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DESIGN AND PERFORMANCE OF ROOFS

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SUMMARY

The factors influencing roof design with respect to energy conservation are surveyed. In particular low-pitched (~15° inclination) roofs have been shown to possess thermal insulation advantages. Thus relatively low-pitched, northerly facing roofs, together with 61° pitch (i.e. the optimal inclination of plane, solar-energy collectors for maximum winter gain in UK latitudes) southerly facing roofs will probably become more commonplace.

ENERGY CONSERVATION

Mechanical engineers are concerned primarily with harnessing and controlling the sources of power. Thus the capture of solar energy together with improving the thermal insulation of systems are important aspects of mechanical engineering. Nevertheless energy considerations for roof design have been neglected, partly because the subject falls between the traditional responsibilities of mechanical and civil engineers. Also in the UK during the 20 years preceding November 1973, plentiful, relatively cheap and assured fuel supplies were readily available, and so buildings were normally designed without giving energy conservation its just significance—the major design factor being to limit initial capital costs. Thus it is hardly surprising that so many buildings perform in such a thermally inefficient way.

There are approximately 19 million dwellings in the UK each of which loses via its roof on average 4·4 GJ per year.[1] Consumption in housing accounts for some 29 per cent of the national demand for primary energy, and more than two-thirds of this is for space heating.[2] In total, more than 42 per cent of the energy consumed in the UK

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is for space heating. Thus the thermal insulation of buildings offers the prospect of achieving considerable energy savings. For example by 1985 in Holland, it has been estimated that the economically justifiable thermal insulation of dwellings will reduce the nation's total energy consumption by 5·7 per cent, compared with that for 1975.[3]

A recent report of the Government's Operations Committee of the United States House of Representatives recommended that (i) the national rate of increase in energy consumption should be reduced from 4·5 to 2 per cent annually, and that (ii) government loans should be given only with respect to building designs which include appropriately more insulation than had been standard practice previously. It is also suggested that older homes, being improved via government loans, should have their insulation upgraded: the Federal Energy Administration predicted that a 25 per cent tax credit for such purchases as insulation for houses would reduce the USA's oil consumption by 5 per cent.

LOCATION OF THERMAL FAULTS

An excessive rate of heat loss, which may occur even with a relatively new roof, can be due to entrapped moisture which leads to a deterioration of the roof's insulating effectiveness. The rapid detection of such adverse changes may also avoid the subsequent necessity for replacing part of the roof system.

The Remote Sensing Institute of South Dakota University offered during 1975/6 an infra-red camera service to survey, from an aircraft, entire communities and so detect sources of excessive rates of heat loss.[4] Colour variations on the thermograms indicate differences in the apparent surface temperatures of the various parts of a roof. Skill is needed however when taking the photographs and analysing them, e.g. to ensure that one is not misinterpreting a solar reflection from the surface as a source of heat leak. Of the house owners contacted,[4] more than 60 per cent could benefit cost effectively by improving the insulation of their roofs.

The US Army Corps of Engineers has evaluated two techniques for rapidly surveying roof moisture conditions—airborne infra-red thermography and nuclear moisture meters.[5,6] Also the US Army Engineer Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, has studied hand-held, infra-red displays.

Because water has a specific heat some 5000 times that of dry glass-fibre insulant, the effective heat capacity of a moist roof section is significantly higher than that for a comparable dry section. A nuclear moisture probe emits fast neutrons from a radio-active source and counts the back-scattered slow neutrons. This count is directly related to the number of hydrogen atoms present in the test sample. Thus for a uniform-section roof, the nuclear meter readings corresponding to 'wet' areas will be consistently higher than readings for the 'dry' areas.

THERMAL INSULATION

The UK Building Regulations lay down *minimum* (rather than recommended) insulation standards for new housing.[7] Application of cavity and loft insulation to these standards would achieve a realisable saving of about 13 per cent for poorly heated housing.[1] The regulations require that the U-value for a roof (see Table 1) should not exceed 0·6 $Wm^{-2}\,°C^{-1}$ but the present authors would recommend less than 0·3 $Wm^{-2}\,°C^{-1}$. Also the regulations only apply to new housing, i.e. annually to less than 5 per cent of existing stock. As more than 70 per cent of buildings have inadequate insulation, local authorities have been recently empowered to award grants of up to 66 per cent of the cost of applying roof insulation to each uninsulated house or £50, whichever is the lower figure.[8]

TABLE 1
TYPICAL U-VALUES FOR ROOFS

Construction	*Normal (standard) U-value* ($W\,m^{-2}\,°C^{-1}$)
Pitched roofs	
(1) Tiles on battens, roofing felt and rafters, with roof space and aluminium foil-backed, 10 mm plasterboard ceiling on joists	1·5
(2) As (1) but with timber boarding on rafters	1·3
(3) As (2) but with 50 mm glass-fibre insulation quilt between joists	0·5
(4) Corrugated aluminium sheeting	3·8
(5) Corrugated plastic-covered steel sheeting	6·7
Flat roofs (35° *slope*)	
(6) Asphalt 19 mm thick or felt/bitumen layers on 13 mm cement and sand screed, 50 mm woodwool slabs on timber joists and aluminium foil-backed 10 mm plasterboard ceiling, sealed to prevent moisture penetration	0·9
(7) As (6) but with 25 mm glass-fibre insulation laid between joists	0·6
(8) Asphalt 19 mm thick on 13 mm fibre insulation board on hollow or cavity, insulating cement decking, with vapour barrier inside	1·5
(9) As (8) but with 25 mm glass-fibre insulant in cavity, with vapour barrier	0·73

During the winter, the rate of heat loss from a typical existing semi-detached house roof having an overall average U-value of 0·7 $Wm^{-2}\,°C^{-1}$ is 630 W.[9] The provision of a 50 mm layer of insulant at ceiling level, immediately below the attic space, reduces the U-value to about 0·55 $Wm^{-2}\,°C^{-1}$, i.e. to an average rate of heat loss of 450 W through the roof during the heating season. A reasonable estimate for the cost of this operation performed by a contractor might be £45 per house,[10] which would result in a potential saving of about 19 per cent of the total energy input, and a realisable saving in practice of about 6 per cent. The pay-back period, i.e. that in which the accrued financial savings resulting from the reduced rate of energy consumption exactly equal the initial cost of installing the insulation, is less than 5 years. If the house occupier undertakes the installation, the cost falls to about £30, and the measure becomes correspondingly more cost effective.

Improving the insulation at ceiling (joist) level will result in attic spaces becoming colder. Thus there will be an increasing need to thermally insulate cold-water cisterns, feed tanks and associated pipes which are located in lofts.

A method for evaluating the minimum insulation requirement for air-conditioned buildings in the tropics was outlined by Agarwal.[11] Once this requirement has been formulated, the economic thickness of insulation can be calculated from the Macmillan equation:[12]

$$x = \sqrt{\frac{ak}{b}} - Rk$$

where: x = required thickness; b = cost of insulation per m^2 per year; $a = (YM(t_1 - t_2)/3000)$; where M in this instance is the cost per ton of refrigeration (£/ton), Y the number of hours of operation per year, and $(t_1 - t_2)$ the applied temperature difference; R = total thermal resistance of the air boundary layers; and k = the effective thermal conductivity of the applied insulant.

