was still a discernable correlation between the BOI, and the total space-heating contribution from the RSC for the whole heating season up to 31st January 1990, for all RSC dwellings (figure 5.2.6).

b) Thermal efficiency of selected RSC's

The distributions of daily gas consumption from six RSC dwellings were selected from figures 5.2.1 to 5.2.5 for further analysis. They were chosen, from the graphs, on the basis of the compatibility of their occupancy patterns with the insolation period. This subjective assessment was supported when further calculations revealed that these six dwellings also had the highest Beneficial Operation Indices.

The thermal efficiencies of each of the selected RSC dwellings was calculated on a monthly basis and were shown to be at their most efficient in December, (figure 5.2.7). This occurs when the space heating load is at its greatest. Correlating these two latter parameters showed a high degree of scatter but this resulted from a significant disparity in their Beneficial Operational Indices, (figure 5.2.8). An improved and more pertinent correlation would be between the BOI and thermal efficiency, (figure 5.2.9). It can be seen that efficiencies, (for the heating season up to 31st January 1990), of up to 65% were achieved as the BOI approached a maximum.

Fig. 5.2.6 BOI v Q_{rsc} for all house types up to 31/1/89

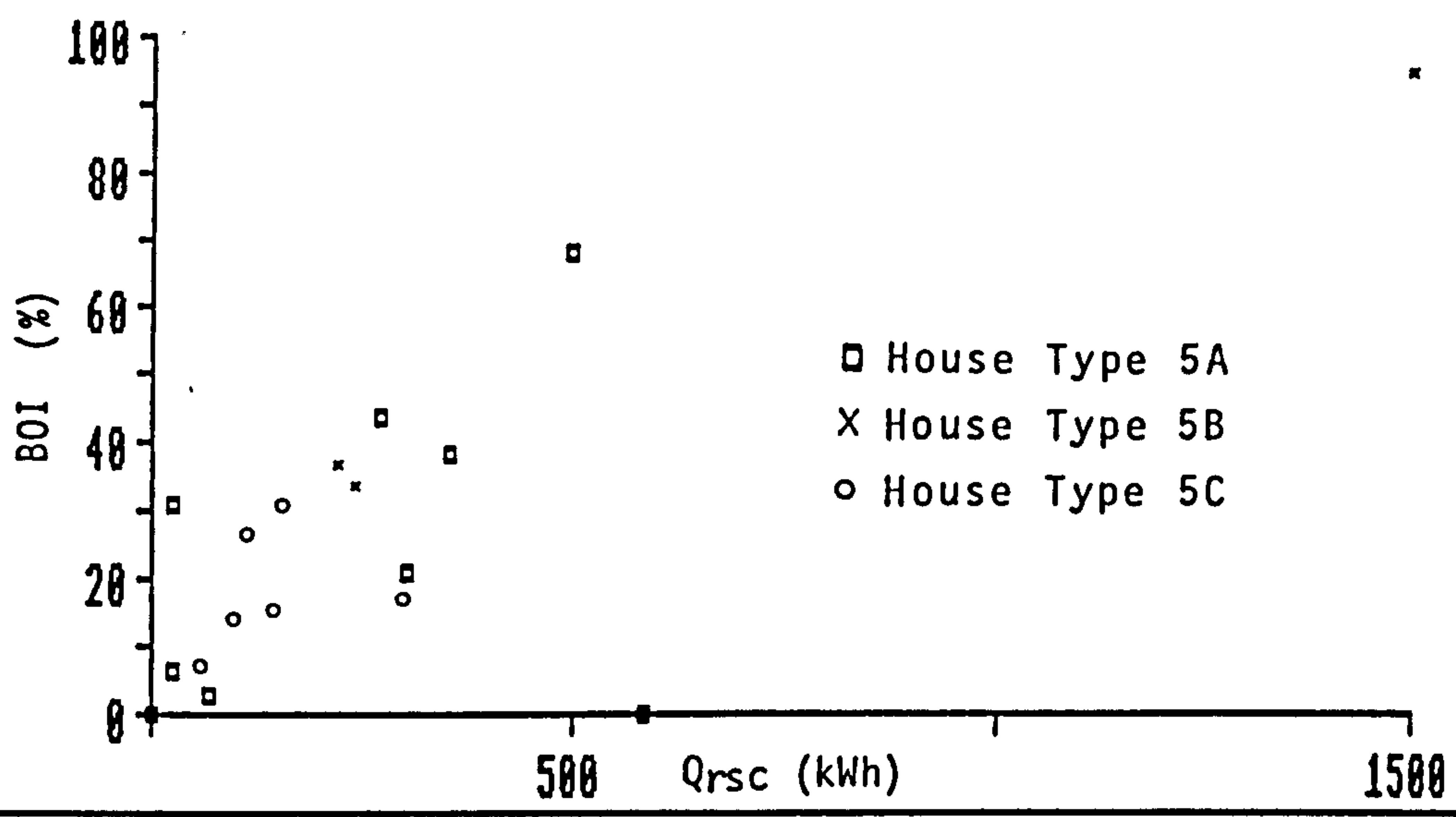


Fig. 5.2.7 Thermal Efficiency v Month for Five different RSC Dwellings 89/90

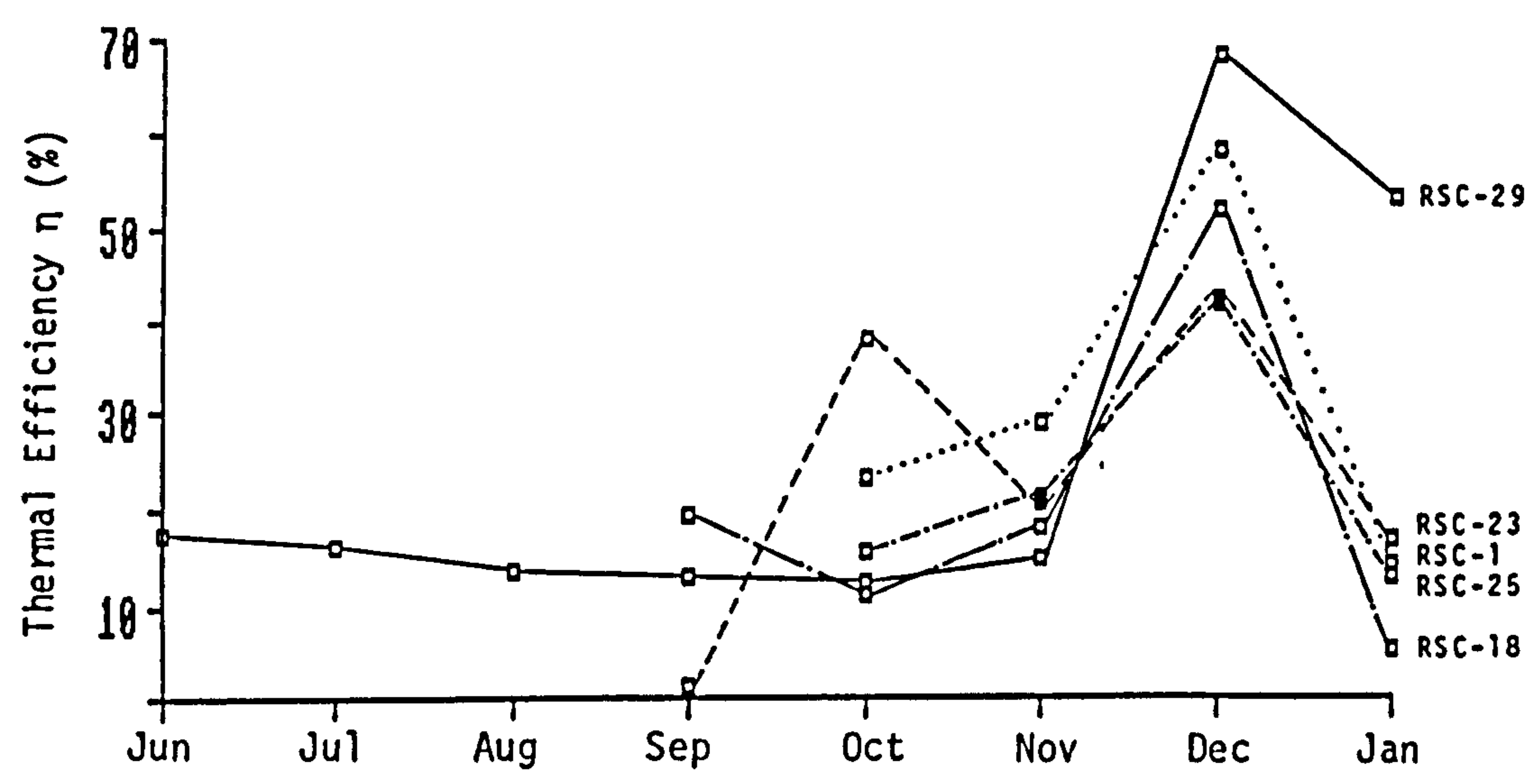


Fig. 5.2.8 Monthly gas consumption v Efficiency for 5 RSC houses 89/90

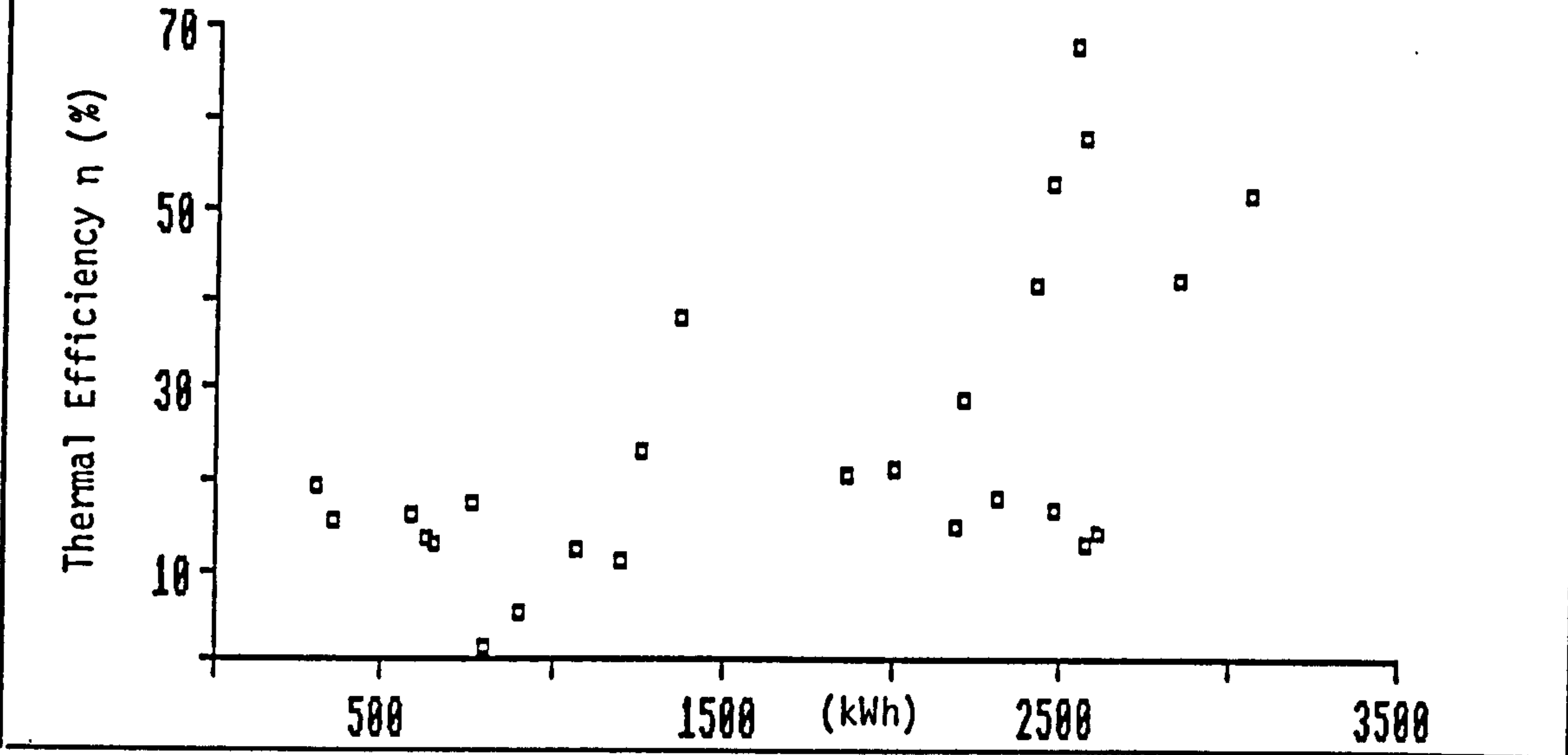
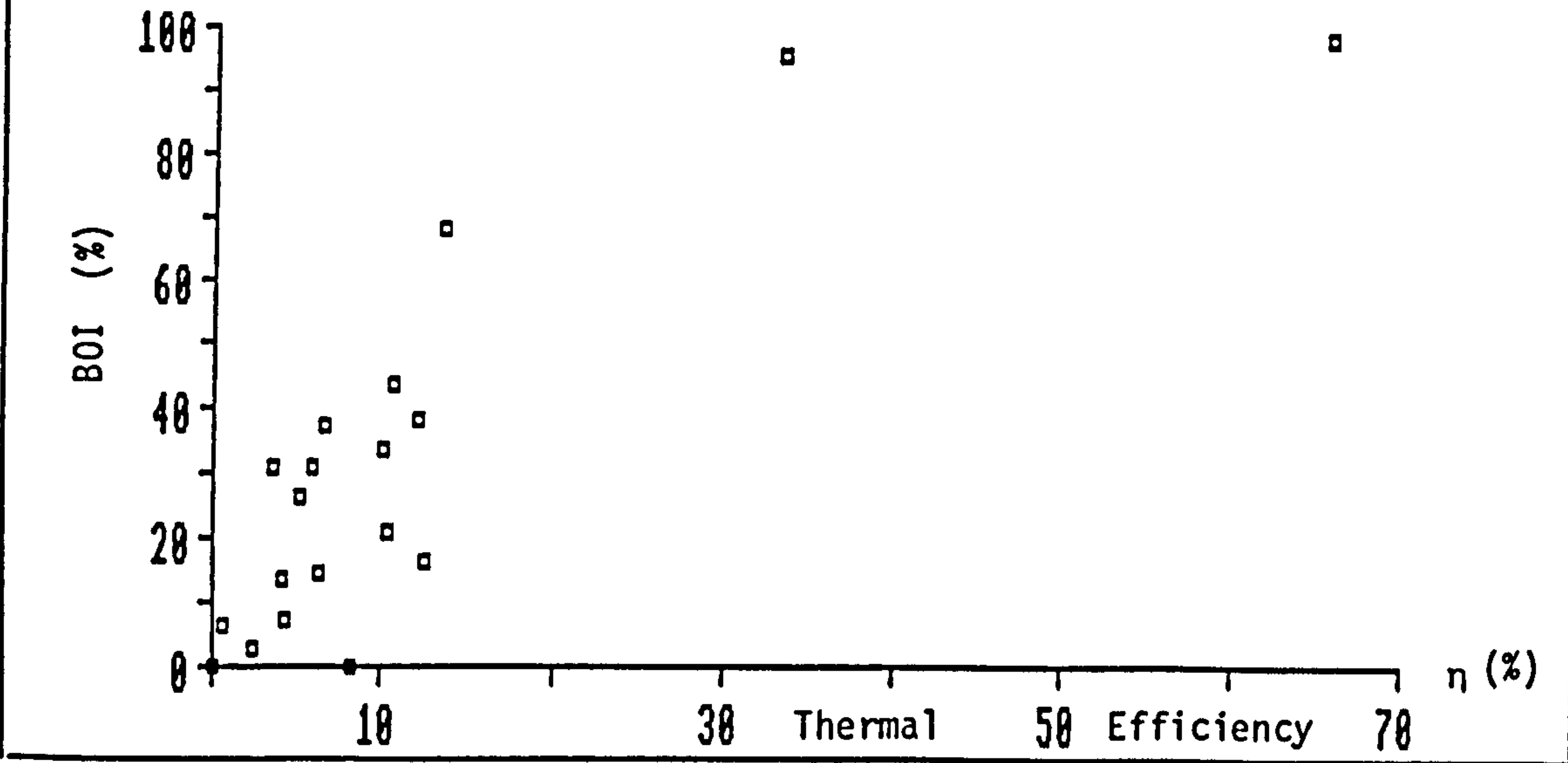


Fig. 5.2.9 Thermal Efficiency v BOI for all houses up to 31/1/90



c) Monthly solar heating fraction of all RSC's

The lightweight timber-framed construction and considerable internal thermal insulation of these dwellings produced a rapid response from the warm-air heating system. This was well suited to the transient heat delivery of the RSC, due to rapid changes in insolation. Very little heat, however, could be stored in the fabric of each RSC, (during the insolation period), for use later in the evening. There were only two dwellings, from 21 monitored houses, where occupants exhibited heating patterns with significant space heating requirements which coincided with periods of insolation.

The solar space heating contribution from the majority of dwellings on the Cockerell Grove estate therefore, formed only a small proportion of the overall auxiliary heating requirement. This was clearly illustrated by the low solar heating fractions of the majority of dwellings as shown in figure 5.2.10. Even at nearly maximum BOI the solar heating fraction of one particular dwelling was still only 20%, at which point the efficiency had reached 65%, (figure 5.2.11), (it is unlikely that this level of efficiency could be improved significantly). The RSC space heating contributions from the majority of dwellings were at least an order of magnitude less than that of the space heating energy requirements, (figure 5.2.12).

d) Thermal gain from control houses

Figure 5.2.12 also illustrates clearly that there is a degree of thermal gain in the air as it passes between the externally mounted ambient air intake and the inlet to the heat recovery unit when ducted through the loft spaces of the control houses. This may have resulted from a combination of any of the following;

- i) direct gain onto the roof tiles via solar radiation, which was radiated into the loft spaces,
- ii) the absence of any insulation around the fresh air intake duct to the HRU, and,
- iii) the high ambient temperatures reached in the first floor rooms of these dwellings.

Fig. 5.2.10 SHF v BOI for all houses up to 31/1/90

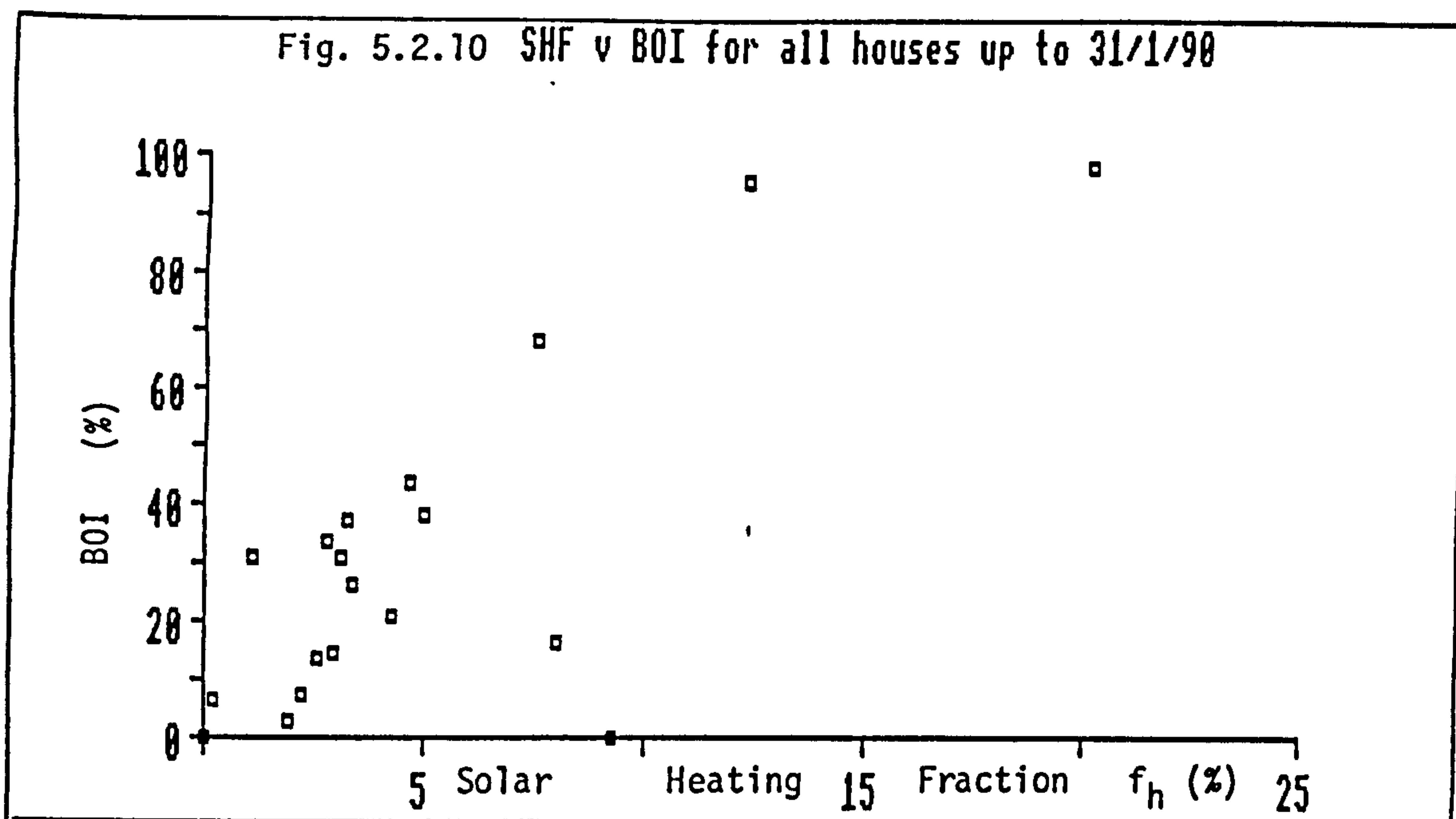


Fig. 5.2.11 SHF v Efficiency for all houses up to 31/1/90

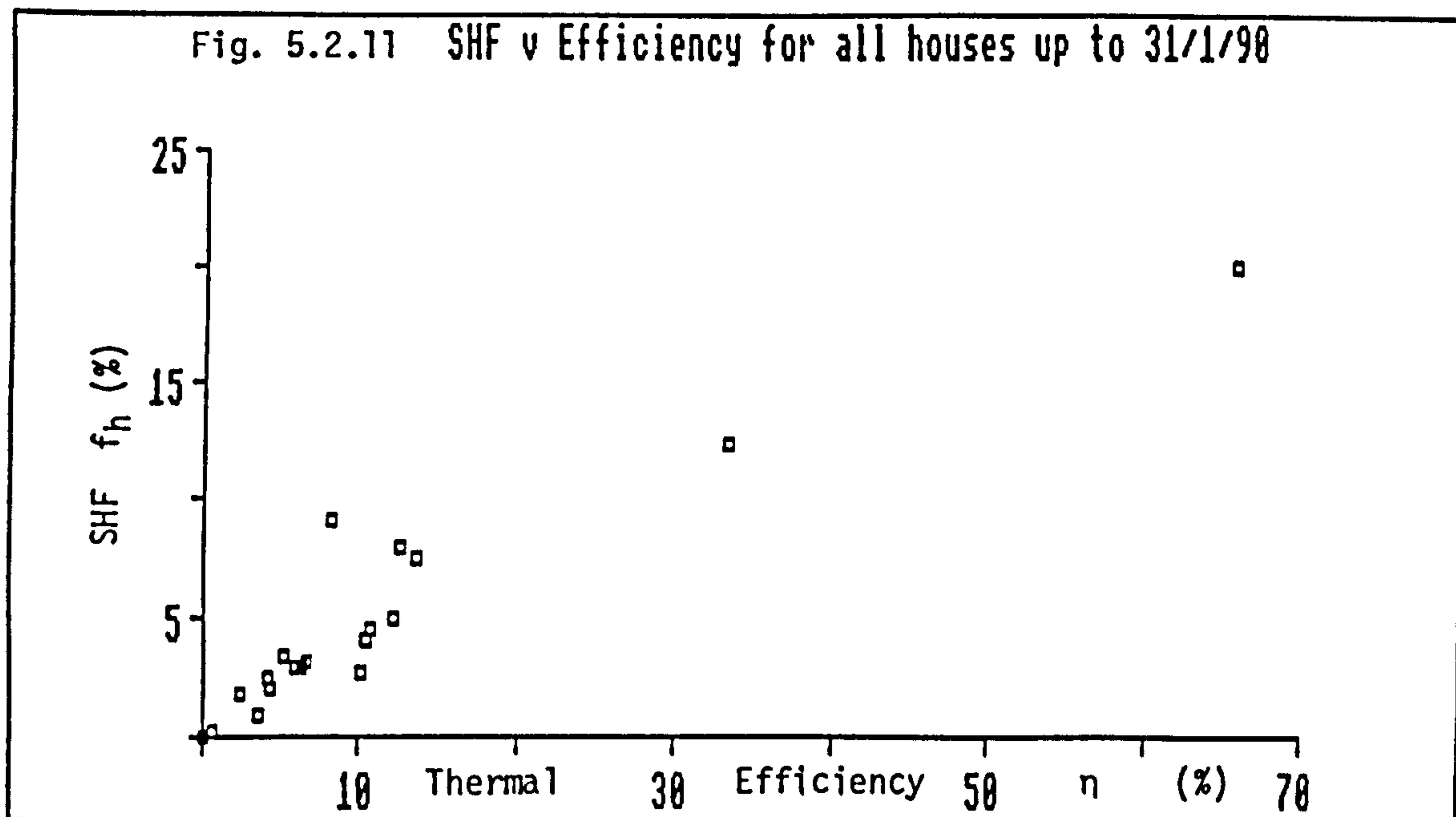
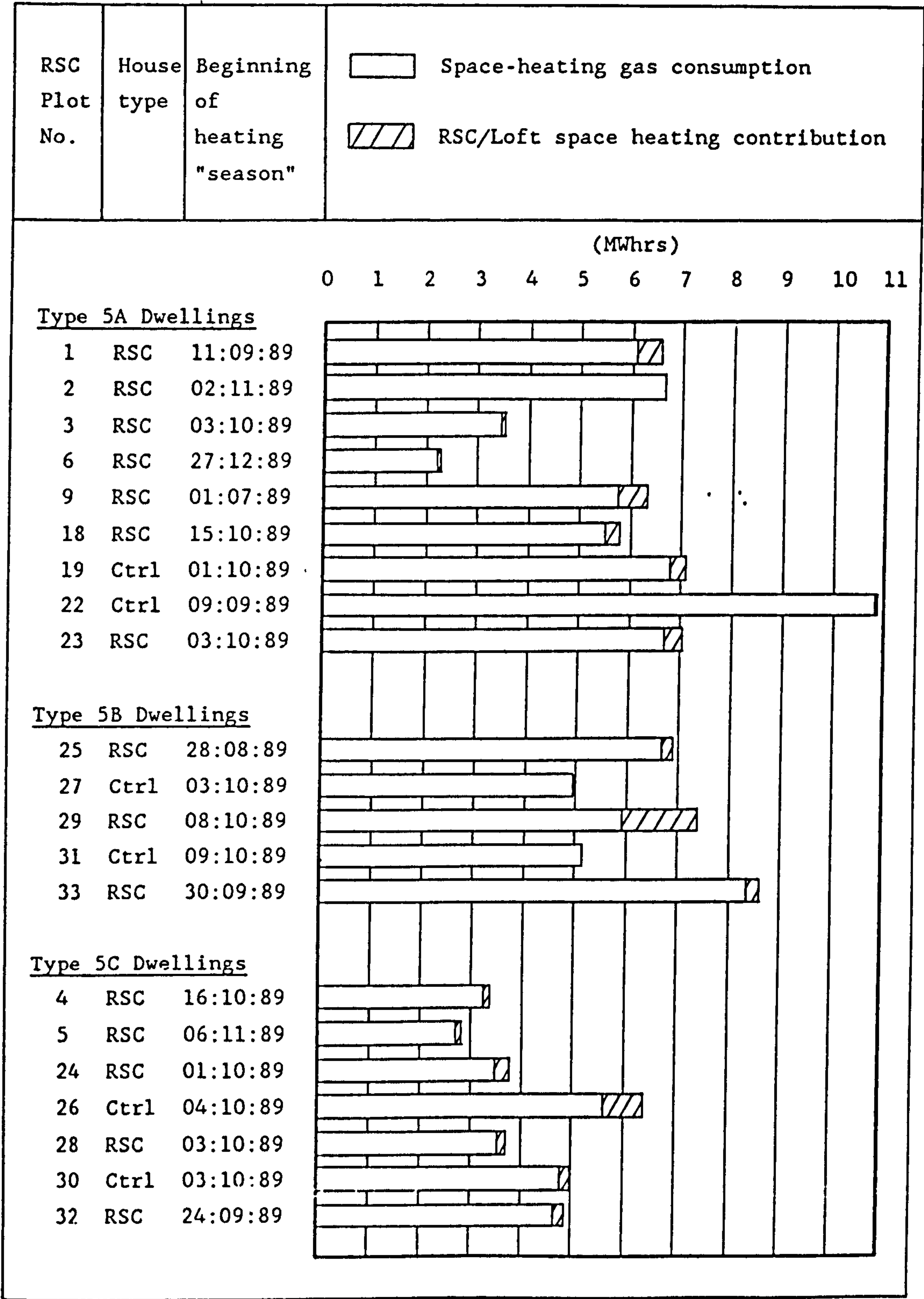


Figure 5.2.12. Total Space Heating Load and Space Heating Contribution from RSC/Loft space for all dwellings at Shenley Lodge 5, Milton Keynes, from the beginning of the heating season up to 31/1/90



RSC - House incorporating Roof-Space Solar Collector
CTRL - Control dwelling

e) Total gas consumption for each different house type

The data was analysed with respect to each house type in order to minimise the very large number of independent variables and the different length of heating seasons for each dwelling. There were a number of temporary sensor failures in three of the twenty-one dwellings, which precluded any calculations of the space-heating gas consumption.

Type 5A The control dwellings had two of the greatest total space heating gas consumptions of any of the nine type 5A dwellings during the heating season up to January 31 1990. However, as the heating "season" for each type 5A dwelling ranged from 36 days to 245 days a more significant indicator of overall auxiliary fuel consumptions were the mean daily gas consumptions. The mean daily gas consumptions from control houses were still higher than the norm for the group type 5A houses.

The greatest contribution from a type 5A Roof-Space collector was 587 kWh at plot 9, 38 Cockerell Grove but the BOI could not be calculated due to insufficient data.

Type 5B The sensors which were monitoring the total daily operation time of the space heating gas valves in both of the type 5B control houses malfunctioned.

The cable for all sensors should have been installed during the initial construction period to avoid externally mounted cable conduits. In the first control dwelling the cable for the time-elapsed counter on the gas valve to the Building Interface Unit had not been included during the construction phase.

In the second type 5B control dwelling one of the mechanical relays, which monitored the space-heating gas consumption at plot 27, 55 Cockerell Grove, was particularly susceptible to mains interference. This manifested itself in the form of a low frequency mains oscillation from the body of the relay which was audible from the adjacent rooms, and a source of irritation to the occupants. The relay would have been

replaced with a more reliable and robust electronic device, but the occupants requested that the device be removed and that they should not be inconvenienced any further. This precluded any comparison between the control houses and the RSC dwellings of house type 5B.

Type 5C There was little disparity in the mean internal temperatures of all the type 5C dwellings, yet the occupants in the RSC houses consumed, an average of, 27% less gas for space heating (i.e. 32.25 kWh/day in comparison to 44.16 kWh/day for the two control dwellings). This apparent mean daily saving of 11.91 kWh was an order of magnitude greater than the mean daily RSC space heating contribution of 1.29 kWh/day for all the type 5C RSC houses! However a greater sample of dwellings of identical building geometry is required before any significant conclusions can be drawn from this difference in mean daily space-heating gas consumption.

Only the total gas consumption of each dwelling, including water heated by gas, could be assessed from the main British Gas meter. A separate gas-valve was installed to measure the auxiliary fuel requirements of space heating alone, which monitored the time that the valve was open. The gas flow rate has yet to be calibrated for each house, and consideration must be given to the gas flow rate characteristics during the operation of this valve. The maximum constant volume-flow rate of the gas was not attained until at least 10-15 seconds after opening the valve. This only influenced the space heating gas consumption reading when the valve was activated many times per hour in order to maintain a near-constant house temperature. The volume flow rate of this gas valve will be measured and calibrated for each of the 21 dwellings. A correction factor will be applied in order to compensate for the number of valve actuations for any given monitoring period.

Until this gas flow rate is calibrated the space-heating gas consumption was calculated by subtracting the mean total daily gas consumption outside of the heating season, (i.e. the water heating gas consumption), from the total daily gas consumption readings during the winter heating period.

5.3 TAP Performance

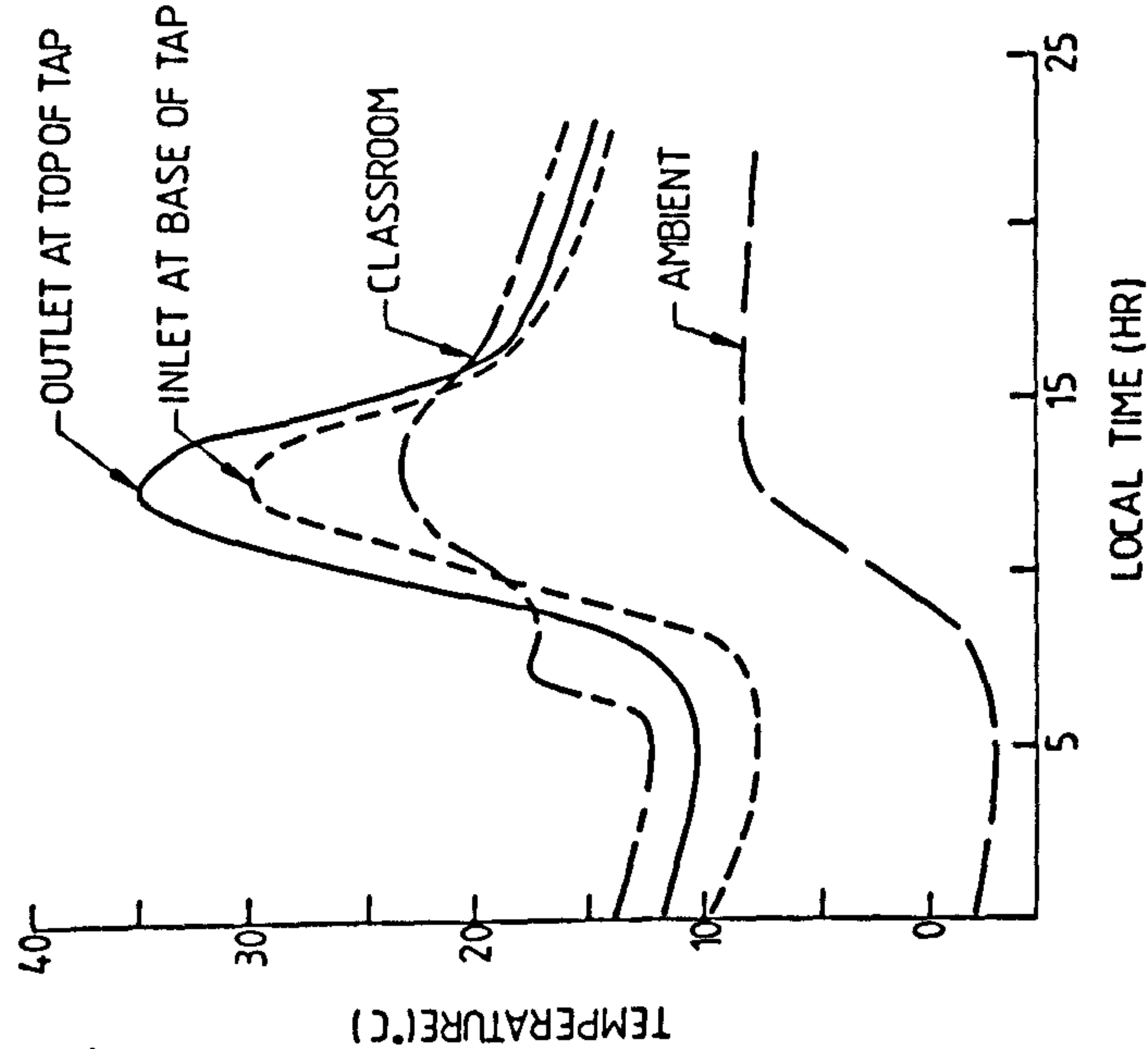
i) Daily data for TAP's on east, south and north facades

Three individual days, in February 1989, were chosen to illustrate typical TAP performance characteristics until more long term data can be collected. These days all exhibited high levels of insolation with low external ambient temperatures which were considered to be optimum conditions for efficient TAP operation (5.3.1).

Figure 5.3.1 illustrates that on a south facing collector at solar noon the temperature difference between the TAP inlet and outlet is only 5°C. The unusually high inlet temperature has resulted from inappropriate siting of the thermocouple; in addition to the inlet temperature, it also measured radiation from the back of the absorber plate. If the classroom temperature was considered as the temperature of the inlet air, the temperature difference between the inlet and outlet rose to 11°C.

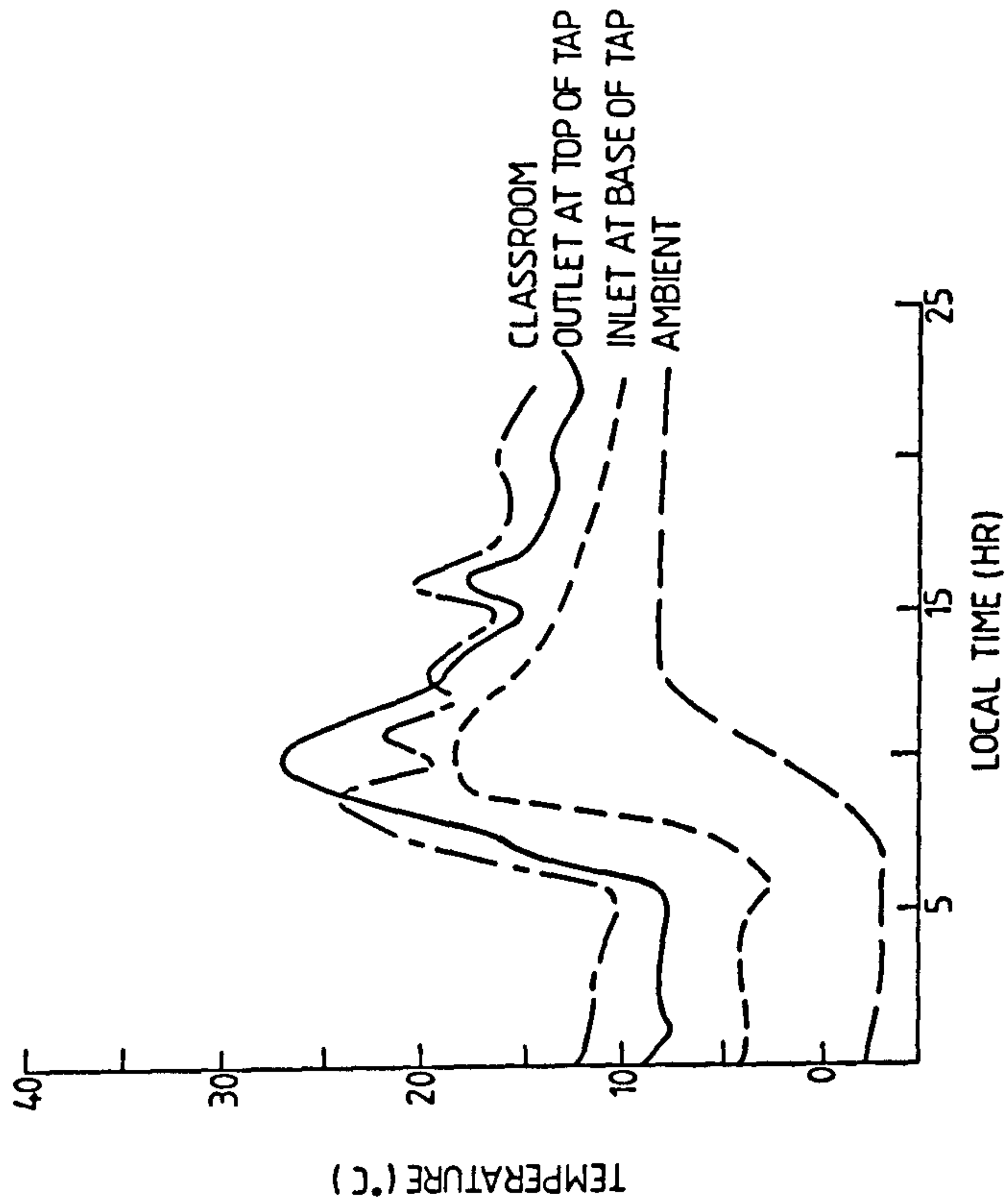
Figures 5.3.2 & 5.3.3 show that the east and west facing collectors, on the same day in February, exhibited similar diurnal temperature distributions. The lower levels of solar radiation incident on these two facades, (Fig. 5.3.4), are reflected in the reduced temperature differences between the inlet and outlet of these TAP's. Figure 5.3.5 shows that on this particular day the solar radiation is predominantly beam radiation rather than diffuse.

The repeatability of such results on another day in February with similar levels of insolation and ambient temperature are shown in Figures 5.3.6 to 5.3.10.



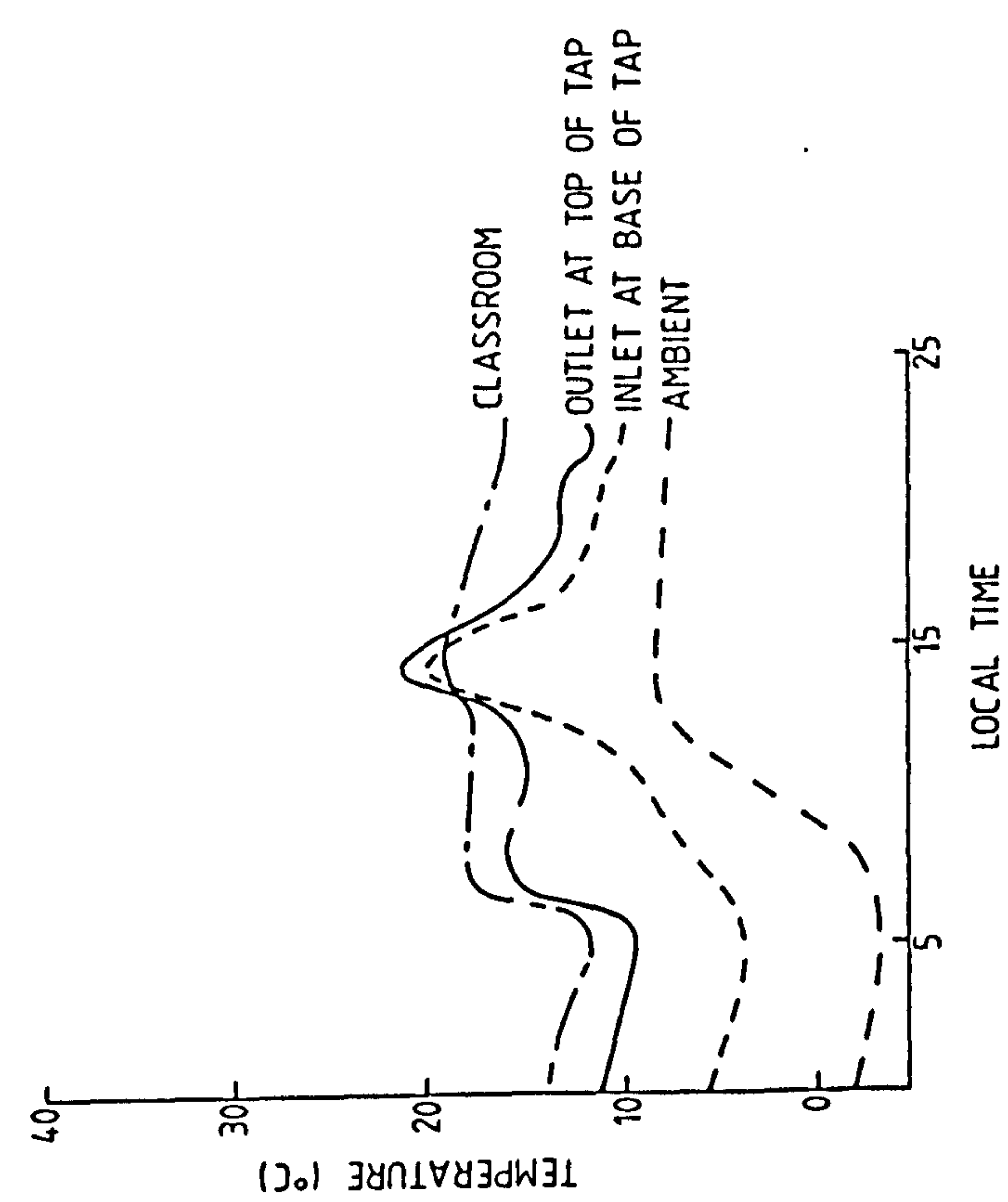
DIURNAL TEMPERATURE VARIATIONS FOR A SOUTH-FACING
THERMOSYPHONING AIR PANEL (TAP) ON 11th FEBRUARY 1989

Figure 5.3.1



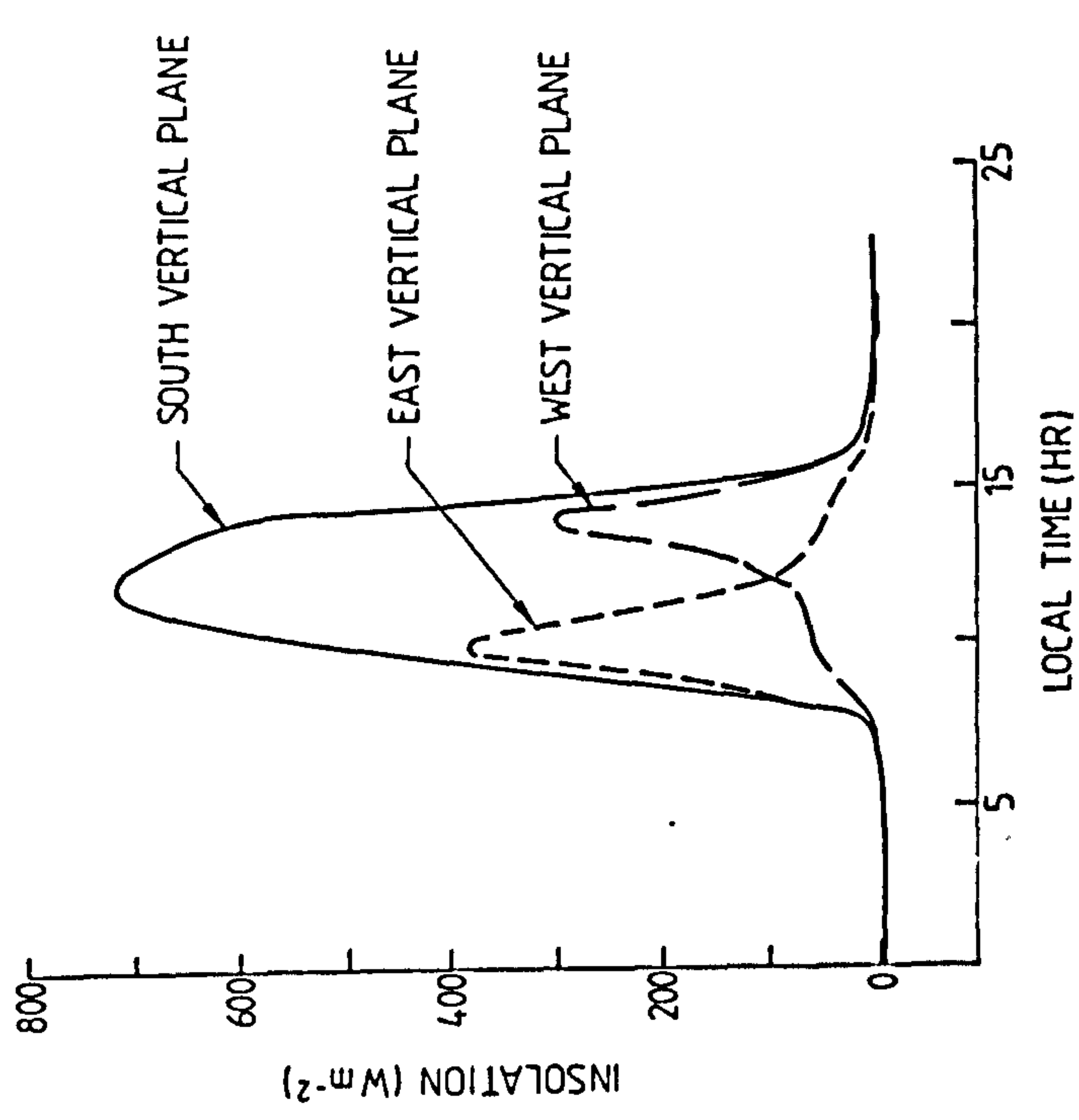
DIURNAL TEMPERATURE VARIATION FOR AN EAST FACING
THERMOSYPHONING AIR PANEL (TAP) ON 11th FEBRUARY 1989

Figure 5.3.2



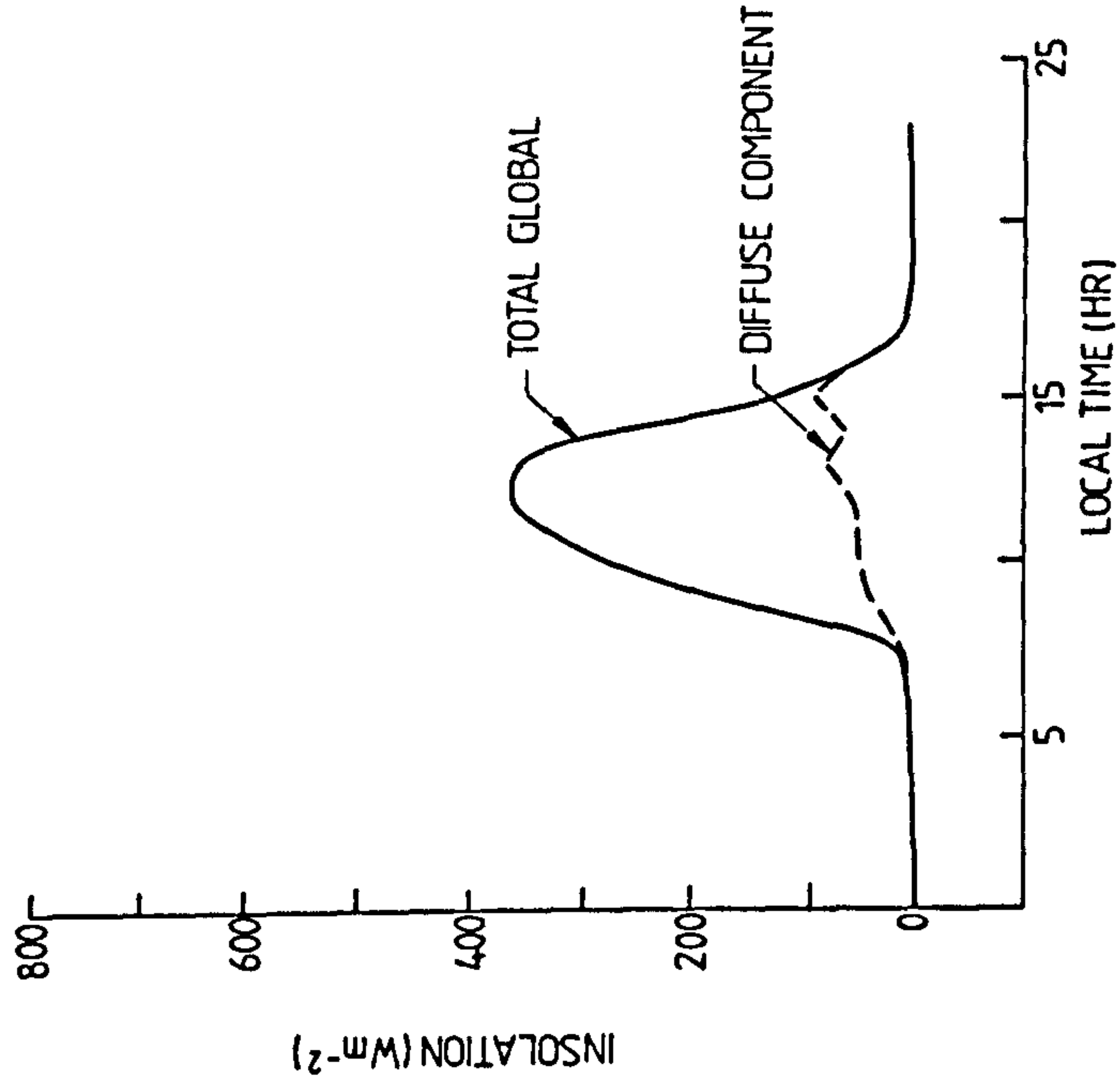
DIURNAL TEMPERATURE VARIATION FOR A WEST-FACING THERMOSYPHONING AIR PANEL (TAP) ON 11th FEBRUARY 1989.

Figure 5.3.3



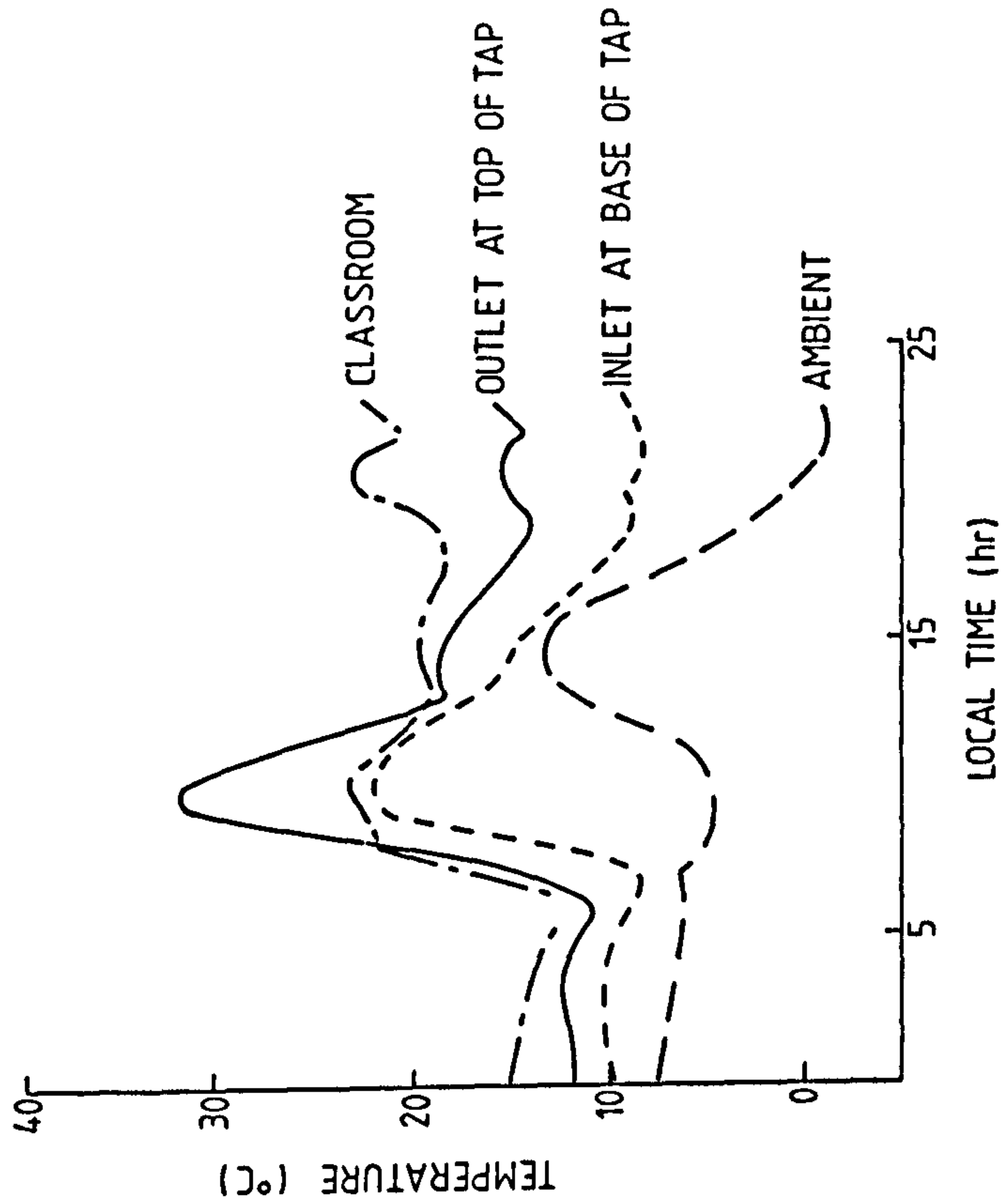
DIURNAL VARIATION OF INSOLATION ON VERTICAL PLANES - 11th FEBRUARY 1989

Figure 5.3.4



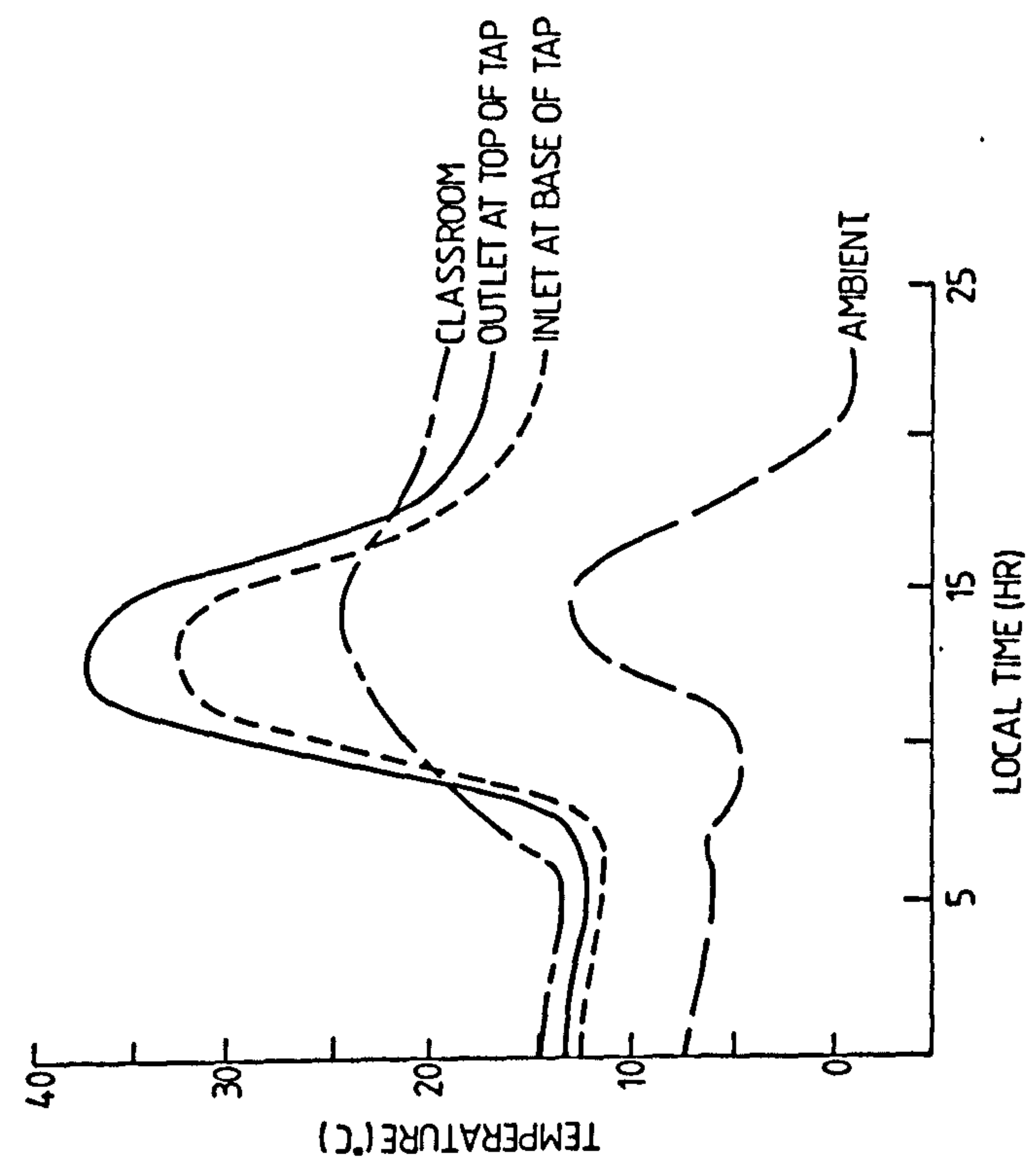
TOTAL HORIZONTAL GLOBAL & DIFFUSE RADIATION
FOR 11th FEBRUARY 1989

Figure 5.3.5



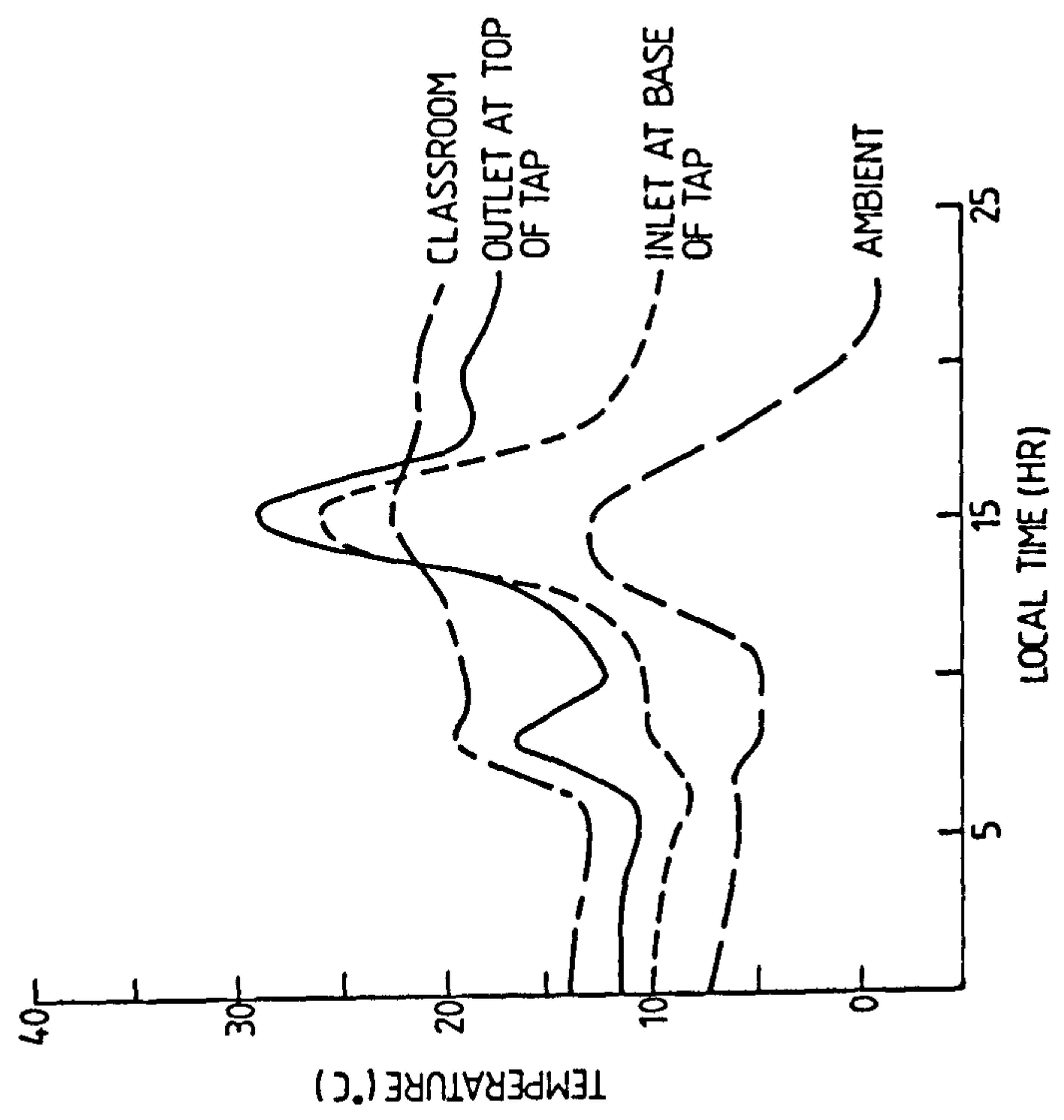
DIURNAL TEMPERATURE VARIATION FOR AN EAST-FACING
THERMOSYPHONING AIR PANEL (TAP) ON 20th FEBRUARY 1989

Figure 5.3.6



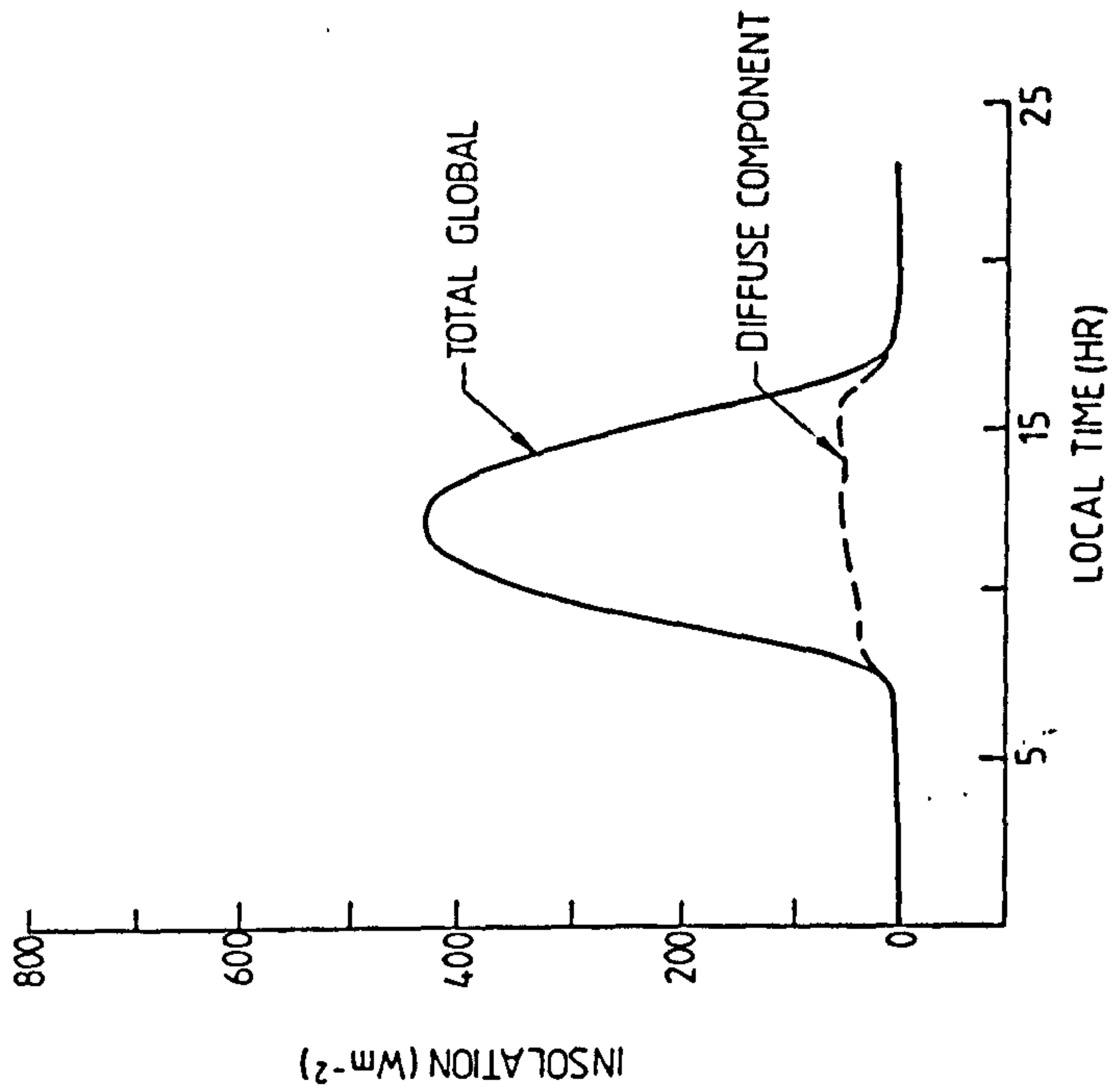
DIURNAL TEMPERATURE VARIATION FOR A SOUTH FACING THERMOSYPHONING AIR PANEL (TAP) ON 20th FEBRUARY 1989

Figure 5.3.7



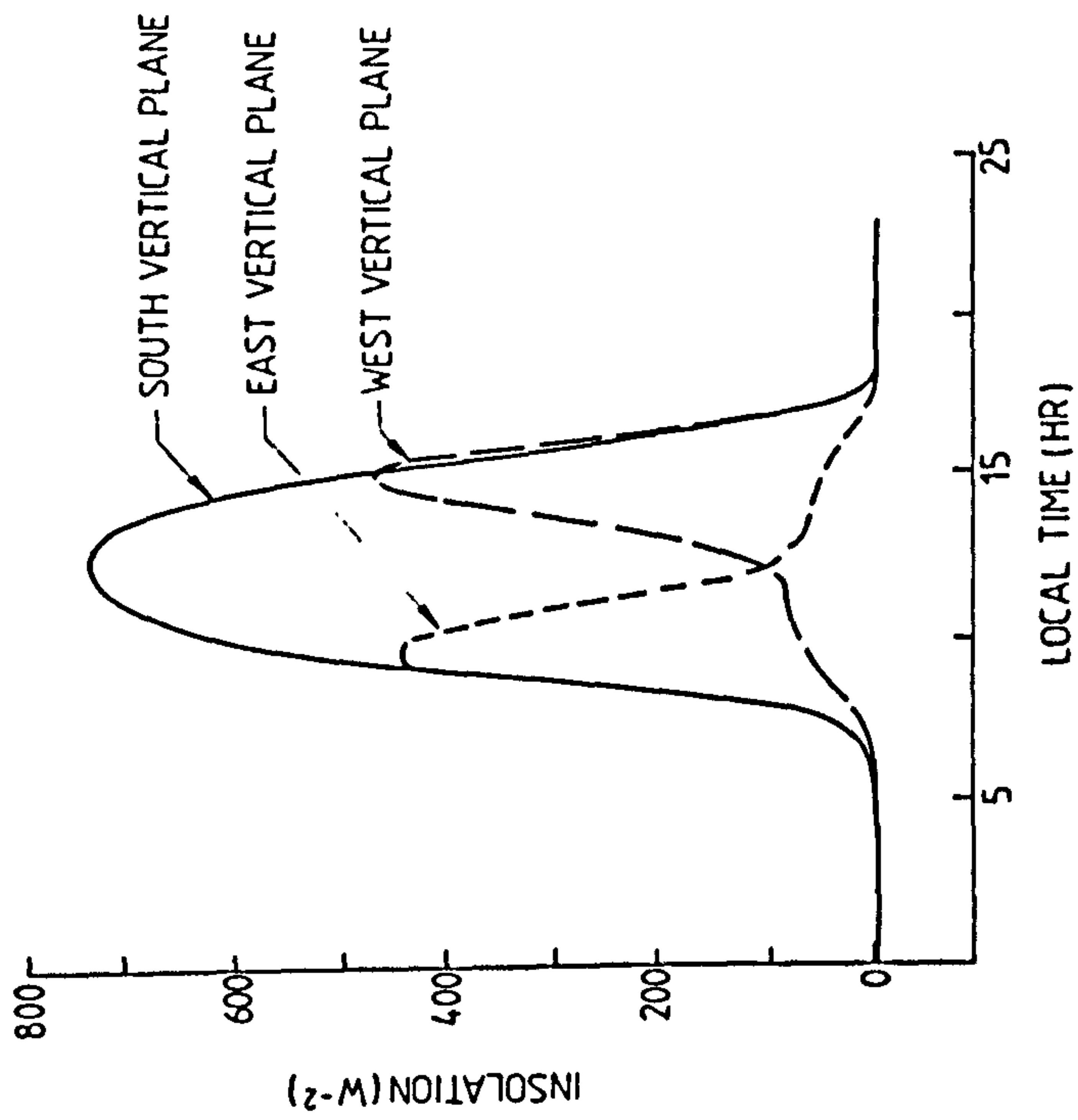
DIURNAL TEMPERATURE VARIATION FOR A WEST FACING THERMOSYPHONING AIR PANEL (TAP) ON 20th FEBRUARY 1989

Figure 5.3.8



TOTAL HORIZONTAL GLOBAL & DIFFUSE RADIATION
FOR 20th FEBRUARY 1989

Figure 5.3.10



DIURNAL VARIATION OF INSOLATION ON VERTICAL
PLANE - 20th FEBRUARY 1989

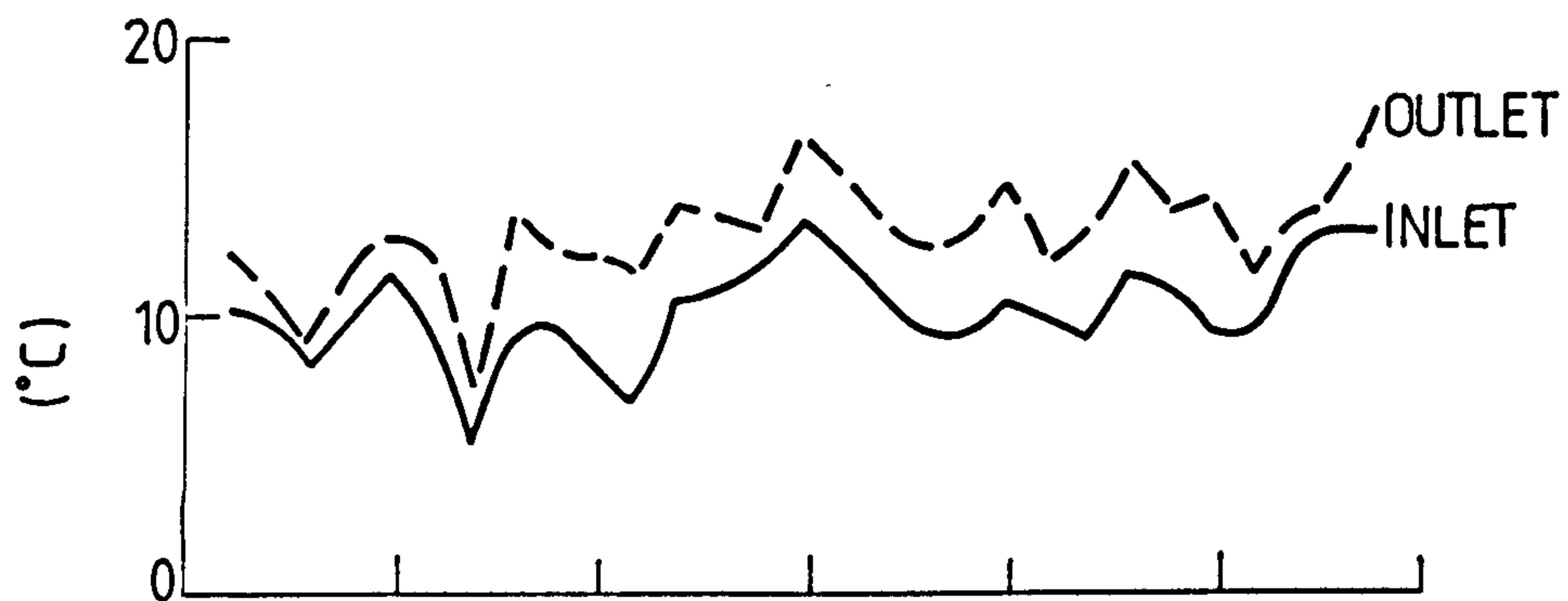
Figure 5.3.9

ii) Monthly data for TAP's on east, south and north facades

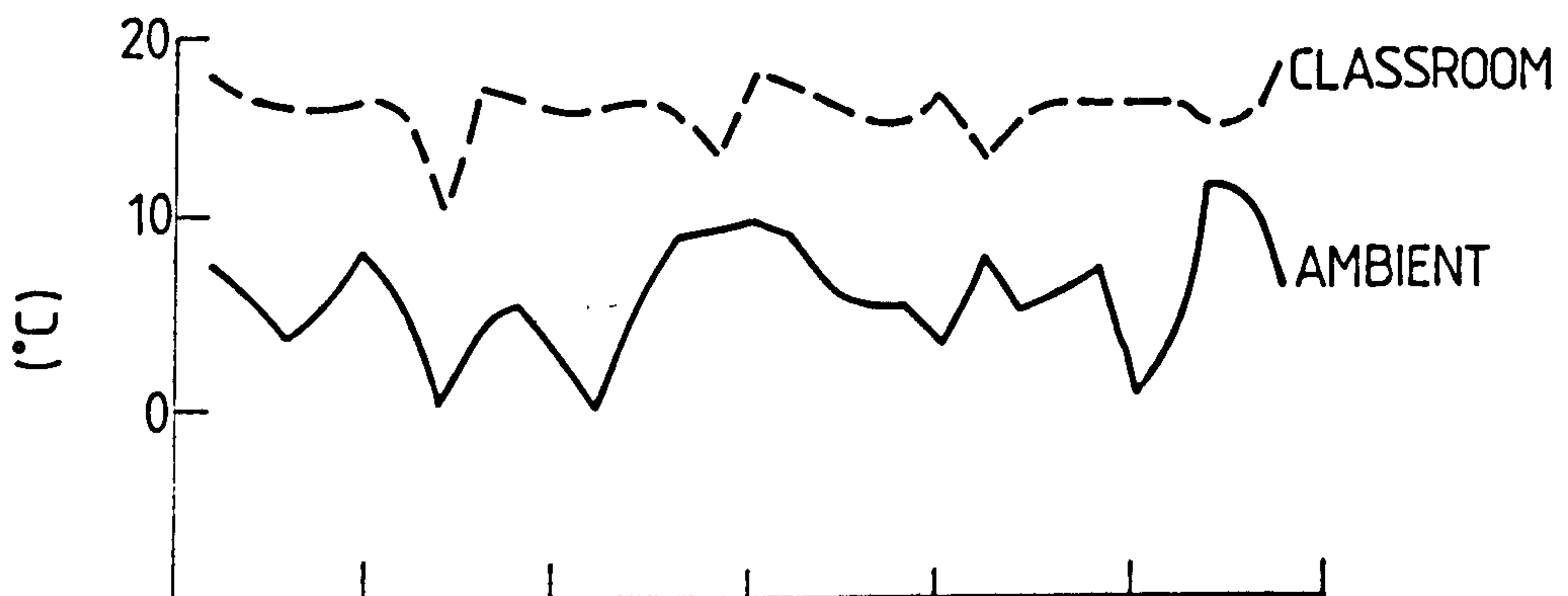
If the daily results are averaged and plotted over a whole month the temperature difference across the collector is reduced because data outside the insolation period are included in the daily average, Figure 5.3.11 - 5.3.13. In order to assess the annual performance of the TAP's, a relationship between their individual efficiencies and the following parameters had to be established;

- a) total daily insolation on the plane of the collectors,
- b) the proportion of diffuse to beam insolation on a daily basis,
- c) the temperature difference accross each panel, and
- d) external environmental conditions.

