EXPLORING VARIOUS ASPECTS OF PASSIVE SOLAR ENERGY COLLECTION, WITH PARTICULAR REFERENCE TO ITS POTENTIAL USE IN THE REHABILITATION OF NINETEENTH CENTURY ROW HOUSING IN ENGLAND

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CONTENTS

ABSTRACT

EXPLORING VARIOUS ASPECTS OF PASSIVE SOLAR ENERGY COLLECTION, WITH PARTICULAR REFERENCE TO ITS POTENTIAL USE IN THE REHABILITATION OF NINETEENTH CENTURY ROW HOUSING IN ENGLAND.

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SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE ON 20 JANUARY 1978 IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ARCHITECTURE IN ADVANCED STUDIES.

This thesis provides a description of passive heating, a comparison of active and passive solar heating systems, and a development of a design philosophy. A workbook is presented which provides design tools for architects working with direct heat transfer passive systems. There are two main design tools and both are presented in the form of TI59 (Texas Instruments programmable desk calculator) programs. The first is a design method which assesses the room air temperature for each of eight hours of a clear day. The second design method computes the yearly heating load of a building and its improvement, by first calculating the degree day base temperature of that building and improvement. It goes on to compute the cost benefit and payback period of the improvement by standard methods of discounted cash flow analysis (life-cycle costing). An attempt has been made to cover all aspects of the approach MIT takes to passive solar design.

The second portion of this thesis presents a solar rehabilitation design of a typical nineteenth century row house in England. Performance analyses are conducted on this suggested design and are presented in detail. This portion of the thesis provides a worked example of the design tools presented within the workbook.

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INTRODUCTION

INTRODUCTION

It is necessary to place the concept of solar heating for England within its context.

England has the ability and the resources needed to build for herself a future in advanced technology. A technology that will make present technology appear cumbersome and inelegant. The resources needed to do this are there in abundance: high-energy fuel (oil, coal and gas), a skilled labor force, and inventiveness. But incorrect use of these resources will cause them to be dissipated. This is the point of departure of my thesis:

High-energy fuels are a resource to be treasured and used sparingly for those tasks, involved in the development of this future technology, which demand its condensed energy. Heat, being the least intense form of energy, does not always require the use of these fuels. Space, heating can be adequately met by good design and the use of solar energy. Moreover, energy-conserving building design can both provide an immediate boost to the building-materials manufacturing industry and make a noticeable difference to the future outgoings payable by the owners and inhabitants of the buildings so designed. While the energy involved in the manufacturing of these building materials is important, it is only equivalent to, at the most, two years of operating costs and most buildings have a life in excess of fifty years. This thesis will concentrate on the domestic sector.

Nine million dwellings, nearly half the total number of dwellings in England, have 9-inch thick solid masonry external walls[1a]- they are vastly wasteful of energy and almost all (98%) are terraced (or row) houses. They were mainly built at the height of the nineteenth century industrial revolution and are mostly in need of extensive repairs to prevent dilapidation. The question facing most local authorities in England is whether or not it is more economical to demolish and redevelop or to rehabilitate these row houses. Demolition and redevelopment involves approximately the same capital expenditure as rehabilitation, mainly because higher densities of housing are possible by redesigning the site layout. However, many authorities have made the decision to rehabilitate because of the powerful sociological arguments against destroying mature communities which have developed over a hundred years. Another alternative to rehabilitation is infill; but although this does conserve the social environment it is usually discounted on the grounds of the high costs involved. This thesis accepts rehabilitation as the direction in which we should strive. The reason for this standpoint are largely those mentioned above, but also include the inherent apparent potential of these houses to be passively solar heated. The energy efficiency of the shared party wall, the large volume and high thermal capacity of masonry, with which the houses are built, and the planning regime and spacing between the rows all lend themselves to the requirements of passive solar heating.

The first aim of this thesis is to attempt to show that passive solar heating can be economically applied in the rehabilitation of these row houses in England. Achievement of this aim will add weight to the growing argument of utilizing some of this vast housing resource as opposed to the present trend, which is largely one of demolition and redevelopment. Not all row houses will comply with the orientation requirements for solar heating. For simplicity one plan form has been selected as the vehicle for this research[1b] and, although not a requirement for solar heating, it has been assumed to be oriented north-south, and located in London.

A review of a number of passively solar heated buildings can be found in the introduction to the chapter entitled "Passive Design Background and Workbook". Despite the publicity given to passive solar heated projects, such as St. George's Secondary School in Wallasey, and their apparent success in saving energy, their design concepts have not been widely adopted. This is largely due to a lack of engineering and costing criteria. Although the calculation of solar gains through fenestration is well understood and documented, the quantative analysis of storage and control of this energy is not within the grasp of the building designer. Nor does the building designer have mastery over the complex computing interactions of predicting the cost effectiveness of implementing a passive design improvement at design stage. The second aim of this research is to remedy this situation by providing a workbook of passive solar design methods for building designers. Another obstacle in the path of widespread architectural use of passive concepts is that the analytical design methods required would be complex and long winded, requiring either too much time for the tight schedule of an architectural practice, or the use of a computer. However, not many practices have access to a computer, so the design methods will be presented in the form of TI 59 programs (Texas Instruments programmable desk calculator). This instrument is within the budget of a one-man architectural practice (£140) and the programs take only minutes to run.

These two objectives will hopefully complement each other by providing a worked example of the tools presented. The first objective is of enormous relevance to the present state of the British economy and housing needs, the second objective is of similar relevance to the architectural profession and researchers in this field.

I

ACTIVE V PASSIVE DESIGN TOWARDS A PHILOSOPHY

ACTIVE VERSUS PASSIVE

An outline of the concepts involved in solar design is needed to identify the reasons for the preliminary design standpoint taken in this thesis.

There are two approaches to low energy house design:

The first uses solar collecting panels, storage tanks or bins, an energy transfer mechanism and an energy distribution system. It is known as an active system and always employs a working fluid(s) which collects, transfers, stores and distributes the collected solar energy.

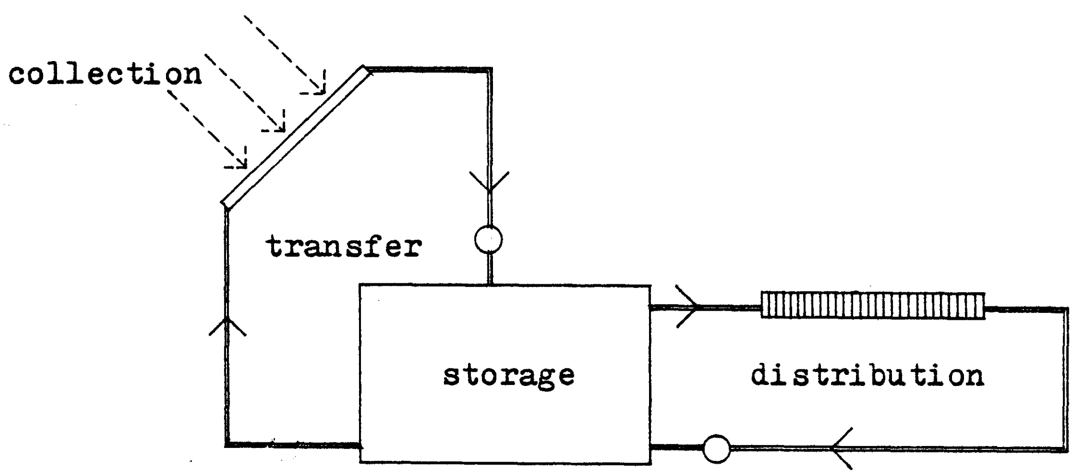


Fig. 1.1 An Active System

Usually being photogenic, the houses with this approach receive much publicity in the architectural press.

The second approach, passive design, seeks to reduce the house's energy budget with close attention to orientation, insulation, window placement and design, and to the subleties of the properties of building materials. Since solar gains are present in every building, each is passively solar heated to some extent. It is when the building has been designed to use solar energy and when solar energy contributes substantially to the heating requirements of the building that it is termed a solar building. It is only due to an era of cheap fuel that we have lost the skills of passive design. Practiced in all indigenous architecture, it is an art that we will have to relearn. As told by the variety of form of vernacular architecture, much like a plant, which in a dark location will grow towards the light, the passively designed building will respond to its location and thus the form will vary with change in site and even more so with change in climate. It presents a comprehensive design philosophy.

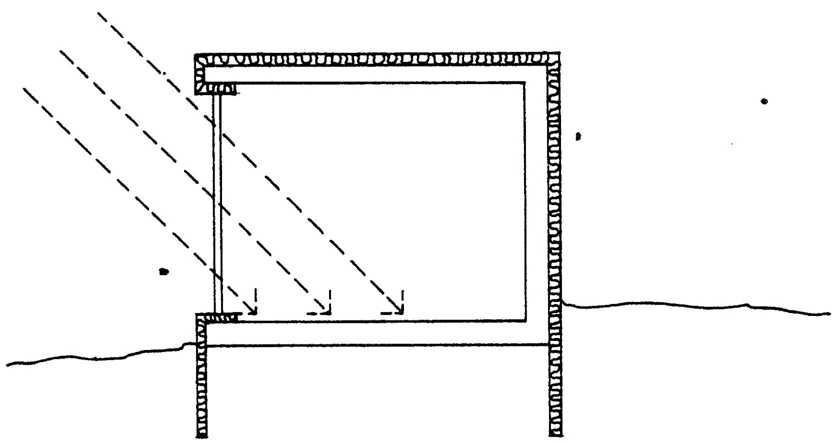


Fig. 1.2 A Passive System

Conceptual comparison of passive and active designs is made by considering the passively designed house acting as absorber, store and delivery - there is no working fluid, all the functions of the active system are carried out by the building materials themselves. Most examples of passively solar heated buildings use extensive south exposure glass to admit low-angle winter sunshine to the building and extensive use of mass heat capacity inside the thermal envelope of the building to store heat energy. The cost of heating (and cooling) is then the incremental cost of the materials required for passive design over the conventional building materials they replace.

Although less spectacular and graphic, this second approach produces better results in terms of energy conservation and money saved as a result of initial expenditure. The method used for cost benefit comparisons is termed Life Cycle Costing. (LCC). This small area in the field of solar energy collection is the package that contains the jewels, for the aim is always economic feasibility, not 100% solar heating. The present value of the money saved over 'n' years is computed with corrections for the effects of borrowing interest rate and the rate of increase in the price of fuels.* From this it is possible to calculate the number of years it will take to recoup the capital cost of an improvement. An active system will have difficulty producing less than a 20 year payback figure. With passive systems, payback periods of anything from one to 13 years are usual. The durability of passive systems further increase their economy. They require little maintenance and will last the life-time of the building. Thus they will never require replacement, as may be the case with active systems.

* See section headed "Costing" in the following chapter, for a more detailed account of Life Cycle Costing.

The English climate is particularly well suited to passive design. The temperature rarely falls below -2°C, despite the high Latitude, due to long periods of cloud cover. This means that the heavy heating loads, mainly produced by a long rather than severe winter, can be substantially met by the low sun angles and clearer skies at each end of the heating season. Under overcast skies or intermittent sunshine, an active system will shut down but a passive system continues collecting. In England, this diffuse solar energy is not insignificant (greater than 50%)[1c].

A combination of the two systems is often sought if passive design will not meet a large enough portion of the total heating requirements. This remains subject to economic feasibility.

Although passive design seems to hold the answers it does have some large design problems. Access, space use, view and ventilation conflict with the energy collection requirements, and the problems of overheating and glare must be contended with.

II

PASSIVE DESIGN BACKGROUND & WORKBOOK

BACKGROUND.

There are two approaches to passive solar heating.

The indirect approach employs massive external building elements to absorb solar radiation. These building elements have no thermal barrier and heat travels by conduction to the internal surface. It takes several hours for this to happen, at which point it provides the room with radiant and convective heat. Moveable insulation and cover glazing may be externally applied to the absorbing surfaces depending on the climate. If cover glazing has been applied, room air can be circulated across the absorbing surface to provide instant heating.

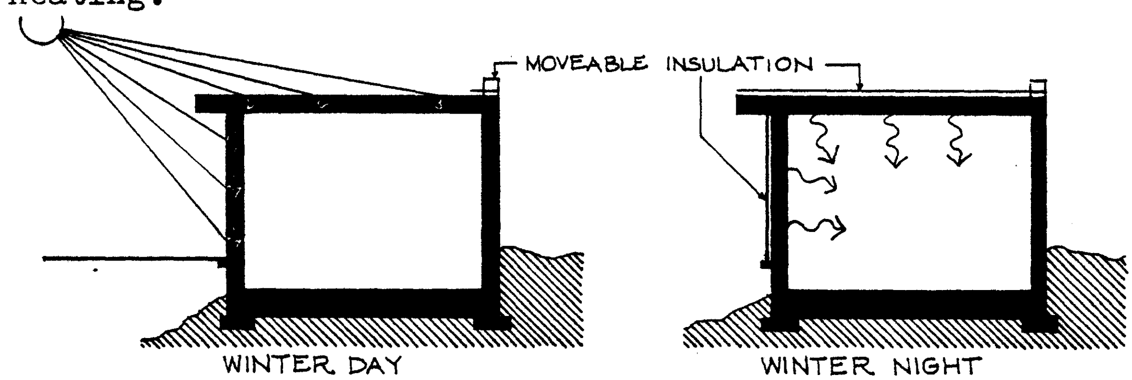


Fig. 2.1. Indirect heat transfer to interior[1d]

The direct heating approach uses a transparent wall to allow solar radiation to enter the space requiring heating. The energy is absorbed and stored by the areas of thermal mass* it strikes. The thermal mass is isolated from the external climate by an insulating envelope. The thermal mass then heats the room by radiation and convection. Moveable insulation can be applied to the transparent wall to prevent

* Thermal mass describes a building element (floor, wall or ceiling) with a high thermal capacity.

large heat losses at night.

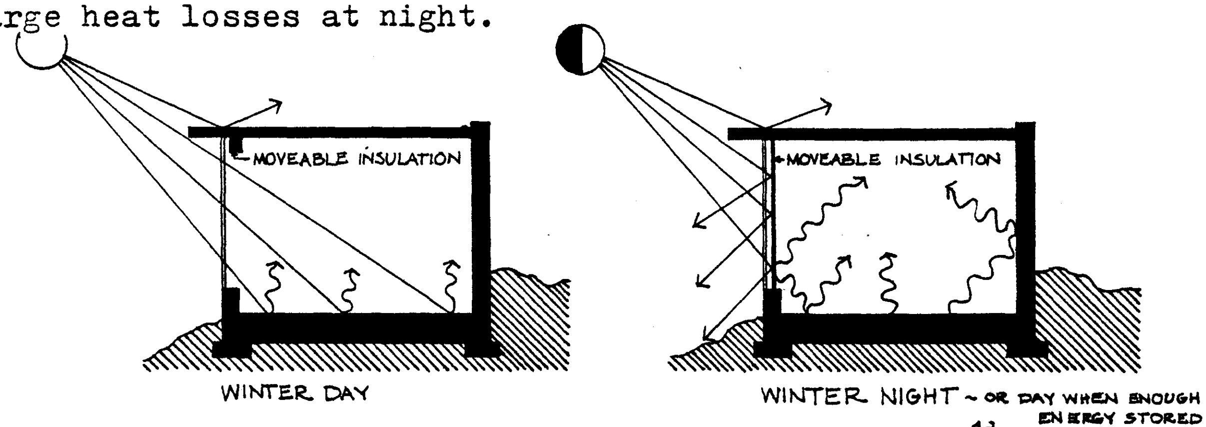


Fig. 2.2. Direct heat transfer to interior[1d].

The following brief outline of examples of both approaches will give some insight into the design conflicts inherent in passively heated buildings:

Indirect Heating Examples.

The two examples that describe this approach most clearly and ingeniously are the Odeillo house by Dr Felix Trombe and Jacques Michel in France (Figs. 2.3 and 2.4) and the Atascadero "Skytherm" house by Harold Hays and Kenneth Haggard (Figs. 2.5 and 2.6).

The Odeillo houses (1956) use a dark-coloured 450mm (18 inch) thick concrete south wall to collect and store energy from the low altitude winter sun. Heat losses are reduced by the use of strengthened single glazing across the face of this wall. The primary method of heating is by convection from the inside surface of this massive concrete wall to the room. It takes several hours for the heat to travel through the wall so instantaneous heating is made possible by circulating room air in the gap between the glass and wall. This is done without

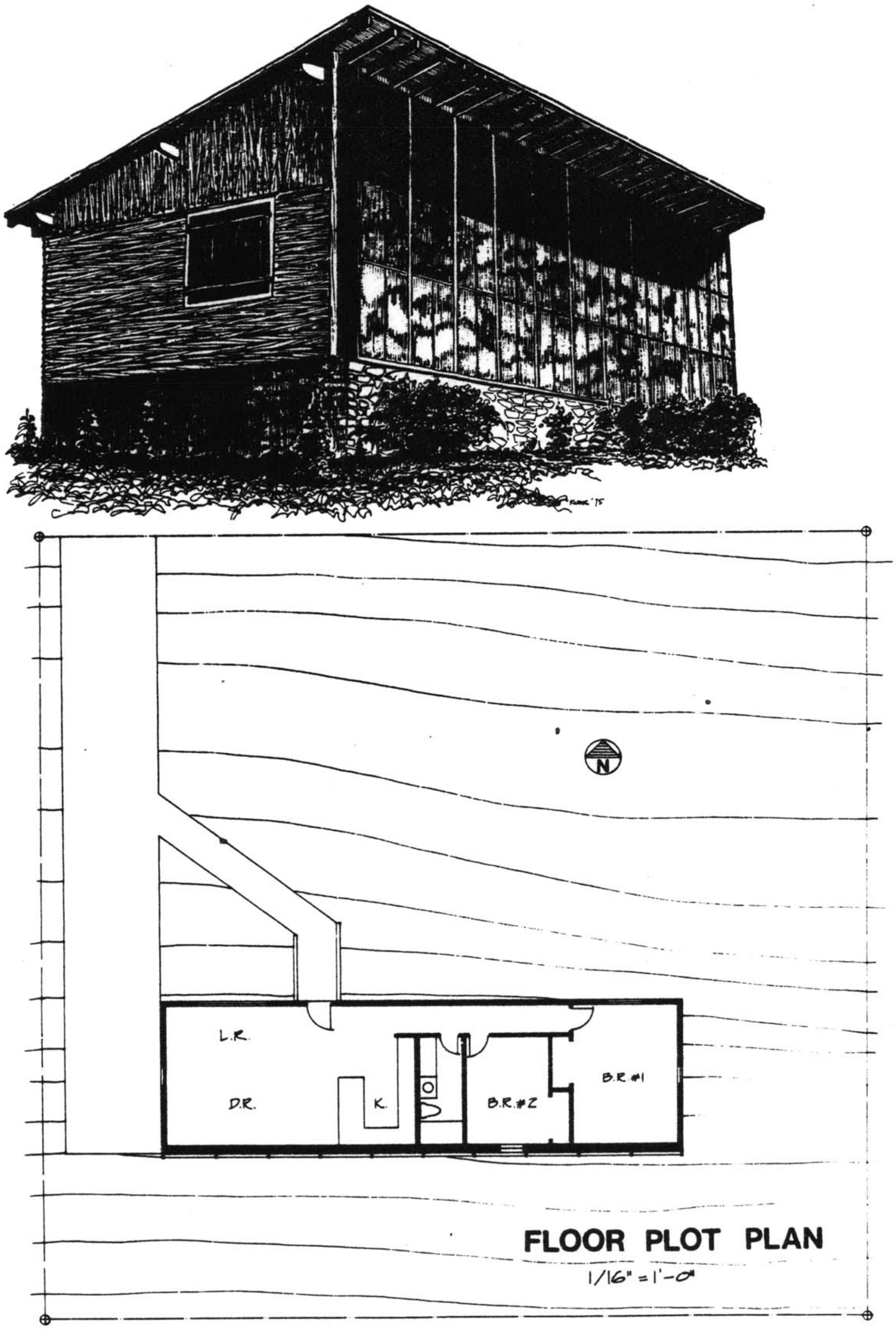


Fig. 2.3. The Odeillo house-type, France.[2]

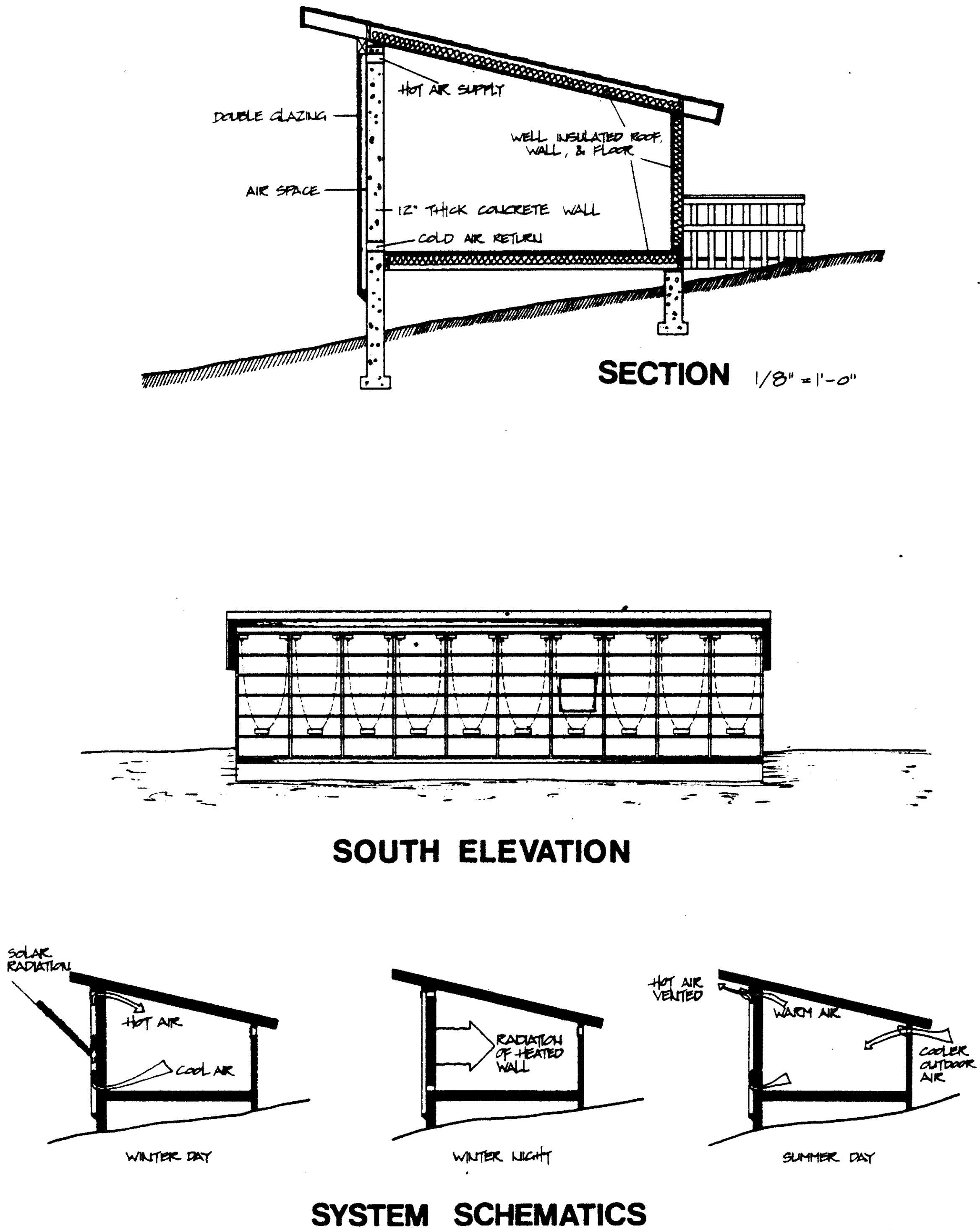


Fig. 2.4. The Odeillo house-type, France.[2]

the use of fans, dampers are used on the lower openings to shut off thermosyphoning at night. The remainder of the structure of this two-bedroomed house-type is well insulated so that the heat requirements are low. The overhang of the roof shades the south wall completely during the summer and the glazing vents can be opened to encourage cross ventilation. Design conflicts are very noticeable in this house type. The south wall is unwillingly punctured by a small window, but if access or view were required here it would be even more unacceptable. North windows have to be provided for additional daylighting; this will add little light, increase heat losses and reduce the mean radiant temperature within the room. The result of this overriding concept for solar heating is a very inflexible building.

The Atascadero house (1973); in California, employs containerized water for its thermal mass. The containers are four 2.7m (8ft.) by 12.7m (38ft.) by 200mm (8inch) deep PVC plastic bags. These are supported by steel decking which is also the ceiling. The water filled bags are covered by moveable insulation which retracts to allow solar radiation to be collected during the winter and radiational cooling in summer to the night sky. The house below is heated by radiation from the steel ceiling. The structural walls needed to support this mass of water also serves the purpose of secondary thermal mass. This is a single story house with a floor area of 107sq.m.(1140sq.ft.). The system gives good

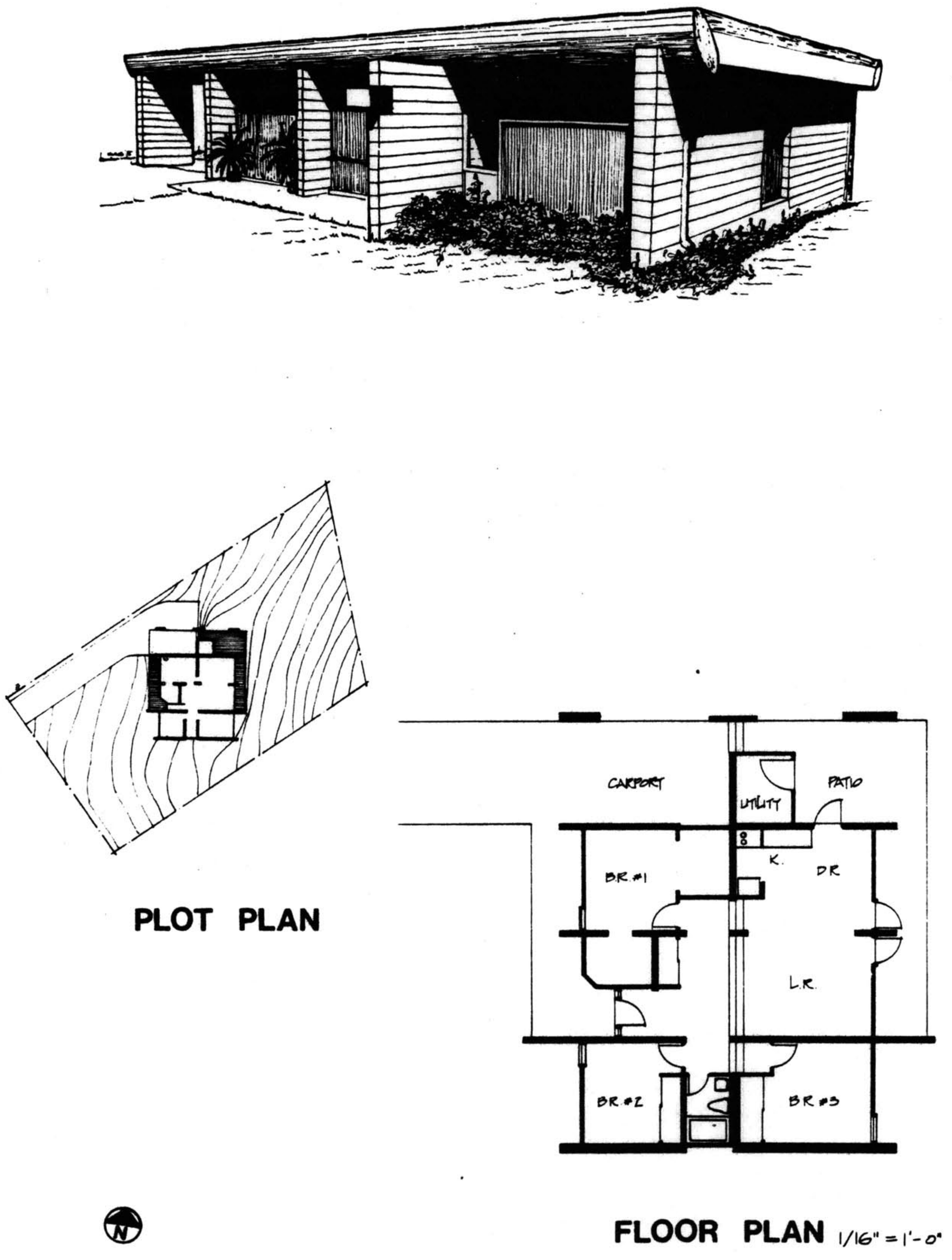
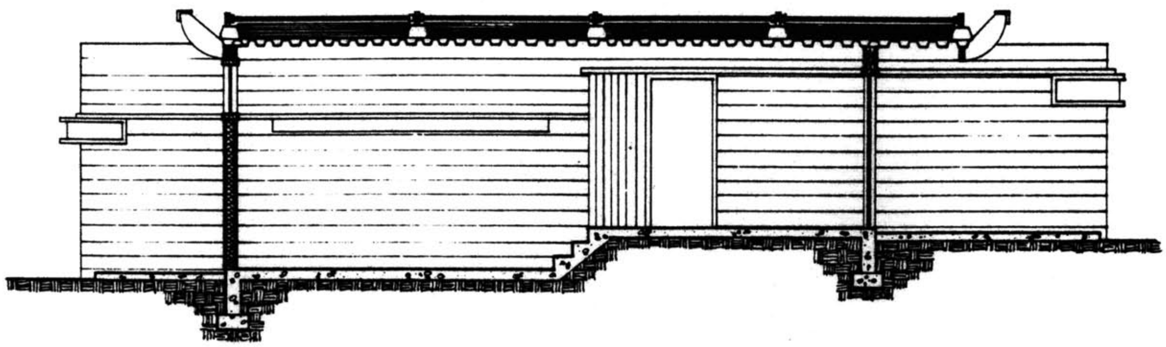
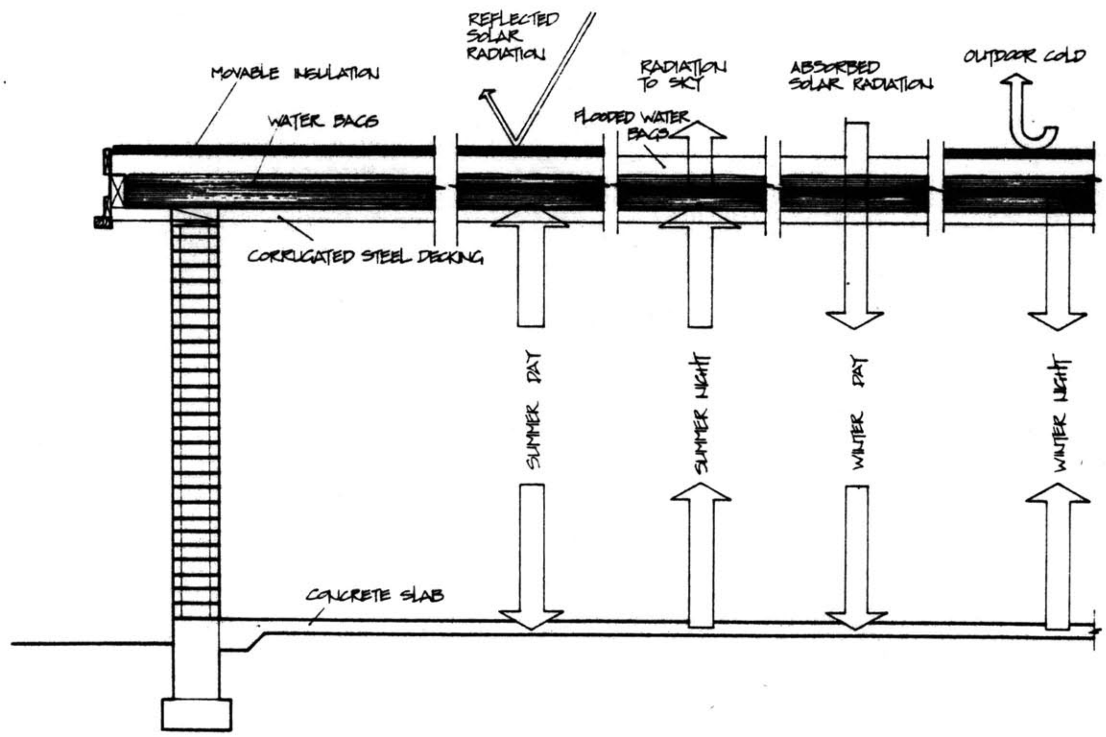


Fig. 2.5. The Atascadero "Skytherm" house, USA.[2]



SECTION 1/8" = 1'-0"



SYSTEM SCHEMATICS

Fig. 2.6. The Atascadero "Skytherm" house, USA.[2]

thermal comfort conditions, no auxiliary heating has been needed since it was built. The insulation panels are moved by a 1/4kW (1/3hp) motor. The limitations of this method of solar heating are less easily detected. The structural walls needed reduce the flexibility of the permissible spaces. The method is limited to a single story structure and to areas where there is little snow fall. Nevertheless, this system is extremely well adapted to its environment.

Direct Heating Examples.

The forerunner of the examples of this type of passive system is the two story 77m (230ft) by 12m (37ft) extension to St. George's Secondary School (Fig. 2.7). The designer was A.E.Morgan and the building was completed in 1961. The entire south wall (500sq.m, 5350sq.ft) is double glazed with the panes set 600mm (2ft) apart to permit easy cleaning. The 180mm (7inch) thick concrete roof and 230mm (9inch) thick brick wall form the thermal mass and are insulated externally with polystyrene. Twelve percent of the area of the inner glazing skin on the south wall is black-painted masonry. Thirty-three percent of the south wall area has reversible aluminum panels which are hung bright side facing outward from April to October and black side facing outward from November to March. Almost all the inner skin of glazing is diffusing glass to prevent discomfort from direct sunshine. There have been no reported complaints about glare. Ventilation, by means of openable dampers, and auxiliary heating, by switching on the

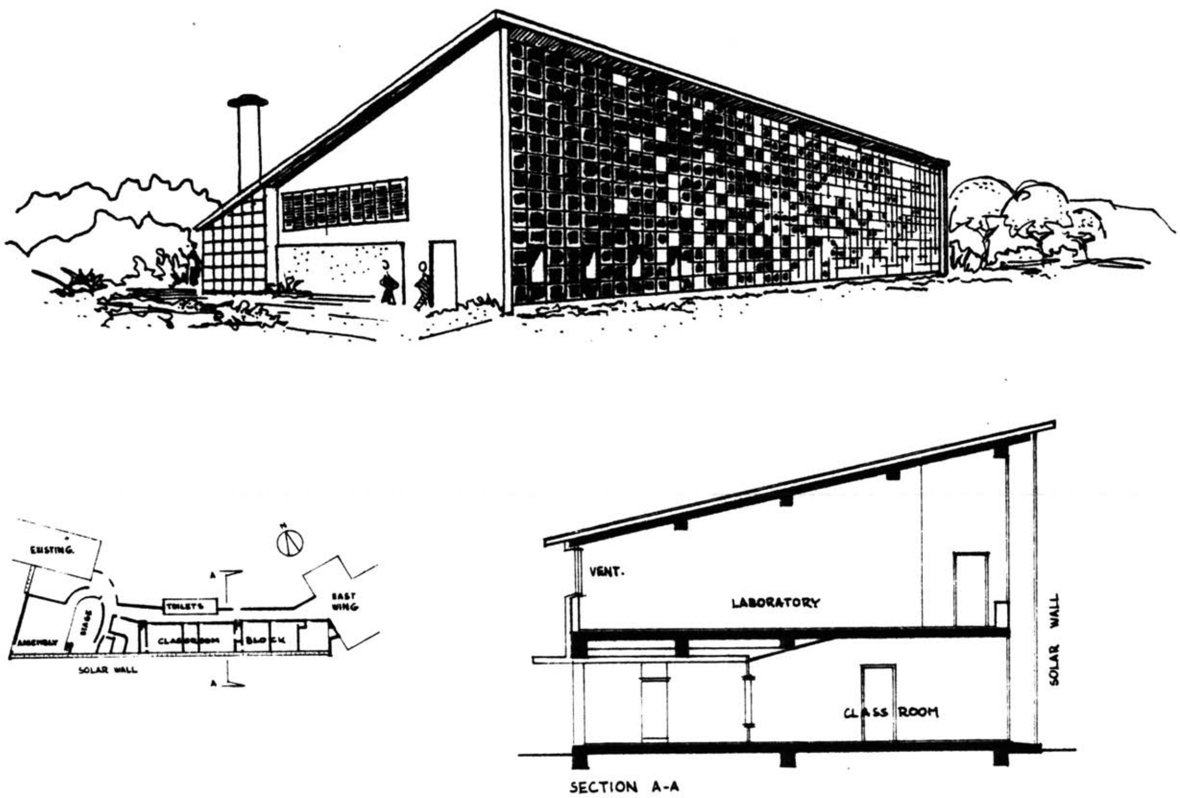
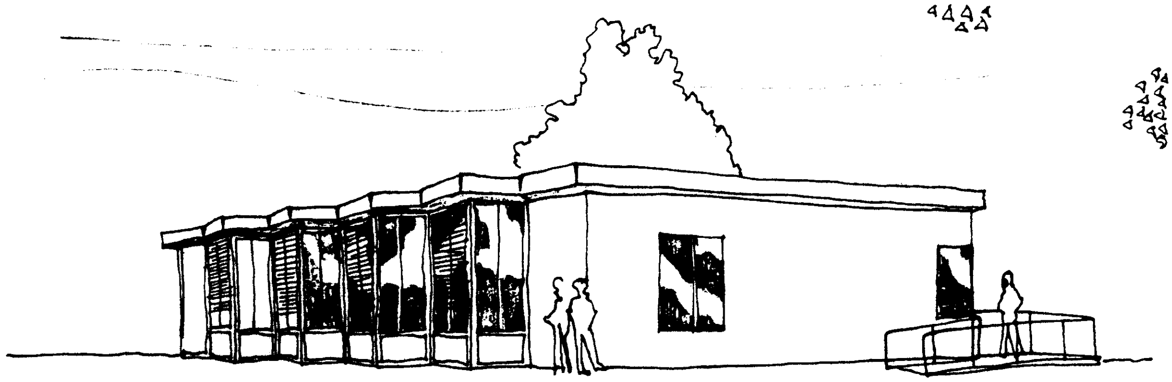


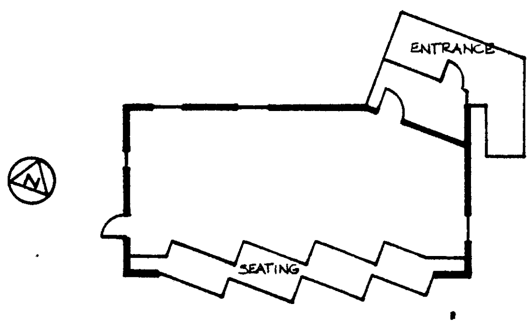
Fig. 2.7. St. George's Secondary School, England.[3]

lights, are the only forms of thermal control. The building has functioned over the past 16 years without any auxiliary heating. The average outdoor temperature in winter is 4.5°C (40°F) with a 9°C (16°F) fluctuation. On average the indoor temperature fluctuation was found to be one half of the outdoor temperature fluctuation; room temperature fluctuation was usually 5°C (9°F) on a clear winter day. The design limitations imposed by such a system are potential glare caused such a large area of glass, the conflict between preventing this and still allowing view, and the conflict between space use and energy absorption. The low ventilation levels needed to maintain comfortable temperatures have caused occaisional complaints of body odors. Admitedly, most of these conflicts have been acceptably resolved in this example but the use of this system for a dwelling would pose these very real problems and without such solutions at hand. The final design conflict is the enormous structural mass required. If this were a block of apartments such mass would usually cause far greater structural and foundation costs than normally encountered.