The optimal thickness depends upon the type of roof, density of insulant and total cost of the insulation system. It was found to be approximately the same for both summer and winter conditions in the tropics. For buildings without air-conditioning, the reduction in ceiling temperatures when insulated led to lower radiant heat loads upon the occupants. For air-conditioned buildings, insulating the roof not only helped in reducing the initial refrigeration plant capacity and running expenses but also stabilised indoor air temperatures. In tropical climates, summer heat gain can be further reduced by ventilation below the roof surface and by judicious selection of its colour (see Table 2): light colours reflect more solar radiation than dark colours so that the rate of heat gain is less.

TABLE 2
SOLAR ENERGY, ABSORPTION COEFFICIENTS

	Surface colour	*Absorption coefficient*
	Black	0·95
	Dark grey	0·85
	Light grey	0·65
	White	0·45
Weathered Metals	Copper—tarnished	0·80
Weathered Metals	Copper—oxidised	0·65
Weathered Metals	Aluminium	0·60
Weathered Metals	Galvanised iron	0·90

The absorption coefficient will increase with (i) the changing colour that results from an accumulation of dirt and (ii) condensation on the surface.

CONDENSATION

Heat losses through roofs can be reduced by insulating lofts and/or cutting down air infiltration.[13] However, recently constructed houses experience less draughts because of, for example, the absence of chimneys for open fires. Also modern emulsion paints tend to make walls less pervious to water vapour. Double glazing normally prevents condensation on windows (where it is obvious and can soon be mopped up) so it occurs insidiously elsewhere, possibly resulting in structural damage. Sometimes the level of thermal insulation and draught-proofing is so effective that 'reverse' condensation ensues, i.e. condensation on the internal walls during summer. Simultaneous with these developments it has become more common to own domestic labour-saving appliances (e.g. dishwashers and washing machines) which release water vapour into the internal environment. This is augmented by more than a pint of water per night which each person on average exhales while asleep.

In calm external air conditions, between 15 per cent and 30 per cent of the air entering a roof space comes from the dwelling below, the exact amount depending on the roof design.[14] Some of the moisture carried with this air usually condenses in the attic space and can cause considerable damage to timbers and insulants.[15]

The lowest temperature attained by a roof occurs during calm, frosty, winter nights when the sky is unclouded. The cooling effect of the low temperature, outside air is then augmented by the roof (of high thermal resistance materials) radiating heat directly to the clear sky, which in these conditions can have an effective temperature as low as −45 °C for radiation exchanges with the Earth.[16] Then dew and frost form on the roof exterior. Also night-sky cooling can cause the underside of the roof to become so much colder than the air of the house that internal condensation may ensue. Under such circumstances, sprayed-on insulants underneath the tiles can incur interstitial condensation if they are permeable to water vapour.

With low thermal capacity roof claddings, the change in temperature of the *inner* surface as a result of a sudden drop in the effective outdoor temperature takes place rapidly, and the cladding could be more than 5 °C below the outdoor temperature for several hours. The Building Research Establishment has developed a mathematical model which allows designers to assess the amount of condensation that is likely to occur in roof spaces under such non-steady conditions (see Fig. 1).

The general principles for avoiding condensation in an attic space are:[17,18]

(a) introduction of a vapour barrier on the *warm* (i.e. inner) side of the ceiling structure so inhibiting the incursion of moisture from the building;
(b) provision in the roof of a shield to prevent the ingress of rain, the shield nevertheless being permeable to water vapour thereby permitting the diffusion of moisture from the house to the outside;
(c) ventilation of the roof space to the outside air;

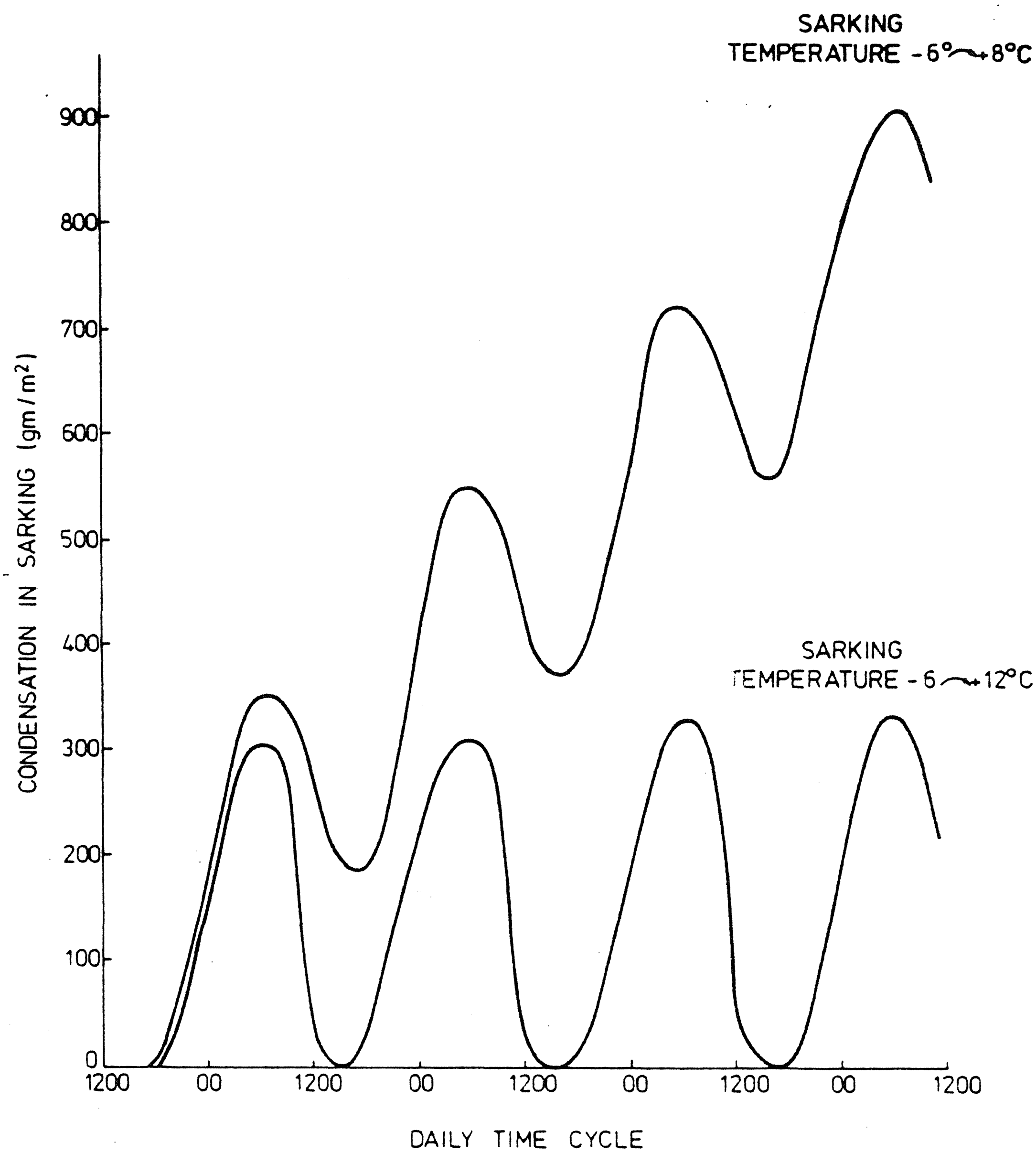

Fig. 1. Predictions from a mathematical model of the moisture condensed in the roof sarking.[17] Assumed ventilation rates: house, $\frac{1}{2}$ air change/hour; roof, 1 air change/hour. Assumed moisture release rates in house: 0·6 kg/hour average; 1·2 kg/hour between 07·00 and 09·00 hours and again between 16·00 and 18·00 hours. A marked reduction in condensation accumulation by a slight increase in the external temperature is shown.