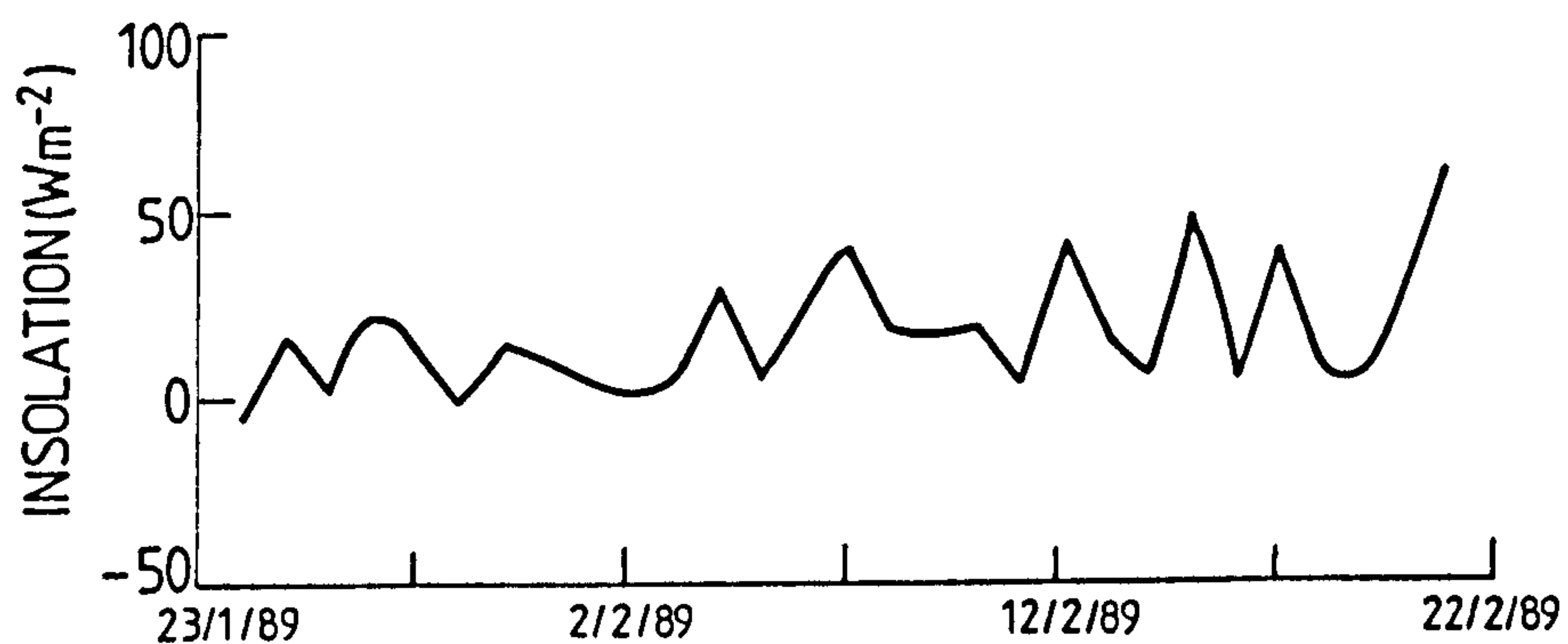
Preliminary results for the hourly insolation and the temperature difference accross the collectors are shown in Figures 5.3.14 - 5.3.16. A strong correlation exists for the south facing TAPs but becomes less well defined for the east and west facing TAPs. A minimum level of insolation may have been required to overcome any inertia within the system, (i.e. the tedlar damper), which could prevent the initiation of flow through the collector. The damper often remained closed at low levels of insolation and the measured temperature difference across the collector resulted from the stratification within the classrooms. (A number of readings, from failed sensors within the absorber, had to be substituted by readings from other suitable locations). The slope from these graphs enabled the individual performance of the collectors to be characterised.



MEAN DAILY TEMPERATURES FOR EAST FACING COLLECTOR

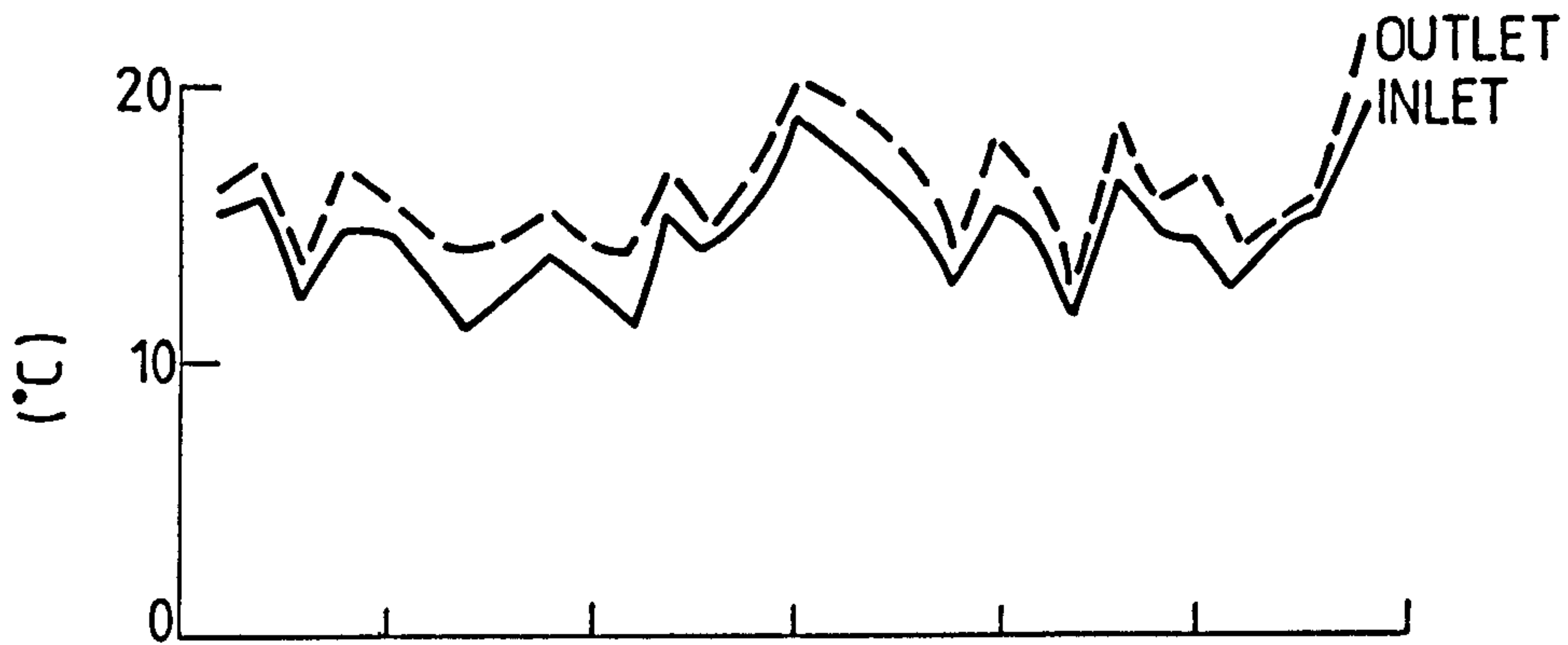


MEAN AMBIENT/CLASSROOM TEMPERATURES FOR AN EAST FACING COLLECTOR

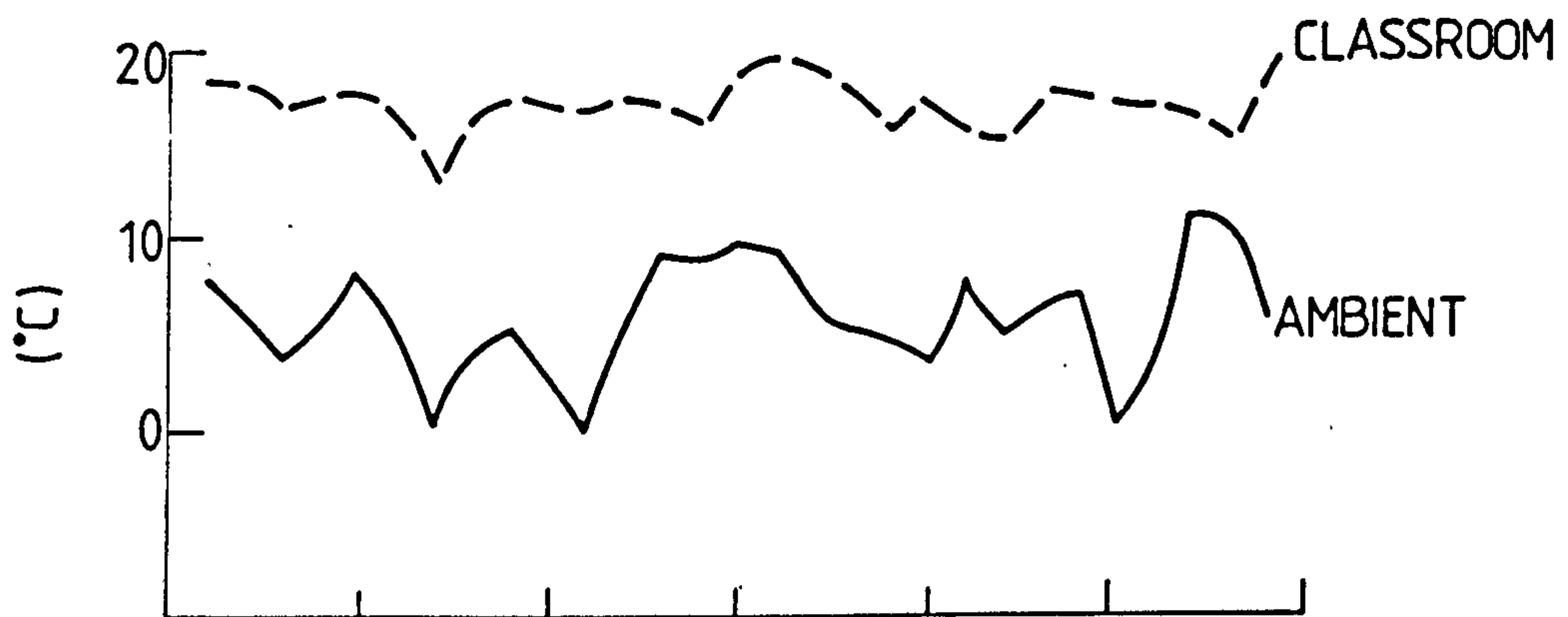


MEAN DAILY INSOLATION ON EAST FACING VERTICAL PLANE

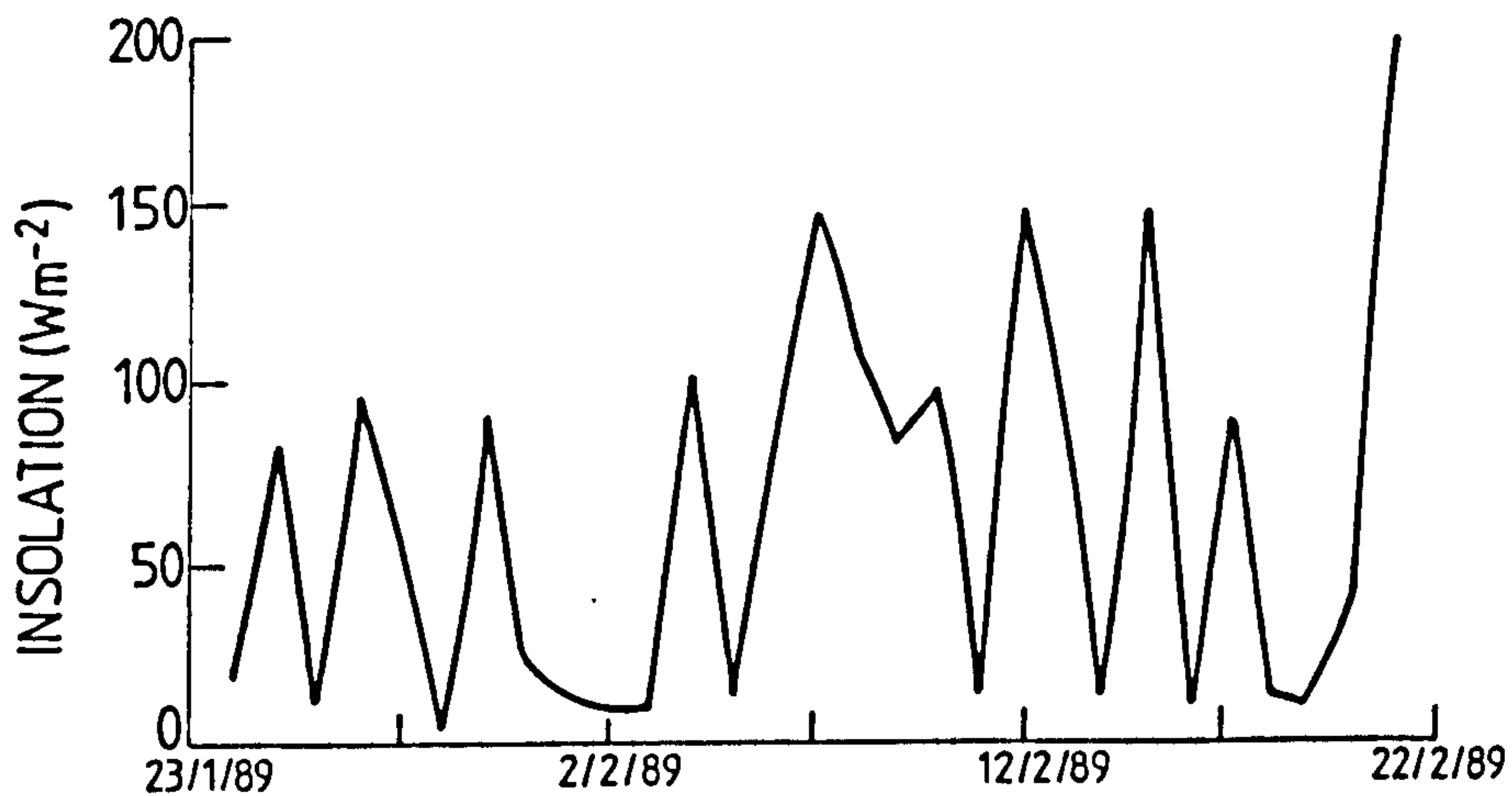
Figure 5.3.11 Long-term daily average results for an east-facing Thermosyphoning-Air-Panel



MEAN DAILY TEMPERATURES FOR SOUTH FACING COLLECTOR

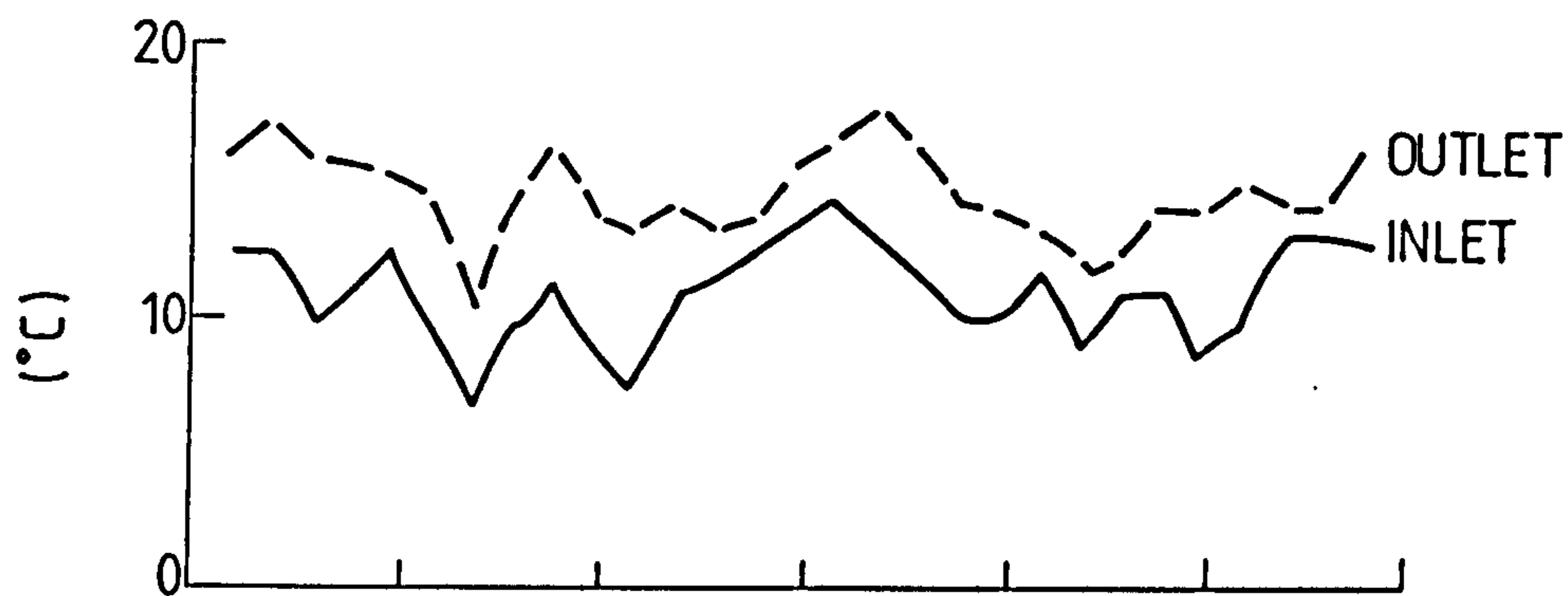


MEAN AMBIENT/CLASSROOM TEMPERATURES FOR A SOUTH FACING COLLECTOR

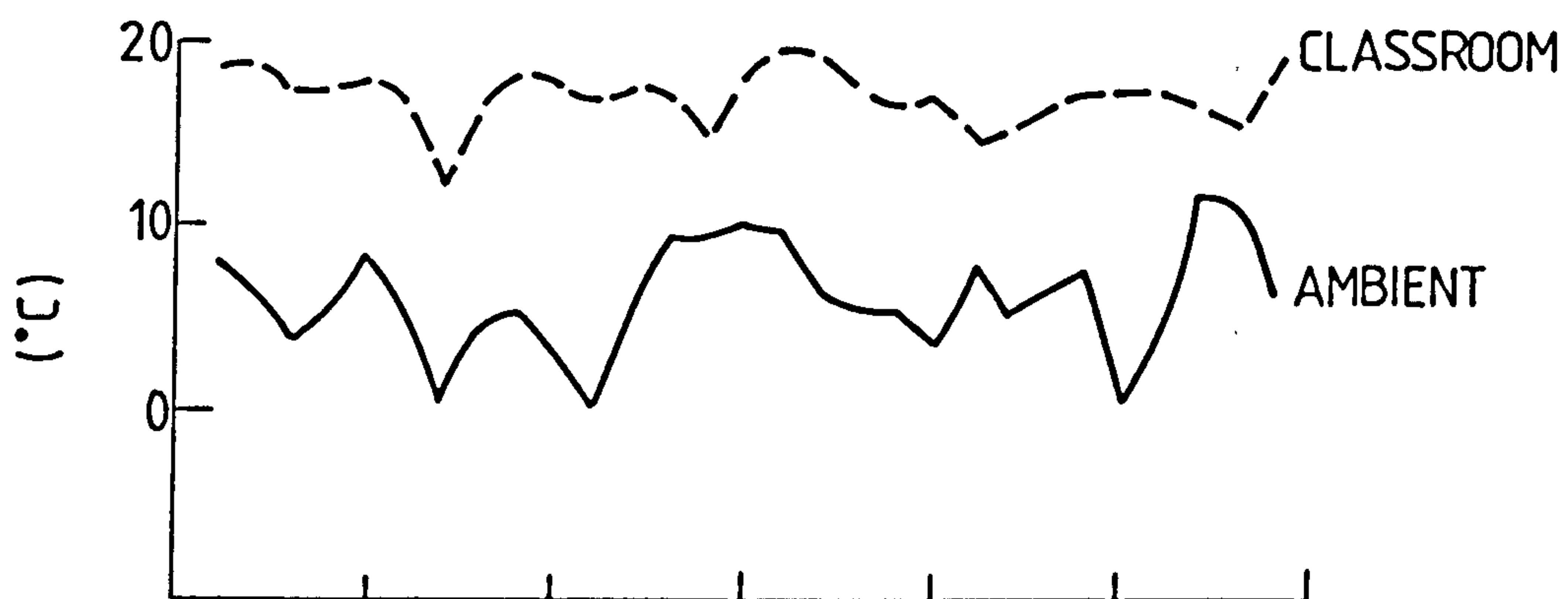


MEAN DAILY INSOLATION ON SOUTH FACING VERTICAL PLANE

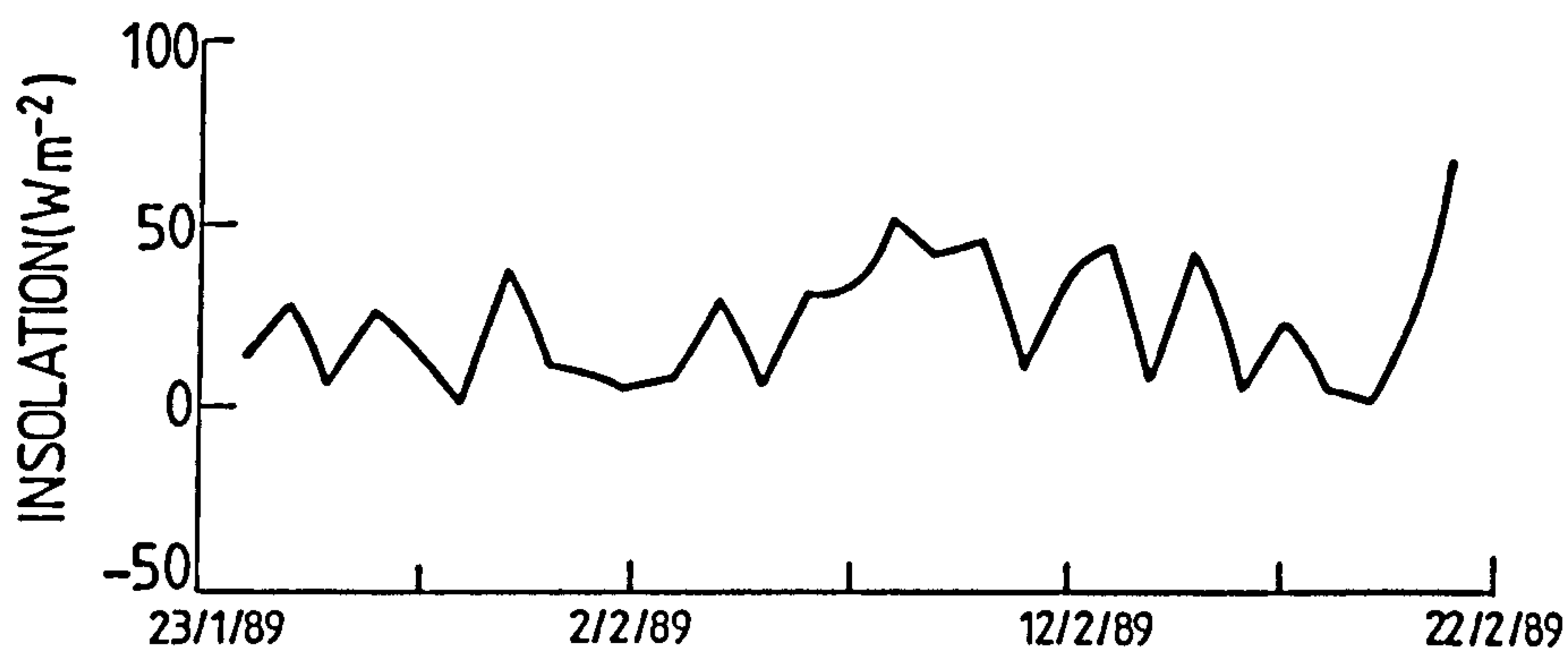
Figure 5.3.12 Long-term daily average results for a south-facing Thermosyphoning-Air-Panel



MEAN DAILY TEMPERATURES FOR WEST FACING COLLECTOR

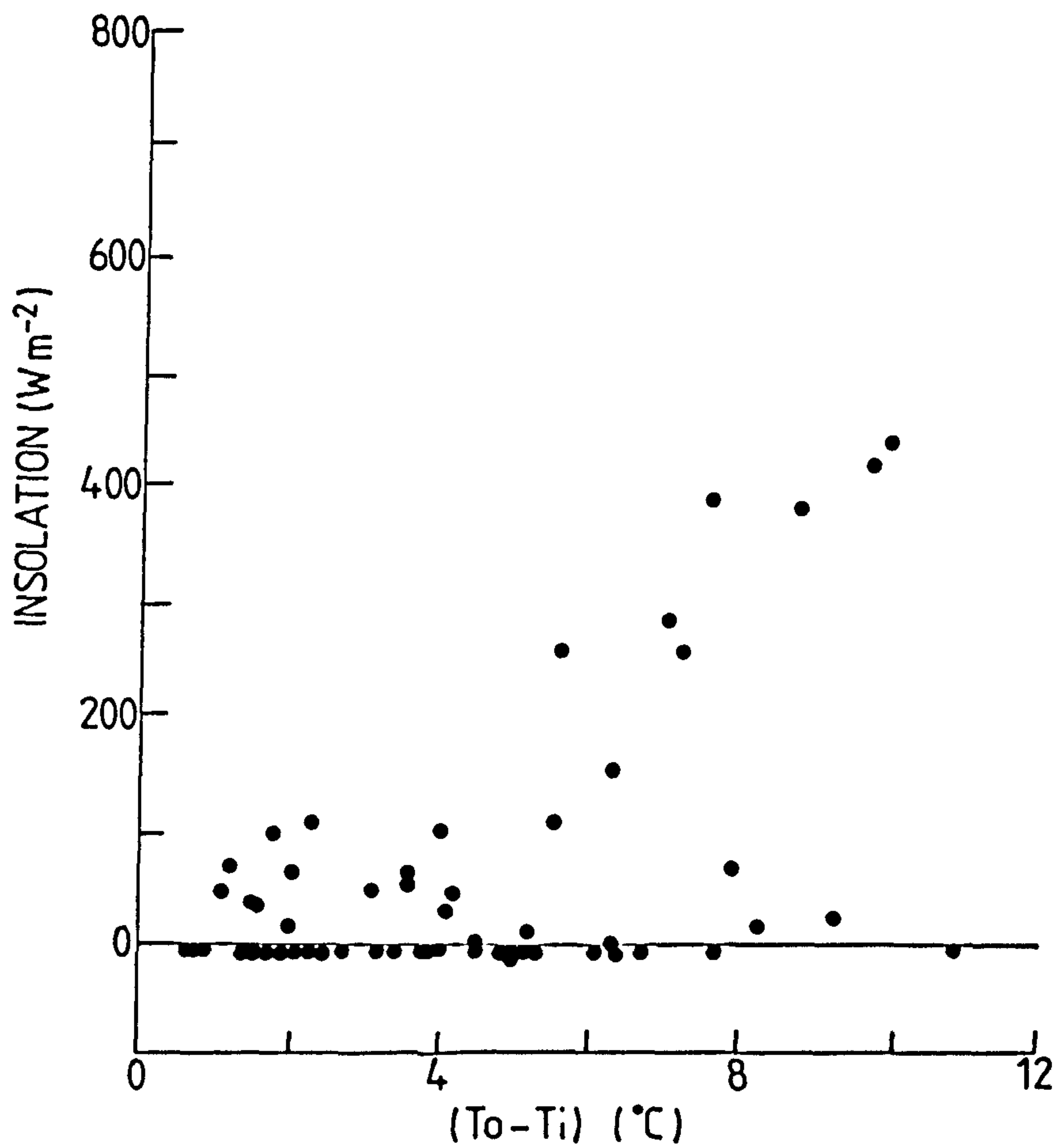


MEAN AMBIENT/CLASSROOM TEMPERATURES FOR A WEST FACING COLLECTOR



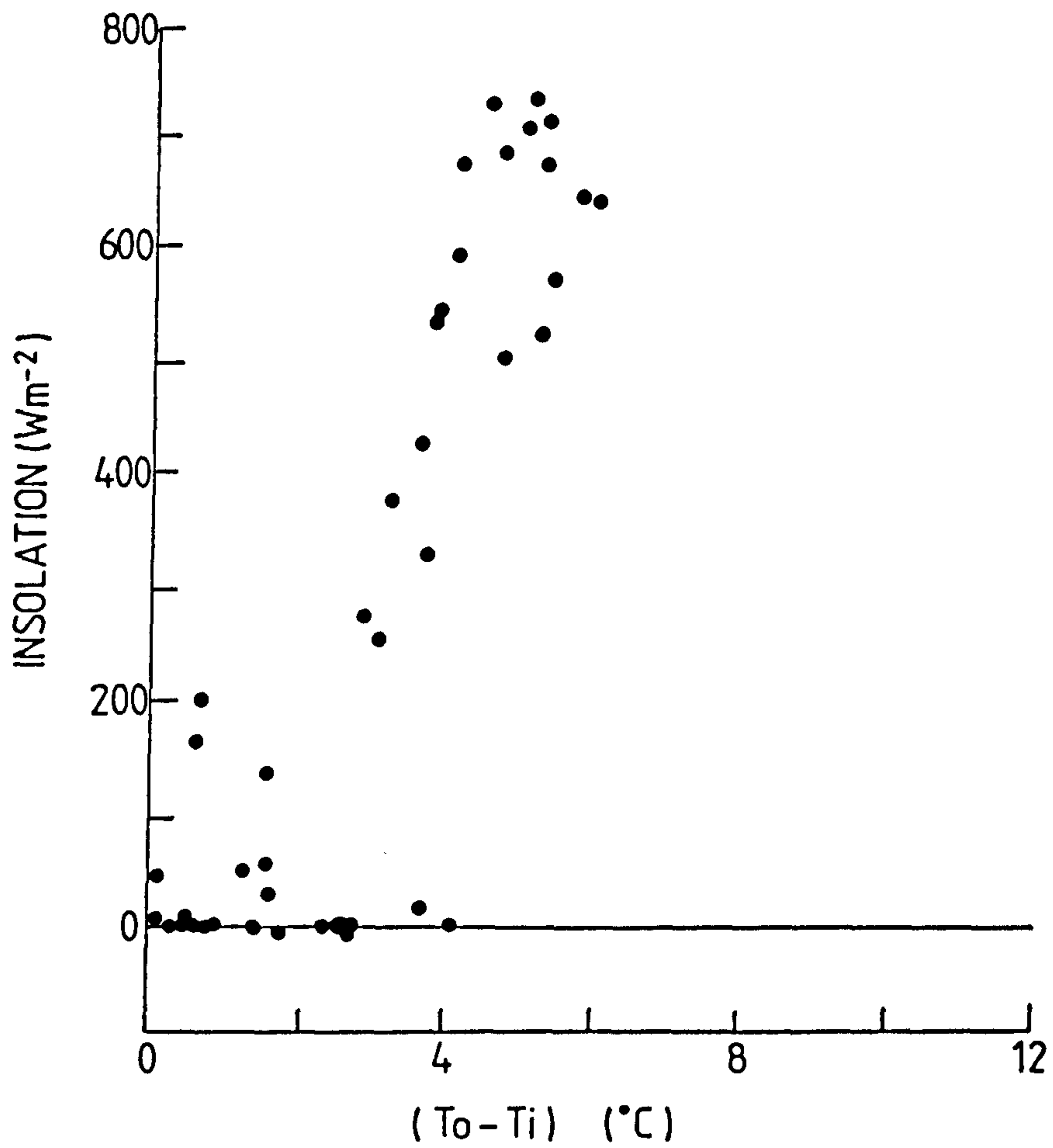
MEAN DAILY INSOLATION ON WEST FACING VERTICAL PLANE

Figure 5.3.13 Long-term daily average results for a west-facing Thermosyphoning-Air-Panel



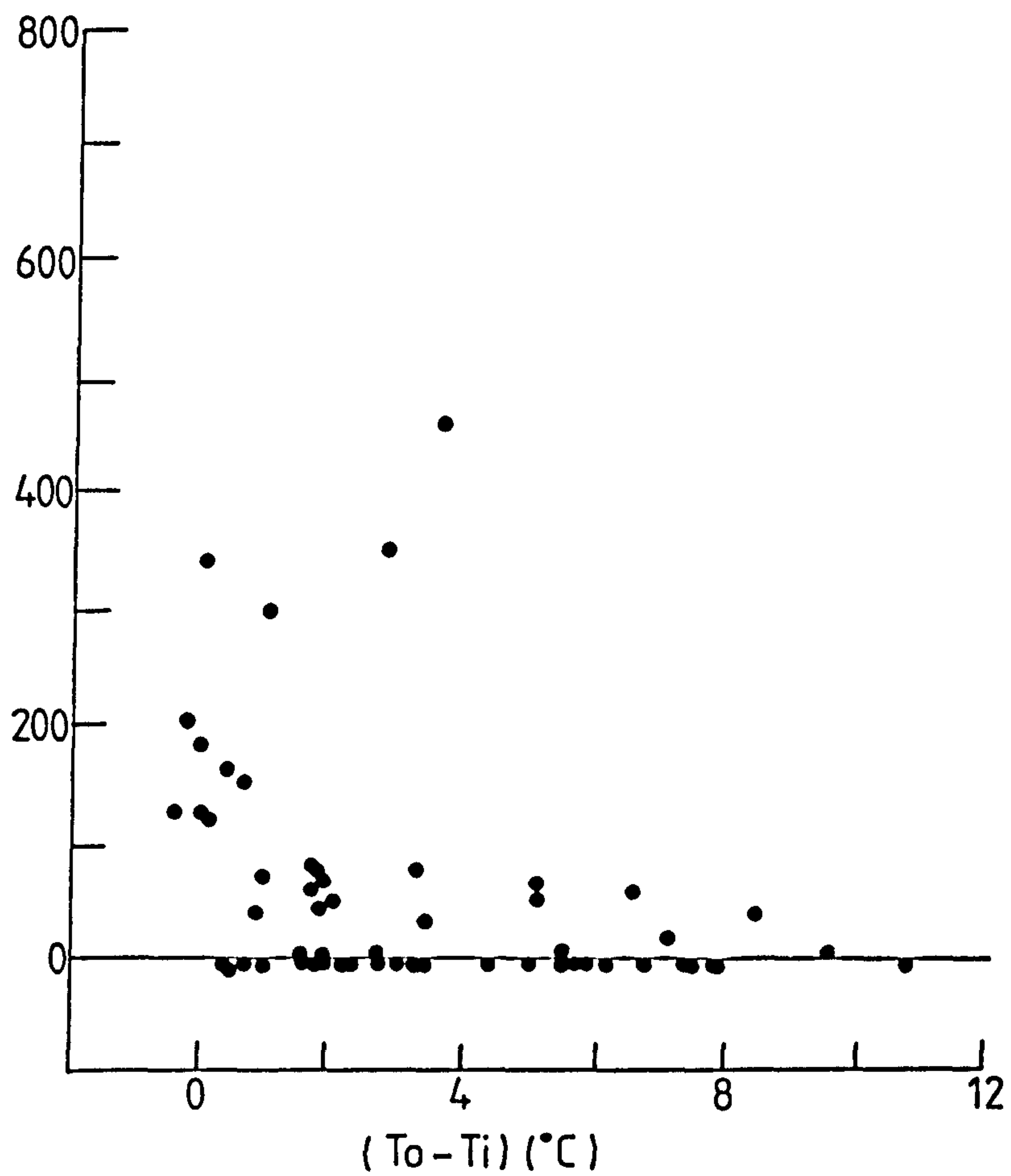
MEAN HOURLY ΔT ACROSS COLLECTOR v s INSOLATION
FOR EAST FACING COLLECTOR ON 6th, 11th, 20th FEB. 1989

Figure 5.3.14



MEAN HOURLY ΔT ACROSS COLLECTOR v s INSOLATION
FOR SOUTH FACING COLLECTOR ON 6th, 11th, & 20th FEB. 1989

Figure 5.3.15



MEAN HOURLY ΔT ACROSS COLLECTOR v s INSOLATION
FOR WEST FACING COLLECTOR ON 6th, 11th, & 20th FEB. 1989

Figure 5.3.16

5.4 Thermosyphon Solar Water Heater Performance

i) Performance indices

The following ratios of energy contents were calculated on a daily, and monthly basis.

$$\text{Solar Fraction} = \frac{\text{Solar heated water consumption}}{\text{Solar + conventionally heated water consumption}}$$

$$\text{i.e. } f = \frac{\sum M_{sw}(T_{sw} - T_m)}{\sum M_A(T_A - T_m) + M_{sw}(T_{sw} - T_m)}$$

The temperature of the solar heated water was taken as the arithmetic mean of the five equidistant temperature readings within the solar store.

$$\text{System Efficacy} = \frac{\text{Solar Heated water consumed}}{\text{Insolation}}, \text{ i.e. } \epsilon = \frac{\sum M_{sw} C_p (T_{sw} - T_m)}{\sum I A_o t}$$

This ratio was termed 'efficacy' rather than efficiency because its calculated value could be greater than unity. If a day of high insolation were followed by an overcast day, the water heated by solar energy on the first day may still have been consumed on the second day. This contribution became less significant if the efficacy was calculated over a greater period of time.

$$\text{System Efficiency} = \frac{\text{Solar heated water consumed + Heat 'in-store'}}{\text{Insolation}}, \text{ i.e. } \eta = \frac{\sum M_{sw} \cdot C_p (T_{sw} - T_m) + M_c \cdot C_p (T_{s0} - T_{st})}{\sum I \cdot A_o \cdot t}$$

This ratio accounted for the energy content of the solar heated water accrued or lost over any chosen period. The "heat in-store" referred to the rise in the sensible heat of the contained water during the period of evaluation. The efficiency could be negative, e.g. if a bright day was followed by an overcast day, there would still be some solar heated water in the store at the beginning of the next day. If, during that

second day, the energy lost by the solar store was greater than the energy content of any solar water consumed, the numerator in the efficiency became negative.

Solar fraction, system efficacy and also system efficiency were plotted against :-

- each other
- time
- volumes of hot water consumed
- insolation
- Solar Load Ratio, - insolation/total energy content of hot (i.e. both solar heated and conventionally heated) water consumed.

The results for the period from May until July 1985 inclusive, (5.4.1), were rather inconsistent and any relationships between the various performance parameters were difficult to identify. Maintaining continuous operation of all three solar water-heating installations was hindered by initial teething problems. Power cuts and mains-induced interference proved to be the most disruptive. These interruptions left some of the occupants in some doubt as to the operational state of the solar-energy water-heaters.

All of the data was reduced down to pertinent daily data and stored on INSTAT (5.4.2) data manipulation files. INSTAT was used to best effect when describing, statistically, the various performance parameters required for the correlation of the system performance

a) Solar fraction

The daily values of solar fraction give merely an instantaneous "picture" of the solar contribution to the domestic hot water demand. During a month in which all three dwellings were both occupied and being monitored, (from 1st to 30th of August 1986), the maximum daily solar fractions for houses Nos.7, 8 and 9 were 0.92, 0.57, and 0.68 respectively (Figs. 5.4.1 - 5.4.3).

To assess more realistically the contribution that a solar-energy water heating system can make one must calculate the total weekly, monthly, and annual solar fractions. The overall cumulative solar fractions attained at the end of August 1986 were 0.28, 0.29, and 0.42. as illustrated in Figure. 5.4.4. The pre-heat installation in house No.9 maintained a near-constant solar fraction over the whole month because every withdrawal of conventional hot water contained a proportion of solar heated water without the user being aware of it. The two third tap systems required much more deliberation when using solar-heated water.

Due to a number of minor system failures during this demonstration project only one solar-energy water heating installation, (the indirect third tap system), was in operation continuously for longer than 12 months. The solar fraction attained at the end of each month from September 1985 to September 1986 is shown in figure 5.4.5, with a maximum of 0.35 occurring in July 1986. Figure 5.4.6 illustrates the cumulative solar fraction for the same period with an overall solar fraction after thirteen months of 0.17.

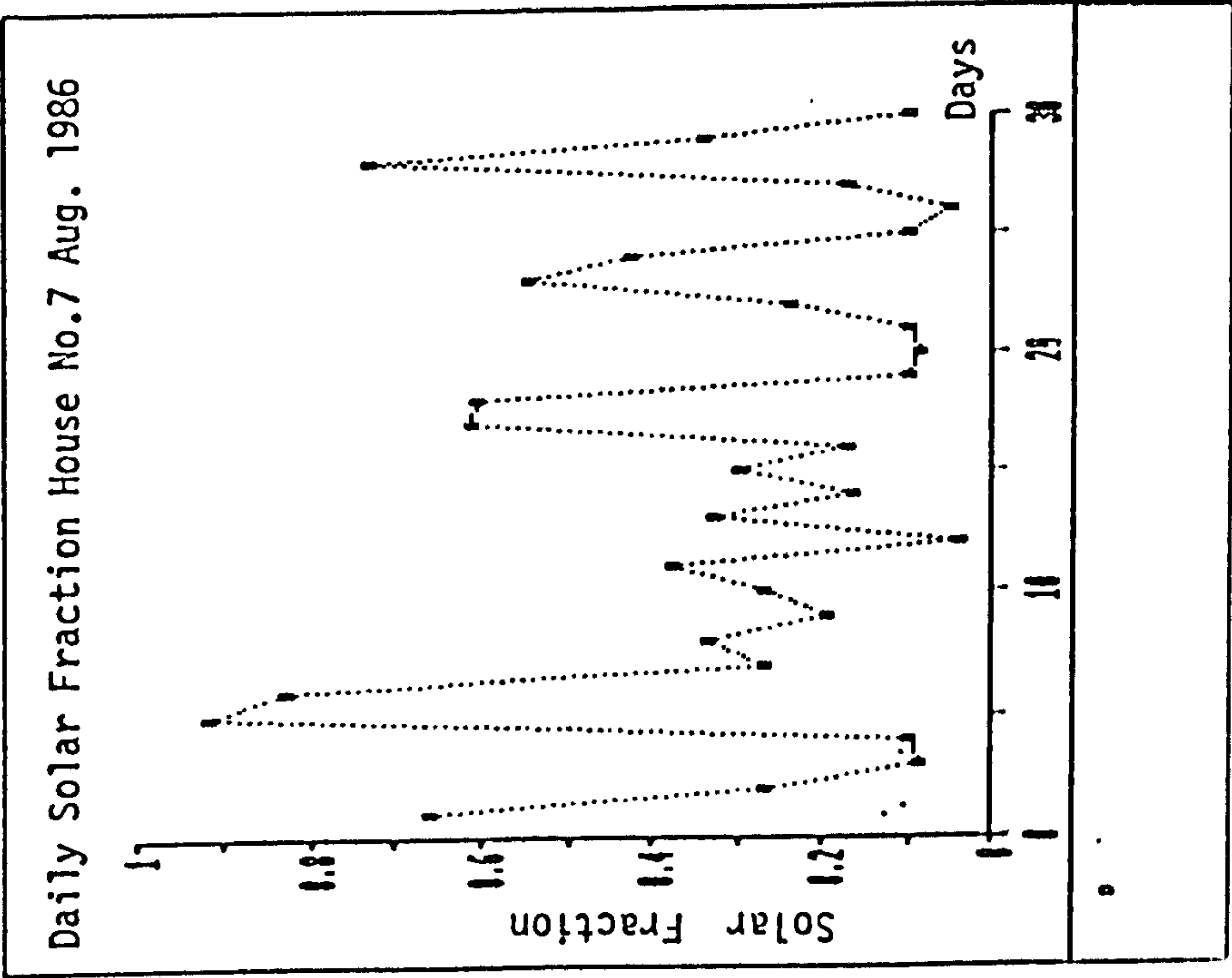


Figure 5.4.1

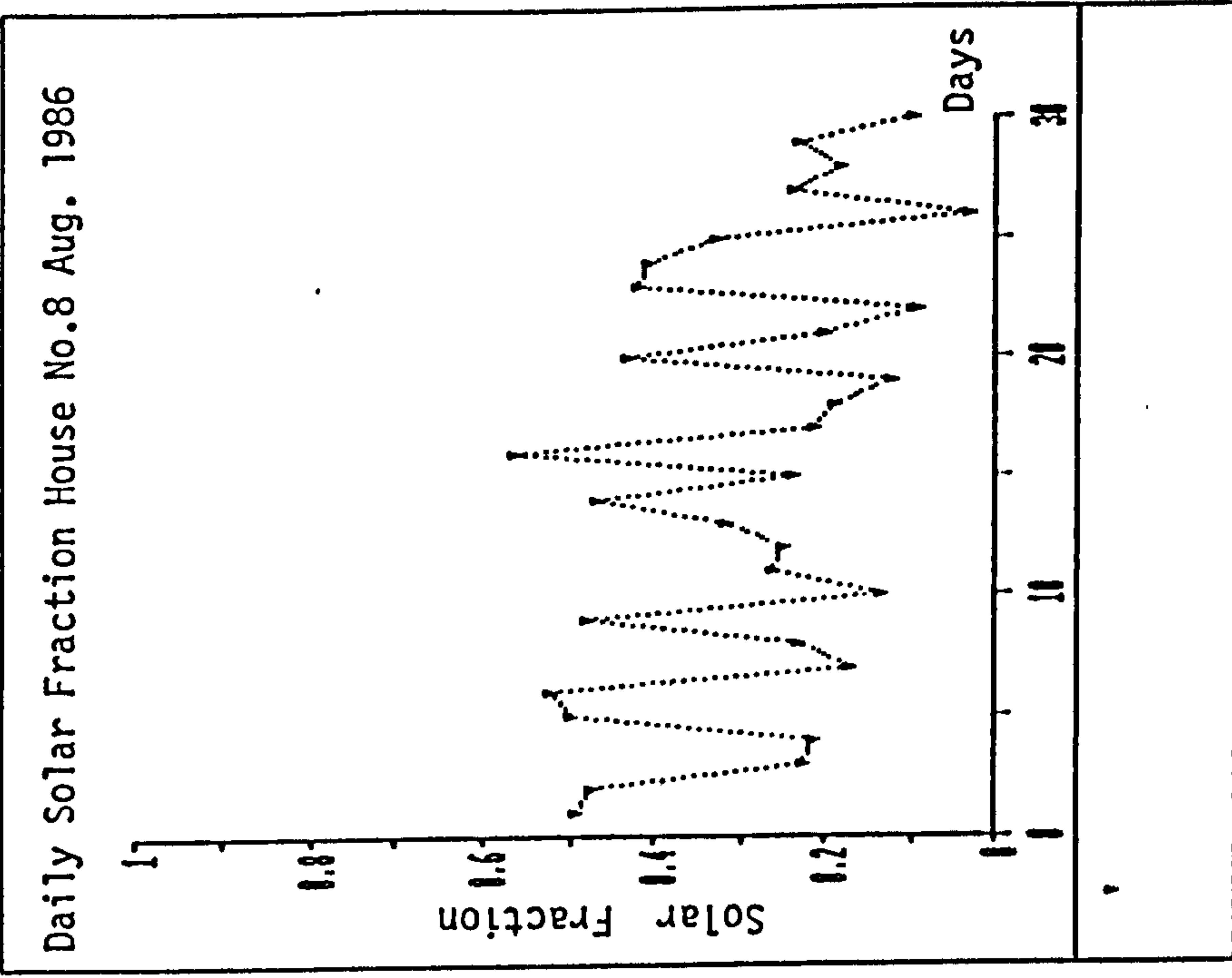


Figure 5.4.2

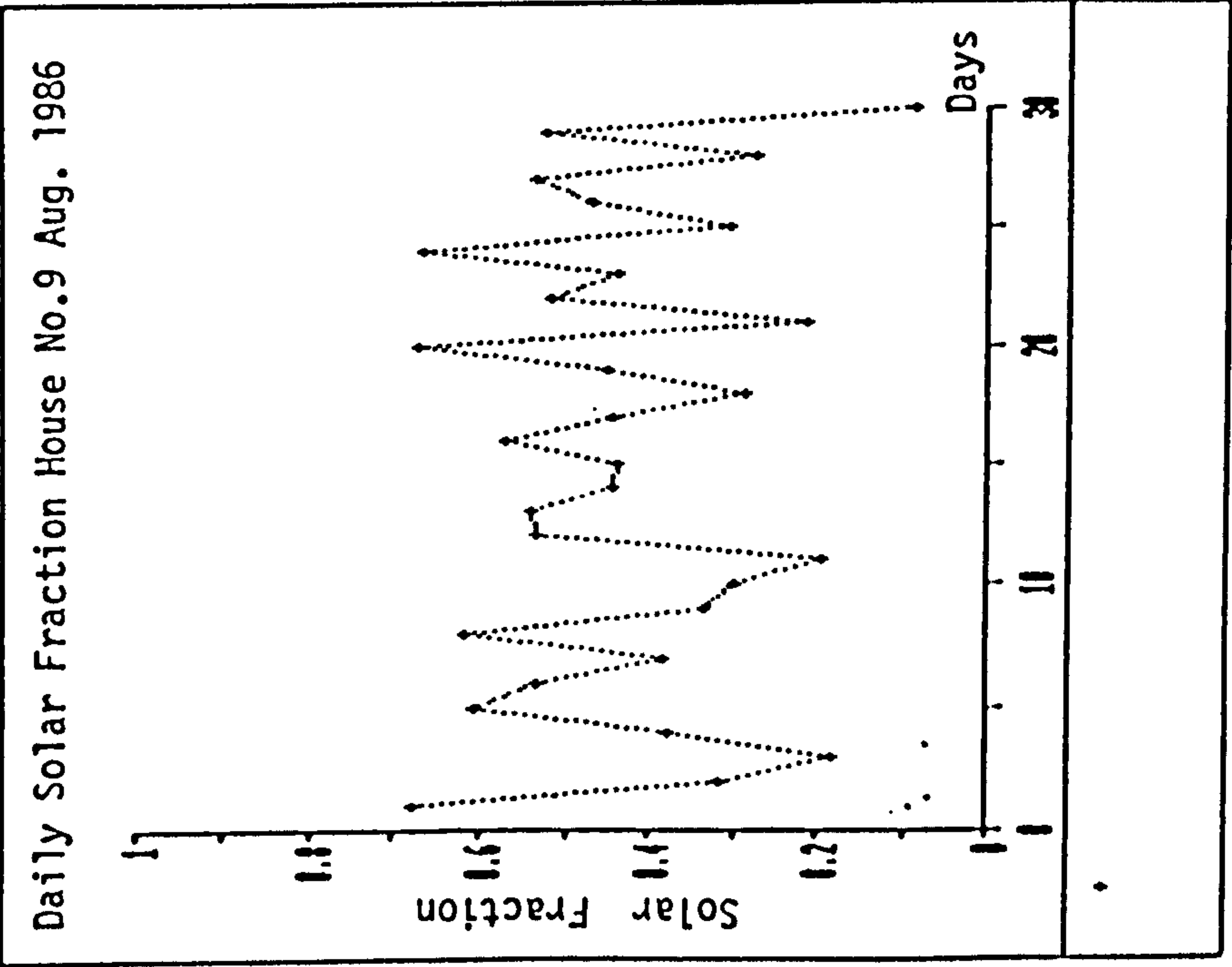


Figure 5.4.3

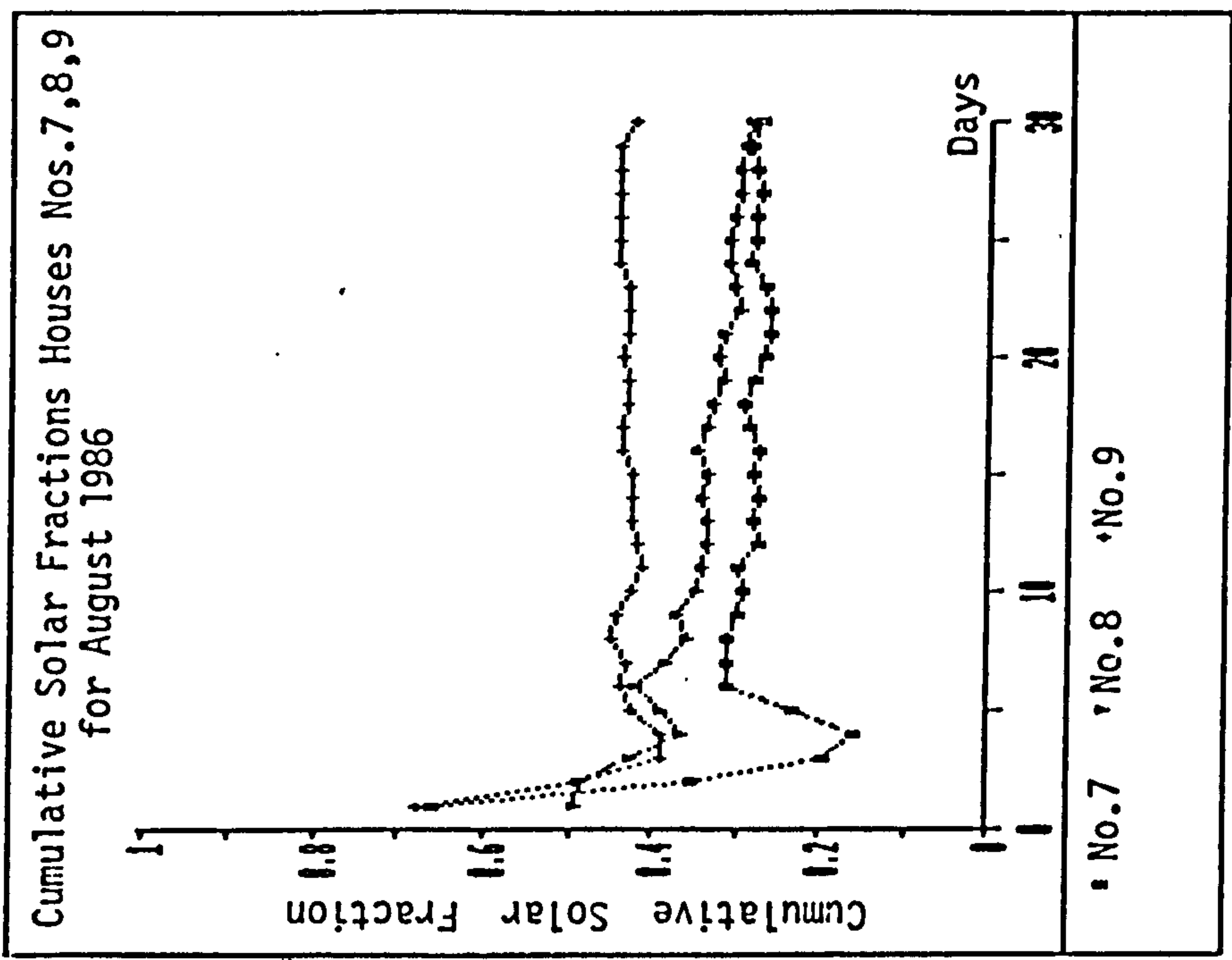


Figure 5.4.4

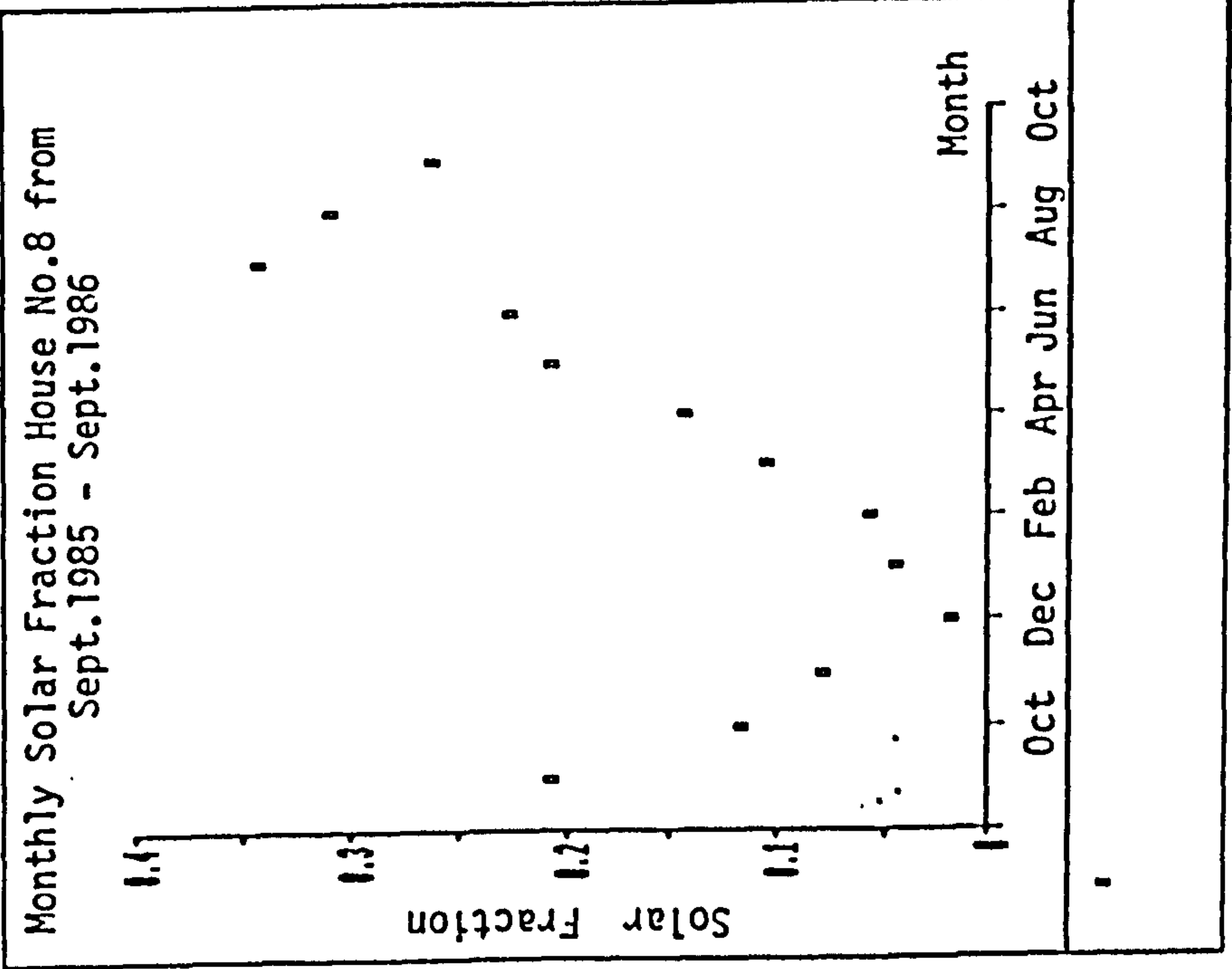


Figure 5.4.5

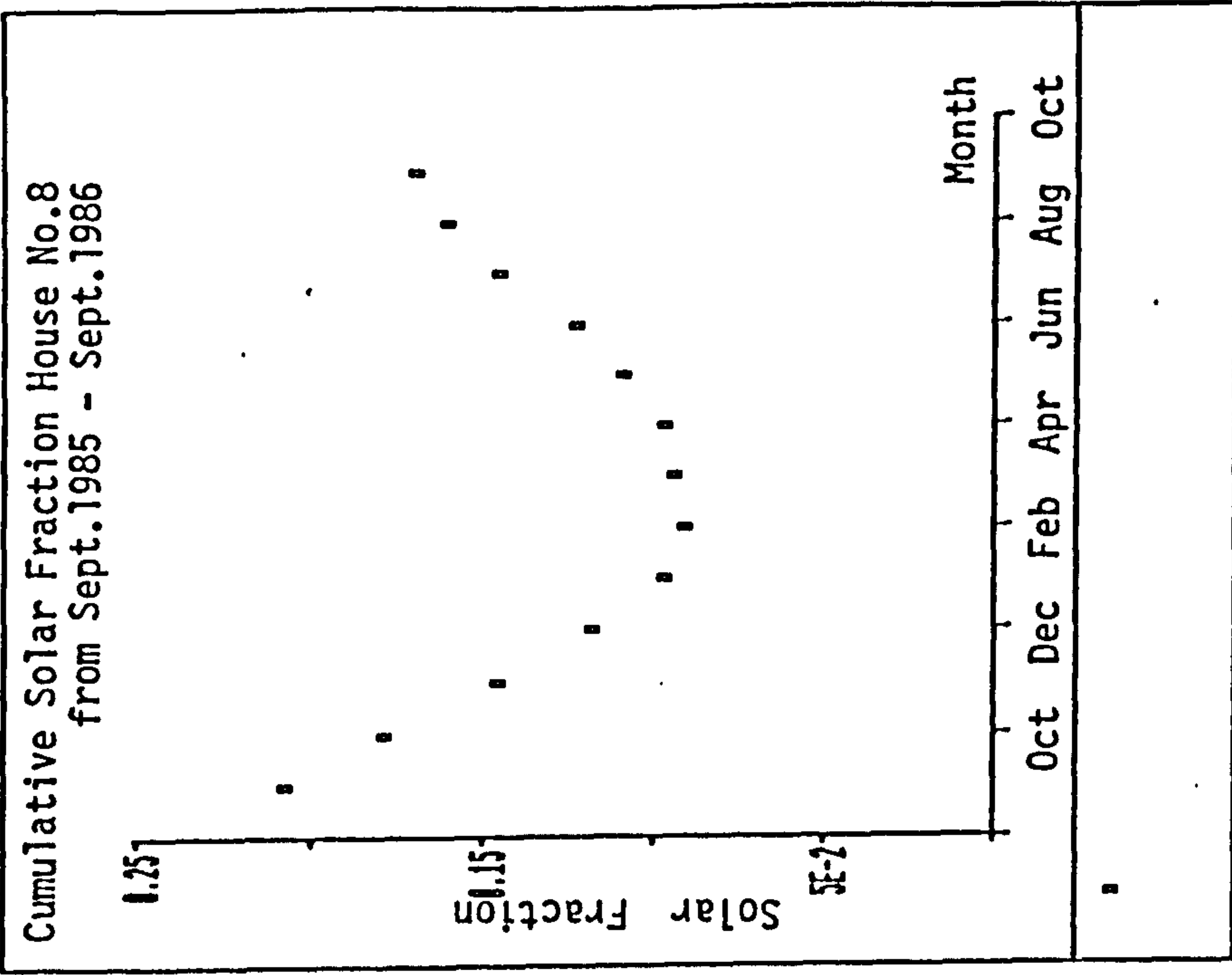


Figure 5.4.6

b) Variation of solar fraction with insolation

If constant volumes of hot water were drawn off each day, and solar-heated water was always used whenever hot water was consumed, then one could expect a correlation between insolation and solar fraction. Unfortunately this was not a realistic pattern of hot water consumption as demonstrated by figs 5.4.7 - 5.4.9. There was tendency for the daily solar fraction to increase with daily insolation but the range of volumes of daily total, (conventionally + solar-heated), water consumption induced significant scatter. The occupants obviously tended to consume hot water for washing and bathing at a time which suited *them* and not the prevailing weather conditions. (Using the solar load ratio i.e. insolation/total energy content of hot + solar heated water yielded little improvement in the degree of scatter). If a longer time base was considered then a stronger correlation between these two parameters emerged, fig. 5.4.10. The variations of total daily hot water consumption with solar fraction, fig. 5.4.11, showed that as the total consumption of hot water increased the solar water heating was less capable of meeting the requirement.

A similar problem existed when attempting to correlate the daily solar contribution and the insolation, figs 5.4.12 - 5.4.14, however, the *cumulative* daily values of solar contribution and insolation showed a very good correlation (figure 5.4.15). Again, the solar pre-heat installation had the greatest solar-heated water contribution at the end of that month. If each monthly solar contribution was plotted against monthly insolation the resultant scatter could be attributed to seasonal variations in the hot and solar heated water requirement, (fig. 5.4.16). As with the cumulative daily values, the cumulative monthly plot of these two parameters (fig. 5.4.17) produced, ultimately the best correlation.