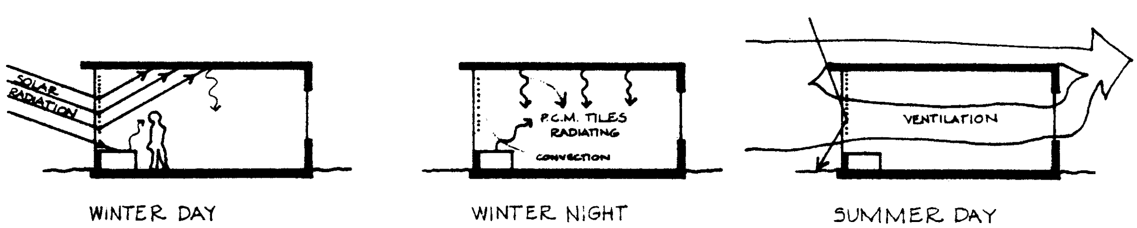
The final example is the MIT Solar Demonstration Building. Designed by Timothy E. Johnson, this building is under construction and due to be completed in December 1977 (Fig.2.8). It has been included here because it illustrates an approach which, using newly developed materials, considerably reduces the design limitations we have noted so far. There is one



perspective



floor plan



system schematics

Fig. 2.8. MIT Solar Demonstration Building

exception to this: it must be used in latitudes where winter sun altitudes are low enough to strike the vertical walls within a 50^{o} angle of incidence. Otherwise reflection losses of useful solar radiation become excessive. This single-story building has a floor area of 75sq.m (800sq.ft). The south wall has 18.5sq.m (200sq.ft) of glazing material. A heat mirror (reflects infrared radiation without appreciably reducing transmittance to solar radiation) has been developed by Suntek Inc., California, and is used on the south glazing of this building. Timothy E. Johnson has developed a phase change material (PCM) tile which is used as the thermal mass. The tile is 25mm (1 inch) thick, dark colored, and is used both as a ceiling finish and placed on the seating areas below the south windows. Direct solar radiation is reflected up onto the PCM tiles and stored there in the form of latent heat. The reflective blinds or solar modulators are designed to require a minimum number (11) adjustments throughout the heating season. The indoor temperature fluctuation on a sunny winter day is expected to be $5.5^{o}C$ ($10^{o}F$). Solar energy is expected to provide over 85% of the seasonal heating requirements. There is no potential conflict between south glazing and view, access or ventilation. Glare is greatly reduced by the blinds which obscure most of the glare source and increase the surround illumination levels at the back of the room. Discomfort from direct solar radiation is avoided by the design requirement of the reflection angle off the louvers being not less than 30^{o}. The PCM tiles weigh a fraction of the weight of an equivalent thermal capacity in other materials, thus no heavy loads are imposed as a solar heating requirement. Because the energy is stored with minimal increase in the surface temperature of the tile, the air temperature fluctuations are minimized. The restrictions on the size or flexibility of the space due to solar heating requirements are greatly reduced.

This final approach is the one I have adopted.

WORKBOOK.

The aim of the passive design philosophy is always to tame the annual and diurnal fluctuations in temperatures to within comfort standards. This task is far from simple, it consists of many different facets. The remainder of this chapter is devoted to an outline of the facets involved primarily in the MIT approach, but applicable to most passive design concepts. The outline gives a brief background and workbook to these facets:

1. ENERGY CONSIDERATIONS.

a. Orientation and Tilt of the Collecting Surface.

The limitations of orientation are not as stringent as they first appear. The design solution will emerge from many such technical limitations and perfection within any is not the goal, otherwise design becomes slave to technology. Balcomb's graph (Fig. 2.9) shows that although, as expected, a due south orientation is optimum, variations of 30° east or west will only reduce performance by about 3%. However, cloud-cover patterns may change these conclusions; a locality may have more overcast afternoons than mornings thus favoring a slightly east of due south orientation.

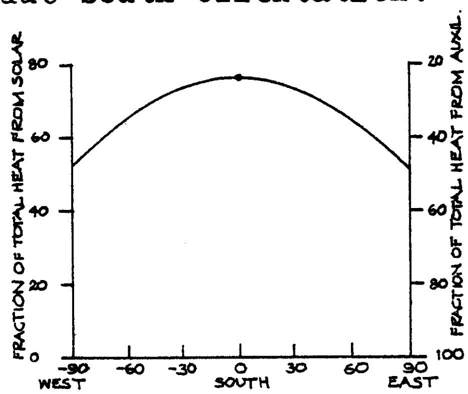


Fig. 2.9. Orientation and its effect on % solar heat fraction[4]

The optimum tilt for passive solar heating differs from that for an active system. A vertically glazed collecting surface is preferred in higher latitudes. The low altitude of the sun in winter is more normal to the glass which, following Fresnel's relationship, enables penetration of a greater proportion of the incident direct solar energy in the months when the most heating is required (Fig. 2.10).

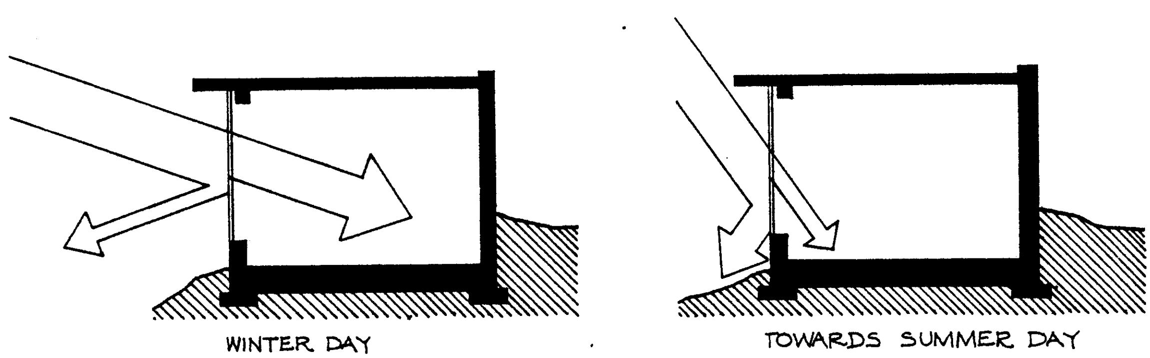


Fig. 2.10. Diagrams of the effect of Fresnel's Law

As shown in figure 2.11, vertical glazing presents a larger aperture to the sun during the winter months, and smaller in the summer months when the energy must be rejected. Thus vertical glazing is almost self-regulating (Fig. 2.12). A reflecting surface placed on the ground in front of vertical glazing will, with very low cost, increase the collection area by approximately 50%.

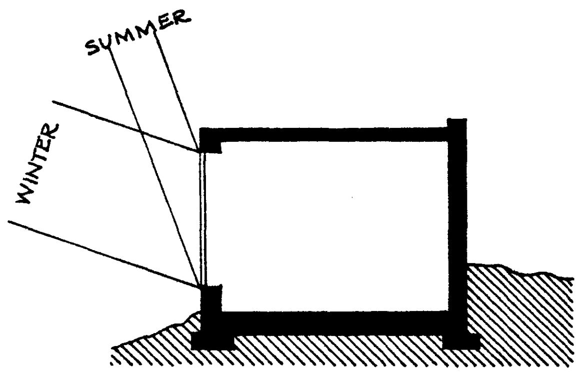


Fig. 2.11. Varying aperture between winter and summer.

Horizontal collecting surfaces are used in lower latitudes where the winter solar radiation arrives at a vertical plane with an angle of incidence greater than 50^{o}. These high angles of incidence greatly reduce the quantity of solar radiation transmitted through vertical glazing (Fig. 2.10). However, horizontal collecting surfaces will require a device to prevent solar gains during summer.

Glazing with other than a 90^{o} tilt must be incorporated into a design with great caution. It will present major overheating and shading problems in summer, and high convection and radiation heat losses in winter by allowing radiative contact between the thermal storage area, glazing and a large

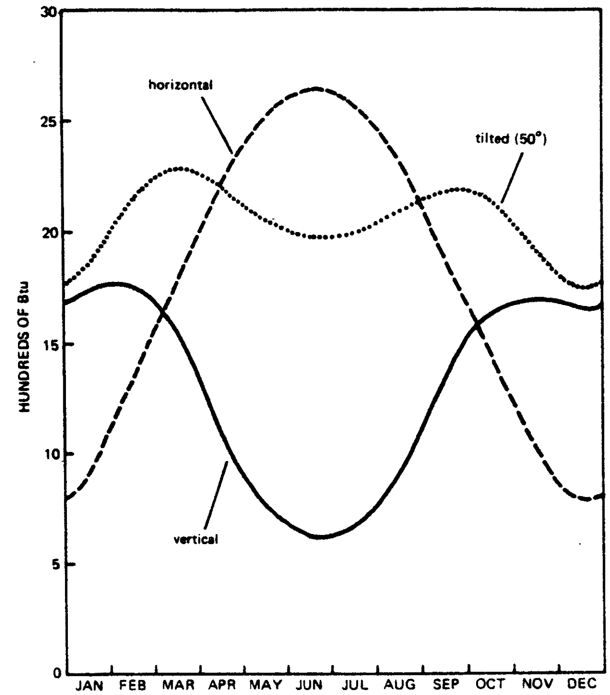


Fig. 2.12. Clear day in Boston, no ground reflection.[5]

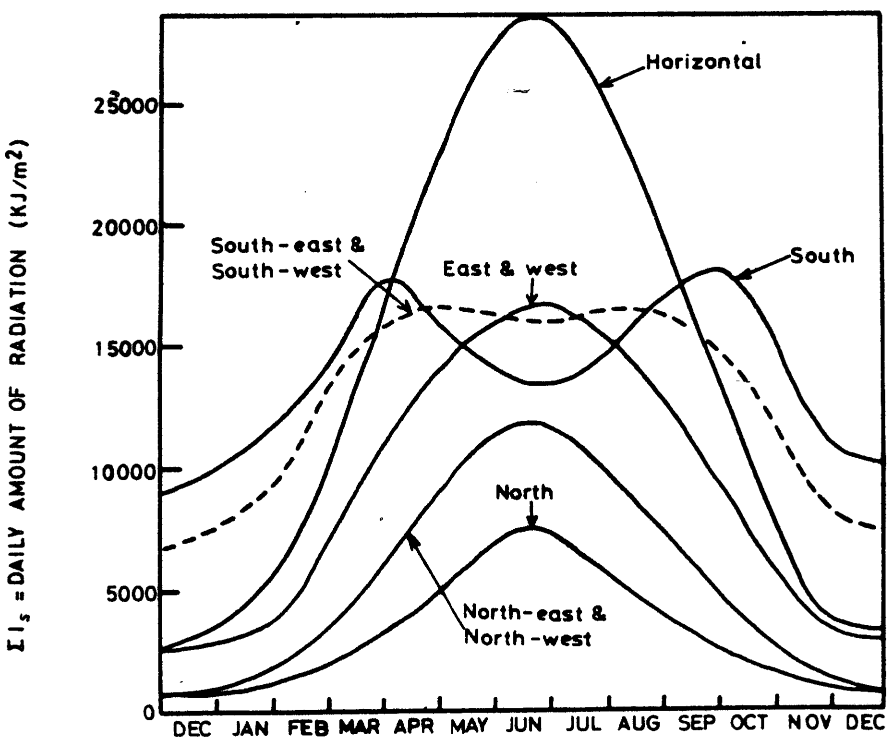


Fig. 2.13. Clear day, London; ground reflection included.[5a]

area of the sky vault.

b. Climate.

Close observation of the winter weather patterns of an area will help in the assessment of the optimum orientation for the building.

Two sets of climatic data are needed to conduct analyses of the passive system:

The first is the mean daily temperature for each month of the year. This is needed to calculate the monthly degree day figures*. The degree day figures must not be taken from tables for this purpose as they will vary according to the heat loss and internal gains of the building. Comparison of several different sources of mean daily temperatures for each month is suggested. The temperatures will have been calculated over different time spans (eg. 10 or 15 years) and due to changing weather patterns the more recent the information the better.
The second set of climatic data is required to assess whether or not the energy collection space is in danger of overheating on a clear winter's day. For this reason the month with the highest solar gains and highest outdoor temperatures is chosen. A comparison of figures 2.12 and 2.13 will show that the month with highest solar gains on a vertical surface will change with change in latitude. However, due to mean daily temperatures, October is the month to assess in both Boston

* See the section of this chapter headed "Heating Load" for more information on degree day figures (p.43).

and London. The data required is the mean hourly outdoor temperature for the mean day of this month. These temperatures are used in the overheating assessment design method in the section of this chapter headed "Overheating" (p.100). If these temperatures are not available and the mean daily minimum and maximum temperatures are, then the former can be approximated to a high enough degree of accuracy for the overheating design method. A sinusoidal graph is drawn using these values for the month chosen as the minimum and maximum points on the graph respectively. The minimum daily temperature usually occurs before sunrise, the maximum usually mid-afternoon. ....

c. The Site and its Microclimate.

The building site plays an important role in determining the energy requirements of a building. Both the summer ventilation or cooling loads and the winter heating load can be reduced by well considered site use. Close observation is required to highlight the preference areas on a site. Existing vegetation, geology and topography all play a part in creating an unique microclimate for every site. The rehabilitation of row houses in London has little opportunity for such considerations and thus little time will be spent on this subject here. Suffice to say, there are powerful analytical tools available for simulating the wind flow patterns around buildings, trees and landforms and for on-site investigation of the microclimate[6,7]. ....

d. Solar Interference Boundaries.

The altitude and azimuth angles of the sun change as it apparently moves across the sky. The Sun Angle Calculator* is an indispensable tool for predicting these and the profile angles of the sun throughout the year for a variety of latitudes. To determine the contribution of solar energy towards the heating requirements of a building it is necessary to know whether the sun will be obscured at any time of the day by buildings, trees or landforms. If the sun is obscured then diffuse solar energy will be the only contribution towards the heating requirements.

The ability to see the sun at all times during the day is another requirement of solar heating to be looked upon as important but not of overriding importance. The optimum solution to this may not be the best design solution. When aesthetics and economic feasibility are weighed against each other the design solution is found.

In all there are four methods presented here for determining solar interference boundaries, and each has its own merit.

(i) Figure 2.14 is a graph showing solar interference for the 21st of February and the 21st of October for a latitude of 52^{o}N. The graph is constructed at a scale of 1:200 and the contours are for the vertical distances marked above ground level. The point of origin of the lines of azimuth for each

* Available from Libbey-Owens-Ford Company, Toledo, Ohio, USA, for approximately £3.00 ($5.00).

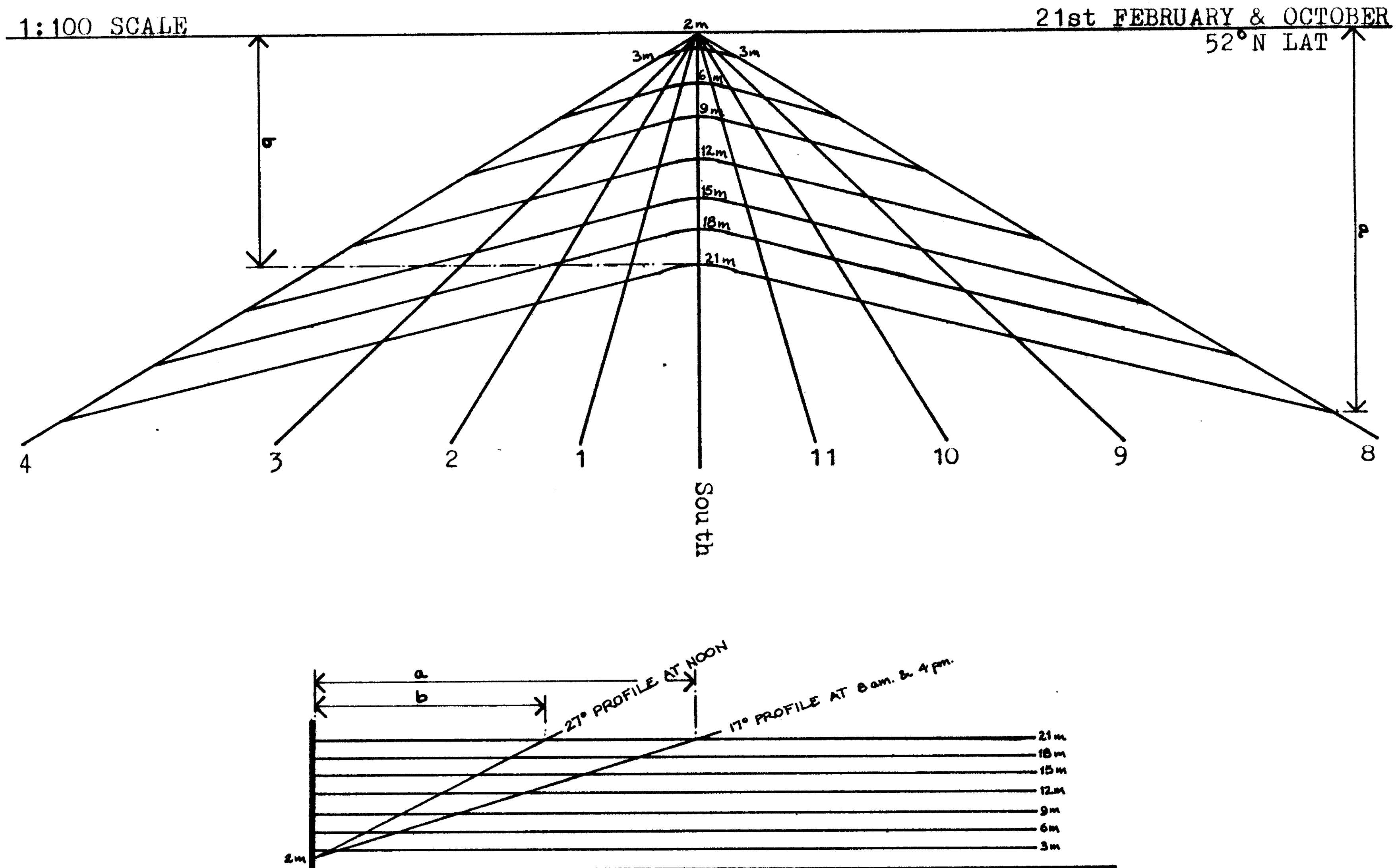


Fig. 2.14. Solar interference boundaries graph and its construction

hour is the point being modeled; assumed to be 2m (6ft) above ground level at the surface of the building. The graph method[8] is used by laying a tracing of the building and site plan, also at a scale of 1:100, over the graph so that the noon azimuth line is due south with respect to the orientation of the building and site. The graph is constructed (Fig. 2.14) by drawing a section of the building face with the profile angles for sunrise and noon drawn originating from the point being modeled. The horizontal distance from the face of the building to the profile angle lines drawn is measured and used in plan to mark off the interference boundaries along the lines of azimuth. This distance in plan is measured at right angles to the east-west axis.

(ii) The sundial-type Heliodon and scaled model can simulate the apparent movement of the sun through the day for each month (Fig. 2.15). The Heliodon can be adjusted to model any latitude. It is constructed from figure 2.16 and mounted on an east-west axis with respect to the orientation of the building model. Either a parallel ray artificial light source or the sun must be used. This method will be more useful than the graph method if the building has a contorted plan shape. For accurate results the mounting must be on an adjustable surface, capable of being clamped. To facilitate estimation of area of window in sun, at any hour, it is suggested that the windows be divided into ten equal rectangles. In this way a percent recording can be made of each window for every hour modeled.

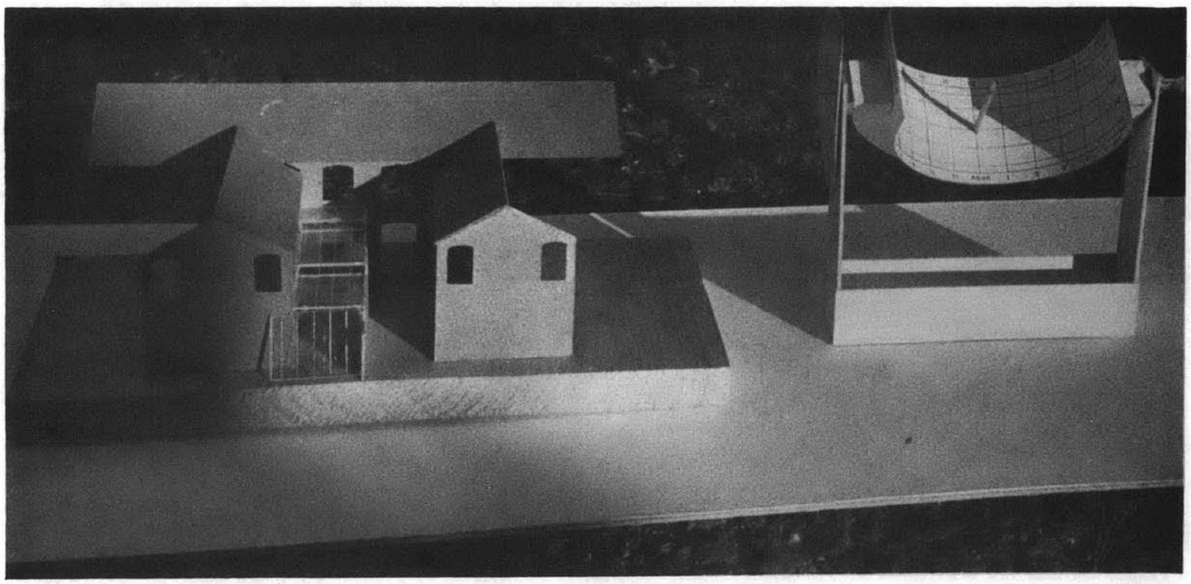


Fig.2.15. The heliodon and scaled model simulating December 21st at 9am at 52°N latitude.

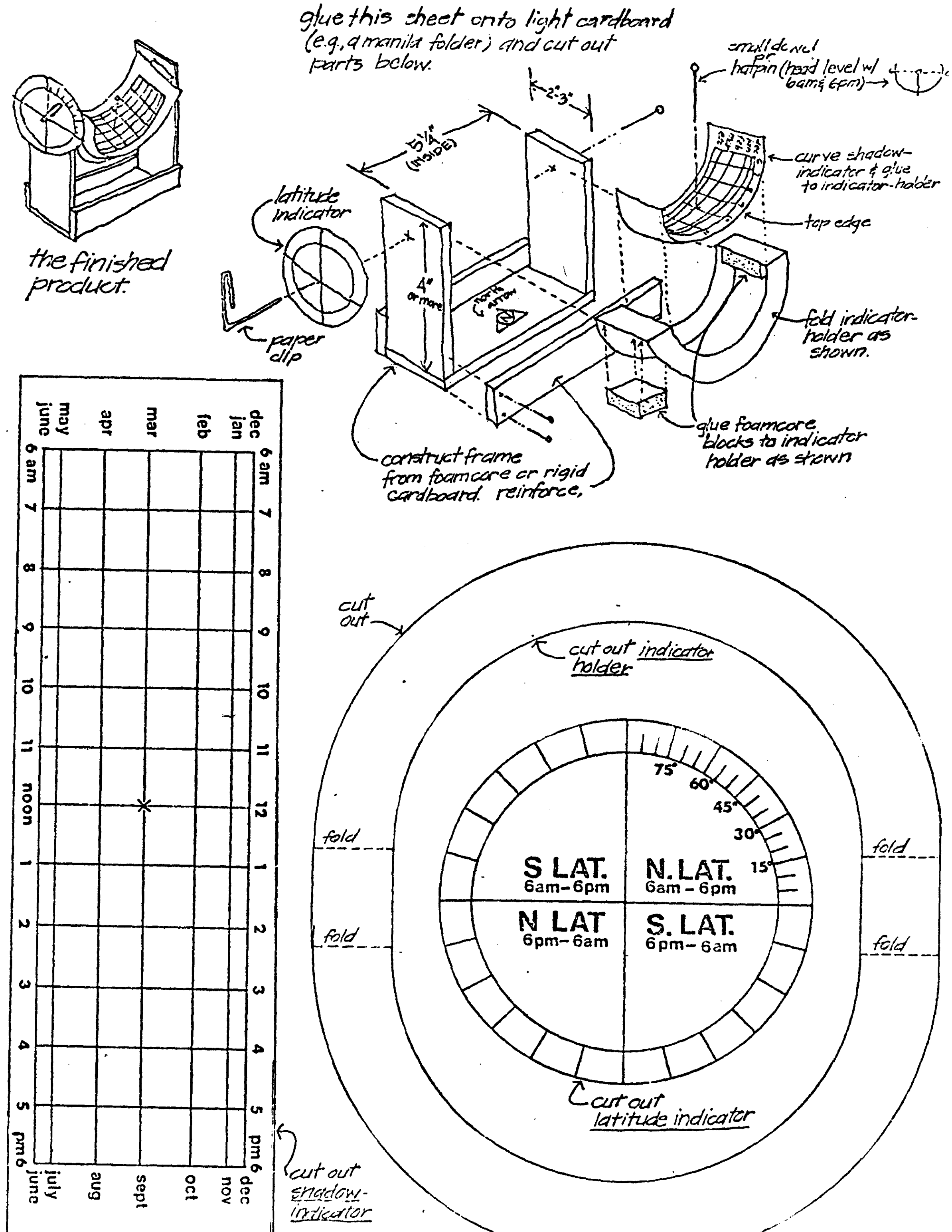


Fig.2.16. A sun-dial type Heliodon - construction sheet.

(iii) Computer simulating the interaction between building shape and solar position for each hour of the day gives good results and is capable of providing great flexibility in building design and window size and placement, without the work involved in making scaled models of the building. This method was adopted in the research presented in this thesis. It is based on trigonometry and is commonly used for commercially offered computer simulation packages for assessing the energy requirements of buildings. Thus it offers nothing new to the field and consequently will not be presented here.

(iv) If the site can be visited there is a new sunlight finding instrument available. It has been invented by Williams* and will tell in minutes which objects will obscure the sun and when.

e. Solar Data.

Again two sets of data are required:

(i) Having determined when the sun is being obscured it is necessary to calculate the resulting monthly total solar gains through the windows and walls for each month of the year. Only with the help of a computer can this be done on a day by day basis. Thus the 21st day of each month is assumed to be a typical day for that month. Tables are available[9,10] giving the hourly radiation on various surface orientations for a

* Available from J.C.C. Williams, 4 Fronwen Terrace, Cradoc Road, Brecon, Powys, LD3 9HB, Wales; at a cost of approximately £1.50 ($2.50).

clear day at a given latitude.

If a window is in shade, only diffuse radiation will be counted; taken directly from the west oriented vertical surface values (for before noon), and the east oriented vertical surface values (for after noon), in the tables for clear day insolation. No correction is necessary because an overcast sky will, if anything, contribute more radiation than a clear north sky; summer mornings and evenings are an exception where, in high latitudes, the sun enters the northern hemisphere.

If a window is potentially seeing the sun the clear day insolation tables will not allow for the days when the sky is partly clouded. Consequently a correction must be made to these figures. The rule of thumb correction method presented by Anderson[5] was found to be inaccurate when applied to the english data. The correction factor can be more accurately calculated if one has access to values of the mean monthly or mean daily total solar radiation. The correction factor for any one vertical orientation is different from another and different again from the horizontal surface correction factor. Also, these correction factors must be determined for each month. Considering a surface with a particular orientation and tilt:

$$C = \frac{Itav}{Itcl} \tag{1}$$

Where C = the correction factor for that month
Itav = the mean monthly total insolation on that surface
Itcl = the clear day monthly total on that surface; from[9,10]

If one has figures for the mean daily total solar radiation for each month the method is identical, except that the daily values replace the monthly values.

It may be the case that the only total radiation figures given are for a horizontal surface, listed as hourly total and diffuse radiation values, and that the building is oriented in a direction other than due south. Converting this horizontal data into insolation values on any vertical orientation is possible, although cumbersome unless a programmable calculator is used. The method is as follows:

Total solar radiation = Direct + Diffuse solar radiation (2)

Considering first the direct portion of the total solar radiation:

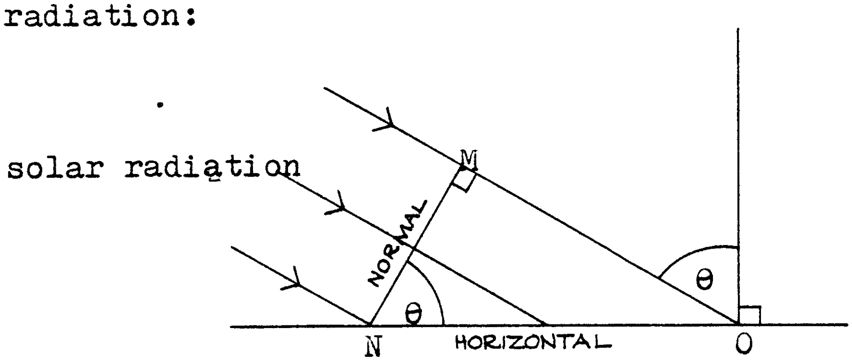


Fig. 2.17. Illustrating the Cosine Law

The Cosine Law states:

$$Idh \times NO = Idn \times MN$$

Where Idh = the direct solar radiation for that hour on the horizontal surface NO.
Idn = the direct solar radiation on the surface MN, normal to the solar radiation.

$$\therefore \; Idn = \frac{Idh}{\cos \theta} \qquad (3)$$

Where θ = the angle of incidence (90-altitude).

In the same way, by simple trigonometric relationship:

$$Idv = Idn \times \cos A \times \cos W \quad (4)$$

Where Idv = the direct solar radiation on the vertical surface for that hour.
A = the angle of altitude.
W = the angle between the sun orientation and the normal to the vertical surface, known as the sun-wall azimuth; varies every hour.

In the above equations only unit areas are considered in the relationships between Idh, Idn and Idv.

The diffuse portion of the total solar radiation must now be considered:

A horizontal surface sees the total sky vault; a vertical surface sees only half the total sky vault. Thus a rough approximation of the diffuse energy falling on a vertical surface is half that falling on a horizontal surface.

From eqn(2):

$$Itv = Idv + (.5 \times Ifh) \quad (5)$$

Where Itv = the hourly total solar radiation falling on a unit area of vertical surface.
Ifh = the diffuse solar radiation for that hour falling on a unit area of horizontal surface.

Incorporating equations (3) and (4) into equation (5):

$$Itv = ((Idh/\cos\theta) \times \cos A \times \cos W) + (.5 \times Ifh) \quad (6)$$

The results of eqn(6) for every hour the sun is up on the 21st day of the month are summed to obtain the mean daily total solar radiation on the vertical surface of that orientation. Then the correction factor can be computed from eqn(1).

The monthly solar gain totals, through windows and walls, are computed by the methods outlined in the section of this chapter headed "Solar Gains" (p. 87).

(ii) The second set of solar data required is that for predicting the possibility of overheating. The hourly clear day intensities of total solar radiation per unit area of the vertical surface orientation and month being modeled are taken from the tables[9,10]. Allowances are made for the results obtained from the design methods in section d (Solar Interference Boundaries). Further information on solar gains for the overheating design method are presented in the sections of this chapter headed "Solar Gains" and "Overheating".

f. Heating Load.

The conventional methods of conducting heating load calculations require some consideration.

A diagramatic representation of the effects of internal gains and insulation on the balance point temperature of a normal modern duplex in England is shown in figure 2.18.

The balance point temperature is the outdoor temperature above which no heating is required in the house. It is the point where the internal gains meet the thermal losses. The heating is not used until the outdoor temperature falls below this balance point. Thus it is the balance point temperature which determines the length of the heating season. Increased insulation, larger internal gains, or lower infiltration rates will lower this balance temperature.

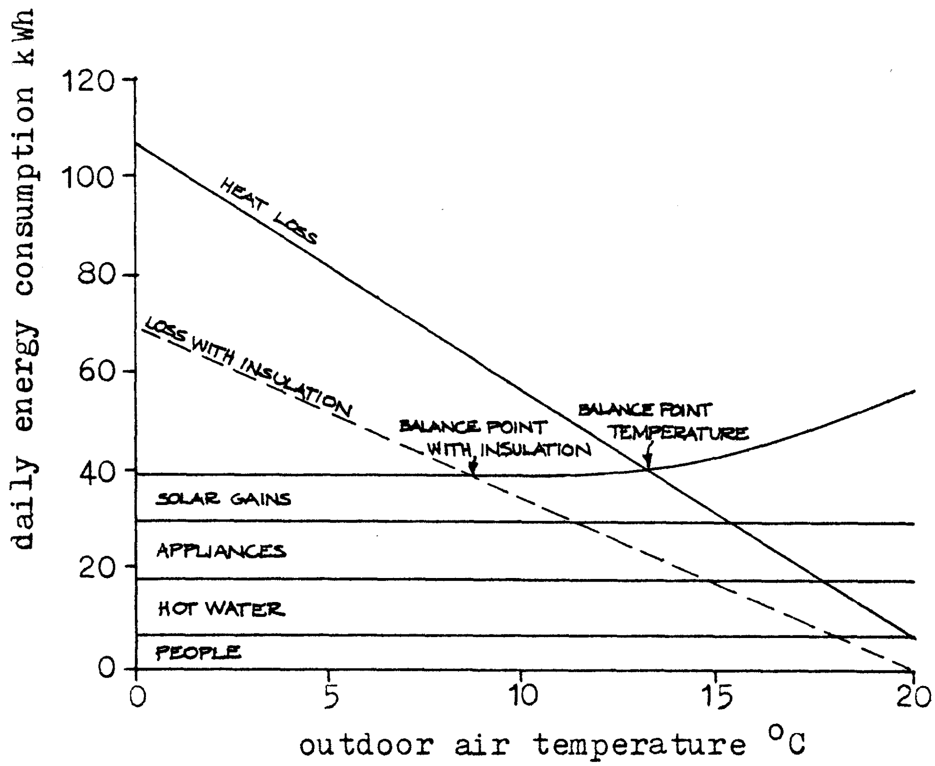


Fig. 2.18. Illustration of the balance point temperature[11]

Conventional methods of calculating heating loads compute the fabric and infiltration heat losses due to the mean temperature differential and do not as accurately account for the length of the heating season. Another conventional method employs the use of published degree day figures for each month. This makes the assumptions that the balance point temperature (degree day base) is 18.3°C (65°F) and the thermostat setting is 21.1°C (70°F). Furthermore, the assumption is made on past performance that the 2.8°C (5°F) difference is contributed by the incidental gains. However, the past performance is that of single family residences, and because the balance point temperature is so sensitive to the thermal properties of the building (see Fig. 2.18) the use of this method for energy conserving buildings will lead to erroneous results. Nevertheless it is to the concept of this final method that we turn in an attempt to find a more realistic method for determining the heating load of a building. The equation which governs this balance point temperature is as follows:

$$Tdd = Tth - (Qi/Q1) \qquad (7)$$

Where Tdd = the balance point or degree day base temperature.
Tth = the average thermostat set point temperature.
Qi = the incidental energy gains per day due to people, appliances and solar energy.
Ql = the heat loss per day ^{o}C (^{o}F).

Where Heat loss/day^{o}C = (((A x V x P) + Uws x Aws)) x H x dt) x .84 (8)

Where A = the number of air changes per hour.
V = the volume of air in the building.
P = the heat capacity (specific heat x density) of air = .34 kWh/cu.m/^{o}C (.018 Btu/cu.ft/^{o}F).
Aws = the area of the weather skin.
H = the number of hours in the day = 24.
dt = internal-external temperature = $1^{o}C$ ($1^{o}F$).
.84 = the correction factor according to Hittman Associates (Ref. 20).
And where Uws = the average U-value of the weather skin:

$$Uws = ((U_1 \times A_1) + (U_2 \times A_2)\ldots\ldots + (U_n \times A_n))/Aws \qquad (9)$$

If converting to kWh, the right hand side of equation (8) must be divided by 1000.

Because the internal gains per day varies each month (due to the sun's altitude, percent sunshine, and inhabitant behavior patterns) it is dependent on the degree day base temperature. But the degree day base temperature is in turn dependent on the internal gains per day figure. Thus iteration of equation (7) is necessary to narrow down on the correct result.

So by knowing the values for the variables on the right hand side of equation (7) it is possible to calculate the balance point temperature for any building. And by knowing this temperature the degree day figures, for each month, for any building can be determined thus:

$$DD = (Tdd - To) \times N \tag{10}$$

Where DD = degree days per month.
To = mean monthly outdoor temperature.
N = number of days per month.

If the result of (Tdd - To) is less than zero then the resulting negative heating load is discounted. Separate calculations are required to determine cooling load if any. In England there is no summer cooling requirement for dwellings.

Then:

$$Qm = DD \times Q1 \tag{11}$$

Where Qm = monthly heating load.

To briefly explain the meaning of a degree day. If the balance point temperature, or degree day base temperature, of a building (Eqn.(7)) is 13°C (55.4°F) and the mean outdoor temperature for one day is 12°C (53.6°F), the number of degree days during this day is 1 (or 1.8).

The TI 59 program for this method of heating load calculation is described in group 3 of this workbook headed "Costing" (p.121).

In this program the balance point or degree day base temperature is determined by the methods set out above. However the method of computing the number of degree days in Eqn.(10) does not allow for the few warm days in say November, or the few cold days in say October. The costing program follows the more accurate 'bin' method of heating load calculation. This does account for those warm and cold days in the data used for determining the number of degree days. This gives the program an added degree of accuracy.

The number of days per heating season of each 1°C (or 5°F) difference in mean daily temperature are found and the number of degree days produced by these are tabulated (as in Table 2.14 on p.125).

For example, if the data obtained is as follows (brief extract only):

Mean daily temperature (°C)	Number of days/heating season
0	22
-1	13
-2	8
-3	5
-4	2
-5	1
-6	0

Then if -5°C is the balance point temperature, the number of degree days is 0. At -4°C balance point the number of degree days = 1.

at - 3°C = 3
at - 2 = 8
at - 1 = 16
at 0 = 29
at 1 = 51

An easy way of doing this is by keeping a running total of the number of degree days and increasing this by the number of days at the temperature 1°C below the balance point temperature being considered. The full table of such figures for London is shown in Table 2.14 (p.125).

From knowing the balance point temperature, the corresponding number of degree days may be found from the table and the resulting heating load is computed using equation (11).

g. <u>Windows: Improvement for Solar Collection</u>.

North windows and horizontal roof lights have high heat losses and the size and number of these should be minimized.

Double glazing will reduce heat losses but to increase the thermal resistance even more becomes a substantial problem. This problem can be tackled in two ways: by means of moveable insulation or by means of improving the thermal performance of the transparent membrane. However the number of economically attractive and well performing solutions to this problem are few. Moveable insulation comes in various forms:

Curtains:

Depending on the materials used and the treatment of the edges of the curtains these can be useful. New insulating materials, low emissivity blinds and multiple layer foil blinds are coming onto the market.

Nightwall*:

Rigid expanded polystyrene sheets inserted within the window

* Patented systems by Zomeworks.

surround and held in place by magnetic strips. This is light, easy to apply and inexpensive but requires storage space unless built in the form of shutters or concertina blinds. Edge treatment is again critical to its performance.

Mechanical methods:

Under this heading come Beadwall*, Skylid* and external moveable insulation panels.

Beadwall[12] is a system whereby polystyrene beads are pumped into the cavity between double glazing at night or during cloudy spells, and removed when the sun is shining. The pump exerts considerable pressure on the glazing during this process. Both single and double strength glass failed to withstand this pressure. Both 5mm (3/16 inch) float glass and 6mm (¼ inch) plate glass have been used without problem. However should the system become clogged and internal pressure build up these glasses will explode into thousands of dangerous glass splinters. Therefore tempered safety glass or fiberglass are recommended. Fiberglass is the obvious choice on the grounds of cost but it degrades with age and an ultra violet sacraficial coating must be applied and maintained. Also fiberglass is not transparent and thus conflicts with any view requirements.

The final point about this system is that it is very expensive: £50/sq.m ($8/sq.ft). U-value of system when full of beads = .6 W/m^2 ^oC (.1 Btu/ft^2 ^oF); when empty = 2.8 W/m^2 ^oC (.5 Btu/ft^2 ^oF).

* Patented systems by Zomeworks.