(d) blowing 'dry' air into the roof space under slight pressure so preventing the ingress of moisture; and/or

(e) sucking into the house the air which has been preheated by losses to the attic space, and expelling the relatively high humidity air intermittently only from bathrooms, toilets, kitchens and bedrooms as the need arises.

VENTILATION

In practice, ventilation accounts for at least 20 per cent of the total rate of heat loss from most houses but for well-insulated buildings this may rise to 50 per cent.[19] An average minimum air-change rate of 0·5 per hour is sometimes needed during the heating season to ensure satisfactory removal of waste products, odours and water vapour. However, modern low draught, no chimney designs of houses are sometimes underventilated. Apart from leading to excessive condensation problems, insufficient air for combustion appliances can result in conditions affecting health and safety due to the internal circulation of combustion products.

The tiles or slates of traditional, pitched roofs were often laid directly on battens on rafters, or fixed to the timber sarking, so that the roof space was freely ventilated through gaps between the tiles or slates. However, it is now standard practice to provide the tiles with an impermeable underlay (see Fig. 2) of saturated bitumen felt, PVC or polythene. This underlay inhibits the rate at which moist air can escape from the attic space so that condensation problems have become more severe and frequent.

To inhibit condensation occurring in attic spaces a 10 mm wide gap, under the eaves around the roof perimeter is recommended (BS 5250). This should permit the water vapour in the air *above* the 100 mm layer of insulant, applied at joist level, to diffuse to the outside of the building. Because of the positioning of these vents, and as free

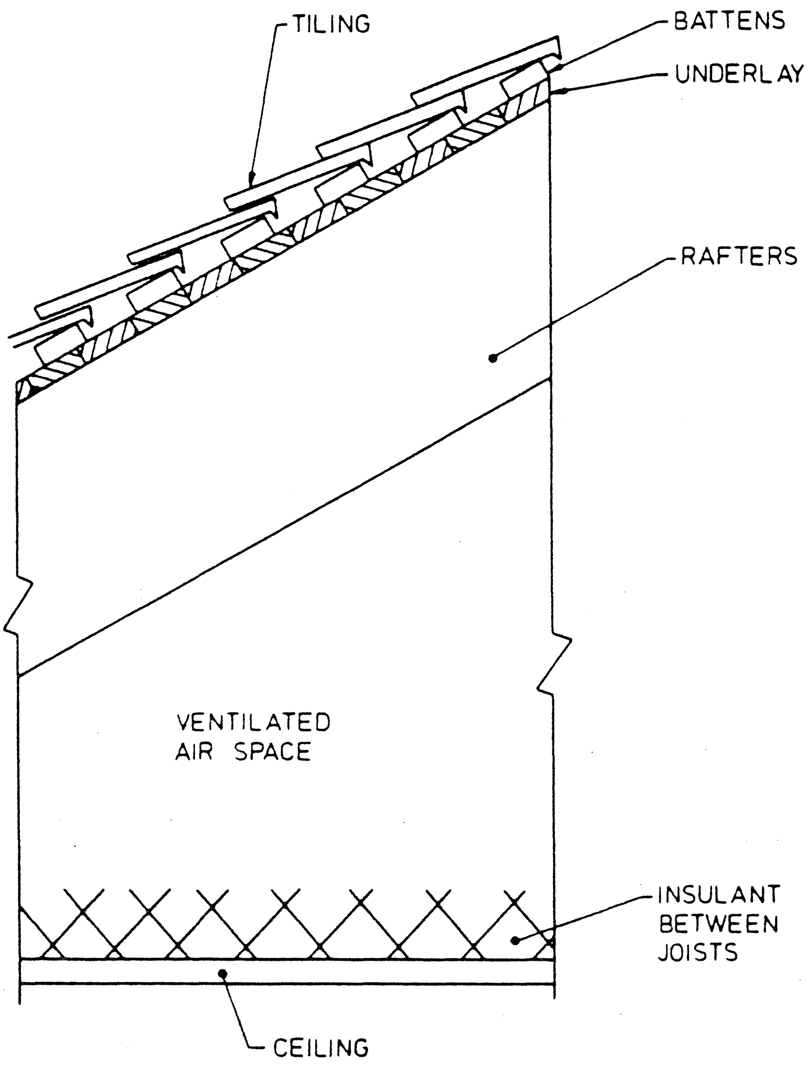

Fig. 2. Cross-section through a typical pitched roof.

convection does not ensue in the presence of a downward temperature gradient, such diffusion occurs without appreciable heat losses. Nevertheless water-vapour diffusion is a relatively slow process compared with ventilation stimulated by a wind.[20,21] Even in the presence of average winds, such narrow ventilation vents properly positioned, will result in only relatively weak draughts and small reductions (dependent upon wind speed and direction) in the effective resistance of the attic space.[22]

Calculations of the effective resistance of the air space within a lined, sheeted roof ventilated to the outside through numerous gaps in the cladding have been made by Pratt.[23] For the attic space considered, the transmittance from the house is hardly affected by cavity ventilation, whereas if the air space is on the warmer side of the insulant, cavity ventilation increases the rate of heat loss considerably.

In tests conducted by Sepsy *et al.*[13] on roofs, the rate of attic ventilation ranked second to ceiling insulation with respect to energy savings and was a much more influential parameter than the solar absorptivity. A cost analysis was carried out to determine how both the roof space ventilation rate and the roof space insulation influence the thermal load (see Fig. 3). To optimise the insulation required, the initial