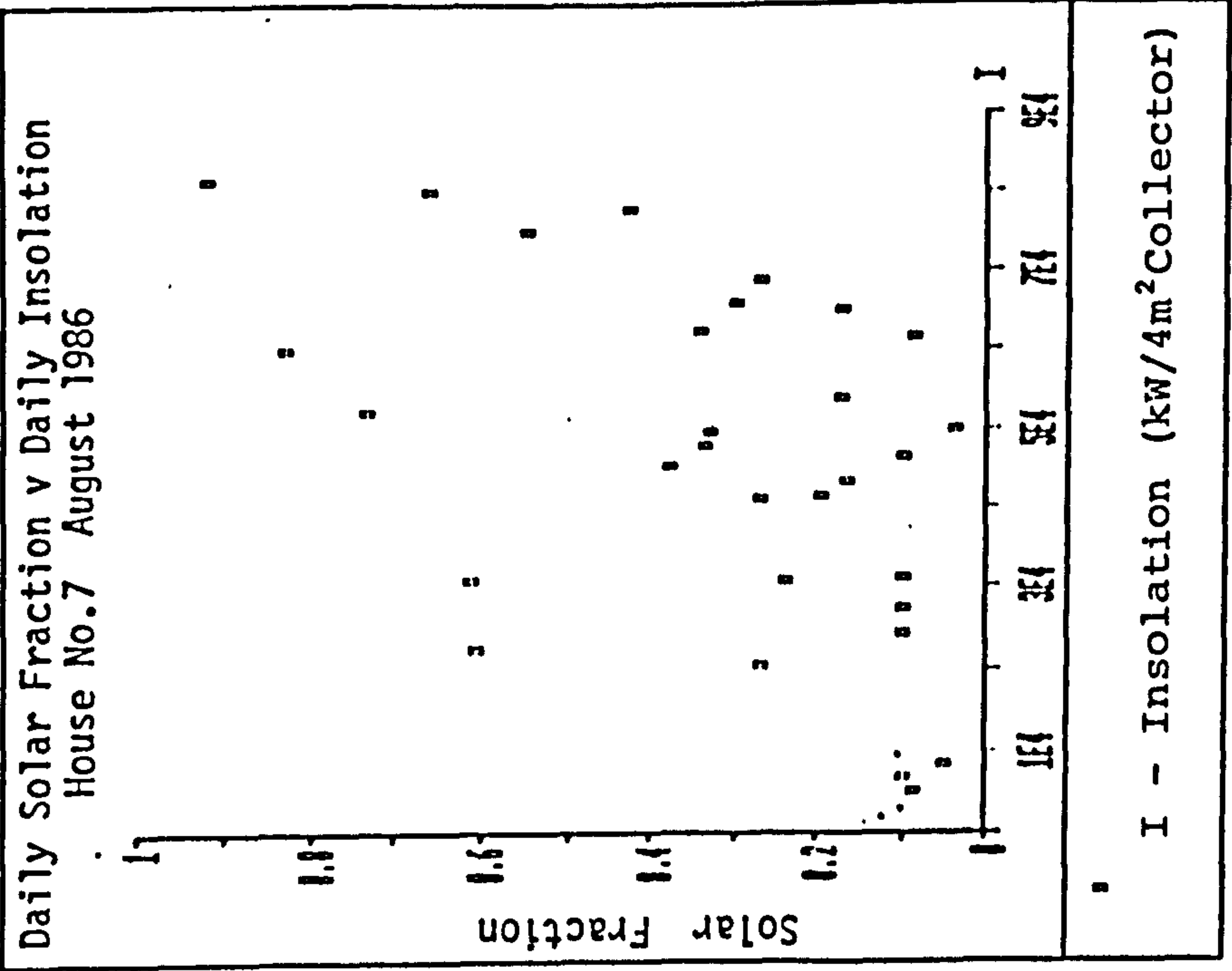


Figure 5.4.7

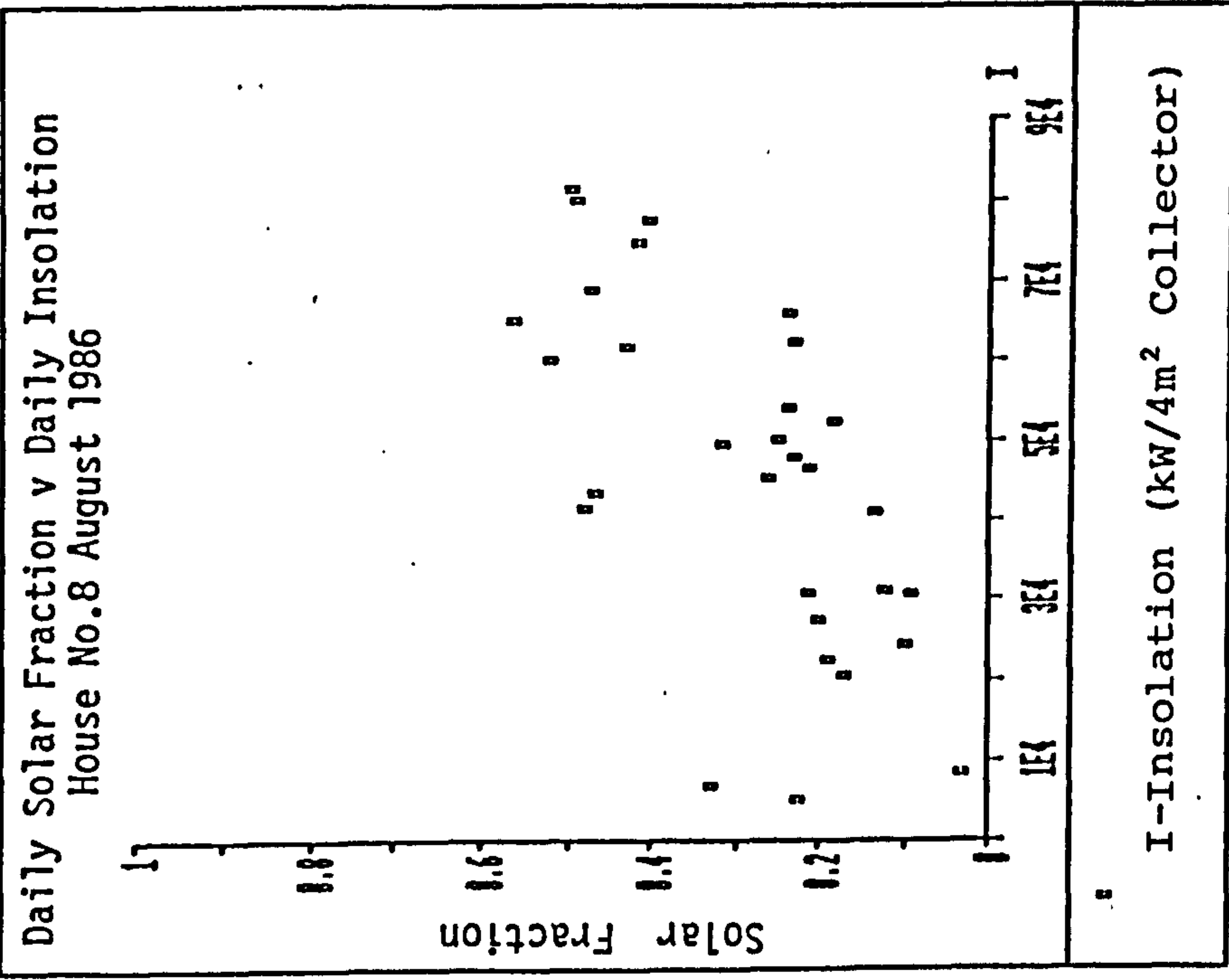


Figure 5.4.8

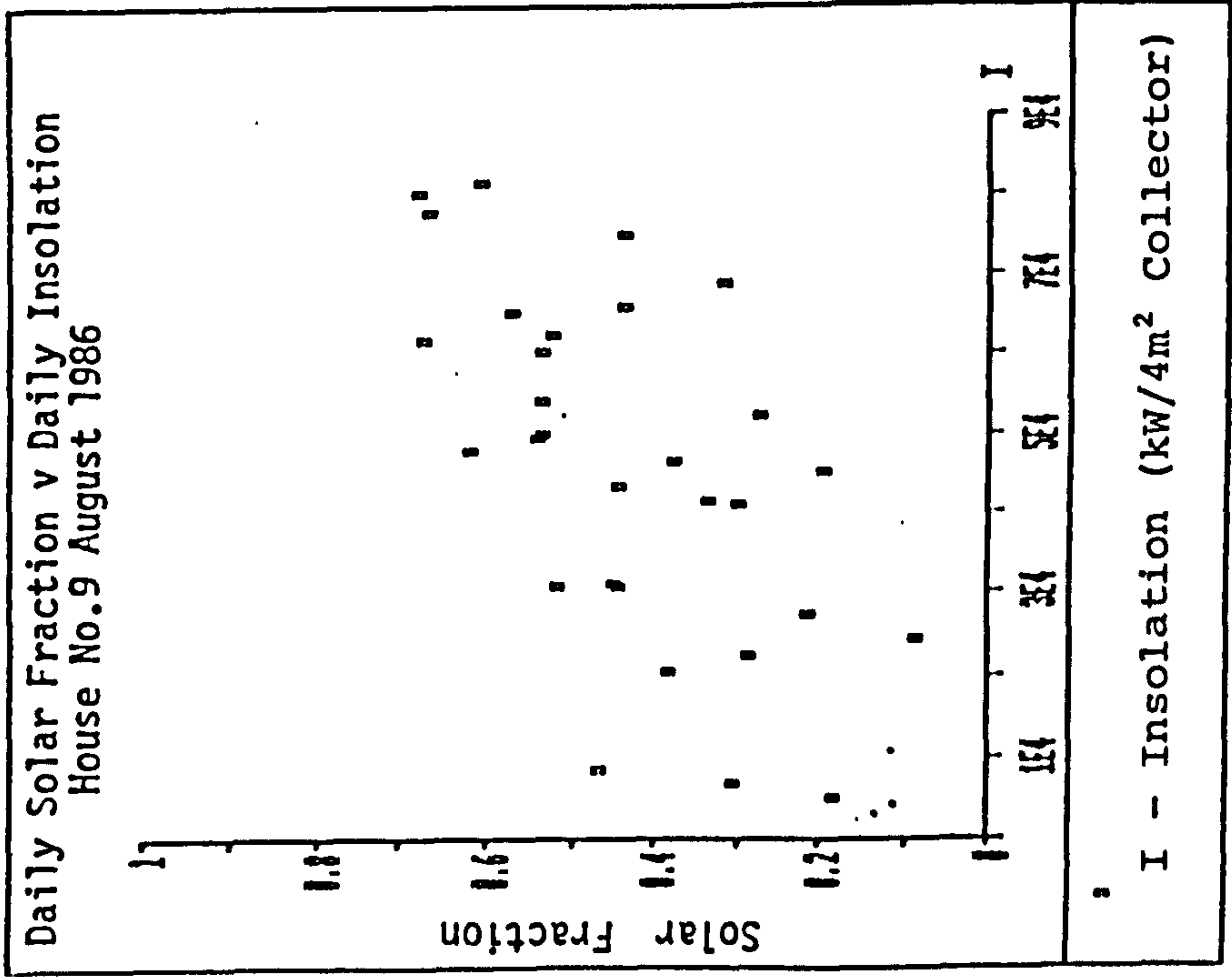


Figure 5.4.9

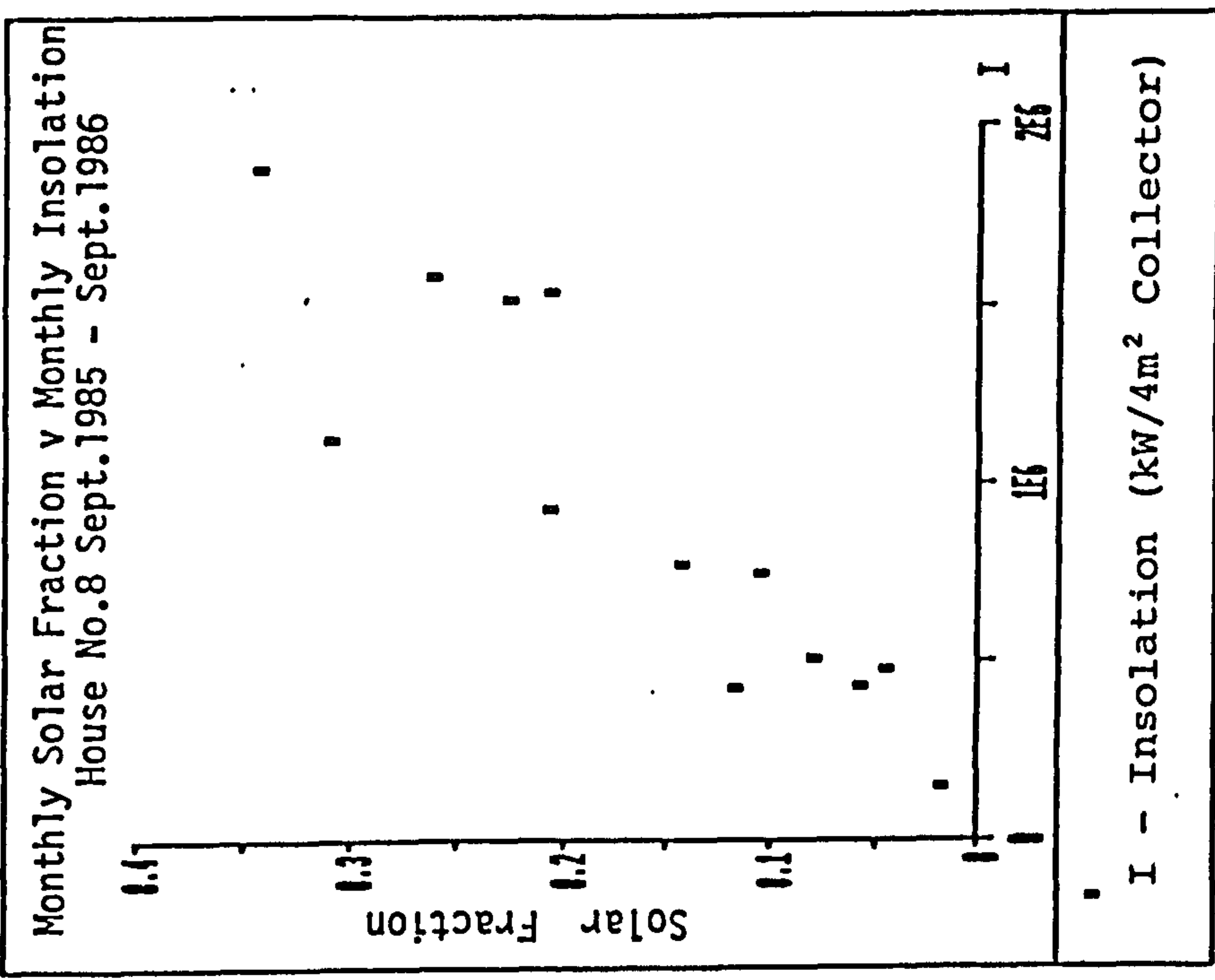


Figure 5.4.10

Daily Solar Fraction Vs Total Daily Hot + Solar Heated Water Consumption for Houses No.s 7, 8 & 9 in August 1986

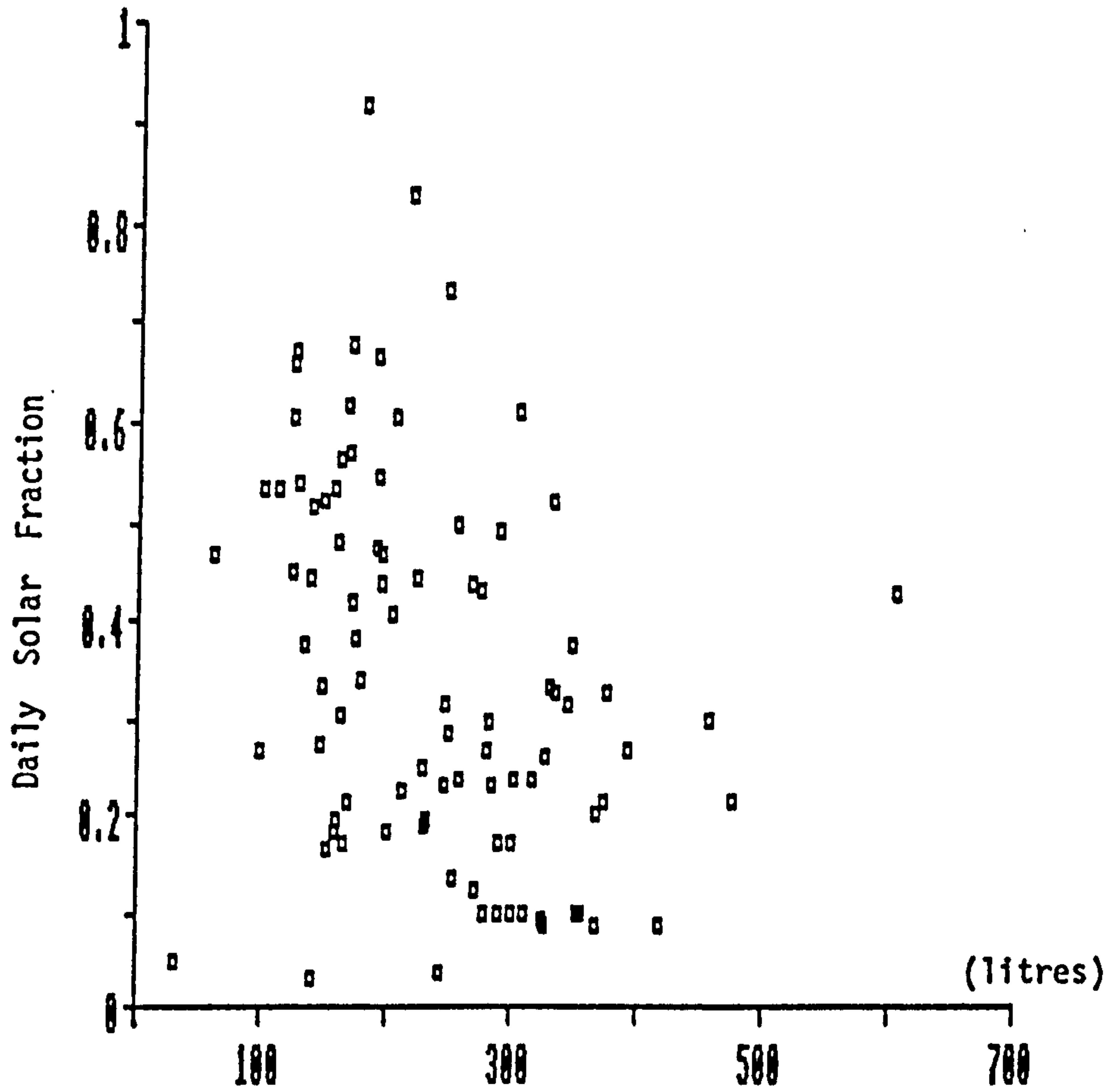


Figure 5.4.11

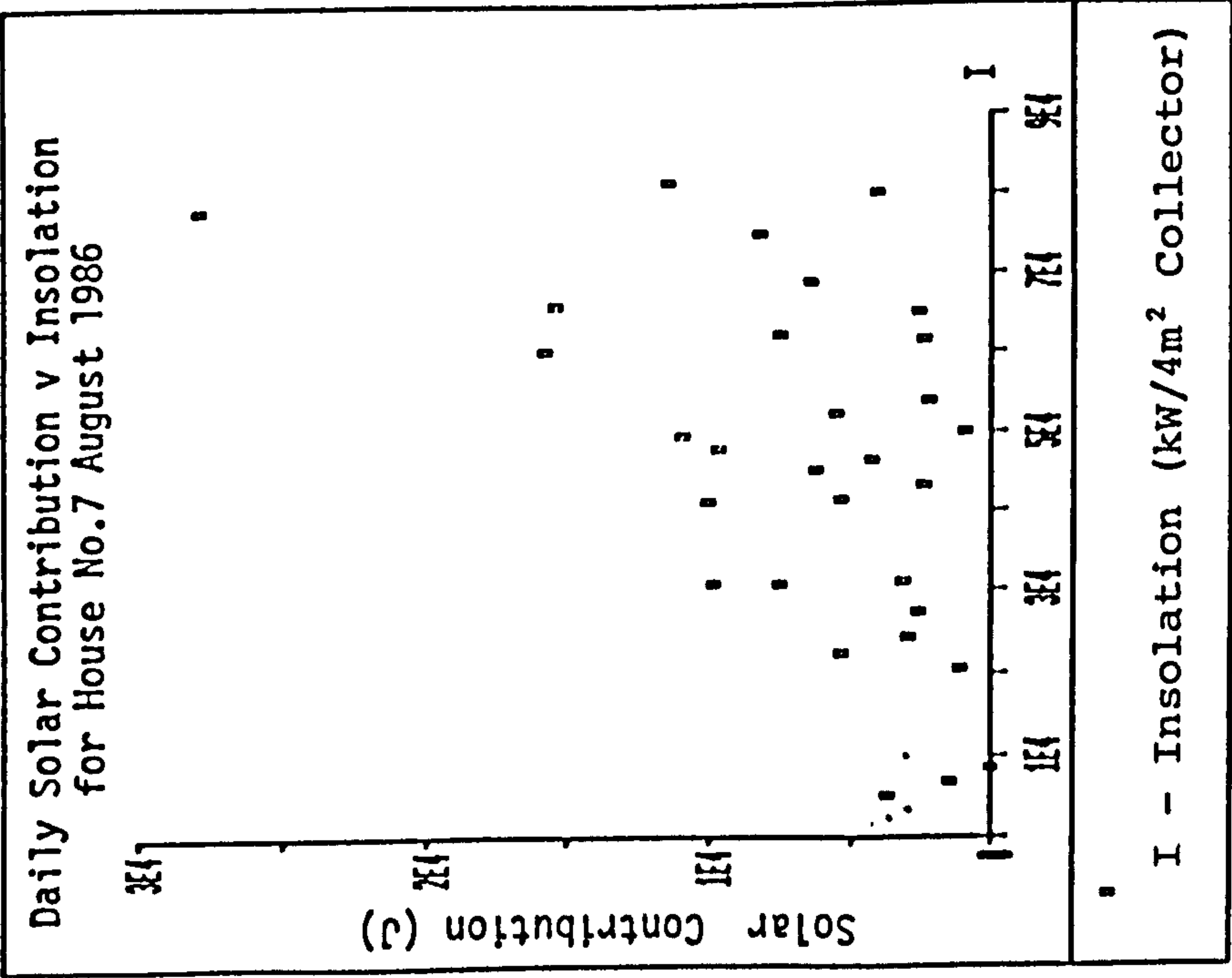


Figure 5.4.12

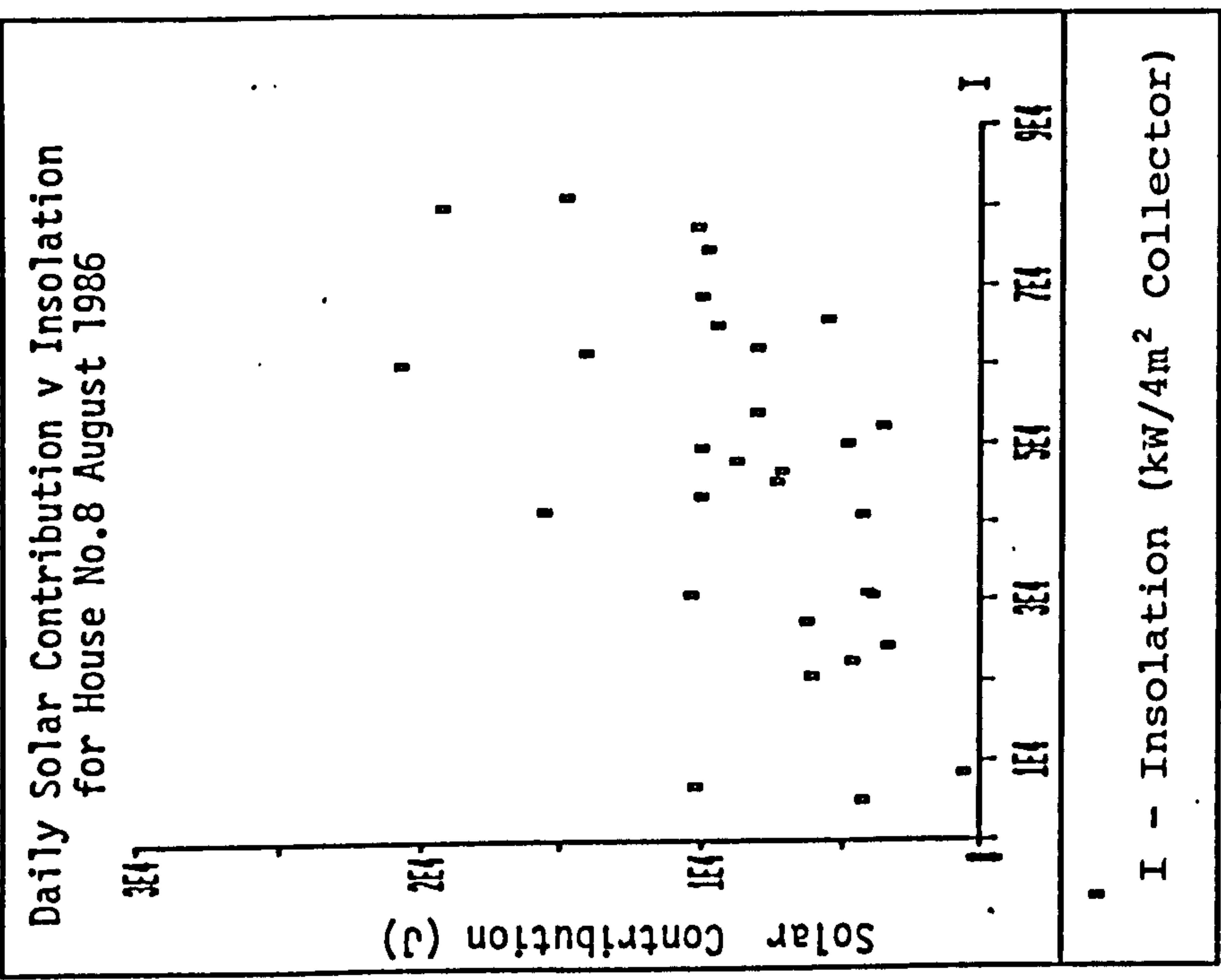


Figure 5.4.13

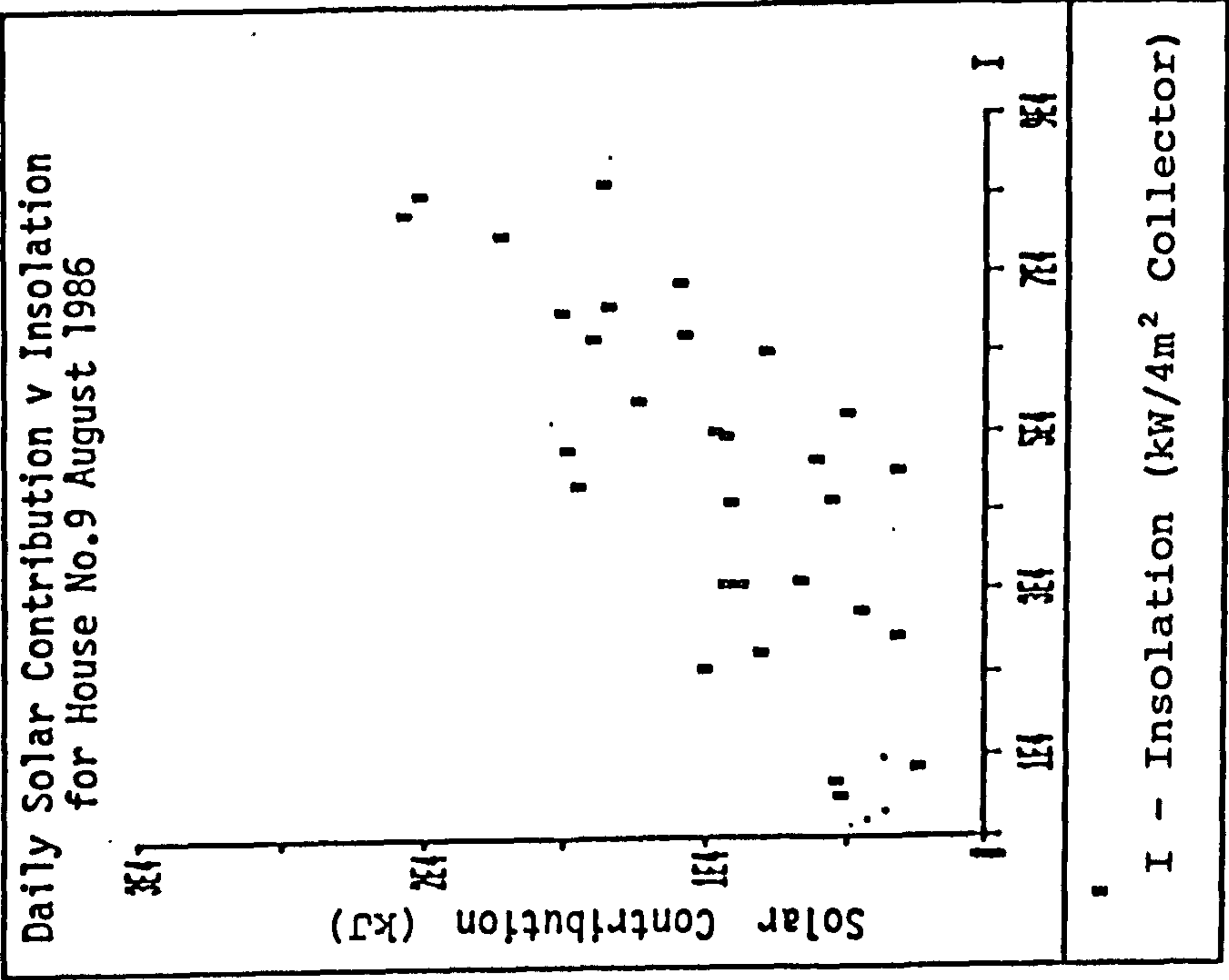


Figure 5.4.14

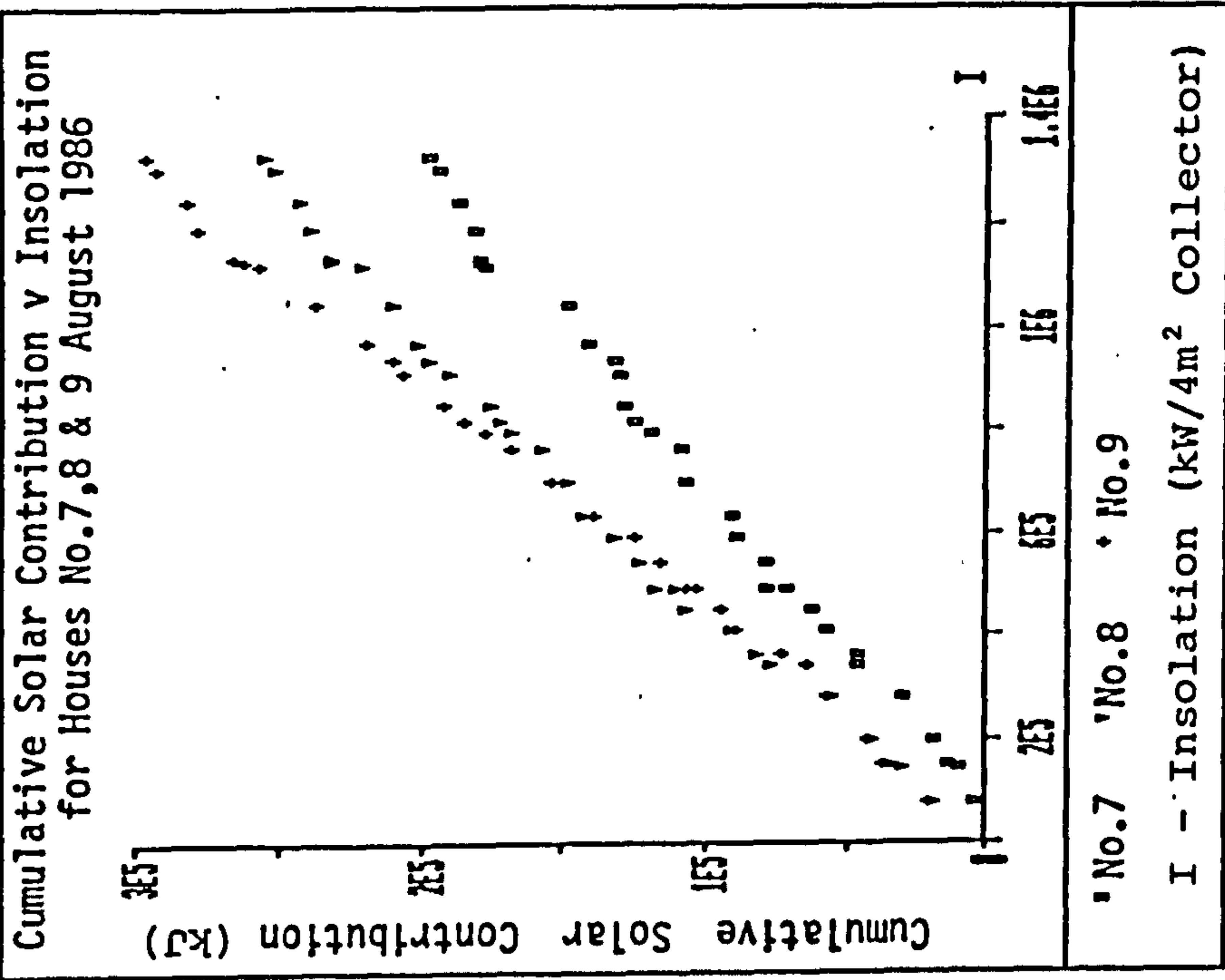


Figure 5.4.15

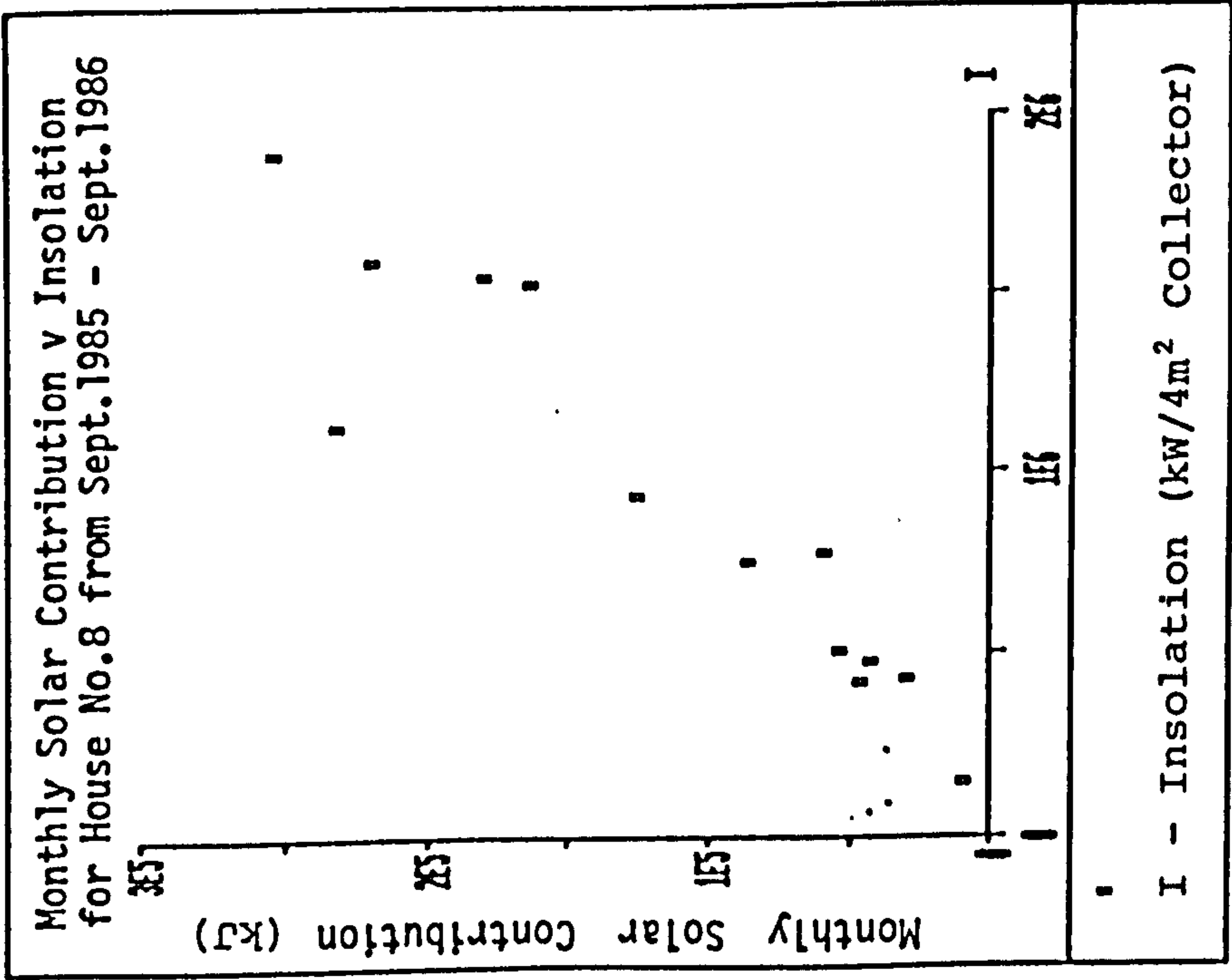


Figure 5.4.16

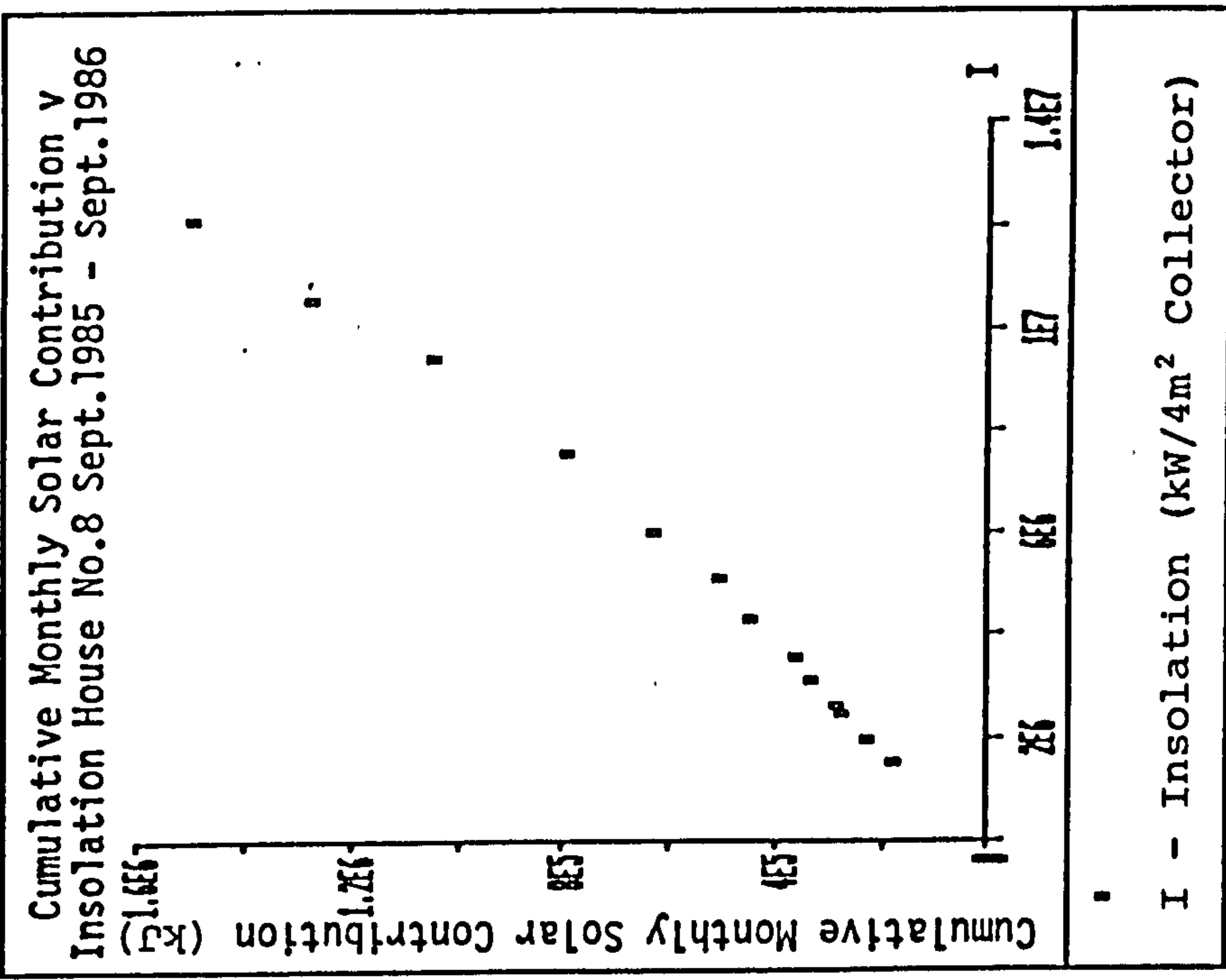


Figure 5.4.17

c) Variation of efficacy with efficiency

The efficacies and efficiencies attained during the monitoring period are summarised in table 5.4.1. It can be seen that some of the daily values of system efficacy were greater than unity. This occurred because this ratio could not account for solar heated water accrued during the previous day's insolation. As with the solar fraction, *daily* efficacy and efficiency could only give an indication of the potential instantaneous performance of a solar-energy water-heating system. Due to the oscillatory nature, (Figs. 5.4.18 - 5.4.19), especially of efficiency, one had to look at the cumulative values in order to evaluate each system. The cumulative daily values of efficiency and efficacy for each installation (figs. 5.4.20 - 5.4.21) showed that the pre-heat system performed better than the two third tap installations.

If the cumulative monthly values of these indices were plotted against time, figure 5.4.22, it was evident that these two parameters became one and the same to within 10%, figure 5.4.23.

Table 5.4.1 Maximum efficacies and efficiencies attained during monitoring period

	Third-tap + heating element	Third-tap + antifreeze	Solar Pre-heat + auto-draindown
Maximum Daily, Efficacies Efficiencies	0.71 0.36	1.48 0.72	1.02 0.92
Maximum Monthly, Efficacies Efficiencies	0.15 0.16	0.19 0.18	0.22 0.22

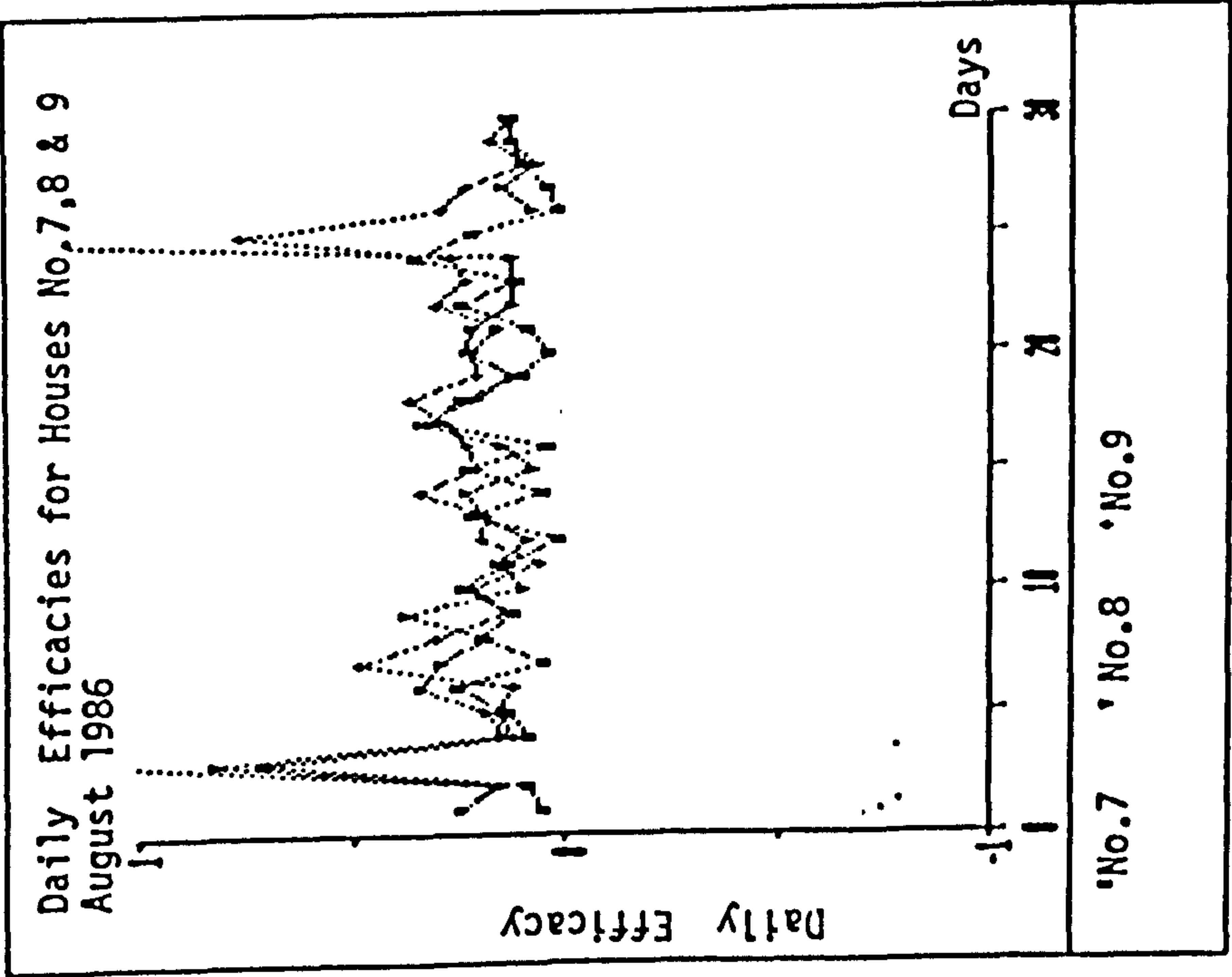


Figure 5.4.18

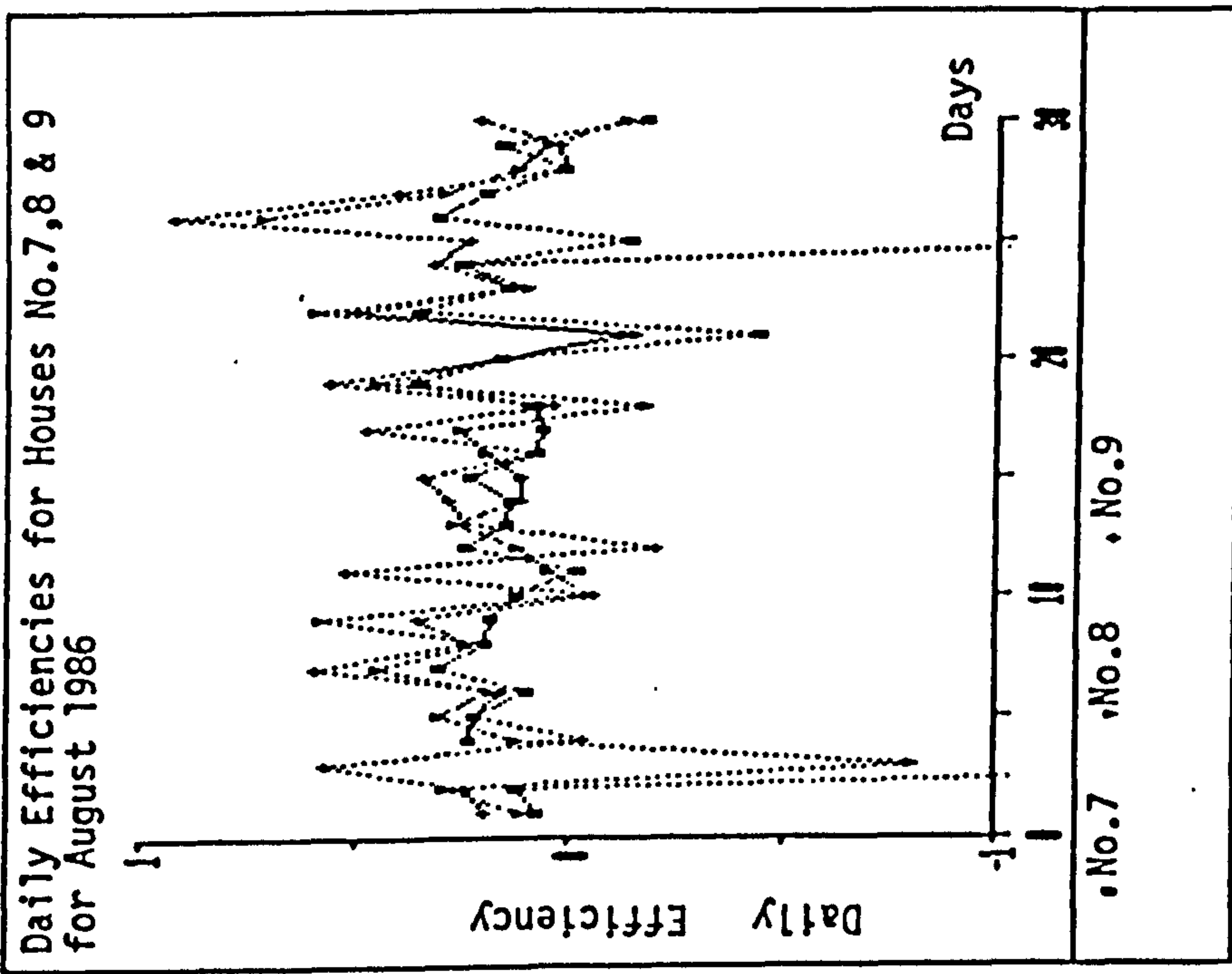


Figure 5.4.19

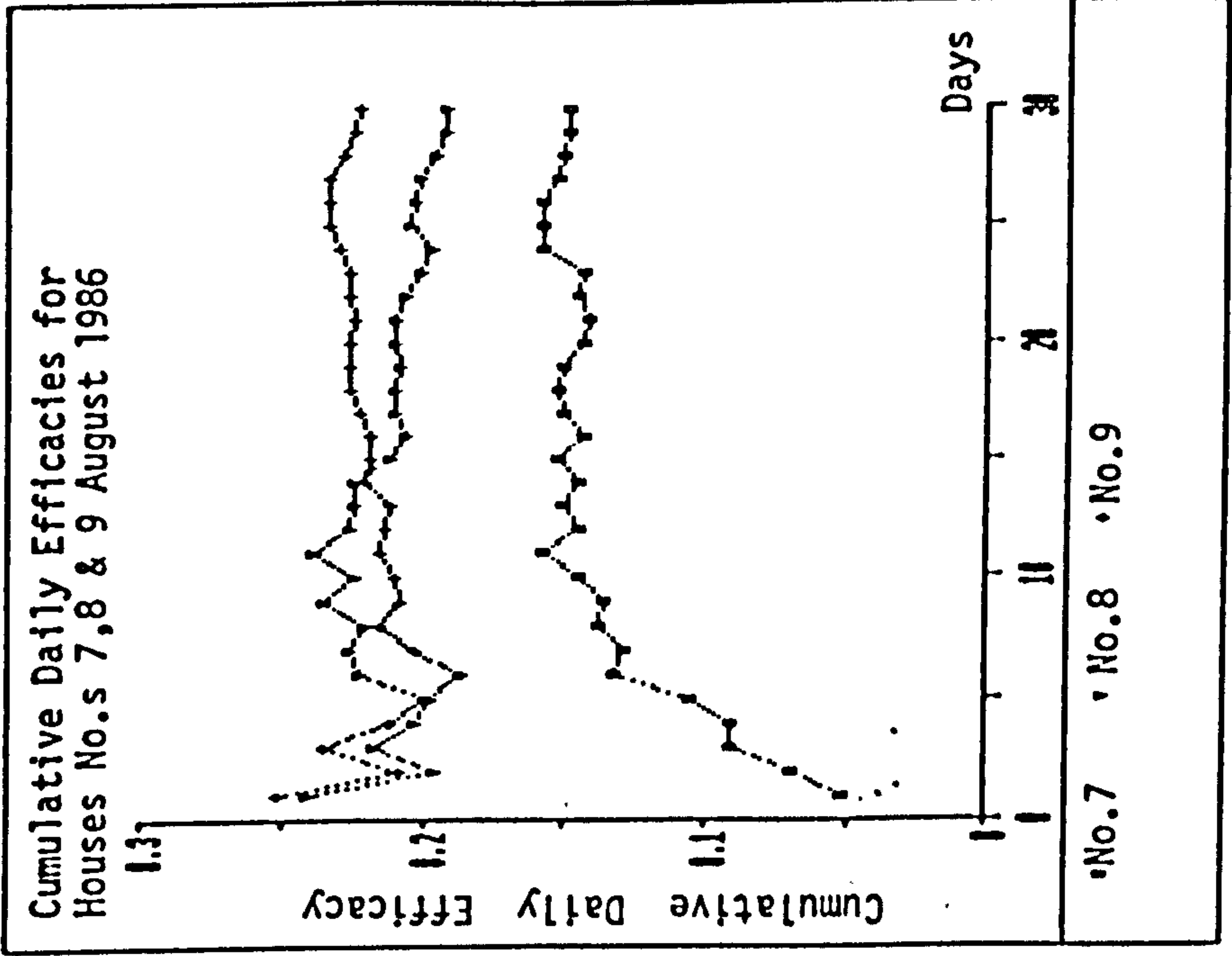


Figure 5.4.20

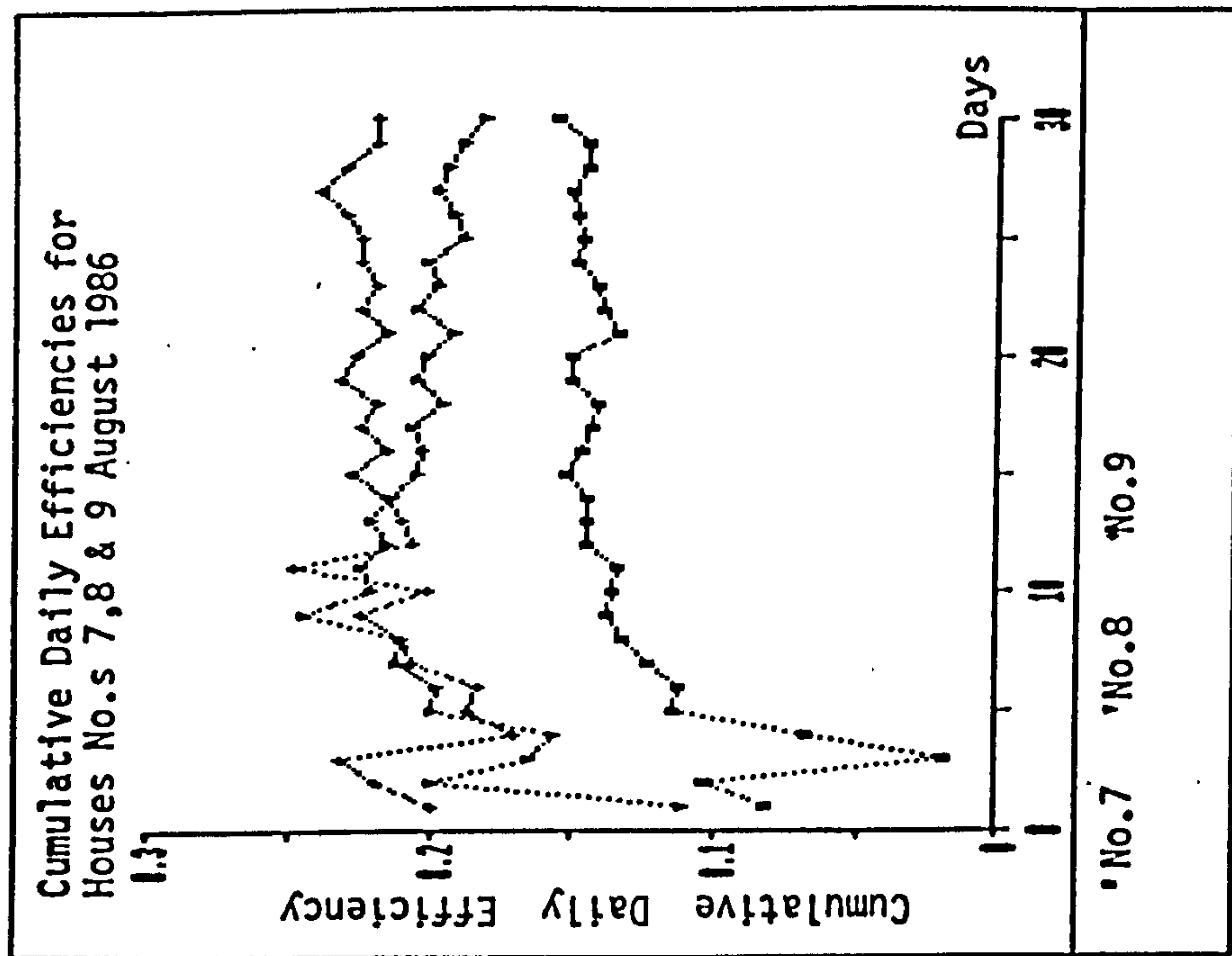


Figure 5.4.21

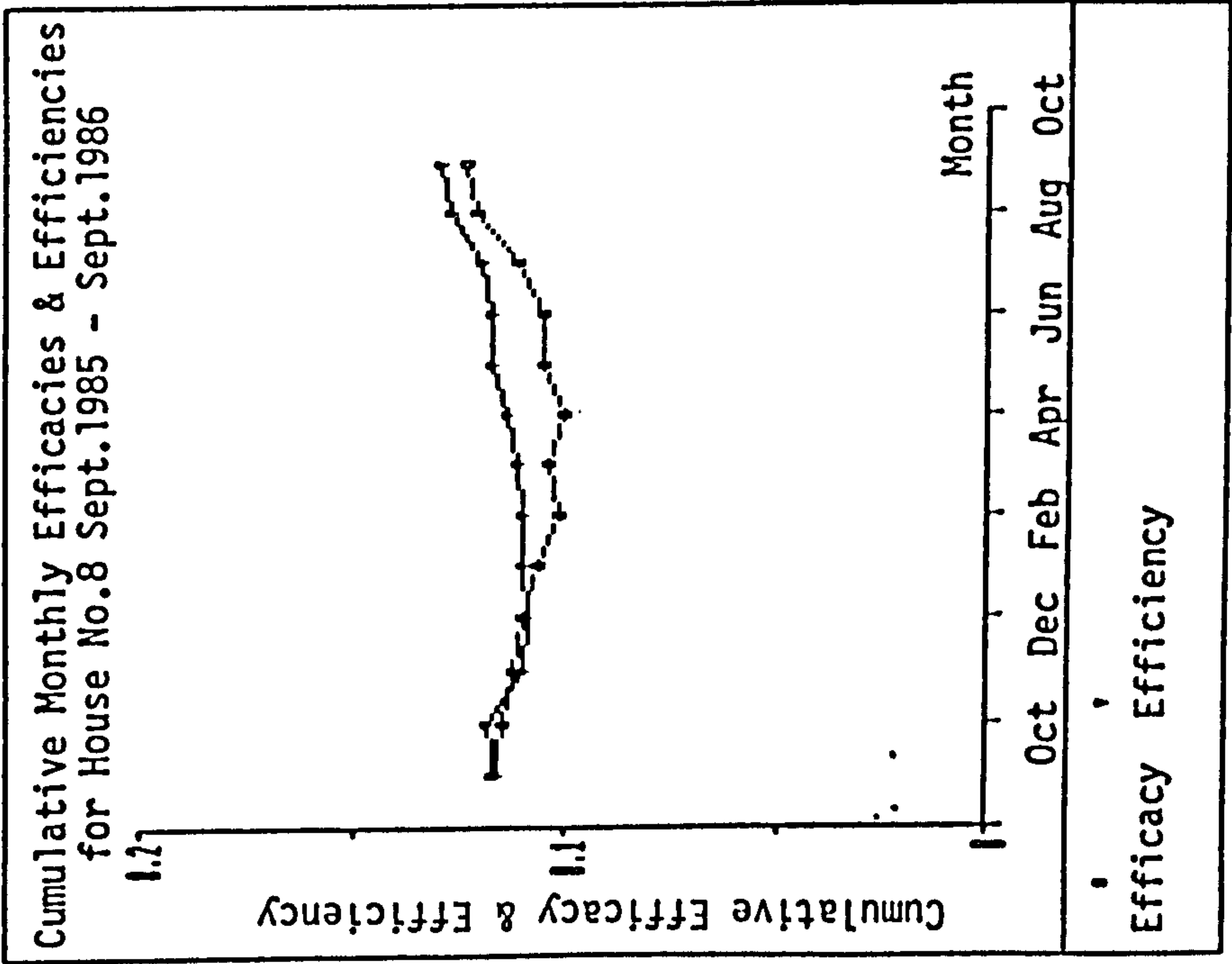


Figure 5.4.22

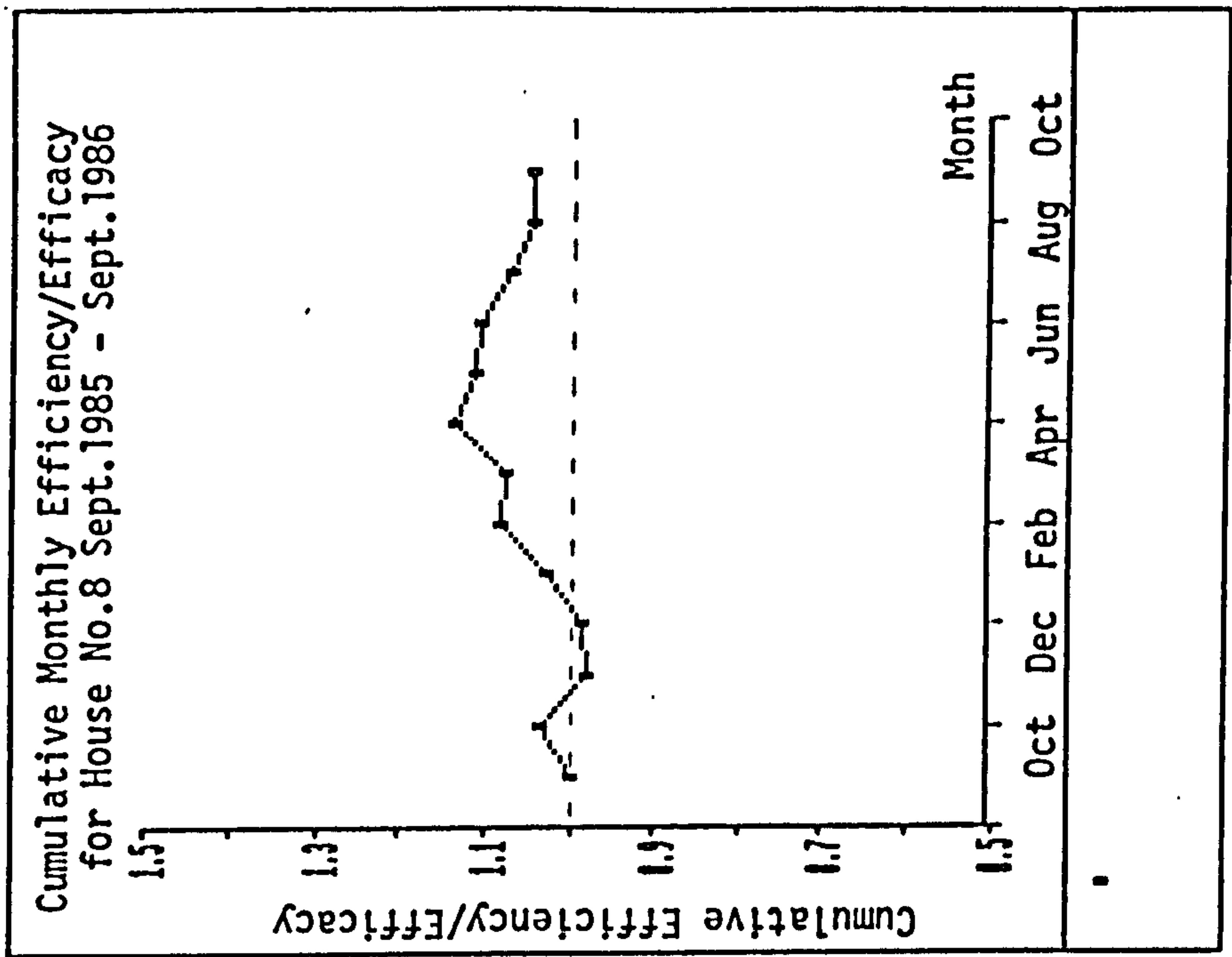


Figure 5.4.23

d) Convergence of efficiency and efficacy

Efficiency and efficacy should converge as the duration of the period over which they are simultaneously evaluated increases. This is because the solar heated water stored at the end of each day, (i.e. the difference between these performance indices), diminishes. Knowledge of the cumulative period of evaluation, after which efficiency and efficacy become equal, may be used to simplify performance measurement. After this time these two performance indices may be used interchangeably. The determination of efficacy required merely the measurement of volume and temperature of the solar-heated water withdrawn, and the insolation on the plane of the collector. Using efficacy allowed system efficiency to be determined non-invasively, and thus incurred a lower cost for instrumentation.

$$\text{Efficiency, defined as;} \quad \eta = \frac{\sum M_{sw}.C_p(T_{sw} - T_m) + M_{tk}.C_p(T_{se} - T_{sb})}{\sum I.A_c.t}$$

$$\text{Efficacy, given by;} \quad \epsilon = \frac{\sum M_{sw}.C_p(T_{sw} - T_m)}{\sum I.A_c.t}$$

$$\text{Thus,} \quad \eta/\epsilon = 1 + \left[\frac{\sum M_{tk}(T_{se} - T_{sb})}{\sum M_{sw}(T_{sw} - T_m)} \right]$$

The energy content of the residual stored sensible heat at the end of the evaluation period could have both a positive or negative value and fluctuated according to solar-heated water draw-off and insolation. Its value became insignificant as the total energy content of the solar-heated water consumed over the evaluation period increased. The smaller the capacity of the storage tank relative to the volume of solar-heated water withdrawn, the smaller the residual heat contained in the store. Thus a large ratio of solar-heated water consumption to store volume will produced a more rapid convergence of efficiency to efficacy as illustrated schematically in Fig. 5.4.24. This pattern of behaviour assumed that heat stored arose from that day rather than the previous one, and that daily solar-heated water consumption and daily total insolation did not deviate significantly from their mean values during the evaluation period.

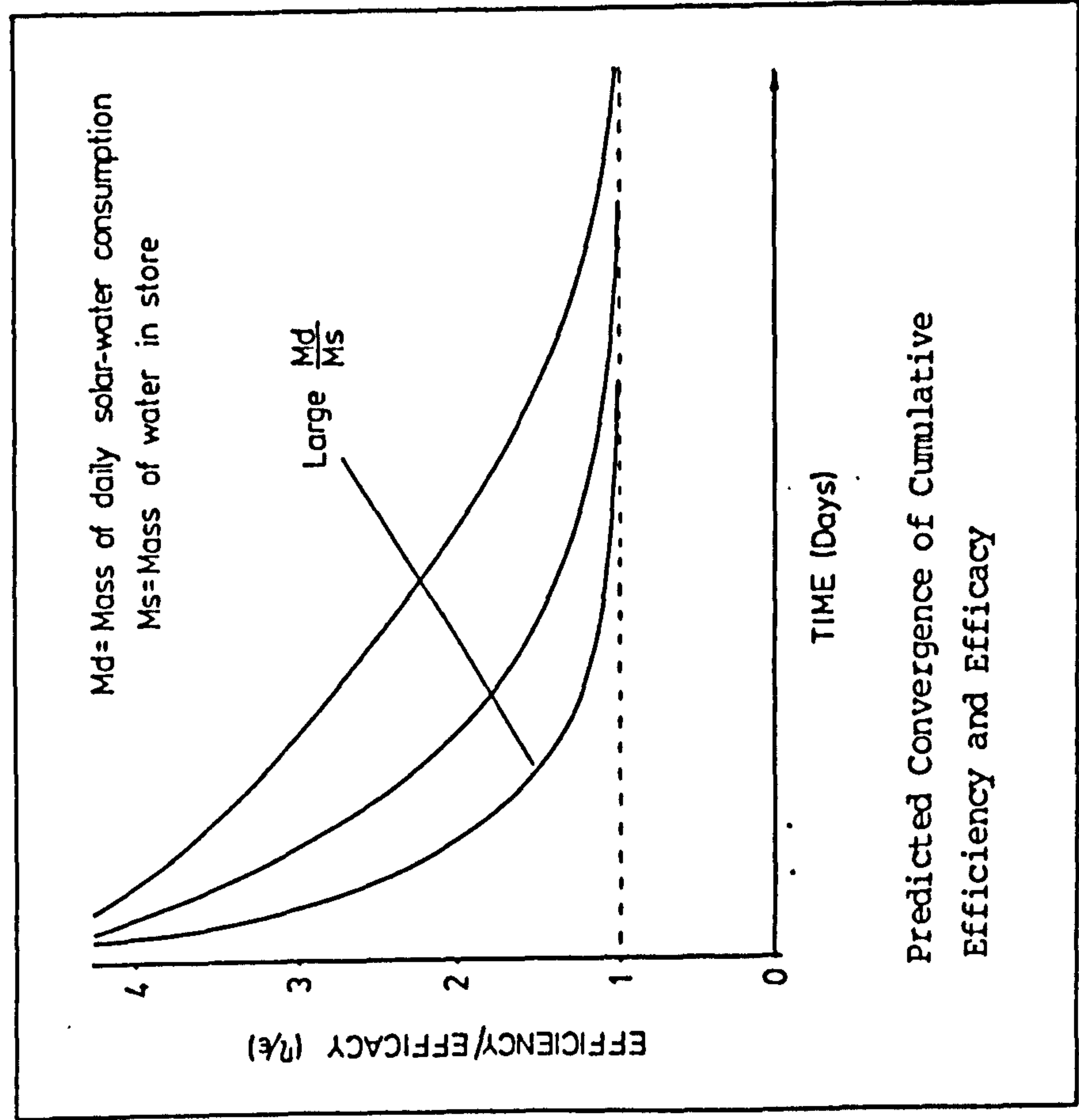


Figure 5.4.24

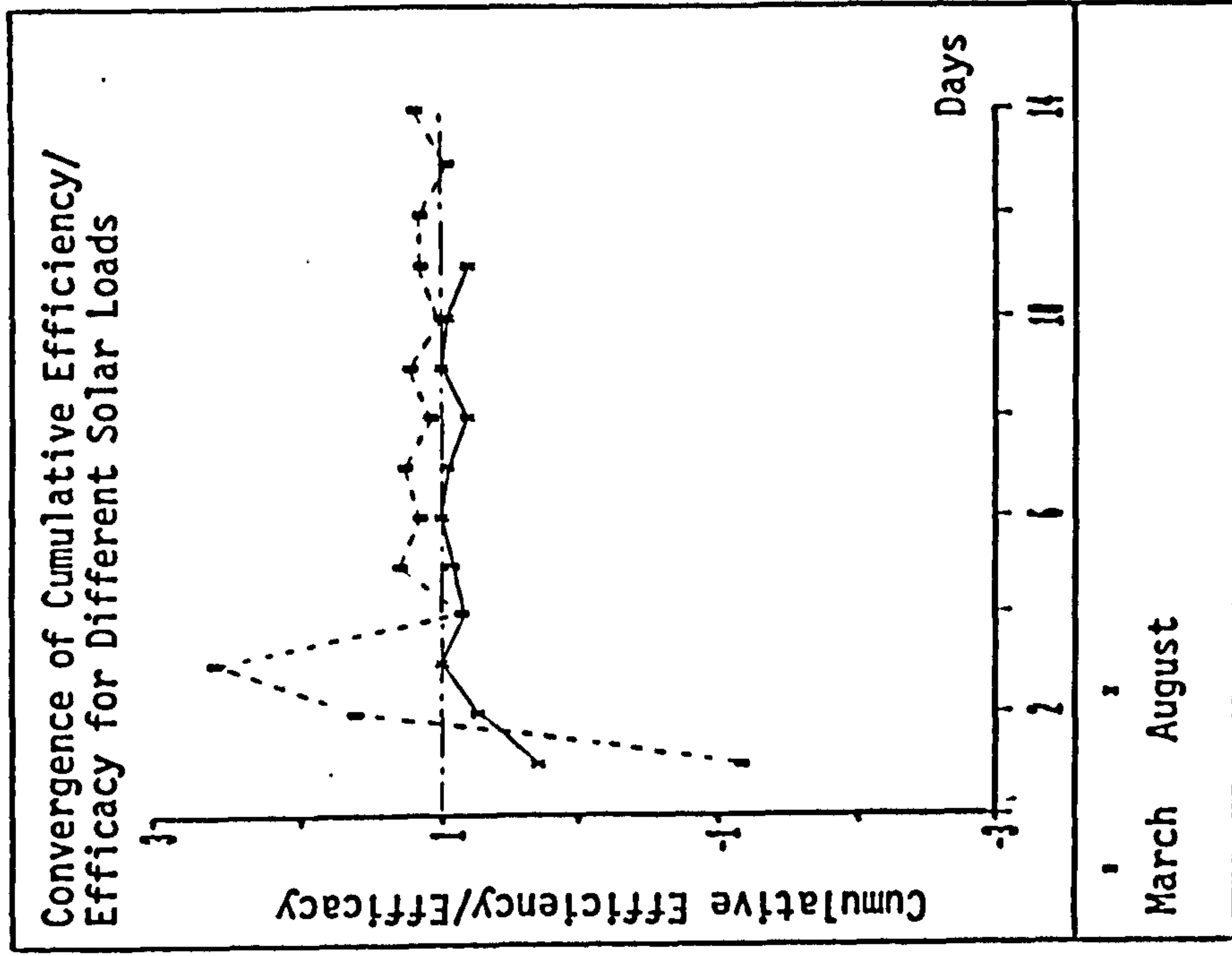


Figure 5.4.25

In reality, day-to-day solar heated water draw-off data are rarely identical. However consecutive days on which the occupants used *similar* volumes of solar-heated water were identified. The convergence of the efficiencies and efficacies was determined and is illustrated in Figure 5.4.25. Two different sequences of total daily solar heated water consumption were chosen, with mean values of 101 & 45.5 litres per day. In the latter case, (45.5 litres), a greater degree of scatter was evident because the residual heat stored in the 200 litre solar store had a more significant effect on the lower values of solar-heated water consumption.

Solar-heated water consumption was governed predominantly by the level of insolation. The U.K. climate is such that consistent levels of insolation occur very rarely, and regular patterns of solar-heated water consumption from such installations are not to be expected. Thus for third-tap systems, the use of the convergence of efficacy and efficiency to simplify system evaluation is not often feasible.

e) Variation of efficiency with solar fraction

The comparisons of efficiency and solar fraction, figs. 5.4.26 - 5.4.29, indicated that the maximum solar fractions yielded efficiencies of 0.2 - 0.25 on a daily basis and 0.12 - 0.15 on a monthly basis. A similar pattern emerged when the daily efficiency was plotted against daily insolation, (figure 5.4.30). After levels of daily total insolation in excess of 65 KJ the efficiency remained at a mean of 0.25 with a range between 0.15 and 0.4. This level of performance also applied to the daily efficacies, figure 5.4.31. (Unfortunately the monthly data did not always include a full quota of days for every month which adversely influenced the measurement of total insolation.)