Skylids can be used both on skylights or vertical glazing. The 300mm (1 ft) wide insulated louvers are automatically opened or closed by a sun-sensitive system consisting of coupled Freon-containing cans. One can is on either side of the louver. When the sun emerges the energy absorbed by the can it sees will expand the Freon and move it into the second can. The resulting imbalance in weight between the cans will cause the skylids to open. The seals around the edges of the skylids are not air-tight and this reduces its potential thermal insulating performance. This is another expensive system: £82/m^2 ($13/sq.ft). U-value when skylids open (dependent on position) = 2.8 W/m^2 ^{o}C (.5 Btu/ft^2 ^{o}F); when closed = 1.14 W/m^2 ^{o}C (.2 Btu/ft^2 ^{o}F).

External moveable insulation panels must be robust enough to withstand the elements. Good seals are again difficult to achieve. If the panels are the type that lower away from the building they can perform the additional function of a reflector, increasing the incident solar radiation on the glass. The cost of these panels is high but cost and U-value will be dependent on their construction. U-value attainable at night = 1.25 - .85 W/m^2 ^{o}C (.22 - .15 Btu/ft^2 ^{o}F).

With all the systems described above, with the exception of Beadwall, there is the problem of attaining air-tight seals.. Without good seals on all four edges the air against the glass surface will cool and fall into the room reducing the potential thermal performance of the system. The time commitment needed on the part of the user, for opening and closing most of the systems described above, is considerable. Furthermore the one basic disadvantage of all moveable insulation systems is that there is no increased resistance to heat losses during solar collection periods. This and other design requirements of windows are being met by materials now being developed in the Unites States.

To appreciate the methods of improving the thermal performance of windows by the use of glazing alternatives it is necessary to understand how the heat is being lost. The original "greenhouse effect" concept is: because glass is transparent in the solar radiation wavelengths and opaque to infrared (longwave) radiation it acts as an energy valve. Figure 2.19 shows, among other things, the different wavelengths of solar and room temperature radiations. However, it turns out that, although glass does have these properties, it is little more than a convection trap. For when polythene, which is fairly transparent in the infrared region, is tested against glass there is no discernable difference in the temperatures produced by glass and those by polythene.

The routes of energy escape are different; the energy leak in glass is in its absorption of infrared radiation and then reradiation of this energy to the sky. Whereas with polythene the majority of the heat lost is through its transmission window at the infrared wavelengths. With either type of transparent cover, the quantity of energy escaping is 60% of that escaping from an equal area of uncovered ground.

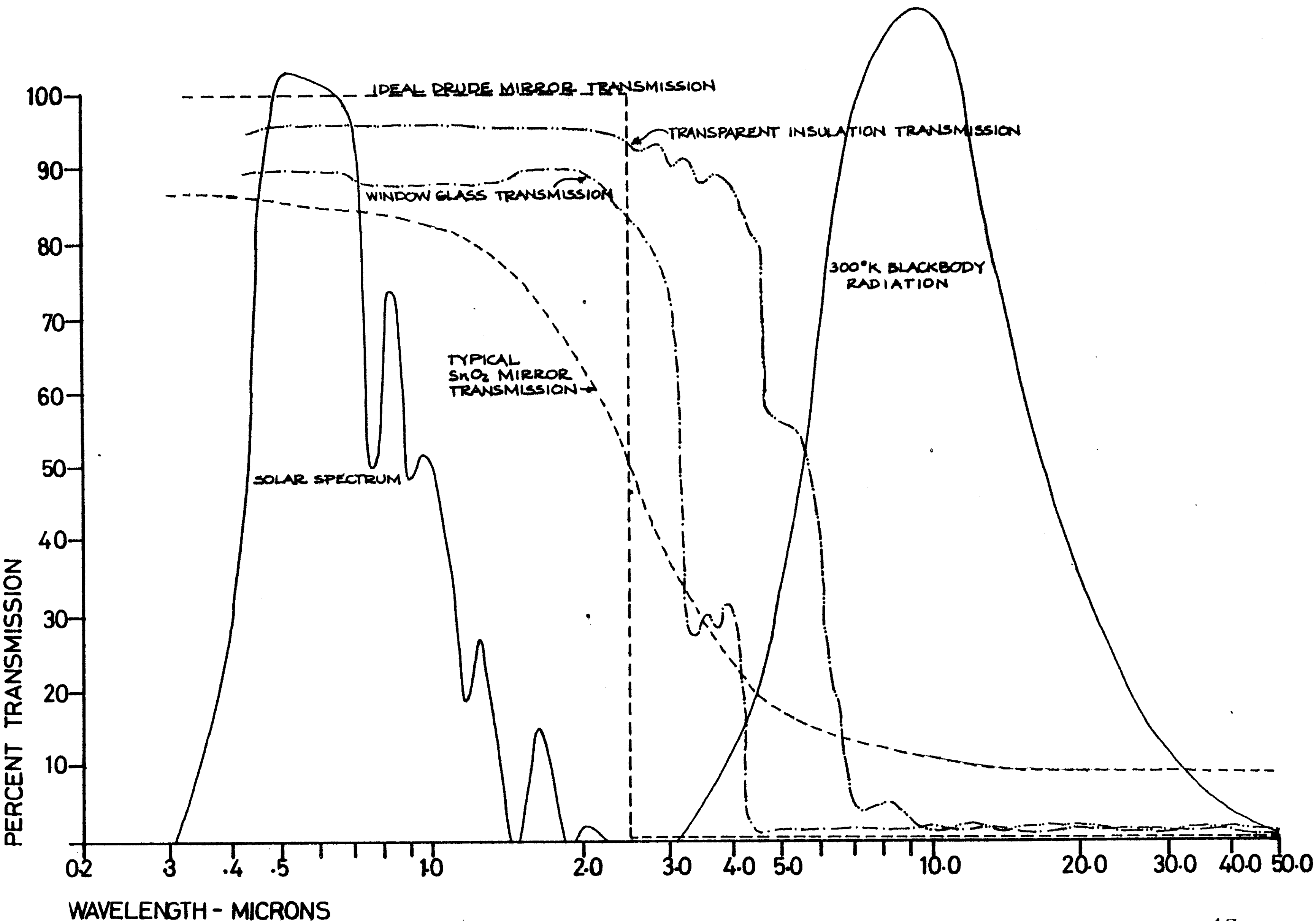


Fig. 2.19. Transmittances of various membranes and superimposed radiation curves[13]

For any material the following two equations are true within a given wavelength:

$$A + R + T = 1 \qquad (13)$$

and

$$A = E \qquad (14)$$

Where A = % absorption
R = % reflection
T = % transmission
E = % emission
And where percentages are expressed as fractions.

Thus it follows that, because glass is opaque to infrared radiation and because its reflection of infrared radiation is negligible, it absorbs almost all and then emits almost all of the infrared radiation absorbed.

		Btu/ft²h degF	W/m² degC
Windows			
exposure S sheltered	— single glazing	0·70	3·97
	— double, ¼in (6·4mm) space	0·47	2·67
	— ¾in (19·1mm) or more space	0·41	2·32
S normal, W, SW SE sheltered	— single glazing	0·79	4·48
	— double, ¼in (6·4mm) space	0·51	2·90
	— ¾in (19·1mm) or more space	0·44	2·50
S severe, W, SW, SE normal or NW, N, NE, E sheltered	— single glazing	0·88	5·00
	— double, ¼in (6·4mm) space	0·54	3·06
	— ¾in (19·1mm) or more space	0·47	2·67
W, SW, SE severe, NW, N, NE, E normal	— single glazing	1·00	5·67
	— double, ¼in (6·4mm) space	0·58	3·29
	— ¾in (19·1mm) or more space	0·50	2·84
exposure NW severe	— single glazing	1·14	6·47
	— double, ¼in (6·4mm) space	0·63	3·58
	— ¾in (19·1mm) or more space	0·53	3·00
exposure N severe	— single glazing	1·30	7·38
	— double, ¼in (6·4mm) space	0·67	3·80
	— ¾in (19·1mm) or more space	0·56	3·18

Table 2.1. U-values of windows[14]

The overall U-value (Table 2.1) of single glazing is not greater than 7.38 W/m^{2o}C (1.3 Btu/ft^{2o}F) and when storm windows are added the U-value is approximately halved to 3.18 W/m^{2o}C (.56 Btu/ft^{2o}F). Approximately 60% of the heat loss from the double glazed window is in the form of infrared radiation.

There are many properties to be considered, other than thermal performance, when comparing alternative glazing materials; a few of these are transmission to solar radiation, durability, and distortion of the image received through the material.

There are several possible ways, other than moveable insulation, of attempting to increase the overall solar collecting performance of the transparent membrane used:

(i) Treatment of the space between double glazing in an attempt to eliminate or reduce convective losses.

(ii) Increasing the transmission to solar radiation.

(iii) Lowering the longwave (infrared) radiation losses by reflecting them back into the room.

(i) By tackling convective losses alone the potential energy savings in reducing radiational losses are missed. Only 40% of the heat lost through double glazing is by convection. Within this category there are two approaches taken: eliminating convection and conduction by evacuating the air space, or inhibiting heat flow by introducing a suitable gas in the interpane space.

Even a partial vacuum, to the extent of reducing convection, would create sufficient pressure (4psi) to warrant a closely spaced structural system within the air space[13]. This structural system would be expensive, would distort the image received, increase losses due to conduction and increase absorption of solar radiation. Absorption increases, and and thus transmission decreases (eqn(13)), by approximately 1% for every 1mm increase in thickness of normal glass.

The introduction of a heavy gas to reduce thermal conduction and convection within the interpane space has been attempted. However it is uncertain in the literature which is being dealt with because low convection and low conduction call for opposite molecular weights[13].

(ii) The transmission of glass to solar radiation will not appreciably deteriorate with age whereas many plastics exhibit proliferation of color centers on exposure to sunlight in a matter of months. A single pane of 4mm (1/6th inch) low-iron glass will have a transmission of 92%* to solar radiation compared to 87% for normal glass. Absorption of solar radiation is increased and transmission decreased if iron is present in the glass. Iron causes a green tint to the glass when viewed from the edge of the pane. Double glazing with low-iron glass will give a transmittance of 85% (.92 x .92) compared to 75% (.87 x .87) for double glazed normal glass. The additional cost of low-iron glass over normal glass is

* Unless otherwise specified, transmission values are for solar radiation normal to the surface.

approximately 25%.

The property which determines the quantity of solar radiation reflected is the index of refraction. This is a surface effect that has a bearing on the quantity of solar radiation transmitted through the material (eqn(13)). The index of refraction for glass is 1.5; anything lower than this will have a higher transmittance to solar radiation and will accept a larger angle of incidence.with greater efficiency.

Teflon FEP is a flexible film produced by Dupont. It comes by the roll, is 2mil thick and costs £3.15/m^2 (50¢/ft^2). Teflon FEP is inert and has an index of refraction of 1.33 which gives it a 96% transmission value for solar radiation[13]. Thus one could have six layers of Teflon FEP and still get a slightly higher transmission value for solar radiation than double glazing. This type of performance is not possible using normal glass because the resulting increase in thermal resistance is less than the decrease in transmission. This use of Teflon FEP in effect reduces convection losses in a similar way to the concept involved in a honeycomb lattice. There are the disadvantages to Teflon FEP; it is not rigid and must be protected both internally and externally and a 2mm film of it has a 40% transmittance to longwave (infrared) radiation. The result is that the gains from decreased convective losses is cancelled by the increased radiation losses. Thus Teflon FEP, used in this way, is only of value because of its slightly lower cost than glass and because it is cheaper to install. Installation is effected by fixing all four edges and heat shrinking it using a blow heater. There is slight distortion of the image seen through it.

Teflon FEP can be used as an anti-reflection coating to glass. Glass is dipped into an aqueous slurry of Teflon FEP and put into a fusing oven at 370°C (700°F). Ordinary glass coated on one side will have an increased transmittance to solar radiation from 87% to 92%. The coating can be marked too easily for external use, thus glass will be coated on one side only. This process has not yet been tried, and costs, although expected to be minimal, are not known. The use of this coating on low-iron glass would improve its performance also.

Suntek Inc., California, is developing a transparent insulation by coupling Teflon FEP to a layer of transparent material which is opaque to infrared radiation. The transmittance to solar radiation is reduced only 1% from the value of Teflon FEP to 95% (Fig. 2.19). By using three layers of this between low-iron double glazing (all separated by 2 inch air spaces) it is possible to reduce convection losses and obtain an overall U-value of 1.25 $W/m^{2\circ}C$ (.22 $Btu/ft^{2\circ}F$), a transmittance to solar radiation of 73%, and at a cost of £9.45/m^2 (\$1.50/ft^2) above the cost of double glazing (excluding framing). The disadvantages are that there is some visual distortion to the image seen through this transparent insulation and the frames become large, cumbersome and expensive to produce.

Multiple layer transparent insulation goes somewhat further than reducing convective losses; it also reduces losses due to infrared radiation by increasing the number of absorption and emission steps to the outside.

(iii) This is the Drude mirror or heat mirror. The ideal transmission curve of a heat mirror is shown in figure 2.19. Heat mirrors have been on the market for 20 years (Fig. 2.19) but at a very high price. There are two approaches to producing heat mirrors. The first is by etching very fine lines on the glass; so fine that they will reflect the longwave (infrared) radiation. The second uses the same concept but instead of using lines, thin inorganic layers are applied to the transparent substrate. With both methods there is little reduction in the transmittance of solar radiation. The high costs are because both are batch methods. Research is being carried out in several laboratories in the United States to produce a heat mirror by an on-line method. This has been achieved by Suntek Inc. The substrate being used is mylar. Only 300mm (1 ft) widths are available at the moment and the price is fairly high. These strips can be bonded together or applied to a glass surface. The two possible assemblies and their properties are shown in figure 2.20.

The expected additional cost due to the heat mirrors in both assemblies is the same: 3.00/m^2 (48¢/ft^2) (fixing included). Heat mirror samples show that there is no visual distortion to

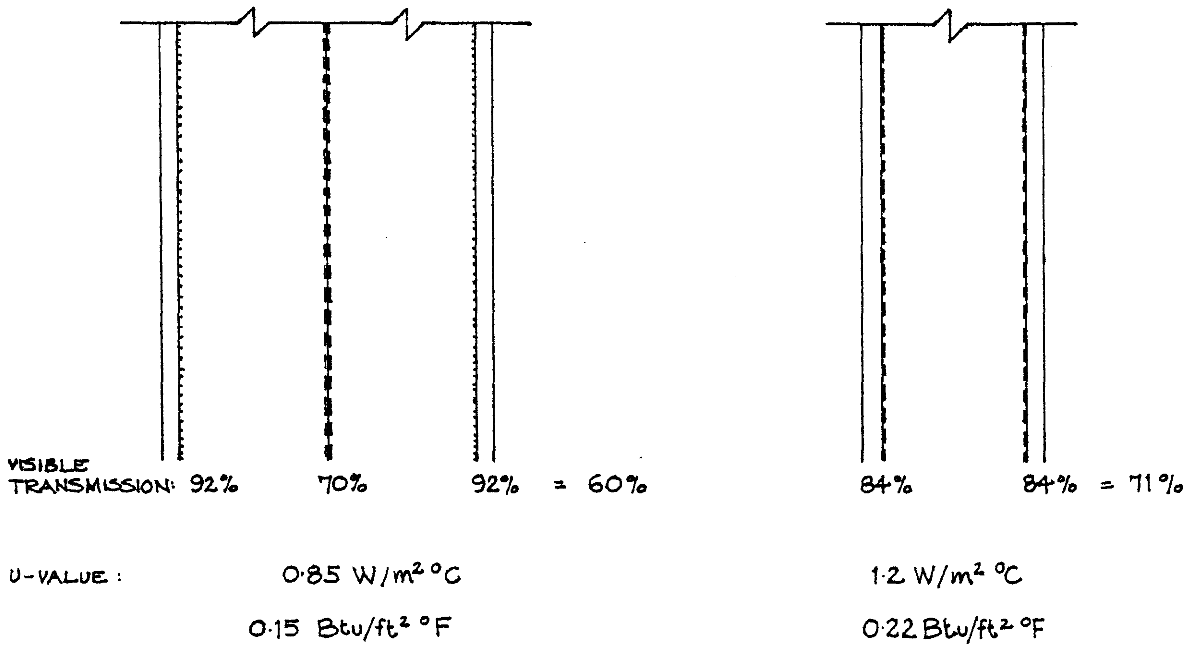


Fig. 2.20. Two possible assemblies of the heat mirror being produced by Suntek Inc., California.

the image received through it.

All the methods of improving the solar collection performance of windows, discussed in this section, can be assessed in terms of cost by the program presented in the section of this chapter headed "Costing" (p121).

h. Fabric Losses.

The average thermal resistance of the building's weather skin must be made as high as is economically feasible. Testing such economic feasibility is possible by means of the design method or program listed in the section of this chapter headed "Costing" (p.121), and not by any intuitive decision.

The weather skin components of the building will be discussed in turn:

Windows: discussed in the preceding section: "Windows; Improvement for Solar Collection".

Walls: insulation should be placed on the external surface of masonry walls. Doing so will bring them within the insulating envelope and allow them to perform as either primary or secondary thermal mass*. Calculations must be conducted to determine if and where condensation occurs and, if necessary, preventative measures taken. The method for determining the likelihood of condensation occuring within the building fabric is outlined elsewhere[15]. The presence of water within the fabric of the weather skin will both gradually destroy most building materials and considerably reduce their thermal resistance. Table 2.2. shows how the thermal conductivity will vary with exposure to rain. In conditions of driving rain[16] and where condensation occurs, much higher moisture contents can be expected[17].

Roof: in most houses on the market, at least 25% of the total seasonal heating load is being lost through the roof. Remedial measures (insulation) are easy and cost effective but condensation should be considered.

Ground Floors:

Suspended timber floors: the temperature differential, and thus the heat losses through the floor, will vary depending on the use of the space below the suspended floor. An openly

* see the section of this chapter entitled "Thermal Mass"

Bulk dry density kg/m³	Thermal conductivity W/m °C		
	Brickwork protected from rain: 1%*	Concrete protected from rain: 3%*	Brickwork or concrete exposed to rain: 5%*
200	0·09	0·11	0·12
400	0·12	0·15	0·16
600	0·15	0·19	0·20
800	0·19	0·23	0·26
1000	0·24	0·30	0·33
1200	0·31	0·38	0·42
1400	0·42	0·51	0·57
1600	0·54	0·66	0·73
1800	0·71	0·87	0·96
2000	0·92	1·13	1·24
2200	1·18	1·45	1·60
2400	1·49	1·83	2·00

* Moisture content expressed as a percentage by volume

Table 2.2. Thermal conductivity of masonry materials[17]

vented space to the outside will produce the same temperature difference as elsewhere on the weather skin. If the space is enclosed but unheated its temperature can be calculated using a resistance split method[18]. In Europe the renown wine cellars at a constant year round temperature of 10°C (50°F) give uniform heat losses. In the United States, where furnaces are usually placed in the cellar, the same constant cellar temperatures are applicable. Insulation installment is usually complicated by the network of water and heat distributing pipes and ducts. Waterproof insulations, such as expanded polystyrene, are usually ruled out by fire regulations. Reflective sheild insulation, as that developed in Holland[19], although highly effective, will soon become covered with dust and no longer reflect infrared radiation.. A multiple layered reflective insulation will perform well and so will polythene covered fiberglass insulation. A low emissivity surface facing the cellar will improve the thermal performance of the suspended floor.

Solid floor: if the ground water table is high, heat will be rapidly stripped away from the building through the floor. In such conditions there is no alternative to insulating below the entire floor. The ground water temperature determines the temperature differential across which heat is lost. The ground water temperature for each month can be measured from the cold water tap (providing the water comes from the mains).

Where water is not present, the ground below the building can be incorporated into the thermal mass by insulating against heat losses at the edges. Effective insulation of the edges of a building in such a location will result in negligible heat losses.

Examining heat movement between two layers of any material(s): the quantity of heat being conducted is proportional to the temperature difference between the two layers. If the ground beneath the building is divided into many layers the resulting temperature differentials between the layers, and thus heat flow downwards, diminish exponentially (Fig. 2.21) until, at a depth of 1.2m (4 ft.), there is negligible heat flow.

In view of this the edge losses become the only problem. Figure 2.21 shows that these can be contained by insulating either horizontally or vertically providing that the paths of heat flow are intercepted.

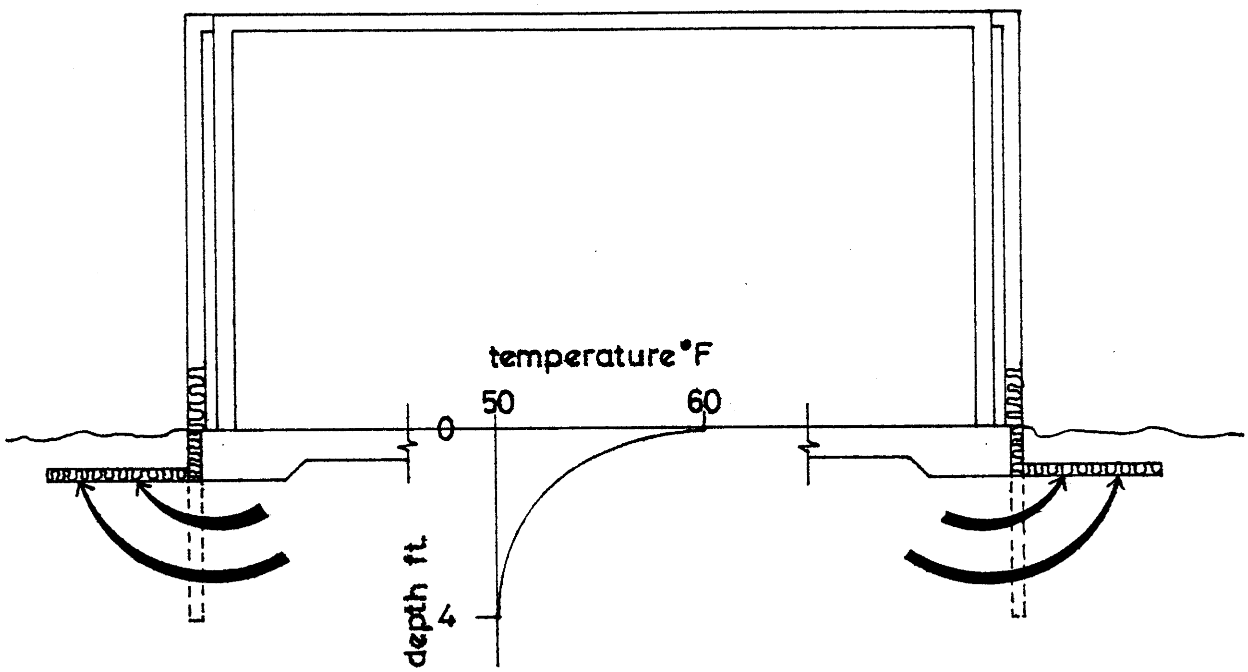


Fig. 2.21. Edge insulation and heat flow into the ground.

i. Infiltration.

The Hittman Report[20] concludes that infiltration accounts for some 28% of the total seasonal heat losses in the majority of houses built in America today. A very well insulated house in America may have infiltration losses of approximately 38% of the seasonal heat losses. Figure 2.22 shows the changing infiltration rates for a standard and then a well insulated and weather stripped dwelling in England and America.

Thus by substantially reducing the infiltration rate, 90+% solar heating is easily attainable. The problem is that infiltration is reduced to this extent with great difficulty. The 1½ air changes per hour for standard construction in America is reduced to about ½ air change per hour by means

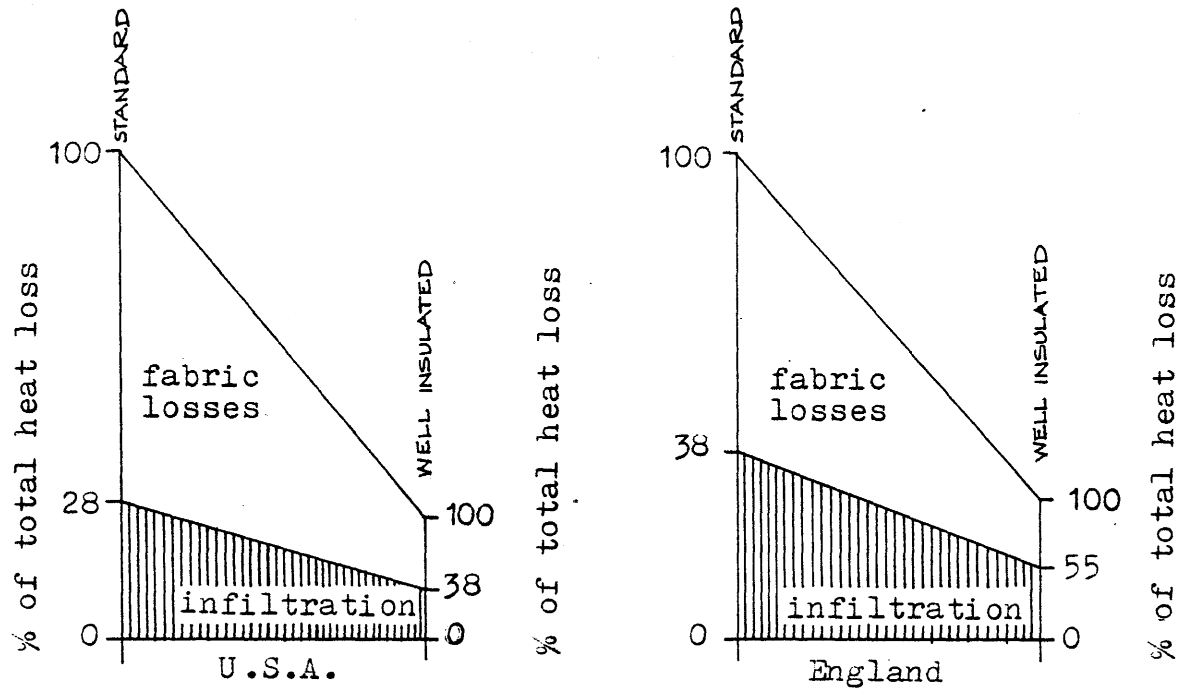


Fig. 2.22 proportional heat losses in standard and well insulated dwellings.

of good weather stripping around openings and by caulking construction cracks.

Such a rule of thumb method is traditionally adopted because up until recently the accuracy in assessment of this air change loss has not been important. The alternative to this method is the crack method which determines the heat loss by knowing the infiltration coefficient of the gap, the length of the gap, the degree of exposure of the building and the wind speed[5]. Both methods call for a sixth sense of what is happening largely based on comparison with measured test data. Becuase infiltration carries such weight in a passively heated building it is necessary to take a more detailed look at the methods of both calculating the heat losses to infiltration and determining the influencing factors involved:

The Crack Method:

Where new windows are being installed, providing relevant manufacturer's data is available, the infiltration air flow can be calculated from the following relationship[11]:

$$V = L \times C \times (\Delta p)^{0.63} \qquad (15)$$

Where V = the volume of air flow cu.m./hr. (cu.ft/hr.)
L = the gap length
C = infiltration coefficient = the volumetric air flow per meter (foot) of opening joint per unit pressure difference cu.m./hr.m.N/sq,m. (cu.ft./hr.ft.lbf/sq.ft.)
Δp = pressure difference across the window.

The effect of wind on a building is to create a differential pressure on the windward face of 0.5 - 0.8 times the velocity pressure of free wind. This is reinforced by a suction pressure of 0.3 - 0.4 times the velocity pressure on the leeward face. The combined pressure difference across the building is therefore approximately equal to the wind velocity pressure. In eqn.(15) Δp refers to half of this, being only the pressure difference across the window; and the crack length taken is for all windows of the building. British Meteorological data are based on readings in open country at a height of 10m. (30ft.). Local velocities will be higher than this for windows at a greater height and lower for lower windows or for buildings sited in built-up areas. Mean monthly wind speeds show an average of approximately 5 m/s (11 miles/hr.) in winter[21] which will be approximately 3 m/s (7 miles/hr.) in surburban areas. This represents wind pressures of

15 N/m^2 (.3 - .1 lbf/ft^2) respectively.

However, Electricity Council Research Center (ECRC) tests on unoccupied houses in England, using a tracer gas[22], have shown that although infiltration rates are closely linked to wind velocity in a normal house, in the well weather stripped house ventilation rates are mainly dependent on internal to external temperature difference. This leaves the crack method somewhat wanting as a design tool. Moreover, neither calculation method includes infiltration due to the behavior patterns of the inhabitants. Window and door opening can, particularly in housing, contribute a significant additional seasonal heat loss.

Dick and Thomas, in 1951 in a thorough but neglected study[23], revealed the British tendancy to open the windows in mild weather. The number of windows open increased linearly with outdoor temperature, with the numbers slightly reduced in high wind conditions (Fig. 2.23). The effect was to increase the air change rate per hour from approximately 1½ at 0°C (32°F) to 3½ at 12°C (54°F) (Fig. 2.24). Such behavior patterns can largely be explained by the high humidity of the air during the heating season in England. For most of the English winter the outdoor air is approximately 90 - 100% saturated with water vapour[24]. Brundrett[11] illustrates how the infiltration rate increases due to inhabitants in the ECRC Bromley field trials (Fig. 2.25). The solid straight line on the graph in figure 2.25 shows where an additional 3/4 of an air change per hour will coencide with the measured

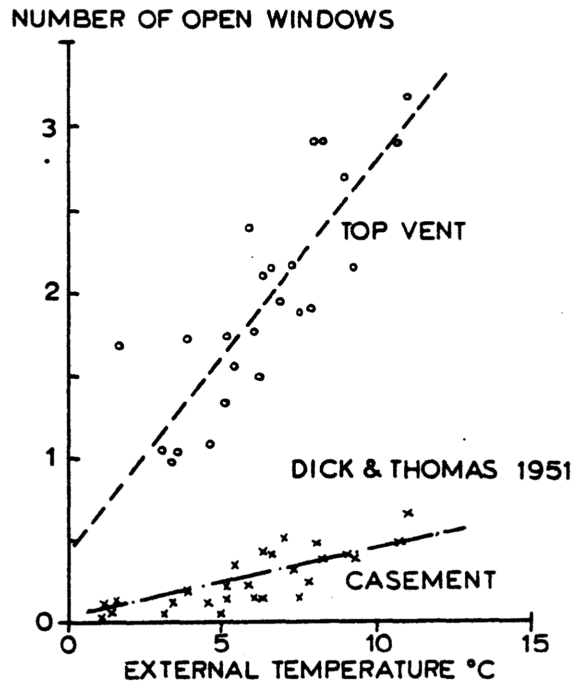


Fig. 2.23. Number of windows open at different outdoor temperatures (Ref.23).

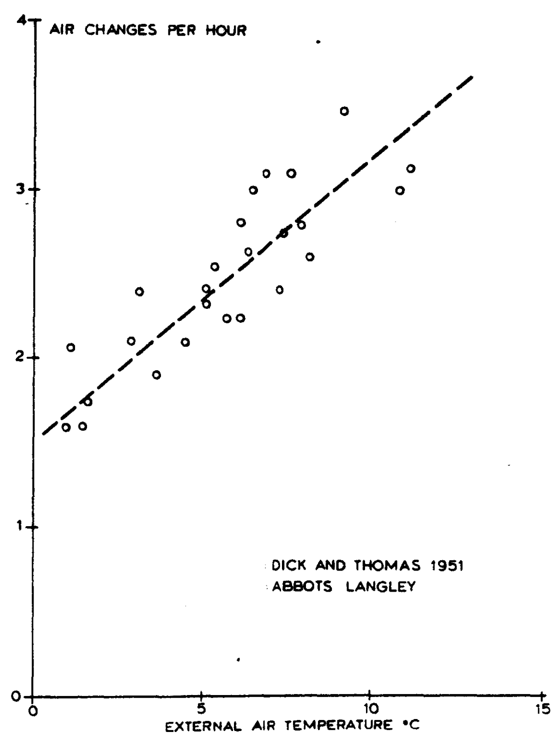


Fig. 2.24. Air change rate related to open windows[23].

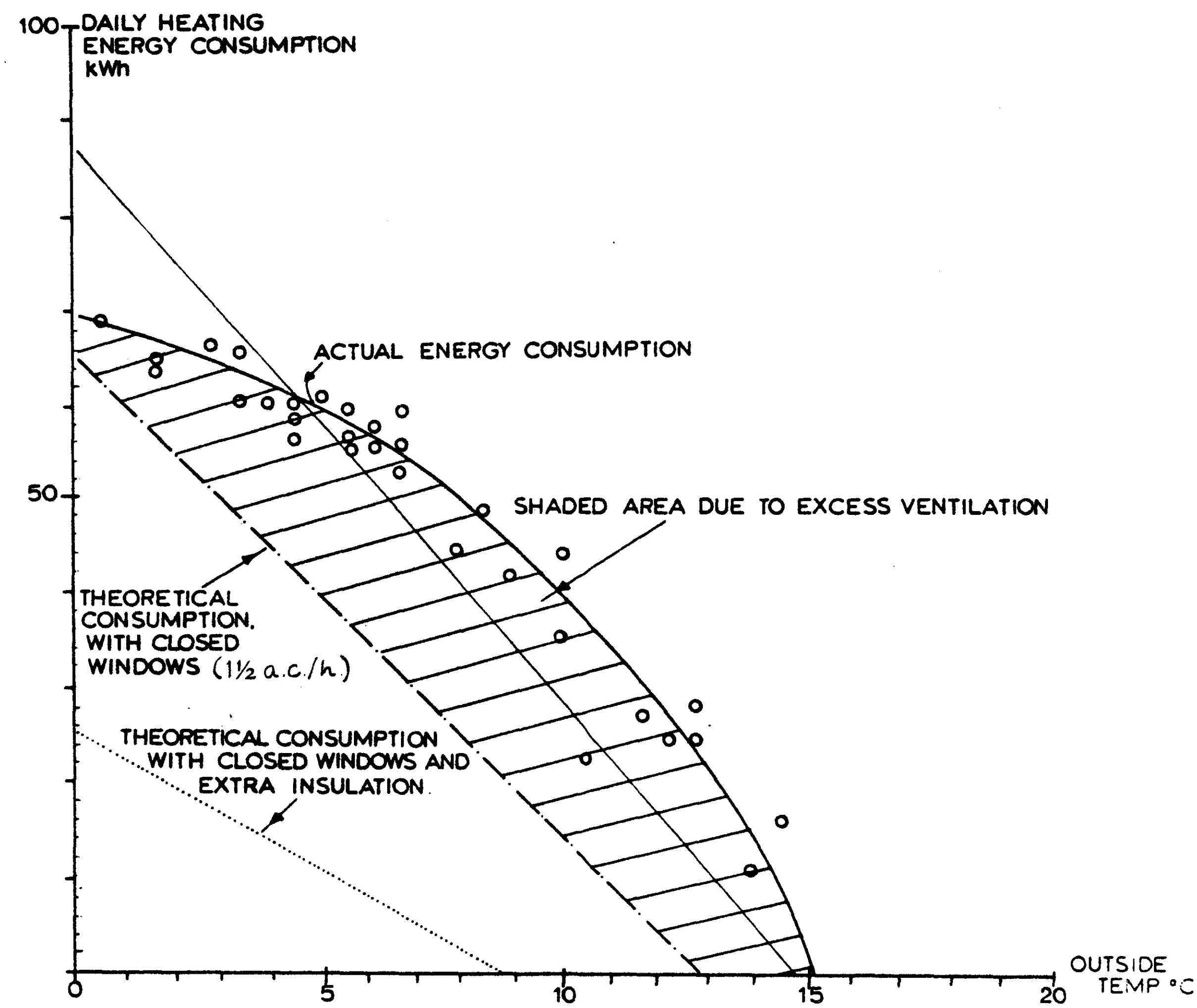


Fig. 2.25. Actual and theoretical daily energy consumption of a typical 3-bedroom row house in England(Ref. 11).

behavioral infiltration loss pattern. The theoretical consumption with closed windows was computed using 1½ air changes per hour as the infiltration rate. Thus in normal building construction we can probably expect something like 2¼ air changes per hour over the heating season in England.

This additional infiltration rate may change with increased insulation, weather stripping, and increased use of man-nade fibers for furnishings. Single glazing will often act as a dehumidifier in an English home. If double glazing or transparent insulation are used condensation will not occur and more ventilation may be required to reduce a build-up of humidity levels in the air. Brundrett[25] argues that the increased use of man-made fibers will also increase the user infiltration rate. The reasoning is that natural fibers within a building, tame the daily humidity fluctuations because they absorb far more moisture than do man-made fibers. However, there are no figures available to verify these probable changes in infiltration rate nor to suggest the magnitude of the change involved. Therefore, until this is known, it is suggested that the same increment of 3/4 an air change per hour be used for the user infiltration rate of a well insulated house in England.

The ECRC tracer gas infiltration tests[22] have shown that the air change rate for a well weather stripped unoccupied house is an average of .18 air changes per hour. Thus a figure of .93 (.18 + .75) air changes per hour can be used for an occupied well insulated and weather stripped house in England.

The obvious progression from here is to determine how much air is actually needed by the inhabitants for comfort and life support, and to see if there is any difference between this and the .93 air changes derived above for the weather stripped house (.5 ac/h in the USA). Looking at each of the constituent needs supplied by fresh air:

(i) Oxygen:

A wide range of percent Oxygen content in the air can be tolerated. At sea level the percent Oxygen in the air can be reduced from 21% to 13% without having any noticeable effect on the rate of breathing. Below 12% will cause an increase in breathing rate. However, this is unlikely to be encountered because we are far more sensitive to the concentration of Carbon Dioxide in the air.

(ii) Carbon Dioxide:

Outdoor air contains 0.03% of Carbon Dioxide. When a concentration of 2% Carbon Dioxide is reached in inhaled air the depth of breathing increases. At concentrations of 3-5% there is a concious need for increased respiratory effort and the air becomes objectionable. Concentrations of over 6% Carbon Dioxide in air are dangerous[26]. In England the maximum recommended concentration of Carbon Dioxide for habitation is 0.5%[21]. This gives a generous safety margin for breathing comfort. The resulting fresh air needs for comfort from this parameter is 3.8m^3/hr per person. For housing this is approximately equivalent to ¼ of an air change per hour.

(iii) Odor Control:

Infiltrating air dilutes odors. Experiments conducted by Yaglon in the USA[27] show that there is no sex difference in the emanation of odors if no perfume is worn, but that age is important since children below the age of 14 create more objectionable odors. Also the strength of odor was shown to be strongly related to the time since the last bath.

Figure 2.26 shows that a 1/3 of an air change per hour is acceptable for both Carbon Dioxide and odor levels, providing that the inhabitants are non smokers and that there is a space of $8m^2$ (85 sq.ft.) per person. Presumably this air change rate can be substantially reduced if it is possible to remove odors and Carbon Dioxide by some means other than the introduction of fresh air.

However, in England a different problem occurs at this point. If the air change rate is reduced to 1/3 per hour we are introducing just over $5m^3$/hr of fresh air per person and, as shown in tables 2.3 and 2.4, the resulting relative humidities will be uncomfortable for a large proportion of the heating season. Current comfort guides[21] recommend a range of 40 - 70% relative humidity. Consequently the inhabitants will open windows. This implies that a method of dehumidifying the air is required for an English home. It is thought that a solar dehumidifier on the lines of that suggested by Wellesley-Miller[28] could, with some modification, adequately do this job.