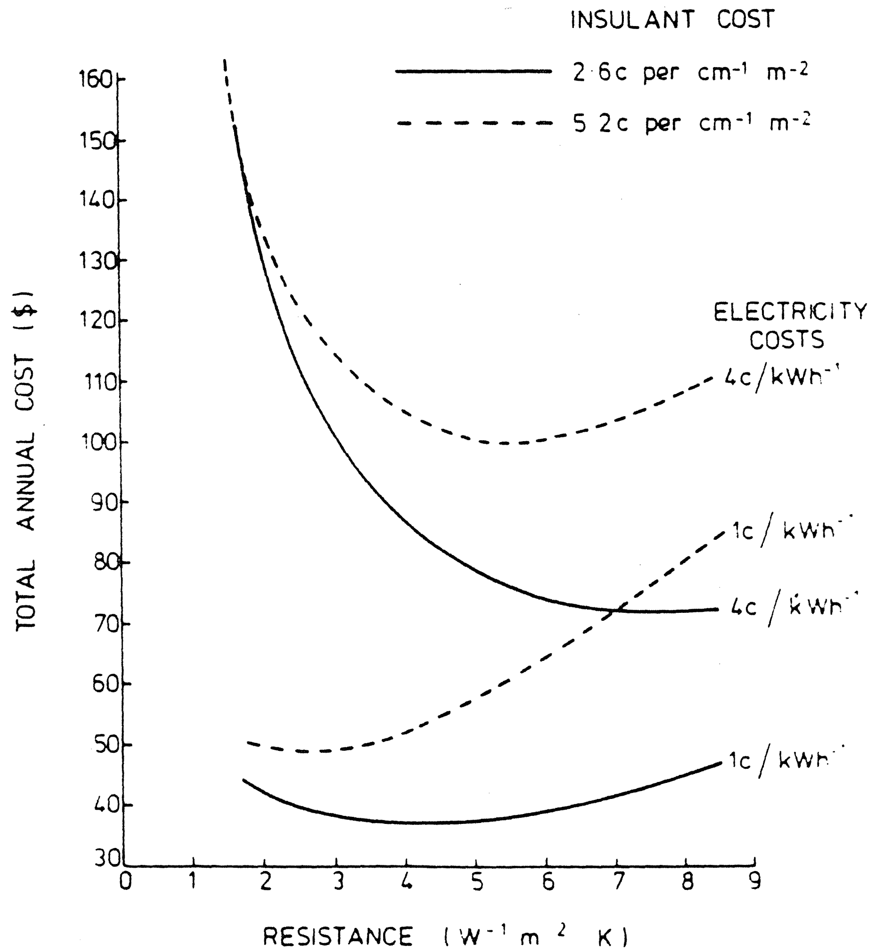

Fig. 3. Average cost (= capital cost plus total running costs divided by lifetime of system) for a typical roof versus its thermal resistance for two different unit energy costs.

cost of the insulation was amortised over the expected lifetime (20 years) of the structure, the resulting year-end payments were then added to the annual heating (and cooling) costs of handling the thermal loads of the ceiling. The resistance which yielded the lowest annual cost is regarded as the optimum.

FLAT ROOFS

Maintaining adequate insulation of flat roofs over longer periods is difficult. Part of the problem is related to poor design. Confusion frequently arises concerning the optimal location of vapour checks or barriers (such as bitumen felt, mopped with hot bitumen) in flat roofs and also about the necessity for ventilation.[24] In general flat roofs fall into two distinct types, which will now be described.

In the first, the thermal insulant is at ceiling level with the roof void being cold relative to the room below and consequently there is a risk of condensation in the void. This problem can be overcome by placing an impermeable vapour check between the ceiling and the insulant—i.e. 'below deck' insulation[14]—and permitting the roof void to be ventilated (via the eaves or perimeter walls) to permit the exit of water vapour that succeeds in by-passing the vapour barrier (see Fig. 4).

The alternative is the inverted roof (see Fig. 5). For this, the insulant is placed immediately under the roof covering but over the roof deck. To prevent interstitial

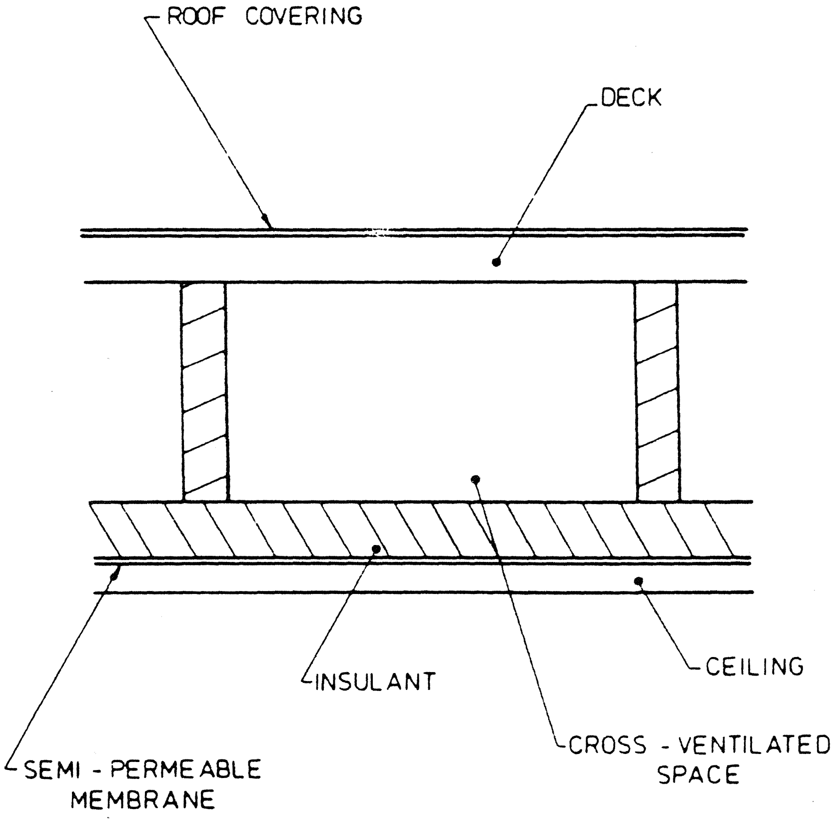

Fig. 4. Flat roof with the air space ventilated to the external environment.

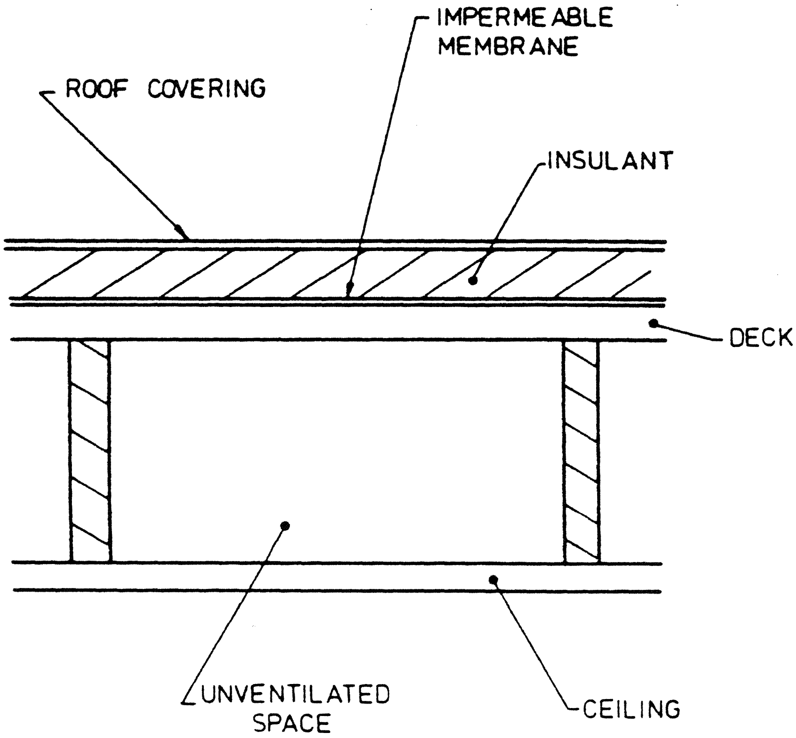

Fig. 5. Flat roof with the air space at near the internal environment temperature.

condensation in the insulant, a complete vapour barrier is interposed between the deck and the insulant. The deck of this particular construction should be kept as near as possible at the internal temperature of the house. Ideally there should be no ceiling, but if one is required it should offer least thermal resistance and be as permeable as possible. No attempt is made to ventilate the roof space, and if the temperature of the vapour barrier is kept above the dewpoint of the air, condensation is avoided. However the insulant in this design needs to be protected both from foot traffic and from the effects of solar radiation. Nevertheless, this is the preferred solution to minimise the risk of condensation.