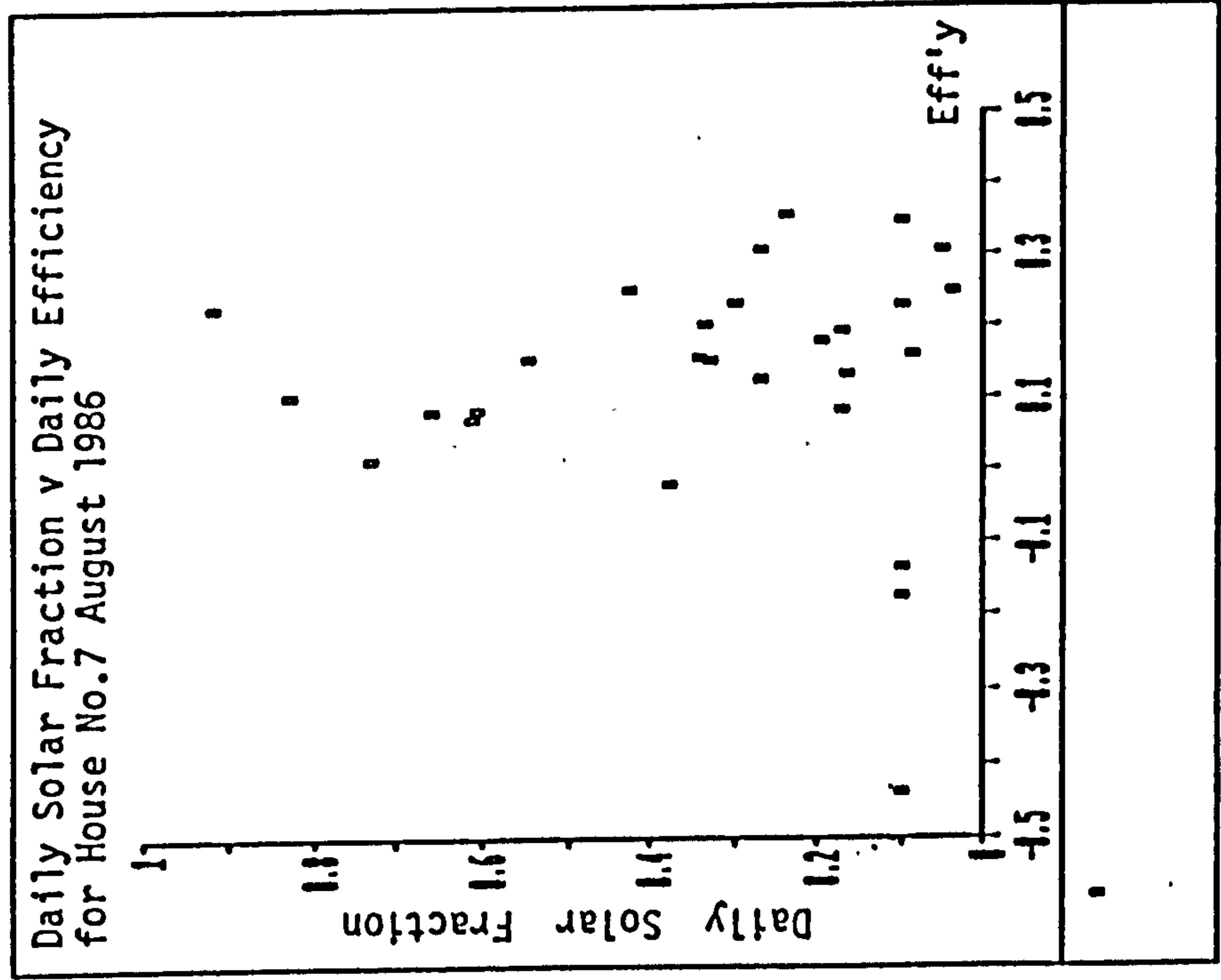


Figure 5.4.26

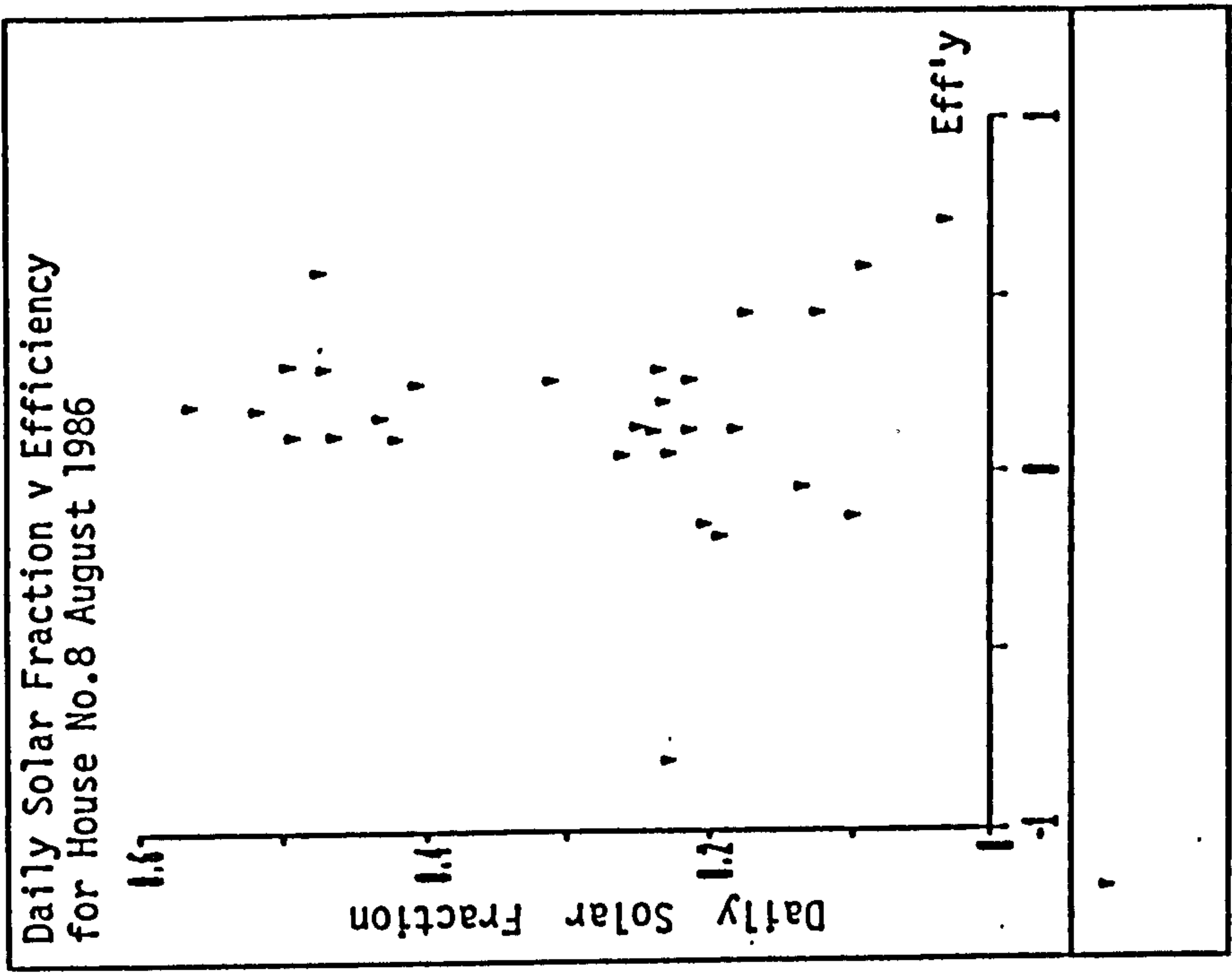


Figure 5.4.27

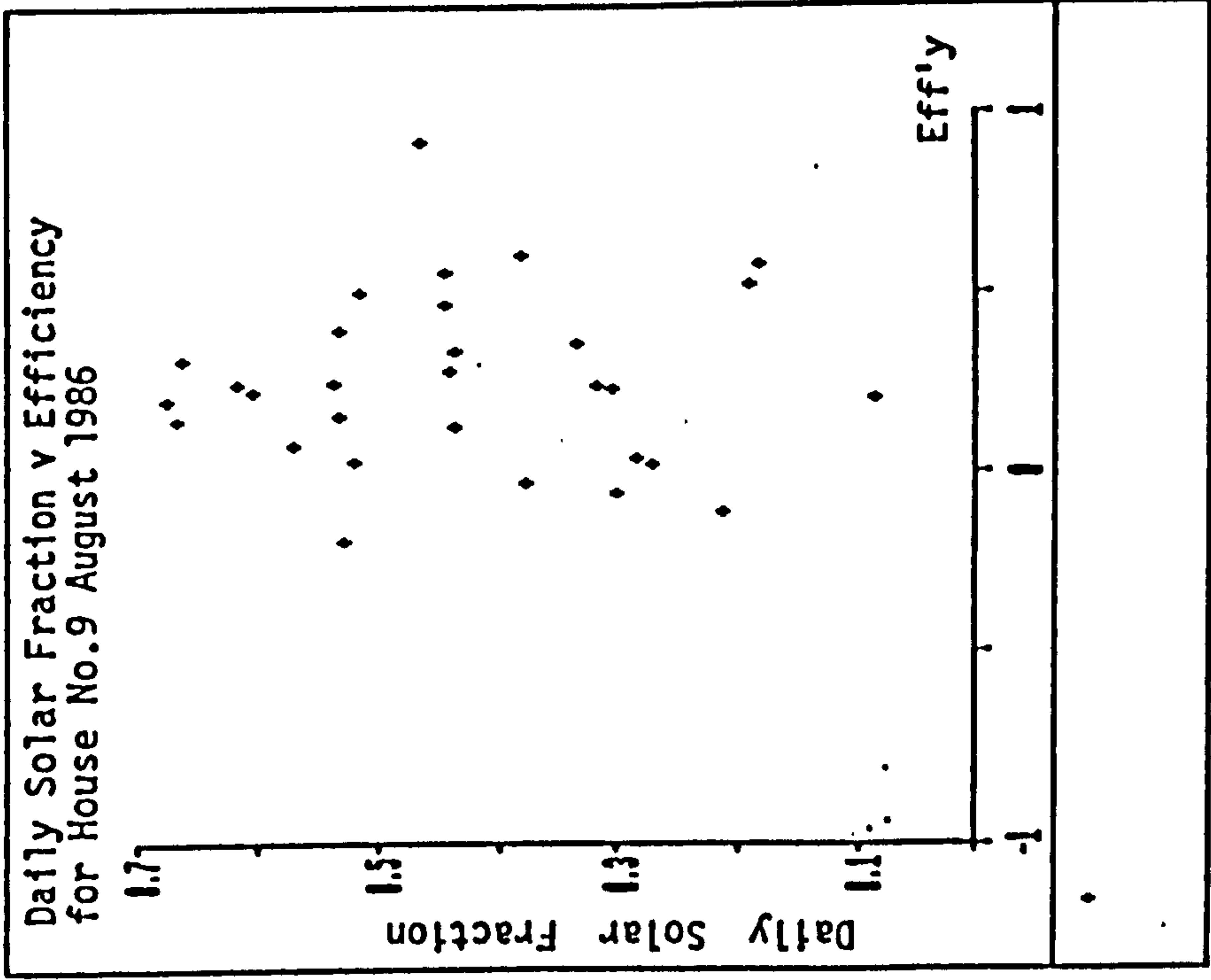


Figure 5.4.28

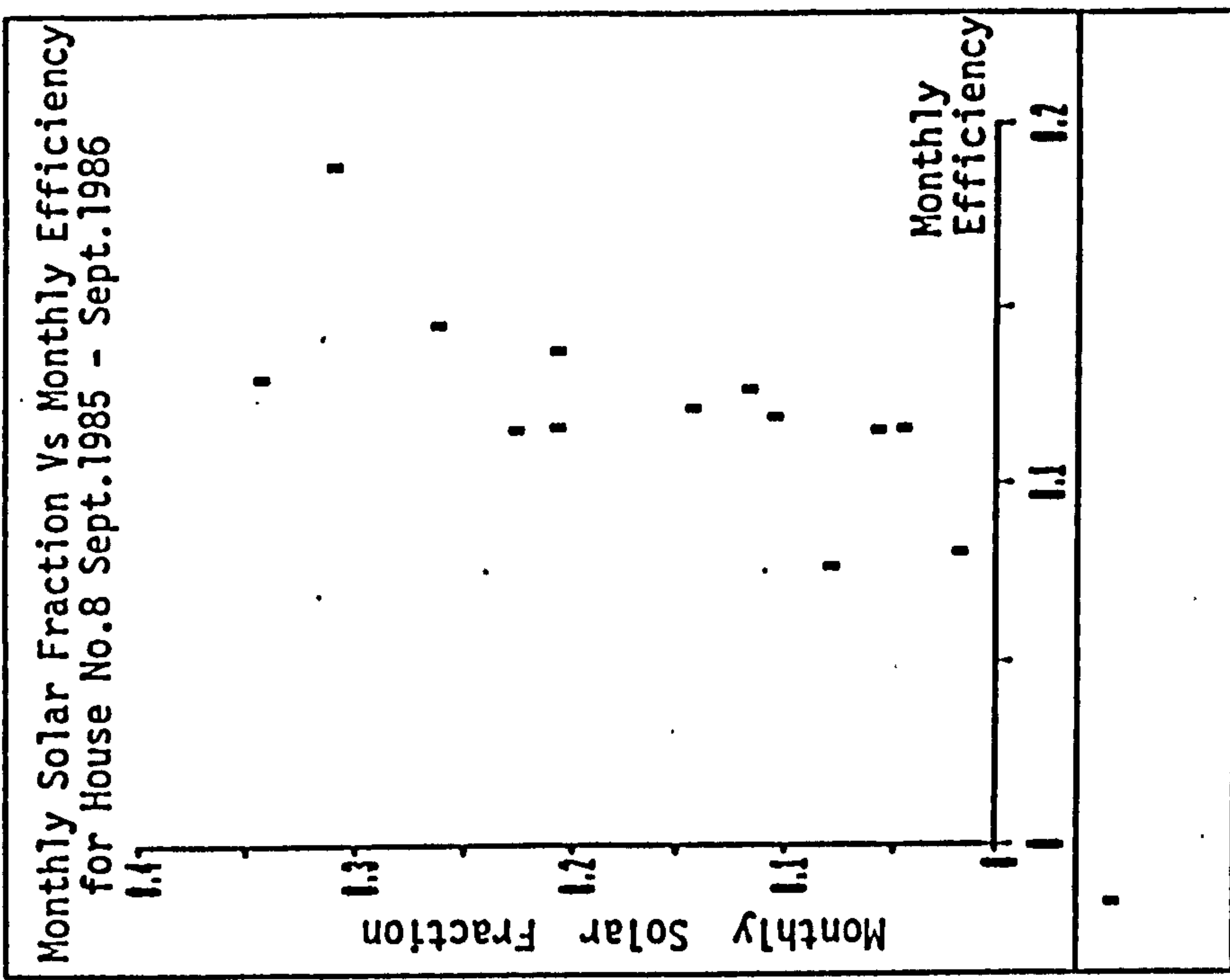
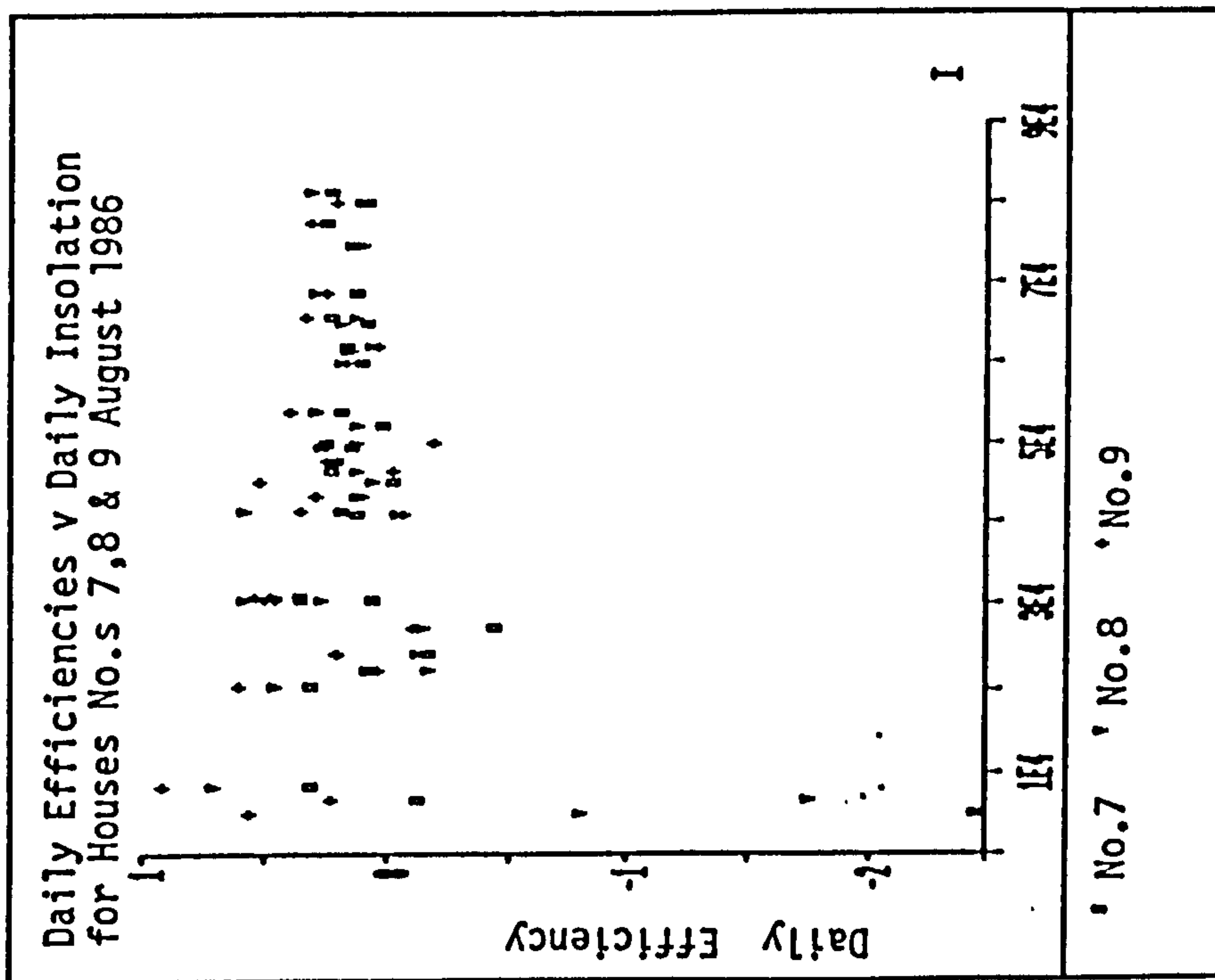
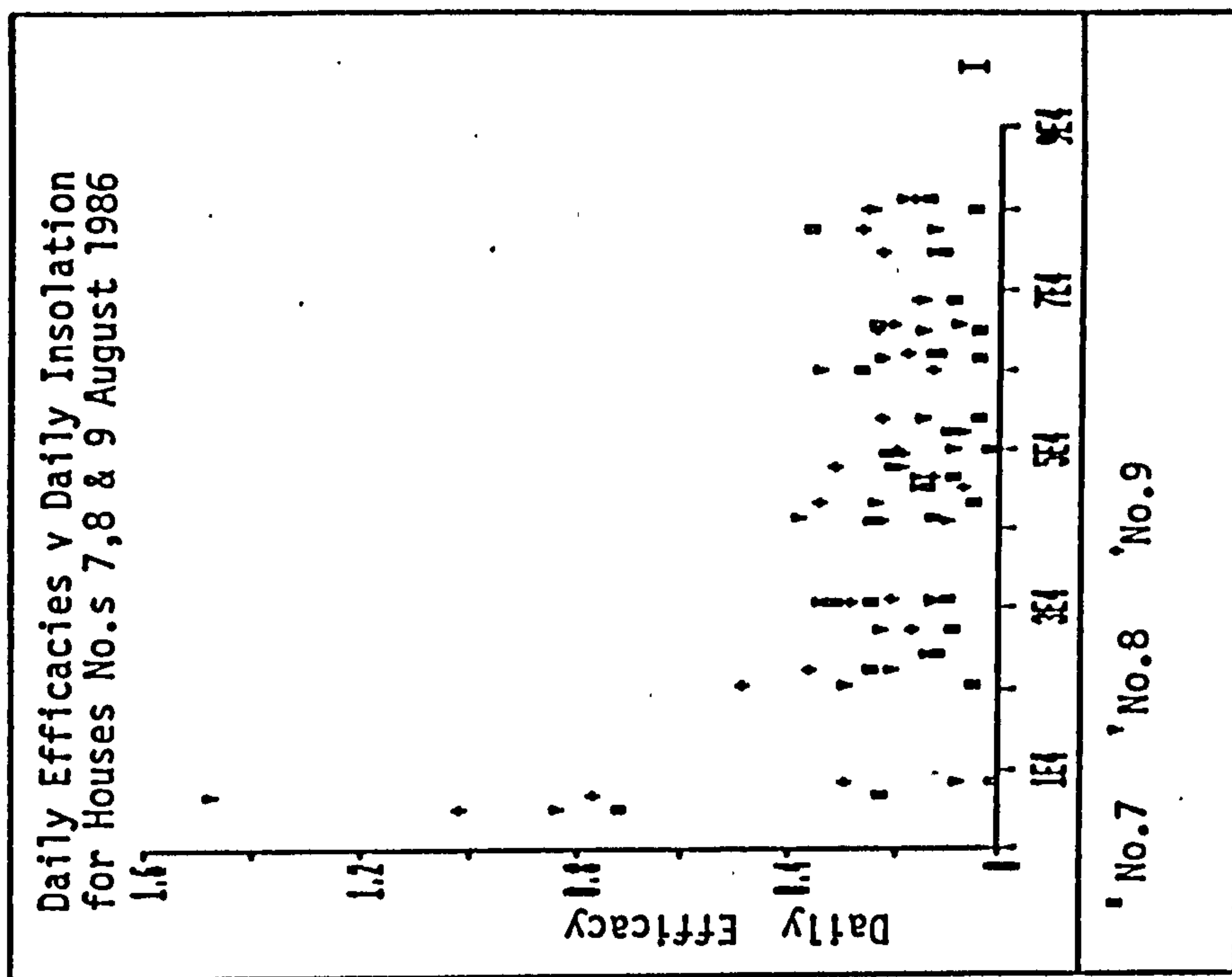


Figure 5.4.29



f) Controlled solar heated water consumption profiles

On the 1st of October the houses with the third tap + heating element, and the solar pre-heat installation with automatic draindown were both vacated. This provided the opportunity to undertake "controlled" draw-offs of the solar heated water. Table 5.4.2 illustrates the load profiles adopted for this test period. The actual patterns of conventional hot water consumption from the third remaining dwelling were used to calculate the solar fraction for the two control houses.

Under the real operating conditions which had prevailed up to October 1986 the solar pre-heat installation provided a greater solar contribution, than that of the third tap systems because all gains were useful. Users of the third-tap thermosyphon solar water heaters would only use solar heated water if the perceived gains were 'useful'. During the control period, (with constant volumes of daily solar heated water consumption), the solar preheat system provided less solar heated water than the third tap installation, Fig. 5.4.32. It's mean daily collector temperature was also higher, while its mean daily store temperature was lower than that of the third-tap with heating element system, figs. 5.4.33 - 5.4.34. This discrepancy corroborated a suspicion held previously that there was greater flow resistance within the thermosyphon circuit of the preheat installation, perhaps due to the motorised draindown valves. This increased resistance would have reduced the flow rate and hence also the heat removal from the collector. An absorber at higher temperatures would incur greater thermal losses and reduce the solar contribution.

The data was used to validate the convergence period of the two installations by plotting the efficiency and the efficacy, Fig. 5.4.35. Even with controlled volumes of solar-heated water in excess of 150 litres the convergence of this performance index still required at least 7 days.

Table 5.4.2 Schedule for controlled solar-heated water consumption

Date	Volume of Solar-Heated Water Drawn-off (litres)					Total Daily Insolation kJ/m ²
	House Number	7		9		
	Time Period	L	E	L	E	
2.10.86			65	50	55	5944
3.10.86		50	50	50	60	9664
4.10.86		50	50	50	50	14647
5.10.86		50	50	50	50	4389
6.10.86		50	50	50	50	6694
7.10.86		50	70	50	70	14592
8.10.86		100	50	120	30	10377
9.10.86		100	50	100	50	10185
10.10.86		100	50	100	50	2922
11.10.86		100	50	100	50	14780
12.10.86		100	50	100	50	8730
13.10.86		100	50	100	50	8281

L - Indicates a lunchtime draw-off from 12.00 - 14.00

E - Indicates an evening draw-off from 17.00 - 19.00

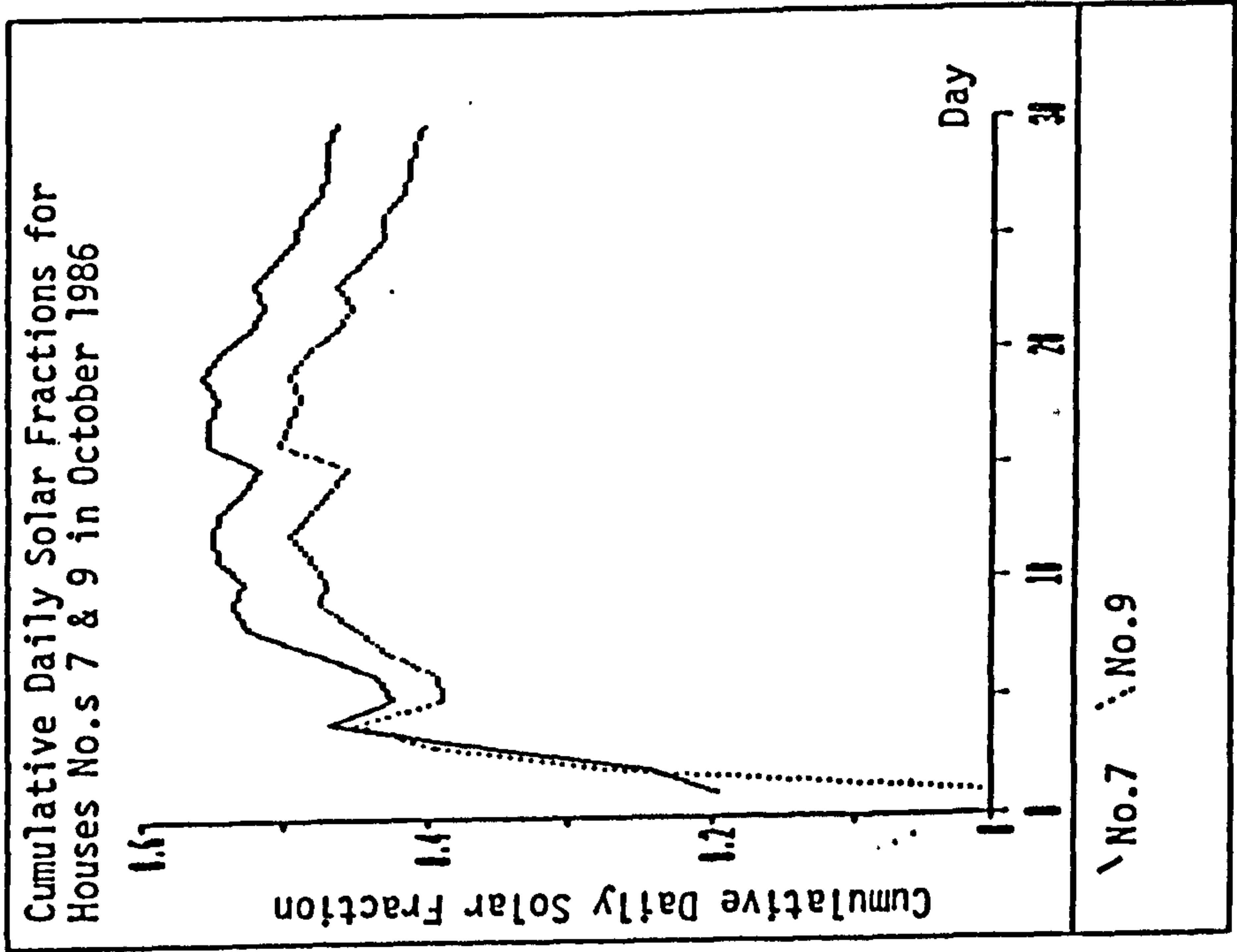


Figure 5.4.32

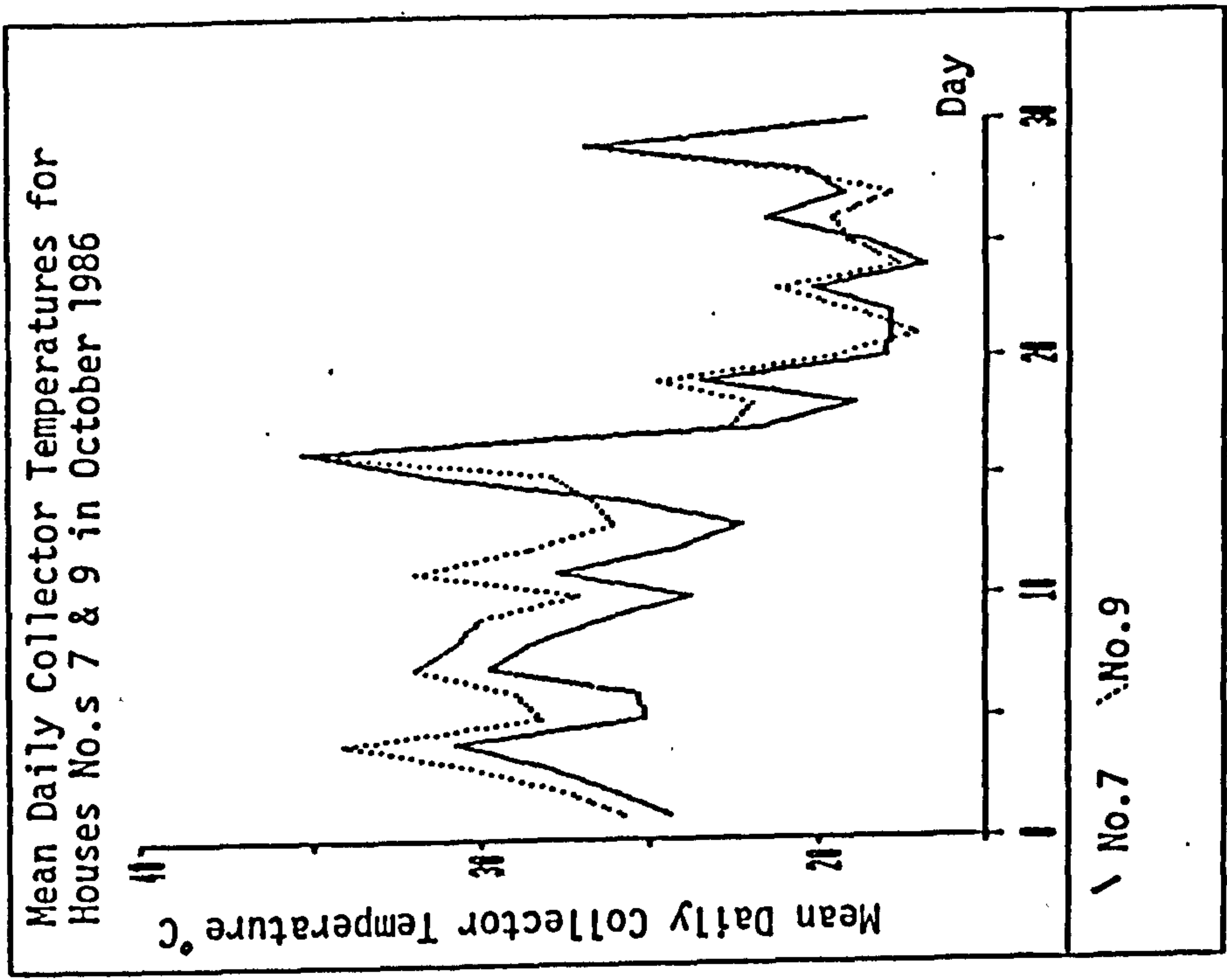


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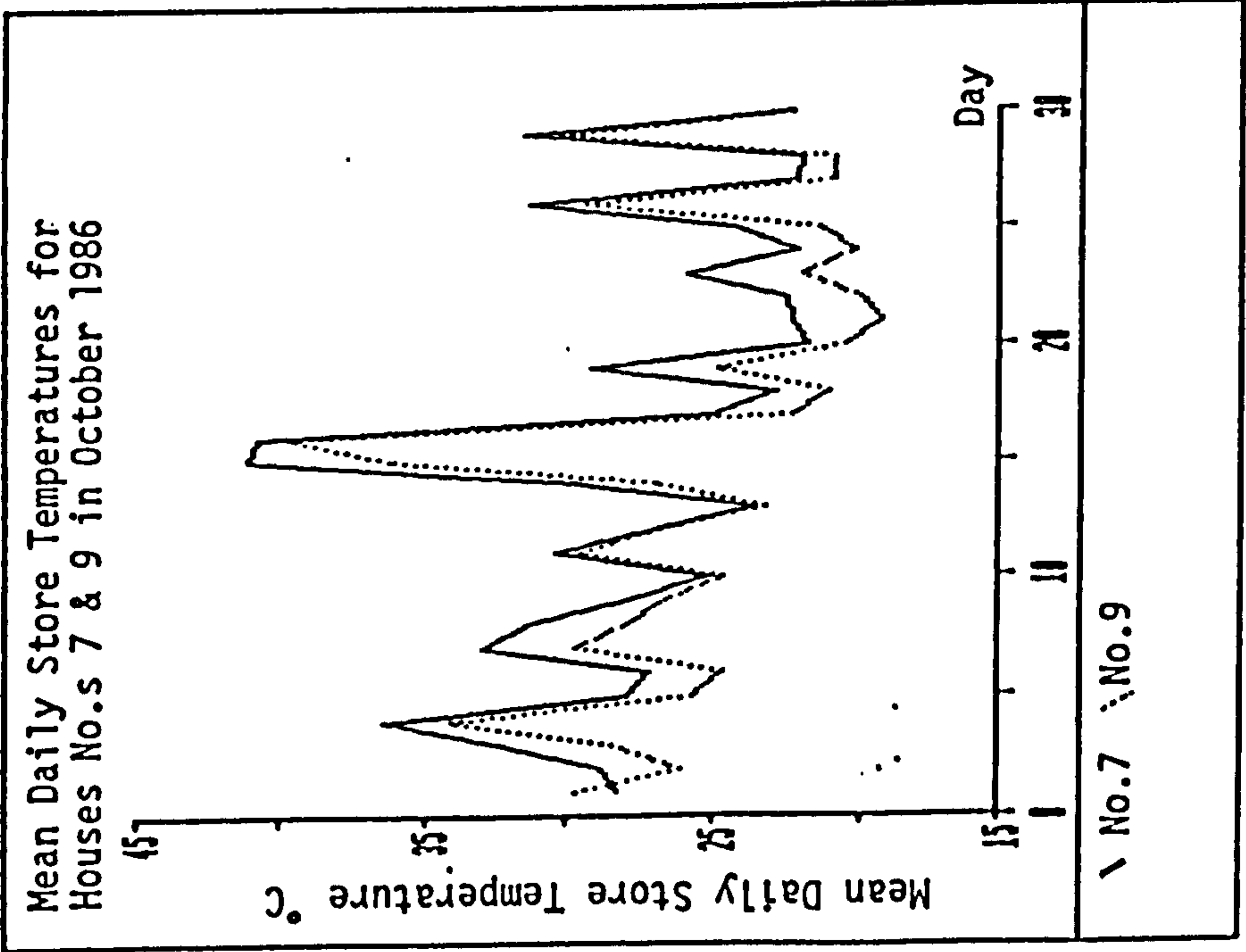


Figure 5.4.34

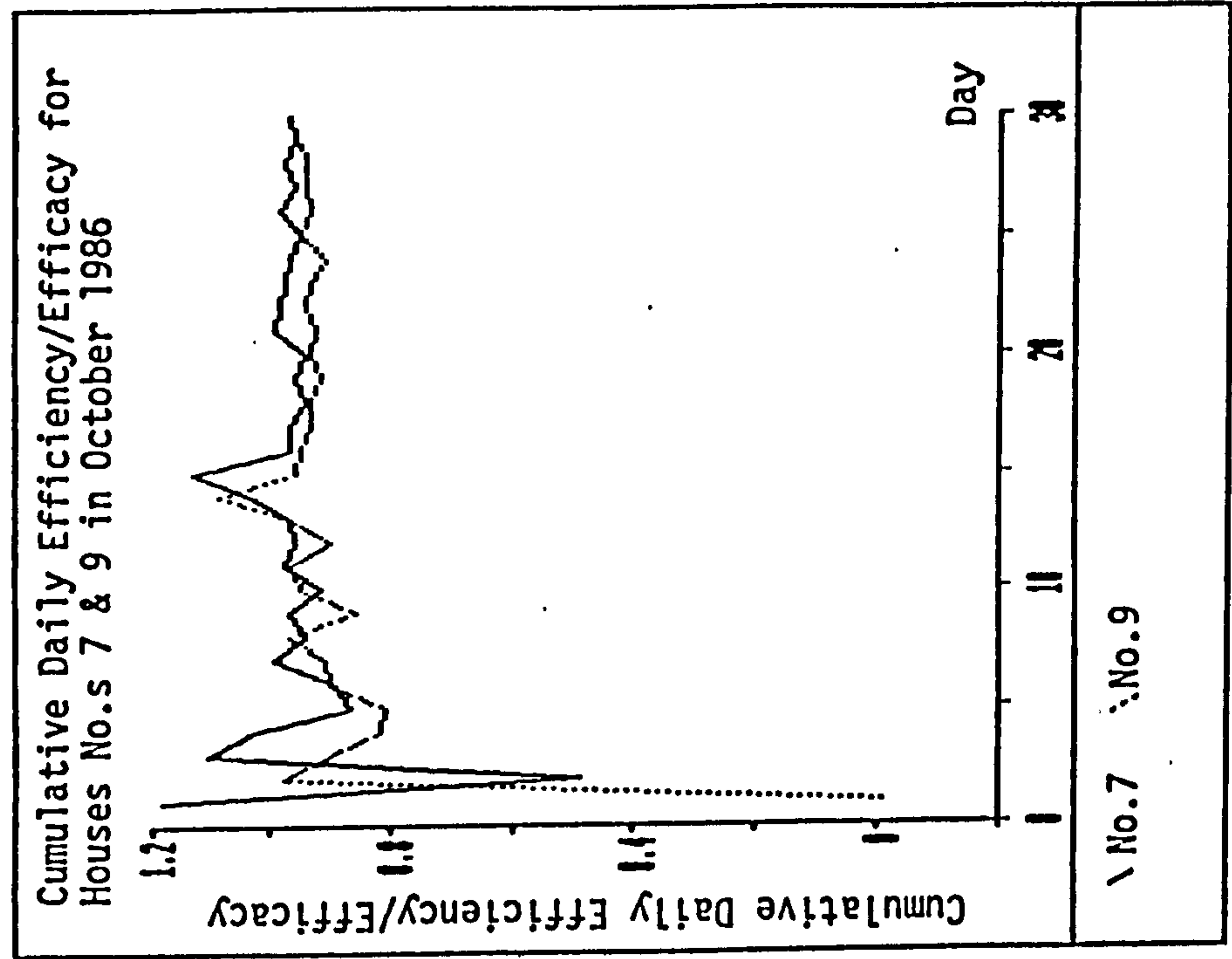


Figure 5.4.35

g) Solar heated water consumption patterns

In order to study the effects of different solar-heated water consumption patterns on individual system efficiency, it was necessary to isolate days of similar total daily insolation and solar-heated water consumption for one particular installation. Figures 5.4.36 - 5.4.37 show the respective distribution of these parameters over a period of 12 months for the indirect third tap system. Unfortunately the most frequent level of total daily insolation rarely coincided with the most regular volume of total daily solar-heated water consumption. In order to isolate compatible days a scatter plot of these factors, Fig. 5.4.38 was studied in detail. The group of six days, with the greatest mean values, were chosen because any selected band width would represent a smaller proportion of the absolute value of each parameter. The diurnal solar heated water consumption patterns for the six days are shown in ascending order of efficiency in figure 5.4.40. Within the confines of one particular installation there were an insufficient number of vastly different solar-heated water consumption patterns to establish any definite relationship between the two parameters concerned. However, using the following relationship, enabling us to determine the time at which the majority of the draw-offs occurred (Fig. 5.4.39);

$$D = (\sum M_{\bullet} \cdot t_{\bullet}) / M_{\bullet}$$

The mean draw-off times showed a tendency toward solar-heated water usage later in the insolation period. The distribution of all the draw-offs during October 1986 indicated that there were three primary solar-heated water consumption periods, i) mid-morning, ii) lunchtime and iii) early evening, as shown in figure 5.4.41. With interval widths of 20 minutes the majority of all draw-off events occurred after sunset when the occupants arrived home from work. However, if all volumes of solar-heated water consumption of less than 4 litres are omitted then it can be seen that only a small number of the lunchtime draw-off events remained (figure 5.4.42). It was considered that all water consumptions in excess of 4 litres constituted the beginning of a bath or a shower.

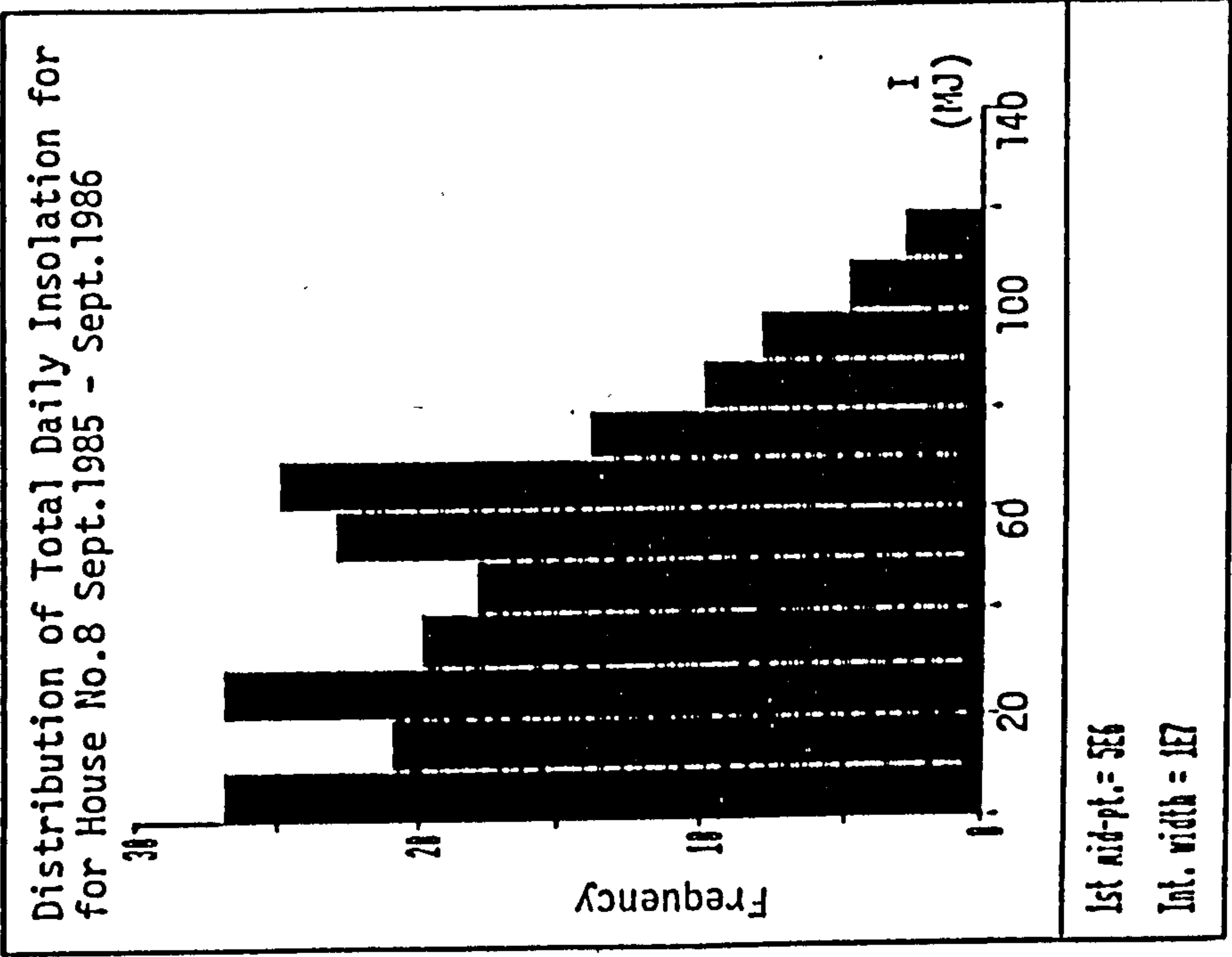


Figure 5.4.36

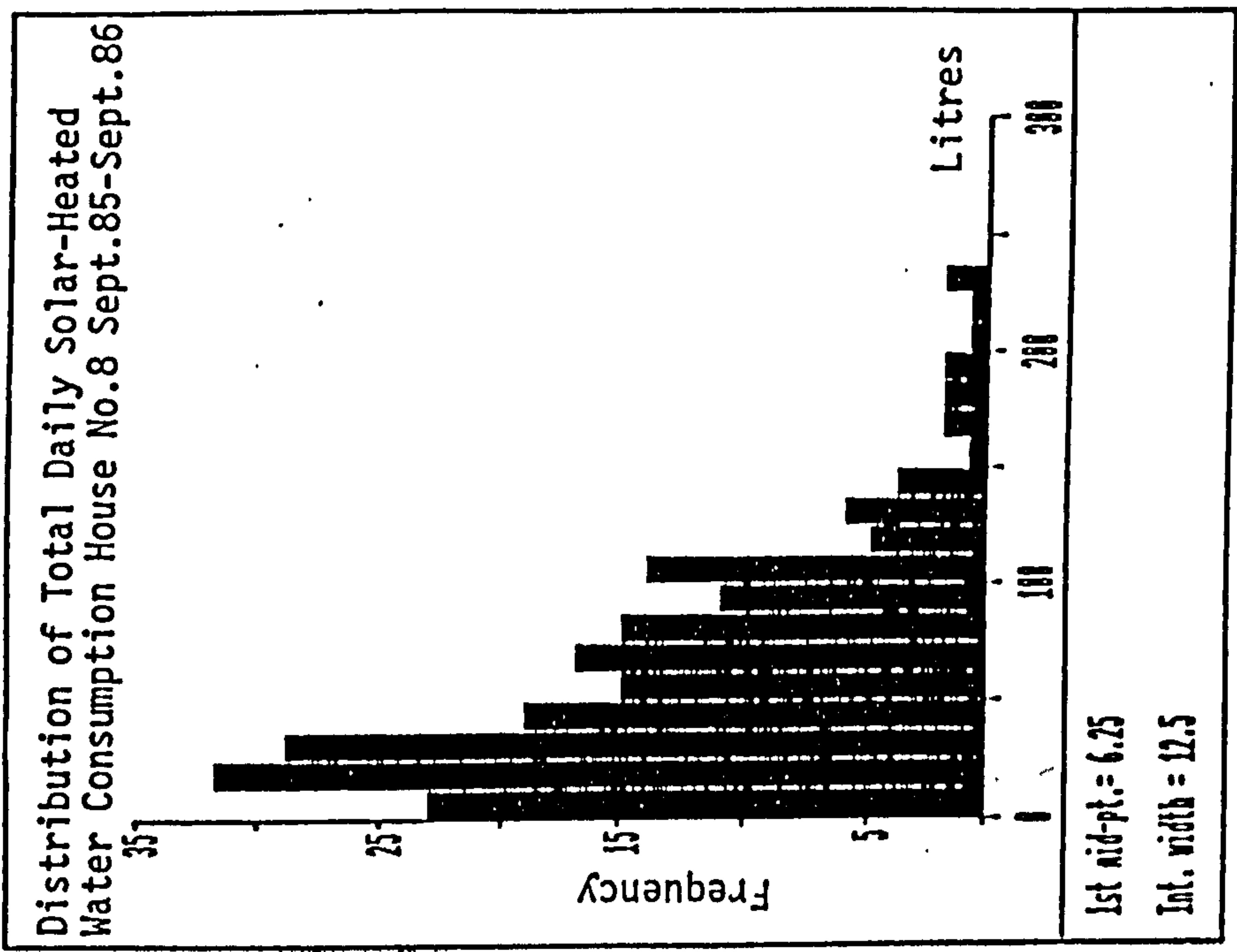


Figure 5.4.37

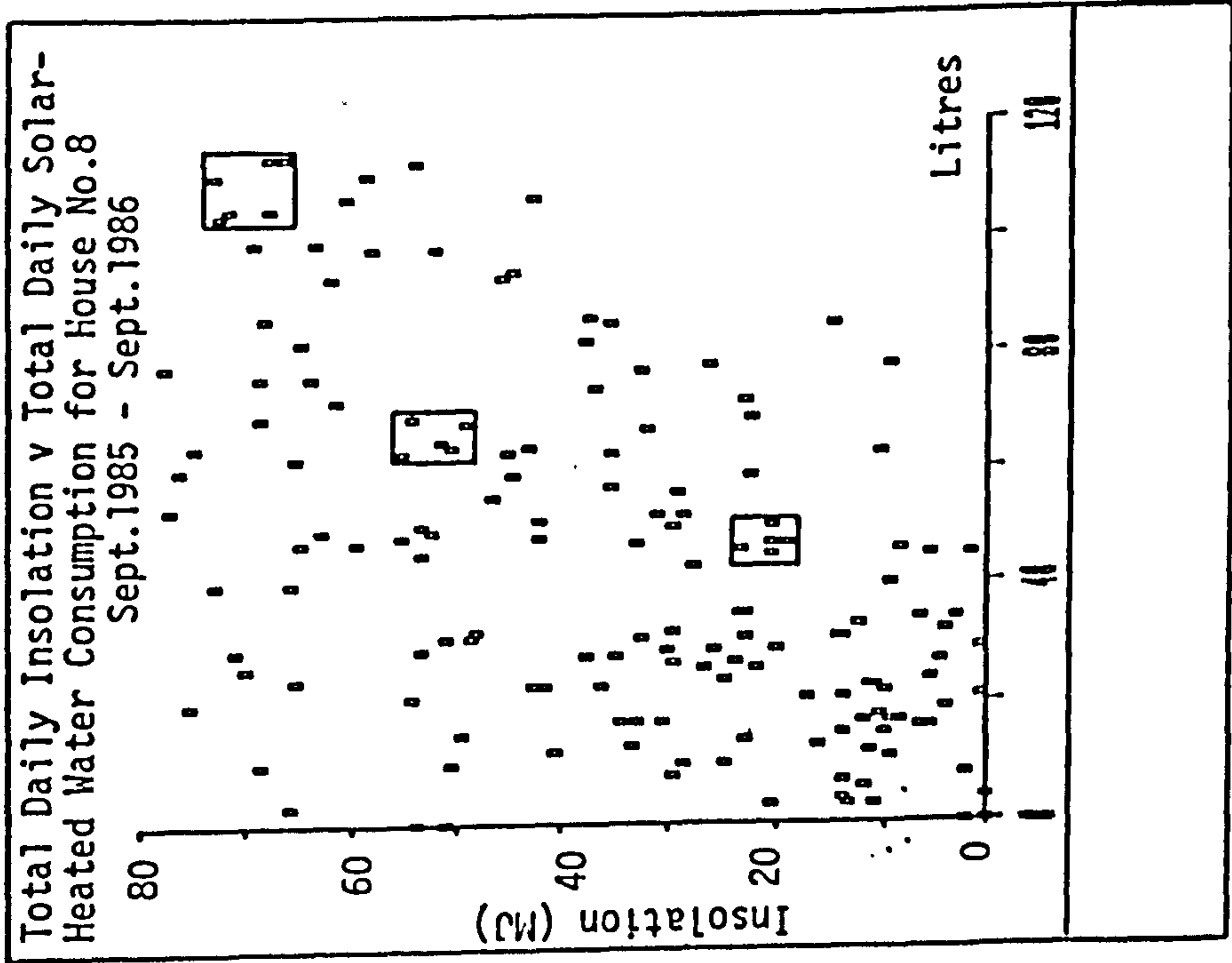


Figure 5.4.38

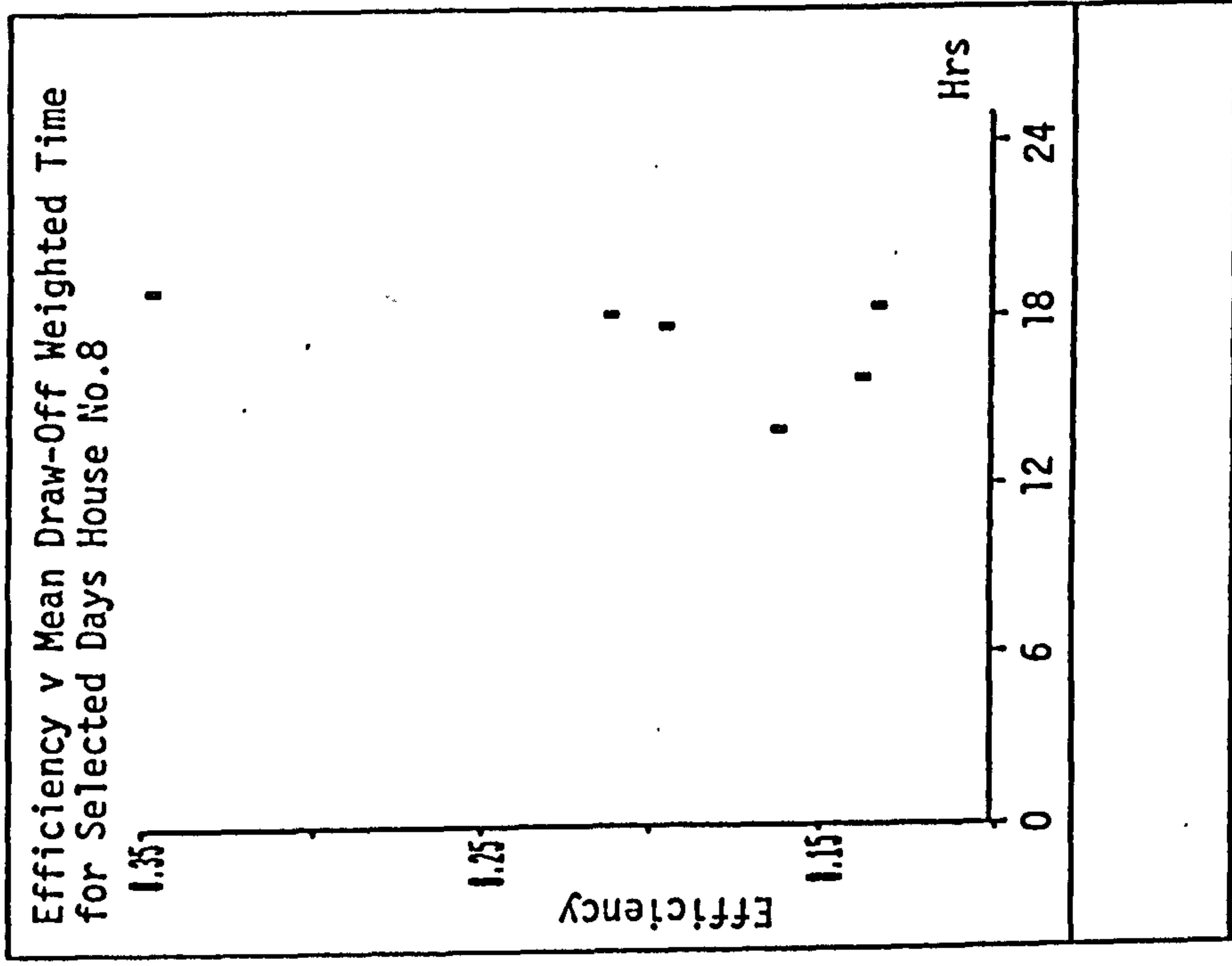


Figure 5.4.39

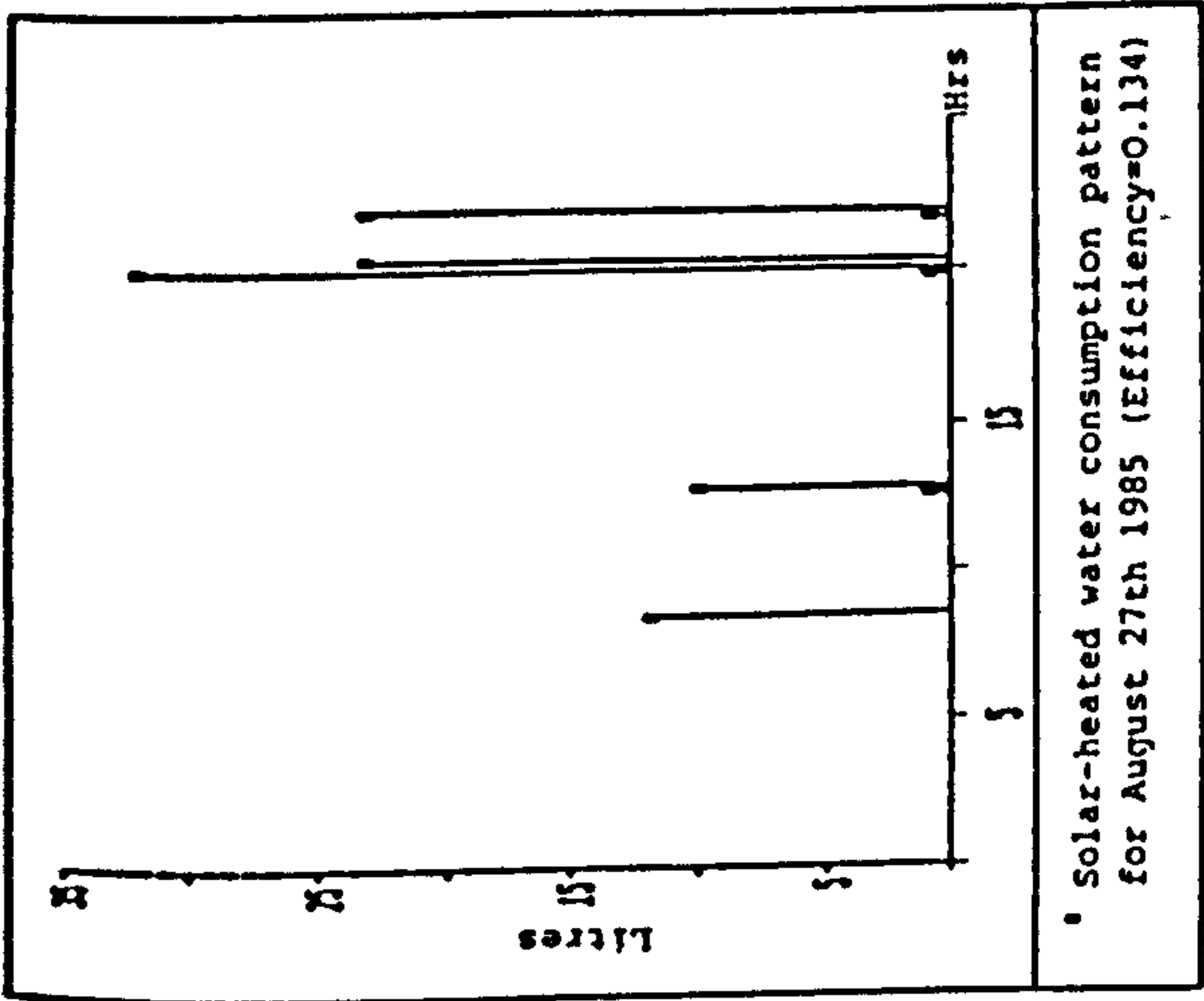
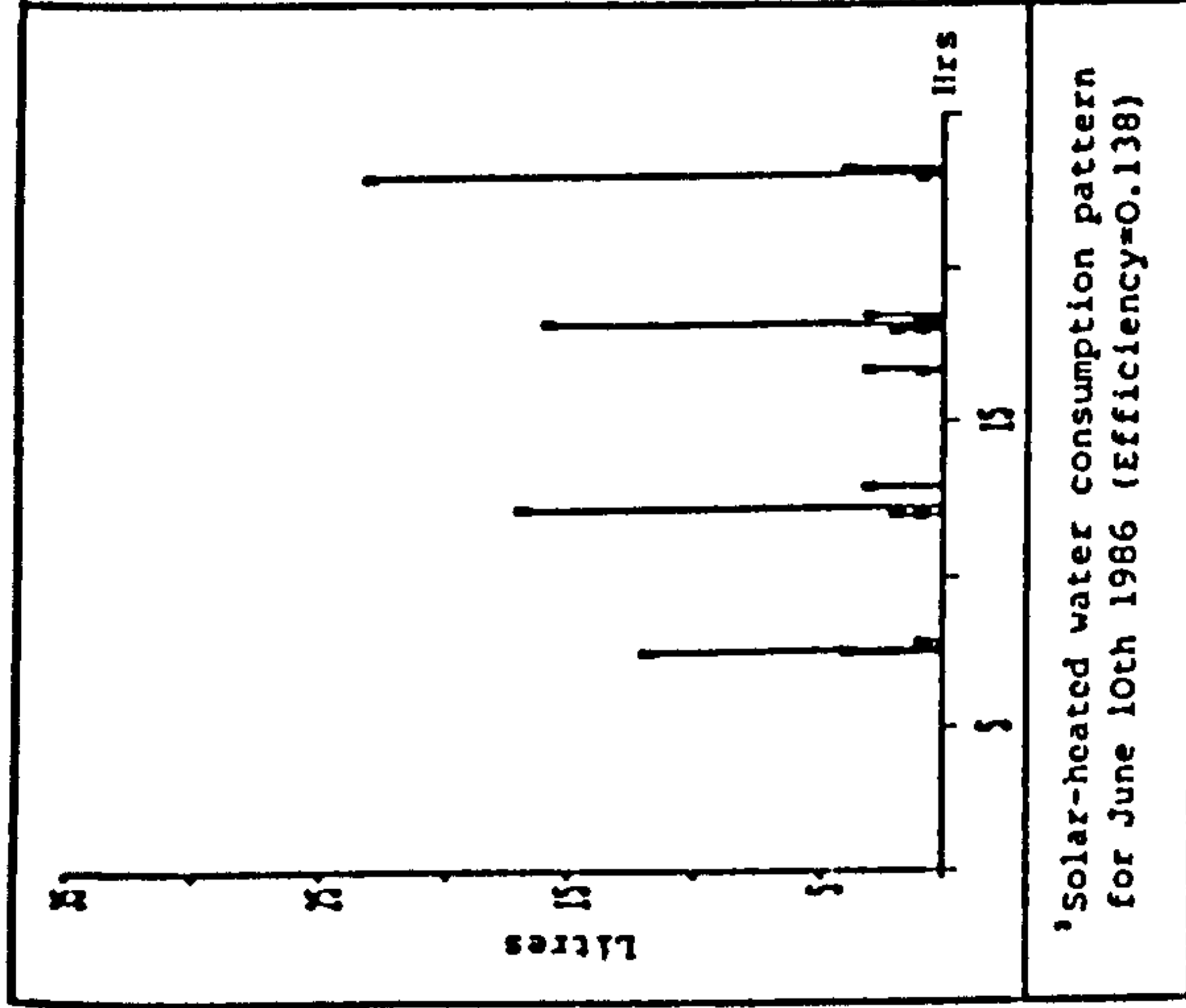
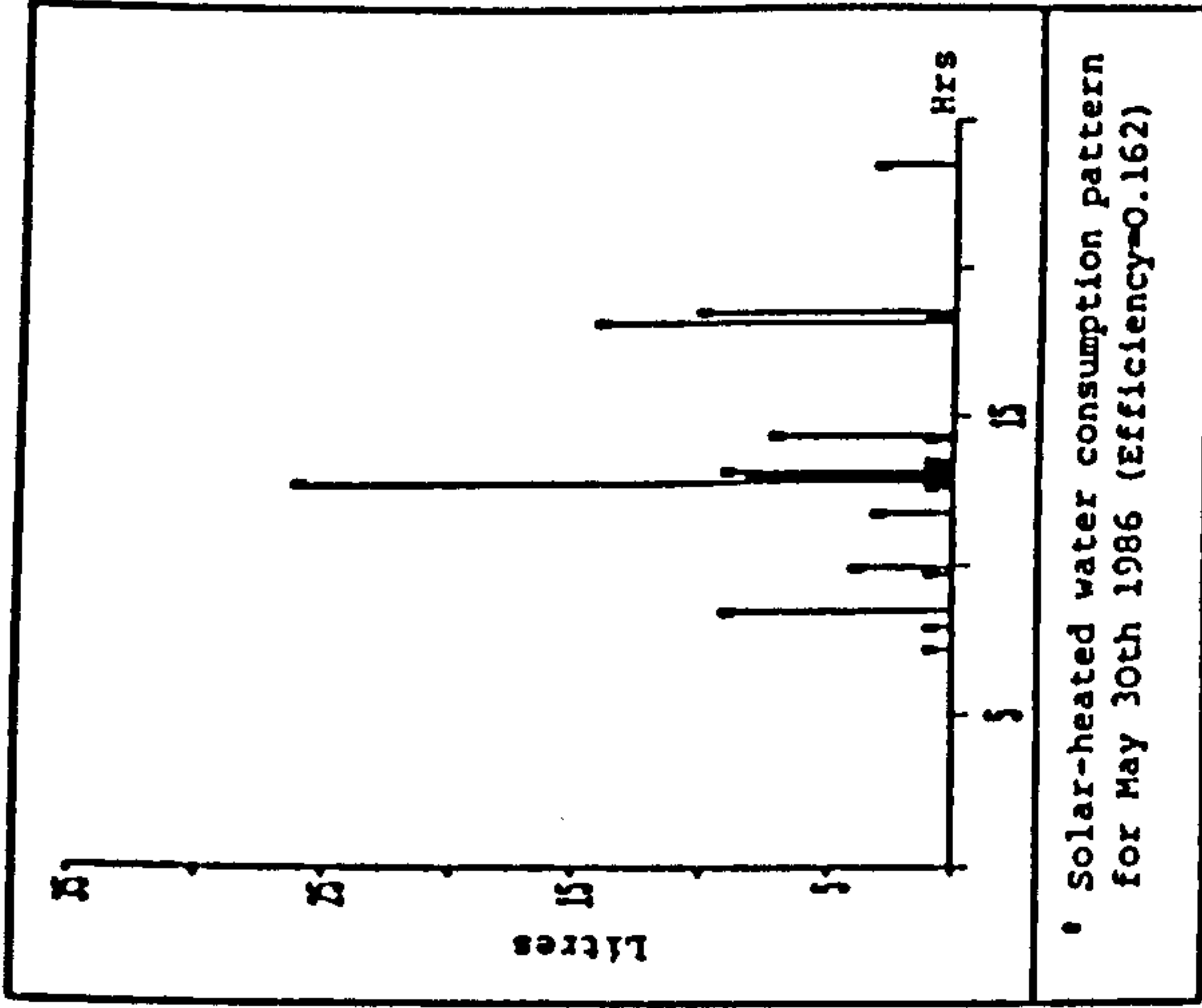
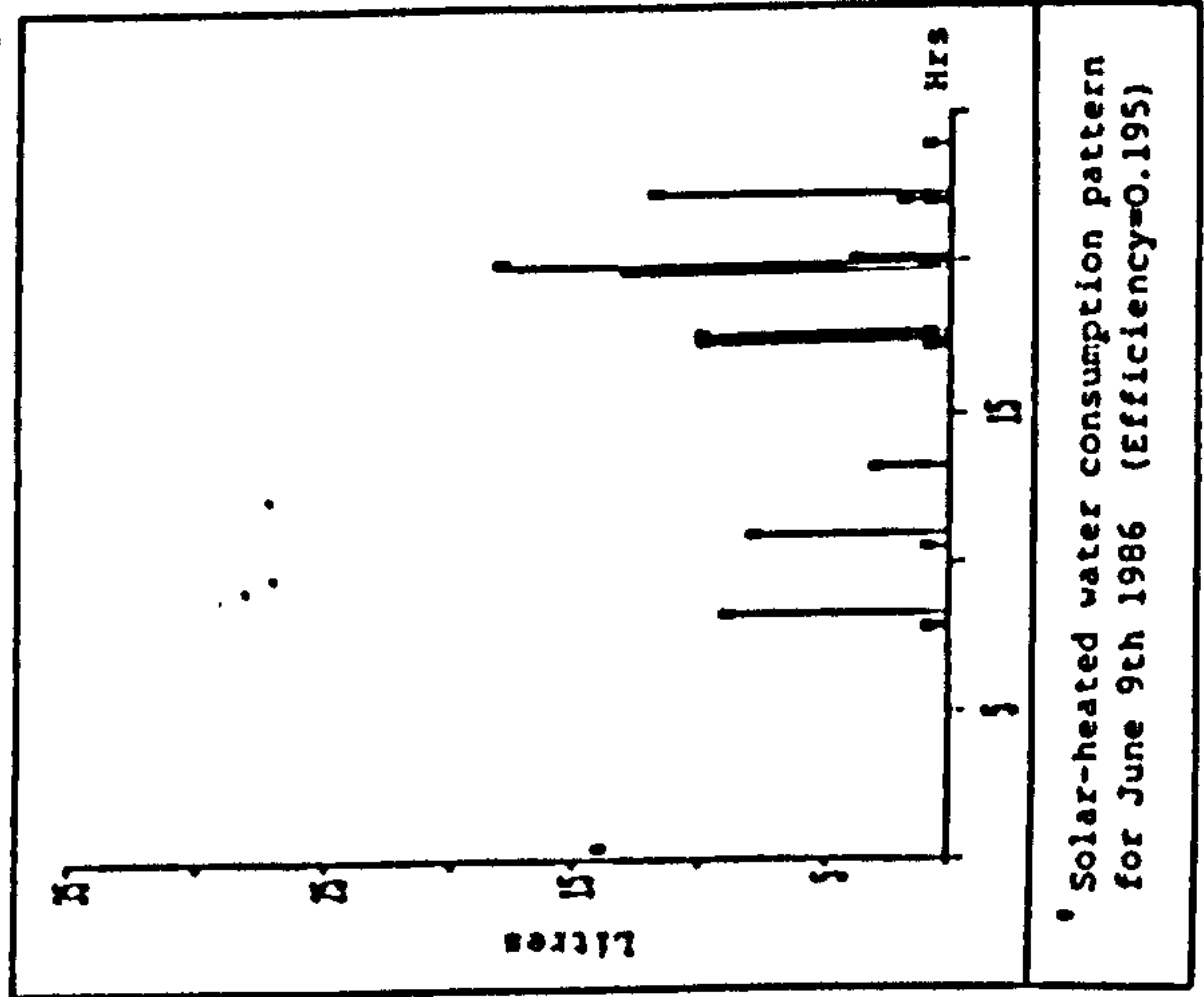
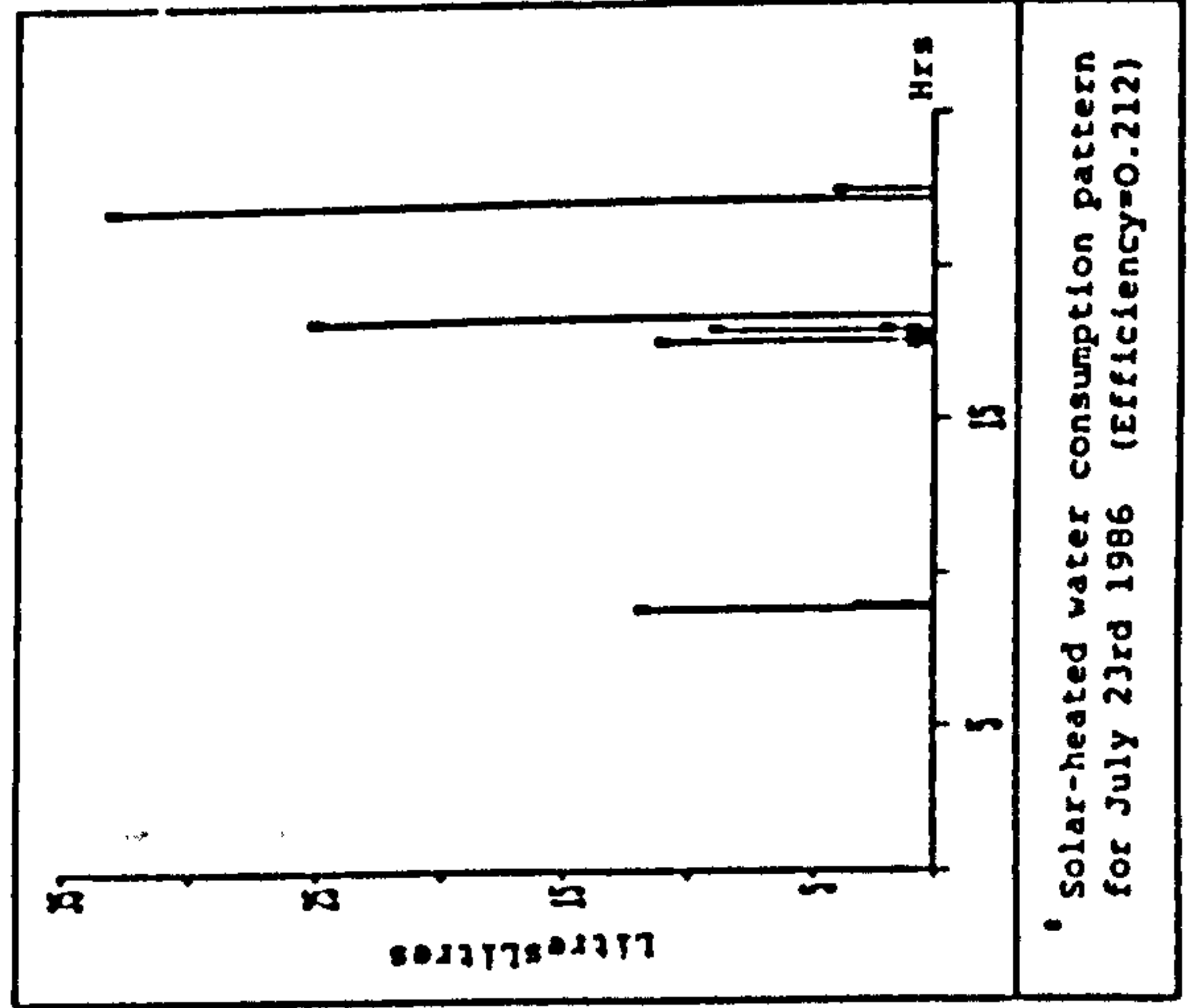
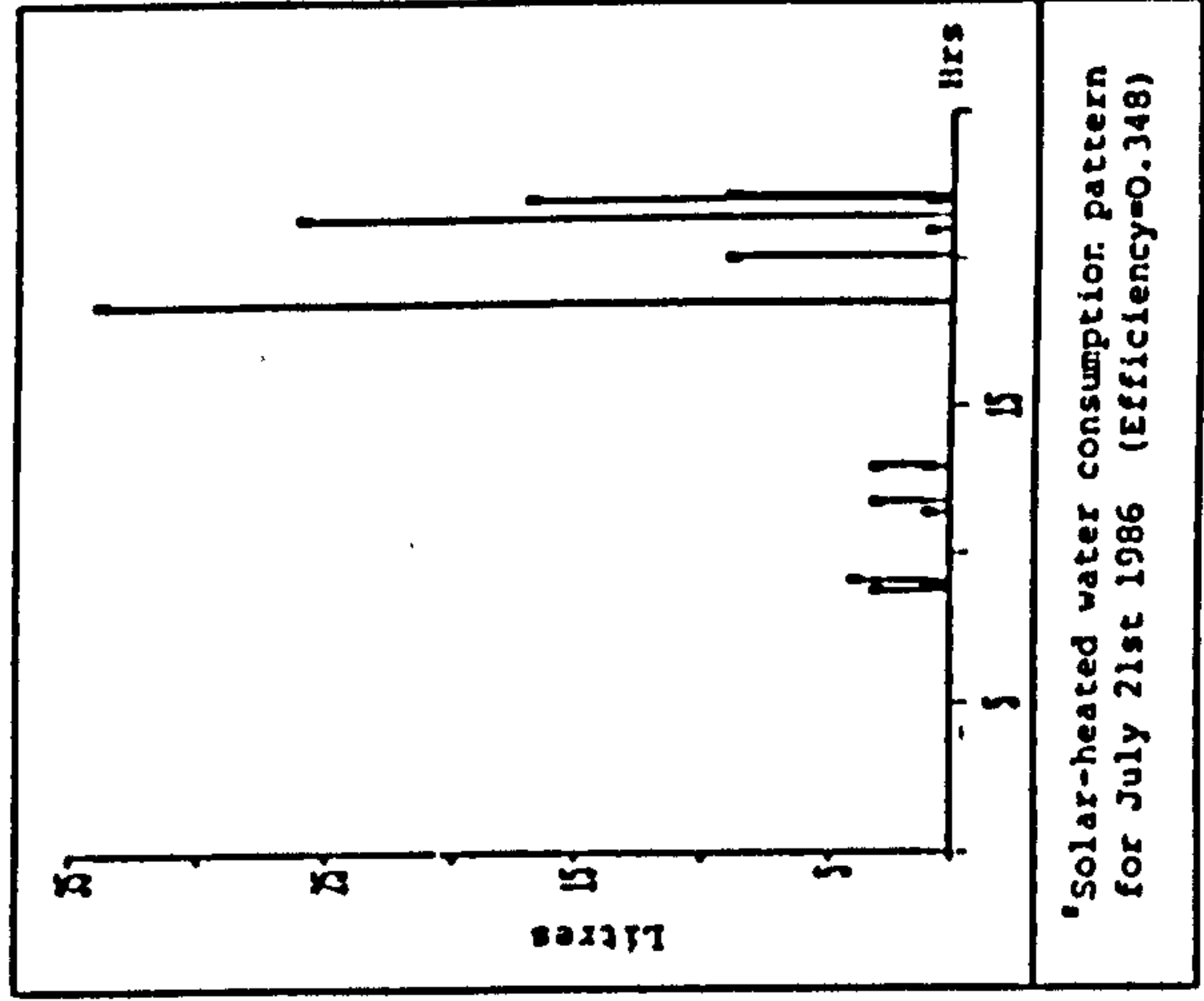


Figure 5.4.40 Solar-heated water consumption patterns for selected days, (house No.8)



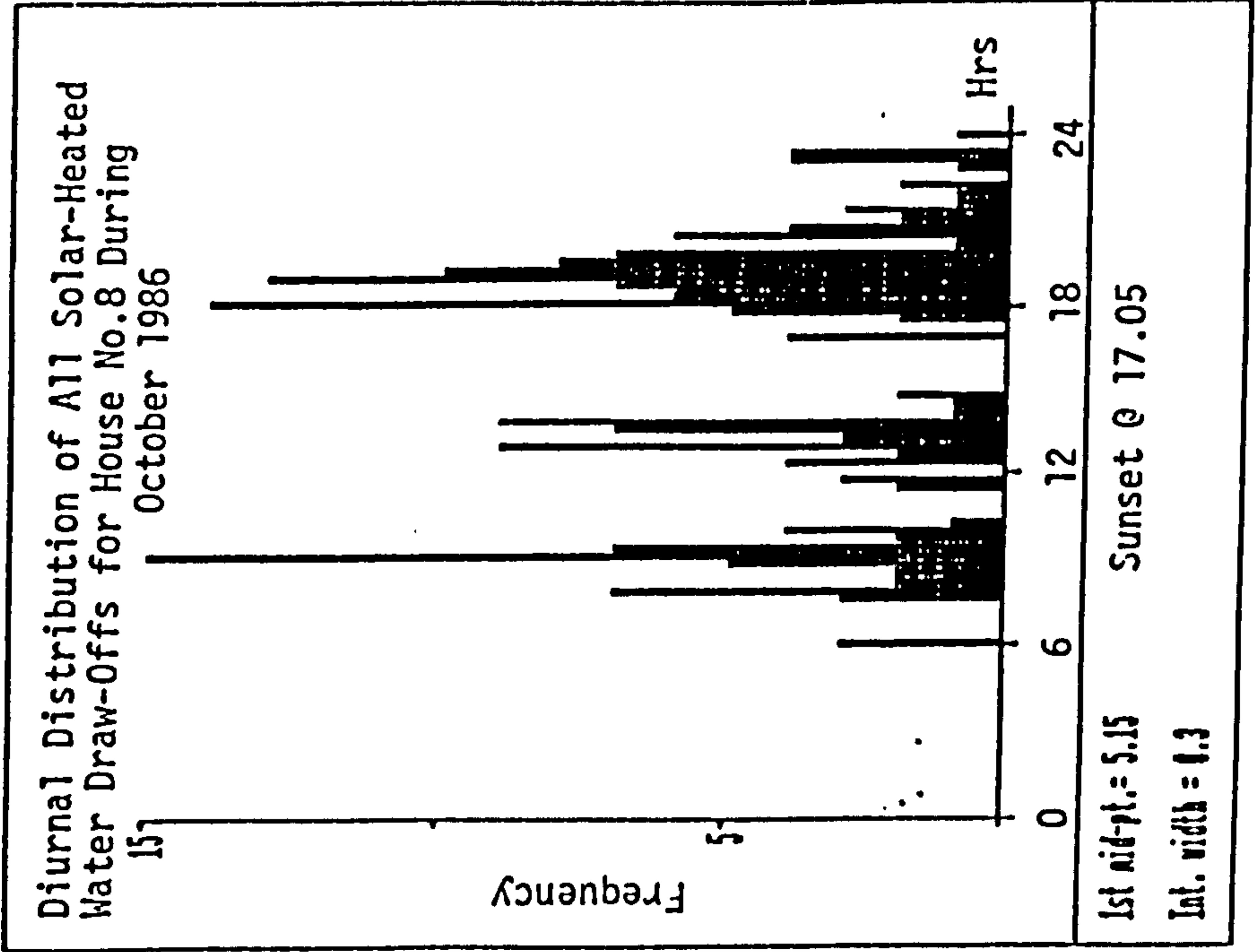


Figure 5.4.41

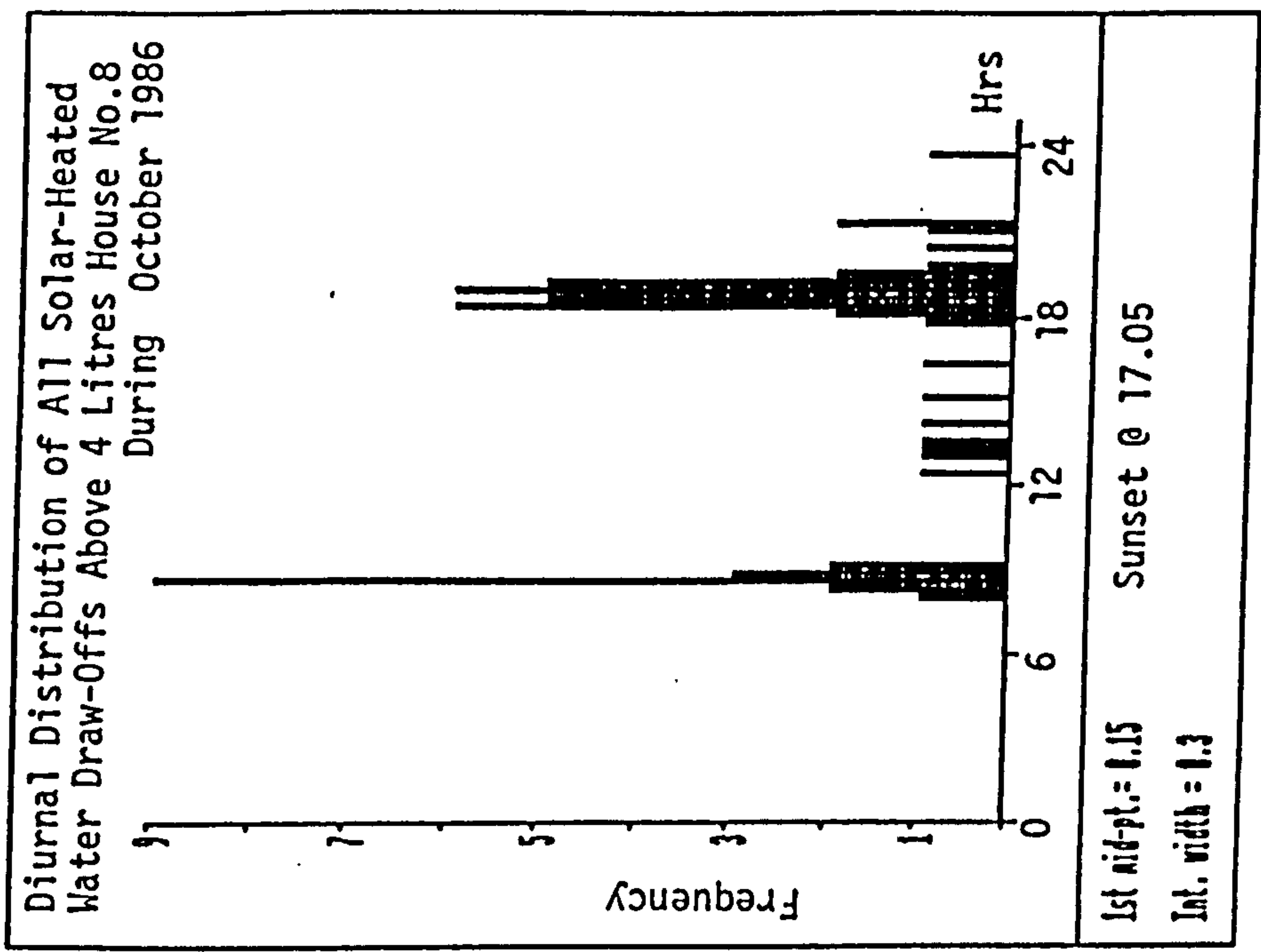


Figure 5.4.42

5.5 References

- 5.3.1. R. A. Hobday, "Passive Solar-Energy Air-Heating Wall Panels", Ph.D Thesis, School of Mechanical Engineering, Cranfield, U.K., 1986.
- 5.4.1. B. Norton, S.N.G. Lo; "Demonstration of Thermosyphon Solar-Energy Water Heating in a Group of Three Dwellings"; EEC Technical Report Number 3, (Project No. SE 034/83), Reporting Period 1st April 1985 - 1st October 1985.
- 5.4.2. R.W. Burn; "INSTAT User Guide Part II Reference Manual"; Statistical Services Centre, University of Reading, 1986.