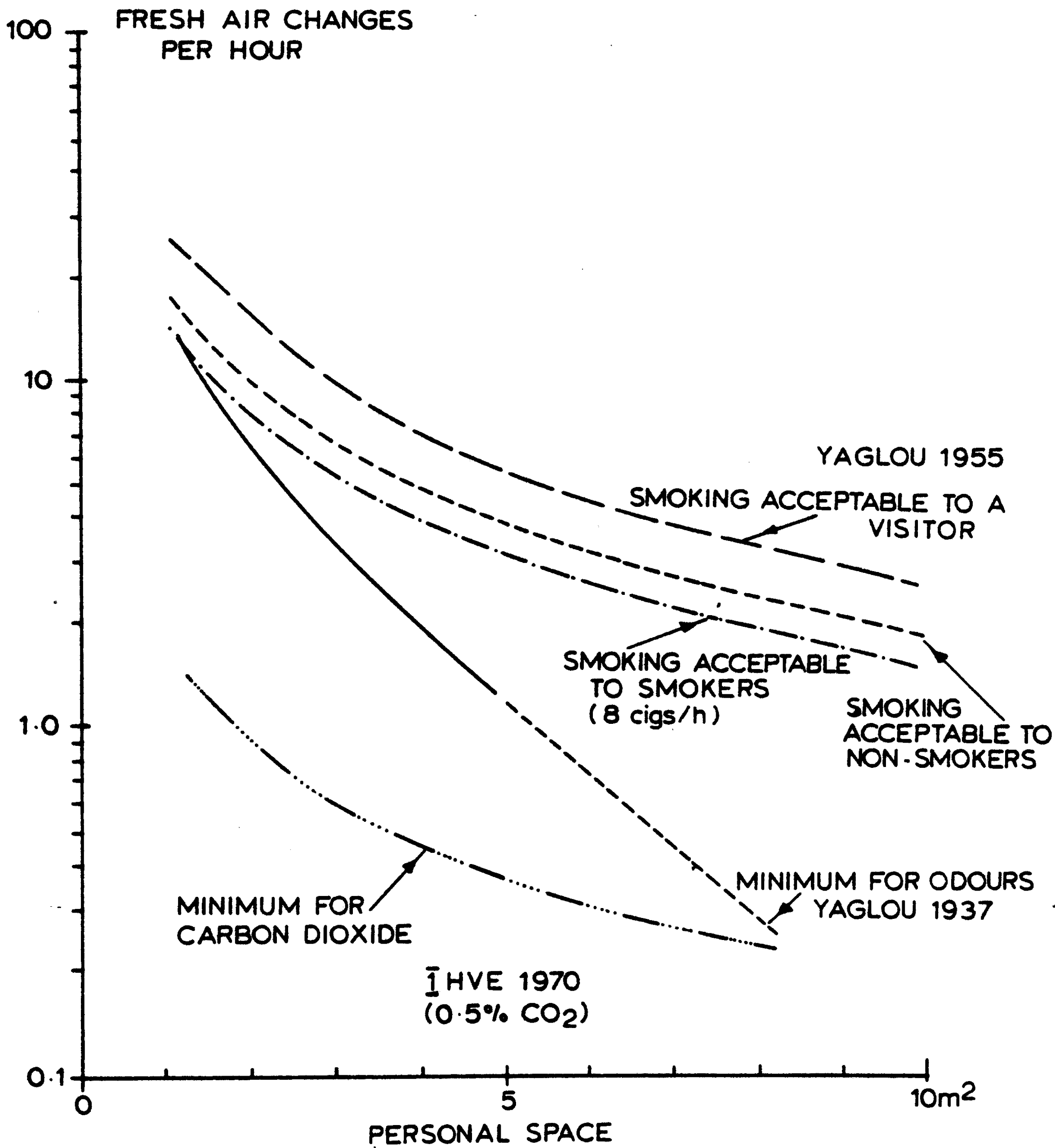


Fig. 2.26. Fresh air changes as a function of personal space (ceiling height 2.4m assumed) (Ref.25).

Table 2.3 (Ref 25).

The Influence of air change on relat.ve humidity for an internal temperature of 17°C

assumptions: one sedentary person contributes 40 gram/hour moisture
: specific volume of air 0.83 m^3/kg

Fresh air per person		Extra moisture added by person	External Temperatures																	
			-5°C			0°C			5°C			10°C			15°C			20°C		
m^3/h	kg/h	g/kg air	initial moisture g/kg air	final g/kg air	r.h. at 17°C	initial moisture g/kg air	final g/kg air	r.h. at 17°C	initial moisture g/kg air	final g/kg air	r.h. at 17°C	initial moisture g/kg air	final g/kg air	r.h. at 17°C	initial moisture g/kg air	final g/kg air	r.h. at 17°C	initial moisture g/kg air	final g/kg air	r.h. at 17°C
5	6.0	6.6	2.2	8.8	73%	3.3	9.9	82%	4.6	11.2*	93%	6.3	12.9	sat.	8.3	14.9	sat.	9.2	15.8	sat.
10	12.1	3.31	2.2	5.5	46%	3.3	6.6	54%	4.6	7.9	65%	6.3	9.6	80%	8.3	11.6	96%	9.2	12.5	sat.
20	24.1	1.66	2.2	3.9	32%	3.3	5.0	41%	4.6	6.3	52%	6.3	9.0	66%	8.3	10.0	83%	9.2	10.9	91%
30	36.2	1.1	2.2	3.3	27%	3.3	4.3	36%	4.6	5.7	47%	6.3	7.4	61%	8.3	9.4	78%	9.2	10.2.	86%
40	48.2	0.83	2.2	3.0	25%	3.3	4.1	34%	4.6	5.4	44%	6.3	7.1	59%	8.3	9.1	76%	9.2	10.0	83%

Table 2.4 (Ref 25).

The influence of air change on relative humdity for an internal temperature of 21°C

assumptions: one sedentary person contributes 40 gram/hour moisture
: specific volume of air 0.843 m^3/kg

Fresh air per person		Extra moisture added by person	External Temperatures																	
			-5°C			0°C			5°C			10°C			15°C			20°C		
m^3/h	kg/h	g/kg air	initial moisture g/kg air	final g/kg air	r.h. at 21°C	initial moisture g/kg air	final g/kg air	r.h. at 21°C	initial moisture g/kg air	final g/kg air	r.h. at 21°C	initial moisture g/kg air	final g/kg air	r.h. at 21°C	initial moisture g/kg air	final g/kg air	r.h. at 21°C	initial moisture g/kg air	final g/kg air	r.h. at 21°C
5	5.9	6.72	2.2	8.9	56%	3.3	10.0	64%	4.6	11.3	72%	6.3	13.0	83%	8.3	15.0	96%	9.2	15.9	sat.
10	11.9	3.36	2.2	5.56	35%	3.3	6.6	42%	4.6	8.0	51%	6.3	9.6	61%	8.3	11.6	74%	9.2	12.5	80%
20	23.8	1.68	2.2	3.88	24%	3.3	5.0	32%	4.6	6.3	40%	6.3	8.0	51%	8.3	10.0	64%	9.2	10.9	68%
30	35.7	1.12	2.2	3.32	21%	3.3	4 4	28%	4.6	5.7	36%	6.3	7.4	47%	8.3	9.4	60%	9.2	10.3	66%
40	47.6	0.84	2.2	3.04	19%	3.3	4.1	27%	4.6	5.4	35%	6.3	7.1	46%	8.3	9.1	58%	9.2	10.0	64%

Such moisture problems do not afflict the American winters. Therefore, theoretically, in the United States, an air change of .3 per hour would be acceptable in the controlled environment described above. For calculation purposes it is assumed that the minimum comfortable air change rate attainable in America is about ½ an air change per hour.

j. Thermal Mass.

This is the means of heat storage and air temperature stabilization that passive design employs. There are two types of thermal mass, namely primary and secondary thermal mass:

Primary thermal mass is the target area hit by direct solar radiation. Because most of the energy received from the sun is in the form of shortwave (visible) radiation it is the surface color of the area it strikes that controls the quantity of energy absorbed. Thus the target area will be painted a dark color; black will give approximately 90% absorption. Of this energy absorbed, some will be conducted into the thermal mass and the remainder will be lost from the surface by convection and radiation. Convective losses will directly increase room temperatures but radiated energy cannot be transformed to heat until it strikes an object or surrounding surface. If these objects are furnishings and the surrounding surfaces have low thermal capacities (specific heat x density) or low conductances (reciprocal of the resistance) their surface temperatures will rise quickly causing large heat losses tothe room air. In such a situation overheating will soon occur.

One of the methods of preventing overheating is the use of secondary thermal mass. The surfaces surrounding the target area are built with materials which have high thermal capacities and high conductances. Thus the energy primed secondary thermal mass stores heat and consequently tames the fluctuations in room air temperature. Unlike the absorption requirements of solar energy, absorption of the energy radiated from room temperature surfaces is not influenced by color. The molecular structure of the absorber surface does however control the quantity of infrared radiation absorbed. All peculiarities of radiation absorption are governed by the relationships described in equations (13) and (14). Thus because polished metal has a low emissivity of infrared radiation it would be a poor choice for the surface of secondary thermal mass (eqn 14). However, fortunately in this case, most building materials are good absorbers of infrared radiation.

Secondary thermal mass in indirect view of the target area can also be used to good effect.

The emphasis here is being placed on infrared radiation becuase after the absorption of direct solar energy this is where most of the action is within a passive system. The proportional heat loss paths from room surfaces shown in table 2.5 illustrate this point.

Surface	Convection	Radiation
Floor	46%	54%
Wall	40%	60%
Ceiling	30%	70%

Table 2.5. Proportions of heat loss paths from various surface tilts.

Computer simulations of the performance of passively solar heated buildings were conducted using the program designed by Timothy E. Johnson. Table 2.6 is an example of the data used for modeling. It will be noticed that the outdoor climate is particularly sivere and that concrete is used for both target area and secondary thermal mass; also that the program does not account for internal gains which, although has an influence on room air temperatures, will not affect the conclusions drawn from the simulations presented here.

<table>
<tr><td colspan="2">Hours of the day</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td rowspan="2">Clr day vert comp. of solar gains*</td><td>Wh/m^2</td><td>141</td><td>279</td><td>354</td><td>392</td><td>354</td><td>279</td><td>141</td></tr>
<tr><td>Btu/ft^2</td><td>45</td><td>89</td><td>113</td><td>125</td><td>113</td><td>89</td><td>45</td></tr>
<tr><td colspan="2">% noon target in sun*</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td><td>100</td></tr>
<tr><td rowspan="2">Outdoor temperature</td><td>^oC</td><td>-6.1</td><td>-5.0</td><td>-4.4</td><td>-3.9</td><td>-3.3</td><td>-1.1</td><td>1.1</td></tr>
<tr><td>^oF</td><td>21</td><td>23</td><td>24</td><td>25</td><td>26</td><td>30</td><td>34</td></tr>
<tr><td colspan="3">mrng start temp 18.3^{o}C, 65^{o}F</td><td colspan="6">Air ch/hr 5522m^3, 195000 ft^3</td></tr>
<tr><td>No auxil heating</td><td>Area</td><td colspan="2">Conduct.</td><td colspan="2">Density</td><td>Sp.Heat</td><td colspan="2">Thickness</td></tr>
<tr><td rowspan="2">Target (area = noon target area in sun)</td><td>508 sq.m.</td><td colspan="2">.13 $W/M^2 °C/M$.</td><td colspan="2">2243 kg/M^3</td><td>.84 kJ/kg/°C</td><td colspan="2">15.0 cm.</td></tr>
<tr><td>5440 sq.ft.</td><td colspan="2">.76 $Btu/ft^2 °F\ hr/ft$</td><td colspan="2">140 lb/ft^3</td><td>.2 Btu/lb/°F</td><td colspan="2">.5 ft.</td></tr>
<tr><td rowspan="2">Secondary thermal mass</td><td>508 sq.m.</td><td colspan="2">.13 $W/M^2 °C/M$.</td><td colspan="2">2243 kg/M^3</td><td>.84 kJ/kg/°C</td><td colspan="2">9.0 cm.</td></tr>
<tr><td>5440 sq.ft.</td><td colspan="2">.76 $Btu/ft^2 °F\ hr/ft$</td><td colspan="2">140 lb/ft^3</td><td>.2 Btu/lb/°F</td><td colspan="2">.3 ft.</td></tr>
<tr><td colspan="9">Area of weather skn 3520M^2, 37668 ft^2; U-value .45 $W/M^2 °C$, .08 $Btu/ft^2 °F$</td></tr>
</table>

* see the section describing solar gains

Table 2.6. An example of the data modeled.

The program models a ceiling target situation with an 85% absorption of the direct solar energy gains. The secondary thermal mass has the same resistance to heat loss as the target, in the program, and is assumed to be opposite, and parallel to, the target area (ie. on the floor). Simulation of the movement of heat throughout the room is accomplished by dividing the materials involved (including the room air) into many separate layers and by iteratively analizing the heat flow between these layers.

Among other things, the simulations revealed that the temperature of the surface of the secondary thermal mass lies somewhere in the region between the temperature of the room air and the temperature of the surface of the target area.

The results drawn on the graph in figure 2.27 indicate several patterns of behavior of passive solar buildings of this type. The area of the secondary thermal mass is maintained equal to the area of the target, and neither of these areas are changed throughout the results shown on this graph. When only the thickness of the secondary thermal mass layer is changed it can be seen that a thin layer will cause large daily air temperature fluctuations within the room. As the thickness of the secondary thermal mass layer is increased the air temperature fluctuation within the room reduces until a point is reached where an increase in thickness will no longer reduce the air temperature fluctuation; this point is termed the turning point thickness.

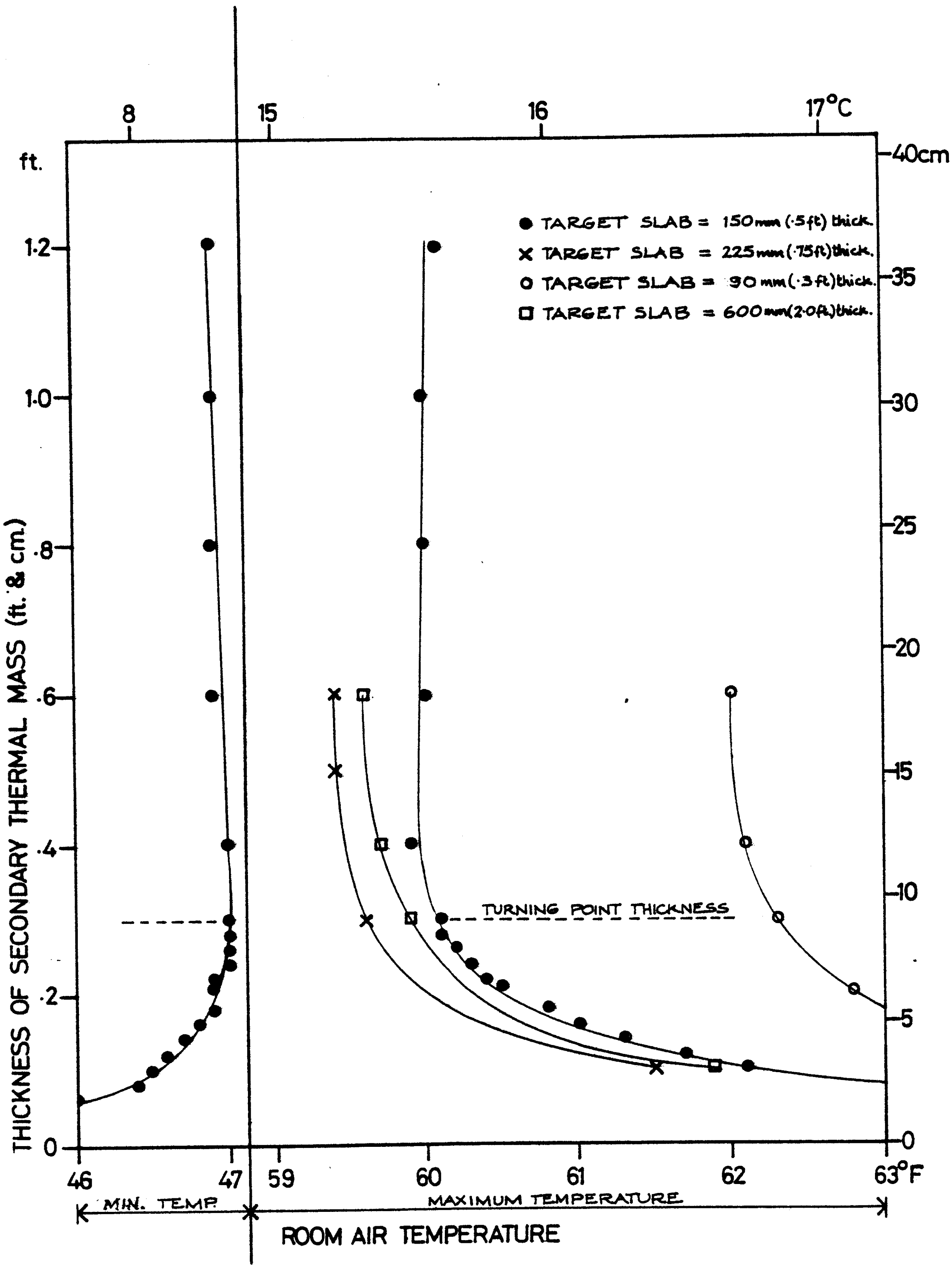


Fig. 2.27. The effect of the thickness of secondary thermal mass on the room air daily temperature fluctuation.

Each of the subsidiary curves has been drawn using a different thickness of primary thermal mass (target) and again changing only the thickness of the secondary thermal mass layer. It can be seen from these curves that the turning point thickness of the secondary thermal mass is not greatly affected by a change in the thickness of the target slab. However, the turning point thickness was seen to change with a change in the insolation values from those listed in table 2.6. A lower turning point thickness was obtained with a reduced insolation value. Furthermore, it is suspected that a change in values of specific heat, density and conductance of both thermal masses will alter the value of the turning point thickness. Additional research is required in these areas.

A change in the proportional area of the secondary thermal mass, with all other parameters unaltered, will cause a change in the turning point thickness of the secondary thermal mass. The resulting changes in the turning point thickness are shown on the graph in figure 2.28.

Figure 2.29 indicates the changes which occur to the air and target surface temperature fluctuations, caused by the changed proportional areas of secondary thermal mass, when the turning point thickness appropriate to that proportional area being modeled is used. The two scales on the y-axis are intended to be read as one scale. Although almost impossible to build, an area of secondary thermal mass 5 times the target area was modeled to reveal the trend of this graph. Such an area of

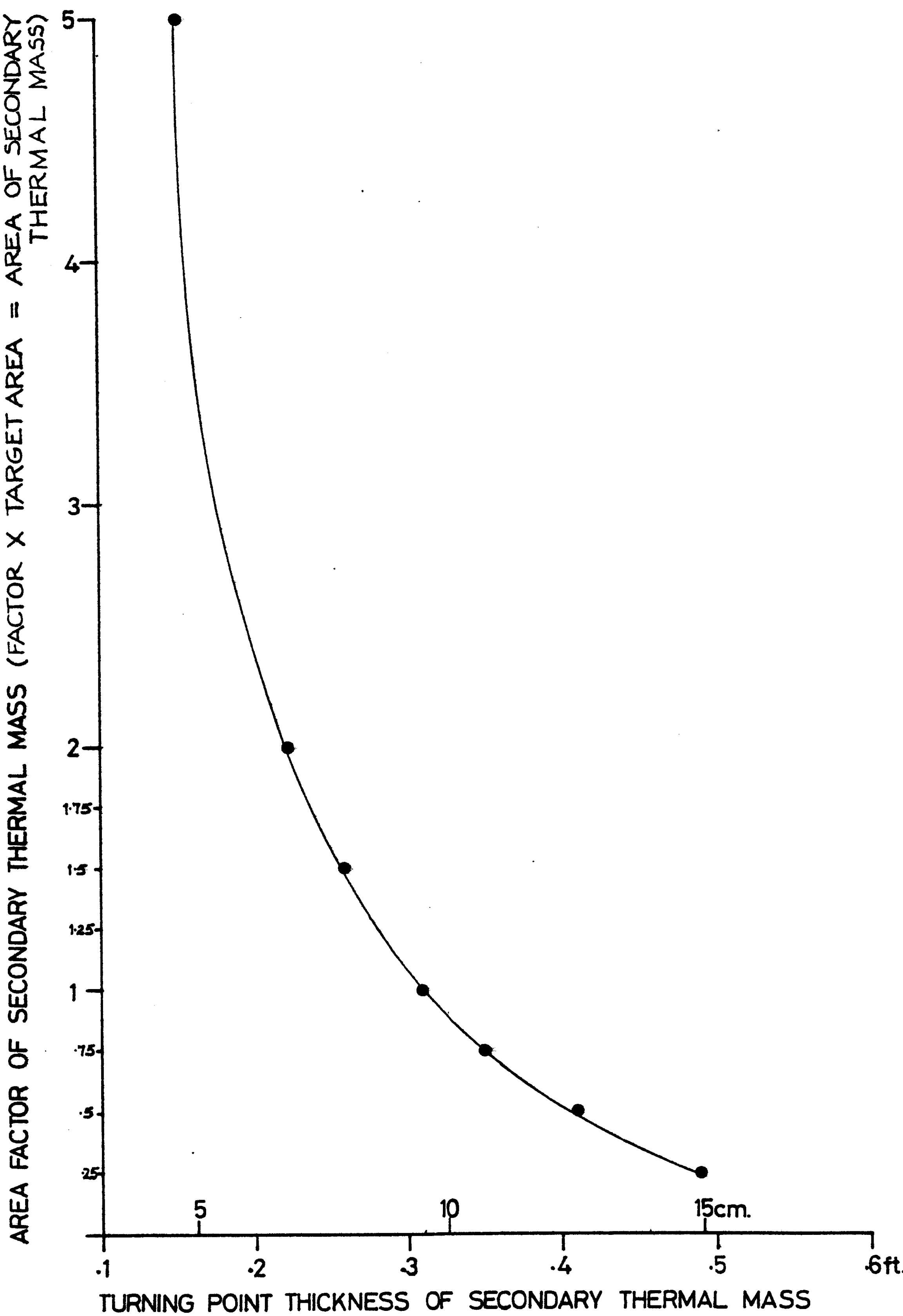


Fig. 2.28. The relationship of the area of secondary thermal mass to its turning point thickness.

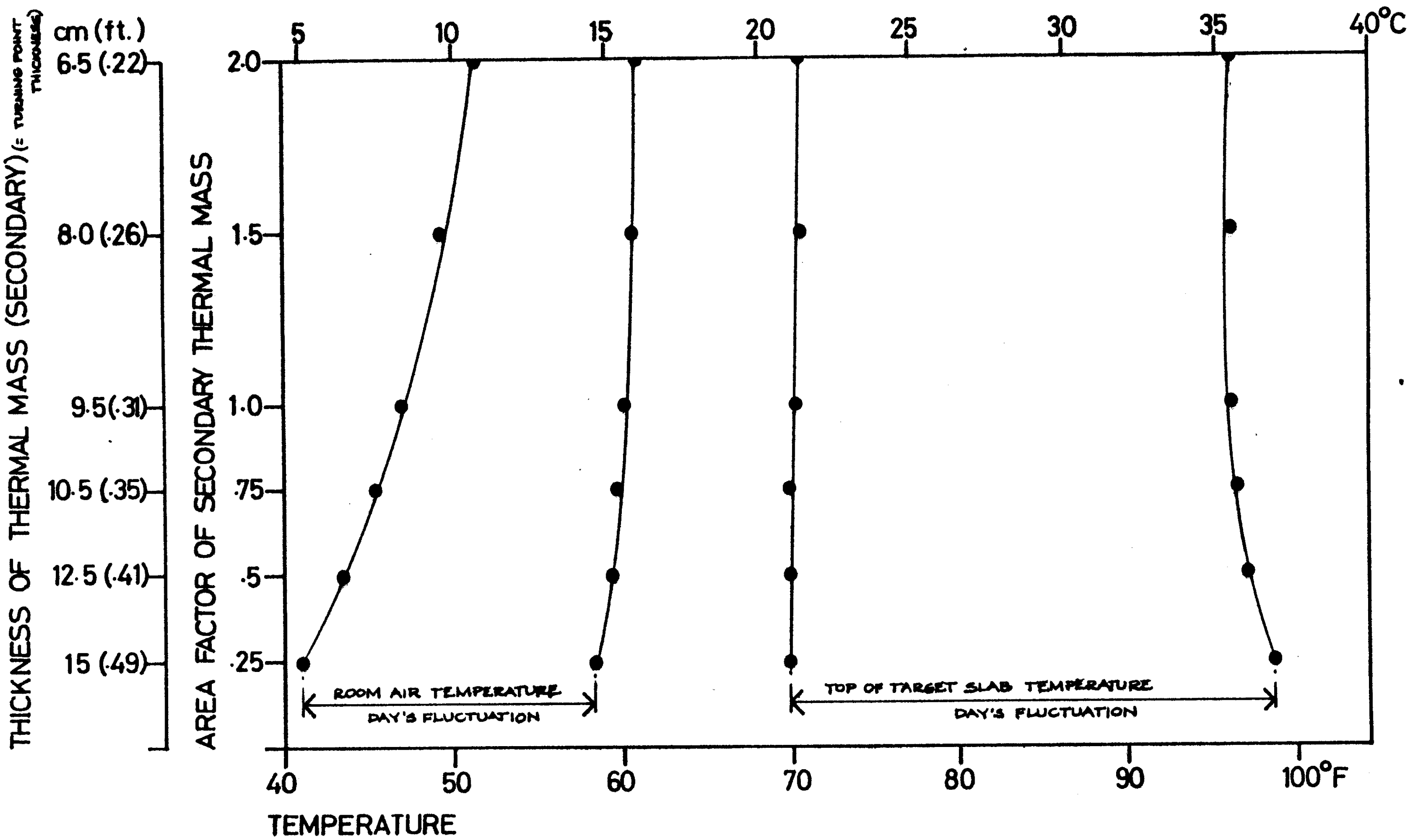


Fig. 2.29. Temperature fluctuations related to a change in linked area plus turning point thickness of secondary thermal mass. For each area of secondary thermal mass modeled, its turning point thickness is used.

secondary thermal mass has a turning point thickness of 4.5cm (.15ft). The resulting air temperature fluctuation was 13.9 to 16.8°C; approx. 3°C (57.0 to 62.2°F; approx. 5°F). Thus it can be seen that although the amplitude of the daily room air temperature fluctuation is greatly reduced with an increased area of secondary thermal mass, the differences in maximum air temperatures produced are small. This indicates that the smaller secondary thermal mass areas will provide the designer with smaller solar heating fractions (requiring more auxiliary heating). It is interesting to see the degree of temperature control that the designer is capable of employing through the use of thermal mass. Such taming of the daily air temperature fluctuations would still be seen if less sivere outdoor temperatures were used, and incidental gains included, resulting in room air temperatures within the comfort zone. It may have provided further information to have recorded the same results using auxiliary heating to raise minimum temperatures to within the comfort zone and then investigate the resulting maximum air temperatures produced.

A third conclusion can be drawn from the information presented on the graph in figure 2.27: it was found that a thickness of approximately 225mm (.75ft) was the optimum for a concrete target slab. This is in good agreement with Balcomb's findings[28a].

In an attempt to reduce the amplitude of the daily room air temperature fluctuation it is necessary to turn to materials with higher heat capacities and conductances than concrete. Table 2.7 indicates that water would be a good choice, although it has peculiar problems of containment and support. Another alternative, developed by Timothy E. Johnson, is the phase change material (pcm) tile (Fig. 2.30).

Material	Concrete	Water	pcm tile
Heat Capacity	5320 kJ/m^2	5320 kJ/m^2	2030 kJ/m^2
	476 Btu/ft^2	476 Btu/ft^2	200 Btu/ft^2
Temperature Swing	10°C	10°C	5.5°C
	20°F	20°F	10°F
Thickness	225mm	115mm	25mm
	.75ft	.4ft	.08ft (1in.)

Table 2.7. Heat capacities and thicknesses of various thermal mass alternatives.

The pcm tile (Fig.2.30) is being produced by Cabot Inc. and the Architectural Research Corporation (ARC) for the MIT Solar Demonstration Building.

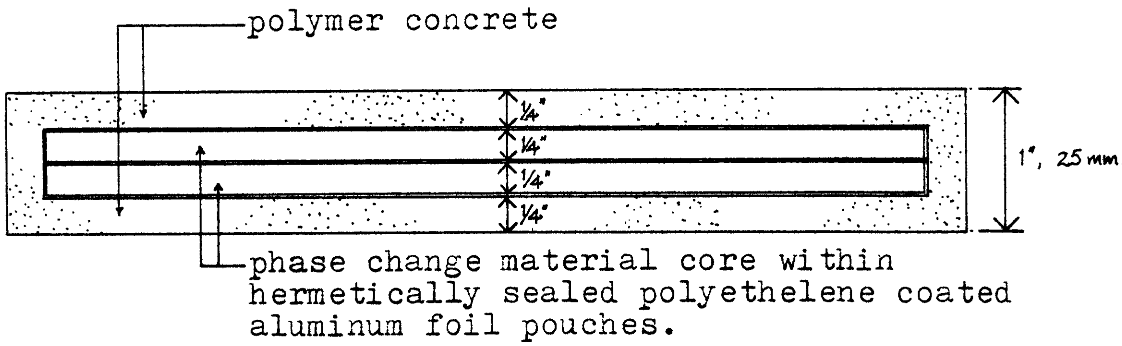


Fig. 2.30. A section through the phase change material tile.

With this tile, heat is stored latently at its freeze-thaw temperature. The phase change material employed is Glauber's

Salts ($Na_2SO_4 \cdot 10H_2O$), which melts at 31.1°C (88°F), but it is modified by additives, to melt at 23.3°C (74°F). The thickness dimension of the tile is critical as the phase change material must be stored in layers no thicker than 6mm (¼ inch) to prevent gravitational separation of the constituent materials. Thus the tile must be mounted horizontally. Polymer concrete is strong, light and waterproof and the surface finish can be varied. The tile weighs 4.5kg/m^2 (10 lb/ft^2); only slightly less than the weight of the same thermal capacity of water and the equivalent of ¼ of the weight of the same thermal capacity of concrete.

The comparative benefits of the pcm tile described above are significant, although not startling. However, the real value of the pcm tile comes to light when the control of room air temperature fluctuations are considered. The phase change of the material enables storage and release of energy with little change in tile core temperature (Fig. 2.31), which in effect provides a built in thermostat. Under steady state conditions, where the pcm tiles are the only source of heat,

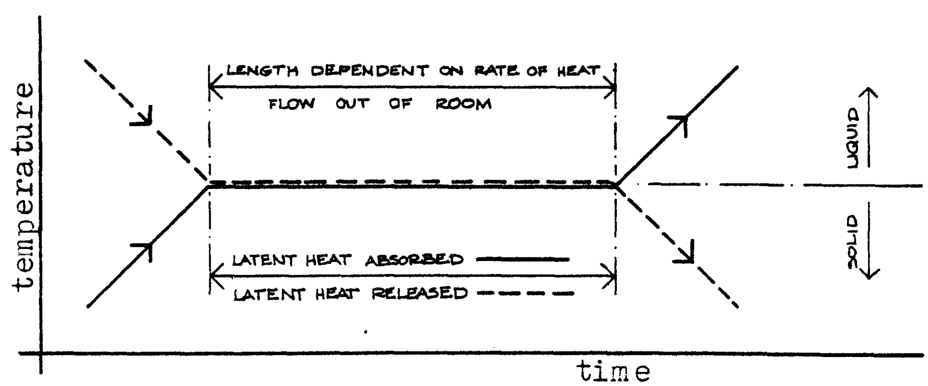
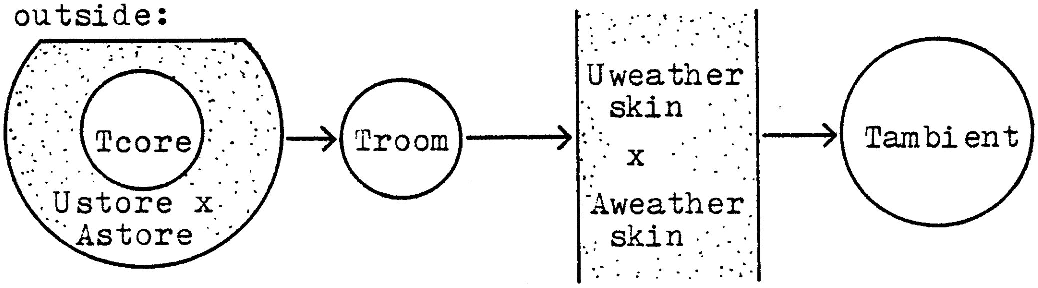


Fig. 2.31. The freeze-thaw temperature pattern of the phase change material (diagramatic) (Ref. 29).

the energy flux from the core and the resulting time it takes for the core to freeze completely is variable depending only on the total heat loss from the room to the outside. This is because the heat flow from the tile core into the room is, in such circumstances, equal to the heat flow from the room to the outside:



Thus under these steady state conditions the air temperature of the room can be found from the relationship:

$$A_{store} \times U_{store} \times (T_{cor} - T_{rm}) = A_{ws} \times U_{ws} \times (T_{rm} - T_{amb}) \qquad (16)$$

Estimation of the air temperatures when the sun is shining into the tested room is more complex[29]. Computer simulations using the pcm tile routines on the same program described above indicate that there is a clamping effect on the room air temperature fluctuation which approximately halves the fluctuation encountered with the use of a concrete slab target area. However, the same minimum air temperature is maintained.

It is possible to construct a rule of thumb resistance split method for estimating the proportion of energy stored by a layer of thermal mass. This method is used in the program presented in the section of this chapter entitled "Overheating" and will be described here:

The rule of thumb method will, with reasonable accuracy, simulate the performance of a target area thermal mass between the thicknesses of 100mm (4inch) and 225mm (9inch).

The energy absorbed by the target has two directions in which it is able to travel: into the air and surrounding objects by means of convection and radiation, and into the target slab by means of conduction.

To find the resistance of the air to energy flow in this direction: because the two paths into the air are in parallel the U-values of each are added and the reciprocal of the result is found; this will be the resistance of the air to energy flow in this direction. This gives the same result as R = (R1 x R2) / (R1 + R2).

The resistance of the slab is found. When the slab exceeds 175mm (7inch) in thickness the resistance is taken to be that of a 175mm thick slab.

Then:

$$Qst = Rair / (Rslab + Rair) \qquad (17)$$

Where Qst = the proportion of the absorbed energy stored in the thermal mass.
Rair = the resistance to energy flow into the air (after absorption)
Rslab = the resistance to energy flow into the slab (after absorption)

Example:

The target area slab is 150mm (6inch) thick concrete.
Assume the thermal coefficient to radiation is 5.1 W/sq m°C (.9 Btu/hr sq ft°F); and the coefficient to convection is 2.8 W/sq m°C (.5 Btu/hr sq ft°F).
Assume also that the thermal resistance of 25mm of concrete

is .018°C sq n/W (.1 F sq ft hr/Btu).

∴ The resistance of 150mm of concrete = .11°C sq m/W (.6°F sq ft hr/Btu) and the combined resistance to energy flow into the air = 1/(5.1 + 2.8) = .13°C sq m/W (.71°F sq ft/Btu).

Then from eqn(16):

$$Qst = .13/(.11 + .13) = .54$$

Thus 54% of the energy absorbed by the target slab will be stored there for later use, and the remaining 46% will be lost by convection and radiation.

k. Solar Gains.

Walls:

The external surface color of the opaque elements of a building's weather skin will determine the percent of the incident solar energy being absorbed. The subsequent movement of this energy through the element can be determined rigorously by methods presented elsewhere[31]. The time lag involved in the conductance of the energy from the external to the internal surface will increase with an increase in the thermal capacity of the element. An increase in the thermal resistance of the element will result in a smaller quantity of energy transmitted. Thus in the passively heated systems normally encountered, where levels of external insulation are high, the solar energy transmitted has been reduced to such an extent that, for the purposes of heat load calculations, it can be neglected.

Where an opaque element of the weather skin has not been well insulated, the resistance split method* is used to determine the quantity of energy remaining within that element. If the element is shaded at any time during the day this should be taken into account.

Windows:

(i) Information for heat load calculations.

As previously described, the proportion of solar energy passing through a transparent membrane is dependent on the transmittance characteristics of the membrane to solar radiation and the hourly angle of incidence made by the sun on the membrane's surface. As the incident angle increases (Fig. 2.32) from $\theta = 0^o$, the transmittance to direct solar radiation diminishes, the reflectance increases and the absorptance initially increases due to the lengthened optical path and then decreases as the impact of the increased reflectance begins to take effect. The energy absorbed is divided equally between its two possible directions of escape: into the building and to the outside. Thus the heat gain factor is a percentage of the incident solar energy which includes both transmission and one-half of absorption.

The results of the interference boundary tests** are used

* This method is presented at the end of the preceding section ("Thermal Mass").

** See section d of this chapter entitled "Solar Interference Boundaries".

to calculate the monthly total solar energy gains. Each window is taken separately, if it is shaded at different times of the day, and analyzed for each hour of the typical day of each month in the heating season. The typical day is usually taken to be the 21st of each month.

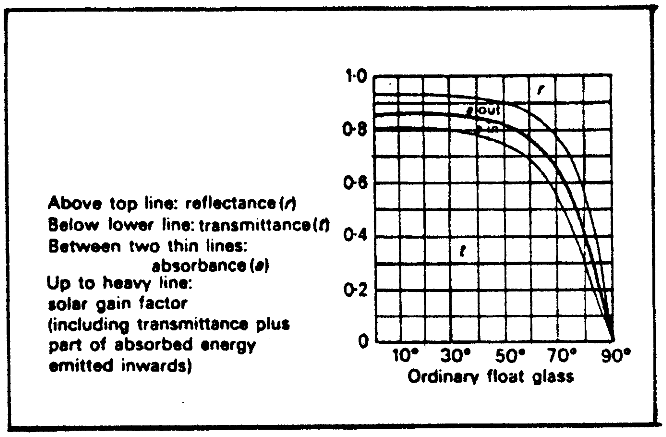


Fig. 2.32. Solar-optical properties of standard glass (Ref. 32).

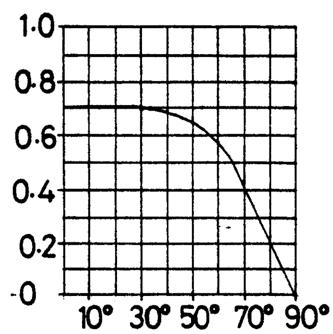


Fig. 2.33. Estimated transmittance of a single layer of Suntek's heat mirror in relationship to angles of incidence.

If an area of window is in shade for that hour then the value for diffuse radiation and the heat gain factor for diffuse radiation are used. However, if the area of window is potentially in sunshine complications develop: rigorous analysis would involve separating the direct and diffuse portions of the energy received for they have different heat gain factors, the mean percent diffuse radiation for each hour would be required, and the heat gain factor for the direct portion would require changing for each hour modeled. To avoid these complexities, an average heat gain factor can be developed for each month of the heating season and for each orientation being assessed. The average heat gain factor is applied only when the area of window is potentially seeing the sun.

Finding the average heat gain factor for each month is conceptually an easy task, but both this and the solar gain method presented below are difficult to perform without the use of a programmable calculator. The programs used will not be presented here because they are simple to construct from the equations provided.

The method used for computing the average heat gain factor is developed from equation(6) (p.42). Equation(6) is expanded to become equation(18) in Appendix A.

Equation(18) is run for each hour of potential sunshine in the day being modeled. The sum of the results of this indicates how much energy is getting through the transparent membrane. The same runs are executed using equation(6). The sum of the results of equation(6) indicates the total quantity of energy incident on the surface of the transparent membrane for that day. The average heat gain factor is attained by dividing the total of the results from equation(18) by the total of the results from equation(6). Not only will the resulting heat gain factor differ for each month but the average heat gain factor for a south facing window will differ from that for an east or west facing window.

The solar gains through each window can be computed by using equation(19) for each hour of the typical day of each month in the heating season.

$$Q_{sg} = ((I_{tvdf} \times F \times A_d \times T_{adf}) + (I_{tvf} \times A_f \times T_{af})) \times M \times R_1 \qquad (19)$$

Where Qsg = the solar gain for that hour and window.

Itdvf = the total (direct + diffuse) clear day insolation value for the vertical orientation concerned, for that hour; from Refs. 9 and 10.

F = the climatic factor needed to convert Itvdf into an average day insolation value for that hour - method for finding this factor is outlined on p.40 ("Solar Data").

Ad = the area, of the window, in potential sunshine that hour.

Tadf = the average heat gain factor for the month and orientation considered; obtained from the method outlined above.

Itvf = the quantity of diffuse solar energy falling on a vertical surface of the orientation, hour and month considered.

Af = the area of the window in shade that hour.

Taf = the solar heat gain factor for diffuse solar energy.

M = a correction factor which includes an area correction to account for the area of window that is taken up by frames ($\doteq$ .9) times a dirt factor.

R_1 = a factor to account for the proportion of solar energy being back reflected out through the windows.