Each layer in a roof experiences a different temperature cycle and so differential movements ensue. If they are restrained, stresses develop and ultimately the components buckle, crack or otherwise fail. The worst conditions apply when a concrete roofing slab has a dark coloured external finish with the insulant immediately beneath it. Rigid concrete slab and membrane roofs should be insulated *above* the slab, and if possible should have a reflective outer surface. This treatment should be associated with the subdivision of the roof (by expansion joints) into areas for which the thermal movement is so small as not to cause cracking or other damage to susceptible materials and finishes.

High temperatures increase the rate of deterioration of many roofing materials through the acceleration of the photo-oxidative processes, softening bitumens and under extreme conditions, softening the plastic insulants underneath.[25] A large temperature rise may produce sufficient expansion of the air or moisture trapped between the layers of a roof membrane (or within an insulant) thereby causing blisters that can destroy the waterproof characteristics of the membrane.

THE EXTERNAL ENVIRONMENT

Wind assault

This is one of the many phenomena over which man has little control.[26] However the direction and strength of the prevailing wind will appreciably affect the energy balance of a building, and thus the heights of buildings in windswept regions should be restricted.

Large pressure differentials can occur around buildings due to winds, and may result in severe damage to roofs. The force experienced by a roof is dependent upon its inclination. If this is less than 30° to the horizontal, windward sloping roofs suffer considerable suction.[27] A leeward sloping roof always experiences suction, and this becomes more severe the lower the pitch.[28,29]

For a flat roof the air flow tends to lift the structure as a whole. Simultaneously localised air flows at the corners, ridge and eaves of a roof produce fluctuating, low-pressure pockets downstream from the air flow separation zones. These pockets exert high lifting forces locally and may result in material fatigue of the structure. Roof overhangs at the same time can produce a lifting component which serves to enhance the upward acting pressure differential across the structure. Under strong winds the uplift on the roof may be far in excess of its dead weight, thus necessitating firm anchorage to a substantial foundation to prevent the roof from being torn away.

Snow loading

Each roof must be designed and built to support the maximum snow load that it *may* experience. A survey,[30] concerning the depth and residence period for snow on roofs in the UK, indicates that for 95 per cent of the localities where flat roofs were observed, the water equivalent of the snow on the ground does not exceed 34·6 mm more than once in five years. For pitched roofs, this became 35·6 mm. These values are equivalent to loads of 0·352 kNm^{-2} and 0·363 kNm^{-2} respectively.

GEOMETRICAL DESIGN CONSIDERATIONS

Thermal insulation design involves selecting the most suitable shape, structure and surface properties for the system which has to be insulated, as well as the application of the economically most favourable thickness of insulant (as evaluated over the proposed lifetime of the system, due allowance having been made for the future inflation of fuel costs). However, too often, extra insulant has to be applied to try to rectify the effects of poor or careless design, but this afterthought engineering incurs an economic penalty.

(*a*) *Insulation*

The style of building dictates what thickness of insulant can be justified economically. For example, in general it is more important to have a well insulated roof for a bungalow than for a two-storey house because the roof of the bungalow represents a greater percentage of the total peripheral area.

As the application of a high level of insulation becomes more common in housing, and because the ventilation of attic spaces is also increasingly inhibited in order to reduce energy losses, interest is now being shown in air movements in attic spaces. It is for instance economically attractive to make even greater use of the insulating value of this air space. For example isosceles triangle, vertical section roofs of buildings, as in Fig. 7, with pitch angles of near 15° result in attic spaces which achieve relatively high degrees of insulation (see Fig. 6), but this roof pitch is much lower than is traditionally adopted in the UK.[31] (The presented data are specifically for an assembly with the sloping roofs lined on their innermost surfaces with

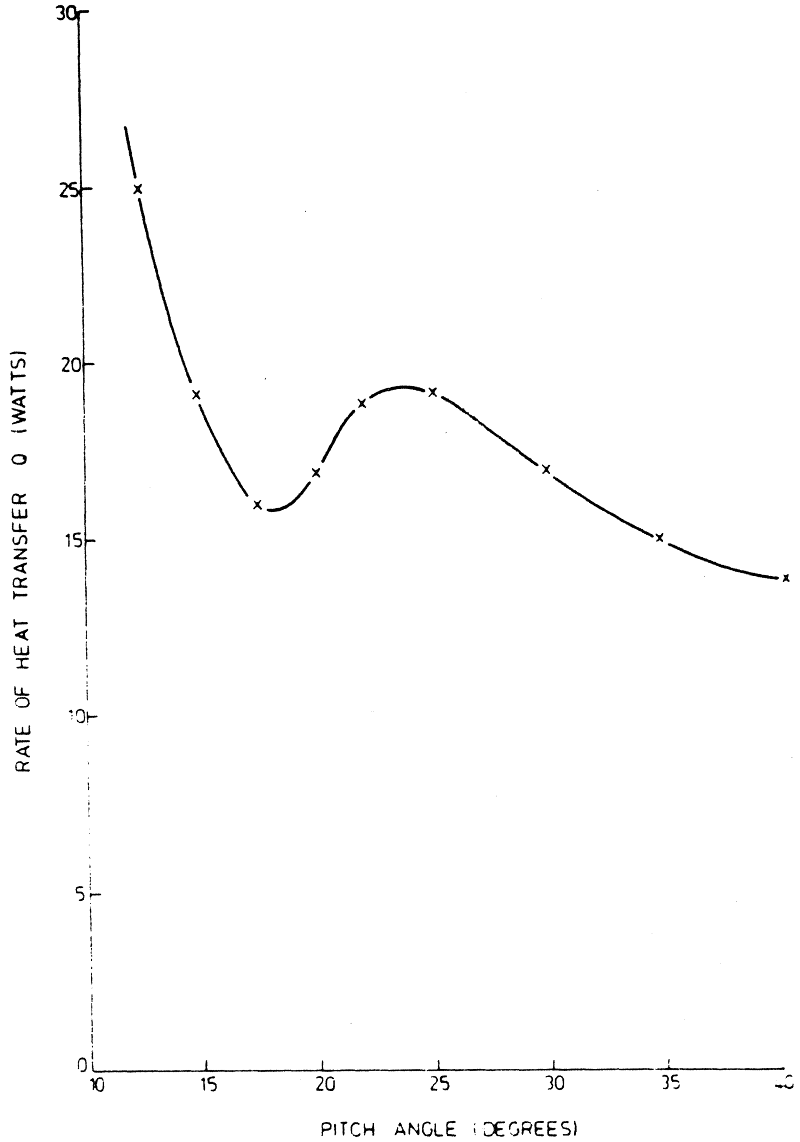

Fig. 6. Experimental data *for a model*. Heat flows upwards across isosceles triangular sectioned model cavities, apex upwards for 20°C steady-state temperature difference between the horizontal base (= 342 mm) and the water-cooled sloping sides. (The vertical triangular, flank walls are very well insulated.)

aluminium foil to minimise the transference of heat by radiation.) In many instances, the centre of the ceiling would tend to be at a slightly higher temperature than near the outer walls[31] and so vortex patterns of the type shown in Fig. 7(a) would be likely to ensue. The air is heated at ceiling level, rises, and is cooled as it passes down the sloping surfaces of the roof. By the introduction of a light-weight baffle of aluminium foil suspended from the roof apex as shown in Fig. 7(b) this