CHAPTER SIX

PERFORMANCE CORRELATIONS

6.1 Derivation of Performance Indices for Roof Space Solar collectors

i) Solar savings fraction & solar load ratio

The Solar Heating Fraction (SHF) only considered the solar gains from the RSC with no allowance for incidental gains from the remainder of the dwelling. However, the Solar Savings Fraction, (SSF), involved a total heat balance for the whole house including solar gains through the windows and casual gains from the occupants.

The Solar Load Ratio, (SLR), was originally devised as a method for estimating the performance of passive solar space heating systems (6.1.1). However, this method did not take into account the effects of occupancy patterns on the buildings' performance. Figure 6.1.1. illustrates the difference between the two extremes of occupancy patterns for one house type when the SLR is plotted against the SSF. Six examples, exhibiting two different occupancy patterns, of the same house type were selected for comparison. Plots 1, 18 & 23 all had relatively high BOI's, (see p 179), while plots 3, 6, & 9 had low BOI's with very sporadic occupancy patterns (Figures 5.2.1-5.2.2, chapter 5).

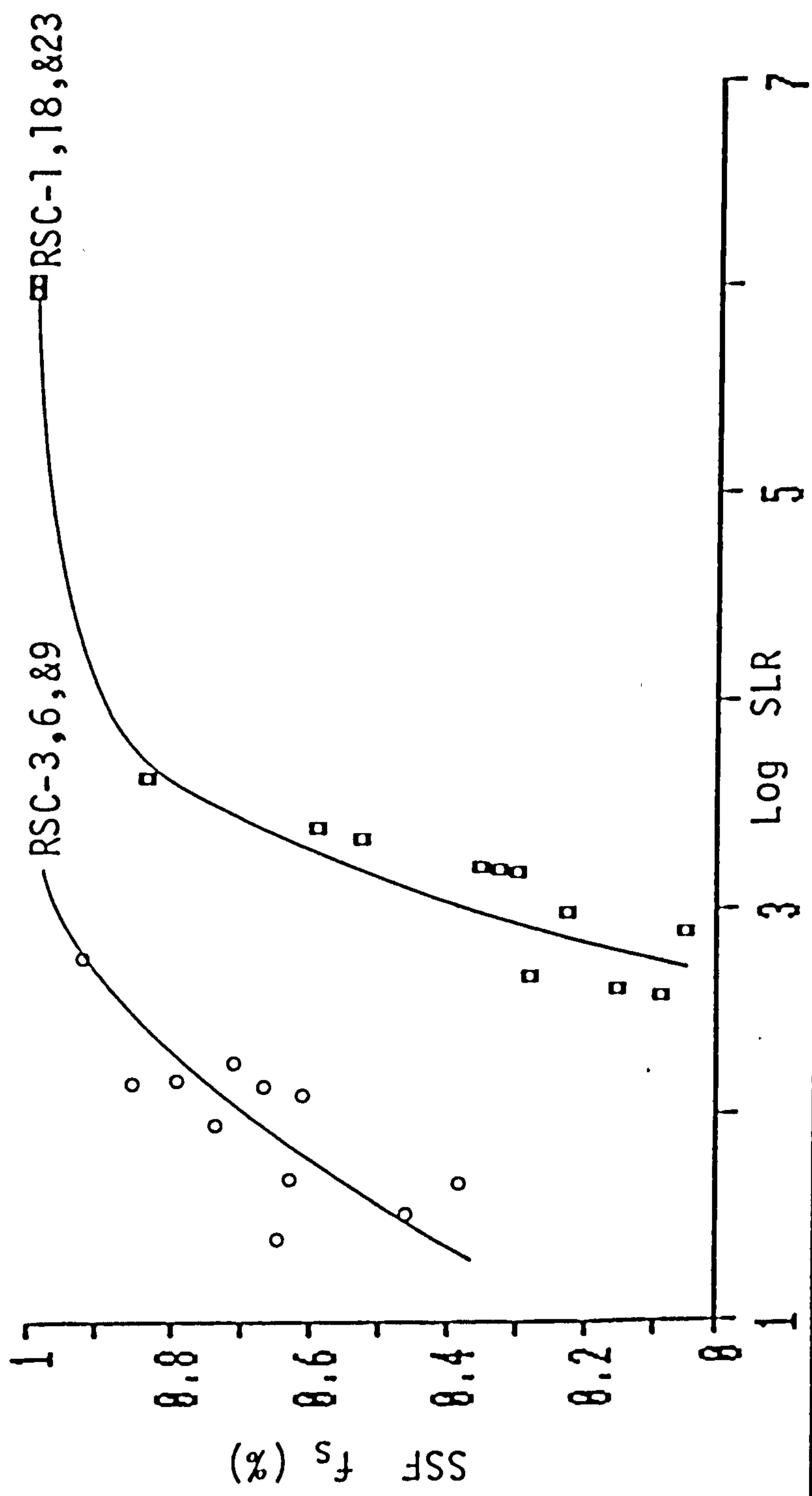
When calculating the SSF and the SLR the degree days were calculated using the real monitored data for the mean internal and external temperatures as there was little difference when standard degree-days were used.

$$\begin{aligned} \text{Solar Savings Fraction (SSF)} &= f_s = \frac{UA (\bar{T}_i - \bar{T}_e) \Delta t - Q_{aux}}{UA (\bar{T}_i - \bar{T}_e) \Delta t} \\ &= 1 - \frac{Q_{aux}}{UA (\bar{T}_i - \bar{T}_e) \Delta t} \end{aligned}$$

$$\begin{aligned} \text{Solar Load Ratio} &= \text{SLR} = \frac{I_{hor}}{UA (\bar{T}_i - \bar{T}_e) \Delta t} \end{aligned}$$

The degree-days, $(\bar{T}_i - \bar{T}_e)$, were calculated both for standard data aswell as the monitored data sets.

Figure 6.1.1.1 Monthly SSF v Log SLR comparing RSC-(1,18,23) & RSC-(3,6,9)



6.2 Correlating the Performance of TAP's using Temperature Differences

i) Measurement of air-flow rate and temperature difference across TAP

Continuous airflow measurement of all of the TAPs at Nazeing County Primary School was considered unviable economically. As an alternative, short-term high-sample-rate monitoring of the TAP flow rate was undertaken over a range of temperature differences between the panel inlet and outlet. This time consuming manual flow-rate measurement procedure was only undertaken for two panels on the south facade. 9mm holes were drilled into the centre of each of the two panels to facilitate the insertion of each hot-wire anemometer probe, (resolution $\pm 0.01\text{m/s}$; accuracy $\pm 0.1\text{m/s}$).

The correlation of air-flow rate with i) TAP temperature differences and ii) insolation on a south facing vertical plane, are shown in figures 6.2.1 & 6.2.2. The correlation coefficients between insolation and temperature difference with TAP flow rate were 0.918 and 0.906 respectively. Figure 6.2.1 also shows that a minimum temperature difference of 5.3°C was required to initiate any thermosyphon air-flow. The data were sampled at 30 second intervals and the average recorded every 5 minutes. Although the maximum recorded insolation levels and flow rates were 430W/m^2 and 0.18m/sec respectively, instantaneous values of these two parameters often reached 700W/m^2 and 0.6m/sec . It was not unreasonable to assume that this relationship would continue in a linear fashion from the initiation of flow at 275W/m^2 up to 700W/m^2 with a corresponding correlated flow rate of 0.513m/sec .

Similarly if the flow rate was extrapolated to this level of insolation when correlated against TAP temperature difference the resulting maximum temperature difference across the TAP would be 9.1°C . This relationship enabled the mass flow rate through each TAP to be calculated and hence also the total energy contribution from the whole system.

DT v Air Velocity for two south-facing TAPs, 13.55pm-14.40pm, 30/11/89

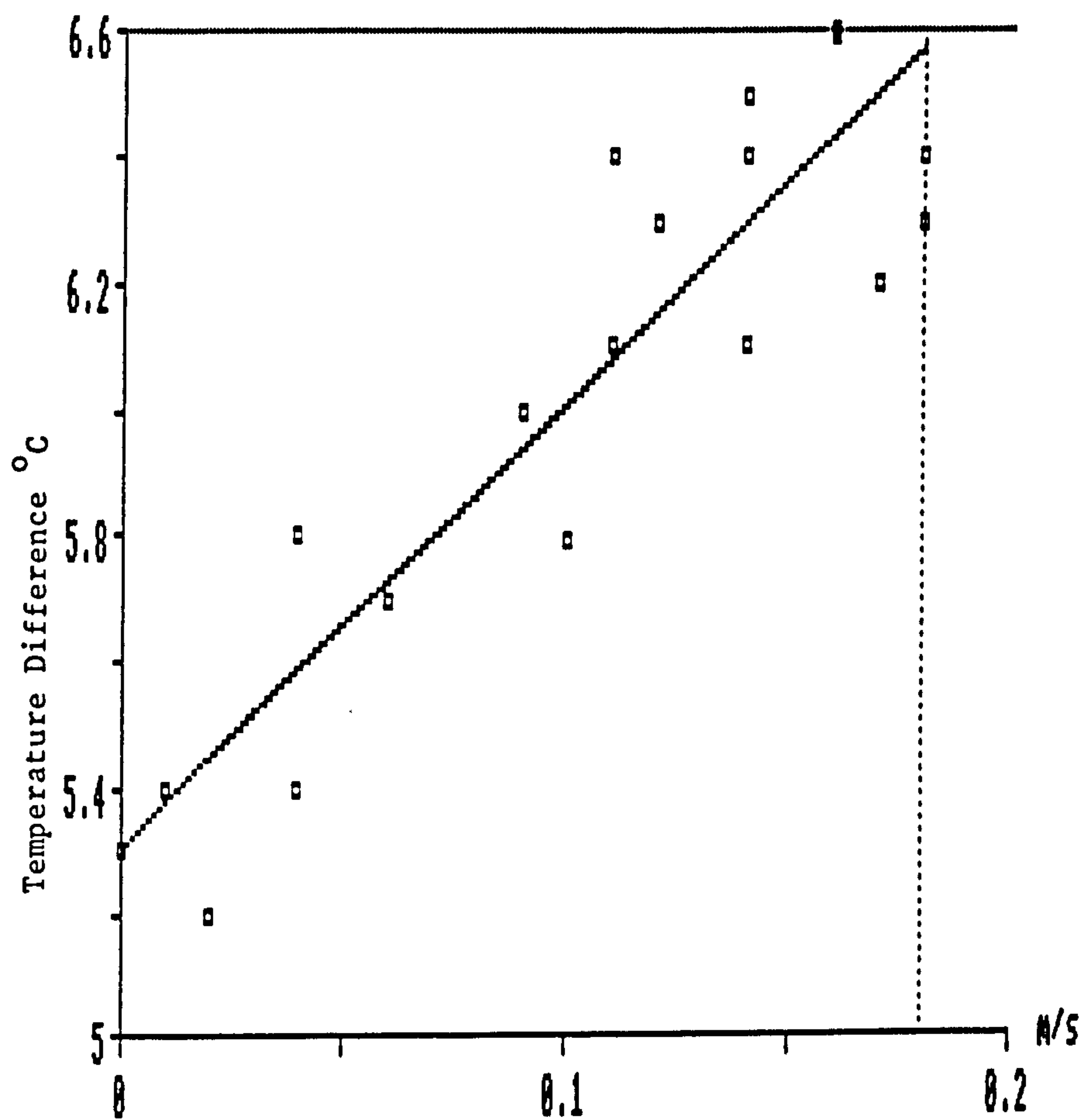


Figure 6.2.1

I v Air Velocity for two south-facing TAPs, 13.55pm-14.40pm, 30/11/89

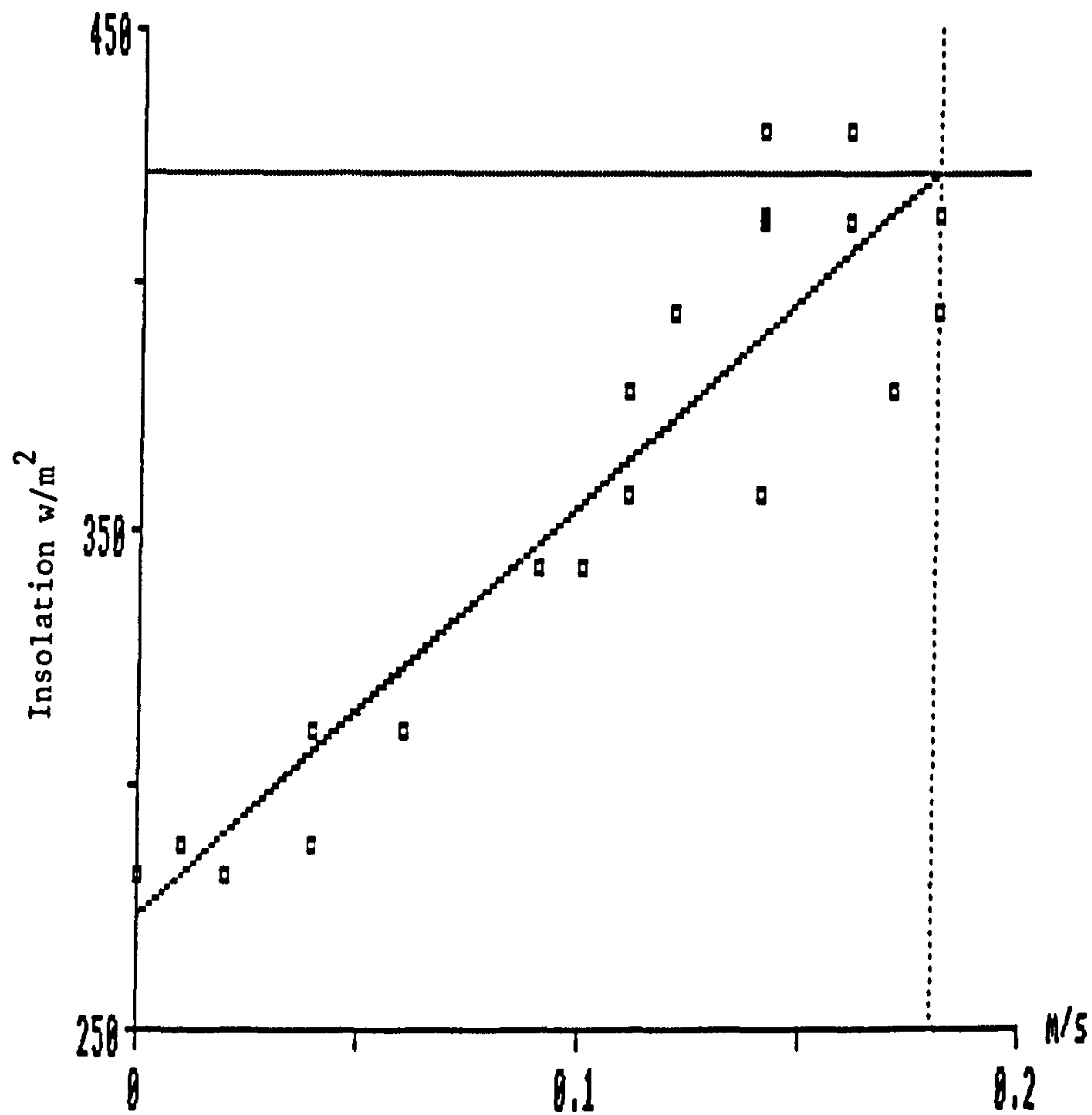


Figure 6.2.2

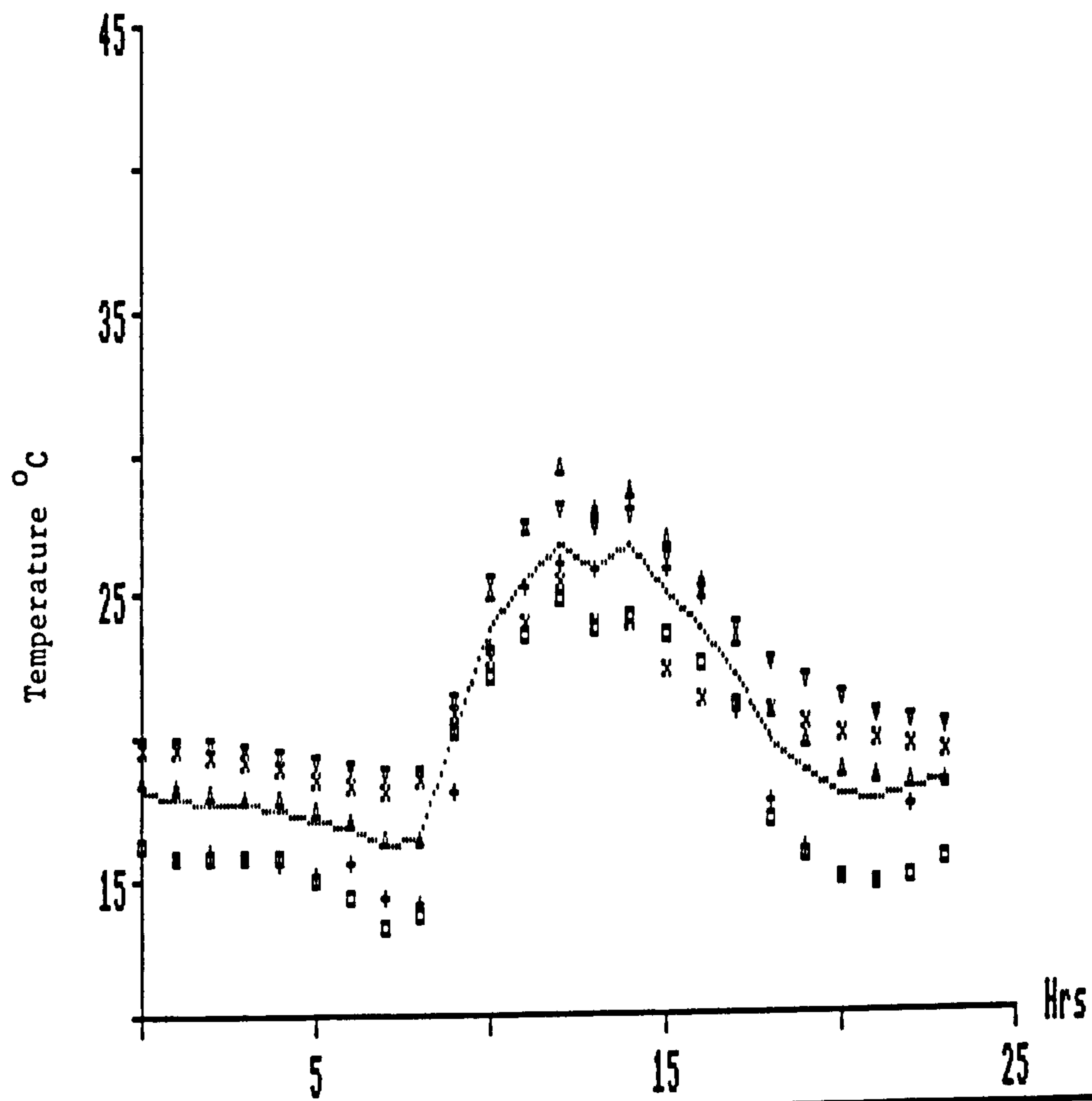
ii) Detailed assessment of the mean daily temperature difference across Thermosyehoning-Air-Panels on each facade

It was far too time consuming to undertake intensive air-flow and temperature measurements from each of the thirty-six collectors. Calculating the contribution from all of the TAPs, (with the correlation between TAP flow rate and temperature difference), was thus achieved by using the mean temperature difference of *all* the TAPs from each facade. Unfortunately the failure of various temperature sensors only permitted temperatures from five south-facing, three east-facing, and two west-facing collectors to be collated with any degree of certainty.

To illustrate the range of temperature differences that were being experienced in each of the selected TAPs, two different days in October 1989 were selected because this particular month exhibited the least number of corrupted data resulting from defective sensors. The peak hourly levels of insolation on each of these days, (20th & 24th October), were 675W/m^2 and 650W/m^2 . Such elevated levels of insolation would ensure that the spurious effects, introduced at the point where the flow had just been instigated, could be minimised. Fig.6.2.3 - Fig.6.2.6 illustrate the inlet and outlet temperatures of the five south facing collectors on both of these days. The inlet temperatures show a minimal level of scatter which was commensurate with the ambient temperatures and levels of occupancy which the classrooms experienced. The greater degree of scatter exhibited by the outlet temperatures resulted from different heat removal factors which were determined by some or all of the following:

- a) The panel depth should have been a nominal 60mm. In practice this varied by as much as $\pm 5\text{mm}$ due to absorber and insulating panel surfaces not being completely flat.
- b) Each Tedlar damper, which was designed to prevent reverse-circulation, did not have identical physical geometries due to the easily deformed nature of the 0.04mm thick Tedlar film. Different levels of impedance to flow arising from these inconsistencies directly influenced the air velocity within each collector.

TAP inlet temperatures for five south facing collectors on 20/10/89



□ TAP_1

△ TAP_2

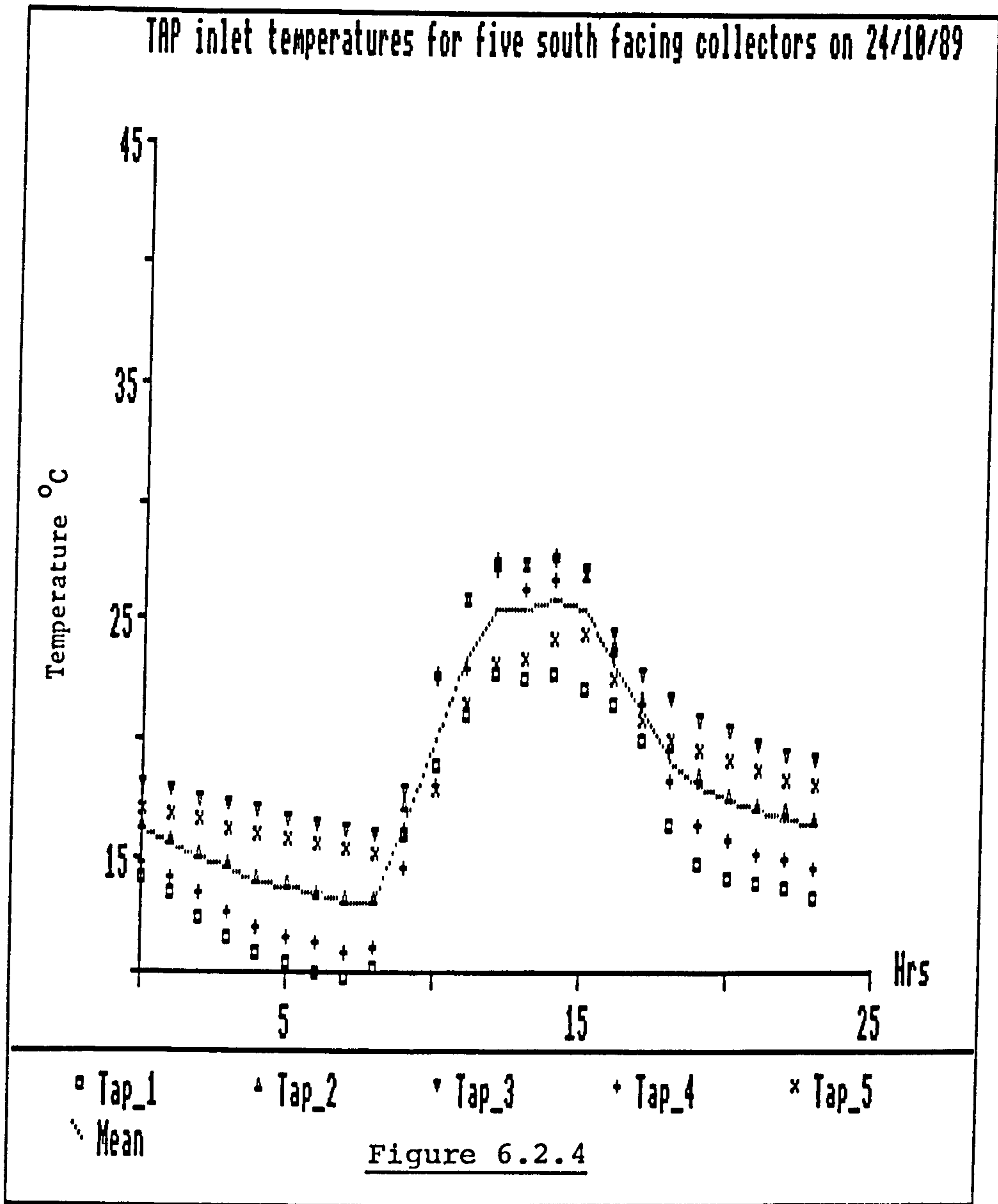
▽ TAP_3

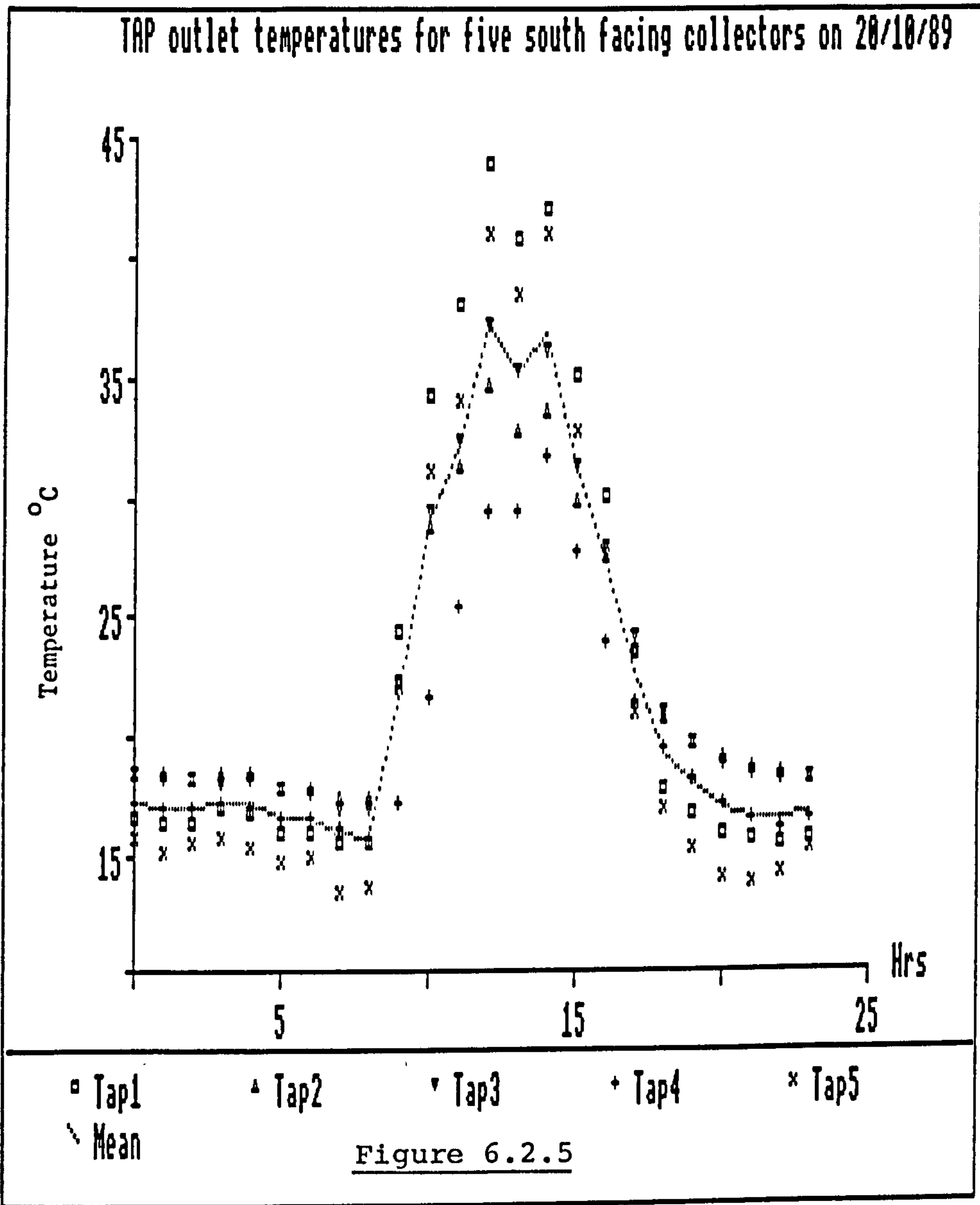
+ TAP_4

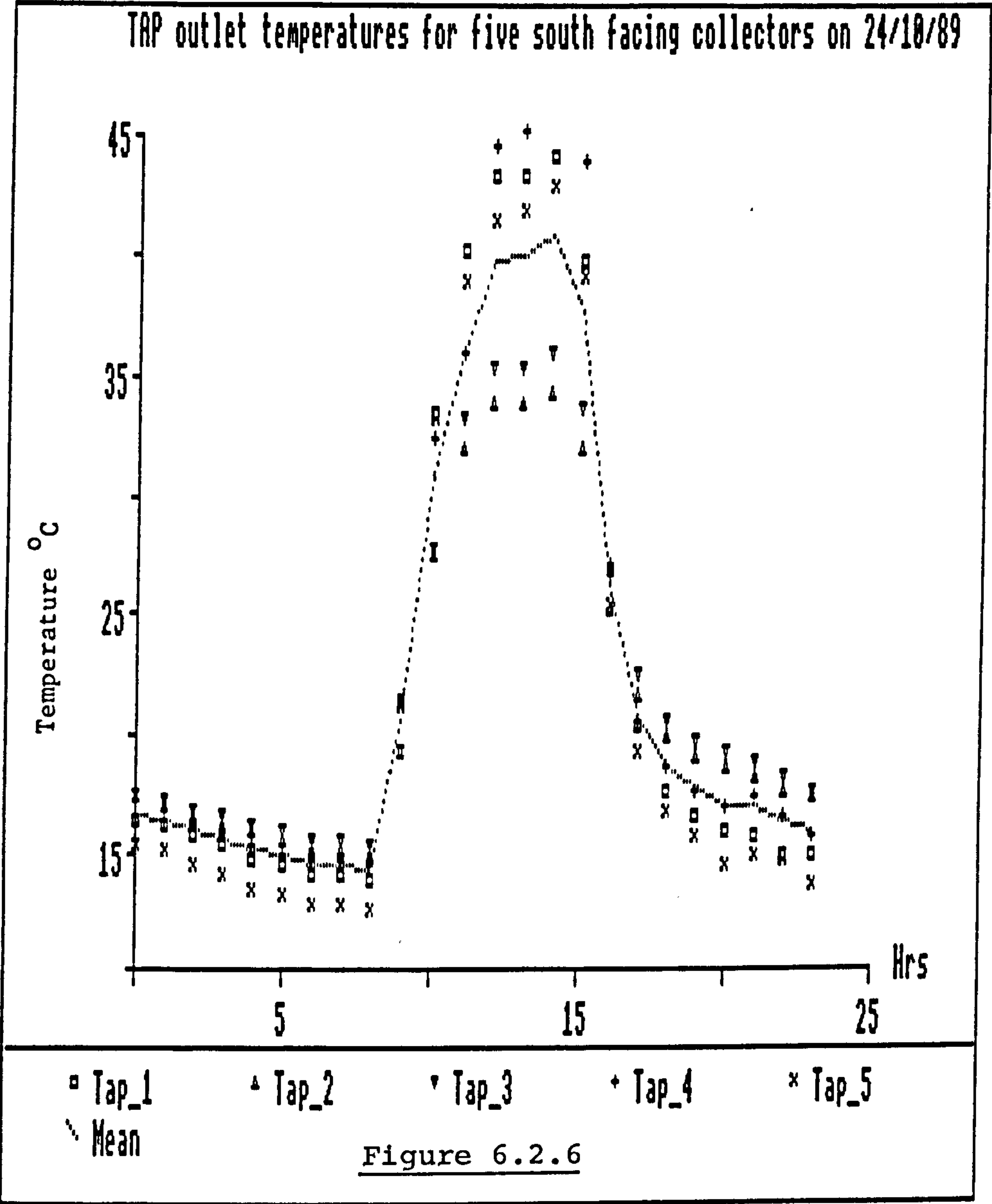
× TAP_5

- - - Mean

Figure 6.2.3





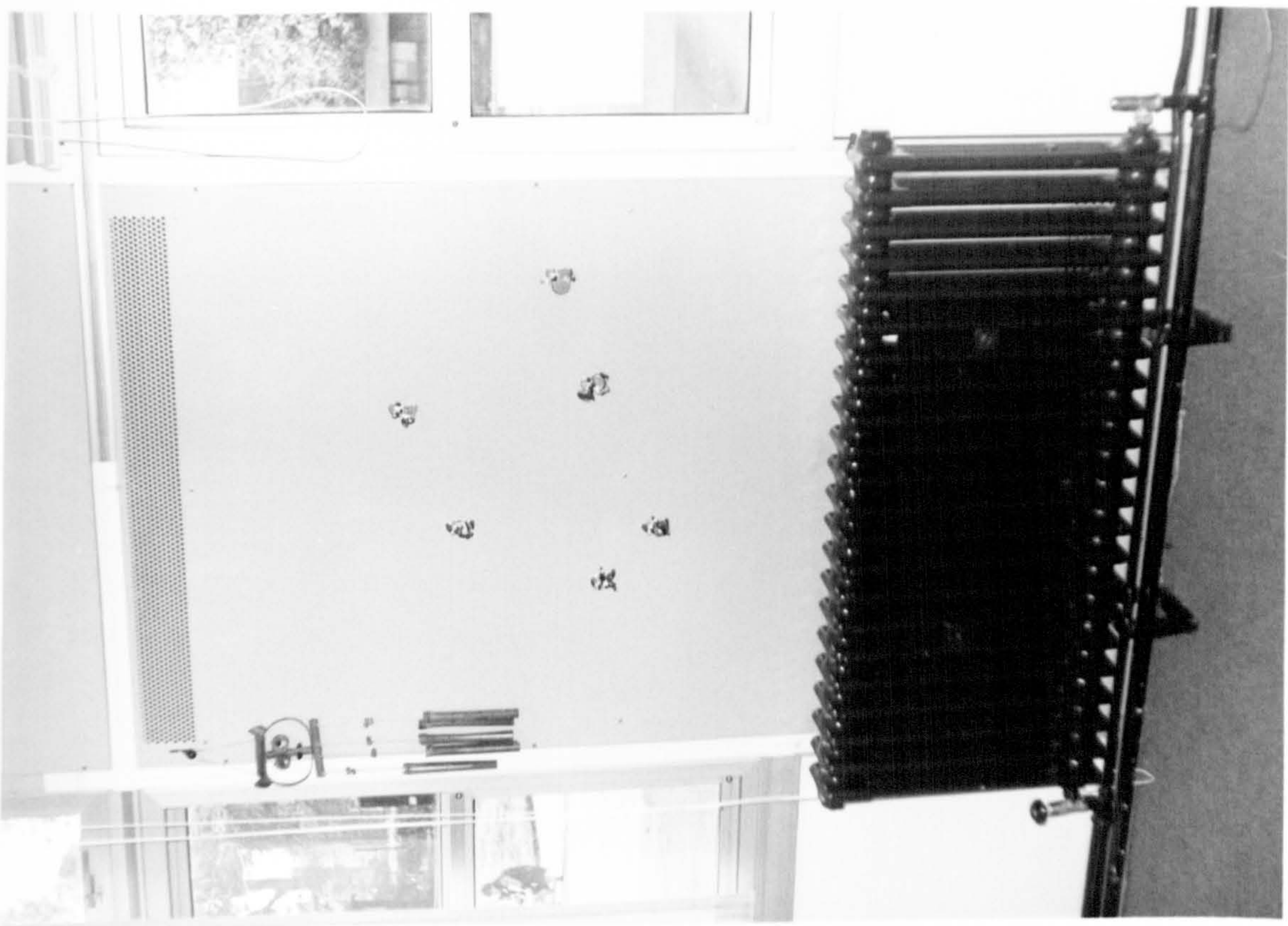


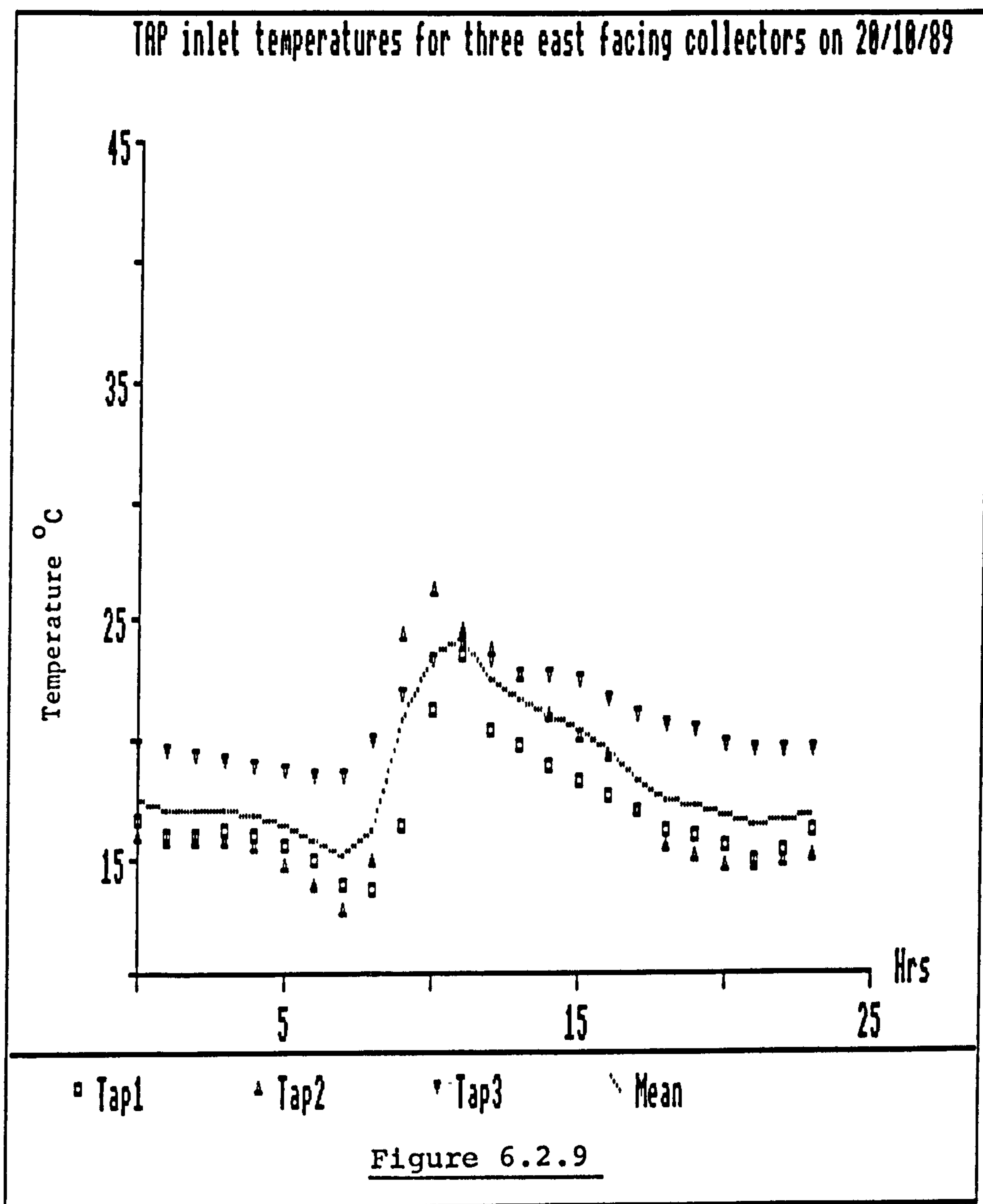
- c) A number of teachers occasionally used the unglazed areas created by the TAPs as additional wall space by placing furniture and posters against/on the back of the insulated panels (see Fig. 6.2.7). This obstructed and restricted the inlet grille to the collector. The ensuing lower flow-rates generated higher outlet temperatures which increased radiative losses.
- d) Three of the collectors had been installed behind the existing radiators (Fig. 6.2.8). Although this did not adversely affect the heat removal from the TAPs the real outlet temperature was augmented by the convective flow of hot air from these radiators.
- e) The flow-paths through the collector inlet and outlet grilles were often restricted when dust accumulated on the cobwebs which had been woven over the 6.5mm holes of these grilles. The level of air-borne particulates was dependent upon the activity taking place in the room concerned, e.g. workshop areas were obvious sources of dust and other contaminants. This problem would not have arisen if the perforated outlet/inlet had been replaced with a continuous open slot or with larger holes, although these particular grille geometries had their own individual drawbacks.

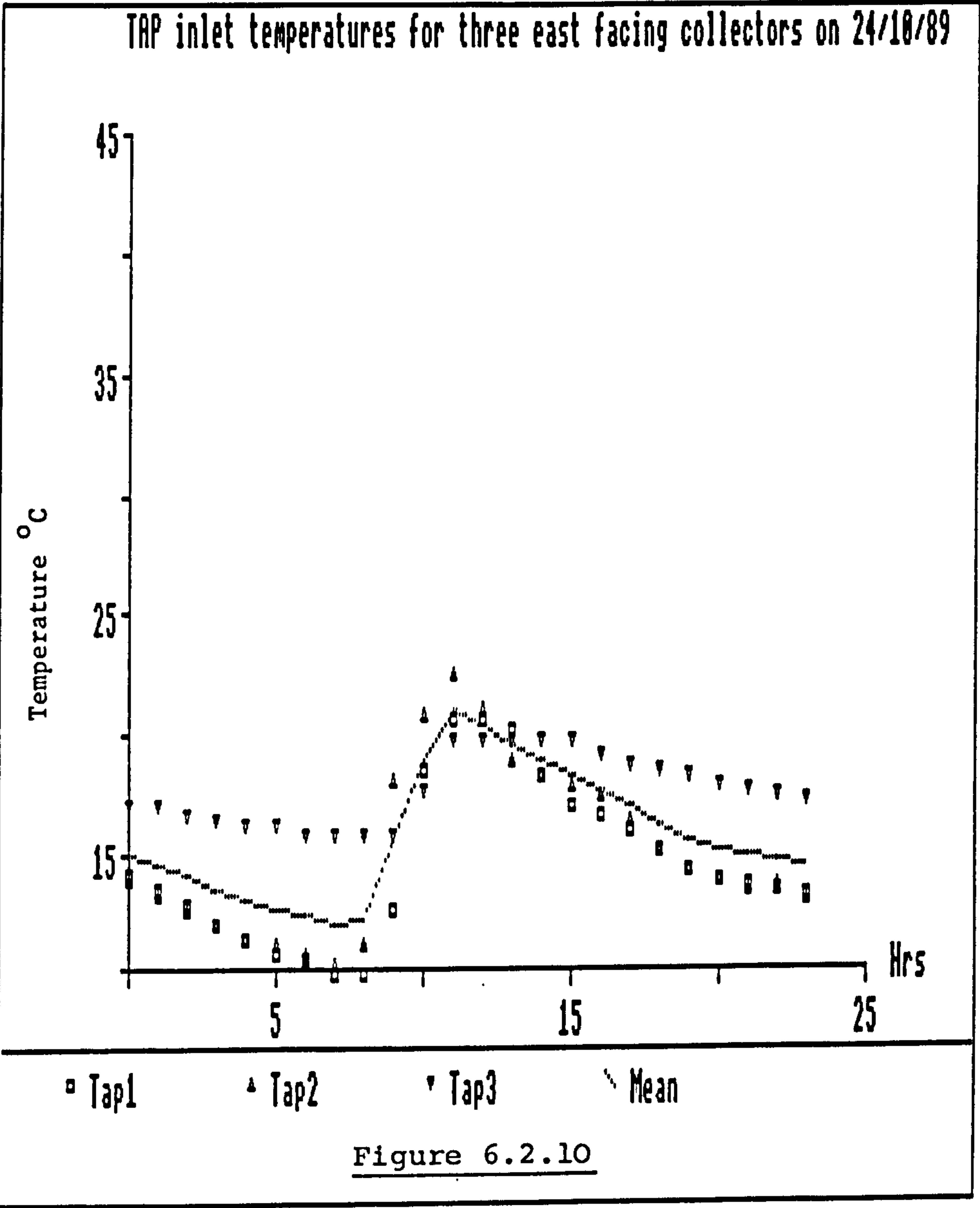
Figures 6.2.9 to 6.2.14 illustrate the inlet and outlet temperatures for the three east-facing and two west-facing TAPs that were chosen for detailed analysis. The offset distributions of their daily temperature differences, (Figs. 6.2.15 & 6.2.16), clearly show how the east and west facing TAPs produced their greatest solar contributions in the morning and evening respectively. As expected, the temperature differences are driven by the daily insolation with lower peak output temperatures for TAPs on both of these than for the south facing collectors. Figures 6.2.17 & 6.2.18 show similar patterns of diurnal distribution of insolation to that of the TAP temperature differences on each facade, however there is less correlation between their absolute values, (Figs. 6.2.19 & 6.2.20). This was confirmed by the poor correlation between the hourly efficiency and insolation levels for the 20th and 24th of October (Fig. 6.2.21).

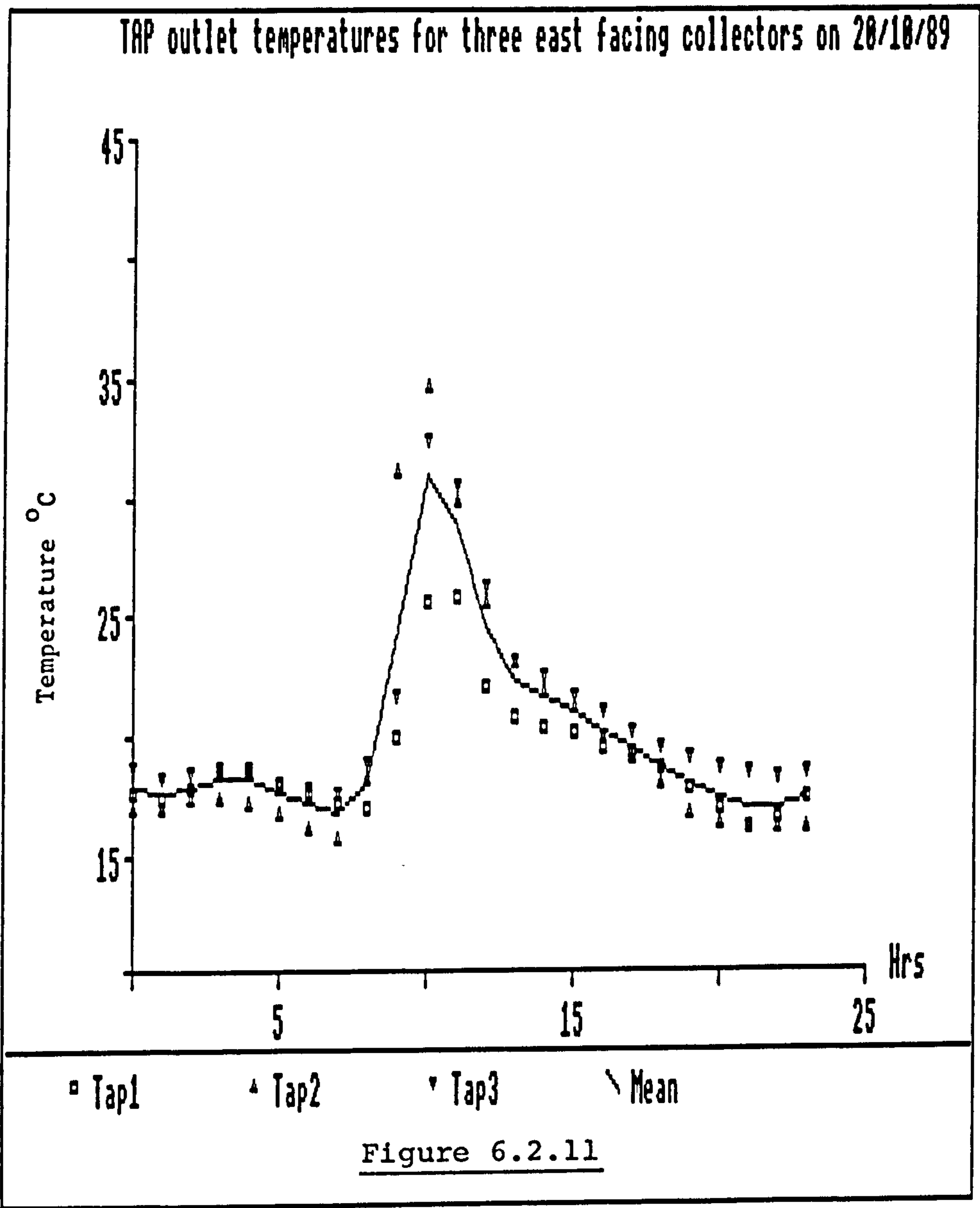
Figure 6.2.7 Classroom furniture
obstructing collector inlet grille

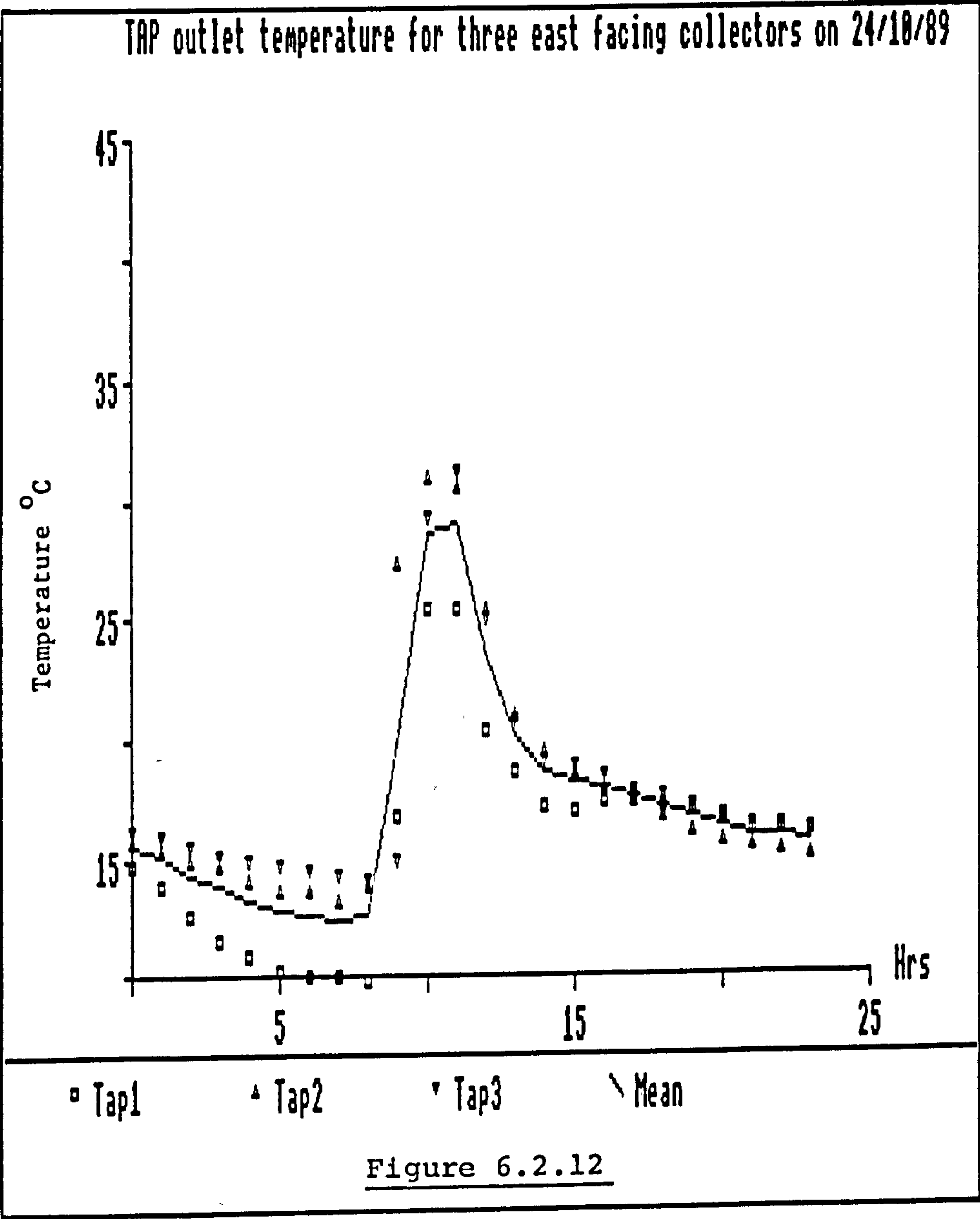
Figure 6.2.8 Thermosyphoning-Air-Panels
installed behind existing radiators