"R_1" in this equation is found by estimating the number of reflections occuring and the quantity of energy absorbed on each reflection, within the room before the light is back reflected out through the window. This factor varies from .6 in a room with large windows and light colored surfaces, resulting in 40% back losses, to .98 in a room with dark surfaces and small windows (or solar modulators) reducing back losses to only 2%.

The presence of dirt on the transparent membrane will reduce transmittance by 2-4%[32a] depending on the frequency of window cleaning and on the presence of pollutants in the air. Thus the dirt factor will be between .96 and .98.

The results of equation(19) are found for each hour, window and month of the heating season. They are multiplied by the number of days in the month being modeled and then divided by 1000 to give kWh gains per month (or by 1000000 to give MBtus per month).

(ii) Information for the overheating program*

The solar data required for this design program is outlined in (ii) of section e, "Solar Data" (p.43). It is the methods of deriving this data which will be discussed in this section.

The insolation values found in the Tables [9,10] for vertical surfaces is the horizontal component of the incident solar energy. The program and design method for assessing overheating models the sunlight falling on a horizontal surface

* Presented in section m entitled "Overheating".

after passing through a vertical window; thus it is necessary to convert these horizontal components of the insolation values into their vertical components. Corrections for transmittance losses and for the losses due to the area of window frame and dirt are applied to both the horizontal and vertical component values; for both are required by the design method. The conversion from the table values to the vertical component of the solar gains is performed by equation (20) in Appendix A.

In equation(20) 'Tad' is obtained from the graph of the solar-optical properties of the transparent membrane being used, allowance being made for the number of layers of transparent membrane. The angle of incidence, needed to find Tad, is obtained from the sun angle calculator.

'Ihor' in equ(20) is the total (direct and diffuse) insolation value for that hour on a clear day. Because it is relatively small, the diffuse portion of the solar energy is treated in the same way as is the direct portion.

A second data requirement for the overheating program is the information which tells how much of the solar energy received by the collecting aperture is falling on the target. It is assumed, within the design program, that of the energy not falling on the target, approximately 50% is going directly into increasing the temperature of the room air; the remaining 50% being back reflected out through the windows. The portion of this energy going directly into heating up the room air is doing so because it is assumed that the surfaces other than the target area are reflective (off white may be as low as 70% reflective) and that, other than the secondary thermal mass area, all surfaces will have low thermal conductances and capacities.

For simplicity of modeling this area of solar impact on the target, the building has been assumed to be facing due south and the month considered will be near the equinox. These are large and constraining assumptions but they facilitate easy handling of this information. At the equinox (September 23^{rd} and March 21^{st}), for a building facing due south, the shadow or profile angle is constant throughout the day. Thus the depth of penetration of sunlight into the room for the whole day is determined by the profile angle (sun angle calculator) and the height of the window (Fig. 2.34). The noon target area is then the product of the depth of penetration and the length of the window.

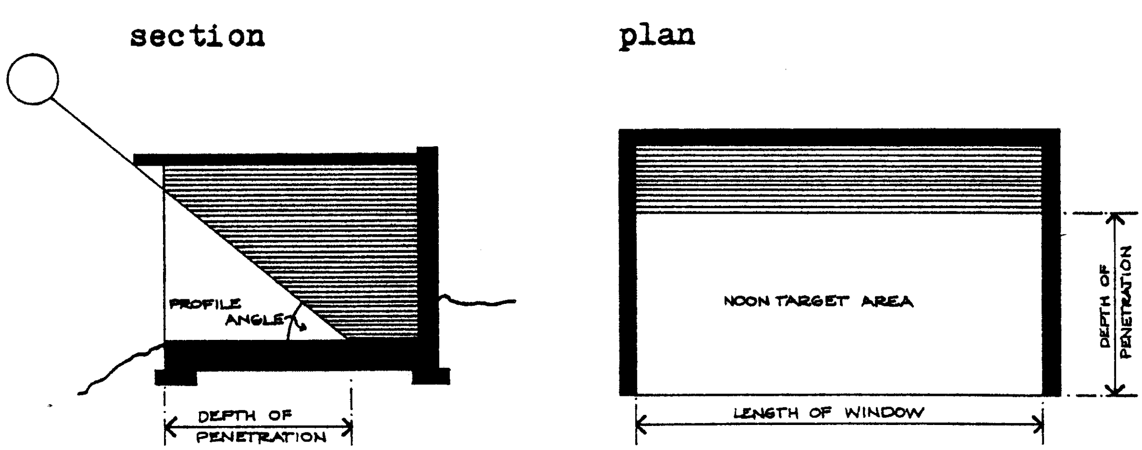


Fig. 2.34. Profile angle and noon target area. Building oriented due south.

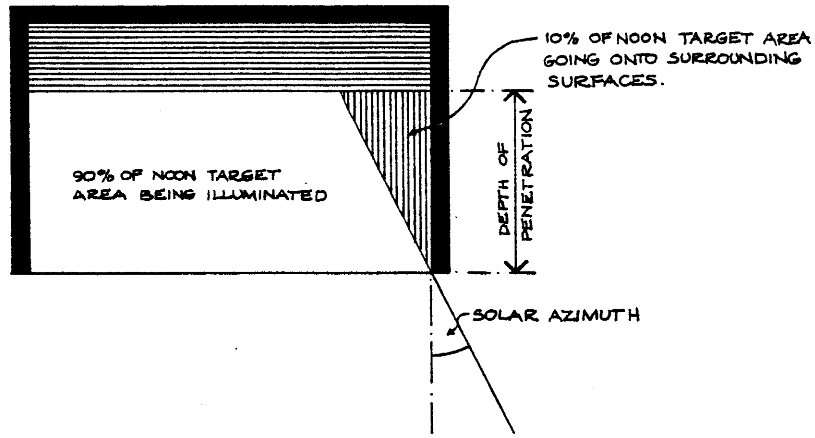


Fig. 2.35 Percent of noon target area illuminated by direct insolation varies throughout the day due to the changing solar azimuth angle. Building orientation due south, time of year is the equnox.

Knowing the solar azimuth for each hour of the day (sun angle calculator) it is possible to calculate the percent of noon target area hit for each of these hours (Fig. 2.35). The percent of the target area hit by solar radiation will be symetrical about noon under these conditions.

If a very long building is being modeled, as is the case in table 2.6 (p76), it will have approximately a 100% illuminated noon target area throughout the day.

The method adopted within the design program is to calculate the solar energy gains by finding the product of the area of target being illuminated and the vertical component of the hourly insolation gains per unit area.

1. Incidental Heat Gains.

To shorten this section, solar gains has been dealt with separately in the preceding section. The incidental gains

	Europe										USA	
Source	Siviour[33]		Billington[34]		Wolf[35]		Brundrett[11]		Heap[36]		Hittman[37]	
Units	kW	Btu	kW	Btu	kW	Btu	kW	Btu	kW	Btu	kW	Btu
Occupants	5	17100	4.8	16400	5.4	18400	6	20500	4	13650	-	-
Lighting	4	13650	1.8	6100					1.4	4800	5	17100
Cooking	4	13650	8.0	27300	12	41000	12	41000	3.4	11600	6	20500
Appliances	4	13650	7.8	26600					3.4	11600	14	47800
Total	17	58050	22	76400	17.4	59400	18	61500	12.2	41650	-	-
From Hot water	5	17100	15	51200	-	-	11	37500	3.4	11600	-	-

Table 2.8. Average daily incidental heat gains from inhabitants, appliances and hot water for a 3-bedroom town or row house in winter (kW/day, Btu/day).

referred to in this section shall therefore not include solar gains.

In a passively heated row house the incidental heat gains will commonly reduce the resulting heating load by 60%, the remaining 30-40% being carried by solar gains. In view of this it is surprising that so little research has been done on incidental heat gains in the United States.

Apart from the Hittman Report[37], which provides half of the required information (Table 2.8), the only research available is analyses of utility company statistics. These analyses do not provide sufficiently reliable data bases to work from for they will not reveal to what extent the hot water heating is contributing to space heating, nor whether the clothes dryer or range is vented to the outdoor air.

In Europe there has been much recent work investigating the magnitude of incidental heat gains in dwellings (Table 2.8). The results are much the same as those reported for American housing, with the exception that there is heavier use of electric appliances in the American home.

Unless appliances are vented to the outdoor air, their total electricity consumption is converted to incidental heat gains.

The energy supplied from the body heat of the occupants is broken down by Siviour[33] thus:

Two adults 100 W each (daytime) 80 W each (night-time)
Two children 60 W each(daytime) 50 W each (night-time)

8 hours overnight	2 X 80 + 2 X 50	2.08 kWh
1 hour morning	2 X 100+ 2 X 60	0.32 kWh
6 hours day	1 X 100+ 2 X 60	1.32
2 hours afternoon	vacant	
5 hours evening	2 X 100+ 2 X 60	1.60
2 hours evening	vacant	
		5.32 kWh/day = 18150 Btu/day

One significant point about incidental heat gains is that they vary throughout the year (Table 2.9). This variance will have repercussions on the balance point temperature* of the building and thus its occurance cannot be overlooked.

Month	Appliances, lights and occupants	Hot Water
January	19	5.0
February	19	5.0
March	18	4.5
April	16	4.0
May	14	3.5
June	12	3.0
July	12	3.0
August	14	3.5
September	16	4.0
October	18	4.5
November	19	5.0
December	19	5.0

Table 2.9. Incidental heat gains (kWh/day) for a typical 3 bedroomed house in England (Ref. 33).

The variation in incidental heat gains throughout the day for a typical English home is shown in Figure 2.36. This type of information, although it does not account for all the heat gains within the house, can be used as a basis for this data needed in the overheating design method program in the following section.

* See Section f entitled "Heating Load".

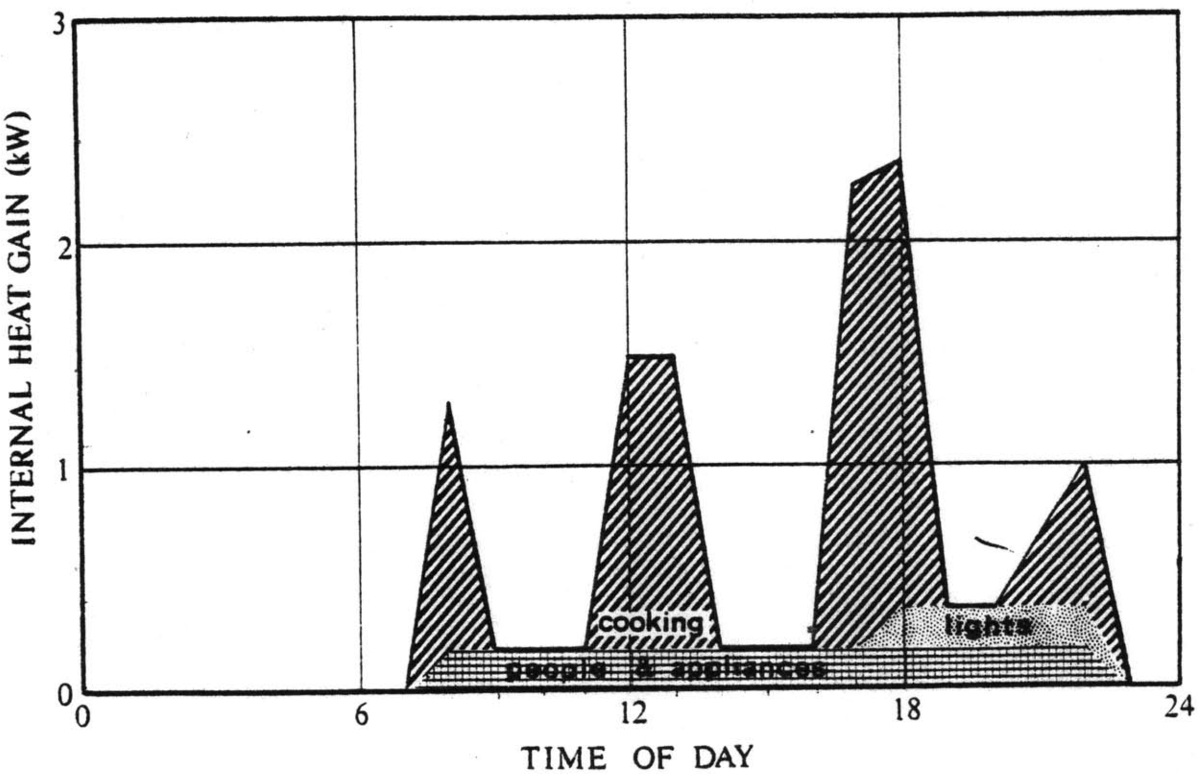


Fig.2.36. Internal heat gain in a well insulated, north facing kitchen on a dull January day (Ref. 37a).

m. Overheating

To avoid the embarassment of providing one's client with a hot box, the program or design method presented in this section with clear day insolation values modeled, can be used to place an upper limit on the open ended design method for system sizing*. Both the design method and the program, for the Texas Instruments desk-top programable TI59 calculator, are a refinement of a design method developed by Timothy E. Johnson. The refinement was done by means of testing against the computer program described in Section j of this Chapter, entitled "Thermal Mass". In such tests the TI59 design method program was seen to give air temperature results within $1^{o}C(1.8^{o}F)$ accuracy against the results of the more complex passive design simulation program.**

Development of this design method program, operable on a desk-top calculator, was considered a necessity if the designer is to have full design control over the environmental implications of passive design systems.

The design method program will allow any latitude and climate to be modeled. A change in the latitude and climate modeled will require a change in the input for hourly outdoor temperatures, insolation values, noon target area and percentages of the noon target area hit. The program models a

* Presented in the section of this chapter entitled "System Sizing".

**Testing the TI59 program against clear day indoor air temperatures for the Wright House(Ref.51) revealed an accuracy to within $1^{o}F$.

single room situation, within which constraints the operator is free to choose the size and form of structure, the area of the collecting window, the colour and material used for the target area, the area and thickness of the secondary thermal mass and the hourly heat contribution from people, appliances and other windows. It is also possible to model the effects of basement or ground floor heat losses and to change either the thermal resistance of the weather skin or the rate of air infiltration. Furthermore none of the input data is changed during program execution. This facilitates comparative modeling of the effects of design alterations.

The program involves the use of a large quantity of data. Both this and the program can be filed onto magnetic cards and used whenever the program is set up. During execution of the program the first figure displayed is the temperature of the surface of the target slab for the first hour of the day. The second figure displayed is the room air temperature for this same hour. Slab surface and air temperatures are then displayed for each of the 8 hours of the day. The final figure displayed is the carry through time period of the system after one clear day of solar energy storage.

Involved in the design of the program are the following assumptions:

(i) That the target area is on the ceiling. Solar modulators*

* See the section entitled "Solar Modulators".

or reflective blinds are used to direct the solar radiation onto the ceiling target. Insolation values are reduced by 10% within the program (locations 055 and 056) to allow for this reflection.

(ii) That the area of secondary thermal mass seen by the target is equal to .5 times the target area and that the thickness of this concrete secondary thermal mass is 120mm (.4 ft). This is the turning point thickness for such a proportional area of concrete secondary thermal mass (Fig. 2.28). If a solid floor mass is concealed by carpets it will not function as secondary thermal mass because the infrared energy will be intercepted by the carpet and thus mostly heat up the room air. If such is the case an area of the wall must be conceived as the 120mm thick concrete thermal mass. The consequences of designing with different areas and thicknesses of the secondary thermal mass can be readily determined from the graphs in Figures 2.27 to 2.29. Tests of the comparative performance of pcm tiles* as the target, using the more complex passive simulation program designed by Timothy E. Johnson, indicated that the room air temperature fluctuation was halved from that observed with a concrete target. However, the minimum daily temperature remained the same for both pcm tiles and concrete.

(iii) That the target area is solid and thus heat moves

* See Section j entitled "Thermal Mass".

within it by conduction only. If the target is changed to containerized water the heat will be transported away from the surface more quickly, by means of convection currents, and lower air temperatures will result. The design program does allow the operator to model the use of water as the target.

The procedures for running the program and the program listing are provided in Appendix B.

It must be noted that the surface temperatures of the target area will not be realistic values and the command to display this value may be removed from the program. The design program was developed to give realistic room air temperatures only. The displayed surface temperatures of the target slab will be below the values obtained in practice.

The following description encompasses the overall design method:

(i) The following data is collected (using the sources in parenthesies):

The area of collection window.
The noon area of target (section k; sun angle calculator).
The percent of the noon target area hit for each hour of the day (section k; sun angle calculator).
The horizontal and vertical components of the solar energy gain values for each hour of the clear day (tables in Refs. 9 and 10; sections d, e, g and k; sun angle calculator).
The density and specific heat of the target.
The volume of the noon target area.
The average U-value x the area of the weather skin (sections c, f, g and h).
The volume of air change per hour (section i).
The U-value and area of the floor or basement (section h).
The resistance split fraction for the target (section j).
The hourly gains from people, appliances and other windows

for each of the 8 hours (section 1; sections e, g, k).
The hourly outdoor temperature for each of the 8 hours (section b).
The morning internal start temperature.
The temperature of the ground (section 1).
The average gains per hour for people and appliances at night (section 1).
The average room air temperature at night.
The average outdoor temperature at night.

(ii) From this point either the design program (Appendix B) or the following design method procedures may be used:

(iii) For each of the 8 hours the following calculations are executed using the data relevant to each of the hours:

The surface temperature of the target is found by the following method:

Calculate the quantity of solar energy absorbed by the slab (Eqn.(21) Appendix A).
Calculate the quantity of that energy absorbed that is stored within the slab. The resistance-split method is used for this (Eqn.(22) Appendix A).
Calculate the rise in temperature of the target surface. If the target is a solid then both Eqns.(23) and (24) (Appendix A) are used. In Eqn.(23) the energy being stored in the target is assumed to uniformly raise the temperature of the total target volume. Such a situation would be almost true of a liquid target but not of a solid target. Equation(24) is used to raise the temperature of the surface of the solid target. Both the factor used in this equation and the thermal coefficient of the target surface air film (Eqn.(26) have been chosen in the testing of the design program so that they produced room air temperatures which coincided with those obtained from the more complex passive simulation program designed by Timothy E. Johnson.
Calculate the new temperature of the target surface (Eqn.(25)).

The temperature of the room air is found by the following method:

Calculate the new room air temperature by considering the energy movements to and from this air. At any given moment in time the energy movements to and from the room air are in equilibrium. Thus the room air temperature can be calculated each hour from Eqn.(26) in Appendix A.

The net energy gain for the entire system each hour is needed to later calculate the number of hours of carry through of the building design. This is computed using Equations(27) to (29) in Appendix A.

(iv) The final step of the design method is to compute the number of hours of carry through the system can sustain after storing energy on a clear day. The net energy gains of each of the 8 hours, computed in Eqn.(27) are summed and Eqn.(30) is employed to find the number of hours of carry through under these conditions.

n. <u>Shading Devices</u>.

The visual-alternative and technical aspects of shading devices are fully described elsewhere[38]; thus little time will be devoted to this aspect of solar control here.

Fixed shading devices have some inherent disadvantages, the first of which is due to their inability to allow for the lack of synchronization between the heating season and the altitude of the sun. If a fixed shading device is designed for Boston to prevent overheating in September, the result is that solar energy will be rejected to the same extent in March. However, March, unlike September, has a relatively high demand for solar heating and such control would be unwelcomed. Fixed shading devices will also usually cast a shadow on a portion, albeit a small portion, of the collection window for most of the heating season. This is expensive in terms of cost of glass and higher energy losses than gains over this area of shaded window.

The alternatives to fixed shading devices are either moveable devices or the use of deciduous vegetation. Both of these have possible economic constraints. Unless the vegetation is placed on a trellice above the collection window, there is a reduction in the quantity of solar energy received even after defoliation. This will necessitate the expense of additional collection window. As for moveable shading devices, these will be usually more expensive than fixed devices.

Large east or west facing windows will require shading devices to prevent excessive heat gains in the spring, summer and fall. Due to the way in which the sun appears to move across the sky, shading devices for these windows will be closely spaced, vertical and, in plan, at an angle to the window.

South facing windows will usually need only horizontal shading devices. . . . .

o. <u>The Solar Modulator</u>*

A diagramatic representation of the use of the solar modulator is shown in figure 2.8 (winter day of system

* Conceived and developed at MIT by Timothy E. Johnson and Dennis A. Andrejko.

schematics). In directly heated examples of passive solar buildings there is a natural tendency to use the floor as the target area. This causes conflicts between solar energy collection and space use. Furnishings within this target area will be the cause of two unwanted effects: they will conceal the primary thermal mass and thus increase the quantity of energy going directly into the room air*, and they will be the cause of contrast glare within the visual field.** Furthermore, the need for large areas of unobstructed sky view will also be the cause of glare.

The solar modulator reduces these conflicts to a minimum by reflecting direct solar energy onto the ceiling. Thus the ceiling, which is usually free from space use requirements, becomes the target area. The development of such a system goes hand in hand with the development of the phase change material tile which, due to its economy in weight, may be applied to the ceiling in place of a normal ceiling finish. By reflecting the solar radiation onto the ceiling, the solar modulator reduces glare to a minimum by obscuring the glare source, by removing the possibility of contrast glare from the field of vision, and by drawing much of the light into the back of the room, resulting in higher levels of surround illumination there. Another advantage of the solar modulator is that it may be used to

* See Section j entitled "Thermal Mass".

** See group 2 of this Chapter, entitled "Glare", for discussion on types of glare.

reflect unwanted solar energy back out through the window in summer. Finally they will serve the same purpose as curtains, providing privacy at night.

The constraints imposed on the design of solar modulators are numerous. They must reflect the solar energy in such a way that it will not cause blinding glare to the occupants. They must be moveable to permit view and access, they must intercept 100% of the incident solar energy, and they must be adjustable to compensate for the seasonal solar altitude changes. To avoid excessive babysitting of the system, a minimum number of seasonal adjustments is aimed for. The radius of the slats is the critical dimension which, together with the spacing between the slats, determines the number of times the angle of the slats requires adjustment each season.

The concept is that the slats of a standard venetian blind are inverted and a 3 mil. layer of aluminized mylar is bonded to the top surface of each slat. However, the slat radii of most standard venetian blinds are too small to accommodate a large range of solar profile angles without adjustment. Thus an optimum radius must be sought. There are two methods for developing and testing the optimum slat radius and spacing between slats: graphic testing using ray diagrams, and a model testing rig.

Ray diagrams are drawn using the various slat radii. The design constraints are that the angle of the reflected energy within the room should not fall below 30° (Fig. 2.37),

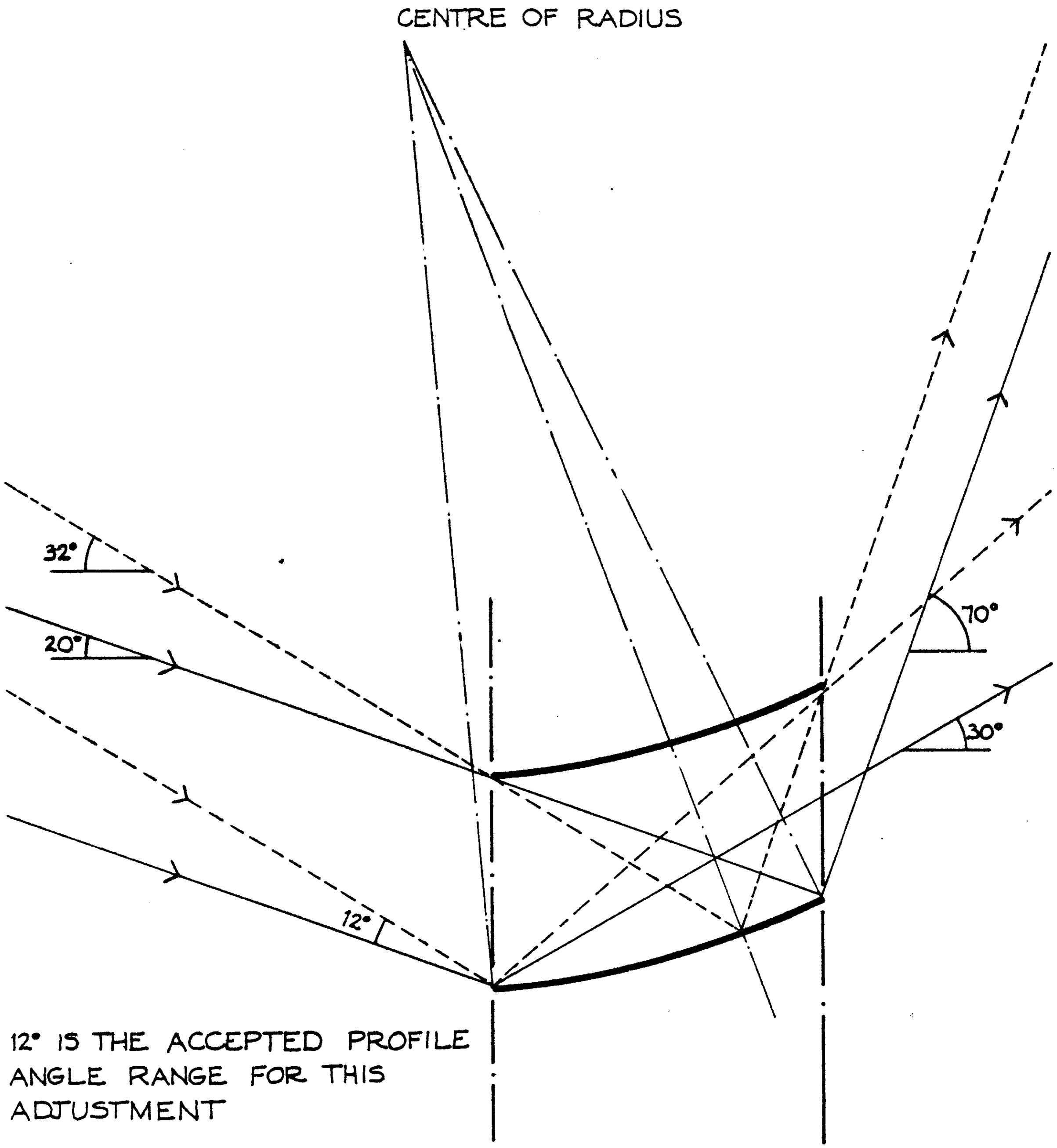


Fig. 2.37. Ray diagram analysis of the solar modulator for the first setting of the season of the season in Boston.

that at the lowest profile angle 100% of the incident solar energy is intercepted while the previous constraint is still enforced (this determines the spacing between the slats), and that none of the reflected solar energy is intercepted by the above slat. If the modulator is placed between the layers of transparent membranes then the maximum reflection angle should not exceed 70° to prevent excessive reflection losses from the face of the membrane.

The testing rig used is shown in figures 2.38 and 2.39. The rig shown here does not give as accurate results as the ray diagram method but it is certainly possible to build a rig with such precision.

Either method has its advantages. The testing rig gives very quick results but requires an actual slat to model. Thus only existing slat radii may be tested. In contrast, the ray diagram method is laborious but versatile. It was found, by the ray diagram method, that the optimum radius for Boston (42°N) is 69.8 mm (2.79 inches) for a 25 mm (1 inch) wide slat with a vertical spacing, computed from the height to width ratio of 1:1.6[32], of 15.4 mm (0.62 inches). It was also discovered that the height to width ratio changes with a change in latitude. A solar modulator located in London (52°N) will require a height to width ratio of 1:2. Thus the spacing between the slats becomes more narrow at higher latitudes and wider at lower latitudes. This suggests that the solar modulator for low latitudes will be less

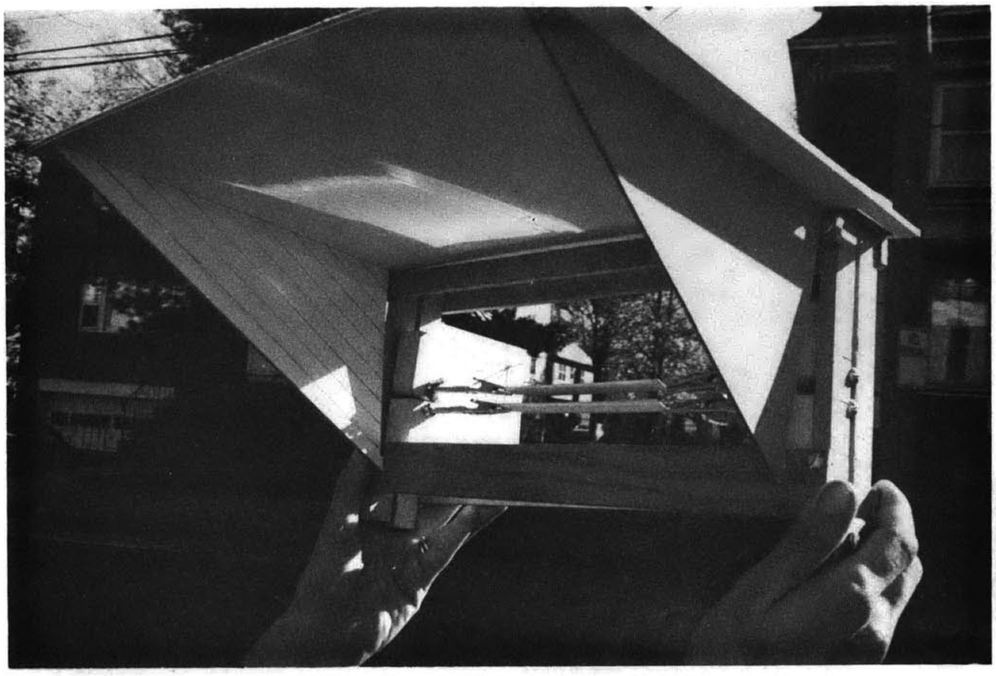


Fig. 2.38. The solar modulator test rig.

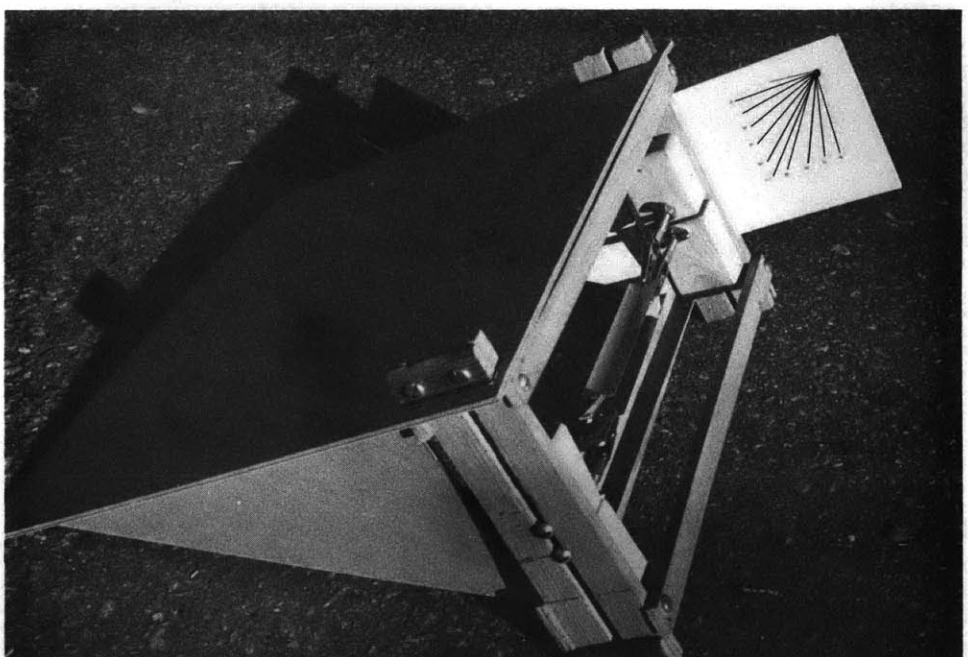


Fig. 2.39. The solar modulator test rig.

expensive per unit area than a solar modulator for high latitudes. With the optimum solar modulator design for Boston described above, it was found that only 11 adjustments per heating season were required. The ray diagrams indicated that as the latitude increased more adjustments per heating season were necessary but there was no evidence to suggest that the optimum slat radius changes with a change in latitude. In the above tests the morning profile angles received were assumed to start at 9:30 A.M. and the evening profile angles assumed to end at 2:30 P.M. This short span was chosen as the time when perfect operation of the modulators is required.

One of the problems of manufacturing aluminum venetian blind slats is that it is almost impossible to predict the final radius of curvature produced by a rolling die. This is because the slat radius will change after the slat is rolled. Thus only by trial and error is it possible to produce the correct radius. This expensive process (due to the high costs of the die) was bypassed in the manufacture of the solar modulators being used in the MIT solar demonstration building. Fortunately Rolscreen Co. of Pella, Iowa was making a venetian blind (Slimshade[R]) which is only slightly different from the optimum radius. The spacing between the slats did require reduction to intercept 100% of the solar radiation received at low profile angles and thus prevent solar energy losses to the floor slab. The resulting design will require 15 adjustments per heating season. The heating season here is assumed to fall between profile angles of 18° and 52°.

p. System Efficiency

The efficiency of a passively heated building is in some ways comparable to that of a flat plate solar collector. However, there are certain prominent differences. The following is a discussion of the similarities and differences and a method for determining the efficiency of a passive heating system.

When considering the efficiency of a flat plate collector, the heat losses of the building it heats are not included in the calculation. Similarly it is proposed that the losses involved in the efficiency calculations of a passive system be only those through the collection window. More difficult to handle, however, are the internal gains, the solar gains from other windows and the infiltration losses of the building. These could be apportioned to a unit area of weather skin and thus included in the efficiency calculations as negative heat losses; but it is suggested that they be ignored for the sake of simplicity.

The active system is thermostatically controlled to cut off or drain down at the end of the day or when the sun goes behind the clouds. Thus the flat plate collector is operating approximately 8 out of the 24 hours in a day whereas, in terms of losses, the passive solar system operates for all 24 hours. Therefore in broad terms one can expect the efficiency of a passive system using normal building materials to be nominally one-third of the efficiency of a flat plate collector. However, certain factors counteract this reduction in efficiency. The passive building is operating at lower temperatures than a flat plate collector; this reduces the heat losses from the system by approximately a factor of 2. There are the additional benefits of the passive system, as mentioned in Chapter I of this thesis, such as the longer hours of collection and the collection of diffuse energy on an overcast day. Thus, considered in broad terms, the passive system probably has an average efficiency of 85% of the average efficiency of an active system built of the same materials and with the same orientation.

The efficiency of the passive collection system is determined by the following equation:

$$\eta = (\dot{Q}_g - (Q_l \times 24))/I \qquad (31)$$

Where η = the efficiency of the collection system.
$\dot{Q}_g$ = the solar energy gain through the collection window on a clear day = I x transmittance x back reflected losses.
Q_l = the heat loss per hour through the collection window = U-value x Area x T.
I = the total clear day incident solar energy on the collection window surface.

In an active system the quantity of solar energy collected is reduced by the absorptance of the collector surface. In a passive system a comparable reduction is due to reflected back losses. At the moment the estimation of these back losses is very much a black art and is further discussed in section k of this chapter entitled "Solar Gains".

When moveable insulation is used in a passive system, the value of Ql in eqn.(31) will differ for the two operation modes of the system. Thus changes to this value must be made when calculating the efficiency of such a system.

q. <u>System Sizing and Auxiliary Heating</u>.

There are many design considerations which go into the determination of the area of collection window used in a system. Hypothetically, if there are no such design constraints, the aim would be to achieve 100% solar heating based on heating load calculations. Such calculations are discussed in section f of this Chapter and further developed in group 3 of this Chapter entitled "Costing". The consequences of the system sizing are then tested by means of the program or design method listed in section m to examine whether or not the air temperatures produced fall within the comfort zone[39,40,40a].

A solar heating fraction of 100% is not usually possible unless seasonal storage is built into the system because of the undependable weather patterns. Overcast weather may last for several days; the longest period of overcast weather recorded in Boston was 29 days. Such spells can never be accounted for by a solar heating system without making the system grossly uneconomical. The highest average solar heating fraction one can hope to achieve is probably 97%. Because of this a solar heated system usually has to bear the brunt of additional capital expenditure on a backup heating system.

Such an auxiliary heating system will vary in capital expenditure from full central heating, when the solar heating fraction is low, to electric or wood-burning heaters when the solar heating fraction is as high as 97%. The high running costs of electric heating will not be a burden if the solar heating fraction is as high as 97%. In the case of rehabilitation, reuse of existing heating systems may enhance the economic viability of utilizing solar energy for space heating.

2. GLARE

Glare is one of the major design conflicts inherent in both the use of natural lighting and direct passive solar energy collection. It is therefore important to be able to understand its nature and identify its causes and remedies. There are many different methods of assessing the likelihood of the occurrence of glare within a designed space. In gathering the information for this group of the Workbook each of these methods was investigated and tested. The method presented here is that which provided the most convenient design tool, and which at the same time gave reliable results.

Glare is related to the contrast in one's visual field, and can be avoided merely by turning away from the light source. The most painful type of glare will occur when the sun shines directly into one's eyes. Reflection off water will also cause this type of glare, but upward reflection will cause more discomfort because the eyes are unprotected by the eyebrows. This is the easiest type of glare to deal with because if it exists it will be intolerable. However, glare is also the result of effects more difficult to define and to counteract.

Disability or veiling glare is detected as the area of indistinct vision around a bright light source. This is caused, as the name suggests, by a scattering of the light in the eye fluids, which casts a veil of light over the image formed on the retina. A simple experiment can serve as an illustration of this effect: look at the mullions of a window - it will be noticed that much of the detail on them is indistinct - now shield the view of the window and visual discrimination should improve. Disability glare is additive - i.e. the brightness of the veil produced by 10 identical glare sources is 10 times the brightness of the veil due to one such source on its own. Old people are particularly susceptible to disability to disability glare as their ocular media are cloudier than young people's; this causes more scattering and thus a brighter veil. Disability glare is seldom of great significance in architectural design other than serving as a pointer to errors in lighting design, such as placing a blackboard in front of a classroom window. However, in extreme cases disability glare becomes discomfort glare.

Discomfort glare is often experienced in conjunction with disability glare but they have to be separated to understand and quantify each. Discomfort glare causes discomfort rather than reduction in visibility. It is thought to be caused by a saturation of neutral response in the retina due to large quantities of light. Because of the nature of this type of glare there are serious architectural implications and consequently it is important to be able to assess the possibility of its occurrence. The luminance of large areas of sky visible through a window is one cause of discomfort glare. Another cause is excessive contrast in the visual field. The contrast sensitivity curve of the eye has an effect on glare perception. At low light levels contrast perception is lower than at high lighting levels. In other words, if no artificial lighting is used, there will be more disability glare from a large window on a dull day (when the interior light levels are lower in proportion to the sky brightness) than on a bright day. The following are two rules of thumb to help avoid glare problems in rooms illuminated by windows on one side only. The room depth should not be greater than 2 to 2½ times the height of the top of the window from the floor, attempt to provide additional light to the rear of the room to increase the average illumination level and thus reduce contrast. Additional lighting can be provided by either clerestory windows or side windows. Dark colored window bars, frames or window walls will all increase the contrast between them and the sky and hence increase discomfort glare.

The first of the tools available which examines the possibility of discomfort glare is the calculation of the glare constant. Laboratory tests have shown that the discomfort glare caused by a bright light source subtending a solid angle of less than 0.05 steradian at the eye is approximately constant when $(Bs^{1.6} \times W^{0.8} / Bb^{1.0})\ p$ is constant[41]. Where Bs and w are the luminance (ft-Lamberts) of and the solid angle subtended (steradians) by the light source causing the glare. Bb (ft-L) is the luminance of the adapting field and p is a position factor for the glare source. Discomfort increases as this constant, the glare constant, increases. One can therefore set a numerical limit on the discomfort glare permissible in a given environment by specifying a glare constant. Because the glare constant is unwieldy we use the Glare Index (Eqn.(32) in Appendix A) to specify acceptable glare levels. Moreover laboratory tests have shown the minimum perceptible change in discomfort glare to be one Glare Index unit, smaller interval being judged correctly only by chance. When the difference is 3 units observers will judge correctly 19 times out of 20.