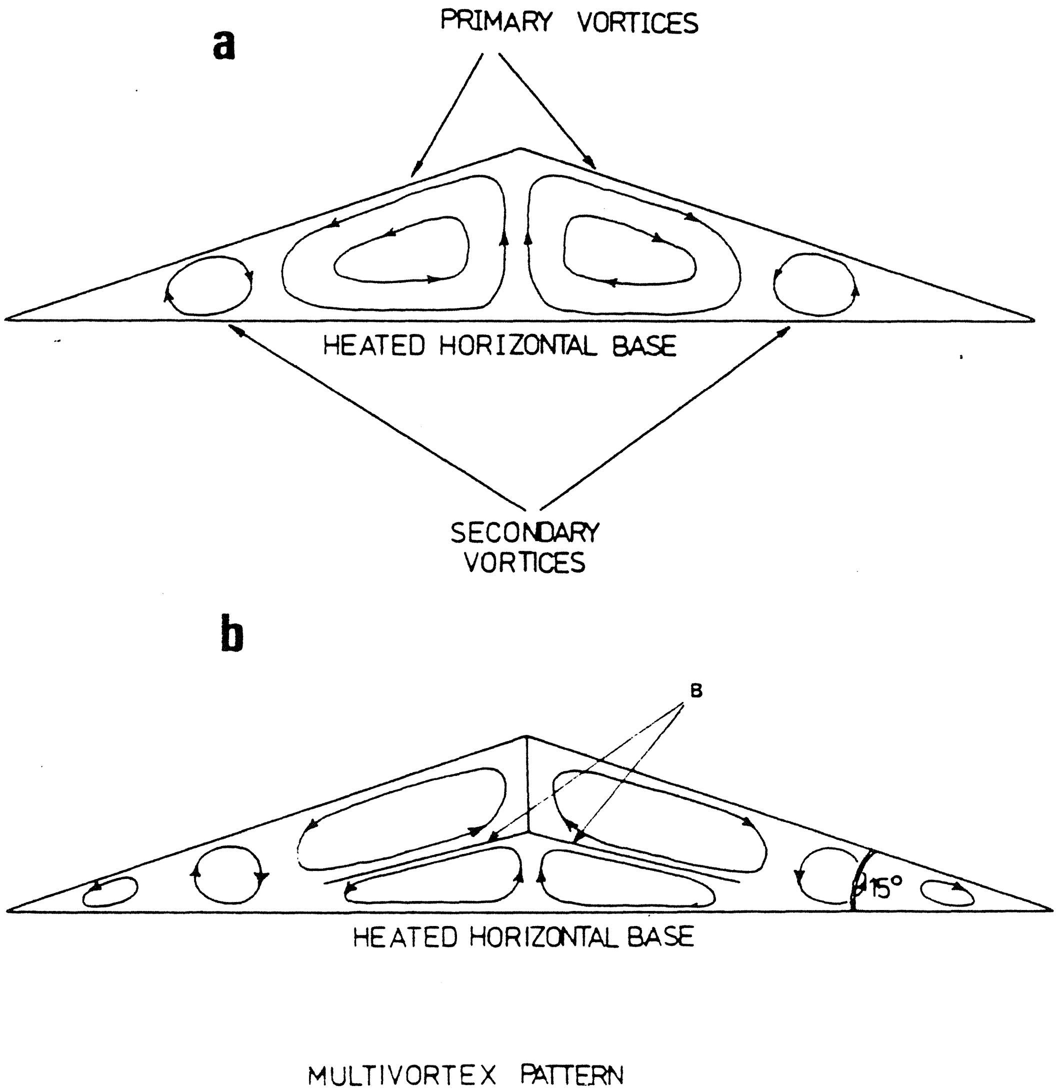

Fig. 7. (a) Convective air-flow pattern within a plain triangular cavity containing air at atmospheric pressure. (b) Inhibition of the convective flows shown in (a) by the introduction of deflector baffles (B).

movement can be redirected, the warm air from the base of the attic being inhibited from impinging directly upon the relatively cold sloping roof. The baffle simultaneously acts as a radiation reflector. Thus by these simple means the rate of heat loss can be reduced appreciably. However, if such baffles are not properly designed and positioned, then their presence can lead to an *enhancement* of convective heat losses. In this model study, the heat losses through the vertical walls were negligible because of externally applied insulant. However the heat losses through the flank walls (extending from the attic floor to the apex of the roof for

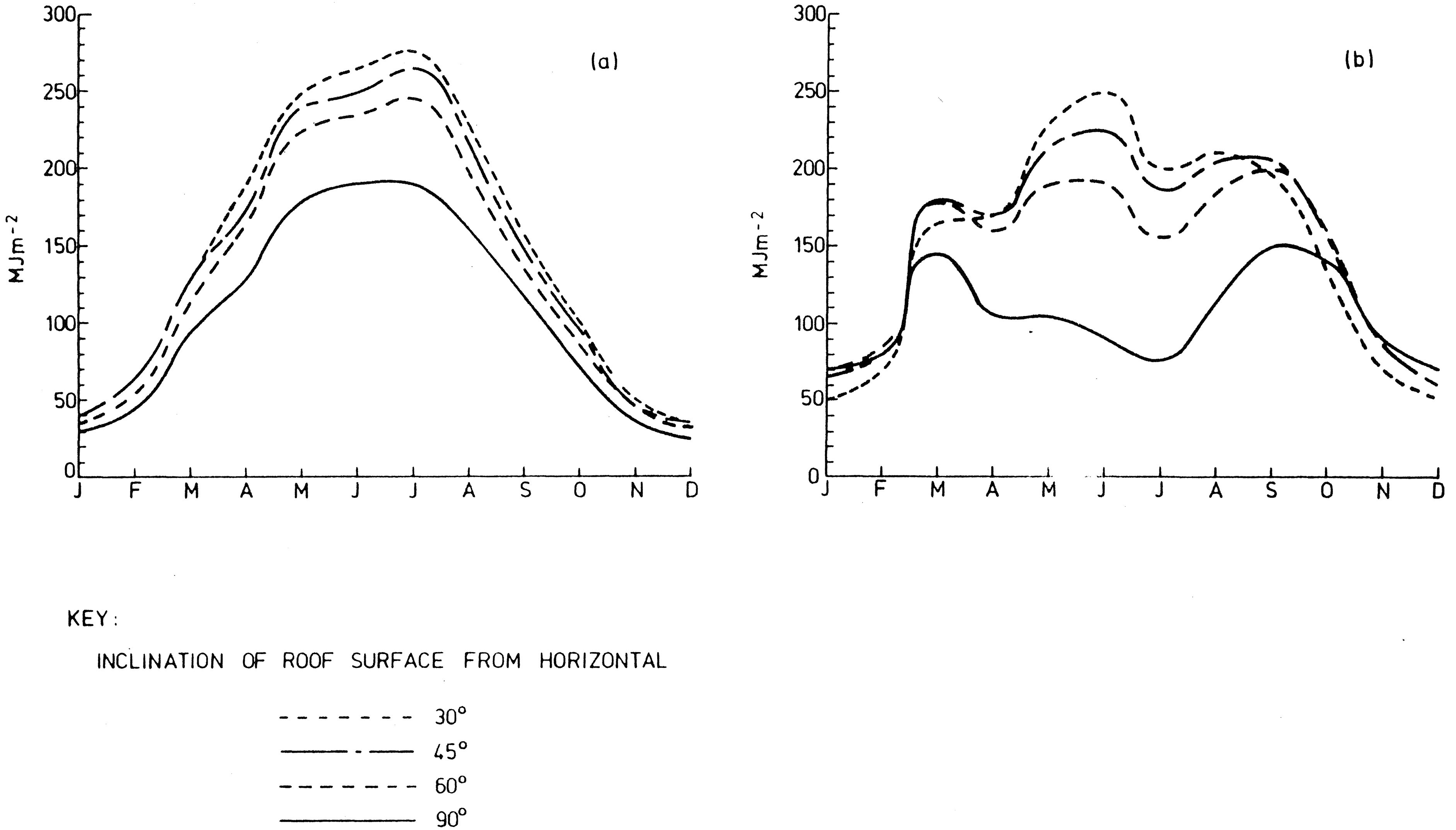

Fig. 8. Solar gain at latitude 51°30′N, longitude 0°0′ for southerly facing surfaces: (a) monthly totals of diffuse radiation on an inclined surface at

normal double pitched roof houses) can be considerable.[33] Thus it is desirable that these flank walls should also be well insulated internally.