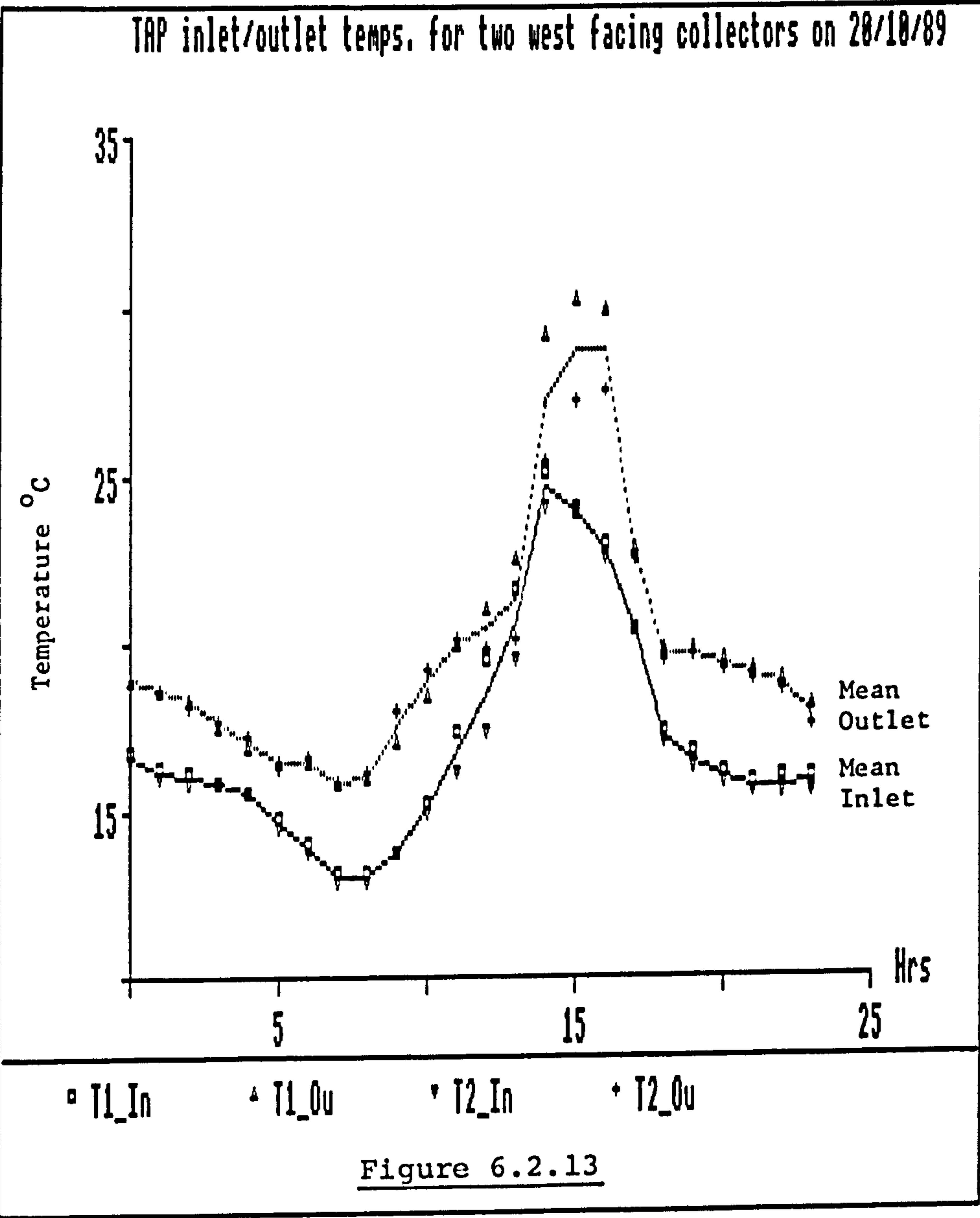


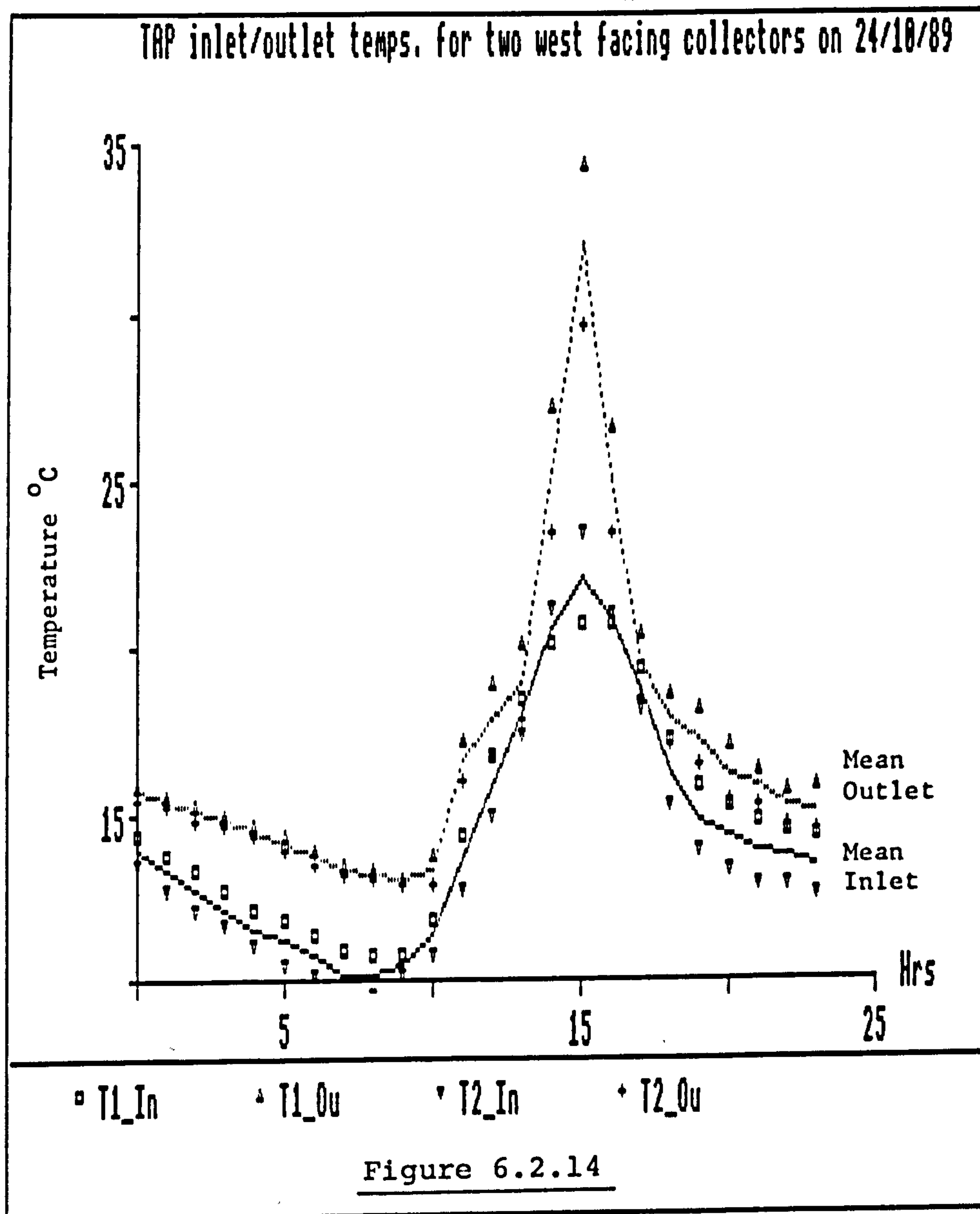


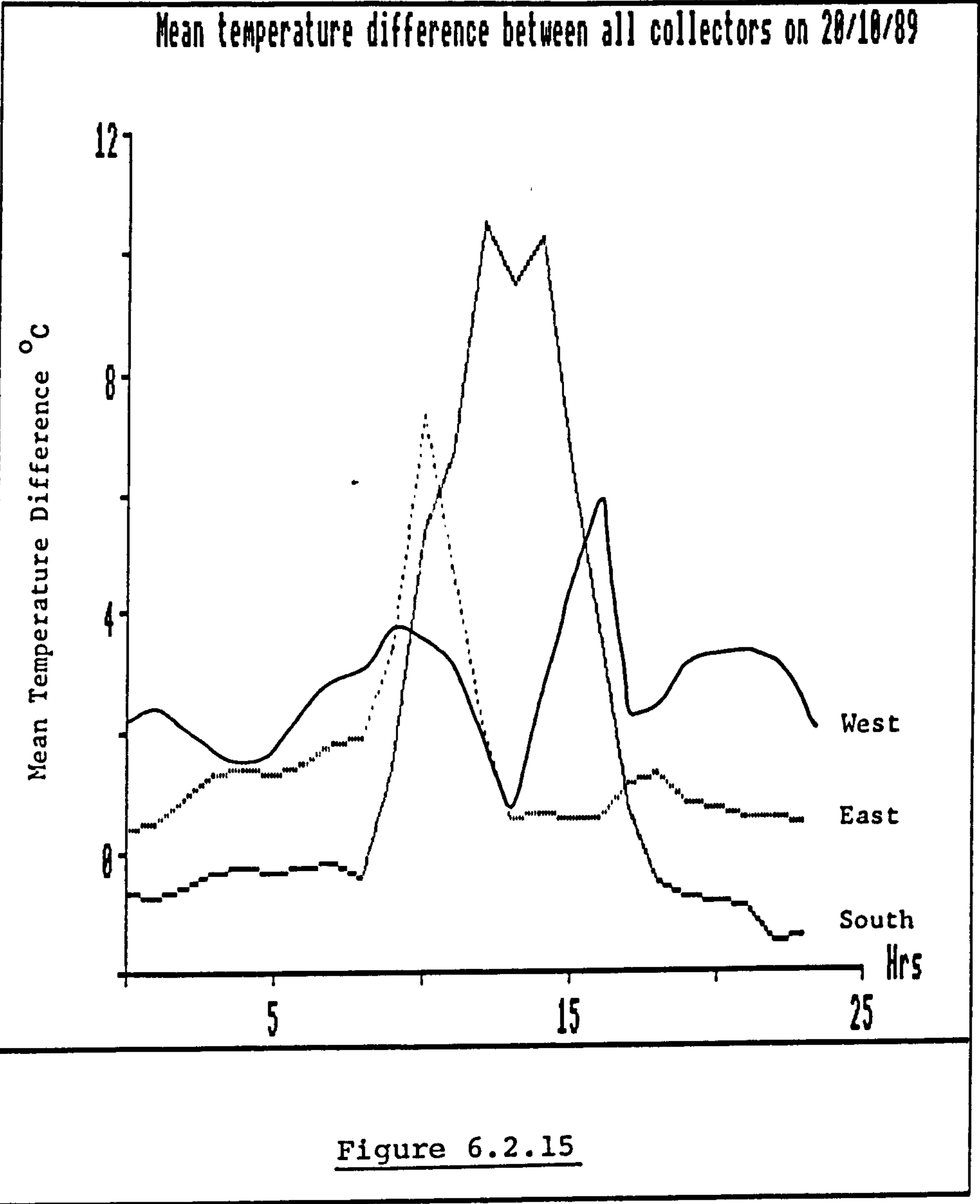


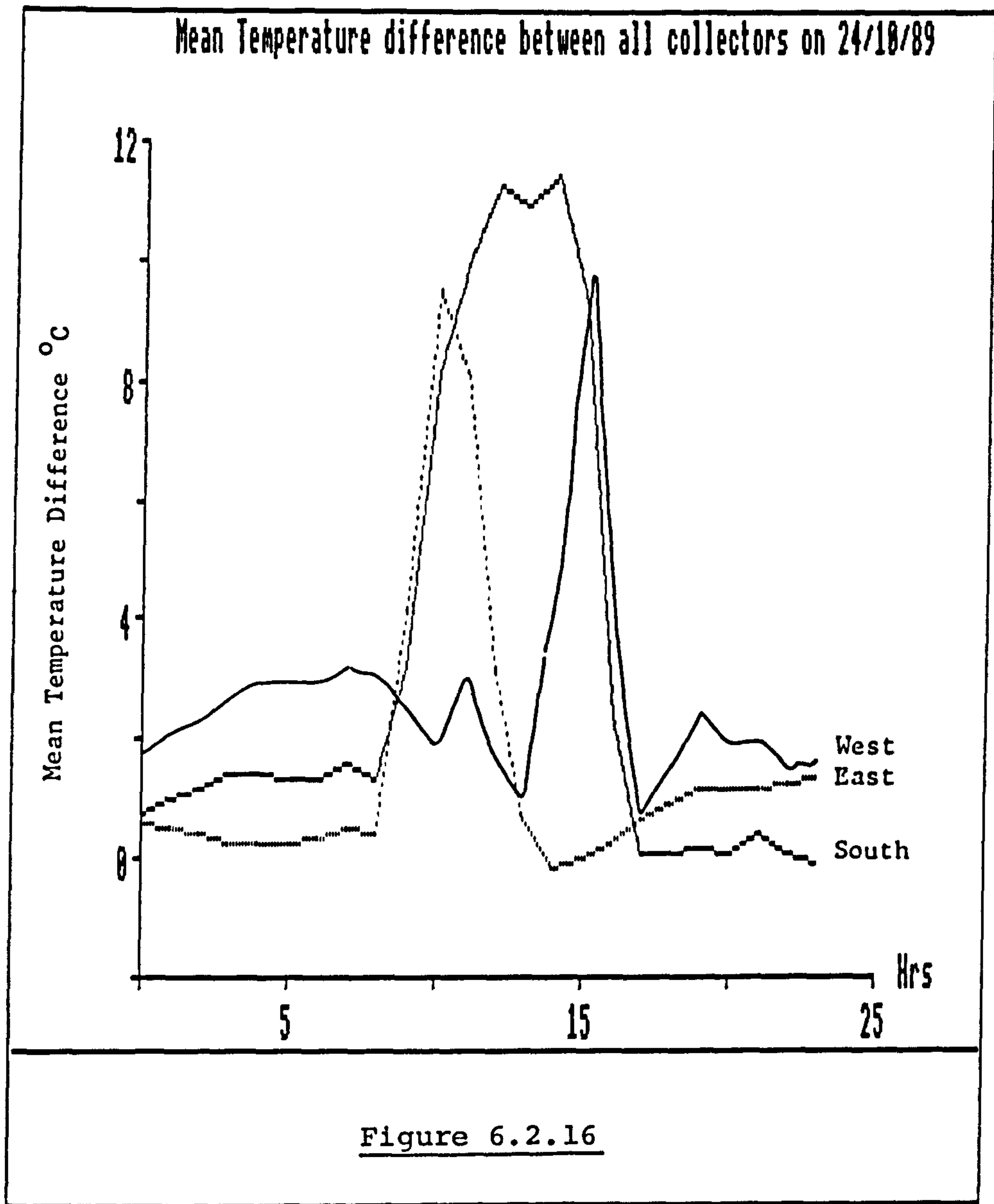


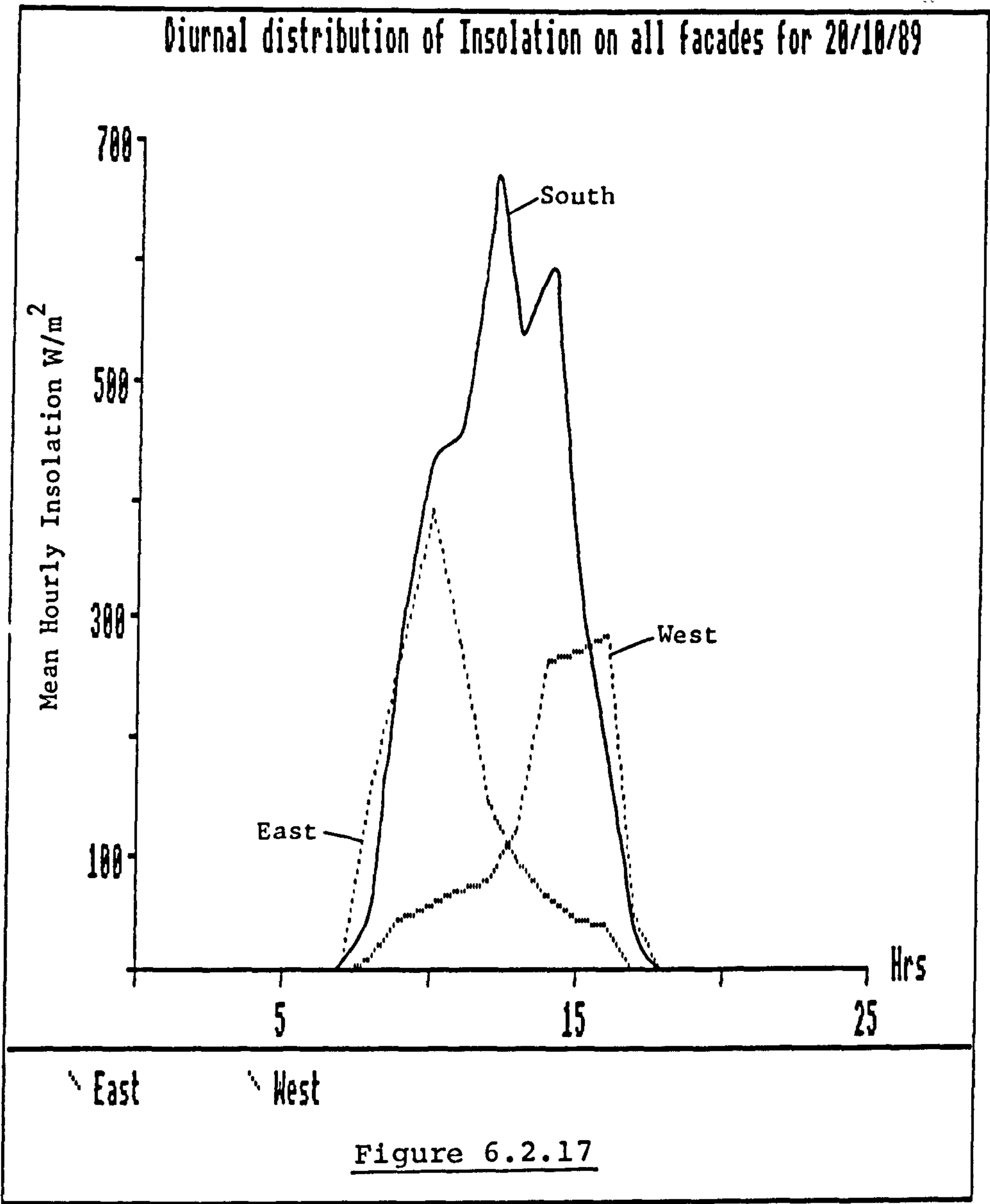


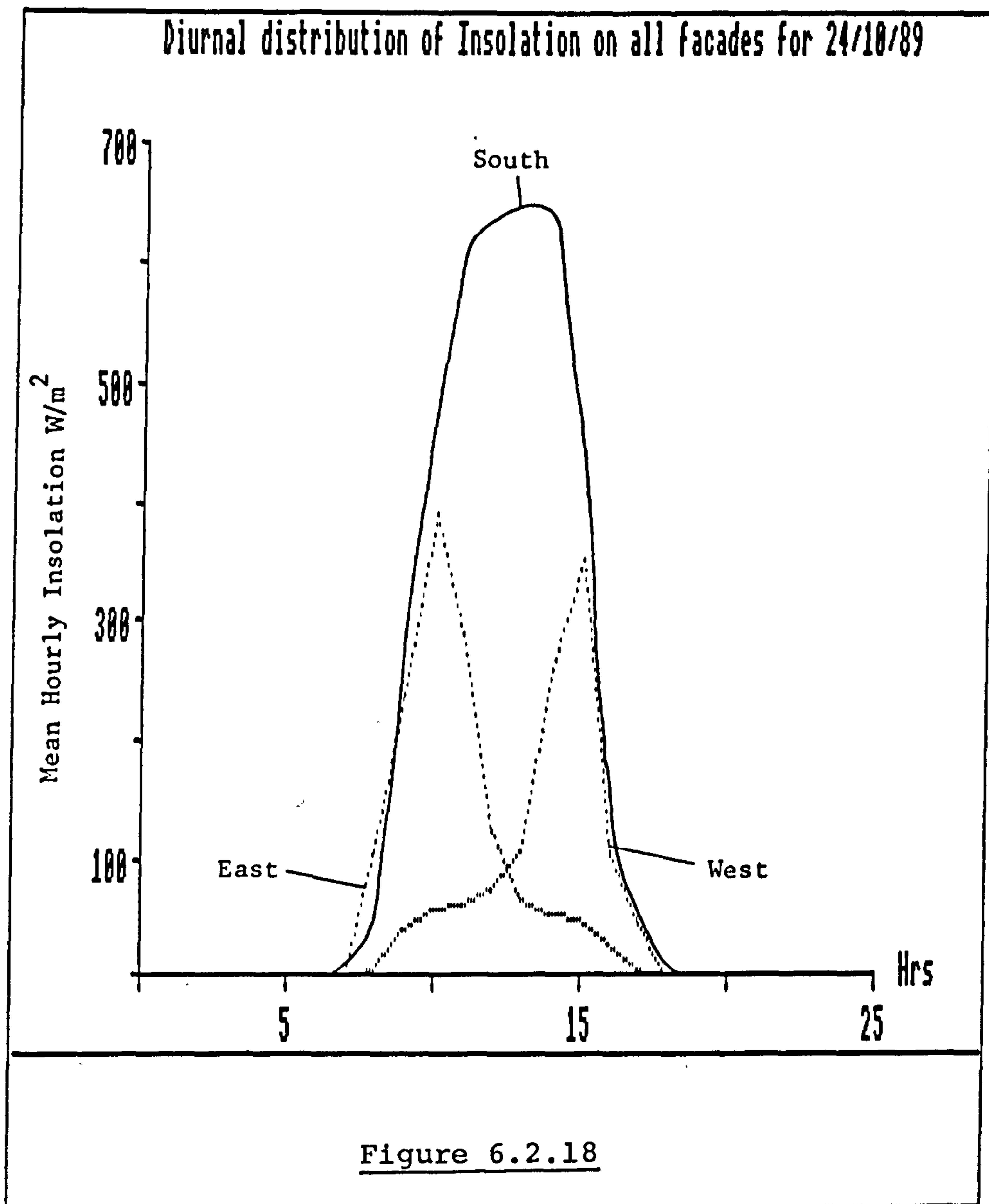


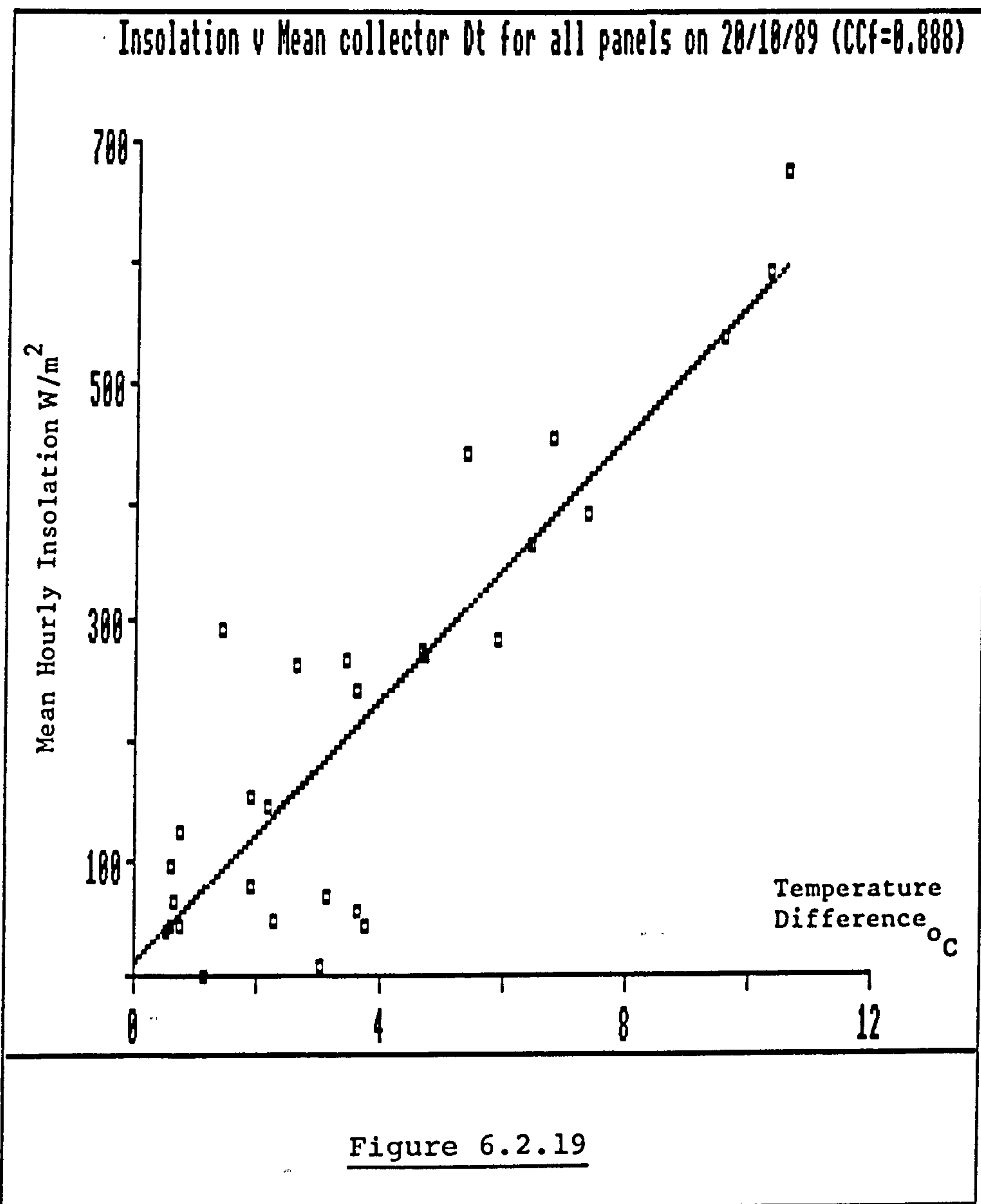


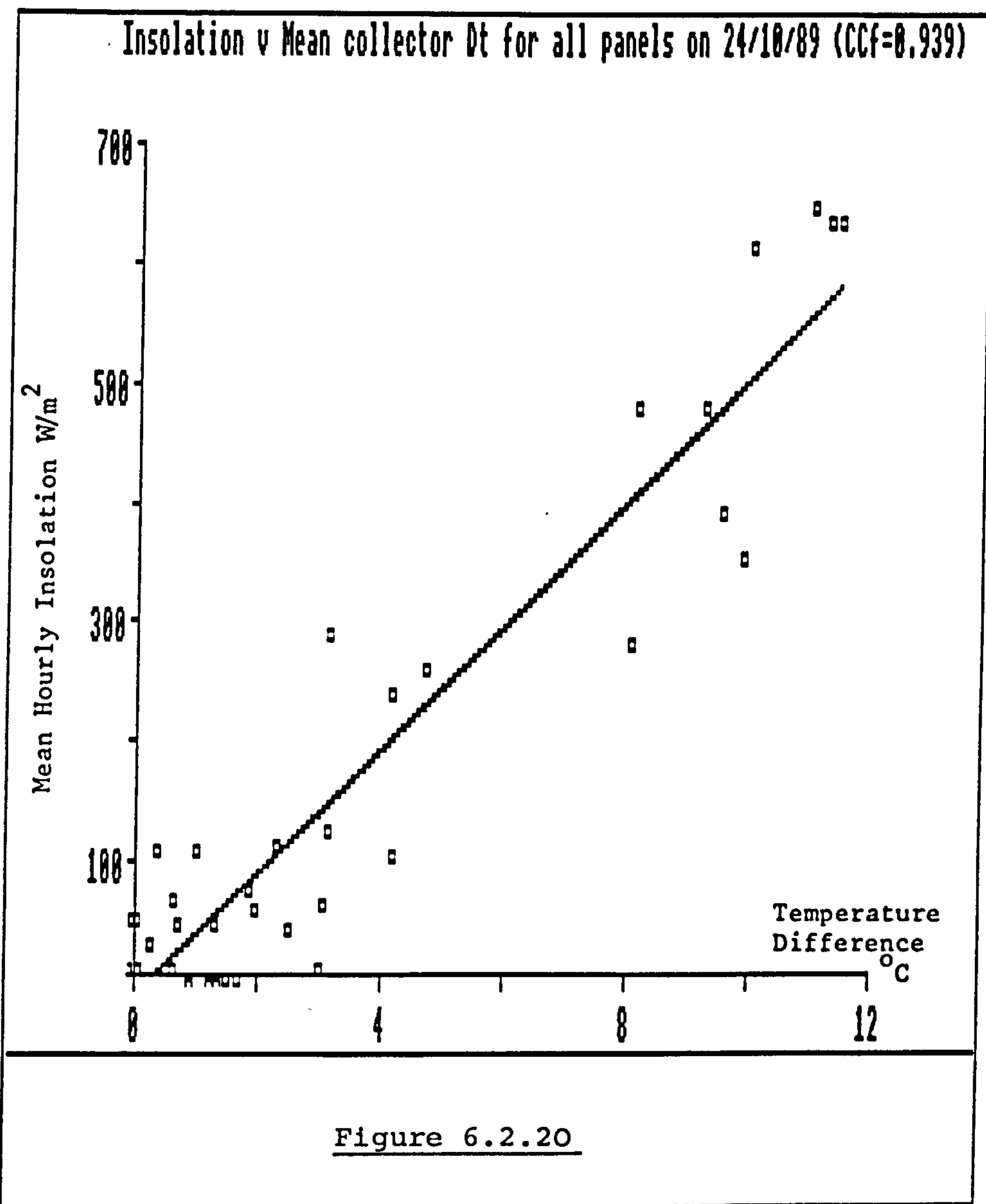


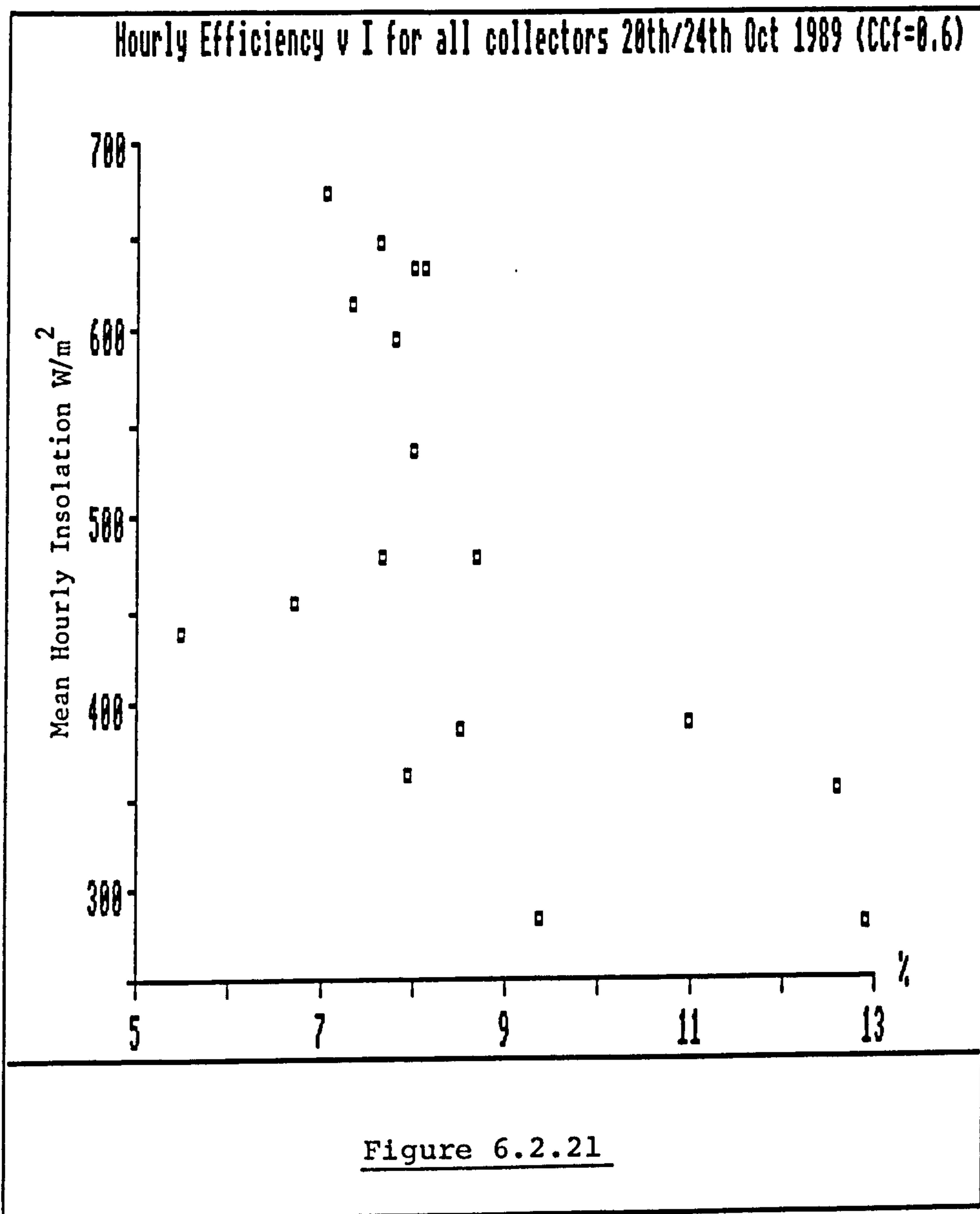










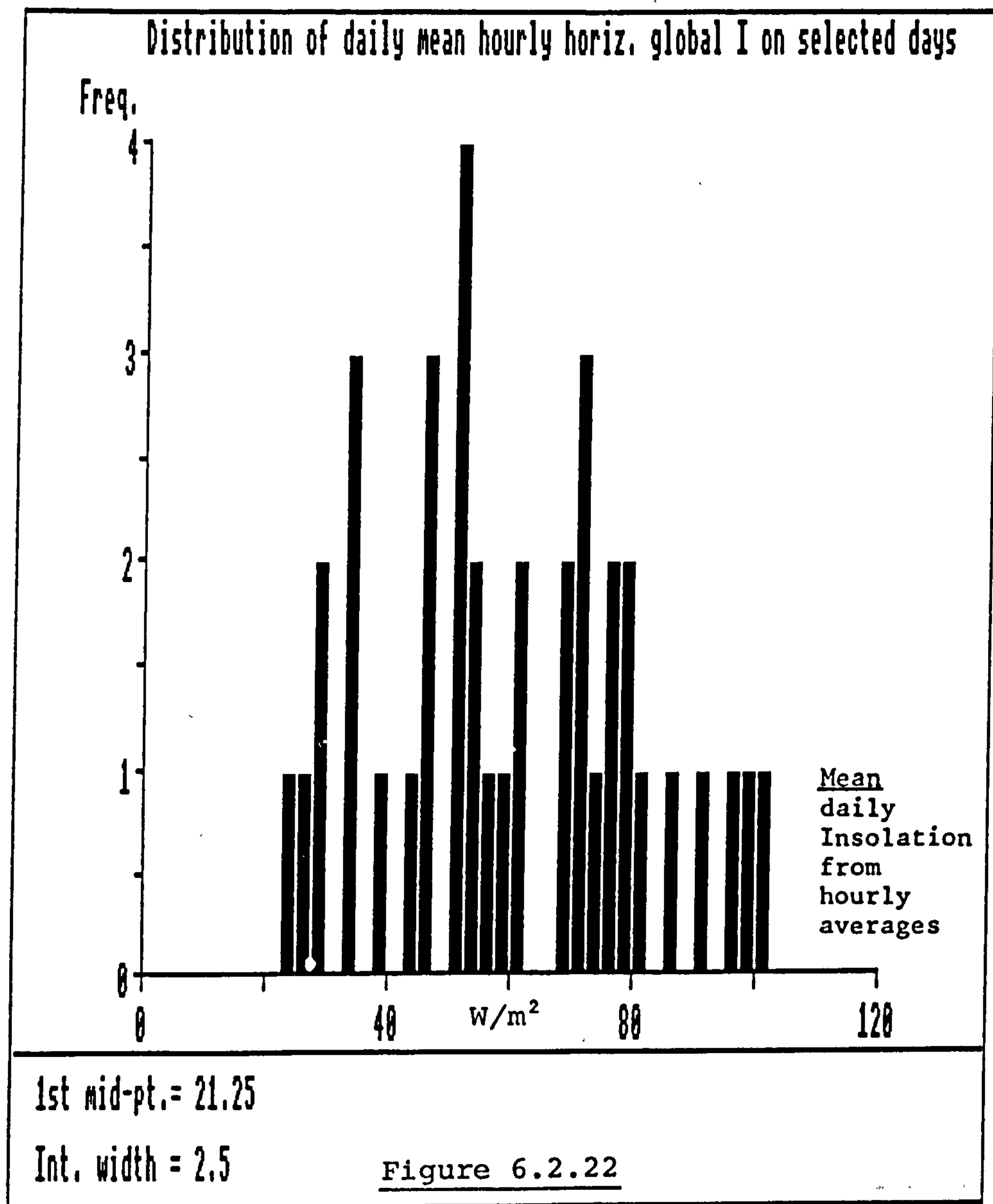


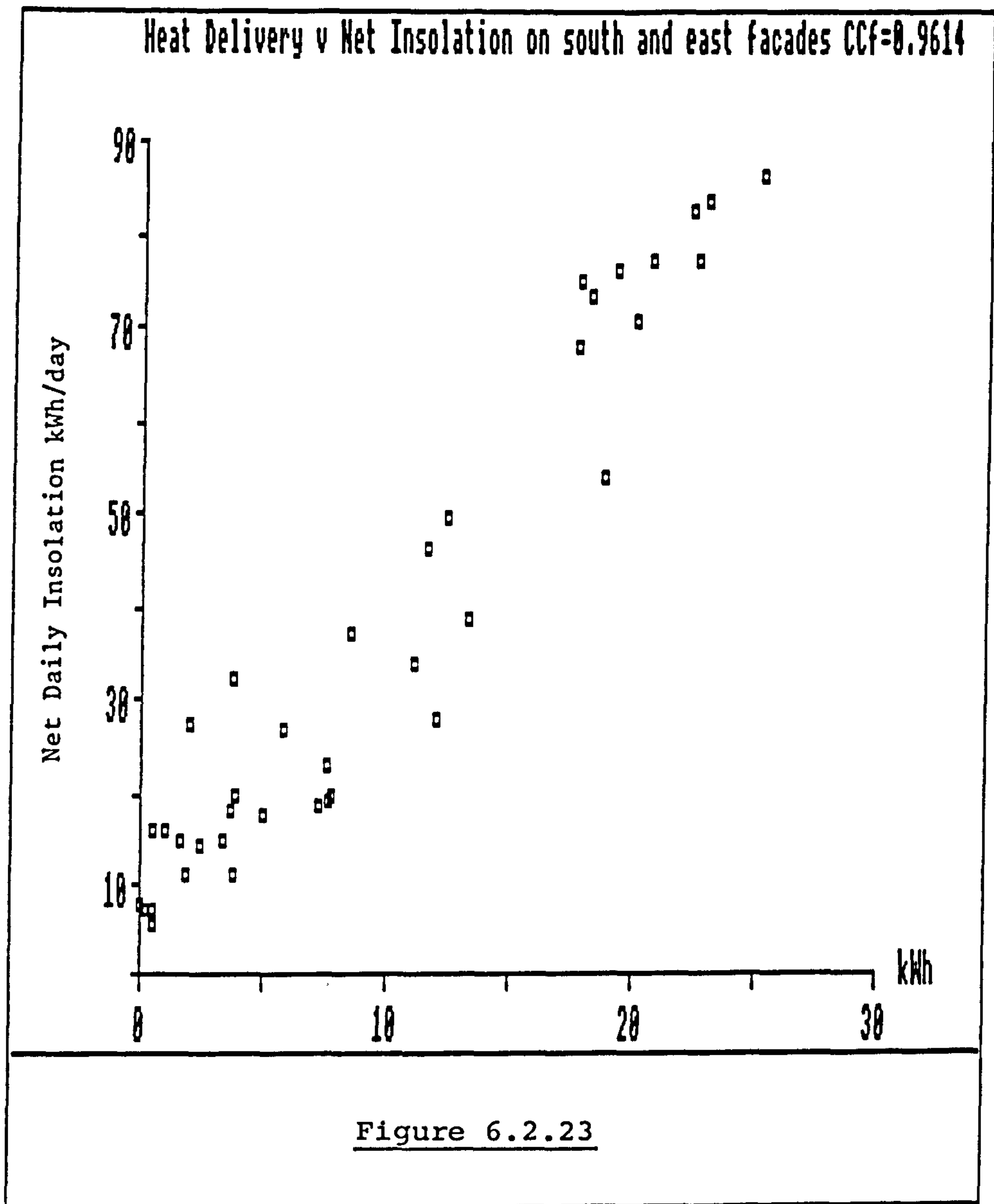
iii) Additional daily measurements of TAP temperature difference and thermosyphon flow-rate to predict daily total heat delivery

The correlation between hourly temperature difference and air flow-rate was applied to 38 days from October 10th until 20th December 1989. These days were selected to represent a typical sample of daily mean hourly levels of global insolation on a horizontal plane for this period. The distribution of these levels of insolation is shown in Fig. 6.2.22 with the majority of values between 50W/m^2 and 80W/m^2 averaged over each 24 hour period. The mean flow rate from each TAP was calculated from the corresponding hourly mean temperature differences whenever this difference exceeded the threshold value at which thermosyphon flow was initiated (Fig. 6.2.1). This enabled the mean hourly heat delivery from the TAPs on each facade to be determined. These hourly heat deliveries were summed over each day to produce a total daily heat delivery from each facade. This process was repeated to determine the total daily insolation and the net daily insolation, (i.e. the insolation during only the hours when the TAP temperature difference exceeded the threshold level), falling on each facade. Unfortunately none of the selected days produced temperature differences above the threshold level on the west facade. This was attributed to the solar radiation being obscured by trees at low winter sun angles. Fortunately, the south facade overlooked a large open field and the school playground lay beyond the east facade.

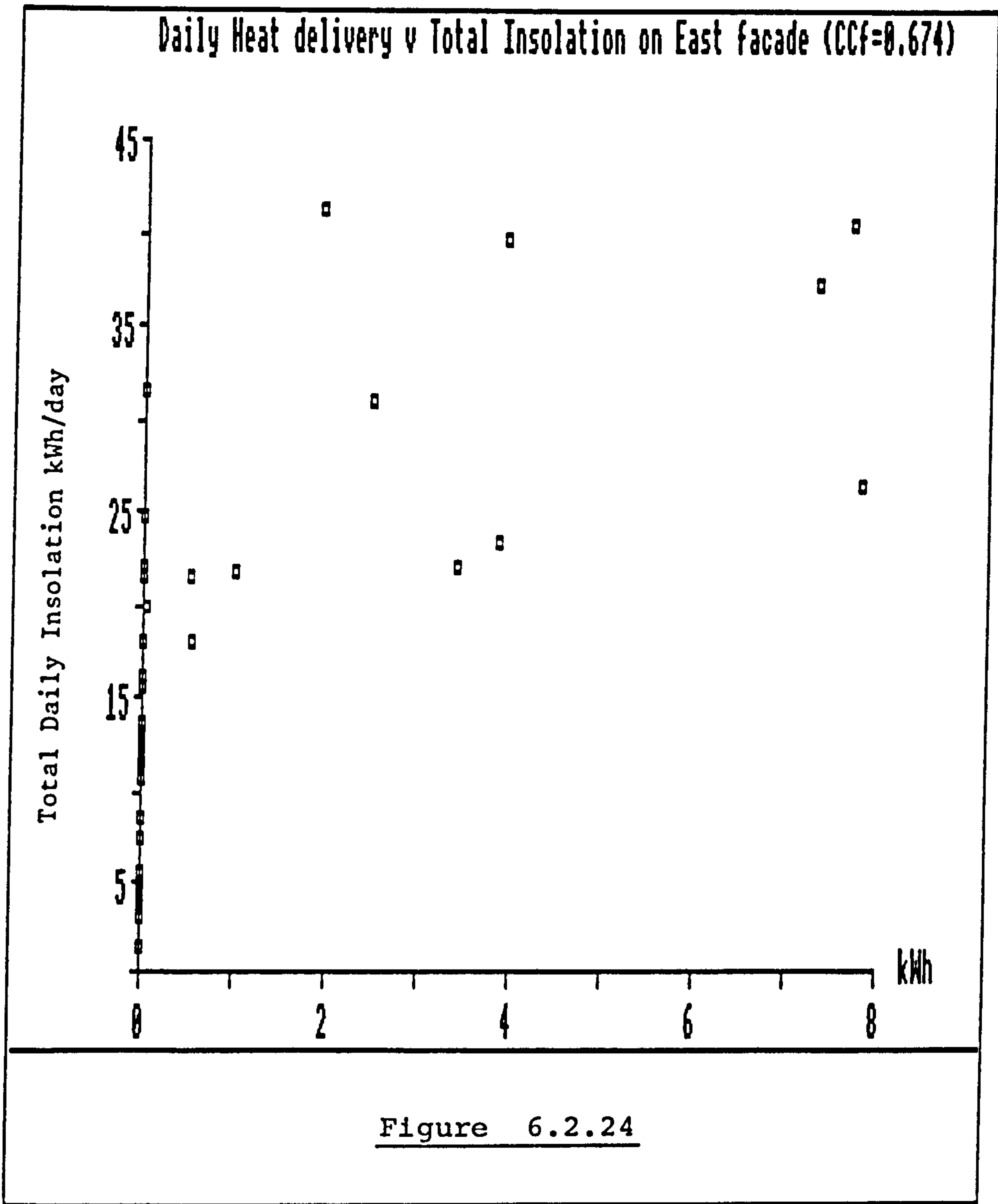
Further examination of the daily results produced strong correlations between the heat delivery and, both the net and the total, daily insolation levels. As expected, there was a very good relationship between the net daily insolation and the total heat delivery of the TAPs on the south facade with a correlation coefficient of 0.9614 as shown in figure 6.2.23. However, this was of little practical significance because the data acquisition equipment was only configured to process and sum the long-term insolation data for whole days.

Investigating each facade in turn, Fig. 6.2.24 showed little correlation between daily total heat delivery and insolation on the east facade. This was due primarily to the inconsistent duration and the generally lower levels of insolation on this plane despite data-sampling intervals of 10 minutes. Such low levels of insolation were of the same order of magnitude as the minimum threshold level required to initiate thermosyphon flow within the collector. Such





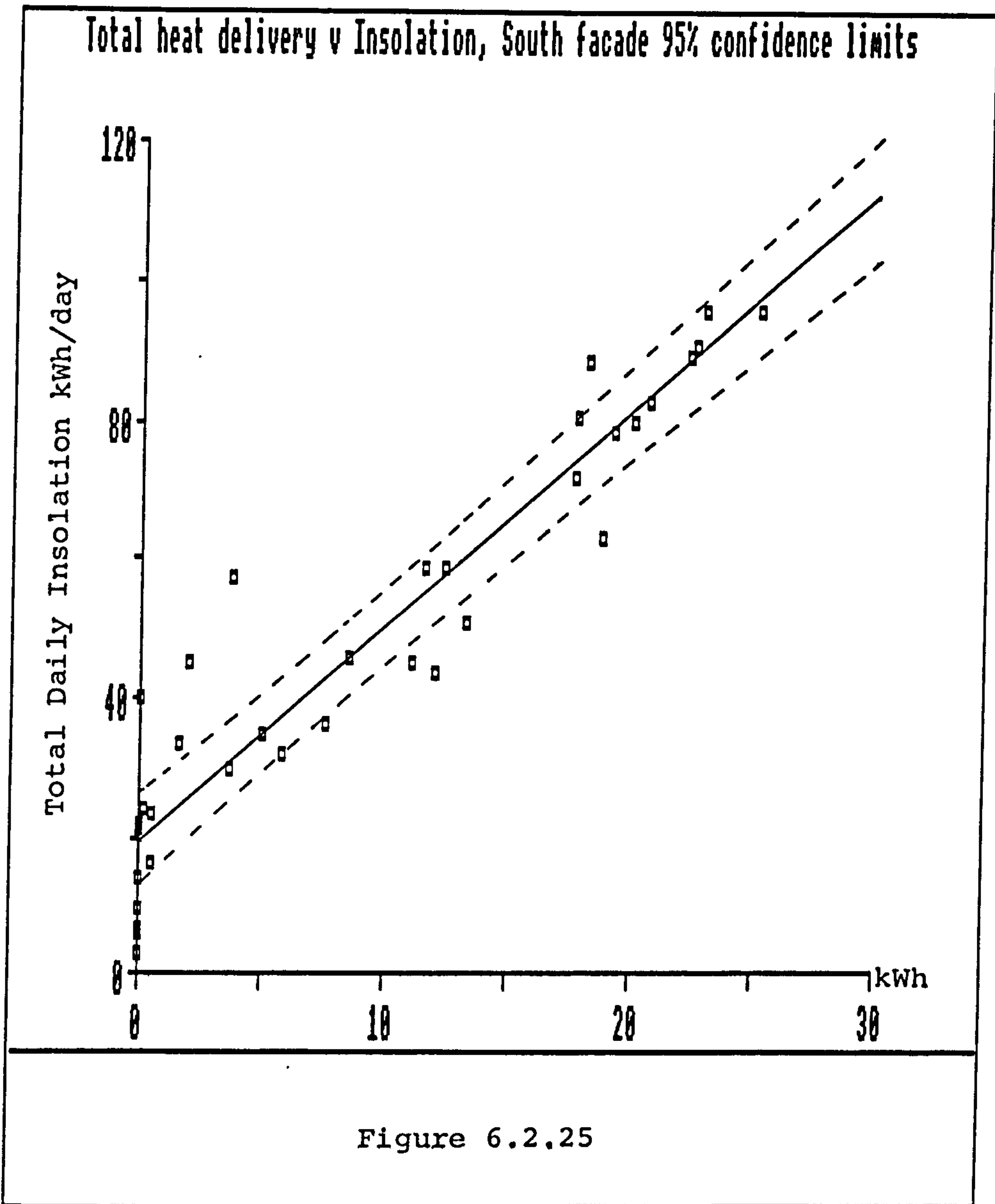
Collector area on east facade = 28m²
Collector area on south facade = 24m²



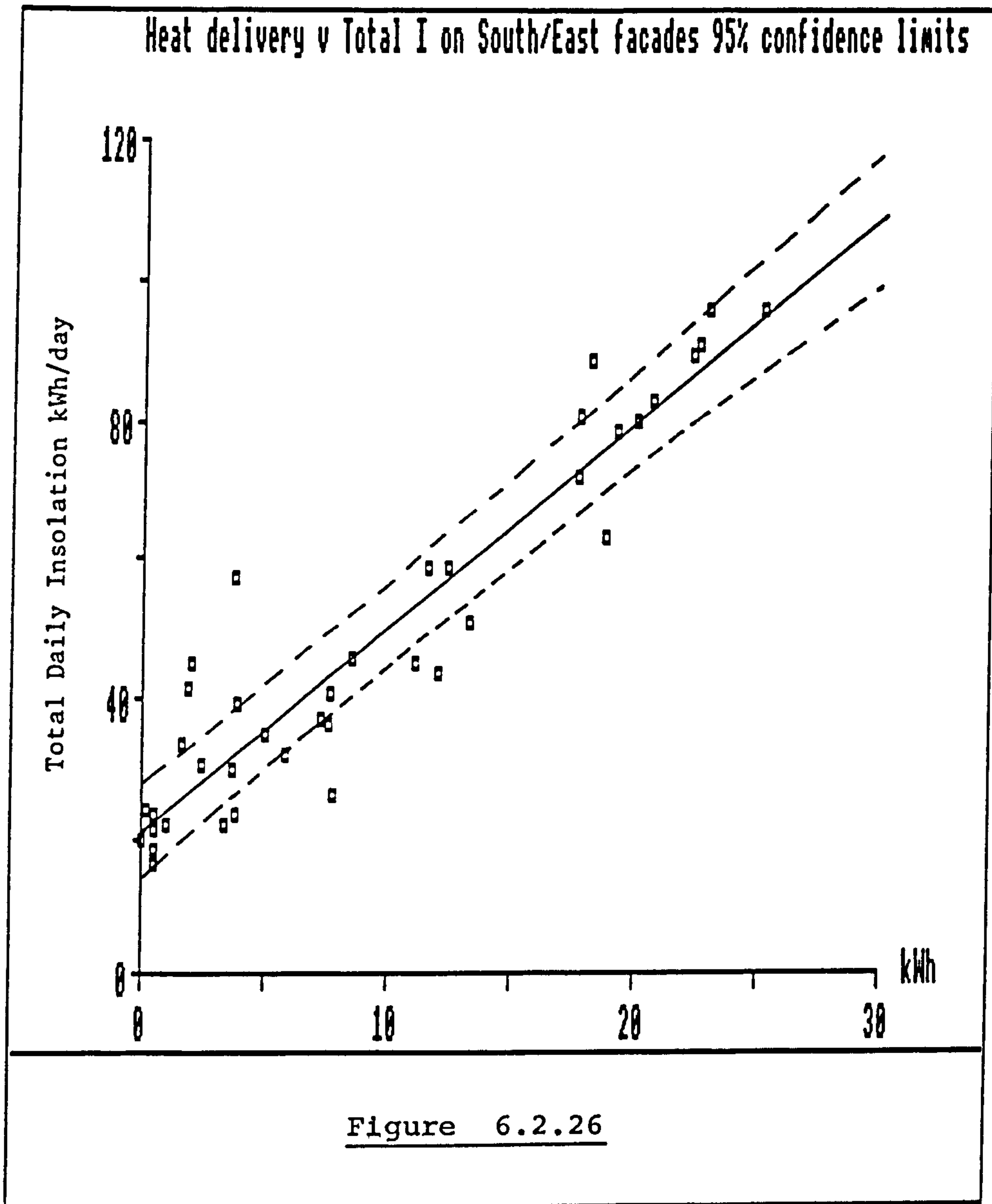
Collector area on east facade = 28m²
Collector area on south facade = 24m²

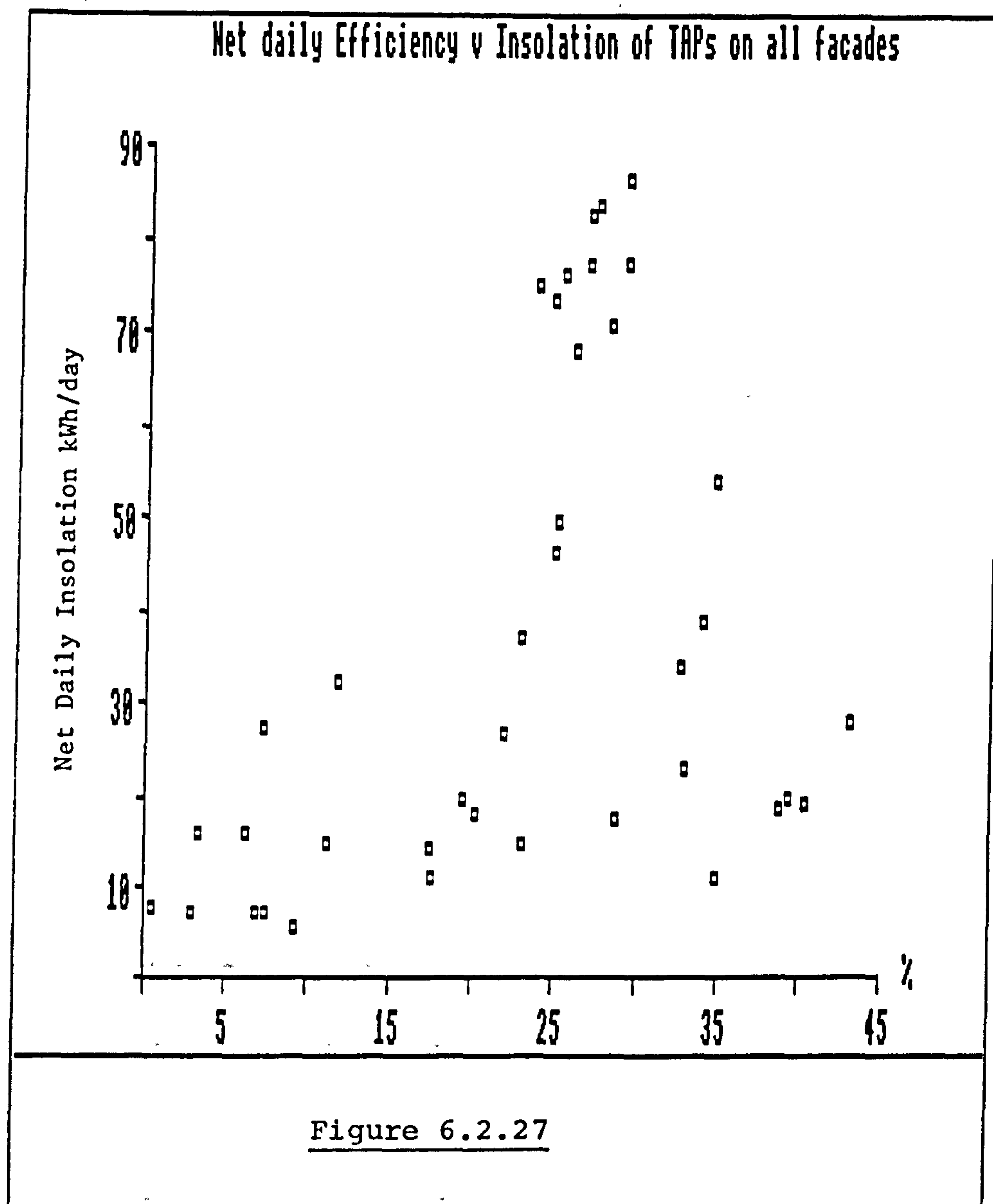
anomalies were less prevalent with the data from the south facade as can be seen in Fig. 6.2.25, where a greater proportion of the data was higher than the threshold level, (correlation coefficient = 0.9326). The 95% confidence limits show that the deviation beyond the best fit regression was only $\pm 6\%$. A more applicable correlation was obtained by deleting all values where there was no contribution from any of the TAPs on either facade, and combining the two data sets, Fig.6.2.26, to improve the correlation coefficient to 0.9391.

Net efficiencies of up to 43% with a mean of 22.7% were monitored for the period from 10th October until 20th December, i.e. only the levels of insolation, during the hours in which the TAP temperature differences were above the flow-initiation threshold were considered (Fig. 6.2.27). More realistic efficiencies, (30% maximum, 16.13% mean), were achieved when they were based on the total daily insolations (Fig. 6.2.28).

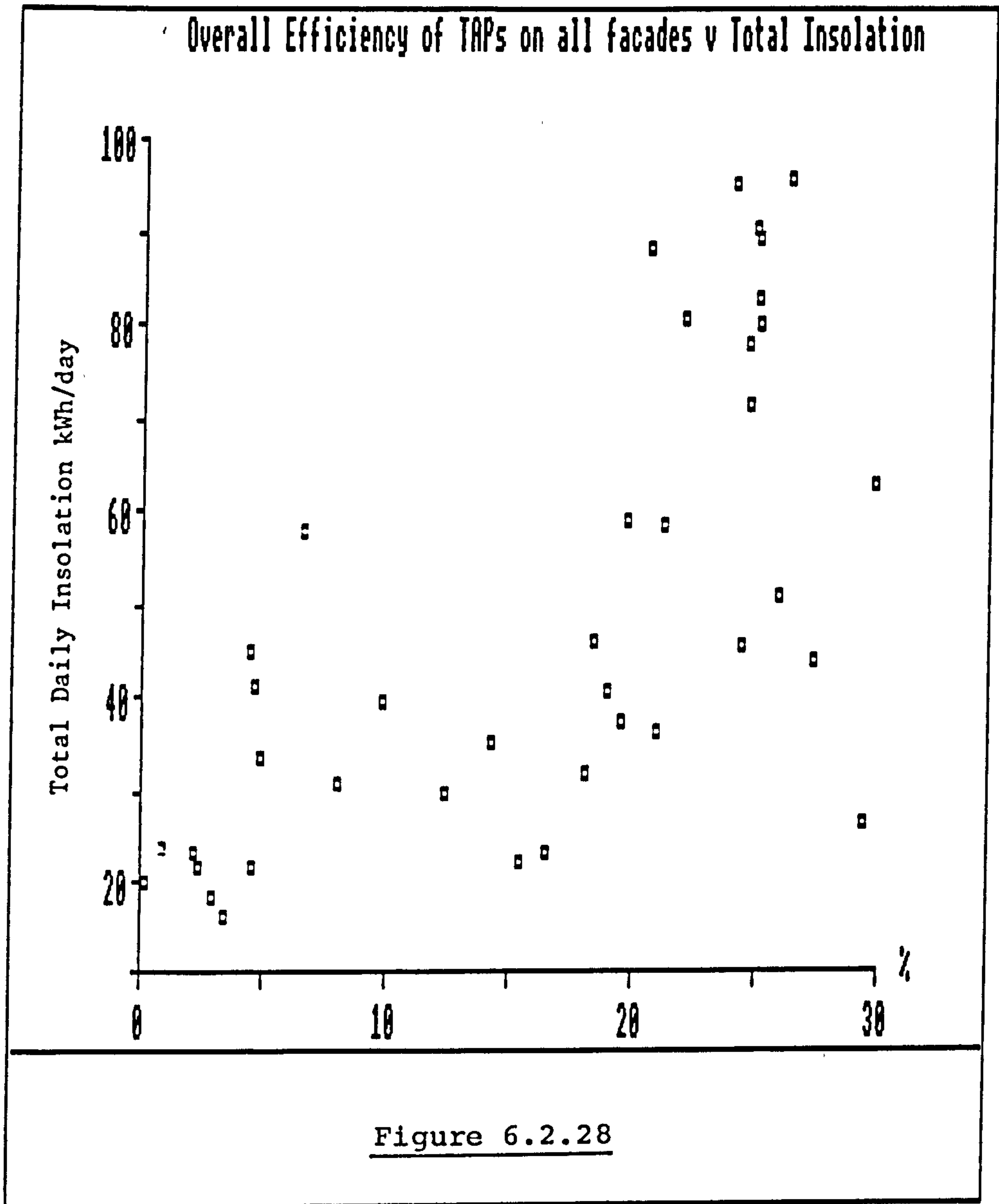


Collector area on east facade - 28m²
Collector area on south facade - 24m²





Collector area on east facade = 28m²
Collector area on south facade = 24m²



Collector area on east facade = 28m²
Collector area on south facade = 24m²

6.3 Applying Daily Correlation to Long-Term Data Sets

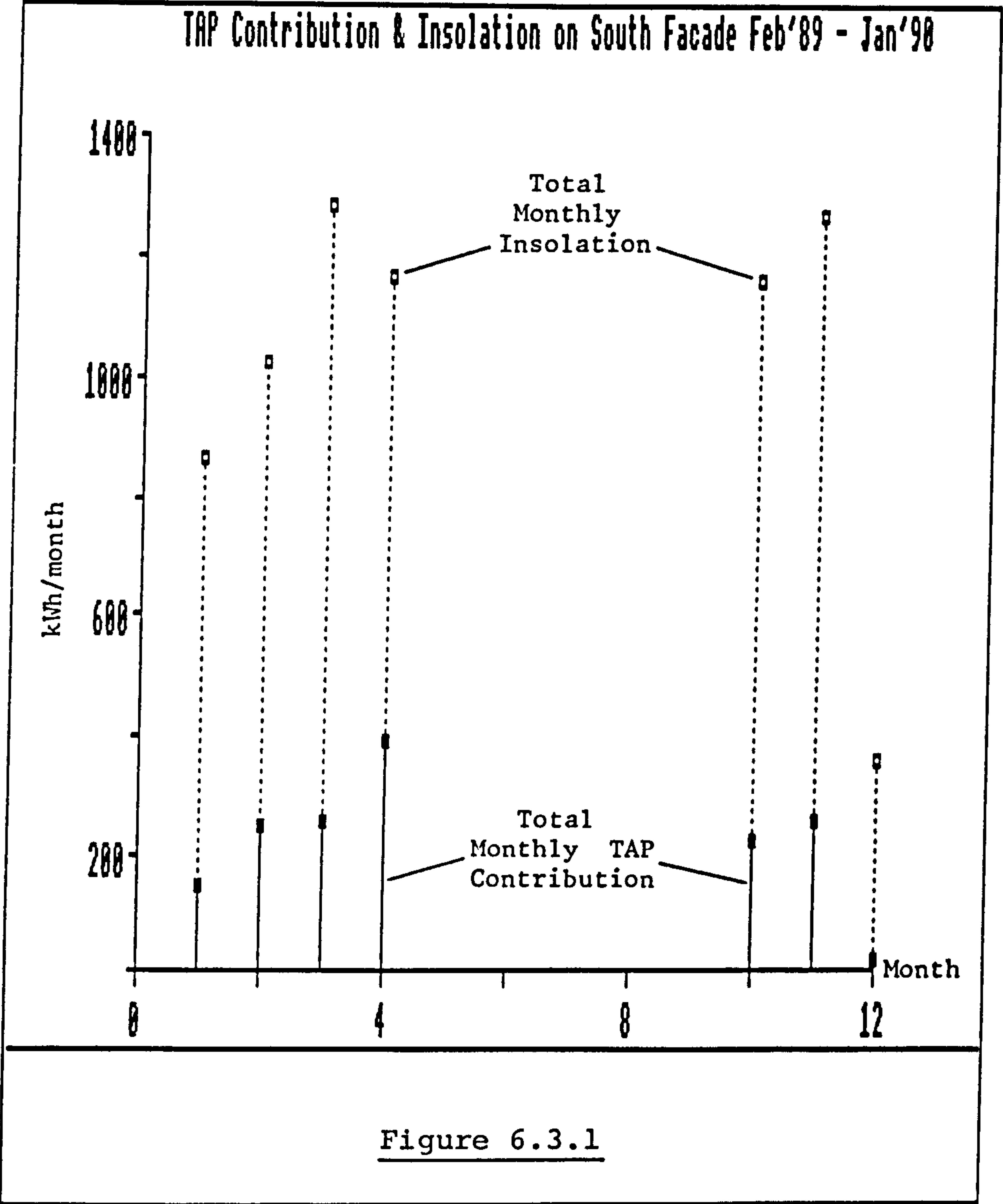
1) Analysis of annual monitored data

Examining all of the hourly temperature and insolation data over a period of 12 months would have been very time-consuming. Thus the relationship between total daily heat delivery and insolation was used to calculate the daily total heat delivery from the 1st February 1989 until the 31st January 1990. This greatly reduced the computational time when analysing such large data sets.

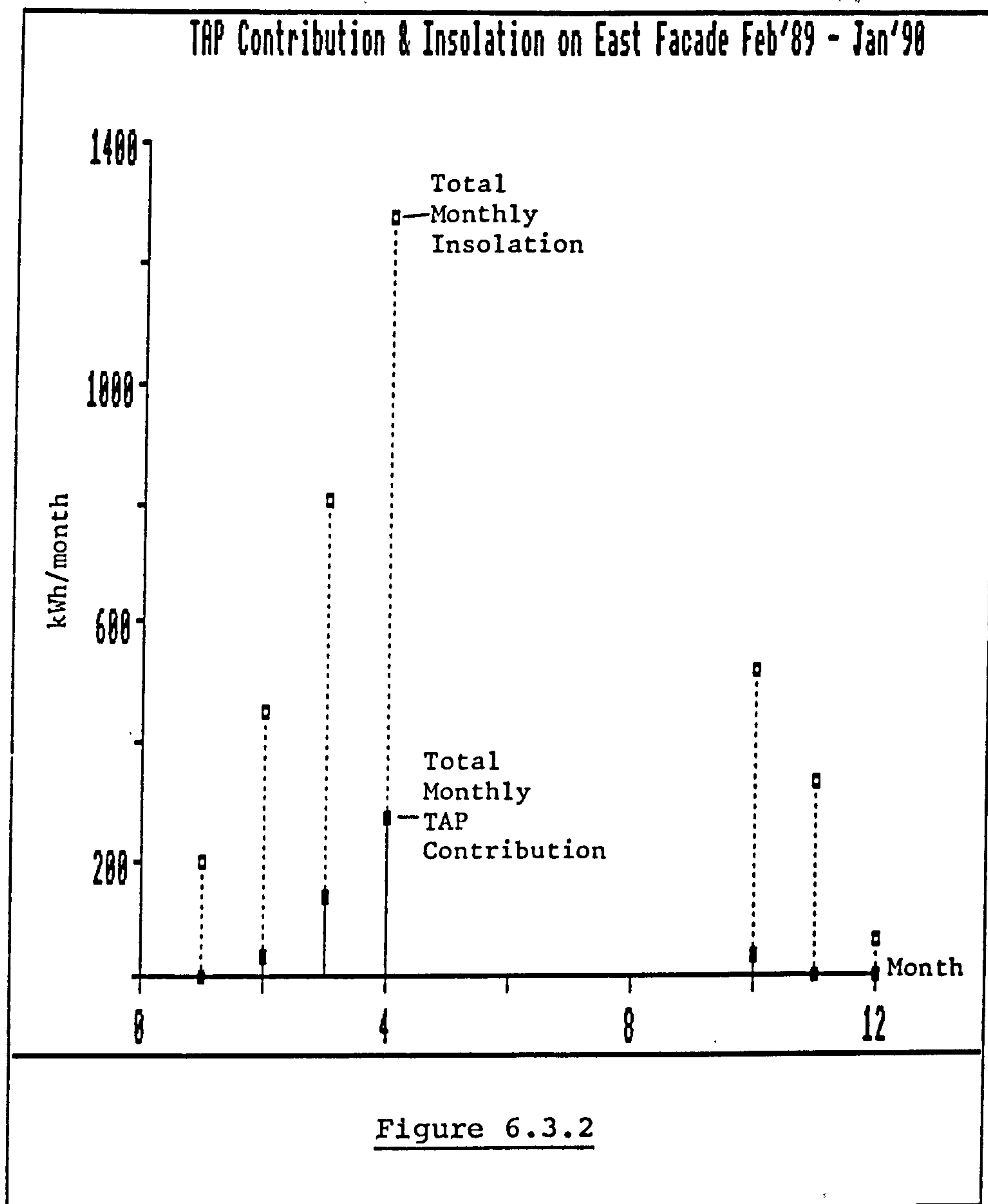
The total monthly heating contributions from the TAPs on both the south and east facades are shown in figures 6.3.1 & 6.3.2. These contributions were summed to give overall monthly efficiencies as shown in figure 6.3.3. Unfortunately the heat meter, which was monitoring the heating load for two adjacent classrooms on the south facade, malfunctioned in the early stages of the monitoring programme and it was deemed too expensive to replace.

The overall heating requirements of the whole school were several orders of magnitude greater than the heat output from the TAPs (figure 6.3.4). The measured heating load during the heating season for the period from 1st February 1989 until 31st January 1990 was 31.66 MWhrs. The contribution from all of the TAPs for the same period was 2049 kWhrs which produced a solar fraction of 0.06. The monthly solar fractions are shown in figure 6.3.5.

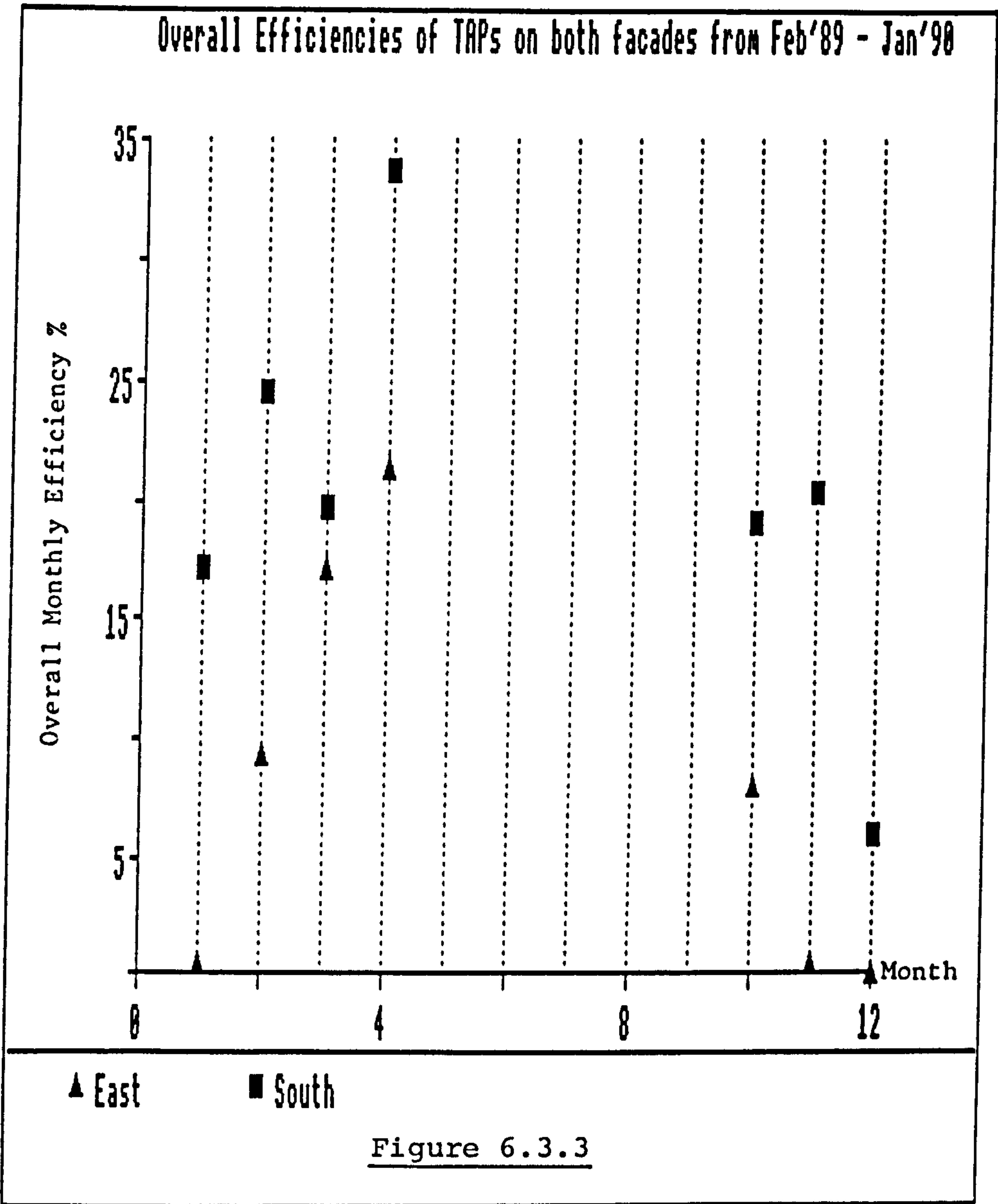
The auxiliary heating load could have been reduced considerably if the system did not continue to operate during the school holidays and at weekends. Figure 6.3.6 shows that there is little reduction in the rate of gas consumption during the Christmas break.

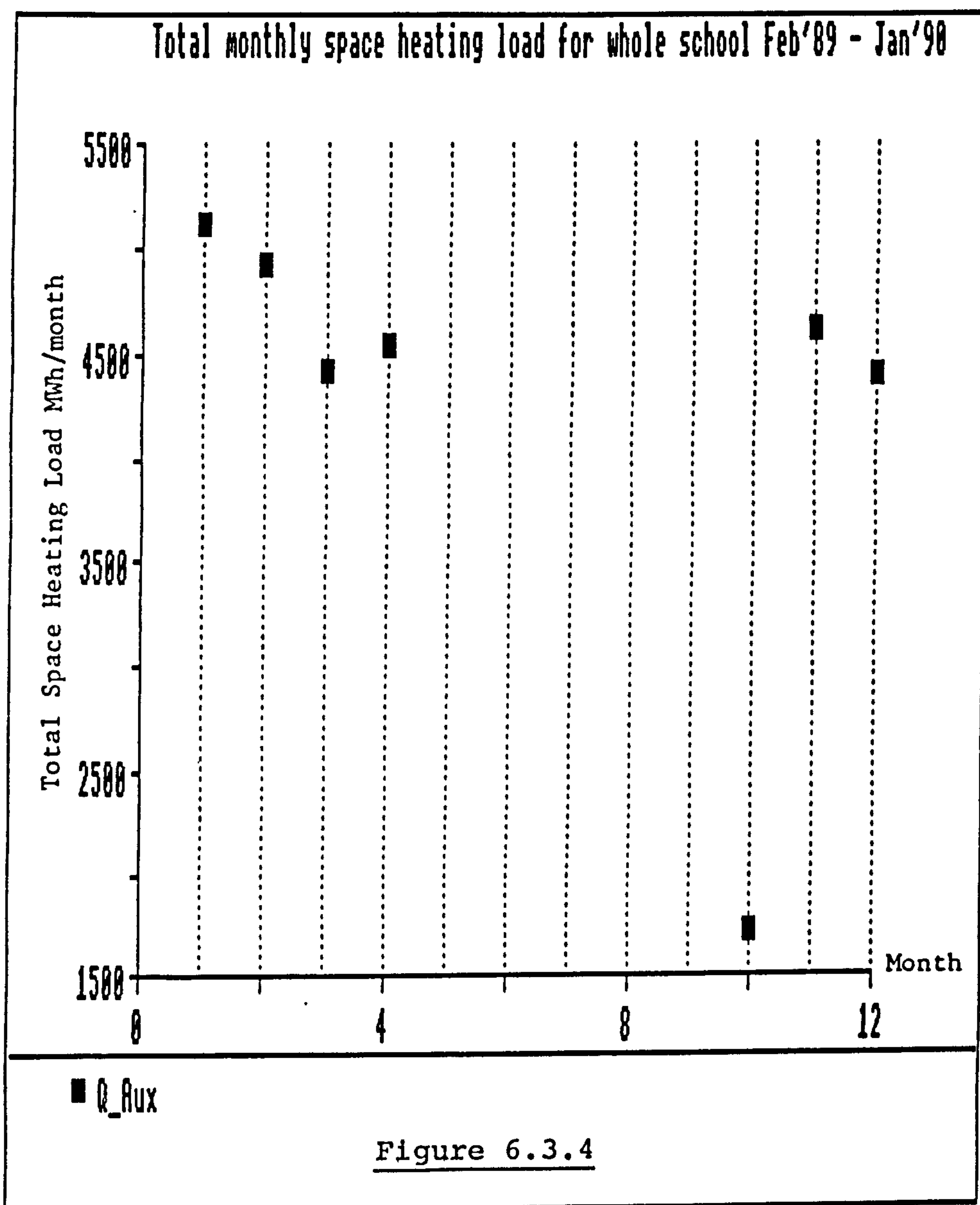


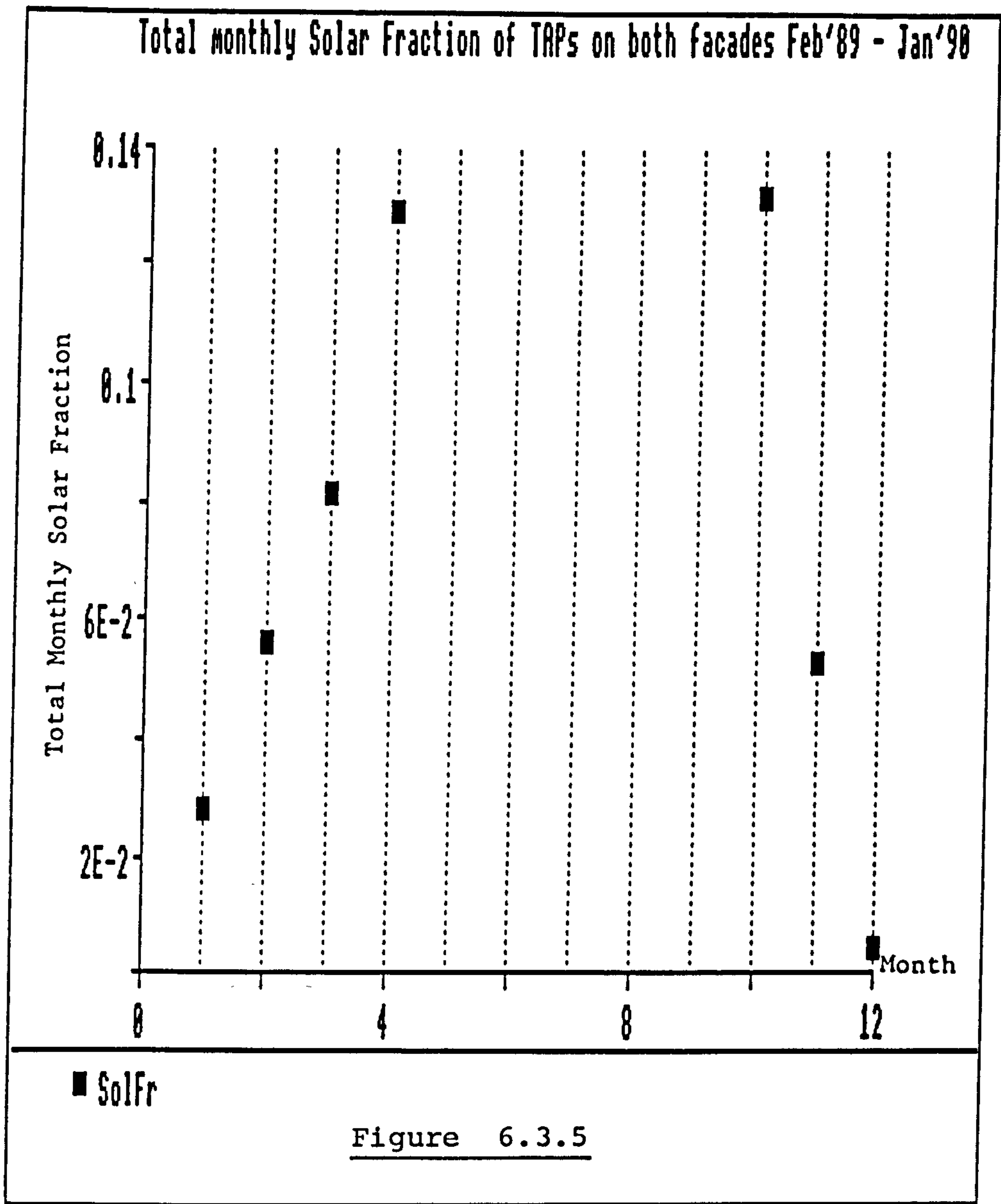
Collector area on east facade = 28m²
Collector area on south facade = 24m²

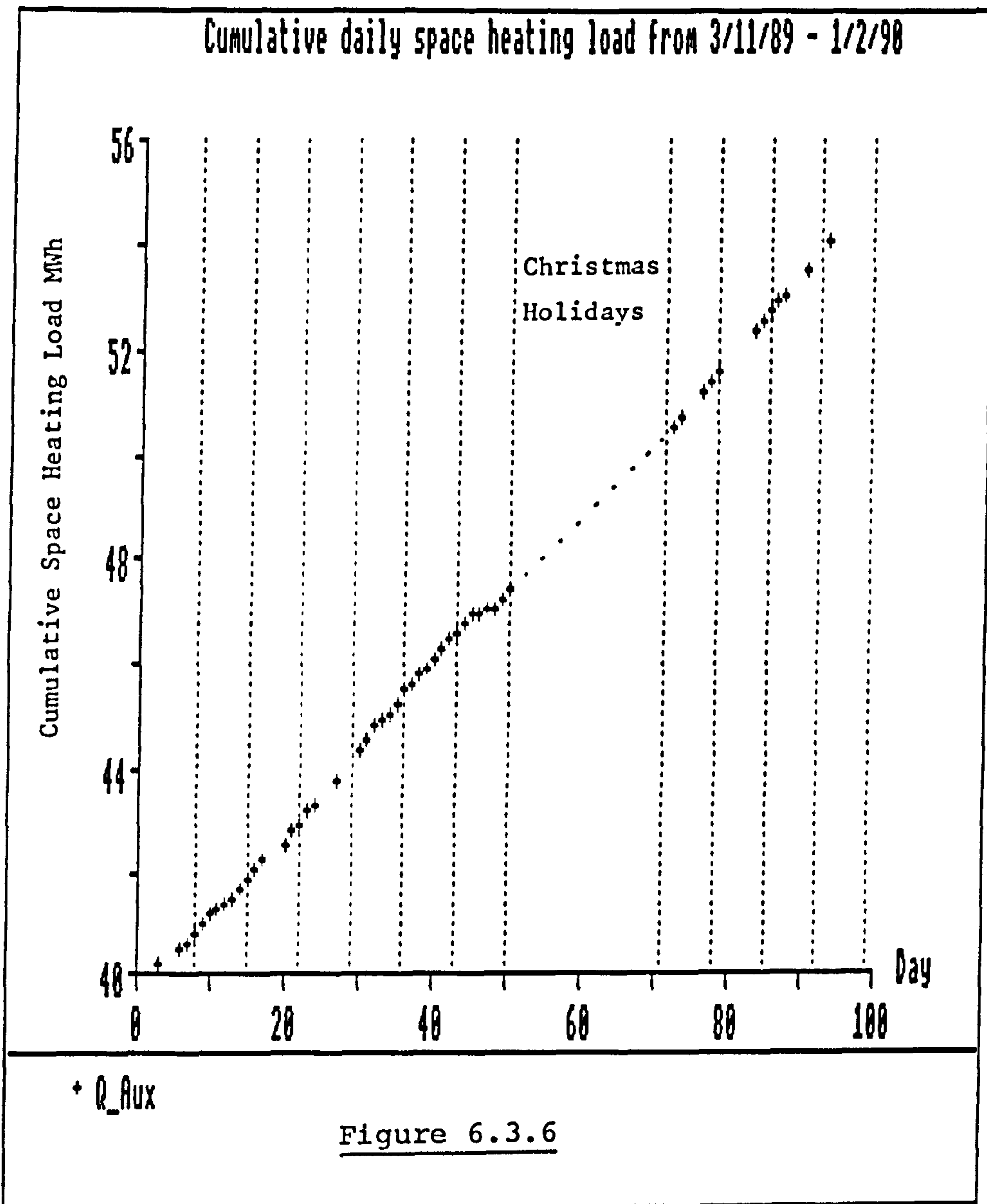


Collector area on east facade = 28m²
Collector area on south facade = 24m²









6.4 Long-Term Correlation of Indirect Thermosyphon Solar Water Heating System Performance

ii) Correlating the daily performance

Numerous detailed studies have been conducted (6.4.1 - 6.4.5) of factors affecting the performances of thermosyphon solar-energy water-heaters. Detailed dynamic hour-by-hour simulation models require large amounts of computer time and hourly meteorological data and do not therefore constitute a practical means of determining *long-term* system performance. The identification of basic grouped parameters from which the thermal characteristics of the system can be determined using the minimum amount of data (either experimentally-measured or generated from numerical simulations) would provide a more viable approach to this problem. Such an approach for forced-circulation solar water heaters, namely the "f-chart", upon which a subsequent correlation for thermosyphon systems has been based (6.4.9), was pioneered by Klein et al (6.4.6). This analysis is derived from a basic heat balance on the system such as that shown in figure 6.4.1. The net change of internal energy (predominantly of the store) was assumed to be negligible, an assumption which becomes more valid as the period of integration increases (6.4.7). Thus the f-chart correlates monthly performance. The solar fraction for a forced-circulation system was found to be related to two main parameters X and Y defined by

$$X = A_c F_R U_L (T_{ref} - T_a) \Delta t / Q$$

and,

equation (6.4.1)

$$Y = A_c F_R (\tau \alpha) H / Q$$

Similar parameters were derived by Liu and Hill (6.4.8) but with the mean monthly water supply temperature as the reference temperature.

Initially the f-chart analysis as applied to pumped systems was not applicable directly to thermosyphon installations, as in the latter, the circulating fluid flow rate, and therefore the heat removal factor F_R , are not constant. A modification of the f-chart method to account for the variation of F_R with system configuration and operating conditions encountered in thermosyphon solar water heaters has been proposed by Malkin et al (6.4.9). The iterative algorithm employed is depicted in Table 6.4.1.

TABLE 6.4.1. F-CHART METHOD FOR THERMOSYPHON SOLAR-ENERGY WATER HEATERS

Step	Procedure
1	A mean monthly flow rate is assumed from which FR is calculated and an estimate of the solar fraction obtained using the conventional f-chart method.
2	From a correlation of mean store temperature against solar fraction (obtained using TRNSYS (6.4.10)) a mean monthly store temperature is determined.
3	The degree of stratification based on an analysis by Phillips and Dave (6.4.11). A mean monthly inlet temperature is then calculated from the mean store temperature.
4	The mean monthly outlet temperature is then determined thereby giving a complete estimate of the temperature variation around the system.
5	Using these temperatures the net buoyancy pressure is found and by equating this with the fluid frictional losses, a new estimate of the mean monthly flow rate is calculated.
6	The process is repeated using the most recent flow rate until the solar fraction calculated in step 1 converges to a constant value.

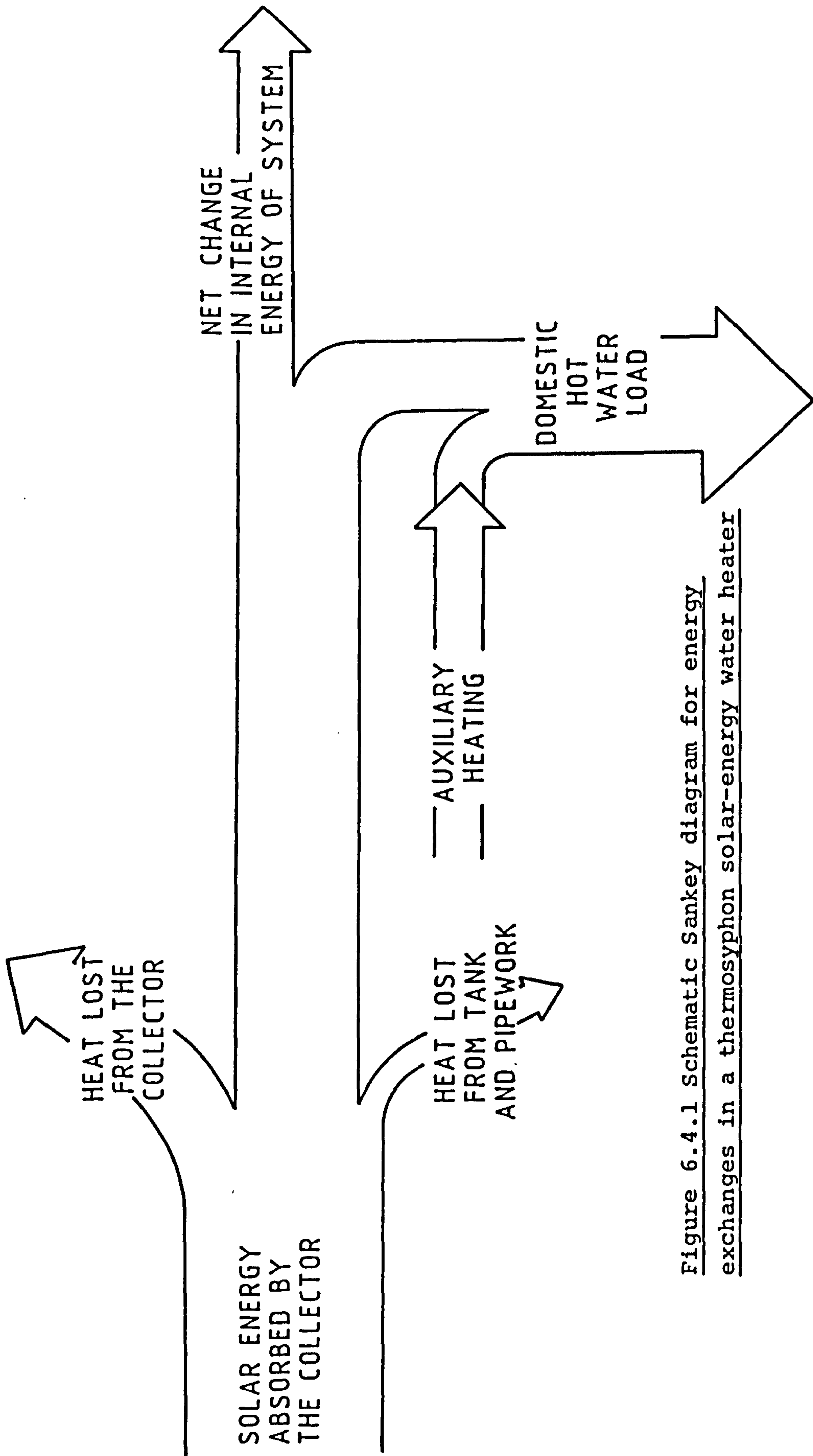


Figure 6.4.1 Schematic Sankey diagram for energy exchanges in a thermosyphon solar-energy water heater

A comparison between the annual solar fraction predicted using TRNSYS (in thermosyphonic mode) and the value calculated from the modified f-chart indicated agreement to within an RMS error of 2.6%.