Degree of discomfort glare	Range of glare index, *G*
Imperceptible	0–10
Perceptible	10–16
Acceptable	16–22
Uncomfortable	22–28
Intolerable	over 28

Table 2.10 The degree of discomfort glare corresponding to various Glare Indicies. (Ref. 42).

The information shown on Table 2.10 is probably more applicable for daylighting design than the often used "Limiting values of Glare Index" recommended by the Illuminating Engineering Society of the U.K. (I.E.S.). This is because the IES recommendations refer to artificial lighting only. Two additional factors, 'proximity' and 'habituation' affect our experience of glare[42]. The 'proximity effect' is that an overhead glare source is more oppressive and contains less visual information than a more distant source (the sky). The 'habituation effect' results from the willingness to accept glare from the sky, which one has known since birth, and yet to react to glare from an artificial source. Most people are quite unconcious of any discomfort glare out-of-doors unless they face the sun, but the fact that they are squinting shows that discomfort glare must be present, even if unnoticed.

Because of the ever changing illuminance of the sky, a standard overcast condition has been internationally accepted as the basis for daylighting calculations; this is the Commission Internationale de l'Eclairage's(CIE) Standard Overcast Sky, which has an average luminance of 500 ft-L.

Determining the glare constant by means of equation is a laborious task and is only little more accurate than the Building Research Station's (BRS) Glare Constant Nomogram. This and the method for using it are presented in Appendix C. No maintenance nor transmittance correction factors for the glazing are necessary because these would occur on both the numerator and the denominator of the glare constant equation and thus would be self-cancelling. It is important to note, however, that the transmittance to diffuse light in the BRS design method is assumed to be .85. Any change in this transmittance by a change in transparent membrane used should therefore not be incorporated in the design method because it will have no bearing on the glare constant. This also means that, from a design standpoint, any change in the transmittance of the glaring material will have absolutely no effect on the glare index of the designed space.

The second useful design tool is a scaled model. The model must be large enough to be able to put one's head inside it. Because the effects of daylighting scale without distortion, a model is expressive in a way that no calculations, drawings, or words can be. It gives a good grasp of the probable feel of the designed space at different times of the day, and will reveal any problems of glare. The model may be built with enough flexibility to enable comparative modeling of lighting design alterations.

3. COSTING

The costing aspect of a solar heating system is probably the single most important aspect within the entire field of solar heating because upon this relies the success or failure of the system. Thus in order to provide a useful design tool for costing analysis, reliable heat load and cost benefit calculation methods must be sought.

The basis of the heating load calculations used in the design method presented in this group is developed in section f, "Heating Load" (p. 43), of this Chapter. The cost benefit calculations are based on well established methods of Life-Cycle Costing and are developed elsewhere[43,44]. The use of life-cycle costing methods makes it possible to compare the capital expenditure of a system with the money saved by it each year due to a saving in fuel use. Corrections are applied to the money saved each year, to account for the effects of inflation and of the rising price of fossil fuel, to give an estimation of the system's worth in terms of the present value of the money saved.

These calculations are time consuming and thus present an obstacle in the way of the use of such methods by building designers. It was thought that by putting such a design method onto a Texas Instruments' TI 59 programmable desk-top calculator, this obstacle would be removed.

The resulting program and the procedure for its use are presented in Appendix B of this thesis.

The following methods are employed in this cost benefit program:

An approximation of the heating load per month is computed following the steps described in section f of this Chapter (Eqns. (7) to (11)) (p.45). This is an approximation only because mean monthly temperatures are used to compute the number of degree days.

Equation (7) is difficult to solve because it contains two interdependent variables: the degree day base temperature (balance point) and the internal heat gains per day. Because the value of the internal heat gains per day varies each month (due to the sun's altitude, the percent sunshine, and inhabitant behavior patterns) it is dependent on the degree day base temperature. But the degree day base temperature is in turn dependent on the internal gains per day figure. Thus iteration of equation (7) is necessary to narrow down on the correct result. The program tests to see if the heat gains are less than the heat losses each month. Only under these circumstances do the heat gains become included in the heat gains per day value in Eqn.(7). To start somewhere, the program initially takes the average heat gains per day for the six winter months and, using this value, computes the approximate heating load per month (Eqn.(11)). If the internal heat gains per month are less than this heat loss then they are included (after dividing by the number of days in the month) in the next iteration of Eqn.(7) as the average heat gains per day. This process is repeated to insure that the new monthly heat loss is not less than some of the previously included heat gains. By means of such iteration, the correct degree day base temperature is narrowed down on. If a passively heated building with a high solar fraction, is being modeled it could happen that in none of the heating months does this approximate heat loss rise above the heat gains figure. In such a case the program takes an average of the heat gains per day during December and January, and uses this value to continue computation.

Once the degree day base temperature is displayed the corresponding number of degree days is entered into the calculator and the program set in motion again to calculate the resulting heating load per year. The method for developing a degree day table is described in Section f of group 1 in this Chapter. An example of such figures (for London) is shown in Table 2.14. It is useful, as shown here, to keep a note of the difference between the degree days for one balance point temperature and the next one up. This is used when, as is often the case, the degree day base temperature (balance point) displayed is between two whole number temperature values.

Having computed the heating loads and costs with and without improvements, the cost benefit of the improvement is calculated by the program. The method used here for this is based on standard methods of discounted cash flow (DCF) analysis. The cost benefit is the present value of the energy saved divided by the capital cost of the improvement. The present value of the energy saved is computed as the sum of a geometric

Balance point temp. (^{o}C)	Degree Days	Difference
-5	0	0
-4	1	2
-3	3	5
-2	8	8
-1	16	13
0	29	22
1	51	32
2	83	45
3	128	60
4	188	78
5	266	98
6	364	118
7	482	139
8	621	161
9	782	178
10	960	194
11	1154	207
12	1361	218
13	1579	224
14	1803	229
15	2032	232
16	2264	233
17	2497	-

Table 2.14. Balance point temperatures with corresponding degree day figures for a typical winter in London (Ref. 11).

series of discounted savings (Eqn.(40) in Appendix A). If the net present value of the total energy saved over 'N' years, due to an improvement, is greater than the initial cost of implementing the improvement then the improvement is cost effective. In other words, if the cost benefit is greater than 1 the improvement will be cost effective and an approximate payback time can be found by dividing 'N' (Eqn.(40)) by this cost benefit figure.

To choose appropriate values for the variables in Eqn.(40) is a considerable problem because it involves a certain amount of forcasting. The following is a discussion on the values to be used for some of these variables[44].

Maintenance costs should be subtracted from the annual fuel saving's value.

Choosing a figure for the discount rate is difficult. If the scheme is carried out by an individual using his own capital, the discount rate should represent the rate of interest (in real terms) gained by investing the money elsewhere. Depending on the country's inflation rate and tax system on unearned income, this interest rate can be lower than expected. In England in recent years, the interest rate (in real terms) has been as low as 0-2% and often negative. The 'real terms' refers to the percentage above the inflation rate percentage; it also takes account of the effects of taxation. However, often the opportunity value of this capital is much more valuable than its interest returns.

This opportunity value will disappear if the money is invested in, say, insulation.

For individuals without private funds, the discount rate will be that of the interest rate (in real terms) on borrowed money. An examination of the past trends in home mortgage rates in England has shown that they are about 2% greater than the rate of inflation from 1955 - 1970 (since 1973 the mortgage rate has been less than the rate of inflation). Thus it seems very worthwhile to make energy saving improvements which give returns greater than 2% of the capital expenditure.

For public sector work in England the Treasury has established a test discount rate (TDR) which it applies to its investments. This is currently as high as 10% p.a. However, various government publications have suggested that this may be lowered to 7% in the near future.

Going by the figures mentioned above, for the individual investor in England with funds of his own, a discount rate of 4% would be more realistic than the 7-10% p.a. used by the Treasury.

The second figure which is difficult to establish is the real rate of increase in the price of fuel. From the figures of a wide range of demand and supply scenarios itwould appear that the real price of fuel will slightly more than double by the year 2000. If this rise occurs smoothly then a 4% p.a. real rate of increase in fuel prices can be expected. This is the increase above the rate of inflation.

The value 'N' in Eqn.(40) will represent the shorter of either the life expectancy of the improvement or the number of years over which the mortgage extends.

If, during execution of the program, the cost benefit displayed is less than 1 and it is attempted to compute the payback period, the display will read 1000 000 years; indicating that the improvement is not economically viable.

Because of the uncertainties of the variables used in Eqn.(40) this section of the program has been designed so that it is possible to compute this program routine only. Thus different values for the fuel spiral rate, the discount rate, the number of years or the area and cost of improvement can be inserted and the cost benefit recalculated.

III

DESIGN SOLUTION PRESENTATION &

PERFORMANCE ANALYSES

DESIGN PRESENTATION

The dwelling type chosen for study within this thesis is similar to that shown in figure 3.1. This illustration differs from the usual basic nineteenth century row dwelling type in several minor ways which are thought to be more typical: the yard is brick paved, the wall between the entrance hall and adjacent living room (Fig.3.1) is of timber and plaster construction, there is a partition and doors between the staircases and the room adjacent to them, and there is no bay window in the dining area. Besides these differences the dwelling is the unimproved version of that illustrated in figure 3.1, indicated by dotted lines where changes have been made. The walls are mainly built of brick, the slated roof has a 30° pitch and there is a basement below two-thirds of the dwelling. The basement is potentially a useful additional space but it would be expensive to waterproof and is perhaps best left to a 'do-it-yourself' extension to the dwelling. The external walls have no damp proof course other than one or two courses of engineering brick, and the windows are single glazed and sash.

The typical urban structure in which these houses are found (Fig.3.2) is very similar to modern planning trends in England and, being built in the nineteenth century, they are located close to city centres or shopping areas.

The room nearest the street is traditionally a self-contained sitting room with access only from the entrance hall. This room was used only on occasions when visitors were received. The garden or yard end of the ground floor was used for unseemly domestic activities such as the outdoor toilet, the coal house and trash cans. The garden or yard was usually used for growing vegetables and keeping animals.

A modern lifestyle is more suited to the rehabilitation design shown in figure 3.3, where the more leisurely living activities are given the privacy and quietness of the garden side. The garden is laid to lawn with flowered borders and plants are introduced to the brick paved area adjacent to the kitchen. Daylighting, in the rooms on the south side of the dwelling, is improved by extending the windows down to the ground, avoiding the expense, wherever possible, of increasing the width of the openings. The living room, dining room and kitchen can all be opened onto the garden in summer and provide comfortable living conditions. A utility room is almost a necessity; it keeps activities such as clothes washing, drying and ironing out of the living areas. The trash can is located so that there is possible access to it from both outside and inside the dwelling. The bathroom and toilet do not require windows; they can be mechanically vented for very little cost. Wash basins and cupboards are provided wherever space permits. The playroom/study is a possible spare bedroom if needed. An attempt was made to avoid openings in the wall between the two main rooms on each floor. This is a load bearing wall and consequently would be expensive to remove. As suggested in figure 3.1, garaging can conceivably be placed at the end of the garden.

To improve this design for solar collection and thermal performance, the changes shown in figures 3.4, 3.5 and 3.6 are suggested. These changes were developed by means of rigorous performance testing. Alternative insulation levels, and collection window design and placement were tested and the solution shown here evolved gradually as a result of these tests. The building has become isolated from the outdoor climate by an external insulating layer. This layer allows the masonry external walls to be used as thermal storage mass. Solar energy collection is carried out in the dining and play rooms. Larger collection areas were attempted but either lack of solar energy received or the expense of changing the building's plan form, ruled against them. Primary thermal mass or target area is provided by the phase change material tiles* (pcm*) on the ceiling of the dining room and play room. Solar modulators reflect the solar energy onto this target area. The area of the secondary thermal mass layer in the collection rooms is approximately twice that of the target and 10 cm (.35 ft.) thick. Because the collection areas are out on a limb, a distribution system is required to move the heat to the other parts of the house. Circulating the room air in this way will have the same effect as the use of a storage bin in an active collection system. Here the masonry walls

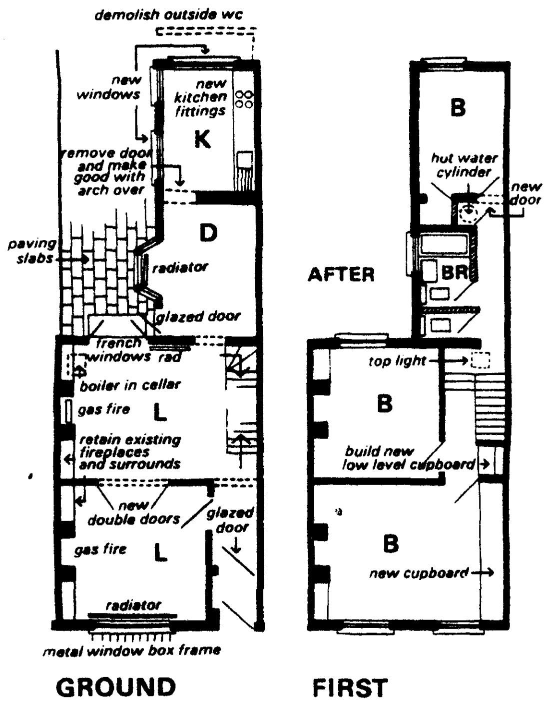
* See section j, of Chapter II, entitled "Thermal Mass".

throughout the house will store any excess energy by means of convective gains from the circulating air. To avoid confusion between the function of these walls and that of the secondary thermal mass, which is in radiative contact with the target area, these masonry walls shall be termed the convective thermal mass. The movement of air is triggered off by a temperature difference of 2.8°C (5°F) between the collection room air temperature and the living room air temperature. The delivery grilles may be hand closed to provide control of where the heat is to be delivered. On a winter evening heating is by radiation primarily, although additional heat may be stripped off the pcm tiles, and delivered to the spaces needing it, by use of the fan. In summer the design relies on natural ventilation which will cool the building at night and leave it less susceptible to overheating in the day. The collection windows may be opened and the solar modulators used (or partly lowered) to reflect the solar energy away from the building. The dining room and play area then become indoor/outdoor spaces, providing a life style met only in more expensive English dwellings.

The following is a discussion of several miscellaneous design decisions taken during the course of the development of this design solution. To attempt to solve the conflict between privacy and solar energy collection, the garden wall is replaced by a thin deciduous hedge. This provides privacy when most needed, in the summer, and transmittance of solar energy in the winter when privacy is less of a problem (Fig. 3.5). Return air flow is by way of gaps under the doors. The sliding screen between the kitchen and dining room is made of open mesh caning to permit air flow. Bedroom 2 is heated by radiation from secondary thermal mass. The kitchen and dining room floors are of brick to give visual continuity between indoors and outdoors and to provide additional thermal mass. All other floors are carpeted except perhaps the bath, toilet and utility rooms. The void between the dining room and play-room allows air to circulate. A handrail is placed in the play-room to provide protection when the windows are open.

The dwelling design shown in figure 3.3 is used as a control case for the costing analysis discussed later in this chapter.

Example C



New work is shown hatched, demolitions dotted.

HOUSE WITH EXISTING TWO STOREY 'LONG' EXTENSION

Total area: 1160 sq ft.

Frontage: 17 ft.

Depth: 24 ft + 24 ft extension.

No. of persons: 5

Entrance: Dual entrance—service entrance through yard. Front door off street.

Garden: 55 ft.

Services: Gas fired boiler for hot water and central heating (radiators). (More rads can be added.) Electrical Immersion heater for hot water in summer.

Fireplaces retained.

Comments: Street environment poor — narrow pavements and streets inhibit tree planting. Well designed window boxes could compensate, and also prevent overlooking into front rooms. Daylighting at rear is very poor—hence need to enlarge windows. Existing cellar should not be wasted.

Special attention has been given to retain high quality of existing internal details (fireplace surround, door and architrave mouldings, door furniture, etc). Part of the existing extension is demolished to improve lighting conditions at rear. Rear window in living room enlarged—new rear kitchen window.

The back lane is wide and pleasant and the garden quite long. Dustbins and garages can be accommodated leaving adequate small gardens.

Fig. 3.1. Typical English row house plans[45].

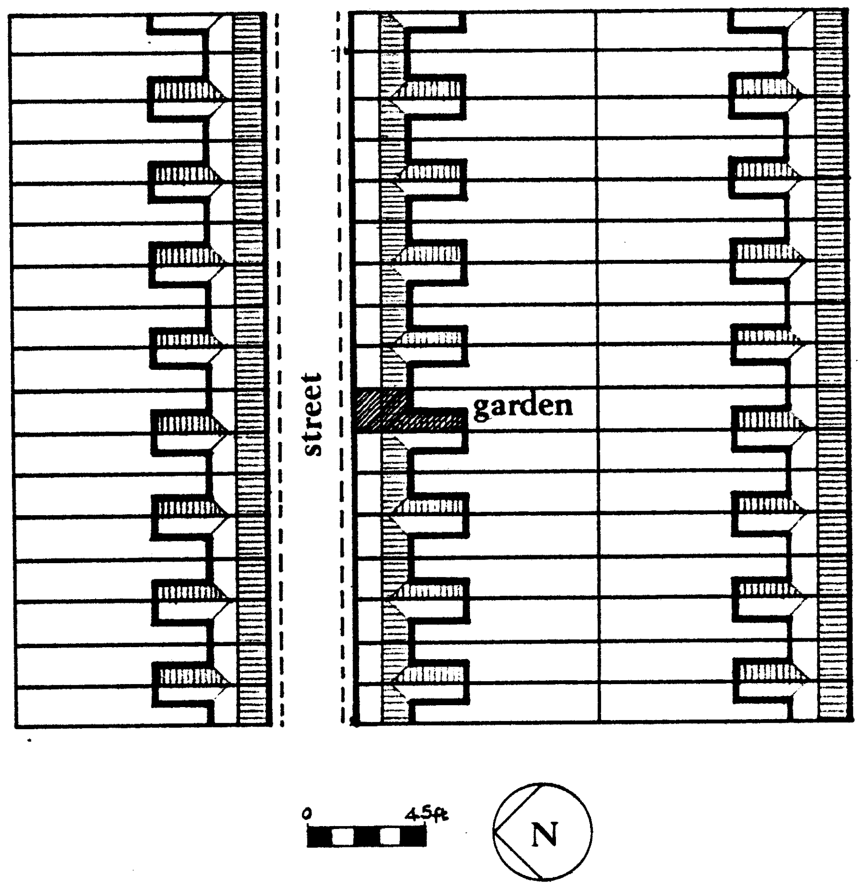


Fig. 3.2. Typical English row house site plan and assumed orientation.

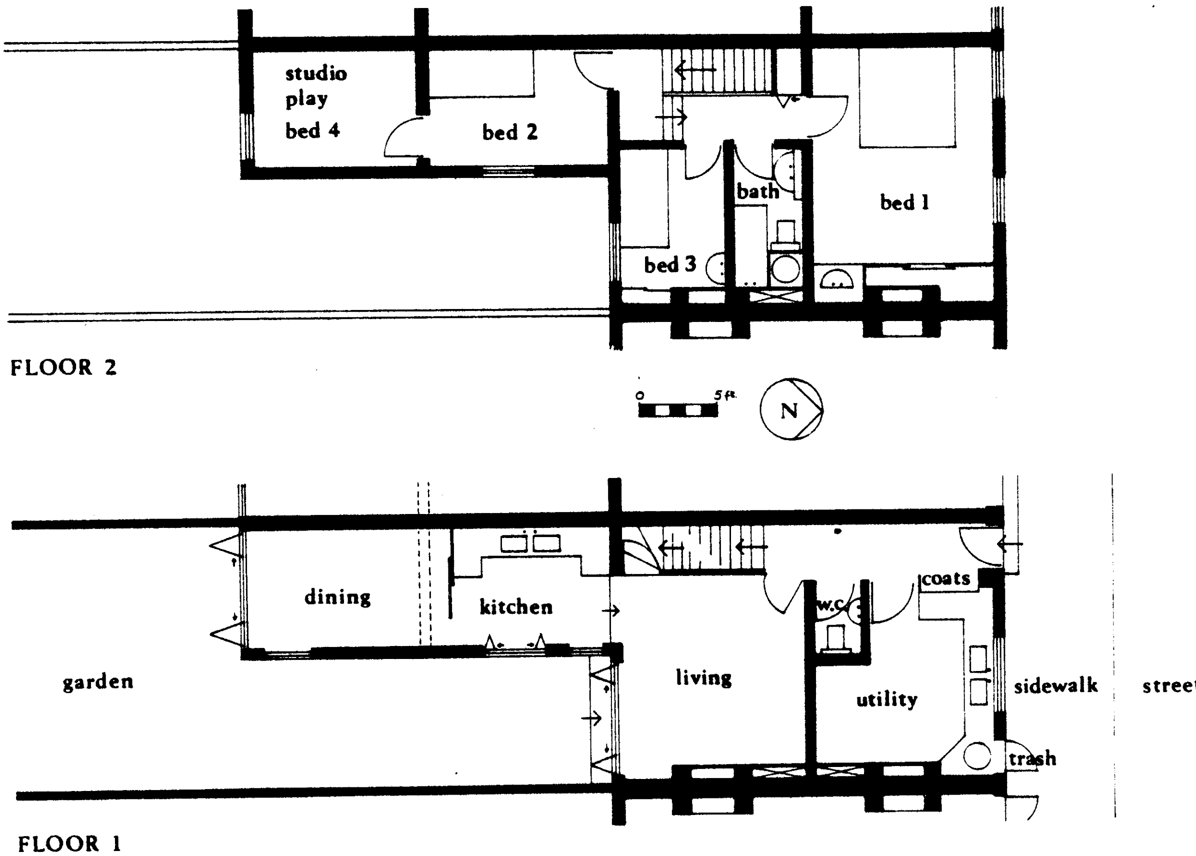


Fig. 3.3. Plans showing suggested improvements to existing row houses. Non-solar design; control test case.

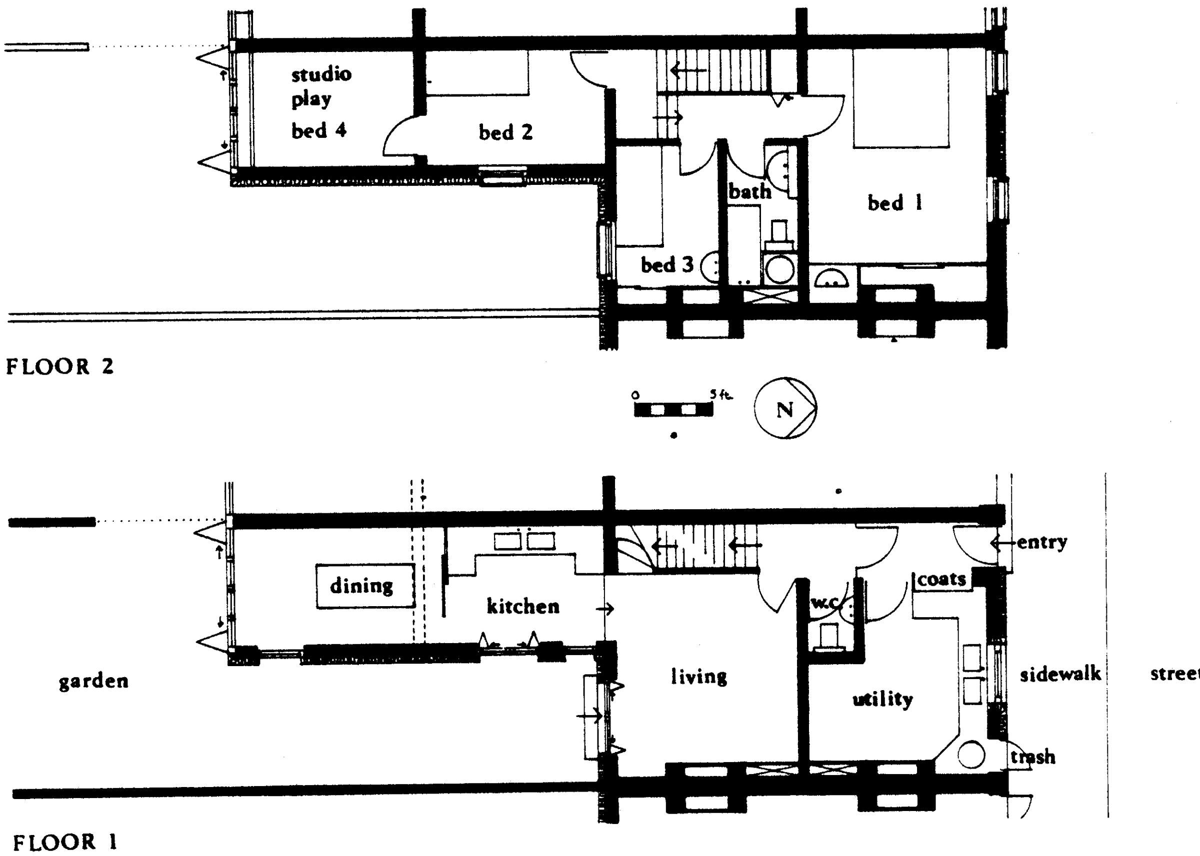


Fig. 3.4. Solar design. Plans showing suggested improvements to existing row houses.

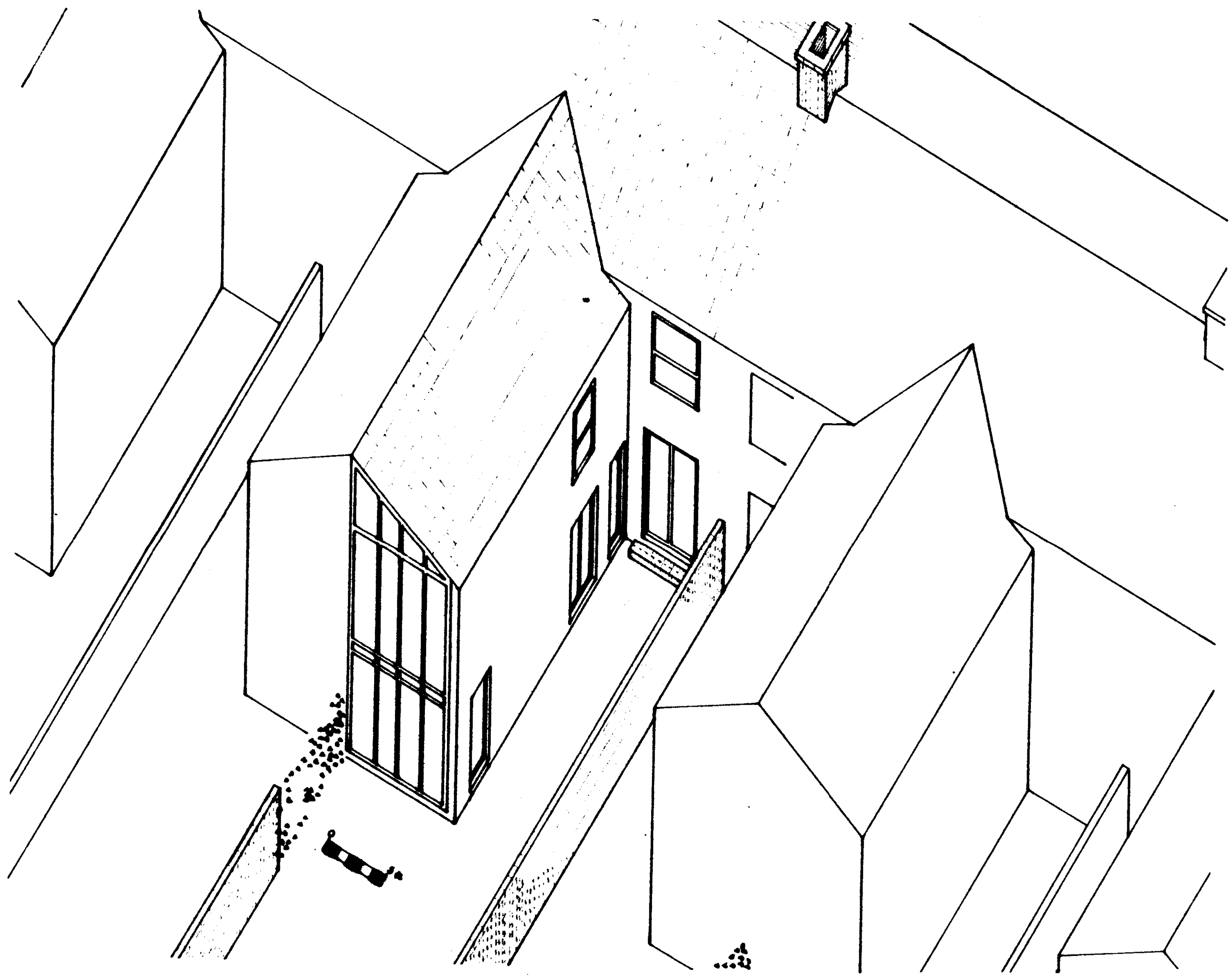
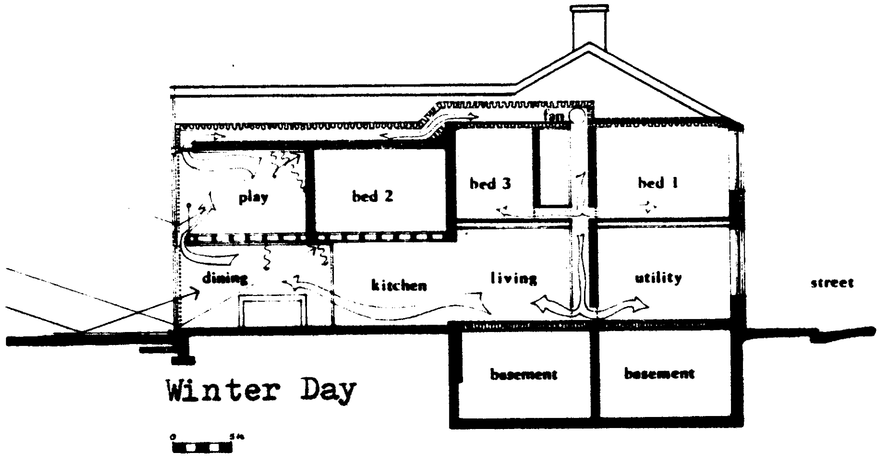
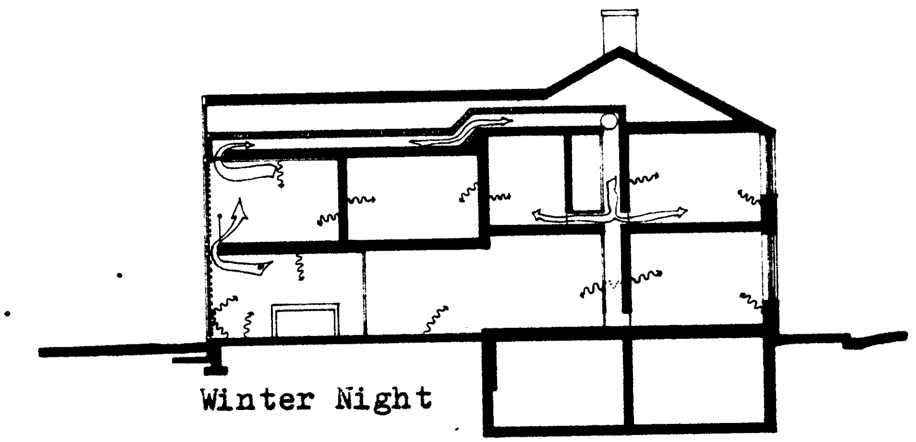


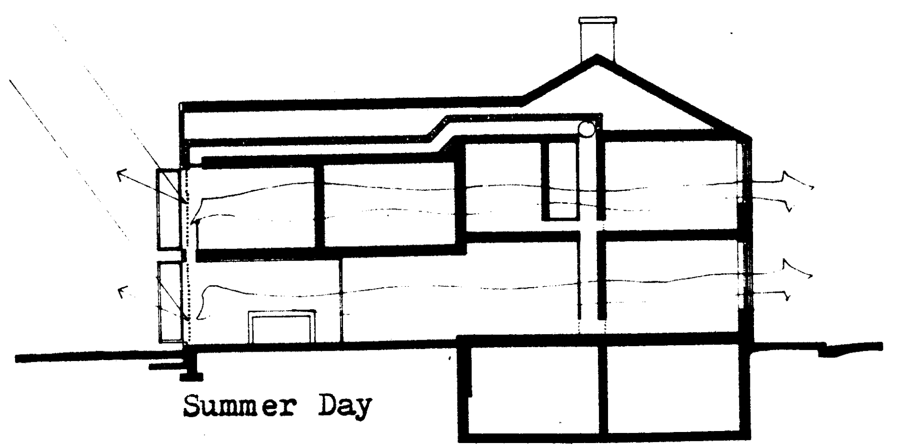
Fig. 3.5. Solar design. Axonometric showing suggested improvements to existing row houses.



Winter Day



Winter Night



Summer Day

Fig. 3.6. Solar design. Section showing suggested improvements, to existing row houses, and operation mode schematics.

PERFORMANCE ANALYSES

1. Overheating.

The data bases collected for this analysis are discussed and listed in Appendix D.

The design program presented in this thesis (Ch II, 1, m and Appendix B) was extended to enable it to model the suggested solar improvements of the row house. The changes made gave the program the ability to model more than one type and size of collection area. This would allow modeling of, say, a collection area in bedroom 3 (Fig. 3.4). This location for a collection area was found to be uneconomical because the recess caused reduced solar gains. Nevertheless, this flexibility in the program allows modeling of the dining room, with its east facing window, separately. A second alteration to the program was made. This enables the program to model the effects of coupling the air in the collection rooms to, what is in effect, a storage bin. When the room air temperature exceeds 2.8^{o}C (5^{o}F) above or below the temperature of the convective thermal mass, the fan (Fig. 3.6) is switched on, circulating air from the collection room to other parts of the house. When this happens, convective gains or losses, to or from the convective thermal mass, occur and the air temperature is decreased or increased respectively. The modeling of this is rather crude; it takes effect after the hourly air temperature has been determined and only divides the hour into eight parts. Nevertheless these crudities have no bearing on the conclusions drawn from the results of the program run: the room air temperature does not overheat (Table 3.1).

Time of Day	Start	9	10	11	12	13	14	15	16
Air temp.	18.3	19.1	19.9	20.3	21.3	21.1	20.1	19.9	21.7
Convective thermal mass temperature	18.3	18.4	18.5	18.6	18.7	18.9	19.0	19.0	19.0
Fan switched on	-	2	2	2	2	2	2	2	0

Table 3.1. Results of the passive design simulation program for the solar row house rehabilitation (Fig.3.4) in London on a clear October day.

The carry through of the system under such conditions is 80 hours. This length of carry through is explained by the relatively high outdoor temperatures in October (p.183).

Each time the fan is switched on represents 7.5 minutes of operating time; thus the fan is on for 15 minutes of each hour of this clear day. This is far from excessive fan use for such low air temperature results and for a clear day with high outdoor air temperatures. The high room air temperature at hour 16 in Table 3.1 is explained by the air temperature being less than 2.8°C above the temperature of the convective thermal mass and thus the fan has not been switched on.

Theoretically corrections to these results would be made to allow for an increased secondary thermal mass area and also to allow for the use of phase change material (pcm) tiles on the target area. The actual area of secondary thermal mass is approximately two times the area of the noon target (p.185), whereas the program assumes an area of secondary thermal mass of .5 times the target area. As shown in Figure 2.29 (p.81) this would mean an effective reduction of about 4.5°C. As discussed in the Workbook chapter of this thesis (Ch II, 1j), the use of pcm tiles would also significantly reduce the daily air temperature fluctuation. However, the effect of the convective thermal mass is so overpowering in determining the results shown in Table 3.1, that these additional factors would probably not change the outcome of the room air temperature results.

2. Costing.

The data bases used for this analysis, and the procedures for obtaining them, are listed in Appendix D.

The program used for this analysis is the Cost Benefit Program (Appendix B) and the design method employed within the program is discussed in the Workbook chapter of this thesis (Ch II, 3).

To conduct a costing analysis it is first necessary to find the difference in yearly heating load between the solar and non-solar rehabilitation designs. Such heating load calculations are performed within the Cost Benefit Program. Consequently all design decisions affecting the heat loss of the two proposals must be made. Such design decisions will dictate the choice of data bases; the following discussion deals with several of these decisions.

(i) The orientation and tilt chosen for the collecting surface is due south and vertical. These decisions were made on the basis of several influencing factors which are discussed in the Workbook (Ch II, 1a).

(ii) It is assumed that the large windows in the dining and living rooms of the non-solar design (Fig. 3.3) have moveable shading devices to prevent overheating in these spaces and to prevent fading of furnishings. These devices are assumed to be in operation for all months other than December, January and February.

(iii) The color tones used in decorating the non-collecting rooms of the solar design (Fig. 3.4) are assumed to be slightly darker than those used on the non-solar design. In England, most dwelling interiors are painted white to help compensate for the low levels of daylight during the winter. This could be achieved by having a light colored floor, which accepts most of the initial daylight entering the room, and slightly darker walls and ceiling. The effect of such slightly darker tones is to increase absorption of solar radiation and thus reduce back-reflected losses.

(iv) The solar design is assumed to have 100mm of external expanded polystyrene insulation on all walls. This is clad with vinyl coated aluminum siding. Both the roof and suspended floor are insulated with polythene wrapped fibreglass insulation; 150mm and 200mm respectively. Finally the windows are all double glazed with a layer of double sided heat mirror between.

(v) The non-solar design is assumed to have 50mm of fiberglass insulation in the roof, single glaring to all windows, a 'Sandtex' or similar waterproof finish to the North wall, and to have an uninsulated ground floor. These specifications are in line with rehabilitation work being executed in England today.

(vi) The microclimate of a densely populated city will have an influence on the heat losses of a building in such a location. Corrections for this influence are made in the references from which the U-values of the weatherskin components are assessed (Appendix D, Table 3.31). The results from the heating load section of the Cost Benefit Program runs are shown in Table 3.2. The price of fuel was taken to be £.0115 per kWh, which is the approximate cost of useful energy from North Sea gas in England (p.202).

Design Type	Balance Point Temp.(°C)	Degree Days (Table 2.14)	Heating Load (kWh/year)	Cost of Heating per year (£/yr.)
Non-Solar	15.26	2091.38	22089.11	254.02
Solar	6.56	430.64	1247.37	14.34

Table 3.2. Heating load results for both solar and non-solar designs from the Cost Benefit Program runs.

The heating load figures for the non-solar design in Table 3.2 are in good agreement with published figures by Burberry[50].

Cost of Improvement(£)	Borrowing Period (Years)	Fuel Cost Spiral Rate (%)	Discount Rate (%)	Payback Period (Years)
1687.51	25	4	7	10
			4	7
			10	13.5

Table 3.3. Results from the Cost Benefit Program showing the time taken to recoup the additional capital expenditure involved in making the solar improvements suggested (the difference between figures 3.3 and 3.4).

Table 3.3 shows the results of several runs of the Life-Cycle costing section of the Cost Benefit Program. Account is taken for the economy's inflation rate and the spiral rate of the increase in fossil fuel prices by using equation (40) (Appendix A) in this section of the program. A breakdown of the total cost of the improvements is taken mainly from Spons[48] and is listed in Appendix D. The improvements will last for the life of the building and thus the borrowing period is assumed to be that of the normal length of a mortgage. Using an assumed Treasury discount rate of 7% (p.126), which would be applicable to local authority work, the payback period is just under 10 years. For every year after this 10 years, the inhabitant will be saving over £ 240 per year on his heating bills. Further discussion on the values used for the fuel cost spiral rate and the discount rate may be found in the Workbook chapter of this thesis (p.121).

CONCLUSION

One of the main objectives of this thesis has been met by showing that these row houses can be successfully rehabilitated incorporating solar heating. It is to be emphasized that only a year ago such successful results were beyond any expactations. They have been made possible by the recent advances in technology by researchers at M.I.T. and in research laboratories in the U.S.A. The heat mirror, the phase change material tile, and the solar modulator may individually seem to be small advances but they will revolutionize architectural thinking in the temperate climates.

The results obtained from the performance analyses, and the design proposal seem to have implications beyond the immediate scope of this thesis. If, as the results of this thesis suggest, a ten year payback period is attainable with improvement work, there is reason to believe that the payback period on new housing may be less.