(*b*) *Solar energy collection*

In the UK the total energy received by a horizontal surface equal to the plan area of an average house is about 100 MWh/year[34] whereas the nationally averaged heating requirement per house is 14 MWh/year.[35] However solar energy is available most profusely when least needed for domestic purposes, i.e. in summer. Measurements for typical houses indicate that they are passive solar energy collectors with efficiencies of *useful* capture of up to 6 per cent.[36–41] so leading to a contribution of between 2 and 3 MWh/year per average house depending on the level of insulation. This can be increased by the use of a translucent cladding to the southerly facing roof thereby freely admitting solar radiation, while simultaneously inhibiting radiation loss from that part of the roof (i.e. the 'greenhouse' phenomenon). Also if the normal glazing is as far as possible restricted to south-facing walls, the useful capture can be increased by between 0·3 and 0·4 MWh/year.

The optimal angles of inclination to the horizontal of a south-facing solar energy collector for maximum resultant energy capture, equals 61·13° for the winter period (October to March inclusive) and 36·31° for the summer period. With data obtained from the Meteorological Office (e.g. see ref. 42), Figs. 8(a)–(e), have been plotted and

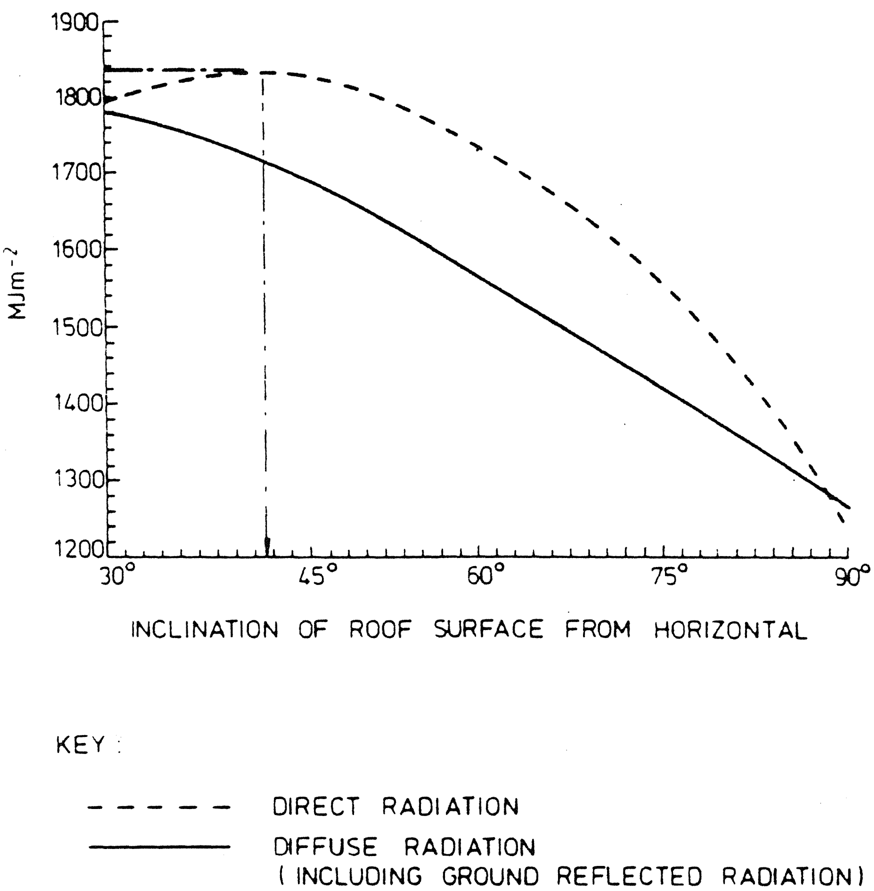

Fig. 8 *contd.* (c) Annual total of solar radiation on an inclined surface.