Morrison and Sapsford (6.4.12) correlated the experimental results obtained from a number of representative thermosyphon solar-energy water-heaters using the non-linear relationship,

$$f = a(H/Q) + b(H/Q)^2 + c(T_m - T_a)/Q \quad \text{equation (6.4.2)}$$

The coefficients a, b and c were determined by a least squares correlation of the monthly average data for each system. In order to reduce scatter of the data due to residual energy in the store, mean values of H and Q evaluated over a minimum period of integration of ten days was required to produce a characteristic curve. The curve produced by equation 6.4.2 is only representative of the performance of the individual system under test and the results cannot be extrapolated to predict the performance of other systems. As with the f-chart correlations, implicit in this analysis is the assumption that any water consumed is heated in part by the solar hot water system. This is not always the case, as systems are sometimes installed (6.4.13) whereby in addition to the conventional hot and cold taps, a 'third tap' is installed with which water can be withdrawn direct from the solar store.

A method of determining the performance of thermosyphon solar water heaters based on predicted or measured daily rather than monthly data, (6.4.14), has the advantage that the amount of data required to characterise the thermal performance of the system is greatly reduced. The system is characterised by the theoretical diurnal variation of the steady-state mean store temperature that would exist if the thermal capacitance of the water store was negligible and a sinusoidal insolation pattern is assumed. The actual mean store temperature only corresponds to the steady-state value when the minimum or maximum diurnal temperatures occur towards (ideally) the onset and end respectively of the insolation period. The mean store temperature variation is then approximated by fitting a simple sinusoidal function such that the characteristic steady-state curve is intercepted at the time of day at which the minimum and maximum temperatures occur. The times of day at which minima and maxima occur are also expressed in a graphical form as functions of basic system parameters. The empirical

analysis used to produce these correlation charts for thermosyphon systems was similar to that used by Close (6.4.1) and therefore suffers from the same limitations - primarily that accurate prediction of the mean store temperature depends on the assumption of identical mean temperatures of the store and the collector. In estimating the amount of heat capable of being delivered by the system, the draw-off of solar water from the store is assumed to take place at the end of the insolation period.

The analysis proposed is aimed at identifying parameters suitable for the correlation of thermosyphon solar water-heater performances based on exogenous component dimensions, thermal characteristics, and mean diurnal meteorological data. Parameters appropriate to both 'third tap' and pre-heat modes of heat delivery have been selected.

ii) Analysis of the system performance

A transient heat balance was carried out on a generic solar water heater system (see figure 6.4.2). By making some basic simplifying assumptions relevant to natural circulation systems, a first order differential equation was obtained from which an explicit algebraic solution could be found. A similar analysis, (6.4.15), has been used for predicting diurnal system performance rather than to establish correlating factors. In the present analysis, the differential equation is solved in its original dimensional form although the ensuing grouped parameters are dimensionless.

The following assumptions were made.

- a) The collector and storage tank both have the same mean temperatures. This assumption is based on experimental observations, (6.4.1), for multiple-pass thermosyphon solar hot water systems.
- b) The solar radiation intensity and ambient temperature are assumed to remain invariant over the day at their respective mean measured values. The insolation was originally included in the analysis (6.4.16) as a sinusoidal function of time. The resulting solution gave basically identical dimensionless groups although this form of the analysis yielded a more complex relationship between the groups which was less amenable to correlation.

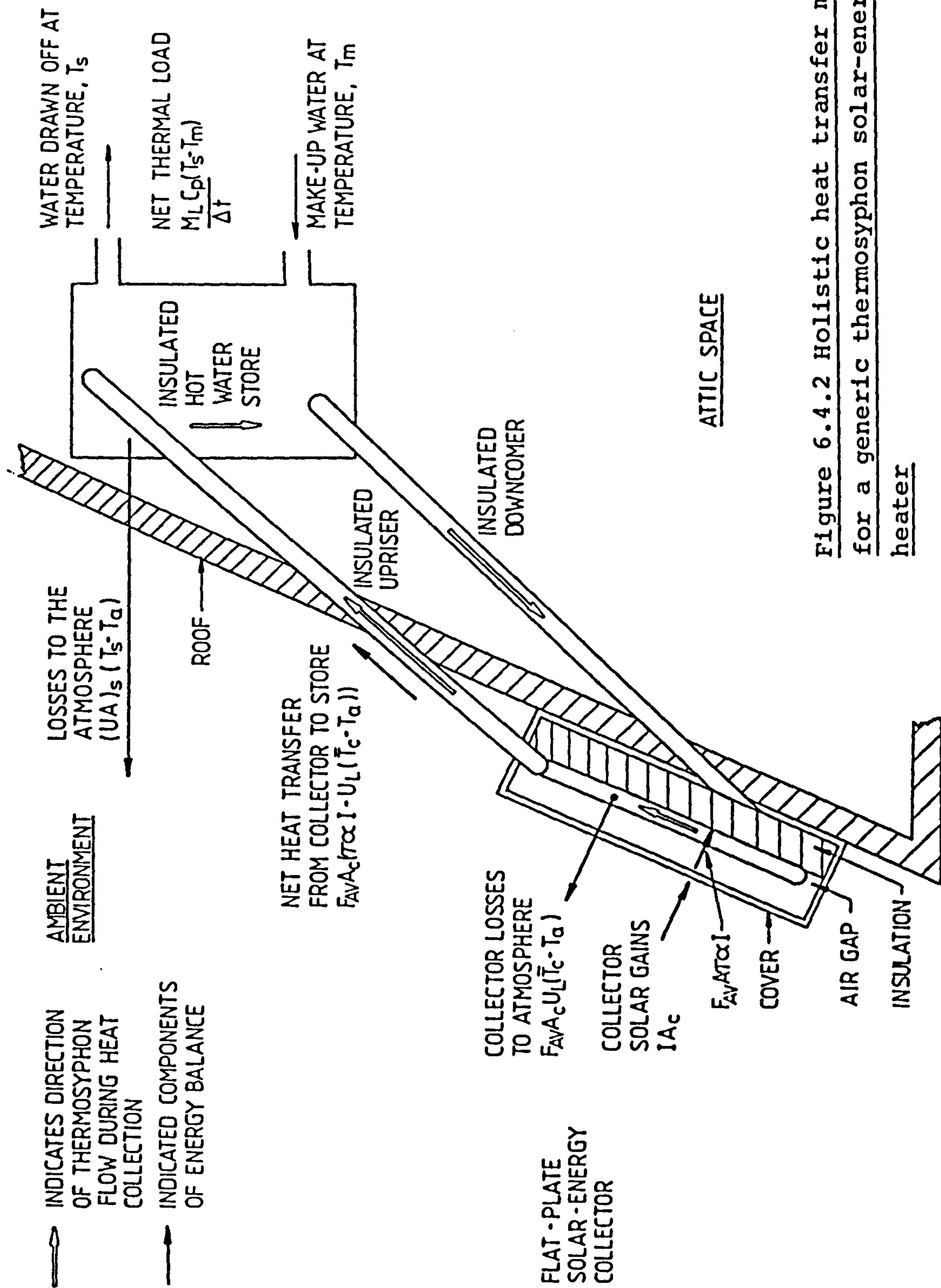


Figure 6.4.2 Holistic heat transfer mechanisms for a generic thermosyphon solar-energy water heater

- c) The total draw-off of water from the solar store is assumed to take place as a single event at the end of the insolation period. By introducing the mass of water drawn off as an independent parameter, the analysis is as applicable to 'third tap' as to preheat systems. A more comprehensive analysis (6.4.16) in which the water was assumed be withdrawn continuously during the insolation period was originally applied, but for the same reasons as mentioned in assumption (ii), was abandoned in favour of the simpler analysis.
- d) Water is drawn off at the mean store temperature and replenished at the mains water supply temperature.
- e) Tank and pipe losses are considered negligible. In the development of the analysis, these losses were included initially. However, observations of night losses from the storage tank under conditions of no water draw-off showed that in addition to these losses being small, a simple heat loss coefficient to account for losses between the storage water and outside ambient temperature was difficult to establish. This was attributed to the large intervening air space in the loft, the temperature of which would depend on a wide range of factors such as solar gains over the day and accumulated heat from the conventional space heating system.
- f) The store is initially at the mains water supply temperature at the onset of the insolation period

An instantaneous heat balance on the system gives with assumption (i)

$$M_s C_p \frac{dT_s}{dt} = F_{av} A_c \left((\tau \alpha)_s \frac{H}{\Delta t} - U_L (T_s - T_a) \right) \quad \text{equation (6.4.3)}$$

Using assumptions (ii) and (v), equation 6.4.3 becomes, after making the substitution $\theta = T_s - T_a$ and rearranging,

$$\frac{d\theta}{dt} + \frac{F_{av} A_c U_L \theta}{M_s C_p} = \frac{F_{av} A_c (\tau \alpha)_s H}{M_s C_p \Delta t} \quad \text{equation (6.4.4)}$$

The solution to equation (6.4.4) using assumption (vi) as a boundary condition gives,

$$\theta - \theta_o = \left[\frac{F_{av} A_c (\tau \alpha)_s H - F_{av} A_c U_L \Delta t (T_m - T_a)}{F_{av} A_c U_L \Delta t} \right] \left(1 - e^{-\left[\frac{F_{av} A_c U_L}{M_s C_p} \right] t} \right)$$

equation (6.4.5)

The difference in the mean store temperature between the beginning and the end of the insolation period is therefore

$$\theta_s - \theta_o = \left[\frac{F_{av} A_c (\tau \alpha)_s H - F_{av} A_c U_L \Delta t (T_m - T_a)}{F_{av} A_c U_L \Delta t} \right] \left(1 - e^{-\left[\frac{F_{av} A_c U_L \Delta t}{M_s C_p} \right]} \right)$$

equation (6.4.6)

From assumptions (iii) and (iv), the solar fraction can be expressed as,

$$f = \frac{M_L C_p (\theta_s - \theta_o)}{Q} \quad \text{equation (6.4.7)}$$

Substituting equation 6.4.6 into equation 6.4.7 and rearranging gives,

$$\frac{f Q}{M_s C_p (T_m - T_a) \left(1 - e^{-\left[\frac{F_{av} A_c U_L \Delta t}{M_s C_p} \right]} \right)} = \left[\frac{F_{av} A_c (\tau \alpha)_s H}{F_{av} A_c U_L \Delta t (T_m - T_a)} \right] - 1$$

equation (6.4.8)

from which three dimensionless groups can be defined as,

$$X = \frac{f Q}{M_L C_p (T_a - T_m)} = \frac{\text{TOTAL HEAT DELIVERED BY SYSTEM}}{\text{CHANGE IN INTERNAL ENERGY OF WATER DRAWN-OFF WHEN RAISED FROM MAINS TO AMBIENT TEMPERATURE}}$$

equation (6.4.9)

$$Y = \frac{F_{av} A_c (\tau \alpha)_s H}{M_s C_p (T_a - T_m)} = \frac{\text{TOTAL DAILY INSOLATION ABSORBED}}{\text{CHANGE IN INTERNAL ENERGY OF STORE WHEN RAISED FROM MAINS TO AMBIENT TEMPERATURE}}$$

equation (6.4.10)

$$Z = \frac{F_{av} A_c U_L \Delta t}{M_s C_p} = \frac{\text{TOTAL COLLECTOR HEAT LOSS COEFFICIENT}}{\text{HEAT CAPACITY OF STORE}}$$

equation (6.4.11)

So in terms of the dimensionless groups defined, equation 6.4.8 becomes,

$$\frac{X}{1 - e^{-Z}} = \frac{Y}{Z} + 1 \quad \text{equation (6.4.12)}$$

Equation 6.4.12 therefore indicates a linear relationship between $X/(1-e^{-Z})$ and Y/Z .

iii) Applying the Analysis to the Experimental Results

Data was collected from the monitoring of the indirect thermosyphon solar-energy water-heater for a total of 250 days. The values of the mean ambient and mains water supply temperature and the total insolation and mass of solar water drawn off from the store were calculated from the available data in order to determine the daily values of the dimensionless groups X , Y and Z defined by equations 6.4.9, 6.4.10 and 6.4.11 respectively. The daily solar fraction, f , was determined from,

$$f = \frac{\sum M_L C_p (\bar{T}_s - T_m)}{Q} \quad \text{equation (6.4.13)}$$

where $\bar{T}_s$ is the mean temperature of all the axially-placed thermocouples in the store contained within a distance from the top of the store corresponding to the volume of the water withdrawn. The duration of the insolation period, Δt , was calculated using the method outlined by Duffie and Beckman (6.1.1).

A plot of $X/(1-e^{-Z})$ against Y/Z for the 250 days monitored, is shown in figure 6.4.3. A strongly linear relationship is observed with a correlation coefficient of 0.96. The scatter of the data points about the origin is due to slight seasonal variations in the functional relationship between the dimensionless parameters. This can be seen in figure 6.4.4. for data monitored over the month of September where the scatter about the origin is minimal. The correlation coefficient for this particular month is 0.99 and is typical of the values obtained for

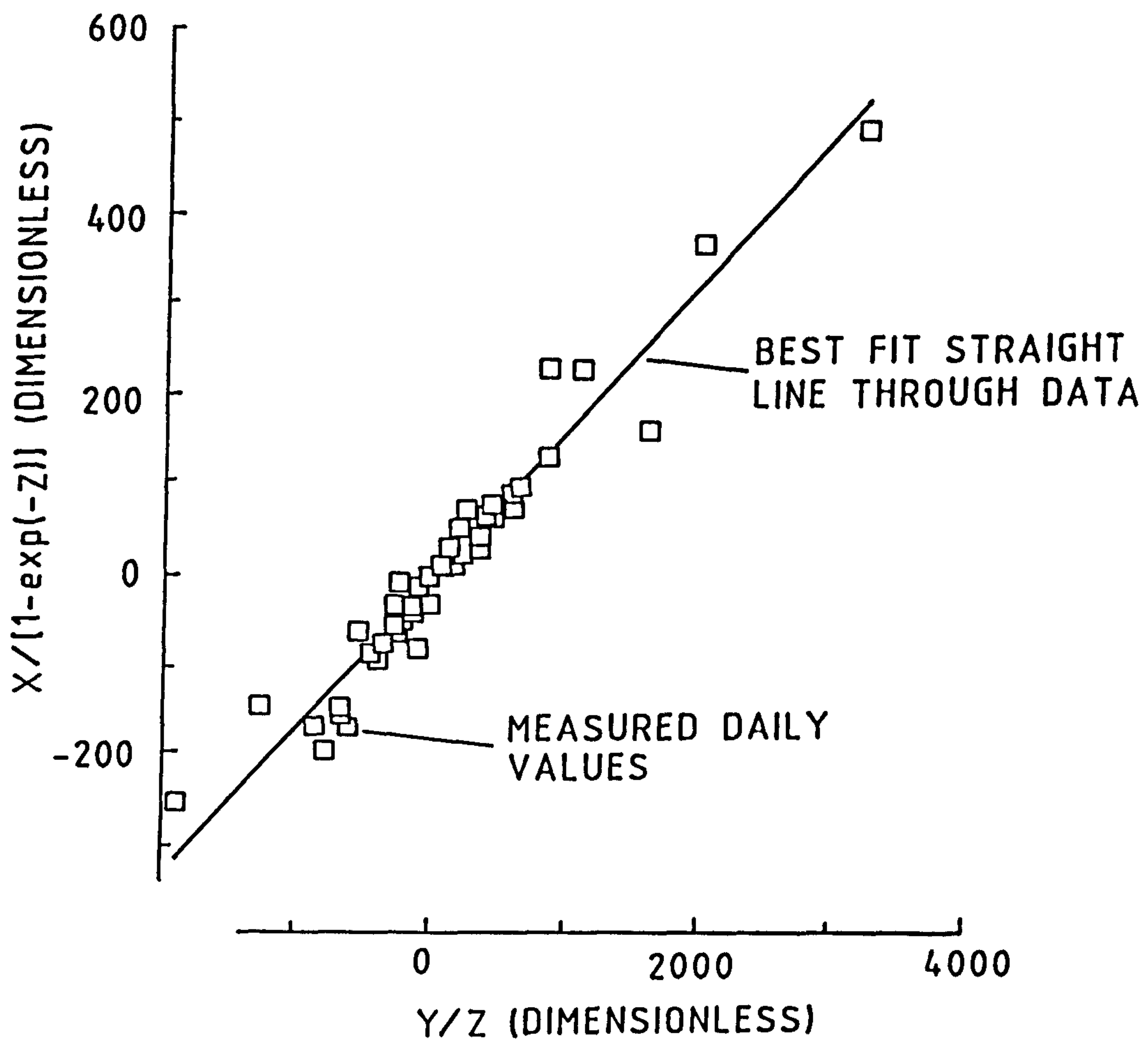


Figure 6.4.3 $X/(1-\exp(-z))$ and Y/Z correlated over a period of 250 days for the monitored indirect thermosyphon solar-energy water heater

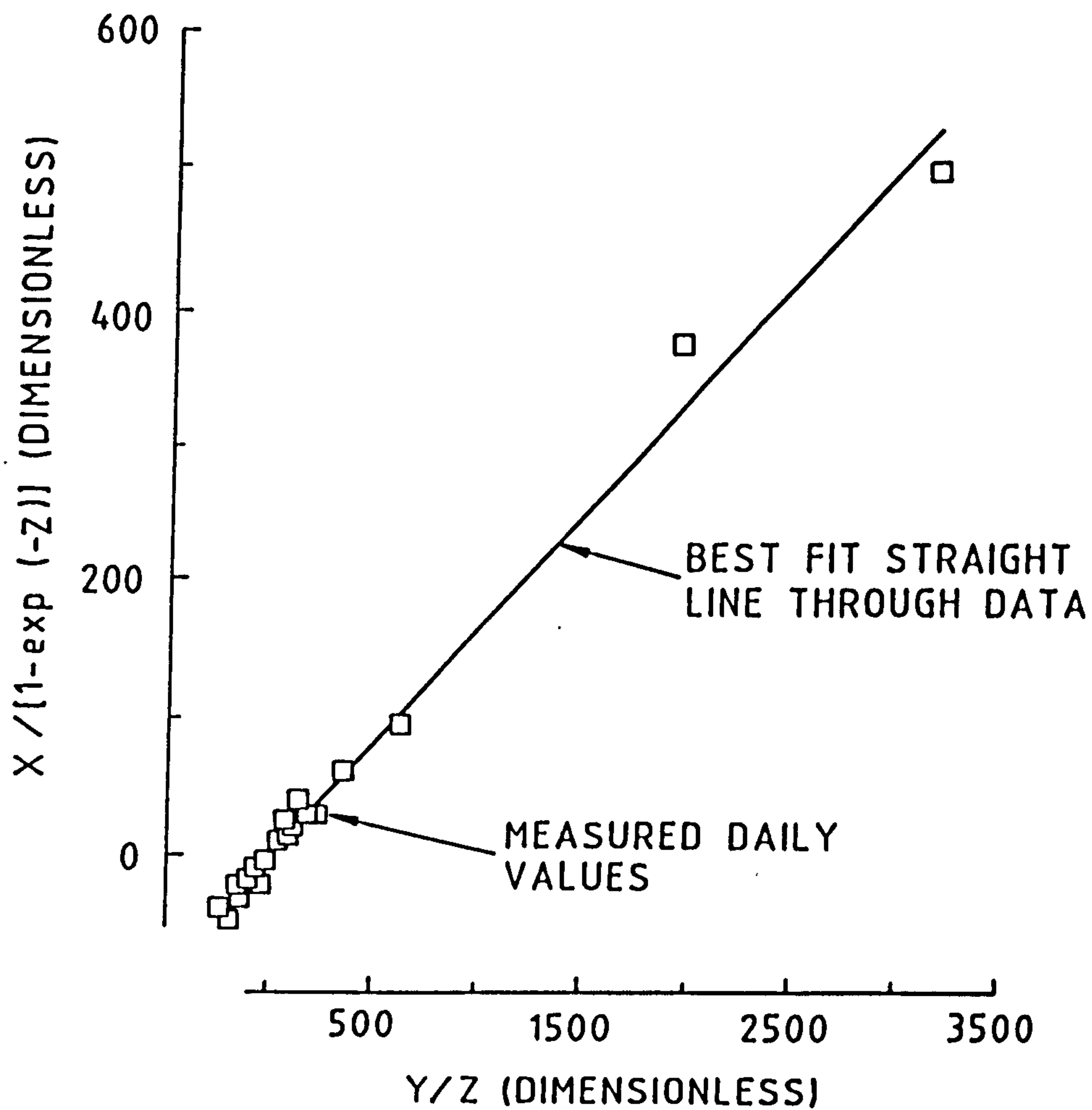


Figure 6.4.4 $X/(1-\exp(-z))$ and Y/Z over the month of September 1985 for the monitored indirect thermosyphon solar-energy water heater

the remaining individual months. A table of the equations representing the best straight lines through the daily data divided into months is given in table 6.4.2. There is evidence of gradual seasonal variations in the gradients of these lines. If a series of daily measured values were to be correlated in order to establish a single mean characteristic thermal performance curve similar to that shown in figure 6.4.3, for a particular system, a wide range of values of X, Y and Z would have to be correlated. In terms of a test method for thermosyphon solar-energy water-heaters, a possible method of obtaining such a curve in a short period of time would be to perform a number of daily outdoor tests during which the temperature of the mains supply water could be raised artificially in order to vary the values of X and Y over a suitably large range.

iv) Using the correlation as a design method

Inspection of the dimensionless groups X, Y and Z indicate that the linear relationship (shown graphically in figure 6.4.3) between the grouped parameters obtained using data measured from the particular thermosyphon solar-energy water-heater described, is applicable to other systems. However, in addition to the exogeneous parameters in the dimensionless groups such namely $F_{av}(\tau\alpha)_s$, $F_{av}U_L$, A_s and M_s which define the system configuration and thermal characteristics, the performances of buoyancy-driven systems also depend on other factors such as the location of the store relative to the collector. The influence of these other factors may be encapsulated in the relationship between the store and collector temperatures. An initial investigation indicated a constant temperature difference between the daily mean collector (T_c) and store (T_s) temperature over the insolation period. Figure 6.4.5 shows a plot of the daily T_c against T_s for the month of August indicating a linear relationship. The best straight line fit through the data gave,

$$T_c = 1.00T_s - 1.41 \quad \text{equation (6.4.14)}$$

with a correlation coefficient of 0.97. Rearranging equation 6.4.14 gives

$$T_s - T_c = 1.41 ; \text{ Thus more generally } T_s - T_c = \beta \quad \text{equation (6.4.15)}$$

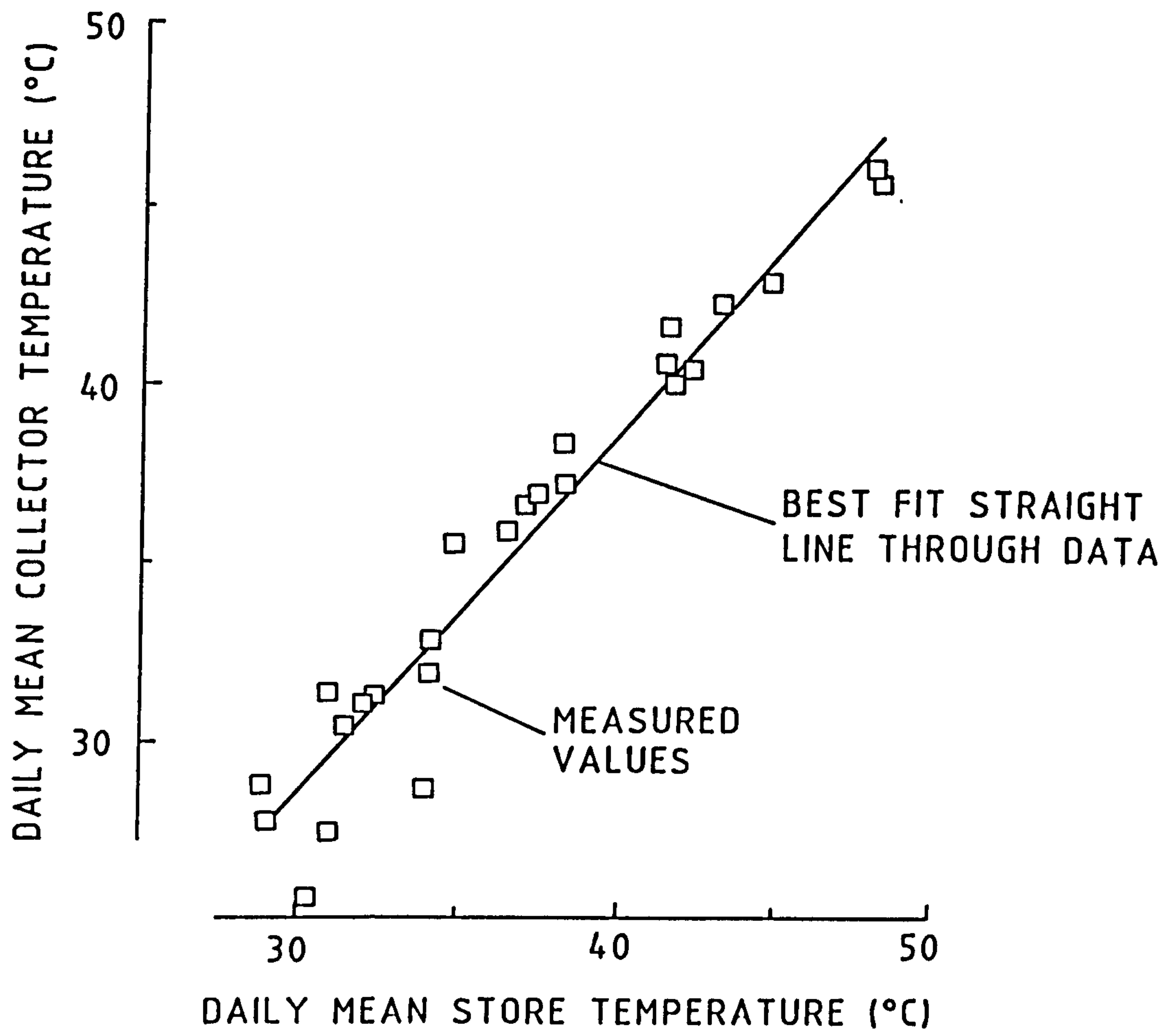


Figure 6.4.5 Correlation of the mean collector and hot-water store temperatures, each averaged over single periods of insolation

Introducing into the analysis such a constant temperature difference Δt , between the store and collector results in the dimensionless group Y being redefined as,

$$Y = \frac{F_{av} A_c ((\tau\alpha)_a H + U_L \beta \Delta t)}{M_s C_p (T_s - T_m)} \quad \text{equation (6.4.16)}$$

Using this modified value of Y , would result in a correlation with a potentially more-universal application potentially. The performance of any system can then be determined from several daily measurements of β . Experimentally determined values of β , would enable X , Z and the modified Y parameter to be used in predicting the daily performance of the system under the applied conditions using a universal correlation. Alternatively, daily values of could be generated using a high-level simulation model (6.4.5) and correlated against the height of the store relative to the collector.

TABLE 6.4.2 Equations of the best straight lines through
daily data on a month by month basis

MONTH	YEAR	SLOPE	INTERCEPT
OCTOBER	1985	0.21	-0.80
NOVEMBER	1985	0.25	0.34
DECEMBER	1985	0.40	0.40
JANUARY	1986	0.22	-0.88
FEBRUARY	1986	0.22	-0.25
MARCH	1986	0.20	-2.02
APRIL	1986	0.16	-5.07
MAY	1986	0.12	-6.10
JUNE	1986	0.12	-3.29
JULY	1986	0.13	4.99
AUGUST	1986	0.20	0.49
SEPTEMBER	1986	0.17	0.53
OCTOBER	1986	0.22	-3.21

v) Conclusion

An analysis has been developed enabling the long-term monitored performance of an indirectly-heated thermosyphon solar-energy water-heater to be correlated, on a daily basis, with the thermal demands made on the system and the prevalent meteorological conditions. The correlation exhibits a high degree of linearity over a wide range of climatic conditions, and draw-off patterns. Some seasonal variation of the data from the annual curve is observed.

The following areas of study require further investigation.

- a) The extent to which the resulting correlation can be made applicable to systems with store capacities and collector characteristics which differ from the particular system tested has to be determined.
- b) The effect of the height of the store above the collector on the correlation.
- c) A wider range of climatic conditions is required to establish the limits if any to which a linear relationship exists between the grouped parameters.

6.5 Summary of System Performances

i) Roof-space solar-energy collectors

As the glazed loft spaces had little or no means of storing daytime solar gains, the primary influence upon the space-heating contribution from the RSC's was the buildings' occupancy patterns. The Beneficial Operation Index, (BOI), was a reliable indicator of occupancy patterns within the insolation period. Dwellings with BOI of between 0% and 99% exhibited efficiencies of 0% to 65%, (with mean efficiencies of 10% - 15% in the majority of dwellings with BOI of less than 25%), for the heating season up to 31st January 1990. The greatest monthly contributions from the five selected RSC dwellings occurred in December 1989, where the individual BOI, and consequently the auxiliary space-heating demands were at their greatest. The maximum Solar Heating Fractions, (SHF), were also dependent upon the BOI of each dwelling with a maximum SHF of 0.2 (20%). One house in particular, with a BOI of almost unity, consistently supplemented the space-heating demands to a greater degree than any other house.

ii) Thermosyphoning-air-panels

The consistent occupancy pattern of a school was more compatible with the transient performance characteristics of the TAP's. Unfortunately the sub-optimally designed collectors only produced maximum monthly efficiencies of 34%. The total annual space-heating contribution from all of the TAP's was 2049 kWh to give an annual solar fraction of 0.06 (6%).

iii) Thermosyphon solar-energy water heaters

The maximum daily solar fractions attained by the three thermosyphon solar water heaters were 0.92, 0.57, and 0.68. However these relatively high daily solar fractions included stored solar heat from the previous day(s). A more representative indication of their performance were the monthly values of this performance index. The maximum monthly solar fractions of 0.28 0.29 & 0.42 were commensurate with the corresponding efficiencies of 15%, 18%, & 22%. "Controlled" solar-heated water consumption profiles in two of the dwellings

increased the monthly solar fractions to 0.4 & 0.46 for houses No.s 7 and 9. The remaining dwelling, (the only one to have sufficient data to enable annual calculations to be made), the manual contribution of 417 kWh to the water heating requirements was recorded, with a corresponding annual solar fraction of 0.17, over the period from September 1986 to September 1987.

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CHAPTER SEVEN
PRACTICAL AND ECONOMIC CONSIDERATIONS

7.1 Practical and Economic Considerations When Constructing RSC's

i) Problems during installation

A number of problems were identified after the original installation of the warm-air heating system and the sensors had been completed.

- a) Warm air is circulated around the dwelling to each room via insulated 150mm aluminium ducts. In order to minimise occupant discomfort, uniform air velocity from these ducts would normally have been accomplished by adjusting a series of dampers and grilles. This task had not, however, been undertaken prior to occupancy, resulting in some unusual temperature distributions throughout each dwelling. In the majority of cases the heating systems were not affected significantly, however, in some cases there were some "uncomfortable" temperature stratifications throughout the buildings concerned. Where possible this was rectified before the heating season had begun in October 1989.
- b) When the loft space in each of the Roof-Space Collectors was being cleaned, the building paper which was used to line the floor of the RSC, (and cover the dust-laden insulant), was found to be in a very brittle condition. Further experimental analysis upon smaller samples of the paper showed that they failed mechanically when exposed to prolonged thermal cycling between 70°C and normal ambient temperatures. (76°C was the maximum recorded temperature in the RSC). The uncovered Rockwool loft insulation allowed dust to be entrained into the heating system. In an attempt to alleviate this problem, and reduce the maximum RSC temperature during the summer months, a more durable building paper was selected. During accelerated testing this replacement building paper withstood continued thermal cycling between 0°C and 90°C without any loss of ductility or mechanical strength.
- c) The area of the original eaves ventilators were considerably below that which was specified. The minimum required ventilation area at the eaves of each RSC, (to avoid overheating during the summer months), was eventually achieved by the addition of a soffit ventilator between each of the RSC trusses in November 1989. This would prevent RSC temperatures from exceeding 60°C during the summer of 1990.

- d) The insolation on the plane of the glazing had not been measured so the results from the solar radiation measurements on the south facing vertical plane were used. The errors incurred when using the data on this plane are shown in Table 7.1.1.

Table 7.1.1 Correction applied to insolation readings

Month	Error when using insolation on vertical plane (7.1.1)	Effects of inclination at 45° of pyranometers after calibration (7.1.2)
October	+14.5%	+1.0% - +2.0% at 45°
November	+2.7%	
December	-3.7%	
January	+3.5%	

All future measurements of insolation on the plane of the glazing will be taken from an appropriately inclined solar-radiation energy-sensor (Table 7.1.2) now installed at the on-site weather station.

Table 7.1.2 Solar energy sensor type ES

Output	10.8 mV/kW/m ² of total solar radiation
Linearity	± 1% from 0 to 1500 W/m ²
Resistance	50 Ohms
Absolute Calibration	± 5% AT 20°C
Azimuth Error	± 1% over 360°
Stability	better than ± 2% per year
Temp. Dependence	-0.1% per °C
Operating Temperature Range	-10 to 50°C

- e) The heat recovery unit was rewired to allow the occupants more flexibility in their control over the warm-air heating system. The new wiring diagram is shown in figure 7.1.1.

A number of other miscellaneous sensors failed or had not transmitted their signals, and once diagnosed faulty they were duly replaced.

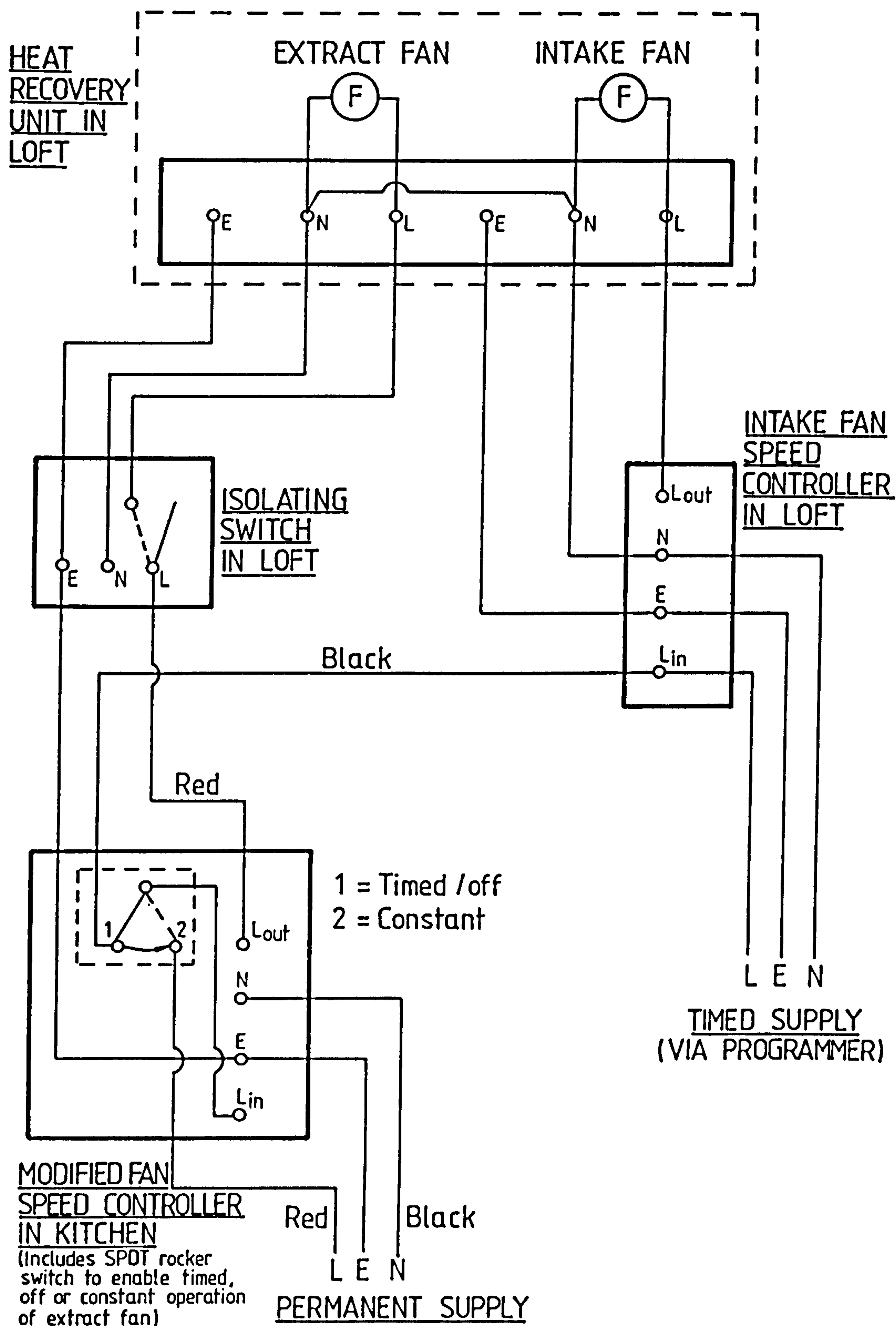


Figure 7.1.1 Modified Heat Recovery Fan Control Wiring Configuration

ii) Estimated construction cost of a Roof-Space-Collector

A detailed analysis of the projected costs is presented in table 7.1.3. The estimated total roof-space collector cost was £93,260 for twenty-one dwellings which was equivalent to an average cost per dwelling of £4440. The largest category of expenditure on the innovative feature, amounting to £3007 per dwelling, was that for the purchase and installation of the wooden structural framework and the weatherproof fabric of the non-southfacing sides of the roof-space collector. The next largest item was the twin-walled polycarbonate cladding and the associated fasteners and fixings at a cost per dwelling of £1609 although this will be partially offset by the cost of the roof tiles that it replaces. The *additional* cost of the roof space collector over a normal tiled roof was £600 - £1000, (7.1.3).

iii) Calculation of simple payback period

The maximum RSC space heating contribution from any of the RSC dwellings for the 1989-1990 heating season up to 31st January 1990 was 1494 kWh from plot No. 29 at 57 Cockerell Grove. It was estimated that this would increase to 1750 kWh if the whole heating season was considered. With an additional cost of £600-£1000, using the current price of gas, (1.36p/kWh), simple payback periods of between 25 & 42 years ensue.

This scenario applies only to one of the RSC houses and is still unviable economically. The additional cost of the passive solar feature per dwelling should be less than £300-£400 to reduce payback periods to acceptable levels. Against this, it should be remembered that £1000 represents the same order of magnitude of capital as that which may be lost or gained during the negotiation process of house purchase. Prospective house buyers may be prepared to accept this small premium to live in a "passive solar house".

<u>PHASE I</u>	£ (1987)	ECU
Structure and Weatherproof fabric (20 Houses)	63,160	
Polycarbonate + fixings	24,140	
Additional Ductwork, Internal Gutter & Drip, Control Sensors, (20 Houses)	5,960	
	<u>93,260</u>	<u>151,372</u>
<u>PHASE II</u>		
BIU's	1,860	
CMO Commisioning	4,180	
Wiring of Houses	3,600	
Data Collection	10,480	
CMO Equipment and Weather Stations	28,836	
CMO Engineers	29,000	
Instrumentation in Houses	7,000	
	<u>84,956</u>	<u>137,893</u>
<u>PHASE III</u>		
Engineers (CIT)	30,000	
	<u>30,000</u>	<u>48,693</u>
<u>PHASE IV</u>		
Engineers (CIT)	2,100	
	<u>2,100</u>	<u>3,408</u>
<u>TOTAL</u>	210,316	341,367

Table 7.1.3 Projected contruction costs of 15 Roof-Space Solar-Energy collectors at Shenley Lodge 5 (1987 prices)

7.2 The Economic Viability of TAP's

1) The potential market for TAP's in the UK (7.2.1)

Many commercial and public organisations are attempting to improve the working environments within their premises, and the refurbishment of an existing building is often a more economic and convenient method of achieving this than the acquisition of new premises. However, a more pressing reason for the refurbishment of buildings is the failure of ageing curtain wall cladding and glazing systems.

The premature deterioration of many buildings constructed in the years since the last war has been attributed to the widespread use of new materials and techniques in the absence of appropriate standards controls or the necessary expertise (7.2.2). The introduction of the curtain wall cladding technique enabled buildings to be constructed with external walls which were lightweight, non-load bearing assemblies of components suspended from structural frameworks. The performance of many of these curtain walling systems could depend on the integrity of the sealants, none of which had a guaranteed life in excess of twenty years (7.2.3). The failure of these sealants and any subsequent water penetration could lead to internal rotting and structural damage. A graphic illustration of this type of damage are the walls of Nazeing County Primary school prior to the refurbishment.

It was estimated in 1984 that the cost of implementing the required level of curtain-wall refurbishment in Britain could be as much as £10 - £12 billion, (7.2.4); this sum being divided equally between public and private buildings. This represents a large potential market for passive solar collectors which they can satisfy only if they are designed to perform adequately both as recladding and as solar heating components.

In a report on passive solar design in non-domestic buildings, (7.2.5), it was shown that modifications to existing buildings were likely to provide the major proportion of the benefits that passive solar heating could offer in the short-term, as so few new buildings were being added to the existing U.K. stock. It was argued that even in times of high economic activity, new building in the U.K. represented only between 1% and 2% of the building stock in any single year. The impact of passive solar design, if it were to be dependent on new building in the

prevailing economic climate, would be almost negligible. They noted, for example, that the public sector school building stock in 1976 consisted of a total of 28,310 buildings of which 12,250, (43%), were built before 1945. The number of new school buildings was likely to be small in view of the reduction in the school-age population predicted for the U.K. However, it was suggested that the effects of reorganisation, maintenance and repair were likely to create opportunities for investment in the existing buildings and some of this investment should be used to increase the passive solar heating capability.

ii) Financial contribution from TAPs

On the east and south facades respectively there were 14 and 12 TAPs installed. Two TAPs on each of these facades were supplementing electric convector heaters and electric radiant heaters, with the remaining TAPs displacing space heating provided by the primary gas-fired central heating system. During 1989 the cost of electricity and gas at Nazeing County Primary School was 5.97p/kWh and 1.34p/kWh respectively. In order to obtain the true cost of the two auxiliary fuels displaced, the number of TAP's which supplemented gas were combined with those which supplemented electricity on each facade. (e.g. for the south facade, ten TAPs supplementing gas @ 1.34p/kWh and two TAPs supplementing electricity @ 5.97p/kWh was equivalent to twelve TAPs displacing auxiliary fuel @ 2.11p/kWh; see Table 7.2.1).

Only the contributions from the TAPs on the east and south facades were considered as the TAP temperature differences from the west facing collectors, throughout the monitoring period, never rose above the threshold level at which thermosyphon flow was instigated.

	South Facade	East Facade
Annual energy contribution from TAPs on each facade (kWh)	1551	498
Number of TAPs supplementing electricity on each facade	2	2
Number of TAPs supplementing gas on each facade	10	12
Overall cost of fuel supplemented by TAPs on each facade (p/kWh)	2.11	2.00
Annual financial contribution TAPs on each facade (£)	32.72	9.96

Table 7.2.1. Auxiliary Fuel Costs and Annual Solar Heating Contribution at Nazeing County Primary School.

iii) Calculation of simple payback periods

The two different annual solar contributions from each facade were used to calculate simple payback periods from the four different scenarios represented in Table 7.2.2. Discounted payback periods were not used because the increase in fuel prices could not be predicted for the expected lifetime of the cladding system. Unfortunately the simple payback calculation had little real value except for the purposes of comparison between various economic scenarios. As can be seen in case D, even the most optimistic scenario gave a simple payback period of 37 years!

In a number of other Essex County Council schools the auxiliary heating was provided by oil fired boilers, (1.82p/kWh), rather than a gas-fired system. The payback period in this last scenario would then be reduced to 31 years. The total overcost still must be reduced to £780 in order to achieve a payback period of 20 years, i.e the expected lifetime of the cladding system. This represented an additional cost of £65 for each TAP above that of a standard cladding unit.

Scenario	Cost (£)	Payback period (years)
A. Total overcost of 36 TAPs installed as part of demonstration project.	£5888	138
B. Total overcost of 36 TAPs as installed on future replication.	£3664	86
C. Total overcost of 14 TAPs on east facade, on further replication.	£1425	143
D. Total overcost of 12 TAPs on south facade, on further replication.	£1221	37

Table 7.2.2. Simple Payback Periods for Thermosyphoning-Air-Panels
Based on Four Different Economic Scenarios.

7.3 Reliability and Maintenance of Thermosyphon Solar Water Heaters

i) Problems and difficulties encountered

During the winter of 1984-85, the thermosyphon solar water heaters in houses 7 and 9 East Road, Wharley End, Bedfordshire, were damaged severely due to frost. This occurred, as a direct result of poor on-site supervision during the installation of the frost-damage protection devices. During the following winter they were drained down before the inevitable sub-zero temperatures could cause any further damage.

During the refurbishment of the frost-protection-by-heating-element installation the header pipes were found to be 22mm outside diameter and not 28mm as specified originally. It was also noted, with some concern, that one half of the collector outlet T-piece pipe-fitting was obstructed by a small roll of badly-corroded wire wool! Surprisingly, the results recorded, up to the time of this discovery, showed that the monthly performance had not been affected adversely.

During the installation of the trace-heating system the heating element had not been wrapped securely around the lower header, thus it had negligible thermal contact with the copper header pipe. In addition, its performance was impaired by the thermostat being located on the gable end of the house. This device measured merely the ambient air temperature, some 3-4m away from the collector, and not the actual water temperature. As expected, the overall heating capability of this configuration was ineffective.

The thermal tape installed initially, was replaced, and the new tape was wrapped around the header pipe as tightly as practicable, thus ensuring good conductive heat transfer. Transient tests undertaken showed that a 28mm copper pipe filled with crushed ice could be heated to a temperature of 5 °C in less than four minutes. To ensure a rapid and reliable response to near freezing temperatures a platinum-film temperature sensor was secured to one of the risers on the absorber plate with high temperature glass fibre tape (Figure 7.3.1). The associated temperature-controller relay was set to activate the heating tape at temperatures below 2 °C and then to switch off the power at temperatures above 4-5 °C.

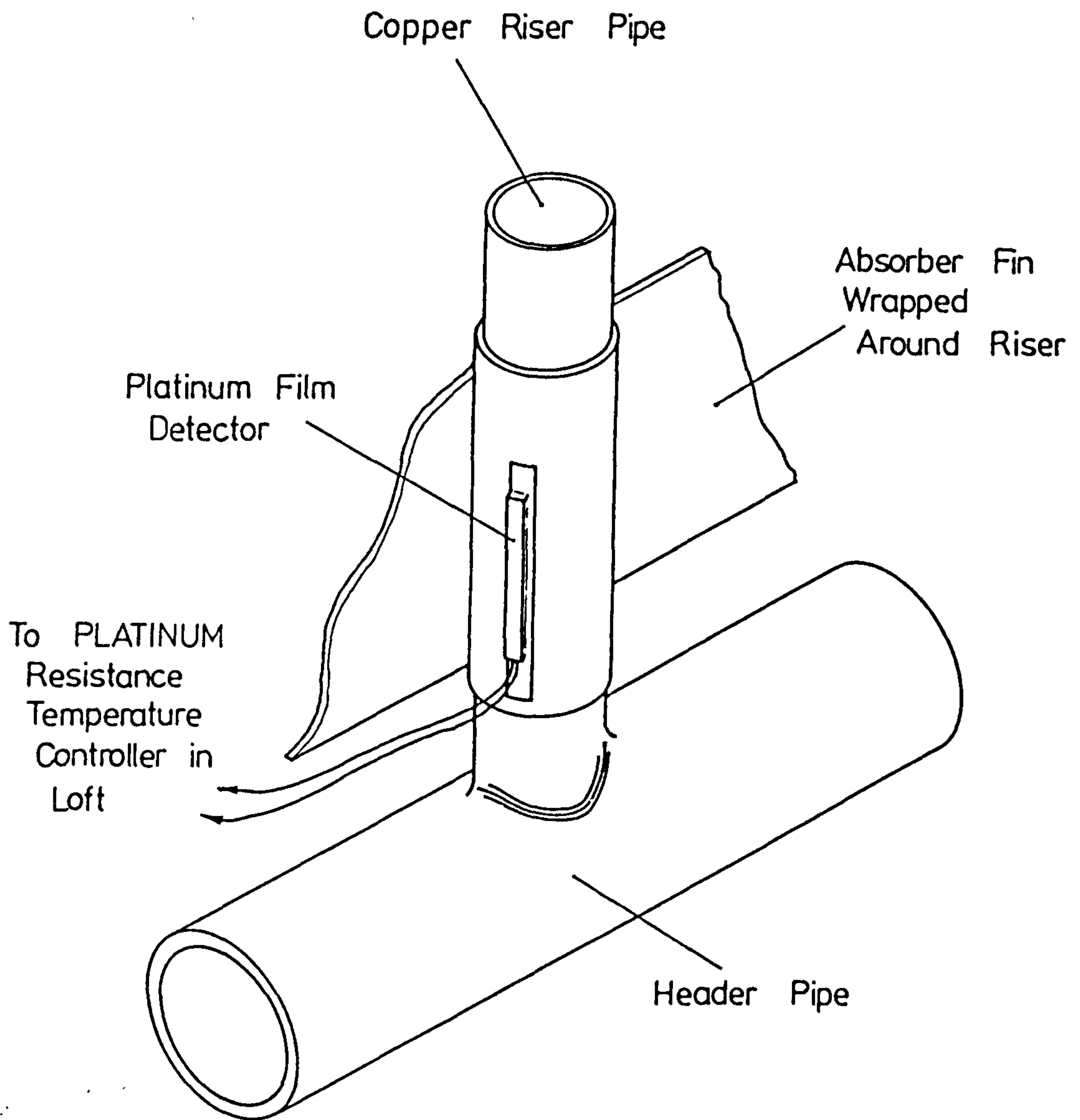


Figure 7.3.1 Platinum film temperature sensor

The automatic draindown method of freeze protection employed at No.9 East Road also proved to be unreliable, again due to lack of "attention-to-detail" by the installaters during it's initial installation. The draindown pipe was not at the lowest point in the collector loop which allowed small quantities of water to remain in the lower header. Subsequent frost-damage due to sub-zero °C temperatures meant that the complete header pipe had to be replaced.

Closer inspection of the damaged absorber plates revealed that the selective absorber surface had also suffered mechanical degradation, (Figure 7.3.2 - 7.3.3). Insufficient care and attention may have been exercised by the collector manufacturers when applying the foil to the absorber plate. Poor adhesion had allowed pockets of air to remain trapped between the selective surface and the copper substrate. The foil no longer allowed all of the heat gained from the incident solar radiation to reach the absorber. The ensuent over-heating affected severely the mechanical properties of the foil. It became brittle and eventually peeled away from the absorber, thus reducing the effective area of the selective surface. In addition, the already degraded selective surface was exposed to further surface contamination from excess moisture, due to the leak from the fractured pipes.

The manufacturers of selective surfaces (7.3.1) were duly notified of this problem. Within four days, all of the degraded material was replaced and a more detailed analysis of a small sample performed. Despite its badly soiled appearance, minimum absorptance and maximum emittance were 0.95 and 0.15 respectively. The absorptance remained well within the manufacturer's guaranteed specification but the nature of this degradation had adversely affected the emittance. The "spots" on the Maxorb surface were subjected to scanning electron microscopic examination and electron micrograph scanning. This revealed the presence of the following contaminants; sulphur, probably present as sulphate, chlorine present as chloride, and silicon. The chlorides, which are aggressive to nickel, arose from either a concentration effect after water leakage and/or as chlorides present in the flux used for brazing the copper fins to the absorber tubes. The scanning electron micrograph photograph showed clearly the resultant corrosion pits and crystalline clusters.

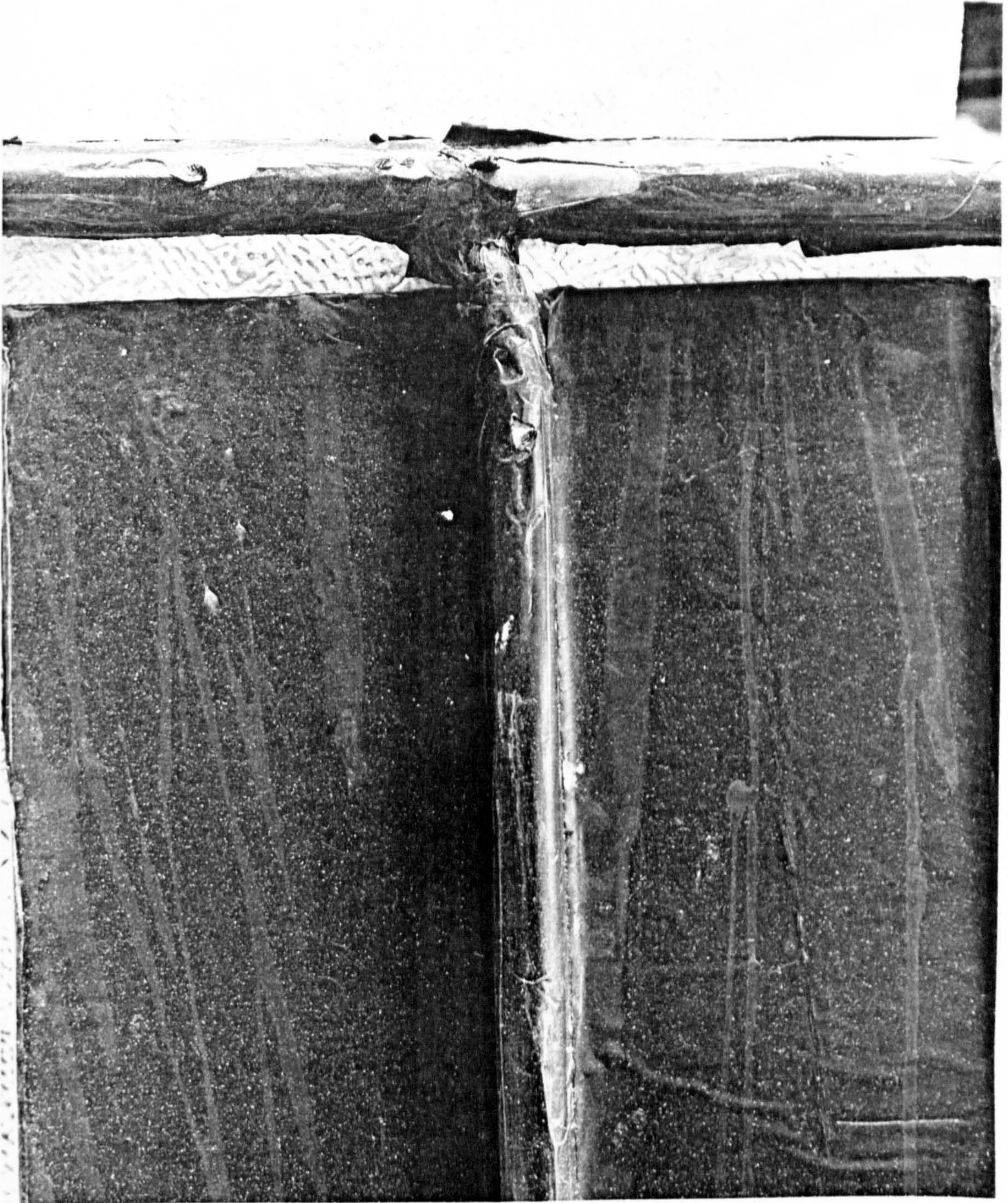


Figure 7.3.2 Detail of selective surface peeling away from
copper risers.



Figure 7.3.3 Degraded selective absorber surface

The reconstructed absorber plates were cleaned with phosphoric acid, then polished with wire wool, and finally rinsed with water to ensure optimum adhesion of the selective foil. When applied correctly with a hard-rubber roller, the copper fins could be covered with little difficulty, even over irregular surfaces. Whilst the collectors were being refurbished, the opportunity was taken to replace the high flow-resistance 15mm solenoid globe valves with full-bore motorized half-shoe butterfly valves, (Figures 7.3.4 - 7.3.5).

On the 20th of October 1986 it was reported that the roof on House No.8 (the third tap with antifreeze installation), was leaking. Due to the condition of the roof tiles, and the weight of the collectors, a number of tiles directly underneath the collector support bolts had sustained minor damage, (Fig. 3.3.9, chapter three). This allowed the wind driven rain to force small quantities of water between the tiles. Cranfield Institute of Technology's Estates Department investigated this problem and decided that the roof would only leak during prolonged severe weather conditions. Such enduring circumstances occur so infrequently that any necessary repair work was being postponed until the end of the demonstration project when the roofs of these dwellings were to be replaced as part of the Institute's on-going maintenance program.

House No.7, (the third tap with heating element system), was vacated in Oct 1986 and the property was not to be relet until it had been redecorated. This seemingly annual task continued until late November when it was let to another family. Meanwhile house No.9, (the pre-heat automatic draindown installation), remained unattended and unoccupied. In mid January, however, its electrical wiring, (first installed in the 1950's!), was replaced, and the interior was refurbished completely which included the installation of an oil-fired central heating system.

As a routine part of the rewiring procedure, the old mains junction box was replaced with one which incorporated an earth leakage detection circuit-breaker. Once an earth leak was detected by this device the mains supply was disconnected automatically. Unfortunately, these devices were so sensitive that the small return current exhibited by the motorized drain-down valves was sufficient to actuate the circuit breaker. Redecoration and rewiring of house No.9 continued for almost two months while the installation of the central heating system, which would normally interrupt the cold water supply for only one or two hours, (7.3.2), continued for four weeks! In a normal domestic

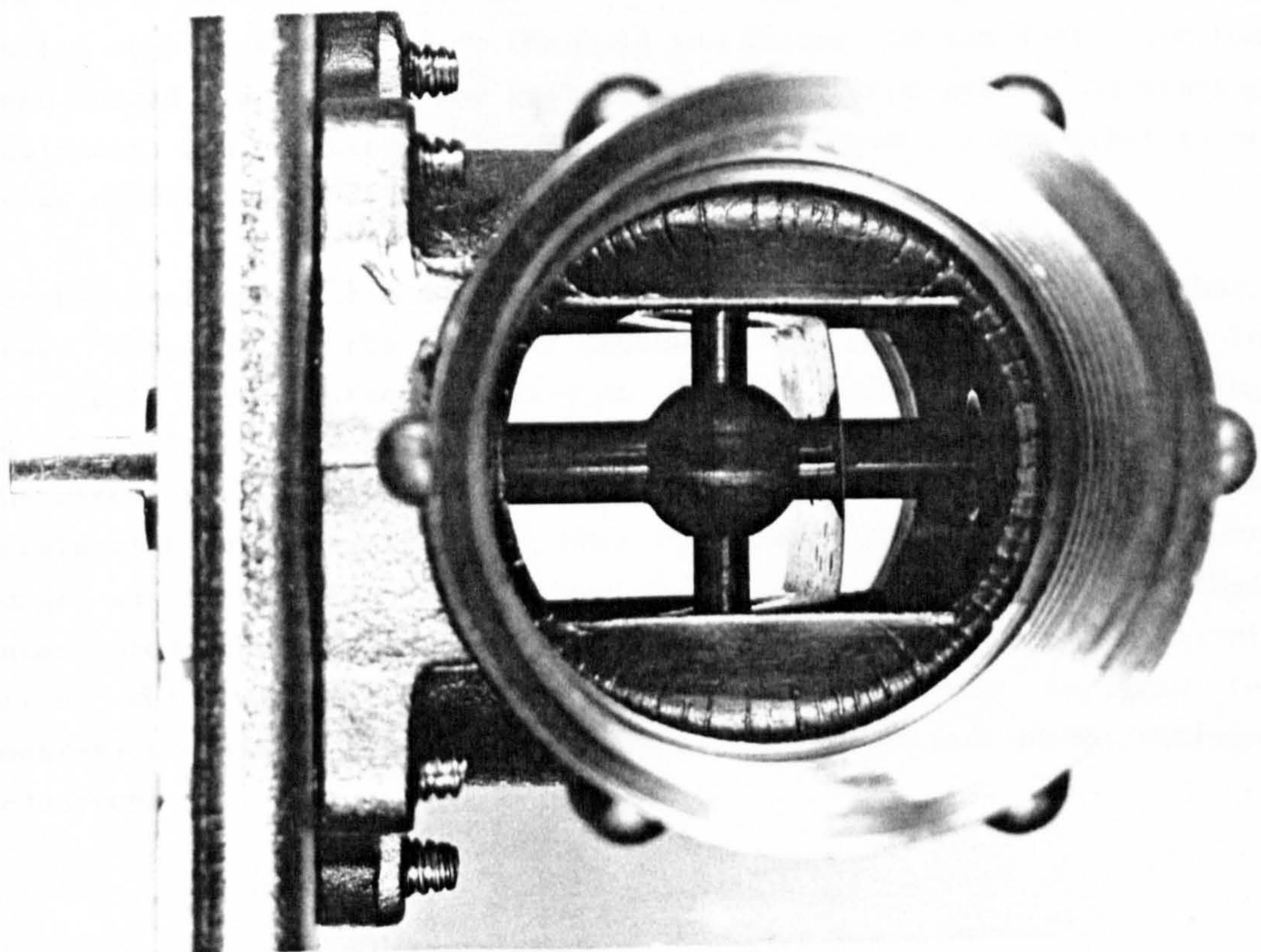


Figure 7.3.4 Twin-shoe valve mechanism

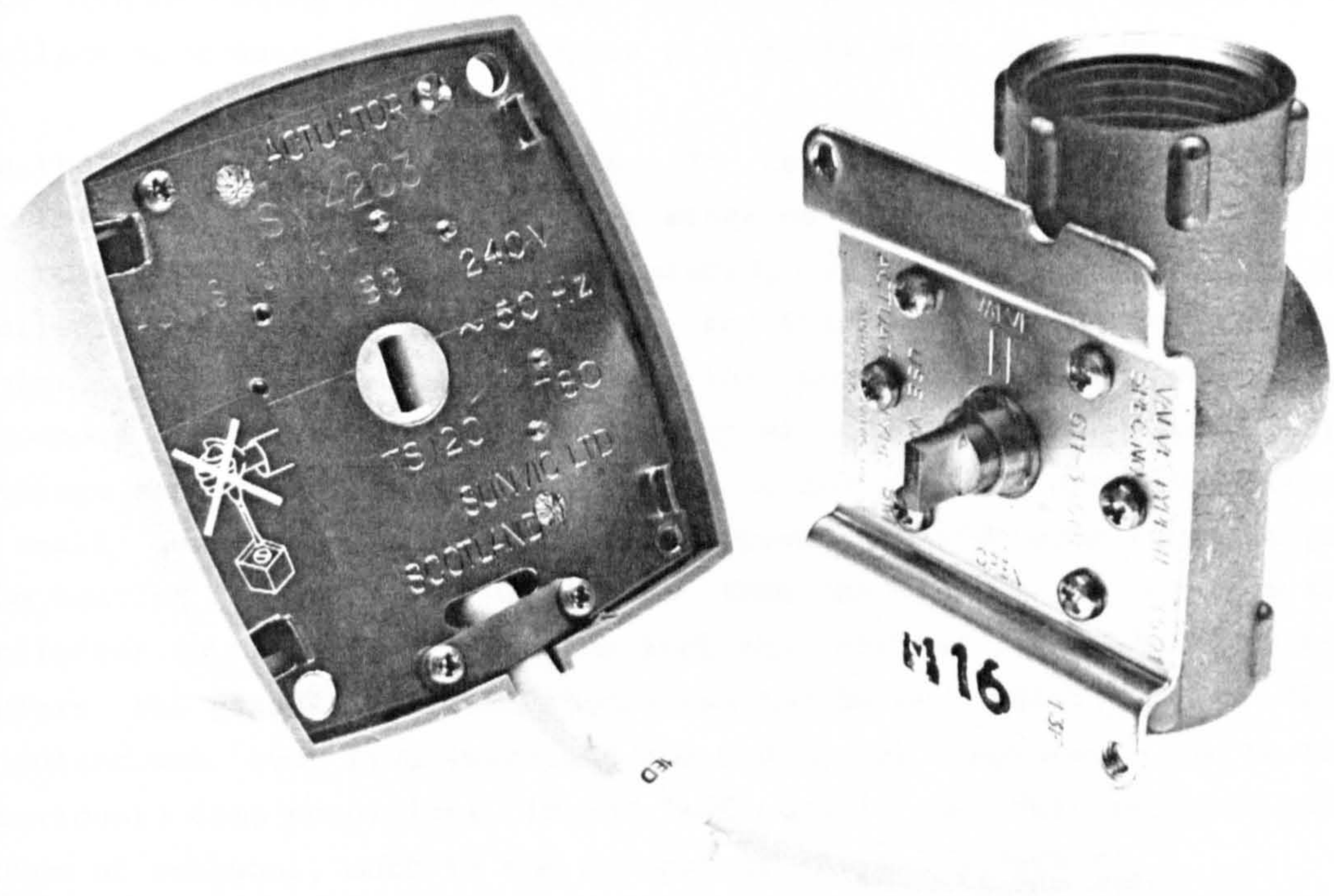


Figure 7.3.5 Valve body and motorised actuator

situation the same tasks would be undertaken over a much longer period but without having to vacate the house. This would have enabled us to collect more data while the houses were still being occupied.

On the 16th of January 1987 the 'T' connector which joined the two collector inlet pipes to the solar store on house No.7 began to leak as a result of frost damage. The building contractors who installed the collectors originally had neglected to insulate around the collector inlet, at the point of entry through the roof into the loft space, with expanded polystyrene foam. This potential cold bridge, combined with average ambient conditions of below -2°C for almost 7 days, had frozen a small quantity of water which was present at this point in the pipe. The heating element was unable to thaw the ice all the way from the collector to the cold bridge. The leak was repaired immediately but not before the glass-fibre loft insulation had become water-logged. This insulant was over five years old and had become compressed, due to the previously damp conditions in the loft, and it was duly replaced with 100mm of rockwool, much to the delight of the new occupants.

As part of the normal procedure of data collection, the external lock-up compartment which housed the monitoring equipment was checked at the beginning of every month in order to renew the data-collection disk. On the 1st of January 1987 it was noticed that the compartment had been pulled away from the wall to which it was bolted and the door latch had been forced. Fortunately the padlock survived intact and the monitoring equipment had continued to operate uninterrupted for the first three weeks of December 1986.

Further analysis of the data revealed that there had been, yet another, power "drop-out" on the 18th of December. Such momentary reductions in the supply voltage often occurred at Wharley End as a result of being an essentially "industrial" environment. Large compressors, as used in the research laboratories at Cranfield Institute of Technology, had substantial power requirements. When they were operated, the switch-on surge was sufficient to reduce the supply voltage which then interrupted the monitoring equipment. Unfortunately the mains filter device which was installed in October 1986 was only designed to suppress transient surges in the supply voltage and not abrupt voltage reductions.

At the end of January 1987 the fan heater located in the lock-up compartment failed, amidst the damp environment at the floor of the compartment. An almost continuous flow of air through the heater had allowed an accumulation of dust (and various insects) on the commutators of the electric motor, and caused it to burn out. Condensation on the monitoring equipment ensued in the sub-zero temperatures then encountered. The microcomputer and the interface bus were unaffected by this environment however the MAPS was introducing some spurious "results".

The original intention of the data-logging program was to monitor the three dwellings as unobtrusively as possible. Yet, in order to maintain continuous collection of data the equipment should have been installed in a less hostile environment with an uninterruptable power supply. Unfortunately the prohibitive cost of these measures was beyond the budget of this demonstration project.

ii) Economic viability of thermosyphon solar water heaters

a) Technical and economic success of the project

The economic and technical success of energy demonstration projects is measured, by the Directorate-General for Energy of the Commission of the European Communities, as the ratio of C_a/C_{eo} , (7.3.3), where C_a is the cost of the energy provided by the solar-energy water heating installation and C_{eo} is the cost of the same quantity of energy from the auxiliary source. Assuming that;

$$C_a = \frac{\text{Installed Cost}}{\text{Annual Solar Fraction} \times \text{Annual Hot Water Load}}$$

and, $C_{eo} = \text{Electricity Price in First Year of Installation}$

For, Installed Cost = £1840
 Annual Hot Water Load = 9.83 GJ
 Annual Solar Fraction = 0.27
 Anticipated Lifetime = 20 years
 Electricity Price = £14.25/GJ

Then, $\frac{C_a}{C_{eo}} = 3.86$

If the projected solar fraction of 0.27 for the pre-heat system were used, the ratio of C_a/C_{eo} would be 2.43. Thus, though the project has provided a wealth of useful information, it cannot be judged an economic and technical success by this criteria. However, Table 7.3.1 indicates initial installed cost targets, which if achieved, would render such systems viable economically in the U.K. climate for the shown range of anticipated useful lifetimes.

Nominal system lifetime (years)	Maximum permitted total installed cost required to achieve economic viability (£)
20	980
10	580
5	320

Table 7.3.1 Cost targets required to ensure economic viability with auxiliary fuel costing 1.425p/MJ

b) Preliminary assessment of economic viability

The initial investment for the purchase and installation of a solar-energy water heater is usually greater than subsequent operation and maintainance costs. In contrast the initial investment in a fossil fuel, or electrical water heating system, is lower usually than the expenditure on fuel over the system's useful working life. Thus, in broad terms, to achieve economic viability, the initial cost of a solar energy unit, depreciated over its useful working life, must successfully compete with the prevailing market cost of depletable fuel resources (i.e. coal, gas) or their delivered forms (i.e. electricity, coke).

c) Economic viability in southern England

The demonstration project on thermosyphon solar energy domestic hot water production was situated in Bedfordshire. This location was not climatologically nor economically atypical of southern England.

The relationship (7.3.4):-

$$P = \frac{n \cdot C}{(H \cdot \eta_c \cdot \eta_m \cdot E \cdot A_c - m) \left[\frac{(1+i)^n - 1}{i \cdot (1+i)^n} \right]}$$

was employed to investigate the discounted payback period that ensued from different initial capital costs, system lifetime and collector efficiencies with constant auxiliary fuel costs in southern England.

Using the annual global insolation for Cranfield the results for system lifetimes of 20, 10 and 5 years are shown in figures 7.3.6 - 7.3.8 respectively. The criteria for economic viability was that the discounted payback period be less than the expected working life of the system. From these graphs the requirements, (in terms of system cost and productivity), for economic viability could be determined. For example, with an annual average collector efficiency of 0.4, the cost targets in Table 7.3.1 could be identified.