New housing lifts many of the constraints imposed by improvement work. Orientation can be chosen, the proportion of solar collection area to floor area could be increased, the materials used for improving solar collection would be replacements of, rather than additions to, conventional materials and thus real cost would be reduced, and dwellings could be designed where natural convection is used to distribute the heat.

England has experienced a change in the structure of its society in the past forty years. This change was caused by the emergence of a skilled labor force which has taken the place of the previous middle class in the house buying market. In most cases the skilled laborer earns more than a member of the previously established middle class (the professional). The skilled laborer has at his disposal more leisure time than a member of the class from which he emerged (the working class) and, as a result, he demands more, in terms of comfort, of his life-style.

Domestic architecture in England has, as yet, not fully responded to this change in society.

The results of this thesis suggest that passive solar design may be able to provide an answer to these new architectural demands: It is possible to rehabilitate row houses or build new houses in England incorporating a nurturing of life-style otherwise unthinkable because of the potentially high heating costs of such a conventional design in winter.

APPENDIX A ~ EQUATIONS

Equation(18)

$$I_{tv} = (((I_{dh}/\cos 0) \times \cos A \times \cos W) \times T_{ad}) + ((.5 \times I_{fh}) \times T_{af})$$

Where Tad = The heat gain factor for direct solar radiation for that hour, month and orientation; dependent on the properties of the transparent membrane and on the angle of incidence.

Taf = The heat gain factor for diffuse solar radiation.

Equation(20)

$$I_{vert} = I_{hor} \times \tan P \times T_{ad} \times M$$

Where I_{vert} = The vertical component of the hourly clear day solar energy gains.

I_{hor} = The hourly horizontal component of the clear day insolation value, taken from the table in Refs. 9 and 10.

P = The profile angle for that hour - a constant at the equinox for a south facing building.

T_{ad} = The heat gain factor for that hour: transmittance plus half the absorptance.

Equation(21)

$$Q_t = \%hit \times A_{nt} \times W_{vert} \times .9 \times .85$$

Where Q_t = The quantity of solar energy absorbed by the target.

%hit = The % of noon target area being illuminated by the sun for this hour.

A_{nt} = The noon target area.

W_{vert} = The vertical component of the insolation gain for that hour.

.9 = A reduction factor due to reflection off the solar modulators.

.85 = The assumed absorption of the target. This will be increased to .95 if a black surface is used.

Equation(22)

$$Q_{sto} = Q_t \times R_{sp}$$

Where Q_{sto} = The quantity of energy stored within the target slab.

Q_t = The solar energy absorbed by the target (result of Eqn.(21)).

R_{sp} = The resistance split fraction of energy being stored.

Equation(23)

$$dT_l = Q_{sto}/(D \times Cp \times V)$$

Where dT_l = The temperature rise of the entire volume of the target.
D = The density of the target.
C p = The specific heat of the target.
V = The volume of the target.

Equation(24)

$$dT_t = dT_l \times 5.3$$

Where dT_t = The incremental increase in surface temperature of a solid target.
dT_l = The result of Eqn.(23).

Equation(25)

$$I_{ts} = T_{tp} + dT$$

Where T_{ts} = The new surface temperature of the target.
T_{tp} = The previous hour's surface temperature of the target. When this is the first hour being modeled T_{tp} will be the morning start temperature.
dT = The incremental increase in the surface temperature of the target. In the case of a liquid target this will be the result of Eqn.(23). In the case of a solid target this will be the result of Eqn.(24).

Equation(26)

Energy gain of room air = Energy loss from the room air.

Where energy gains consists of:

The incidental heat gains from the people, appliances and other windows, for that hour. The window gains must be reduced by the proportion being lost to reflected back losses (see Section k "Solar Gain").

plus

The heat gains by convection (radiation is included but hidden) from the target area = U x A x T. Where U, the thermal coefficient of the air film, is 3.86W/sq.m °C (.68 Btu/sq.ft. °F). And where A is the noon target area. T is the surface temperature of the slab minus the room air temperature.

plus

The quantity of energy which, due to the positon of the sun in that hour, falls outside the target area. This is obtained by subtracting the percent target area hit from 100. This quantity is reduced by the proportion lost to reflected back losses.

plus

The energy reflected off the target area minus the portion of this lost to reflected back losses.

plus

The 10% of the solar energy not reflected onto the ceiling target by the solar modulators.

The energy losses consist of:

The fabric losses = U average x A weather skin x $(T_{room} - T_{outside})$ x .84

plus

Infiltration losses = V x .34 x $(T_{room} - T_{outside})$ x .84

plus

basement losses = U x A x $(T_{room} - T_{ground})$ x .84

Where U	=	The overall U-value of the element.
A	=	The area of that element.
Troom	=	The temperature of the room air for this hour; which we are attempting to find.
Toutside	=	The outside temperature for this hour.
Tground	=	The ground temperature.
V	=	The volume of infiltrated air per hour.
.34	=	The density x the specific heat of air (W/cu.m/°C) (.018 Btu/cu.ft./°F).
.84	=	The correction factor for heat loss calculations (Ref.20).

Equation(27)

$Q_{ts} = Q_{gs}$ - Energy loss from the room air

Where Q_{ts} = The energy stored by the system for this hour.

Q_{gs} = The total energy gains of the system for this hour; the result of Eqn.(29).

Energy loss from the room air is the same as in Eqn.(26).

Equation(28)

$$Q_e = A_w \times W_{hor}$$

Where Q_e = The solar energy entering the room through the collection window for this hour.

A_w = The area of the collecting window.

W_{hor} = The horizontal component of the solar energy gains for this hour.

Equation(29)

$$Q_{gs} = (Q_e - Q_{bl}) + P$$

Where Q_{gs} = The total energy gains of the system for this hour.

Q_e = The result of Eqn.(28).

Q_{bl} = The back reflected solar energy losses. This is made up of several separate quantities (as developed in the energy gains of Eqn.(26).

P = The energy gains from people, appliances and other windows for this hour.

Equation(30)

$$H = Q_{ts}/(Q_{ul} \times .84)$$

Where H = The number of hours of carry through of the building design.

Q_{ts} = The summed energy stored for all of the 8 and results of Eqn.(27).

Q_{ul} = The hourly night losses of the system due to fabric and infiltration losses.

.84 = The Hittman heating reduction factor (Ref.20).

Equation(32)

$$\text{Glare Index} = 10 \times \text{Log}_{10}\text{Gc}$$

Where Gc = the glare constant.

Equation(40)

$$\text{NPV} = F \times \frac{a\ (a^N - 1)}{a-1}$$

Where NPV = the net present value of the money saved over N years.
- F = this year's value of the annual fuel savings.
- a = (1 + g)/(1 + r).
- g = the rate of increase of fuel prices (% p.a. expressed as a fraction).
- r = the discount rate (% p.a. expressed as a fraction).
- N = either the lifetime of the improvement or the number of years of borrowing, whichever is the shorter.

APPENDIX B ~ TI 59 PROGRAMS

PASSIVE DESIGN PROGRAM

The program may be changed from metric to imperial units by changing 3.86 to .68 in locations 019 to 022; and by changing .34 to .018 in locations 029 to 031.

Procedure:

Step #		Enter	Press	Display
1	Change the partitioning of the calculator	7	2nd Op 17	399.69
2	Enter the data being modeled into the data registers listed below and then write them onto a magnetic card:			

06 Area of collection window.

07 Average room air temperature at night.

08 Average gains from people and appliances at night/hr.

09 Average outdoor temperature at night.

10 Density of target.

11 Specific heat of target.

12 Volume of target.

13 Noon area of target.

14 U-value x Area of weather skin.

15 Volume of air change per hour.

16 U-value x Area of basement.

17 Temperature of the ground.

18 Resistance split fraction.

19 Morning start temperature.

20, 25, 30, 35, 40, 45, 50, 55 % (fraction) of noon target area hit from hour 1 to hour 8.

21, 26, 31, 36, 41, 46, 51, 56 The vertical components of the solar energy gain values from hour 1 to hour 8.

22, 27, 32, 37, 42, 47, 52, 57 The horizontal components of the solar energy gain values from hour 1 to hour 8.

23, 28, 33, 38, 43, 48, 53, 58 People appliance and other window gains from hour 1 to hour 8.

24, 29, 34, 39, 44, 49, 54, 59 Outdoor temperature from hour 1 to hour 8.

3 Load program into calculator and record on a magnetic card.

		Enter	Press	Display
4	Place either 1 (liquid) or 0 (solid) in t to model the type of target area.	1 or 0	x≷t	
5	Run program and display target slab surface temperature for hour 1.		A	Top of slab temp 1.
6	Calculate the room air temperature for hour 1.		R/S	Air temp 1.
7	Repeat until all 8 values of both have been displayed.		R/S	Hours 2 - 8.
8	Compute the number of hours of carry through achieved by the system modeled under these conditions.		R/S	Carry through.

TITLE PASSIVE DESIGN PROGRAM **PAGE** 1 **OF** 01

PROGRAMMER RALPH LEBENS **DATE** AUG. '77

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
000	76	2nd Lbl		5	43	RCL		110	05		
1	11	A	START PROG.	6	13	13		1	55	÷	
2	43	RCL		7	65	×		2	43	RCL	
3	10	10		8	93	.9	% reflected off	3	02	2	
4	65	×		9	09		louvres	4	95	=	
5	43	RCL		060	95	=		5	42	STO	
6	11	11		1	42	STO		6	66	66	
7	65	×		2	62	62		7	85	+	
8	43	RCL		3	43	RCL		8	43	RCL	
9	12	12		4	14	14		9	67	67	
010	95	=		5	85	+		120	95	=	
1	42	STO		6	43	RCL		1	42	STO	
2	02	2		7	04	4		2	67	67	
3	25	CLR		8	95	=		3	01	1	if water is
4	42	STO		9	42	STO		4	67	2nd x=t	used as target
5	01	1		070	61	61		5	14	D	
6	43	RCL		1	43	RCL		6	43	RCL	
7	13	13		2	03	3		7	67	67	
8	65	×		3	85	+		8	75	−	
9	03			4	43	RCL		9	43	RCL	
020	93	3.86	Thermal coefficient	5	63	63		130	66	66	
1	08		of target slab	6	95	=		1	85	+	
2	06			7	42	STO		2	53	(	
3	95	=		8	60	60		3	05		
4	42	STO		9	08	08	setting up for	4	93	5.3	
5	03	3		080	42	STO	loop.	5	03		
6	43	RCL		1	04	04		6	65	×	
7	15	15		2	01	19		7	43	RCL	
8	65	×		3	09			8	66	66	
9	93			4	42	STO	setting up for	9	54	)	
030	03	.34		5	63	63	indirect addressing	140	95	=	
1	04			6	43	RCL		1	42	STO	
2	95	=		7	19	19		2	68	68	
3	42	STO		8	42	STO		3	76	2nd Lbl	
4	04	4		9	67	67		4	52	EE	slab surface
5	53	(		090	76	2nd Lbl	start of loop.	5	91	R/S	temperature
6	43	RCL		1	12	B		6	71	SBR	is displayed
7	14	14		2	71	SBR		7	13	C	for hour i
8	85	+		3	13	C		8	65	×	
9	43	RCL		4	71	SBR		9	43	RCL	
040	16	16		5	13	C		150	06	6	
1	85	+		6	42	STO	temporary data	1	95	=	
2	43	RCL		7	05	5	storage	2	42	STO	
3	04	4		8	65	×		3	69	69	
4	54	)		9	43	RCL		4	53	(	
5	65	×		100	64	64		5	71	SBR	
6	93			1	65	×		6	13	C	
7	08	.84		2	43	RCL		7	42	STO	temporary
8	04			3	62	62		8	66	66	data storage
9	95	=		4	95	=		9	85	+	
050	42	STO		5	42	STO					
1	63	63		6	65	65					
2	43	RCL		7	65	×					
3	18	18		8	93		% absorbed by				
4	65	×		9	08	.85	target				

TEXAS INSTRUMENTS INCORPORATED

TITLE PASSIVE DESIGN PROGRAM PAGE 2 OF 01 **TI Programmable Coding Form**

PROGRAMMER RALPH LEBENS DATE AUG. '77

LOC	CODE	KEY	COMMENTS
160	43	RCL	
1	03	3	
2	65	×	
3	43	RCL	
4	68	68	
5	95	=	
6	53	(	
7	71	SBR	
8	13	C	
9	65	×	
170	43	RCL	
1	61	61	
2	85	+	
3	43	RCL	
4	16	16	
5	65	×	
6	43	RCL	
7	17	17	
8	54	)	
9	65	×	
180	93		
1	08	·84	correction
2	04		factor
3	85	+	
4	43	RCL	
5	64	64	
6	85	+	
7	53	(	
8	43	RCL	
9	05	5	
190	65	×	
1	43	RCL	
2	13	13	
3	75	−	
4	43	RCL	
5	65	65	
6	55	÷	
7	43	RCL	
8	18	18	
9	54	)	
200	65	×	
1	93		
2	04	·48	
3	08		
4	85	+	
5	43	RCL	
6	65	65	
7	55	÷	
8	43	RCL	
9	18	18	
210	65	×	
1	53	(	
2	01	1	
3	75	−	
4	93		
5	08	·85	% absorbed
6	05		by target
7	54	)	
8	65	×	
9	93	·6	
220	06		
1	54	)	
2	55	÷	
3	43	RCL	
4	60	60	
5	95	=	
6	42	STO	
7	00	0	
8	91	R/S	Air temperature
9	43	RCL	displayed for
230	69	69	hour i
1	75	−	
2	53	(	
3	43	RCL	
4	69	69	
5	75	−	
6	43	RCL	
7	65	65	
8	65	×	
9	93		
240	08	·85	% absorbed
1	05		by target
2	55	÷	
3	43	RCL	
4	18	18	
5	54	)	
6	65	×	
7	93	.4	
8	04		
9	85	+	
250	43	RCL	
1	66	66	
2	75	−	
3	53	(	
4	43	RCL	
5	61	61	
6	65	×	
7	53	(	
8	43	RCL	
9	00	0	
260	75	−	
1	73	RCL 2nd Ind	
2	63	63	
3	54	)	
4	85	+	
5	43	RCL	
6	16	16	
7	65	×	
8	53	(	
9	43	RCL	
270	00	0	
1	75	−	
2	43	RCL	
3	17	17	
4	54	)	
5	54	)	
6	65	×	
7	93		
8	08	·84	correction
9	04		factor
280	95	=	
1	44	SUM	
2	01	1	
3	97	2nd Dsz	
4	04	4	
5	12	B	End of loop
6	43	RCL	
7	61	61	
8	65	×	
9	53	(	
290	43	RCL	
1	07	7	
2	75	−	
3	43	RCL	
4	09	9	
5	54	)	
6	85	+	
7	43	RCL	
8	16	16	
9	65	×	
300	53	(	
1	43	RCL	
2	07	7	
3	75	−	
4	43	RCL	
5	17	17	
6	54	)	
7	54	)	
8	65	×	
9	93		
310	08	·84	correction
1	04		factor.
2	75	−	
3	43	RCL	
4	08	8	
5	95	=	
6	42	STO	
7	65	65	
8	43	RCL	
9	01	1	

TEXAS INSTRUMENTS INCORPORATED

TITLE PASSIVE DESIGN PROGRAM **PAGE** 3 **OF** 01

PROGRAMMER RALPH LEBENS **DATE** AUG. '77

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
320	55	÷	
1	43	RCL	
2	65	65	
3	95	=	
4	42	STO	Number of hours
5	00	0	of carry through
6	91	R/S	is displayed
7	76	2nd Lbl	SUBROUTINE
8	13	C	C
9	42	STO	
330	64	64	
1	01	1	
2	44	SUM	
3	63	63	
4	73	RCL 2nd Ind	
5	63	63	
6	92	INV SBR	
7	76	2nd Lbl	If water is
8	14	D	used as the
9	43	RCL	target
340	67	67	
1	42	STO	
2	68	68	
3	61	GTO	
4	52	EE	
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			

LOC	CODE	KEY	COMMENTS
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

LOC	CODE	KEY	COMMENTS
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			

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COST BENEFIT PROGRAM

The program may be changed from metric to imperial units by changing the average thermostat set temperature in locations 302 to 306 to the equivalent temperature in Farenheight. The thermostat set temperature of 18^{o}C was established for a dwelling in England and may have to be changed to model any other building type or location (country). Consistency of units is necessary; for metric the following may be used: KWh, m^2, £($)KWh, ^{o}C and KWh/day ^{o}C. When using imperial units the following may be used: MBtu, ft^2, $/MBtu, ^{o}F and MBtus/day ^{o}F. The following data is collected from the sources in parenthesies:

The mean daily outdoor temperature for each month - January to December (Chapter II, section b).
The number of days in each month - January to December.
The internal gains per month from inhabitants, appliances and windows. This includes direct solar gains. (Chapter II, sections d, e, f, k, l).
The Heat Loss/day ^{o}C (Chapter II, section f, eqn(8), sections g, h, i). This includes fabric plus infiltration losses. The cost of the heating fuel, £ ($)/KWh.
A table of degree days is drawn up (Chapter II, sections f and group 3).

Procedure

Step #		Enter	Press	Display
1	Change the partitioning of the calculator.	7	2ndOp 17	399.69
2	Enter the data being modeled into the data registers listed below and then write them onto data storage card 1.:			

Step #

J F M A M J J A S O N D

24.27.30.33.36.39.42.45.48.51.54.57. Mean daily outdoor temperature for each month, Jan-Dec °C.

25.28.31.34.37.40.43.46.49.52.55.58. Number of days per month for each month.

26.29.32.35.38.41.44.47.50.53.56.59. Internal gains per month from people, appliances and solar. KWh/month.

11. Heat loss/day °C (fabric + infiltration losses)x .84) KWh/day °C.

9. Cost of heating fuel £($)/KWh.

3 Load program into calculator and record on a magnetic card.

Step #		Enter	Press	Display
4	Compute the balance point temperature, of the building without improvements.		B	Balance point temperature.
5	Enter the number of degree days for this balance point temperature (see Chapter 2, group 3, Table 2.14) and calculate the resulting heating load per year.	Degree days.	R/S	Heating load without improvement.
6	Compute the cost of this heating load.		R/S	Cost of heating without improvement.
7	Enter new heat loss/day °C.	Heat loss/day °C	C	Heat loss/day °C
8	Enter cost of improvement £ ($)/$m^2$	Cost	D	Cost
9	Enter area of improvement m^2	Area	E	Area
10	Enter discount rate (fraction)	Discount rate.	2nd C'	Discount rate.

Step #		Enter	Press	Display
11	Enter fuel cost spiral rate (fraction).	Fuel increase rate.	2^{nd}B'	Fuel increase rate.
12	Enter borrowing period or life span of improvement.	Years.	2^{nd}D'	Years.
13	Compute the balance point temperature for the improved building.		A	Balance point temperature.
14	Enter the number of degree days for that balance point temperature and calculate the resulting heating load per year.	Degree days.	R/S	Heating load with improvement.
15	Compute the cost of this heating load.		R/S	Cost of heating with improvement.
16	Compute the cost benefit of the improvement.		R/S	Cost benefit.
17	Can change any of the values corresponding to labels D, E, B', C', D' and test the cost benefit again.		2^{nd}E'	Cost benefit.
18	Compute the payback period (approx.).		R/S	Payback period.

The following is a list of the remainder of the data registers employed by the program and their purpose:

0. Counter and later holds the money saved per year by improvement.
1. Cost of heating without improvement.
2. Number of years of borrowing or life span of improvement.
3. Discount rate.
4. Fuel cost spiral rate.
5. Storage within SBR x⇄t.
6. Dsz for looping.

7. Area of improvement (m^2).
8. Cost of improvement £($)/$m^2$.
10. Degree day base temperature or balance point temperature.

J F M A M J J A S O N D
12.13.14.15.16.17.18.19.20.21.22.23 Degrees difference and approximate heating load/month.

60. Total heating load/year.
61. The variable 'a' in eqn(40) (Appendix A).
62. Cost of heating/year with improvement.
63. Indirect address for degrees difference array.
64. Indirect address for mean temperature, days/month, and internal gains array.
65. Temporary storage.
66. Sum of internal gains.
67. Sum of days of internal gains.
68. Internal gains/day.
69. Cost benefit and payback period.

The program enables the operator to model comparative improvements in two different ways:

Method 1: The cost benefit is computed by continually comparing the heating costs of the improved building with those of the unimproved building. This allows the modeling of different alternatives to see which gives better returns on the investment. This method is made possible by writing the data registers onto a data storage card 2 (the contents of the registers above 59 never need to be stored) between steps 12 and 13. Then this card is read into the data registers after step 18 and new values are entered for the variables associated with labels C, D, E, B', C' and D' and then A is run again (step 23).

Method 2: the cost benefit is computed by comparing the heating costs of the improved building with those of the building improved by the previous improvement made. This method is made possible by pressing 2^{nd} A' after step 18. This places the heating cost per year (of the improved building) into data register 1. Register 1 usually holds the cost of heating without improvements. Following this, steps 7 to 18 are executed.

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PROGRAMMER RALPH LEBENS DATE AUG. '77

TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS
000	76	2nd Lbl	START PROG.
1	12	B	FOR PERFORMANCE
2	71	SBR	WITHOUT
3	59	2nd Int	IMPROVEMENT
4	43	RCL	
5	60	60	
6	65	×	
7	43	RCL	
8	09	9	
9	95	=	
010	42	STO	cost of heating
1	01	1	without improvement
2	91	R/S	
3	76	2nd Lbl	START PROG
4	11	A	FOR PERFORMANCE
5	71	SBR	WITH
6	59	2nd Int	IMPROVEMENT
7	43	RCL	AND TO
8	60	60	COMPUTE
9	65	×	COST BENEFIT
020	43	RCL	
1	09	9	
2	95	=	
3	42	STO	cost of heating
4	62	62	with improvement
5	43	RCL	
6	01	1	
7	75	−	
8	43	RCL	
9	62	62	
030	95	=	
1	42	STO	
2	00	0	
3	76	2nd Lbl	Gives external
4	10	2nd E'	access to
5	53	(	cost benefit
6	43	RCL	section of the
7	04	4	program
8	85	+	
9	01	1	
040	54	)	
1	55	÷	
2	53	(	
3	43	RCL	
4	03	3	
5	85	+	
6	01	1	
7	54	)	
8	95	=	
9	42	STO	
050	61	61	
1	65	×	
2	43	RCL	
3	00	0	
4	65	×	

LOC	CODE	KEY	COMMENTS
5	53	(	
6	43	RCL	
7	61	61	
8	45	y^x	
9	43	RCL	
060	02	2	
1	75	−	
2	01	1	
3	54	)	
4	55	÷	
5	53	(	
6	43	RCL	
7	61	61	
8	75	−	
9	01	1	
070	54	)	
1	95	=	
2	55	÷	
3	53	(	
4	43	RCL	
5	08	8	
6	65	×	
7	43	RCL	
8	07	7	
9	54	)	
080	95	=	
1	42	STO	
2	69	69	
3	91	R/S	Cost Benefit
4	01	1	displayed
5	32	$x \rightleftharpoons t$	(= present value
6	43	RCL	of money saved
7	69	69	÷
8	77	2nd $x \geq t$	improvement
9	79	2nd $\bar{x}$	cost.)
090	01	10	
1	00		
2	45	y^x	
3	06	6	
4	95	=	
5	42	STO	
6	69	69	
7	76	2nd Lbl	
8	97	2nd Dsz	Display of
9	91	R/S	payback
100	76	2nd Lbl	period
1	79	2nd $\bar{x}$	(= 1000000 yrs
2	43	RCL	if Cost Benefit
3	02	2	< 1)
4	55	÷	
5	43	RCL	
6	69	69	
7	95	=	
8	42	STO	
9	69	69	

LOC	CODE	KEY	COMMENTS
110	61	GTO	
1	97	2nd Dsz	
2	76	2nd Lbl	Enter spiral
3	17	2nd B'	rate of fuel
4	42	STO	price
5	04	4	increase.
6	91	R/S	
7	76	2nd Lbl	Enter borrowing
8	18	2nd C'	interest rate
9	42	STO	
120	03	3	
1	91	R/S	
2	76	2nd Lbl	Enter number
3	19	2nd D'	of years
4	42	STO	borrowed
5	02	2	
6	91	R/S	
7	76	2nd Lbl	Enter new
8	13	C	Heat Loss/day °C
9	42	STO	due to
130	11	11	improvement
1	91	R/S	
2	76	2nd Lbl	Enter cost of
3	14	D	improvement
4	42	STO	per unit
5	08	8	area.
6	91	R/S	
7	76	2nd Lbl	Enter area 4
8	15	E	improvement
9	42	STO	
140	07	7	
1	91	R/S	
2	76	2nd Lbl	For additive
3	16	2nd A'	improvements
4	43	RCL	
5	62	62	
6	42	STO	
7	01	1	
8	91	R/S	
9	76	2nd Lbl	SUBROUTINE
150	59	2nd Int	that calls
1	53	(	main
2	43	RCL	subroutines
3	53	53	
4	85	+	
5	43	RCL	
6	56	56	
7	85	+	
8	43	RCL	
9	59	59	

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TI Programmable Coding Form

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LOC	CODE	KEY	COMMENTS
160	85	+	
1	43	RCL	
2	26	26	
3	85	+	
4	43	RCL	
5	29	29	
6	85	+	
7	43	RCL	
8	32	32	
9	54	)	
170	42	STO	
1	66	66	
2	01		
3	08	182	
4	02		
5	42	STO	
6	67	67	
7	71	SBR	
8	39	2nd cos	
9	71	SBR	
180	49	2nd Prd	
1	71	SBR	
2	44	SUM	
3	43	RCL	
4	10	10	
5	53	(	Balance point
6	91	R/S	temperature
7	65	×	displayed.
8	43	RCL	Number of
9	11	11	degree days
190	54	)	entered.
1	42	STO	
2	60	60	
3	91	R/S	Heat load per
4	92	INV SBR	year displayed.
5	76	2nd Lbl	MAIN
6	49	2nd Prd	SUBROUTINE
7	71	SBR	computes
8	35	$1/x$	heating load
9	25	CLR	based on
200	42	STO	monthly
1	65	65	average
2	76	2nd Lbl	temperatures.
3	89	2nd π	START OF LOOP
4	01	1	
5	44	SUM	
6	63	63	
7	44	SUM	
8	64	64	
9	53	(	
210	43	RCL	
1	10	10	
2	75	−	
3	73	RCL 2nd Ind	
4	64	64	

LOC	CODE	KEY	COMMENTS
5	54	)	
6	71	SBR	
7	77	2nd $x \geq t$	
8	01	1	
9	44	SUM	
220	64	64	
1	53	(	
2	43	RCL	
3	05	5	degrees/ave.
4	65	×	monthly day.
5	43	RCL	
6	11	11	heat loss/day °C
7	65	×	
8	73	RCL 2nd Ind	
9	64	64	number of days/
230	54	)	month.
1	72	STO 2nd Ind	
2	63	63	
3	01	1	
4	44	SUM	
5	64	64	
6	97	2nd Dsz	
7	06	6	
8	89	2nd π	LOOPING
9	92	INV SBR	
240	76	2nd Lbl	MAIN
1	44	SUM	SUBROUTINE
2	71	SBR	computes new
3	35	$1/x$	degree day base
4	25	CLR	temperature.
5	42	STO	
6	66	66	
7	42	STO	
8	67	67	
9	76	2nd Lbl	START OF LOOP
250	33	x^2	
1	01	1	
2	44	SUM	
3	63	63	
4	02	2	
5	44	SUM	
6	64	64	
7	25	CLR	
8	32	$x \rightleftarrows t$	
9	73	RCL 2nd Ind	
260	63	63	heat load/mo.
1	67	2nd $x = t$	
2	25	CLR	
3	73	RCL 2nd Ind	
4	64	64	
5	44	SUM	sum of days
6	67	67	when heat load/
7	01	1	month > 0
8	44	SUM	
9	64	64	

LOC	CODE	KEY	COMMENTS
270	73	RCL 2nd Ind	
1	64	64	
2	44	SUM	
3	66	66	sum of internal
4	76	2nd Lbl	gains/month
5	78	2nd Σ+	when heat load/
6	97	2nd Dsz	month > 0
7	06	6	
8	33	x^2	LOOPING
9	25	CLR	
280	32	$x \rightleftarrows t$	
1	43	RCL	
2	66	66	if sum of
3	67	2nd $x = t$	internal gains/
4	34	$\sqrt{x}$	month = 0
5	76	2nd Lbl	
6	52	EE	
7	71	SBR	
8	39	2nd cos	
9	92	INV SBR	
290	76	2nd Lbl	SUBROUTINE
1	39	2nd cos	CALLED BY
2	53	(	MAIN SBR
3	43	RCL	SUM: computes
4	66	66	the new
5	55	÷	balance point
6	43	RCL	temperature
7	67	67	
8	54	)	
9	42	STO	
300	68	68	
1	53	(	
2	01		Average
3	08		thermostat set
4	93	18.00	temperature (°C)
5	00		
6	00		
7	75	−	
8	53	(	
9	43	RCL	
310	68	68	
1	55	÷	
2	43	RCL	
3	11	11	
4	54	)	
5	54	)	
6	42	STO	new balance
7	10	10	point
8	92	INV SBR	temperature
9	76	2nd Lbl	

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TI Programmable Coding Form

LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS	LOC	CODE	KEY	COMMENTS
320	35	1/x	SUBROUTINE	5	67	67		0			
1	01	11	SETS UP	6	61	GTO		1			
2	01		DATA REGISTER	7	52	EE		2			
3	42	STO	ENTRIES FOR	8				3			
4	63	63	MAIN	9				4			
5	02	23	SUBROUTINES	380				5			
6	03			1				6			
7	42	STO		2				7			
8	64	64		3				8			
9	01	12		4				9			
330	02			5				0			
1	42	STO		6				1			
2	06	6		7				2			
3	92	INV SBR		8				3			
4	76	2nd Lbl		9				4			
5	77	2nd x≥t	SUBROUTINE	0				5			
6	42	STO	tests if	1				6			
7	05	5	number ≥ 0	2				7			
8	25	CLR		3				8			
9	32	x⇌t		4				9			
340	43	RCL		5				0			
1	05	5		6				1			
2	77	2nd x≥t	SKIP (conditional)	7				2			
3	45	y^x		8				3			
4	25	CLR		9				4			
5	42	STO		0				5			
6	05	5		1				6			
7	76	2nd Lbl		2				7			
8	85	+		3				8			
9	92	INV SBR		4				9			
350	76	2nd Lbl	SKIP (conditional)	5				0			
1	45	y^x		6				1			
2	61	GTO		7				2			
3	85	+		8				3			
4	76	2nd Lbl	SKIP (conditional)	9				4			
5	25	CLR		0				5			
6	01	1		1				6			
7	44	SUM		2				7			
8	64	64		3				8			
9	61	GTO		4				9			
360	78	2nd Σ+		5				0			
1	76	2nd Lbl	If internal gains/	6				1			
2	34	√x	month = 0	7				2			
3	53	(	then December	8				3			
4	43	RCL	and January	9				4			
5	26	26	values are	0				5			
6	85	+	used.	1				6			
7	43	RCL		2				7			
8	59	59		3				8			
9	54	)		4				9			
370	42	STO		5							
1	66	66		6							
2	06	62	number of days	7							
3	02		in December	8							
4	42	STO	and January.	9							

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APPENDIX C ~ GLARE CONSTANT NOMOGRAM

Procedure: Draw a line on figure 2.40 from the source luminance (Bs) on Scale 1 to the source solid angle(ω) on Scale 2; through the intersection of this line on Scale 3 draw a line from the surround luminance (B6) on Scale 4 to meet Scale 5, which gives the glare constant for a source displaced 10° vertically above the direction of view. For any other source displacement determine the position factor (p) from Table 2.13, then draw a line between the glare constant on Scale 5 to the position factor on Scale 6: the glare constant modified for source position is given by the intersection of this line on Scale 7.

Sky component (C.I.E. overcast sky) = Sky component (uniform sky) × *Z*-factor, where the *Z*-factor corresponds to the average angle of elevation (θ) of the relevant area of sky

$\theta°$	Z	$\theta°$	Z	$\theta°$	Z
0	0·429	30	0·857	60	1·170
1	0·444	31	0·870	61	1·178
2	0·458	32	0·882	62	1·185
3	0·473	33	0·895	63	1·192
4	0·488	34	0·908	64	1·198
5	0·503	35	0·920	65	1·205
6	0·518	36	0·932	66	1·212
7	0·533	37	0·944	67	1·218
8	0·548	38	0·956	68	1·224
9	0·563	39	0·968	69	1·229
10	0·578	40	0·980	70	1·234
11	0·592	41	0·991	71	1·239
12	0·606	42	1·002	72	1·244
13	0·621	43	1·013	73	1·248
14	0·636	44	1·024	74	1·252
15	0·650	45	1·035	75	1·256
16	0·664	46	1·045	76	1·260
17	0·679	47	1·055	77	1·264
18	0·694	48	1·065	78	1·267
19	0·708	49	1·075	79	1·270
20	0·722	50	1·085	80	1·272
21	0·736	51	1·095	81	1·275
22	0·750	52	1·104	82	1·277
23	0·763	53	1·113	83	1·279
24	0·777	54	1·122	84	1·280
25	0·791	55	1·131	85	1·282
26	0·804	56	1·139	86	1·283
27	0·818	57	1·147	87	1·284
28	0·831	58	1·155	88	1·285
29	0·844	59	1·163	89	1·286
				90	1·286

Table 2.11. Table of sky luminance ratios[41].

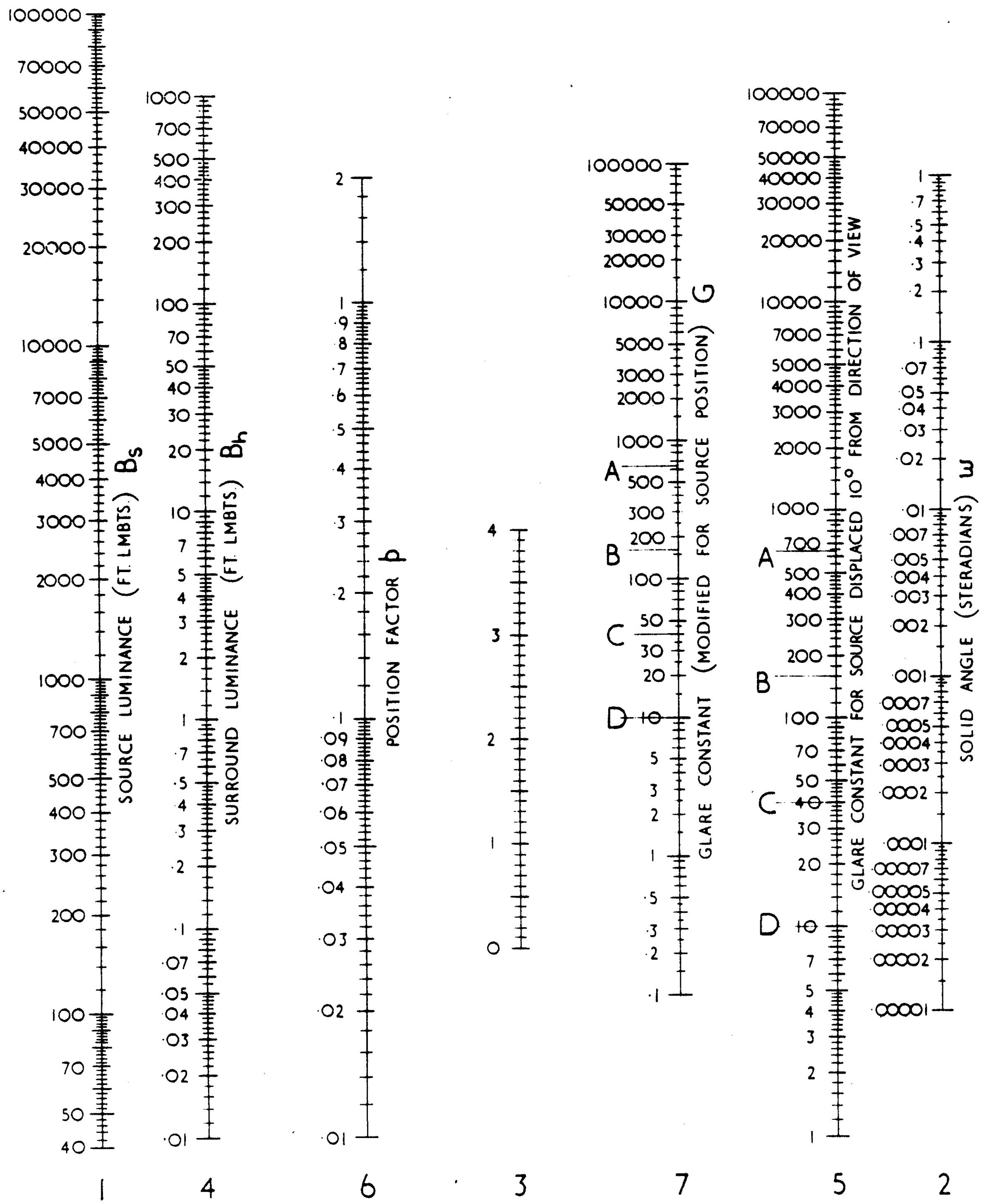

Fig. 2.40. The Building Research Station's Glare Constant Nomogram (Ref. 41).

Scale 1:

Sky luminance is found by means of the following two equations:

$$Bs = L \times Z \times t \qquad (33)$$

Where Bs = the sky luminance.
L = 500 ft-L (Standard Overcast Sky).
Z = the CIE sky luminance ratio or Z-factor. This is dependant on the angle of elevation (eqn(34)) and is obtained from Table 2.11.
t = the transmittance of the glaring material to diffuse radiation - assumed to be .85 regardless of material.

$$E = \arctan (V/R) \qquad (34)$$

Where E = the angle of elevation.
V = the vertical distance from eye level to the centre of the glare source (not necessarily the centre of the window because any buildings obstructing the view of the sky will not form part of the glare source).
R = the horizontal distance from the viewer to the window plane.

Scale 2:

The solid angle (ω) subtended by the glare source is found by the following equation:

$$\omega = A/d^2 \qquad (35)$$

Where ω = the solid angle subtended by the glare source (steradians)
A = the area of the glare source (not the window area) (ft^2).
d = the horizontal distance from the observer to the window plane (ft).

However, if the window is displaced from the line of sight, then the solid angle is obtained from equation(36):

$$\omega = \frac{A \times \cos\theta \times \cos \phi}{d^2} \qquad (36)$$

Where ω = the solid angle subtended by the glare source.
A = the area of the glare source.
θ = the azimuth angle of displacement of the centre of the glare source from the line of sight.
ϕ = the altitude angle of displacement of the centre of the glare source from the line of sight.
d = the horizontal distance from the observer to the window pane.

Scale 4:

The surround luminance is found by means of the following equation:

$$Bb = 5 \times (IRC\ \%)$$

Where Bb = the surround luminance
5 = the condition for a 500 ft-Lambert sky.
IRC% = the Internally Reflected Component percent.

The Internally Reflected Component percent (IRC %) needed for this equation will have to be determined by the long method if the ceiling is being used as the target area, since all the tables and monograms available for quick calculations assume light colored ceilings.

The magnitude of the IRC is dependent on the average reflectance of all the room surfaces. The IRC is not uniform throughout the room, it reduces as one moves away from the window. The Split-Flux Principle, introduced by Hopkinson, Petherbridge and Longmore, based on the theory of the integrating sphere, is a well accepted method for determining the IRC. It does have certain inherent errors because the room is not a sphere, but these are largely compensated for by empirical corrections. Equation (38) is used to determine the IRC by a Building Research Station (BRS) approximation of the first reflected flux (Fig. 2.41).

$$IRC\% = \frac{0.85 \times W}{A(1-R)} (CRfw + 5\ Rcw) \qquad (38)$$

Where IRC% = the Internally Reflected Component percent.
W = the area of glazing material.
A = the total area of all internal surfaces of the room (including the window).
R = the average reflectance of all the surfaces in the room (including that of the windows, assumed to be 15% - the average reflectance is obtained from eqn (39)).
C = a function of the sky luminance distribution and the obstruction angle of any exterior building (measured from the centre of the window), taken from Table 2.12.
Rfw = the average reflectance of the floor and those parts of the walls below the plane of mid-height of the window (not including the window wall).
Rcw = the average reflectance of the ceiling and those parts of the walls above the plane of mid-height of the window (not including the window wall).