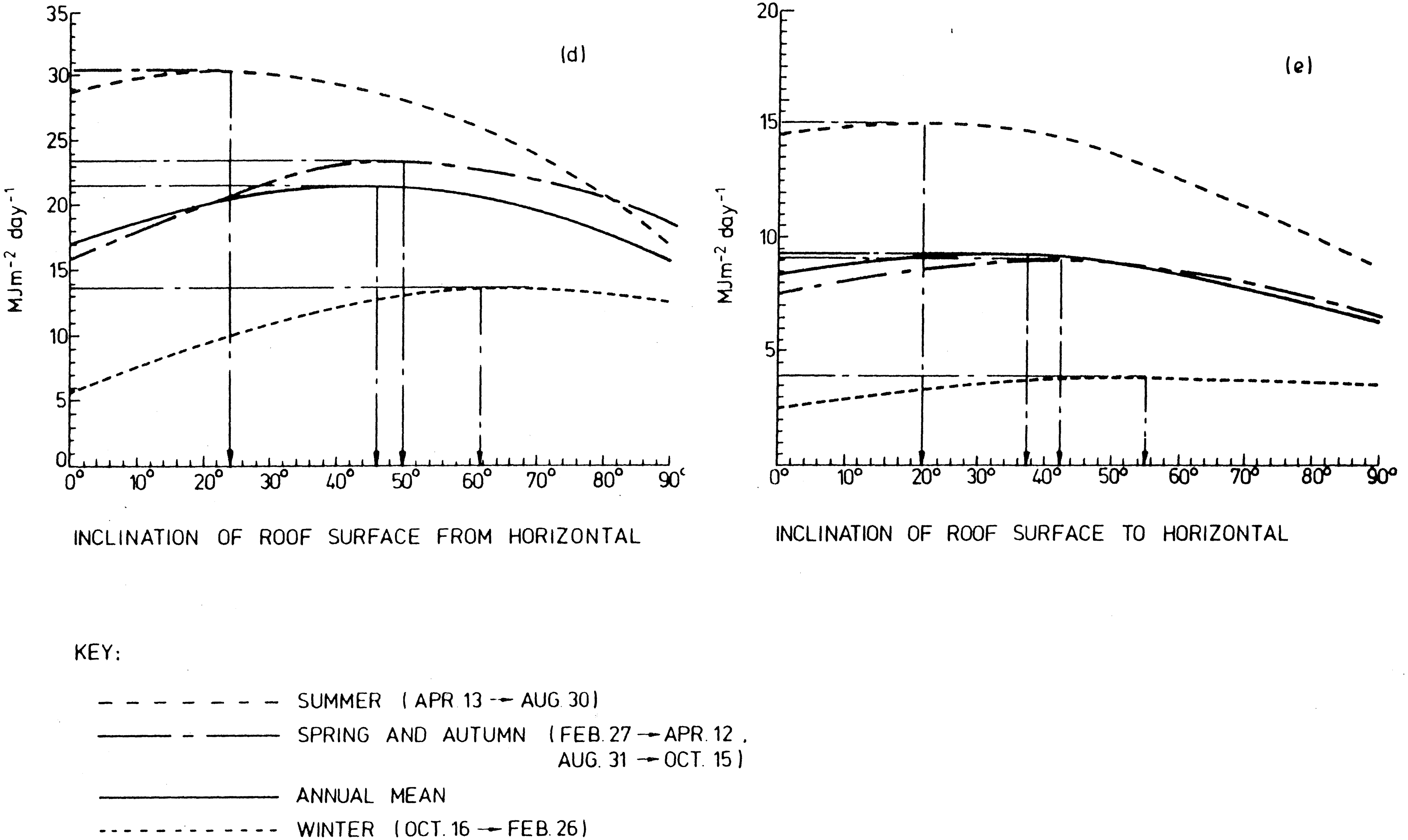

Fig. 8 *contd.* (d) Total radiation in bright sunlight conditions, (e) total radiation under average conditions.

these substantiate these statements. It can also be seen from the standpoint of total annual energy flux captured, that there is little to be gained in having a variable-inclination collector.

Usually modern houses in the UK incorporate a large south-facing window wall. During winter, the Sun is relatively low in the sky, and so solar energy will bathe the southerly facing rooms in sunlight—a highly desirable feature. In summer such sunshine penetration may lead to overheating thereby increasing the loading on the air-conditioning system. However if the roof incorporates an appreciable overhang, in summer this can provide a completely passive heat shut-off. The optimal dimensions of the overhang can be determined from trigonometry and depend on the amount of solid wall above the windows and the depth of the windows (see Fig. 9).

No part of a building or its services should be considered in isolation—all are inter-related from an energy viewpoint. For example from energy conservation considerations the position of the solar energy collector plates on the roof should be

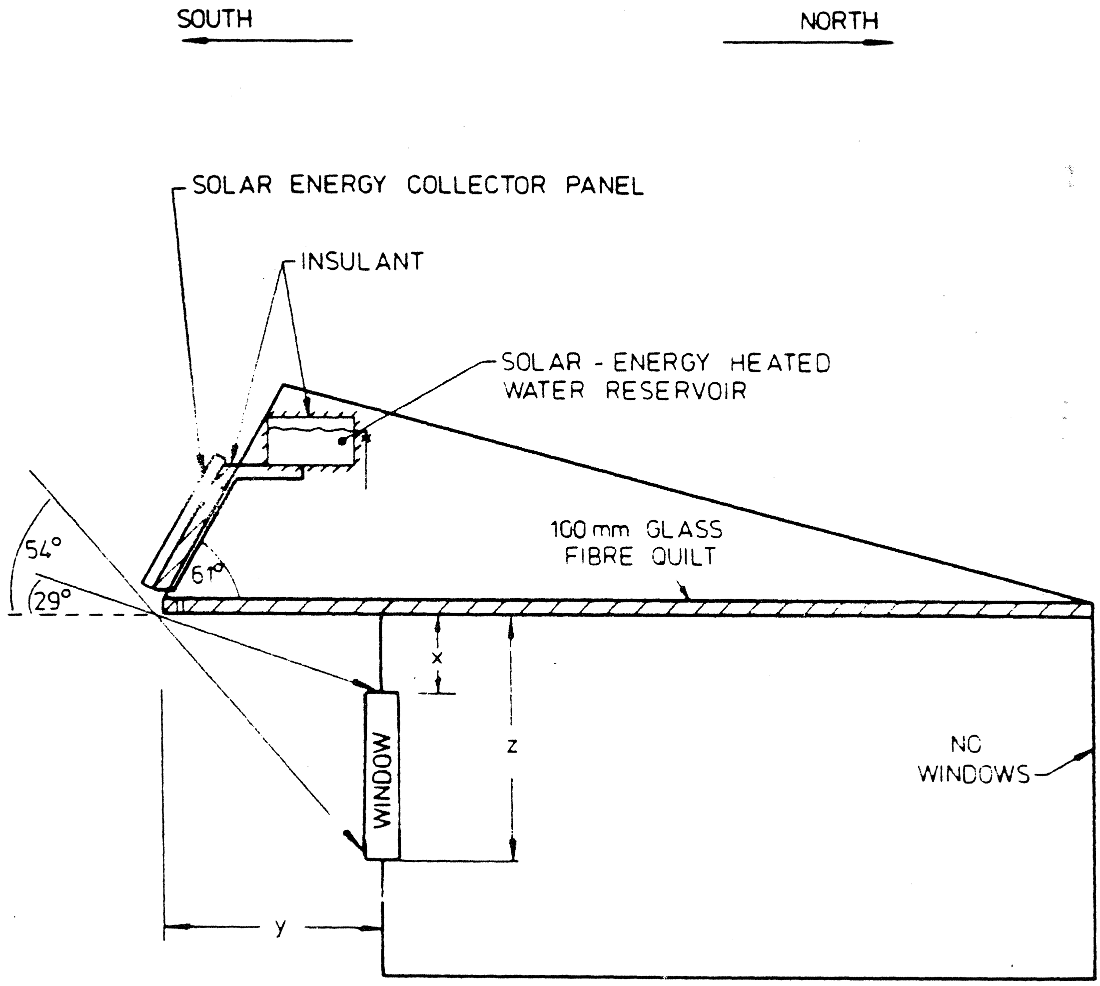

Fig. 9. Schematic building design suggestions (exaggerated and distorted in parts to give emphasis) for energy conservation. The magnitude of y can be calculated using the following information: x = height of masonry above south-facing window; z = distance from eaves to the window's lower edge; $y_{min} = z/\tan 54°$ (because 54° = inclination of summer sun at mid-day, UK); and $y_{max} = x/\tan 29°$ (because 29° = inclination of sun in winter at mid-day, UK).

below the base of the hot-water reservoir (see Fig. 9). This avoids the necessity of having an electric pump for circulating the solar-heated water *downwards* to a thermal store, and so makes the system more than 3·5 times as attractive with respect to the ratio of the energy obtained from the solar collector to that required to build, operate and maintain it throughout its life.

CONCLUSIONS

Eight out of ten buildings which will be standing in AD 2000 have already been built, yet surprisingly little attention has been given to research into heat losses through their roofs. Also many buildings currently being erected for an expected lifetime of at least 60 years, are likely to suffer severely because of poor thermal design and the consequent effects of the rapid inflation of energy costs. Thus future buildings should have energy conservation as a prime consideration. The design of a roof inevitably involves many compromises and the layout suggested in Fig. 9 may serve to remind architects of some of the more desirable thermal features. The roof system should be a single integral unit so that neither the insulation nor the solar energy collector (if incorporated) and associated thermal energy store become afterthoughts and hence more expensive. A comprehensive economic assessment now needs to be undertaken for each building at the design stage so that the accrued cost (i.e. capital cost plus total running cost over the expected lifetime of the roof) can be evaluated for different pitch angles, various geometric designs, applied insulant thicknesses and attic ventilation rates.

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