Figure 7.3.6 Relationship between discounted payback period and initial system cost per unit collector area for a projected system lifetime of 20 years

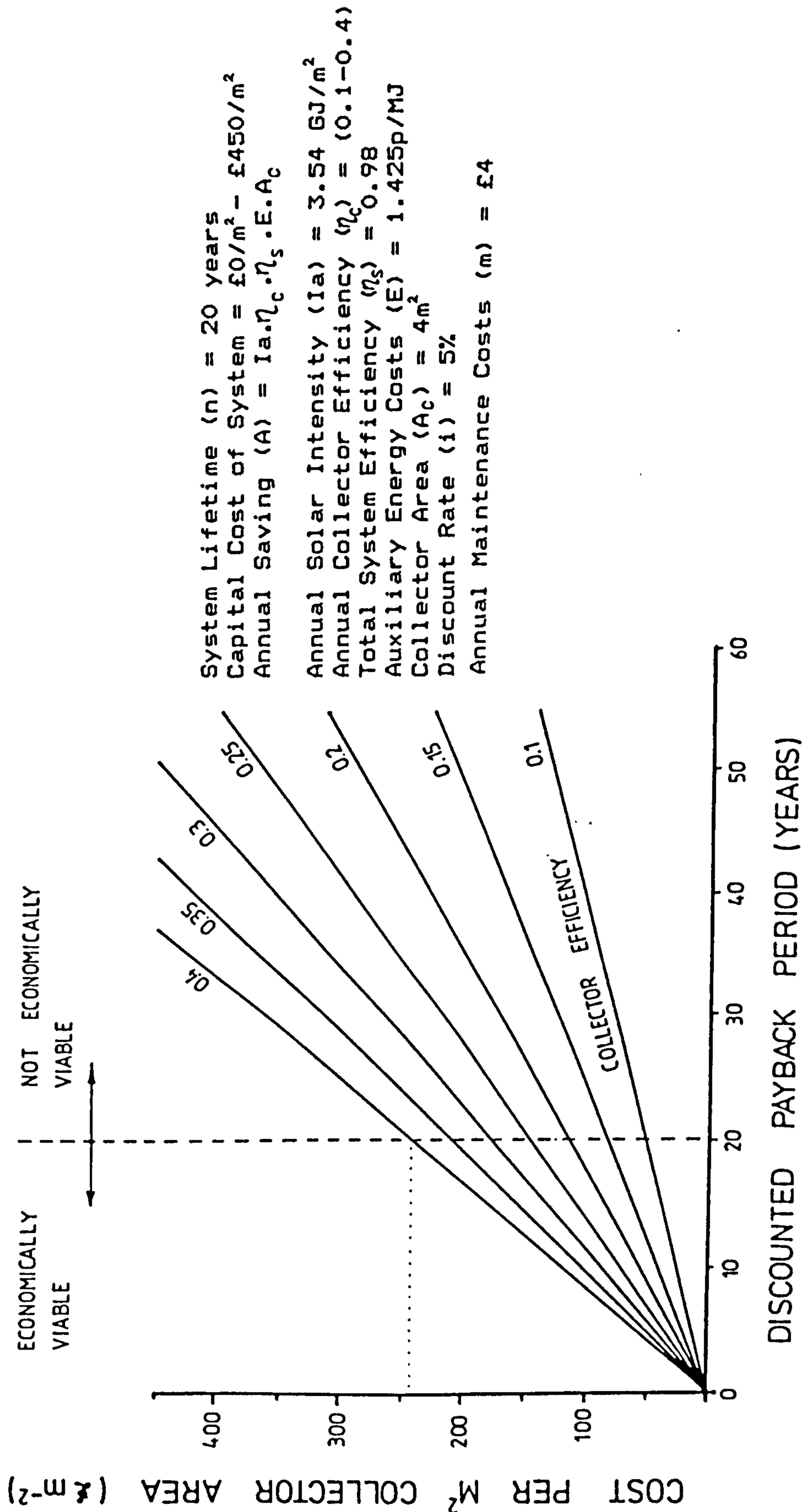


Figure 7.3.7 Relationship between discounted payback period and initial system cost per unit area for a projected system lifetime of 10 years

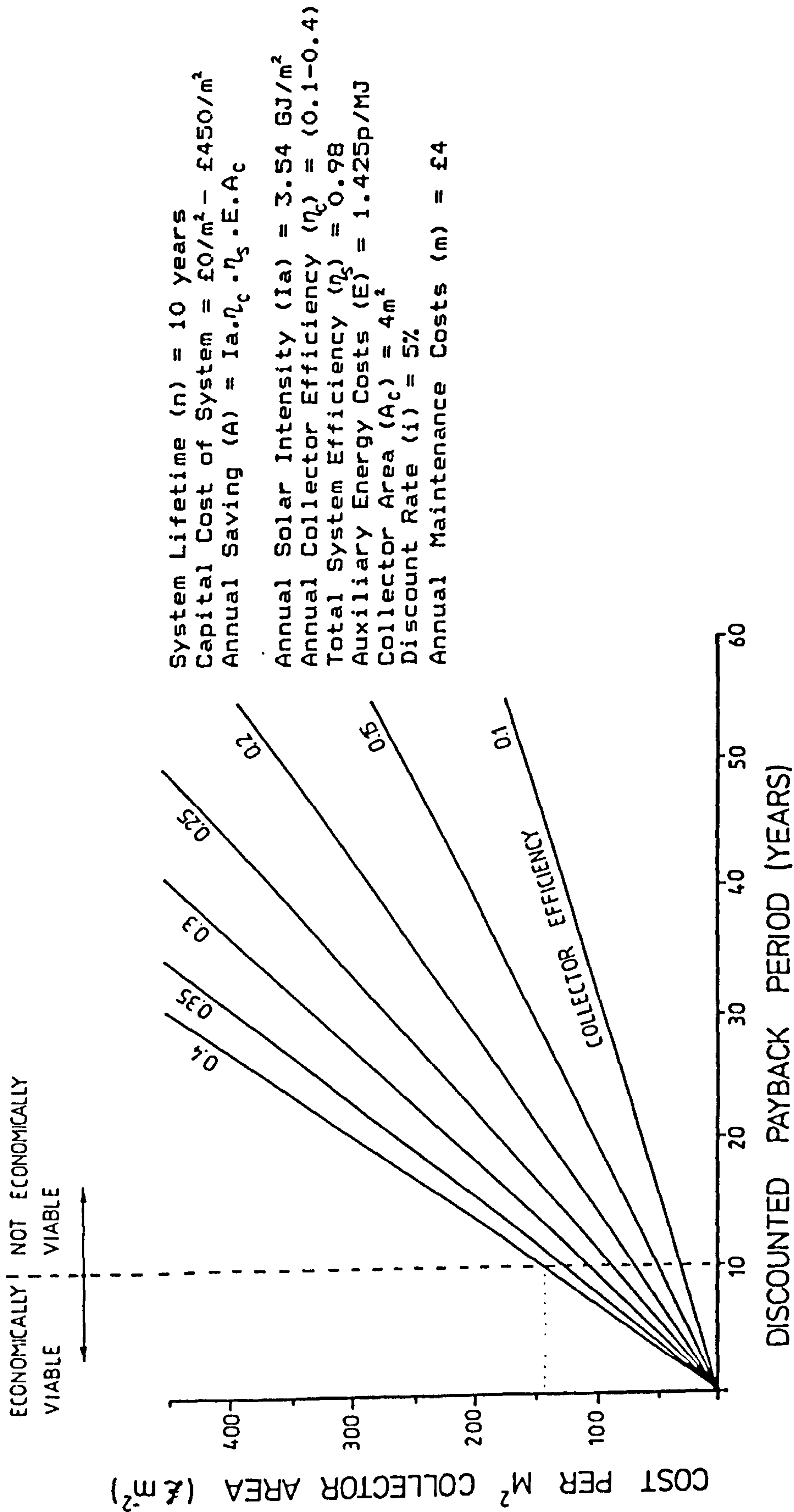
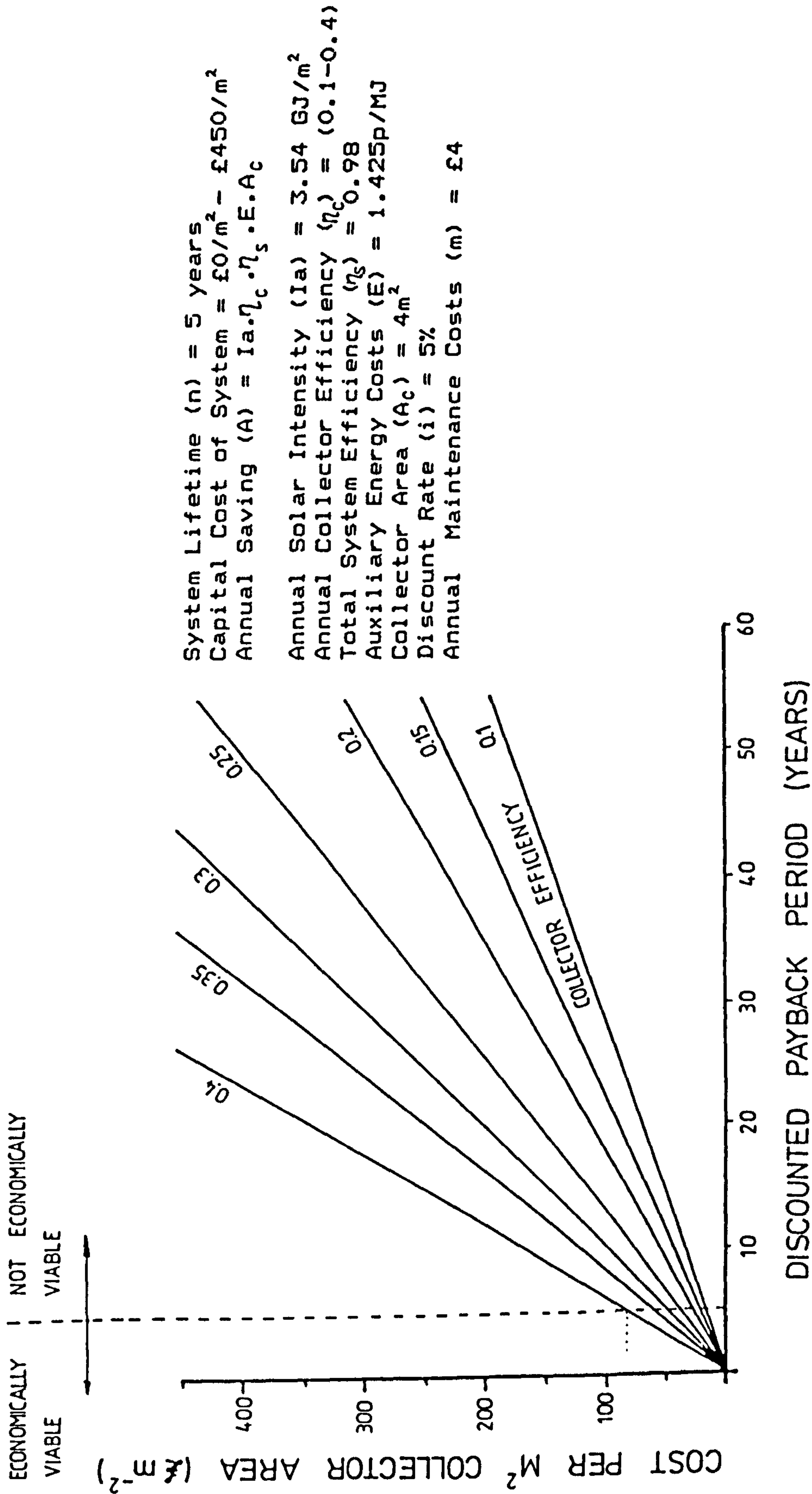


Figure 7.3.8 Relationship between discounted payback period and initial system cost per unit collector area for a projected system lifetime of 5 years



If the total system cost were reduced to £1000 and a solar-energy water heater with an overall annual system efficiency of 0.4 were used, these particular solar-energy water heaters would then achieve a discounted payback period of 21.4 years. The mechanical integrity of the system must, of course, be guaranteed for this period and the low maintenance costs as employed in deriving Figs. 7.3.6 - 7.3.8 may be difficult to sustain in practice. Figure 7.3.9 illustrates that the financial allowance for annual maintenance, effectively seen as an insurance premium, may increase to £10 - £12 without significantly increasing the discounted payback period. The maintenance cost will be different for various systems and in a thermosyphonic unit the lack of a pump nor any control sensors minimises these costs.

d) Economic viability elsewhere in Europe

Using the data for total global insolation incident on a collector inclined at the latitude of the particular location, (Table 7.3.2), the discounted payback period using two annual solar-energy-collector efficiencies were calculated. All the cost and performance parameters were set to U.K. values for the purposes of initial analysis. The base-case system configuration was selected and the resulting economic projections are illustrated in Figure 7.3.10. Such solar-energy water heaters situated at the various locations throughout Europe would exhibit different discounted payback periods as a result of the various localised levels of insolation. The annual levels of global radiation on a plane inclined at the latitude angle of these locations are also shown in Table 7.3.2. Fig. 7.3.11 illustrates how the original discounted payback periods changed when the auxiliary energy costs, (1986), for particular European locations were used. All other parameters, (capital cost, system lifetime etc), remain constant. Some of the payback periods increased due to lower auxiliary energy costs when using comparable data, (i.e. at the same tariff band), for these aforementioned locations. As more accurate data of all the performance parameters for each location becomes available, a realistic impression of the true discounted payback period with location will emerge.

These characteristic parameters may not be entirely representative of current European experience but they provide a reference for comparative purposes.

Figure 7.3.9 Annual average maintenance costs v discounted payback period

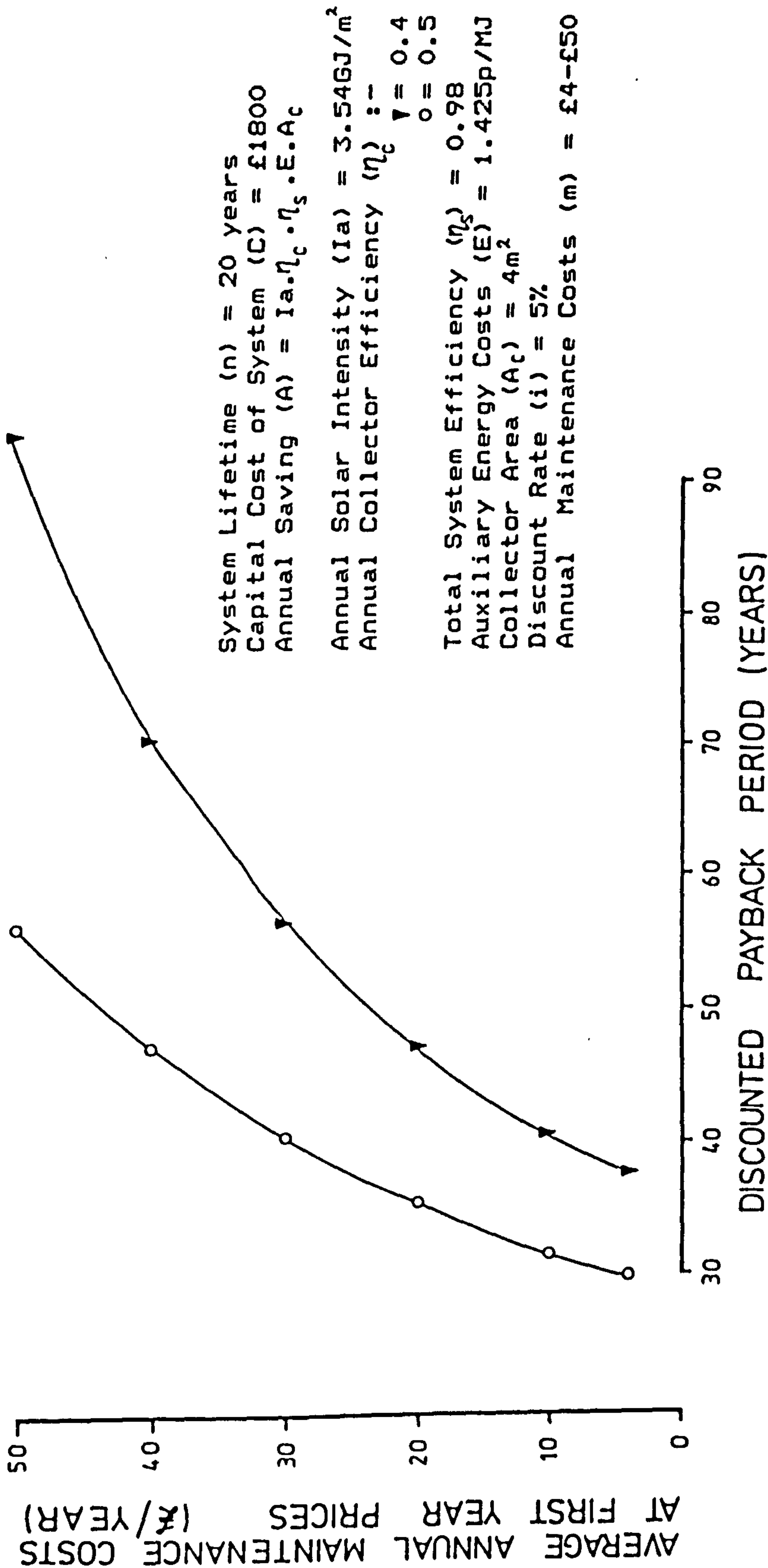


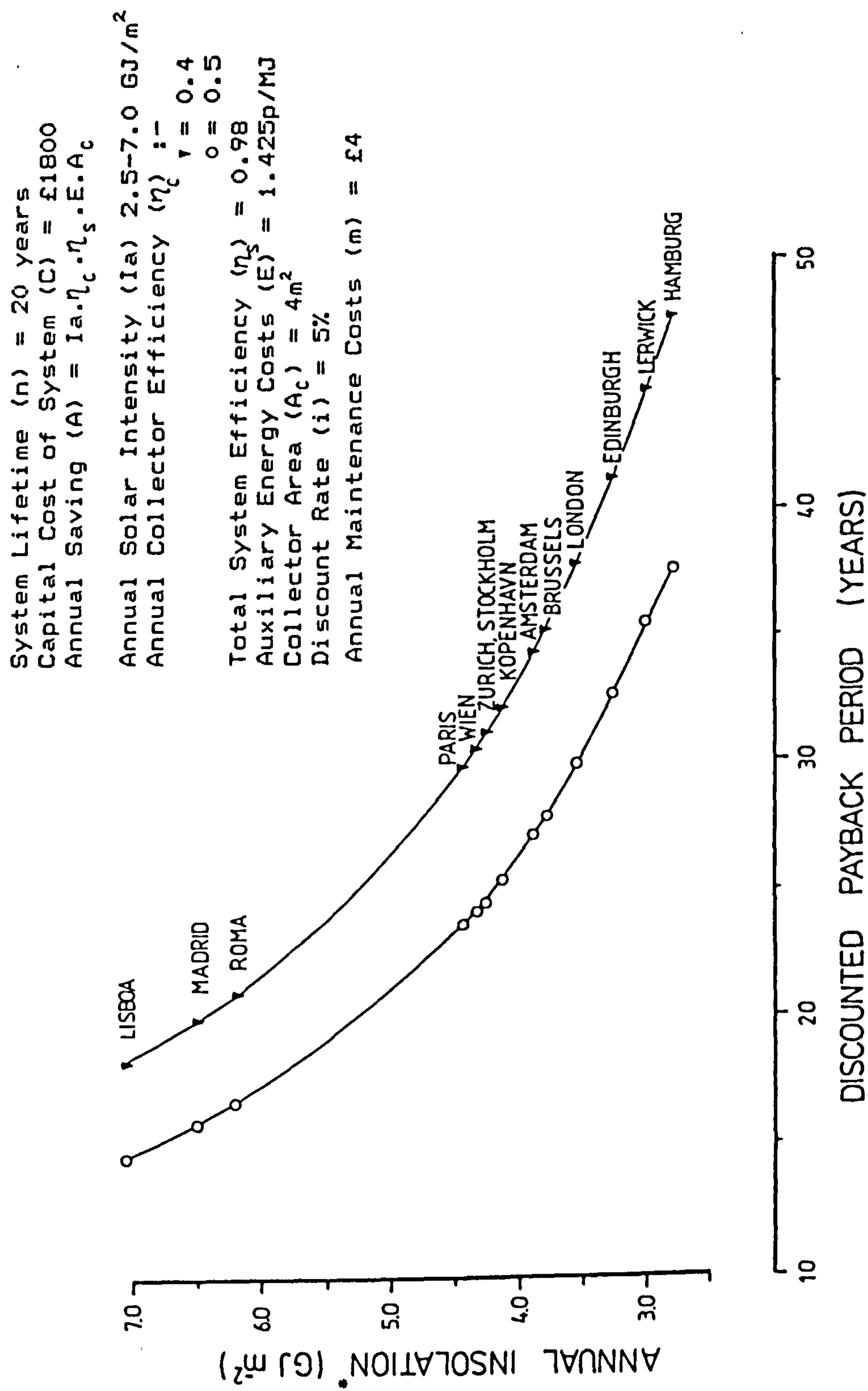
Table 7.3.2 European insolation data* and corresponding discounted payback periods

Location	Total Annual Global Insolation on a Plane Inclined at same angle as Latitude of Location GJ/m (MJ/m Daily)		Total Annual Global Insolation on a Horizontal Plane (Data provided for reference only) GJ/m (MJ/m Daily)		Discounted Payback Period with collector efficiencies of:-	
					0.4	0.5
					(Years)	
Hamburg	2.84	(7.78)	-	-	47.55	37.55
Bergen	2.97	(8.14)	3.5	(9.59)	45.32	35.81
Lerwick	3.0	(8.21)	2.5	(6.85)	44.91	35.49
Edinburgh	3.25	(8.89)	3.0	(8.22)	41.28	32.65
London	3.52	(9.65)	3.23	(8.85)	37.86	29.97
Brussels	3.77	(10.33)	3.5	(9.59)	35.24	27.92
Amsterdam	3.88	(10.62)	3.51	(9.61)	34.32	27.13
Helsinki	-	-	3.58	(9.81)	-	-
Copenhagen	4.11	(11.27)	3.71	(10.16)	32.17	25.51
Stockholm	4.23	(11.59)	3.71	(10.16)	31.25	24.78
Cologne	-	-	3.78	(10.36)	-	-
Zurich	4.26	(11.66)	4.08	(11.18)	31.05	24.24
Vienna	4.32	(11.84)	3.98	(10.9)	30.56	24.24
Paris	4.41	(12.08)	4.1	(11.23)	29.87	23.7
Rome	6.19	(16.96)	5.5	(15.07)	21.06	16.75
Madrid	6.49	(17.78)	5.73	(15.7)	20.06	15.96
Lisbon	7.07	(19.37)	6.22	(16.7)	18.38	14.63

* All data obtained from
U.K. Meteorological Office,
Bracknell.

System Lifetime (n)..... 20 years
Capital Cost of System (C)..... £1800
Annual Solar Intensity (Ia)..... GJ/sq.m
Annual Collector Efficiency (η_c)..... 0.4 - 0.5
Total System Efficiency (η_s)..... 0.98
Auxiliary Energy Costs (E)..... 1.425p/MJ
Collector Area (A_c)..... 4sq.m
Annual Saving (A)..... Ia. η_c . η_s . E.A_c
Discount Rate (i)..... 5%
Annual Maintenance Costs..... £4

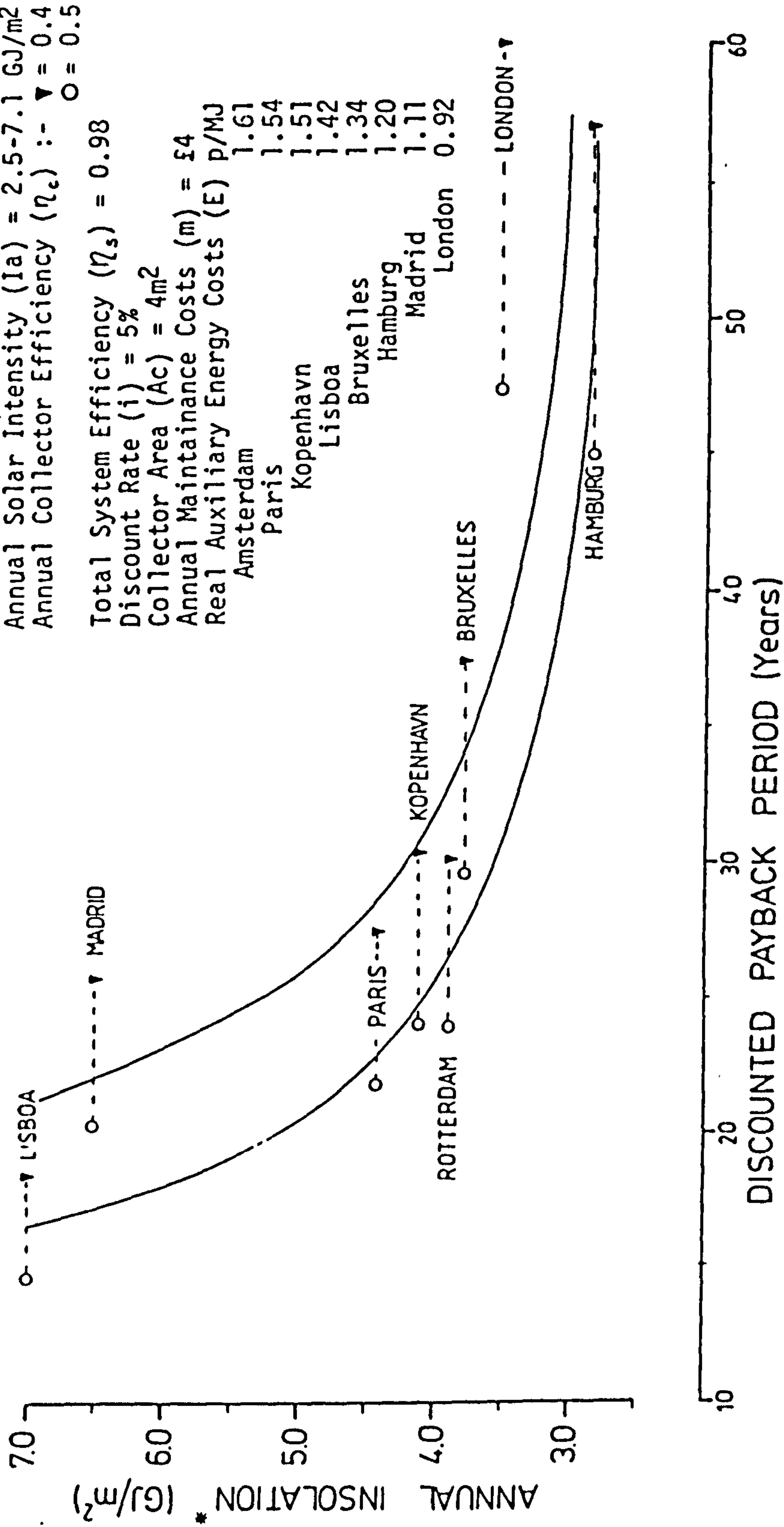
Figure 7.3.10 Relationship between average annual insolation and discounted payback period



* Total annual global radiation incident on a plane inclined at the same angle as the latitude of location.

Figure 7.3.11 Relationship between average annual insolation and discounted payback

periods using regional European
auxiliary price data



* Total annual global radiation incident on a plane inclined at the same angle as the latitude of the location.

For the various different European locations the following major differences could be identified,

Capital cost	"Do-it-yourself" systems would reduce the installation cost, consequently lower discounted payback periods would ensue. Unfortunately, "home-built" units are also likely to exhibit shorter system lifetimes and reduced reliability. In more southerly European climates, as frost-protection is unnecessary, systems may also be cheaper.
System Lifetime	Greater levels of insolation over a longer period, as experienced over southern Europe, may accelerate scaling and corrosion thereby decreasing system efficiency and lifetime respectively.
Collector Efficiency	As a general rule, in Europe, higher ambient temperatures are synonymous with higher insolation. More efficient collection of solar energy is associated with higher ambient temperatures due to lower thermal losses. This allows reduced collector areas and thus collector cost which reduces the payback period.
Auxiliary Energy Costs	Figure 7.3.11 has already shown how various regional auxiliary energy costs can influence the payback period at any given European location.

Despite the above caveats, Figs. 7.3.10 - 7.3.11 provide a sound basis for intercomparison of the potential for the economic viability of solar water heating and the steps required to achieve it within the European Community. Unfortunately it is unlikely that the collectors reported upon herein will ever be viable economically within their current projected lifetime. The annual solar fraction achieved for the indirect third tap system was 0.17 which gave a projected annual solar fraction of 0.27 for the pre-heat system resulting in a discounted payback period of 58.5 years! In order for this particular scenario to become viable economically the total installed cost would have to be less than £600.

e) Economic optimization of collector area (7.3.4)

The optimum collector area is the area at which the installed cost plus the cost of the auxiliary heating, is at a minimum when evaluated over a period of time. This can be refined to be more realistic if the time value of the costs are considered, i.e. its Net Present Value, (NPV). The NPV method of evaluation identifies the investment level which yields the greatest profit when the savings of future years have been discounted back to their present day value. In order to discount the annual saving in auxiliary water heating costs over a particular evaluation period, (e.g the system lifetime), to its present value, it must to be multiplied by;

$$NPV = \frac{(1 + i)^n - 1}{i(1 + i)^n}$$

where n is the system lifetime, in years, and i is the rate used to discount savings to their present value. Using an anticipated system lifetime of 20 years and a discount rate of 5% the NPV factor becomes;

$$NPV = \frac{(1.05)^{20} - 1}{0.05(1.05)^{20}} = 12.46$$

Given all the system parameters one may then calculate the equivalent capital cost of the annual saving and the installed cost.

Whereas the NPV method of evaluation discounts all future savings and seeks the maximum profitability on the installed cost, the Equivalent Capital Cost method discounts all future heating costs and defines that collector area which requires the lowest total outlay as the optimal economic collector area, Table 7.3.3. This is best illustrated using different scenarios with system characteristics, A, B, and C, (Table 7.3.4), to produce optimum collector areas, Figs. 7.3.12 - 7.3.14 respectively. Scenario B is representative of current state-of-the-art UK flat-plate thermosyphon solar-energy water heating technology. The correlation has been recalculated using the pertinent performance characteristics with a typical auxiliary energy load to give a different optimum collector area, Fig. 7.3.13. It is hoped that future more efficient installation techniques will reduce the overall system costs to the target levels depicted in condition C (Fig. 7.3.14).

Table 7.3.3 Equivalent capital cost of installation

A	B	C	D	E	F	G	H
0	0.000	176.7	0	176.7	2202.0	0	2202.0
1	0.424	"	74.9	101.8	1268.6	500	<u>1768.6</u>
2	0.522	"	92.24	84.46	1052.5	800	1852.5
3	0.564	"	99.66	77.04	960.1	1100	2060.1
4	0.587	"	103.7	72.98	909.4	1400	2309.4

- A. Collector Area in m²
B. Area dependent solar fraction
C. Annual cost of water heating of typically 12.4 GJ, (1.425p/MJ)
D. Annual saving i.e. B x C
E. Net cost of auxiliary heating, C - D
F. Product of net present value factor and net heating cost
G. Typical collector cost per unit area including installation, (UK)
H. Equivalent capital cost of annual heating and installed costs

Table 7.3.4 Comparison of various economic scenarios

	A	B	C
1. Anticipated system lifetime, (yrs)	15	20	20
2. Total installed cost, (£)	1840	1400	800
3. Collector area (m ²)	4	4	4
4. Area dependent cost, (£/m ²)	280	240	120
5. Auxiliary energy costs, (p/MJ)	1.425	1.425	1.425
6. Water heating load, (GJ)	9.83	12.4	12.4
7. Prevailing discount rate, (%)	5	5	5

Figure 7.3.12 Optimum collector area under projected UK conditions

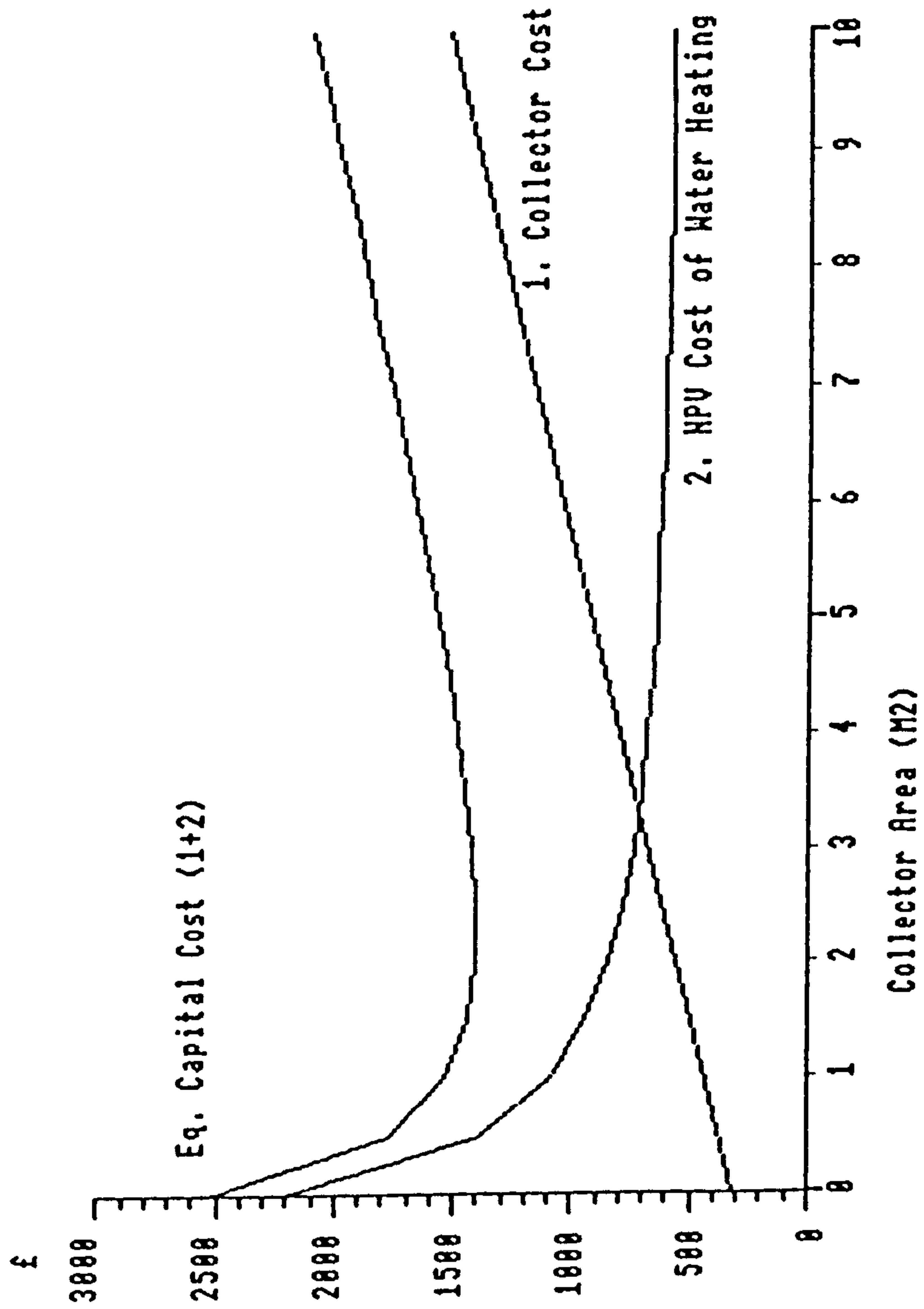


Figure 7.3.13 Optimum collector area for (GULL-AIR) indirect
third-tap system

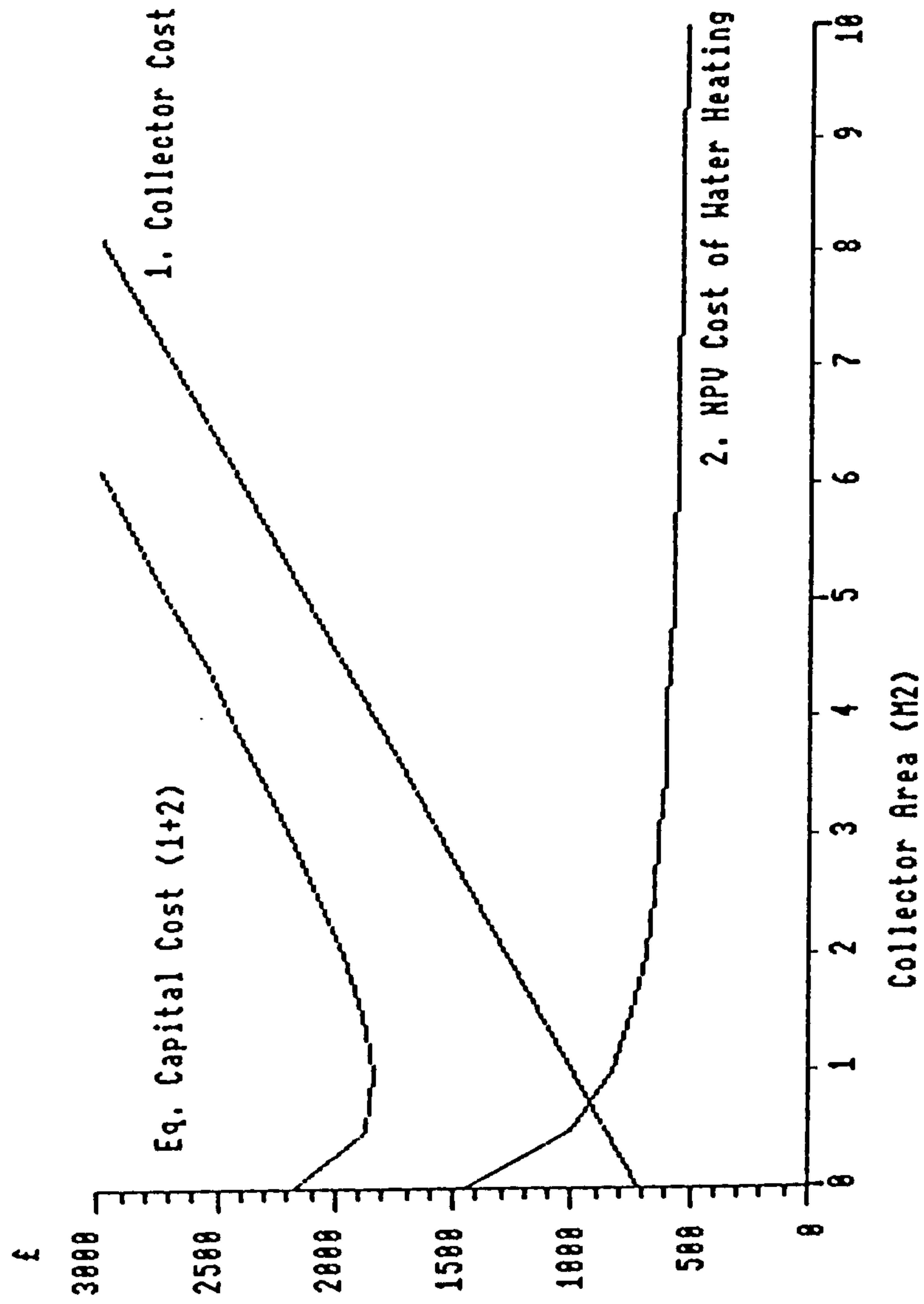
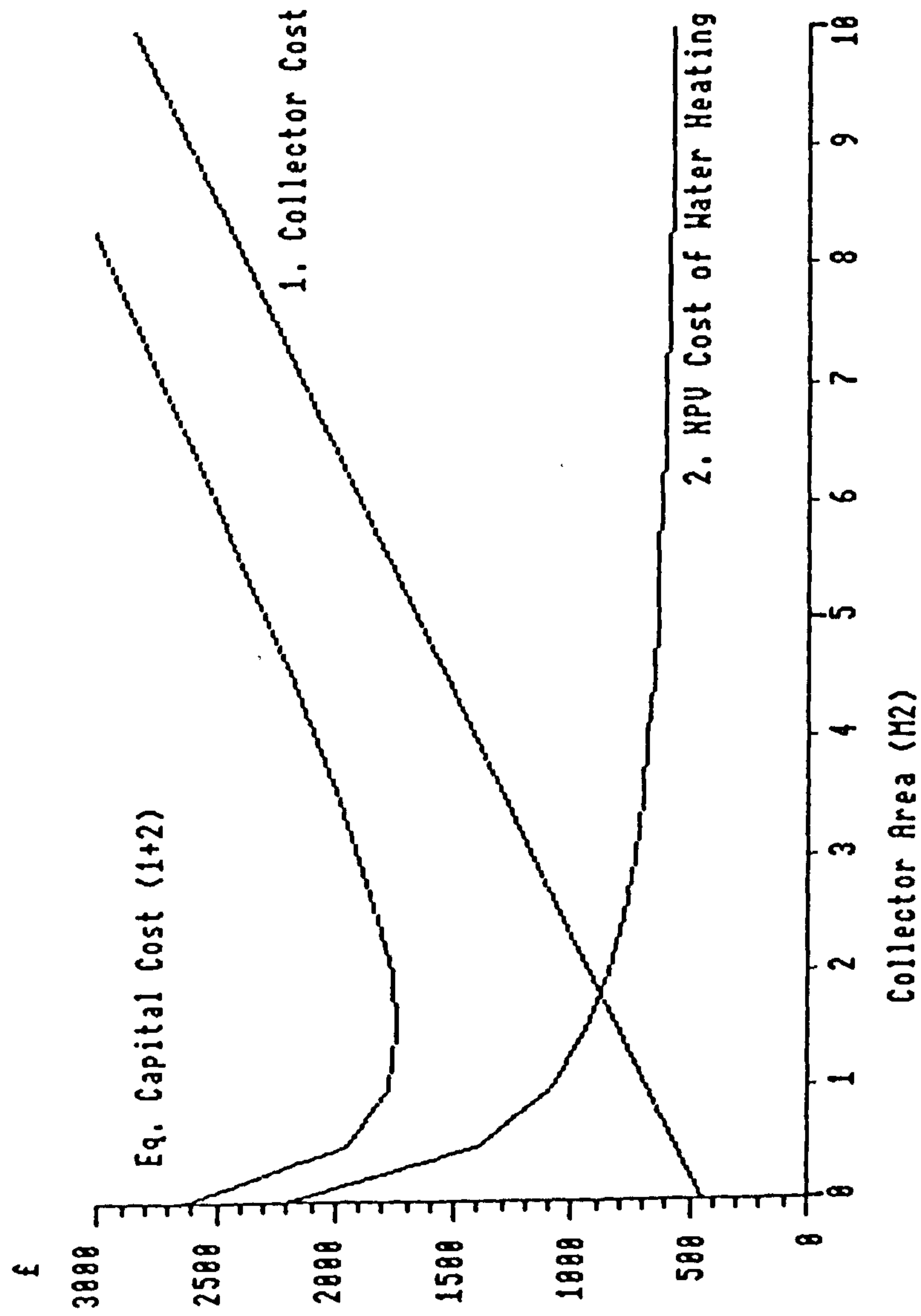


Figure 7.3.14 Optimum collector area under ideal UK conditions



iii) The users comments

Questionnaires were sent to the five different occupants of the three dwellings, throughout the monitoring period. Unfortunately only three were returned, though each house was represented. The size of the three families were similar, as were their comments regarding the effectiveness of the solar-energy water heaters. All of them agreed that the solar-heated water was supplied at a sufficiently high temperature, i.e. equivalent to that of the auxiliary hot water supply. There were, however, some reservations concerning the quantity of solar-heated water provided and also it's strong dependance on the prevailing levels of solar radiation.

The problem of insufficient supply may have stemmed from the lack of "information" which was given by the system. The solar heated water in the third-tap systems was often utilised merely to assess the quantity and temperature of solar heated water which was available. The user of the preheat system, which was without a third tap, would find it difficult to ascertain the solar contribution to the hot water demand. A more tactile indicator of the quantities of solar heated water available may have enabled the users to match the supply to the demand and auxiliary requirements.

Only one user correctly estimated the installed cost of these thermosyphon solar-energy water heating systems. This was hardly surprising as the systems were not purchased by the users.

7.4 References

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CHAPTER EIGHT
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The performance of three types of passive solar feature has been studied:- fifteen Roof-Space Collectors on an estate of low energy houses at the Milton Keynes Energy Park, Buckinghamshire; 101m² of Thermosyphoning Air Panels at a county primary school in Nazeing, Essex; and three Thermosyphon Solar Water Heaters installed on a group of three terraced cottages at Wharley End, Bedfordshire. Each of these passive solar features was monitored intensively for at least one heating season using dedicated data-acquisition systems. The maximum annual solar contributions to space or water heating were 128 kWh/m², 78 kWh/m², and 104 kWh/m² respectively, with, upon replication, corresponding payback periods of 25, 37 & 21 years.

i) Roof-space solar-energy collectors

As the glazed loft spaces had little or no means of storing daytime solar gains, the primary influence upon the space-heating contribution from the RSC's was the buildings' occupancy patterns. (This was far more significant than for the TAP's and thermosyphon solar water heaters.) It was not anticipated that such a disparate variety of occupancy patterns would prevail. There proved to be a strong correlation between the performance of the individual dwellings and the Beneficial Operation Index, (BOI). This was evident by the relationship between the BOI and efficiency, with maximum values of 99% and 65% respectively, for the heating season up to 31st January 1990.

However, only two of the fifteen RSC dwellings tended consistently to be occupied over the major part of the insolation period. These yielded the highest RSC efficiency. The efficiencies of the majority of RSC's were between 10% and 15% with corresponding low BOI (< 25%). The greatest monthly contributions from the five selected RSC dwellings occurred in December 1989, where the individual BOI, and consequently the auxiliary space-heating demands, were at their greatest.

The maximum Solar Heating Fractions, (SHF), were also dependent upon the BOI of each dwelling with a maximum SHF of 0.2 (20%). One house in particular, with a BOI of almost unity, consistently supplemented the space-heating demands to a greater degree than any other house. Its auxiliary space-heating contribution up to 31st January 1990 was 1496 kWh (for an RSC area of 11.81m²).

Too small a sample of each of the three dwelling types, which formed the Cockerell Grove estate, inspired little confidence in a comparison of their performance with the control houses. A larger sample of dwellings of near-identical form and external arrangement would be required for a more definitive demonstration of their potential performance to be made. With the exception of the few occupants who required a high proportion of their auxiliary heating during the insolation period, this type of passive solar feature would be more suited to institutional or industrial buildings. Such buildings have occupancy patterns which would ensure that near-maximum Beneficial Operation Indices prevailed.

ii) Thermosyphoning-air-panels

The consistent occupancy patterns observed at Nazeing County Primary school were more compatible with the transient performance characteristics of the TAP's. Unfortunately the sub-optimally designed collectors only produced maximum monthly efficiencies of 34%. The total annual space-heating contribution from all of the TAP's was 2049 kWh to give an annual solar heating fraction of 0.06 (6%).

The minimum temperature difference required to initiate thermosyphon air flow was never exceeded in the TAP's on the west facade, and rarely so in the TAP's on the east facade. Unfortunately the contribution to space heating from the south facing TAP's was also insufficient to recover the cost of the initial investment within the expected lifetime of the cladding units on that facade.

iii) Thermosyphon solar-energy water heaters

The maximum monthly solar fractions of the three solar-energy water heaters were 0.28, 0.29 & 0.42 with corresponding efficiencies of 15%, 18% & 22%. "Controlled" solar-heated water consumption profiles in two of the dwellings increased the monthly solar fractions to 0.4 & 0.46 for houses No.7 and No.9. The remaining solar water heater, (the only system to provide sufficient data to enable annual calculations to be made), contributed 417 kWh to the water heating requirements, with a solar fraction of 0.17, from September 1986 - September 1987. All three systems were unable to meet the hot water demands of the occupants yet the cost of an installation of greater area would be prohibitive.

If the prevailing system characteristics were used to calculate discounted payback periods for various sites in Europe then the economic viability of this particular thermosyphon solar-energy water-heater was directly related to the levels of regional insolation. In reality the total installed costs and the local tariffs for auxiliary energy differed significantly from the U.K. base-case. However, as more data become available the process can be refined quite considerably.

iv) Monitoring

In all three passive solar systems, almost without exception, the failure of sensors disrupted the continuity coverage of the monitoring processes. Even the use of costly - and reputedly more reliable - solid state devices in the RSC dwellings did not guarantee error-free monitoring! Conversely the surplus of thermocouples used to monitor the TAP's, though relatively cheap and less accurate, allowed failed sensors to be substituted or their likely output inferred from the remaining sensors. These advantages more than justified such additional expense. This economic-but-more-robust approach for monitoring air heating collectors was not entirely compatible with the more hostile environment within the thermosyphon solar water heaters, especially when the circulating fluid was propylene-glycol. (It proved more difficult to seal the thermocouple sensor pockets in the indirect system which used propylene-glycol as the heat-transfer fluid).

v) Construction

Incorrect on-site supervision proved to be one of the most costly problems encountered for all three passive solar features. Communication between architects, contractors, builders and on-site supervisors was very often non-existent, and in the best cases was usually restricted to drawings which showed form but not function. The contractors found the unconventional construction of the innovative passive solar feature confusing occasionally, and many misunderstandings arose.

There is also an unfortunate dichotomy between the widely perceived need for non-intrusive passive solar features, (both in terms of operation and architectural obtrusiveness), and the possible

optimization of system performance which ensues from sympathetic occupant interaction. This was clearly illustrated by the influence of the occupants on the TAP's and the thermosyphon solar water heaters. In the latter case they optimised the solar contribution by waiting until the end of the day to use the solar heated water. By contrast some of the teachers at Nazeing County Primary School did not fully understand TAP operation; many of the TAP's were obstructed by posters and bookcases. Perhaps only energy-saving measures which reduce fuel bills that the occupants are directly responsible for, are more likely to promote behaviour which optimises system performance.

The additional cost of these passive solar systems, especially the two retro-fit installations, (i.e. the TAP's and water heaters) gave unacceptably long payback periods.

"Do-it-yourself" installation of the RSC's and thermosyphon solar water-heaters by an appropriately instructed enthusiast would reduce the overall cost. It would also avoid any confusion regarding the operation of the system concerned as such installers should also be more aware of the conditions which encouraged optimum performance.

vi) Recommendations for further work

Despite the wealth of theoretical and "laboratory" studies concerning the performance of the particular passive solar systems considered, there is relatively little published data regarding thermal and economic performance together with system reliability in occupied buildings. Sadly the cost of such a thorough demonstration of all facets of system design, configuration, and their interactions with occupancy patterns and weather would be prohibitive.

Further monitoring of the TAP's and RSC's over a full heating season is required to evaluate accurately the potential annual performance.

Detailed measurements of flow rate and TAP inlet/outlet temperatures up to insulations of 800W/m^2 are required to validate fully the correlation between these two parameters. In future work the space-heating gas flow-rate in the warm-air heating system must be calibrated in order to calculate the true space-heating gas consumption.

APPENDIX A
CONSTRUCTION DETAILS OF TAP's

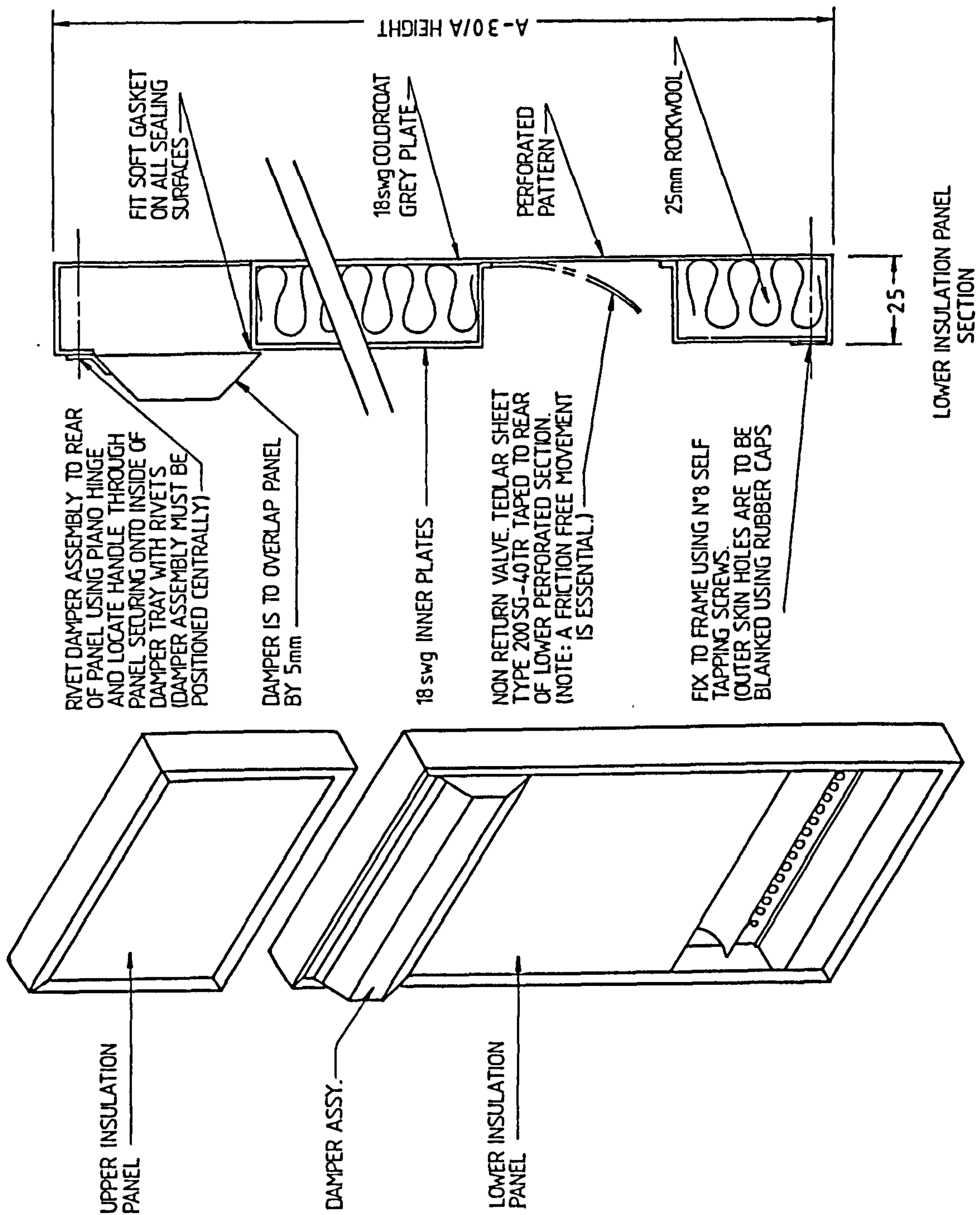


Figure A.1 General arrangement of insulation panel of TAP

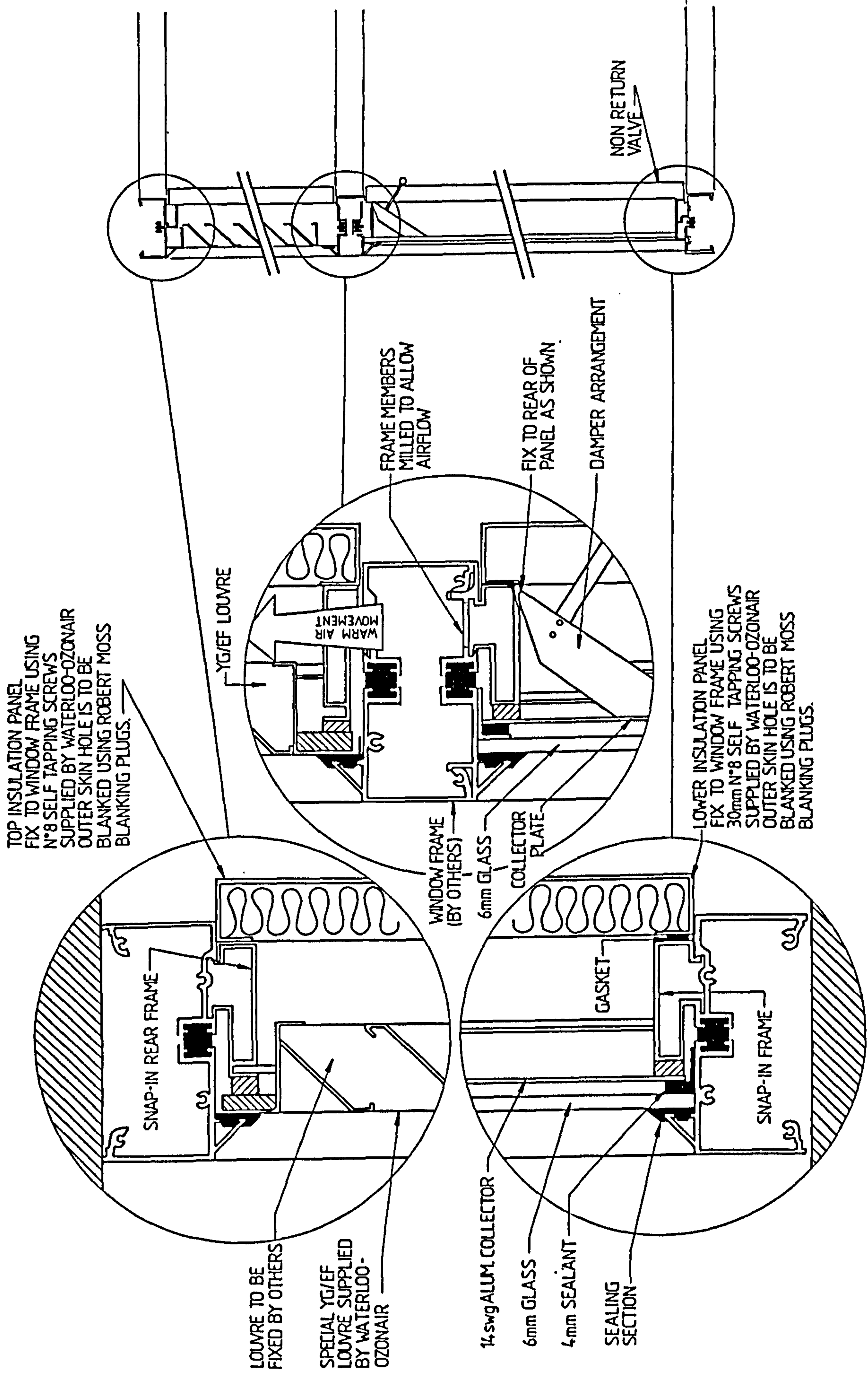


Figure A.2 Construction details of glazing/damper assembly

TABLE A1 COST BREAKDOWN FOR SOLAR CLADDING ASSEMBLIES
FOR NAZEING COUNTY PRIMARY SCHOOL

(REFERENCE DRG. 1042-2B) ACL 25-08-87

Element	Current Project (1 off Batch)	Estimated Production Costs (10 No Batch)
1. Collector Plate (Alum.) 2m x 1m x 14 swg Powder Coat	£70	£40 (Plasticised Aluminium)
2. Lower Panel Plus Damper & Non-Return Flap (Plastisol)	£173	£142 (Alum. Frame & Flat Sheet)
3. Vent Louvre 1m x 0.7m Powder Coat Insect Screen	£119	£98
4. Upper Panel 1m x 0.7m (Plastisol)	£72	£51 (Alum. Frame & Flat Sheet)
5. Development Costs, Design Time, Site Visits, Meetings, CNC Tapes.	£143	£28 (Typical including Survey)
Total per collector Assembly	£577 (£213/m ²)	£359 (62%) (132/m ²)

NOTE: Large scale production cost could be reduced still further by use of different materials and finish specifications such as PVC framing and pre-insulated panels.

LIST OF MATERIALS AND SUPPLIERS

Solar Collector Panels

Steel Panels	1.6mm thick colourcoat Grey ref 10A05 (BS Stockist)
Insulation	25mm thick Rockwool density 50 kg/m ³ (local Stockist)
Non-Return Flap	Tedlar Sheet 200SG - 40 TR (from Kensulat, London W4)
Inner Steel	1.6mm thick galvanised steel (local Stockist)
Manual Damper	1.0mm thick galvanised steel to (WOZ detail drawing 7250-E)
Louvre	YG/EF louvre to 7254-E. Colour RAL 8131 matt. (Waterloo type or equivalent).
Absorber Plate	2.0mm thick aluminium sheet. Colour RAL 8130 matt
Fixing Screws	No. 8 self tapping x 25-50mm
Blanking Clips	Robert Moss Ref. 10233
Damper Gasket	Specially supplied extra to order, tesa-moll Ref. 4791
Valve fixing tape	50 mm wide Silver Duct Tape (from Zest P J Holloway or local ductwork stockist). Later replaced by foil tape Ref. 98080 from Sheffield Insulation, Bedford.

Ref: ACL
25:08:87

WATERLOO-OZONAIR,
Quarry Wood Industrial Estate,
Aylesford, Maidstone,
Kent, ME20 7NB.

APPENDIX B
LISTING OF DATA-ACQUISITION PROGRAM
USED TO MONITOR THERMOSYPHON SOLAR WATER HEATERS


```

10 ONERRORGOTO2400
20 *IEEE
30 G%=10:REM ensures relays are closed prior to reading next module
40 P%=0:REM... used to keep pulse counting on same channel
50 K%=0:REM K% used as marker for PROCdisc if there has been previous error message
60 MODE7
70 PROCinitialise
80 DIMV$(3,9),V(3,9),T$(3,9),R$(1,5),F$(1,5)
90 lastminute=0
92 solav%=0
94 nsolav%=0
100 CLS
120 PROCgetdatetime:CLS
130 CLS
140 *IEEE
150 REPEAT
160   PROCshowtime
170   PROCdrawoff
180   PROCdisplay
190   UNTILFALSE
200 END
210 DEFPROCinitialise
220 CLOSE#0
230 cmd%=OPENIN("COMMAND")
240 data%=OPENIN("DATA")
250 PRINT#cmd%,"BBC DEVICE NO",0
260 PRINT#cmd%,"CLEAR"
270 PRINT#cmd%,"REMOTE ENABLE"
280 PRINT#cmd%,"UNTALK"
290 PRINT#cmd%,"UNLISTEN"
300 ENDPROC
310 DEFPROCgetdatetime
320 PRINTTAB(0,6)"Do you wish to change the draw-off time";
330 PRINTTAB(0,7)"delay ( currently set at approximately  ";E%;" minutes)";:INPUT" (Y
or N)";an$
340 IFan$="Y"ORan$="y"THEN350ELSE370
350 PRINTTAB(0,12)"The time delay is between reading the";:PRINTTAB(0,13)"current (1 lit
re per second) flow and";:PRINTTAB(0,14)"the next(1 litre per second)flow."
360 INPUTTAB(0,16)" New delay (in minutes) is";E%
..

```



```

370 CLS
380 PRINTTAB(0,0)"eg 24 12 1984"
390 REPEAT
400   PRINTTAB(5,10);"Day ";
410   INPUTTAB(12,10)"day
420 UNTILday""OANDday~32
430 REPEAT
440   PRINTTAB(5,12);"Month ";
450   INPUTTAB(12,12)"month
460 UNTILmonth""OANDmonth~13
470 REPEAT
480   PRINTTAB(5,14);"Year ";
490   INPUTTAB(12,14)"year%
500 UNTILyear%~1799ANDyear%~2500ORyear%~OANDyear%~99
510 IFyear%~99THENyear%=year%+1900
520 CLS
530 PRINTTAB(0,0)"time,using 24 hour clock"
540 REPEAT
550   PRINTTAB(5,10);"Hours ";
560   INPUThour
570 UNTILhour""~LANDhour~24
580 REPEAT
590   PRINTTAB(5,12);"Minutes ";
600   INPUTminute
610 UNTILminute""~LANDminute~60
620 CLS
630 TIME=100*60*(minute+60*hour)
640 PRINTTAB(0,10);CHR$(141);"
NOW INSERT DATA DISC":PRINTTAB(0,11);CHR$(141);"
650 PRINTTAB(0,13);CHR$(141);"      AND PRESS RETURN":PRINTTAB(0,14);CHR$(141);"
AND PRESS RETURN"
660 INPUT"cont$:IFcont$~""GOTO670
670 ENDPROC
680 DEFPROCshowtime
690 IFTIME~8640000THENTIME=TIME-8640000
700 hour=TIMEDIV360000MOD24
710 minute=TIMEDIV(100*60)MOD60
..

```



```

720 second=TIMEDIV100MOD60
730 IF(hour=0ANDminute=0ANDlastminute=59)THENPROCincdate
740 lastminute=minute
750 PRINTTAB(0,0);"Date= "day;" ";
760 RESTORE770
770 DATA Jan, Feb, Mar, Apr, May, June, July, Aug, Sept, Oct, Nov, Dec
780 FORX=1TOMonth
790 READmonth$
800 NEXTX
810 PRINTmonth$;" ";year$;" ";
820 PRINT"GMT= ";
830 IFhour~10THENPRINT" ";
840 PRINT;hour;" : ";
850 IFminute~10THENPRINT" ";
860 PRINT;minute;" : ";
870 IFsecond~10THENPRINT" ";
880 PRINT;second;" ";
890 IFsecond=0ANDminute=0THENPROCrec
900 IFsecond=0ANDminute=30THENPROCrec
905 IFsecond=0ANDminute MOD 5=0THENPROCsolar
910 ENDPROC
920 DEFPROCdrawoff
930 r$="L":PROCevent
940 J#=65
950 I#=1
960 IFP#~5THENP#=0
970 IFP#~0THENJ#=66:I#=P#:GOTO1040:REM... stay with same channel if still counting
980 IFF$(J#-65,I#)=0THEN1060
990 IFF$(J#-65,I#)=F$(0,2)ANDF$(J#-65,I#)~0THENPROCrec:GOTO1090:REM...record if there i
s a
1000 IFF$(J#-65,I#)=F$(0,1)ANDF$(J#-65,I#)~0THENPROCrec:GOTO1090:REM...pulse on a free c
hannel
1010 IFF$(J#-65,I#)=F$(0,I#)THEN1060:REM...don't record if pulse on "cold mains"
1020 IFF$(J#-65,I#)=1THENPROCrec:PROCdisplay:GOTO1090:REM record at start of d
raw-off
1030 IFI#~5GOTO950
1040 IFR$(J#-65,I#)~F$(J#-65,I#)THENR$(J#-65,I#)=F$(J#-65,I#):PROCdelay:PROCdisplay:CLOS
EEW#:P#=I#:GOTO1110:REM...if previous ~ present don't record : GOTO1080 avoids 1070 P#=0

```



```

1050 IFR%(J%-65,I%)~~0ANDR%(J%-65,I%)=F%(J%-65,I%)THENR%(J%-65,I%)=0:PROCrec:GOTO1090:REM
...record if previous pulse = present pulse and ~ 0. i.e. end of draw off
1060 IFI%~4THENI%=0:J%=J%+1
1070 IFJ%=67THEN1090
1080 I%=I%+1:GOTO980
1090 CLOSEEW%
1100 P%=0:N%=0
1110 ENDPROC
1120 DEFPROCOFF
1130 VDU23;8202;0;0;0
1140 ENDPROC
1150 DEFPROCincdate
1160 day=day+1
1170 IF(month=2)AND(day~29)THENday=1:month=3
1180 IF(month=2)AND(day=29)THENIFNOTFNLEAP(year%)THENday=1:month=3
1190 IFday~31THENday=1:year%=year%+1
1200 IFmonth~12THENmonth=1:year%=year%+1
1210 ENDPROC
1220 DEFNLEAP(Y)
1230 IFYMOD4=0AND(YMOD100~0ORYMOD400=0)THEN=TRUEELSE=FALSE
1240 DEFPROCrec
1250 r$="L":PROCevent:REM.. read all event counts
1260 r$="R":PROCevent:REM.. re-set to zero:using B% to dump the values!
1270 C%=C%+1:G%=10
1280 FORM%=65TO68
1290 FORN%=0TO9
1300 A%=OPENIN("7")
1310 m%=CHR$(M%)
1320 n%=STR$(N%)
1330 IFG%=M%THENY%=m%+n$+"T"ELSEY$="AJTBJTCJTDJT"
1340 IFM%=65ANDN%=1THENrange$="E0":GOTO1360
1350 IFN%=0THENrange$="E0"ELSErange$="E3"
1360 PROCoutput(A%,Y$,range$)
1380 response$=FNinput(A%)
1390 CLOSEEA%
1400 IFG%~M%THENG%=M%:GOTO1300
1410 IFresponse$="$$$"THENT%(M%-65,N%)=200:GOTO1500
..

```



```

1420 v(M%-65,N%)=FNasci:REM in volts if N%=0 or N%=1 and M%=65, else in mV
1430 IFN%=0THENCJC=10*(v(M%-65,0)):T%(M%-65,N%)=CJC:x=CJC/100:CJCmv=100*(-3.4898E-6+x*(0
.0386+x*(4.1998E-3+x*4.7914E-5))):GOTO1500
1440 IFM%=65ANDN%=1THENT%(M%-65,N%)=v(M%-65,N%):GOTO1500:REM zero drift compensation (sen
sitive to temperature)
1450 IFM%=65ANDN%=8THENV(M%-65,N%)=v(M%-65,N%)*1:GOTO1500:REM thermosyphon flowmeter cali
bration
1460 IFM%=65ANDN%=9ANDsolav%=""0THENT%(M%-65,N%)=INT(solav%/nsolav%):solav%=0:nsolav%=0:GO
TO1500:REM Take mean solar insolation value
1465 IFM%=65ANDN%=9ANDsolav%=0THENT%(M%-65,N%)=INT(v(M%-65,N%)/9.91E-3):GOTO1500:REM If m
ean not available, take inst.insolation value.
1470 T=(v(M%-65,N%))+CJCmv:REM mv
1480 x=T/4.277
1490 T%(M%-65,N%)=INT(4.277*(1.0299E-3+x*(25.8751+x*(-2.9834+x*0.4868)))):REM temps
1500 NEXTN%
1510 G%=M%:NEXTM%
1520 PROCdisplay
1530 IF(F%(0,2)=""0)OR(F%(0,1)=""0)THEN1540ELSEPROCdisc
1540 ENDPROC
1550 DEFPROCevent
1560 W%=OPENIN("6")
1570 FORJ%=65TO66:j%=CHR$(J%)
1580 PRINTcmd%, "UNTALK"
1590 PRINTcmd%, "LISTEN", W%, "EXECUTE"
1600 FORX=0TO200:NEXTX
1610 PRINTdata%, j%+r%+"Q"
1620 PRINTcmd%, "UNLISTEN"
1630 PRINTcmd%, "TALK", W%
1640 FORX=0TO200:NEXTX
1650 PRINTcmd%, "READ BINARY", 5
1660 FORI%=1TO5
1670 IFr%="L"THEN1680ELSEB%=BGETdata%:GOTO1690
1680 F%(J%-65,I%)=BGETdata%
1690 NEXTI%:NEXTJ%:CLOSEW%
1700 ENDPROC
1710 DEFPROCdisc
1722 *DR.0
..

```



```

1724 fle8=0
1730 X=OPENUP("].DATA")
1740 PTREX=EXTEX
1750 BPUTEX,day
1760 BPUTEX,month
1770 BPUTEX,hour
1780 BPUTEX,minute
1790 BPUTEX,second
1800 FORJ8=65TO66:FORI8=1TO5
1810     BPUTEX,F8(J8-65,I8)
1820     NEXTI8
1830 NEXTJ8
1840 FORM8=65TO68:FORN8=0TO9
1850     IFT8(0,9)~0THENT8(0,9)=0
1860     IFM8=65ANDN8=1THENT8(M8-65,N8)=INT(10*T8(M8-65,N8)):REM zero offset drift in mV
-- *10 to store on disc i.e. 0~T8~255
1870     IFM8=65ANDN8=8THENPRINTEX,V(M8-65,N8):GOTO1940:REM thermosyphon flow 1/second
1880     IFM8=65ANDN8=9THENPRINTEX,T8(M8-65,N8):GOTO1940:REM solarimeter W/sq m -- INTEG
ER
1890     IFT8(M8-65,N8)~0THEN1900ELSE1910
1900     T8(M8-65,N8)=255+T8(M8-65,N8)
1910     BPUTEX,T8(M8-65,N8)
1920     IFM8=65ANDN8=1THENT8(M8-65,N8)=T8(M8-65,N8)/10
1930     IFT8(M8-65,N8)~210THENT8(M8-65,N8)=T8(M8-65,N8)-255
1940     NEXTN8
1950 NEXTM8
1960 CLOSEEX
1970 *IEEE
1980 ENDPROC
1990 DEFPROCdelay
2000 S8=minute
2010 REPEAT
2020     PROCshowtime
2030 UNTILminute"=(S8+E8)MOD(60)
2040 ENDPROC
2050 DEFPROCdisplay
2060 S8=&8
2070 PRINTTAB(0,1)"
2080 PRINTTAB(0,2)" zero =" ;v(0,1);"V CJC=" ;T8(0,0);"C Latrine = " ;T8(0,6);"C
..

```



```

2090 PRINTTAB(0,3)" T/S flow=";v(0,8);"1/s Sol rad.=";T%(0,9);"W/sq.m"
2100 PRINTTAB(0,4)" Ambient temp.=";T%(0,7);"C Recording No. ";C%;"
2110 PRINTTAB(0,5);CHR$(141);" TEMPERATURE degrees C ":PRINTTAB(0,6);C
HR$(141);"
2120 PRINTTAB(0,7)"HouseCJC Col. Con. Cold"
2130 PRINTTAB(0,8)"No. in out. hot main"
2140 PRINTTAB(0,9),T%(1,0),T%(1,1),T%(1,2),T%(1,3),T%(1,4)
2150 PRINTTAB(0,10),T%(2,0),T%(2,1),T%(2,2),T%(2,3),T%(2,4)
2160 PRINTTAB(0,11),T%(3,0),T%(3,1),T%(3,2),T%(3,3),T%(3,4)
2170 PRINTTAB(0,9)"7"
2180 PRINTTAB(0,10)"8"
2190 PRINTTAB(0,11)"9"
2210 PRINTTAB(0,12);CHR$(141);" SOLAR STORAGE TANK"
2215 PRINTTAB(0,13);CHR$(141);" SOLAR STORAGE TANK"
2220 PRINTTAB(0,14)"House Top Bottom"
2230 PRINTTAB(0,15),T%(1,5),T%(1,6),T%(1,7),T%(1,8),T%(1,9)
2240 PRINTTAB(0,16),T%(2,5),T%(2,6),T%(2,7),T%(2,8),T%(2,9)
2250 PRINTTAB(0,17),T%(3,5),T%(3,6),T%(3,7),T%(3,8),T%(3,9)
2260 PRINTTAB(0,15)"7"
2270 PRINTTAB(0,16)"8"
2280 PRINTTAB(0,17)"9"
2290 PRINTTAB(0,18);CHR$(141);" WATER DRAW-OFF litres
;CHR$(141);" WATER DRAW-OFF litres"
2300 $%=&9
2310 PRINTTAB(0,20)"House Cold Hot Solar Hot+Solar"
2320 PRINTTAB(0,21)"
2330 PRINTTAB(0,21),F%(0,3),F%(1,1),F%(1,2)," -"
2340 PRINTTAB(0,22),F%(0,4),F%(1,3),F%(1,4)," -"
2350 PRINTTAB(0,23),F%(0,5)," -",F%(1,5)
2360 PRINTTAB(0,21)"7"
2370 PRINTTAB(0,22)"8"
2380 PRINTTAB(0,23)"9"
2390 ENDPROC
2400 K%=1:REM if K%=1 then PROCdisc. If there has been an error then store data on disc
2410 *D.
2420 IFERR=222THENPROCdscerror
2430 IFERR=&C2THENCLOSE%0:GOTO140:REM.....file open
2440 IFERR=17THEN*D.:REM...escape key pressed

```



```

2450 IFERR=&88THENCLOSE0:GOTO140:REM out of range IEEE
2460 IFERR=&BFTHEN2490:REM....Can't extend
2470 IFERR=&BETHEN2490:REM....disc full
2480 IFERR=233THEN2490:REM.....end of file else end programme and report error
2490 REPORT:PRINTERL:PRINTERR:END
2530 DEFPROCinitialise
2540 CLOSE0
2550 cmd%=OPENIN("COMMAND")
2560 data%=OPENIN("DATA")
2570 PRINT%cmd%,"BBC DEVICE NO",0
2580 PRINT%cmd%,"CLEAR"
2590 PRINT%cmd%,"REMOTE ENABLE"
2600 PRINT%cmd%,"UNTALK"
2610 PRINT%cmd%,"UNLISTEN"
2620 ENDPROC
2630 DEFNinput(device%)
2640 LOCALmessage$
2650 PRINT%cmd%,"TALK",device%
2660 INPUT%data%,message$
2670 PRINT%cmd%,"UNTALK"
2680 =message$
2690 DEFPROCoutput(device%,message$,range%)
2700 PRINT%cmd%,"LISTEN",device%,"EXECUTE"
2710 PRINT%data%,message$
2715 FORX=1TO200:NEXT
2720 PRINT%data%,range$
2725 FORX=1TO200:NEXT
2730 PRINT%cmd%,"UNLISTEN"
2740 ENDPROC
2750 DEFNasci
2760 LOCALm$,r$,l$:l%=LEFT$(response$,1):m%=MID$(response$,2,1):r%=RIGHT$(response$,1)
2770 A=ASC(l$)-64:B=ASC(m$)-64:C=ASC(r$)-64
2780 N=256*C+16*B+A
2790 =(N-2048)/204.8
2800 DEFNerror
2810 LOCALerror%

```



```

2820 PRINTcmd$, "STATUS"
2830 INPUTcmd$, "error$"
2840 IF(error&AND&800000)=0THENerror&=FALSEELSEerror&=TRUE
2850 =error&
2930 DEFNspoll(device$, nochr&)
2940 LOCALmessage$
2950 PRINTcmd$, "SERIAL POLL", device$, nochr&
2960 INPUTcmd$, message$
2970 =message
2980 DEFNppoll
2990 LOCALresponse&
3000 PRINTcmd$, "PARALLEL POLL REQUEST"
3010 INPUTcmd$, response&
3020 =response&
3030 DEFPROC solar: REM..Records solar insolation when measured at short intervals
3040 A&=OPENIN("7")
3050 M&=65
3060 N&=9
3070 m$=CHR$(M&)
3080 n$=STR$(N&)
3090 Y$=m$+n$+"T"
3100 range$="E3"
3110 PROCoutput(A$, Y$, range$)
3130 response$=FNinput(A&)
3140 CLOSEA&
3150 sol=FNasci
3160 sol&=INT(0.001*sol/(9.91E-6))
3161 solav&=solav&+sol&
3162 nsolav&=nsolav&+1
3170 *D.
3180 *DR.2
3182 fle&=2
3190 X=OPENUP("].SOL")
3195 PTREX=EXTREX
3200 BPUTEX, day
3210 BPUTEX, month
3230 BPUTEX, hour
3240 BPUTEX, minute
..

```



```

3250 PRINTEX,sol%
3260 CLOSEEX
3270 *DR.0
3280 *IEEE
3290 ENDPROC
3300 DEFPROCdserror:REM....Opens appropriate disk file
3310 IFfile% = 0 THENX=OPENOUT("].DATA"):PRINTEX,"Solar Energy Technology Centre":PRINTEX,"EE
C contract SE034/83 C.":PRINTEX,year%:CLOSEE0:GOTO140
3320 IFfile% = 2 THENX=OPENOUT("].SOL"):PRINTEX,"Solar Energy Technology Centre":PRINTEX,"EEC
contract SE034/83 C.":PRINTEX,year%:CLOSEE0:GOTO140
3400 ENDPROC
..

```