In this equation R is determined by the method shown below in equation (39).

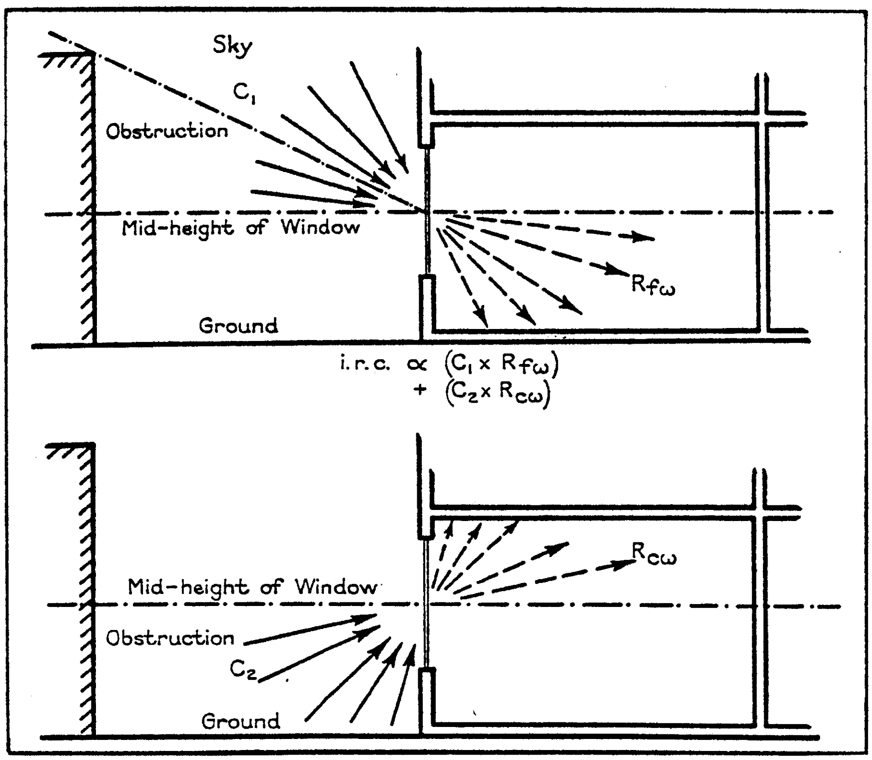

Fig. 2.41. The 'split-flux' principle applied to the calculation of the Internally Reflected Component(Ref.41).

Angle of obstruction measured from centre of window (degrees above horizontal)	C
0 (no obstruction)	39
10	35
20	31
30	25
40	20
50	14
60	10
70	7
80	5

Table 2.12. Variation of the function C with angle of obstruction[41] for use with eqn(38).

$$R = ((R_1 \times A_1) + (R_2 \times A_2)......+(Rn \times An))/A_{TOTAL}$$

Where R = the average reflectance of all the surfaces in the room (including the window).
R_1 = the reflectance of component 1.
A_1 = the area of component 1.
A_{TOTAL} = the total area of all the room surfaces (including the window).

The assumptionsin Table 2.12 are that there is a CIE standard overcast sky, ground and buildings have a luminance of 10% of that of the average sky luminance, obstructions are assumed to be infinitely long and parallel to the window wall and with a horizontal outline, and that the glazing has a .85 transmittance to diffuse solar radiation.

Equation (38) will need to be adjusted to account for the effect of reflecting louvres if they are being used.

Figure 2.42 is a correcting graph to find the minimum IRC as a ratio to the average IRC. It assumes a ceiling reflectance of 70% which is incorrect for a passively heated building with a ceiling target. However, it can be used to give approximate results if one assumes the ceiling to be the floor.

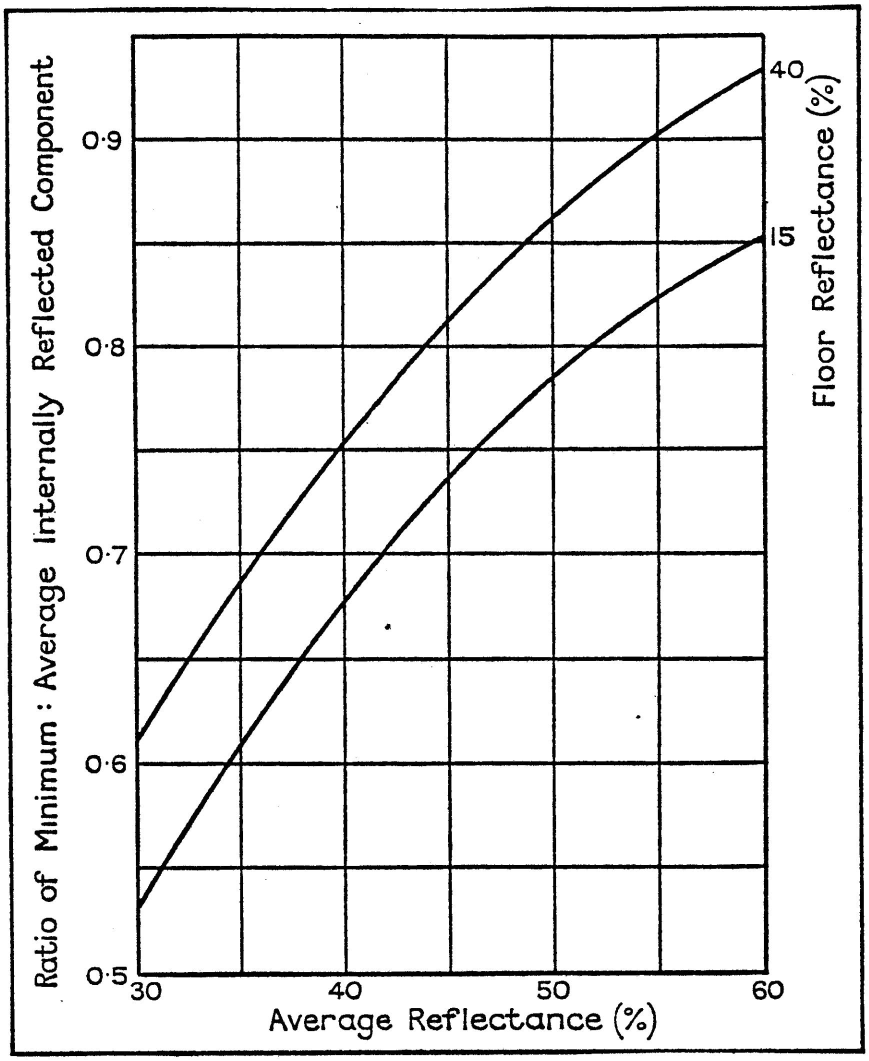

Fig. 2.42. The variation of the ratio minimum/average IRC with average reflectance of room interior. (Applicable to rooms having a ceiling reflectance of 70% approx.) (Ref. 41).

<u>Scale 6</u>:

The glare source position factor (p) is found from Table 2.13 using the vertical and horizontal displacement of the centre of the glaring part of the window from the horizontal line of vision.

Vertical displacement (V/R) \ Horizontal angle ($\phi = \tan^{-1} L/R$)	0°	6°	11°	17°	22°	27°	31°	35°	39°	42°	45°	50°	54°	58°	61°	63°	68°	72°	Vertical angle ($\theta = \tan^{-1} V/R$)
1·9	—	—	—	—	—	—	—	—	—	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	62°
1·8	—	—	—	—	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	0·02	61°
1·6	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	0·03	58°
1·4	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·04	0·03	0·03	54°
1·2	0·05	0·05	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·06	0·05	0·05	0·05	0·05	0·04	0·04	0·04	50°
1·0	0·08	0·09	0·09	0·10	0·10	0·10	0·10	0·09	0·09	0·09	0·08	0·08	0·07	0·06	0·06	0·06	0·05	0·05	45°
0·9	0·11	0·11	0·12	0·13	0·13	0·12	0·12	0·12	0·12	0·11	0·10	0·09	0·08	0·07	0·07	0·06	0·06	0·05	42°
0·8	0·14	0·15	0·16	0·16	0·16	0·16	0·15	0·15	0·14	0·13	0·12	0·11	0·09	0·08	0·08	0·07	0·06	0·06	39°
0·7	0·19	0·20	0·22	0·21	0·21	0·21	0·20	0·18	0·17	0·16	0·14	0·12	0·11	0·10	0·09	0·08	0·07	0·07	35°
0·6	0·25	0·27	0·30	0·29	0·28	0·26	0·24	0·22	0·21	0·19	0·18	0·15	0·13	0·11	0·10	0·10	0·09	0·08	31°
0·5	0·35	0·37	0·39	0·38	0·36	0·34	0·31	0·28	0·25	0·23	0·21	0·18	0·15	0·14	0·12	0·11	0·10	0·09	27°
0·4	0·48	0·53	0·53	0·51	0·49	0·44	0·39	0·35	0·31	0·28	0·25	0·21	0·18	0·16	0·14	0·13	0·11	0·10	22°
0·3	0·67	0·73	0·73	0·69	0·64	0·57	0·49	0·44	0·38	0·34	0·31	0·25	0·21	0·19	0·16	0·15	0·13	0·12	17°
0·2	0·95	1·02	0·98	0·88	0·80	0·72	0·63	0·57	0·49	0·42	0·37	0·30	0·25	0·22	0·19	0·17	0·15	0·14	11°
0·1	1·30	1·36	1·24	1·12	1·01	0·88	0·79	0·68	0·62	0·53	0·46	0·37	0·31	0·26	0·23	0·20	0·17	0·16	6°
0	1·87	1·73	1·56	1·36	1·20	1·06	0·93	0·80	0·72	0·64	0·57	0·46	0·38	0·33	0·28	0·25	0·20	0·19	0°
Lateral displacement (L/R)	0	0·1	0·2	0·3	0·4	0·5	0·6	0·7	0·8	0·9	1·0	1·2	1·4	1·6	1·8	2·0	2·5	3·0	

V = vertical distance from horizontal line of vision
L = lateral distance from horizontal line of vision
R = horizontal distance from eye of observer

Table 2.13. Position factor p[41].

The glare constant is then found. If there are more than one window, the sum of the glare constants replaces the glare constant in equation (32) (Appendix A).

APPENDIX D ~ DATA BASES

I. OVERHEATING PROGRAM - DATA BASES.

The following data bases were collected for the solar design (Fig. 3.4), using the sequence suggested in the Workbook (Ch II, 1 m).

1. The area of collection window.

Both collection rooms have a south glazed area of 4.9 m^2. This area does not include frames.

2. The noon target area.

On 21st October at a latitude of 52°N the profile angle of the sun at noon is 27°.

Thus $$p = \frac{H}{\tan P}$$ (Ch II, 1 k (ii))

Where p = the depth of penetration of the sunlight.

H = the height of the window.

P = the profile angle at noon.

the depth of penetration is 1.4 m on October 21st.

The noon target area is thus 10.6 m^2 (p x width of room).

3. The percent of noon target area hit on each of the eight hours modeled.

Hour of day	9	10	11	12	13	14	15	16
% target area illuminated	.25	.42	.73	1.	.73	.42	.25	.15

Table 3.4. Percent of target hit (Ch II, 1 k(ii)).

4. The horizontal component of the energy gains for each hour modeled.

Time of Day	9	10	11	12	13	14	15	16
Horizontal Component (W/m^2)	204	317	383	401	383	317	204	82

Table 3.5. The horizontal component of the solar energy gains on a clear day in October through two layers of glass and one layer of heat mirror (by Suntek) (Ref 10).

The figures in Table 3.5 are obtained by reducing reference data[10] for a clear day on a vertical south facing surface, by a dirt factor and by the transmittance of the transparent membrane. The transmittance is found producing a graph similar to that in Figure 2.33 for the transparent membrane used, and by finding the angle of incidence of the sun from the sun angle calculator (p. 34).

5. The vertical component of the solar gains for each hour modeled. These are obtained by multiplying the horizontal components (Table 3.5) by the tangent of the profile angle. The profile angle for all hours of the day are taken to be that of the noon profile angle so that during program execution the total energy intake is not reduced from its true value.

Time of Day	9	10	11	12	13	14	15	16
Vertical Component (W/ sq m)	104	162	195	204	195	162	104	42

Table 3.6. The vertical component of the solar energy gains per hour on a clear day in October (52^{o}N lat).

6. The density and specific heat of the target.

The target is considered to be concrete for the purposes of the design method calculations. This is because the design method does not model latent heat storage materials. A rule of thumb is then applied to the air temperature results (Ch II, 1 j).

Density = 2243 kg/m^3

Specific Heat = 0.837 kJ/kg^{o}C

7. The volume of the noon target area.

The target is assumed to be 150mm thick. Therefore the volume is 1.6m^3.

8. The average u-value x the area of the weatherskin.

A detailed breakdown of the fabric losses is listed in the following section of this appendix (Tables 3.31 and 3.32). It is seen, in Table 3.32, that the heat loss/hour^{o}C is 61.8 Watts.

Area of weatherskin = 162.12m^2

Average U-value = 61.8/162.12 = .38 W/m^2 ^{o}C

And average U-value x area = 61.8 Watts/ ^{o}C

9. The volume of air change per hour.

This is .93 x the volume of air in the dwelling (p.197).

= .93 x 258.95 = 240.8m^3

10. U-value and area of suspended floor

The heat losses from the solid floor are assumed to be negligible, because it is well insulated. The u-value of the suspended floor = 0.16 (p.193).

The area of the suspended floor is $42.1m^2$.

11. The resistance split fraction for the target.

As in the example shown on p.   (Ch II, 1 j), the resistance split is 0.54.

12. The hourly gains from people, appliances and other windows for each of the 8 hours modeled.

a. Gains from people and appliances.

The following values (Table 3.7) are taken from a comparison of the data shown in Figure 2.36 and Table 2.9 (p.   ).

Time of day	9	10	11	12	13	14	15	16
Gains(W)	200	200	200	1499	1499	200	200	200

Table 3.7. Hourly gains from people and appliances in a typical English dwelling.

b. Gains from other windows.

The results of the solar interference boundary tests (as shown in Fig. 3.8 and Table 3.17 on p.188) are used to determine this information. Clear day insolation figures are taken directly from the reference tables[10] and reduced in the same way as in Step 4 above.

Time of Day	9	10	11	12	13	14	15	16
South Windows	48	38	30	27	30	38	48	60
East Windows	46	61	76	-	-	-	-	-

Table 3.8. The angles of incidence of the sum at the two vertical orientations being considered (October 21st, 52^oN. Lat.), taken from the sun angle calculator.

Time of Day	9	10	11	12	13	14	15	16
South Windows	.53	.59	.6	.6	.6	.59	.53	.42
East Windows	.55	.41	.18	.47*	.47*	.47*	.47*	.47*

Table 3.9. The resulting transmittance values of double glazing with a layer of double sided heat mirror (by Suntek) between (October 21st, 52°N Lat.). Values marked with an asterisk are for diffuse radiation only.

Time of Day	9	10	11	12	13	14	15	16
Solar Gains(W)	987	1751	2174	2289	1149	856	464	200

Table 3.10 Clear day solar gains through all windows other than the windows in the collection rooms.

c. The resulting total internal gains.

Time of Day	9	10	11	12	13	14	15	16
Gains(W)	1187	1951	2374	3788	2648	1055	664	399

Table 3.11. The total internal gains from people, appliances and solar energy, other than the solar gains within the collection rooms.

13. The hourly outdoor temperature for each of the 8 hours modeled.

Time of Day	9	10	11	12	13	14	15	16
Temperature °C	11.5	12.4	13.2	13.8	14.3	14.5	14.4	14.0

Table 3.12. Mean hourly outdoor temperatures in England in October (Ref. 46).

14. The morning internal start temperature.

18.3°C.

15. The temperature of the ground.

In this case it is the temperature of the cellar = 10°C.

16. The night gains from people and appliances per hour.

This is assumed to be 293 Watts/hour.

17. The average room air temperature at night.

The typical night time temperature in an English dwelling is 15.6°C.

18. The average outdoor temperature at night.

10.5°C (Ref. 46).

19. The hourly gains from the east window in the lower collection room. Window E4 (Fig. 3.8 p.188) is assumed to be furnished with a solar modulator.

Time of Day	9	10	11	12	13	14	15	16
Gains through E4	276	247	70	57	54	50	34	19

Table 3.13. Hourly solar gains through window E4 (Fig.3.8).

20. The coefficients for the solar gains through the east window (E4).

This coefficient is a product of the resistance split into the the target and the percent being reflected off the solar modulators. In the morning the value of this coefficient is .49 (.54 x .9), but in the afternoon it reduces to .24 because all the radiation is diffuse and only an estimated 50% of this will be reflected in the direction of the target.

Time of Day	9	10	11	12	13	14	15	16
Coefficient	.49	.49	.49	.34	.24	.24	.24	.24

Table 3.14. Coefficients for the solar gains through window E4 (Resistance split x % reflected off solar modulators).

21. The area and thickness of the secondary thermal mass. This is not a requirement for the design program but it is used to correct the air temperature fluctuations results provided by the program. In the playroom the area of secondary thermal mass is $18.8m^2$ which is about 1.75 times the noon target area. It has an approximate thickness of 150mm. The area and volume of secondary thermal mass in the dining room will be about the same. In this room there is no end wall but the brick paved floor compensates for this.

22. The area and volume of the convective thermal mass.

Area = $160m^2$

Volume = $18.94m^3$

23. The specific heat and density of the convective thermal mass.

Specific Heat (brick) = 0.837 kJ/kg ^oC

Density (brick) = 1970 kg/m^3.

II COST BENEFIT PROGRAM - DATA BASES

The following data bases were collected using the sequence suggested in Appendix B, relating to the Cost Benefit Program:

1. Mean daily outdoor temperature for each month.

Month	Mean Daily Temperature(°C)
January	4.0
February	4.9
March	6.8
April	9.4
May	12.5
June	15.9
July	16.9
August	16.5
September	14.7
October	11.8
November	7.5
December	4.9

Table 3.15. Mean daily outdoor temperature for each month of the year at Kew, London (Ref. 46).

2. Number of days in each month.

   January 31, February 28, etc.

3. The internal gains per month.

   a. Solar gains.

      Graphic solar interference boundary tests (Ch II, 1d(i)) revealed that only in December do the row houses at the opposite end of the garden obscure the sun. The sun is obscured in December for one hour at either end of the day (Fig. 3.7).

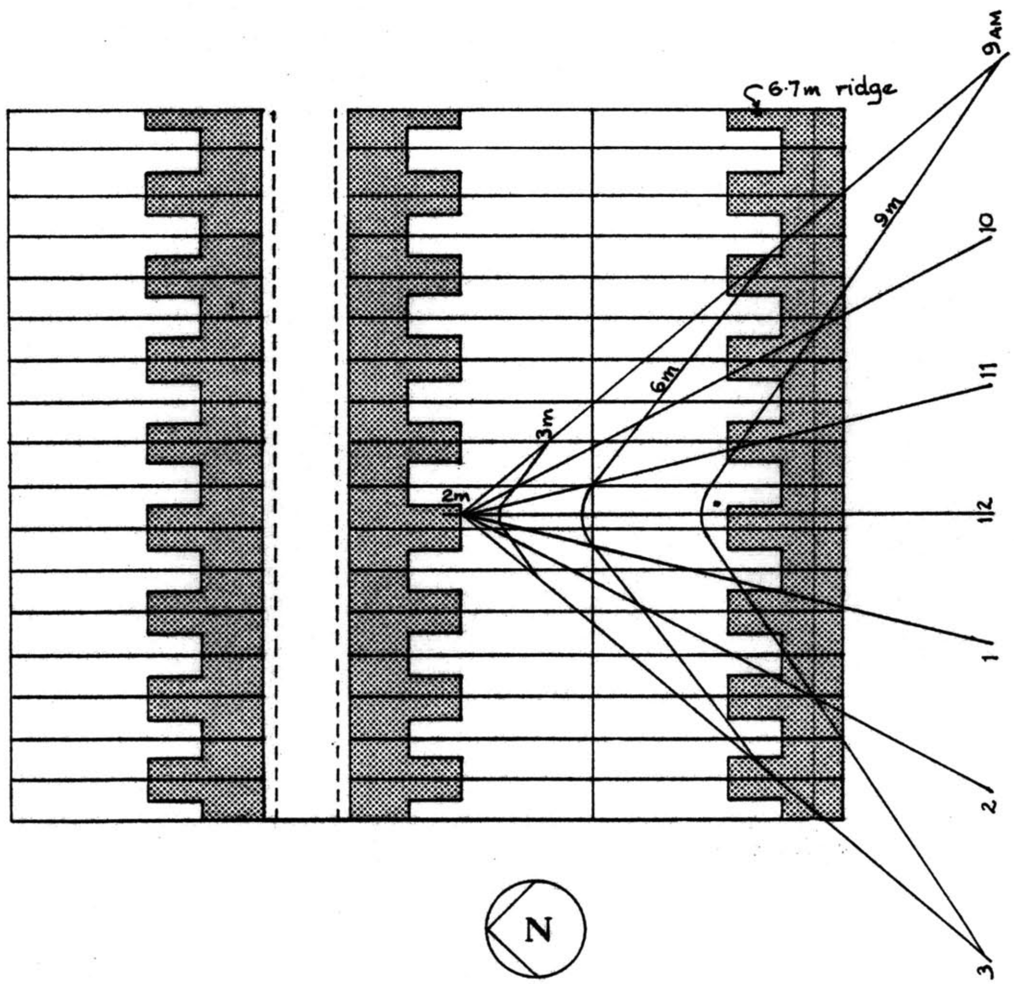

Fig.3.7. December 21st solar interference boundary graph on assumed site plan shows the sun being obscured for almost an hour either end of the day. Scale 1:100; 52°N lat.

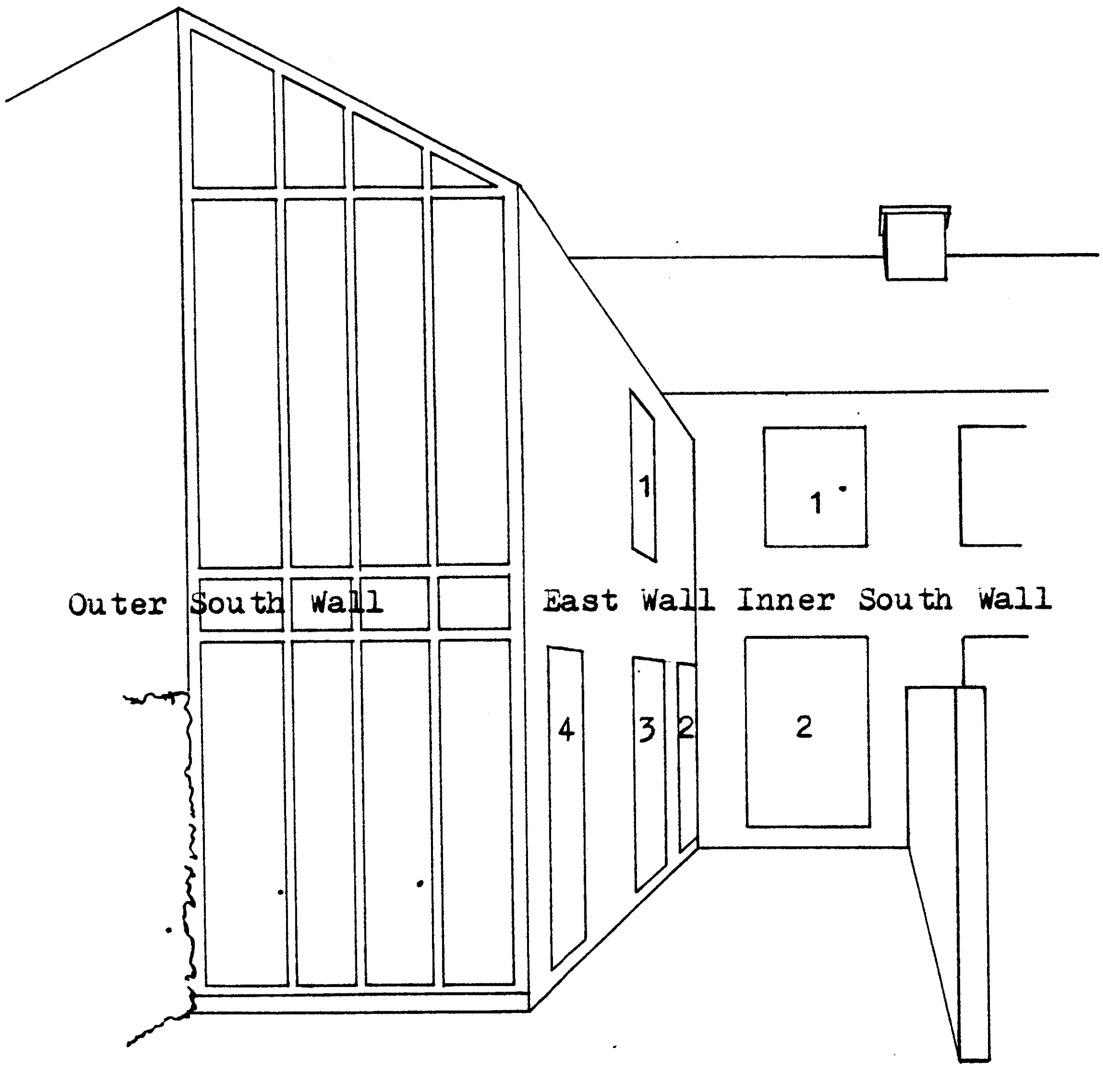

Fig. 3.8. Solar design. Perspective view.

Symbol	Meaning
Sun	Area in potential sunshine
Shade	Area in shade
OS	Outer South Wall
IS	Inner South Wall
E	East Wall

Table 3.16. Key to the symbols used in Table 3.17.

Window # (Fig3.8)	Area of Window(s) including frames	State	Time of Day							
			9	10	11	12	13	14	15	16
OS1	11.6 + 1.5= 13.1	Sun	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
North	5.0	Shade	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
IS1	2.1	Sun	1.3	2.1	2.1	2.1	2.1	1.2	0.8	0.5
		Shade	0.8	0.0	0.0	0.0	0.0	0.9	1.3	1.6
IS2	3.7	Sun	0.0	1.7	3.6	3.7	0.2	1.4	0.0	0.0
		Shade	3.7	2.0	0.1	0.0	3.5	2.3	3.7	3.7
E1	1.4	Sun	1.4	1.4	1.4	0.0	0.0	0.0	0.0	0.0
		Shade	0.0	0.0	0.0	1.4	1.4	1.4	1.4	1.4
E2	1.9	Sun	0.0	1.5	1.9	0.0	0.0	0.0	0.0	0.0
		Shade	1.9	0.4	0.0	1.9	1.9	1.9	1.9	1.9
E3	2.7	Sun	1.3	2.1	2.7	0.0	0.0	0.0	0.0	0.0
		Shade	1.4	0.6	0.0	2.7	2.7	2.7	2.7	2.7
E4	2.1	Sun	1.1	1.7	2.1	0.0	0.0	0.0	0.0	0.0
		Shade	1.0	0.4	0.0	2.1	2.1	2.1	2.1	2.1

Table 3.17. Solar Design. An example of the data drawn up for each month (and for both the solar and non-solar designs) of the areas of each window in shade or in potential sunshine from combined computer and graphic solar interference boundary tests. The results displayed here are for the solar design in January and November. The methods of testing are described in the Workbook (Ch.II,1,d,(i) and (iii)).

Vertical Orientation	Time of Day							
	9	10	11	12	13	14	15	16
South	290	430	545	580	545	430	255	35
North	30	40	50	55	50	40	25	5
East	285	225	180	55	50	40	25	5

Table 3.18. Clear day total insolation values (W/m^2) incident on various surfaces, taken from the IHVE guide (Ref. 10). Values are for Jan. and Nov.

Vertical Orientation	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
South	.29	.29	.45	.49	.64	.70	.60	.56	.51	.44	.37	.34
East	.4	.48	.5	.51	.64	.7	.6	.56	.56	.6	.69	.56

Table 3.19. Correction factors to convert clear day insolation values (Table 3.18) to average day insolation values on the same surfaces.

For the South correction factors in Table 3.19 mean monthly insolation values were taken from the results of the Building Research Establishment's computer program of measured values at Kew (London) over the years 1959-1968[47]. For the East correction factors, insolation values were taken from the UK-ISES report[5a]. The methods used to determine these factors are described in the Workbook (Ch II, 1, e, (i)). Both sets of correction factors were checked against the results of the method outlined in eqns.(2) to (6) (p.41), using horizontal insolation values provided by Lacy[46].

The normal transmittance, of the assembly described in Table 3.20, to solar radiation is 60%. The figures shown in Table 3.20 are computed using the information found on figure 2.33 (p.89), a transmittance to diffuse radiation of .47, the

Vertical Orientation	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
South	.59	.57	.51	.39	.39*	.39*	.39*	.39	.51	.51	.58	.59
East	.45	.55	.55	.55	.56*	.56*	.56*	.57	.57	.57	.48	.45

Table 3.20. Solar Design. Average heat gain factors for a window assembly consisting of two layers of glass with a layer of double sided heat mirror (Suntek) between for the English climate (52°N Laf).

horizontal insolation values provided by Lacy[46], and the method outlined in the Workbook (Ch II,1k(i))

Window #	OS1	North	IS1	IS2	E1	E2	E3	E4
Percent of solar radiation not back reflected	.98	.95	.95	.95	.9	.9	.9	.9

Table 3.21. Solar Design. Factors determining the quantity of energy remaining within the dwelling after back reflected losses (Ch II., 1k(i)).

Combining the data provided in Tables 3.17 to 3.21 the monthly solar energy gains can be computed using equation (19) (p.91). This is then multiplied by the number of days in each month and divided by 1000 to give kWh/month.

Month	J	F	M	A	M	J	J	A	S	O	N	D
kWh/mo.	294	388	671	700*	700*	700*	700*	700*	723	552	350	255

Table 3.22. Total solar gains for the solar design in London (52°N lat).

The solar gains through the windows of the non-solar design are computed in precisely the same way as described for the solar design above. However, there are also solar gains through the walls which may be determined using the resistance split method described in the Workbook (Ch II, 1, j).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Solar gains through the walls(kWh/mo)	78	113	234	278	433	493	407	332	250	189	106	74

Table 3.23. Non-Solar Design. Solar gains through the masonry walls (Ch.II, 1, j and k).

Month	J	F	M	A	M	J	J	A	S	O	N	D
kWh/month	242	328	431	550	720	700*	700*	700*	449	328	201	201

Table 3.24. Non-Solar Design. Solar gains through the windows.

b. Gains from people and appliances.

Month	J	F	M	A	M	J	J	A	S	O	N	D
kWh/month	744	672	698	600	543	450	465	543	600	698	720	744

Table 3.25. Heat gains per month from inhabitants and appliances (Table 2.9, p. 98).

c. Total incidental heat gains per month.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Solar design kWh/month	1038.4	1059.6	1368.6	1300	1242.5	1150	1165	1242.5	1322.9	1249.8	1070.4	999.1
Non-solar design kWh/month	1064.1	1113	1363	1428.8	1695.7	1642.8	1572.2	1574.2	1298.8	1214.3	1026	1019.5

Table 3.26. Solar and Non-solar Designs. Total incidental heat gains per month from inhabitants, appliances and solar energy (combined information from Tables 3.22 and 3.25, and from Tables 3.23, 3.24 and 3.25).

d. Constant heat losses to the cellar.

The cellar is assumed to be at a constant temperature of 10°C throughout the year. Thus the heat losses to the cellar can be determined and set directly against the total incidental heat gains to give a resulting net heat gains per month which is then used in the Cost Benefit Program.

Design	Layer	Depth (m)	k	R	ΣR	U-value $W/m^2{}^oC$
Solar	Int. air film (Rsi)			.149	6.38	0.16
	Carpet	.007	.055	.127		
	Underlay	.007	.1	.07		
	Wood	.025	.15	.17		
	Fiberglass insulation	.2	.035	5.71		
	Ext. air film (Rso) (= Rsi)			.149		
Non-solar	Rsi			.149	.665	1.5
	Carpet	.007	.055	.127		
	Underlay	.007	.1	.07		
	Wood	.025	.15	.17		
	Rso (= Rsi)			.149		

Table 3.27. Solar and Non-solar designs. Computation of the U-values of the suspended floor.

The resulting heat losses per hour are calculated using the standard equation:

Heat loss = Area x U-value x Δt

Where Δt is the temperature difference between the two surfaces. The average indoor temperature in an English dwelling is 18^{o}C. Thus Δt is 8^{o}C and the heat losses per month are computed. The area of suspended floor is 42.1m^2.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Heat losses to cellar	40	36	40	39	40	39	40	40	39	40	39	40

Table 3.28 Solar design. Heat losses per month to the cellar (kWh/mo).

Month	J	F	M	A	M	J	J	A	S	O	N	D
Heat losses to collar	376	339	376	364	376	364	376	376	364	376	364	376

Table 3.29 Non-solar design. Heat losses per month to the cellar (kWh/mo).

Design Type	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Solar	998.4	1023.6	1328.6	1261	1202.5	1111	1125	1202.5	1283.9	1209.8	1031.4	959.1
Non-Solar	688.1	774	987	1064.8	1319.7	1278.8	1196.2	1198.2	934.8	838.3	662	643.5

Table 3.30 Solar and non-solar designs. Resulting net heat gains (combined values of Tables 3.26, 3.28 and 3.29.

4. The heat loss per day ^{o}C.

a. Fabric losses.

Fabric losses for both the solar and non-solar designs are computed using equation (8) (p.45). Reference was made to the IHVE guide[21], the A. J. Metric Handbook[14] and the B.R.E. digest 108[17] for the values shown in Table 3.31.

Component	Layer	Thickness(m)	Conductivity	Resistance ($m^2 {}^oC/W$)	R_{total}	U-value ($W/sq.m^oC$)
Roof	Rsi(internal air film)			0.106	4.534	0.22
	Plaster	0.016	0.50	0.032		
	Fibreglass	0.15	0.035	4.29		
	Rso(external air film) still air			0.106		
Trash door	Rsi			0.123	3.776	0.26
	Wood	0.04	0.15	0.27		
	Cavity			0.18		
	Expanded polystyrene	0.1	0.033	3.03		
	Wood	0.013	0.15	0.093		
	Rso			0.08		
Front door	Rsi			0.123	0.533	1.88
	Wood	0.05	0.15	0.33		
	Rso			0.08		
Walls	Rsi			0.123	3.83	0.26
	Plaster	0.016	0.5	0.032		
	Brick	0.205	0.54	0.38		
	Expanded polystyrene	0.1	0.033	3.03		
	Cavity			0.18		
	Rso			0.08		
Windows	Rsi Glass Cavity Double sided heat mirror Cavity Glass Rso		Measured U-value (Suntek)			0.85

Table 3.31. Solar Design. Determining the U-values of the weatherskin components.

Component	Area (m^2)	U-Value ($W/m^2\ ^oC$)	AXU
Roof	63.08	0.22	13.88
Trash door	0.63	0.26	0.16
Front door	2.24	1.88	4.21
Walls	65.85	0.27	17.78
Windows	30.32	0.85	25.77
Totals	162.12		61.8

Table 3.32. Solar design. Determining the fabric heat loss per hour ^oC of the dwelling.

Thus the heat loss per hour ^oC through the weatherskin of the solar design dwelling is 61.8 watts. The heat loss per day ^oC is determined by multiplying this by 24 (hours in the day) and dividing by 1000 to give kWh/day ^oC. Exactly the same process is done for the non-solar design to obtain the results shown in Table 3.33. The water table is well below ground level in most parts of London[49] and thus will have no bearing on the heat losses from the solid floor of either design.

Component	Area (m^2)	U-Value ($W/m^2\ ^oC$)	AXU
Solid Floor	20.98	0.9	18.88
Roof	63.08	0.61	38.48
Trash Door	0.63	1.34	0.84
Front Door	2.24	1.88	4.21
Sandtexed N. Wall	22.36	1.63	36.45
All other walls	44.64	1.94	86.6
Windows	29.24	4.8	140.35
Totals	183.17		325.81

Table 3.33. Non-solar design. Determining the fabric heat loss per hour ^oC of the dwelling.

b. Infiltration

Equation (8) (p. 45) is used to determine infiltration losses also. See the section of the Workbook on "Infiltration" (Ch II, 1, i) for an explanation of the data bases used in Table 3.34.

Dwelling Type	Basic Air Change	Inhabitant Caused Air Change	Total
Solar design	.18*	.75	.93
Non-solar design	1.5	.75	2.25

Table 3.34. Solar and non-solar designs. The number of air changes per hour.

c. Fabric + Infiltration Losses

Volume of both buildings = 258.95 m^3

Dwelling Type	Heat loss/day °C
Solar design	2.897
Non-solar design	10.562

Table 3.35. Solar and non-solar designs. The resulting heat loss/day °C (kWh/day °C)

5. Degree Day Table

Table 2.14 (p.125) is drawn up using the methods outlined in the "Heating Load" section of the Workbook (Ch II, 1, f).

6. Costing

The following is an outline of how the costs were broken down. Wherever possible Spons[48] was used as a reference

* Attainable when dwelling unoccupied.

for these figures; otherwise prices were obtained from local (Boston) firms and converted directly to pounds using a conversion factor of $1.7 to £1.

COSTING

Component & Breakdown	Assumed Cost(£)/unit
Perimeter Insulation	
Hand digging trench/m^3	4.12
75mm expanded polystyrene insulation/m^2	1.06
Backfilling trench; depositing and compacting in layers/m^3	1.82
Polythene flashing over perimeter insulation (300mm wide) plus labor/m^2	1.00
Evostik 863 for expanded polystyrene application to brickwork/litre	0.75
Labor/hr	1.60
Roof	
Additional 100mm polythene faced fibreglass insulation (excluding duct). No labor charge/m^2	1.38
Roof Duct	
Timber framing: Worked timber/m^3	70.00
@ 40 man hours/m^3 of timber labor/hr.	1.66
Plasterboard and taping: cut and fixed in place/m^2	0.38
@ ½ an hour/m^2 labor/hour	1.66
Insulation: 150mm polythene faced fibreglass/m^2	2.22
Fan and Motor	
1/3 H.P. delivers 1000 cfm @ 5/8" pressure - 9½" diam. wheel	38.69
Running cost for 25 years at £5/year present value	88.20
Cutting opening through into roof/opening	.70
Grille to opening into playroom plus labor/grille	6.04
Suspended Floor	
200mm polythene faced fibreglass insulation plus labor/m^2	2.90

Component & Breakdown	Assumed Cost(£)/unit
N. Wall	
100mm expanded polystyrene sheets 2 X 50mm/m^2	1.42
Lattice timber framing in 50 X 50 studs plus labor/m^2	1.13
Vinyl faced cladding installed with foil backing plus rain collection plus roof flashing to gutter, optional extras/m^2	10.00
Saving on Sandtex finish @£.74/m^2 and every four years - over 25 years present value/m^2	2.91
N. Window to Utility Room	
Remove window/window	3.50
Insert kitchen window into opening, block out in timber and plasterboard plus finish with plaster and paint including labor/window	19.06
E. Walls	
Timber framing, polystyrene insulation and foil backed vinyl faced aluminum cladding plus labor/m^2	12.55
Saving on partial repointing @£1.69/m^2 done now and in 10 and 20 years. Present value/m^2	3.87
S. Walls	
Framing + insulation + cladding + foil + labor and rainwater + roof extras/m^2	12.55
Saving on repointing, 25 yr. present value/m^2	3.87
N. Windows	
Weather stripping/window	1.76
Storm windows installed/m^2	30.00
Double sided heat mirror installed/m^2	6.00
Saving of £2 maintenance on each window after 1st four years and then every four years. 25 year present value/window.	5.88

Component & Breakdown	Assumed Cost(£)/unit
Doors	
Weather stripping front door/door	3.53
Weather stripping trash door/door	1.50
Insulating trash door with 100mm expanded polystyrene	1.70
Heating Grilles	
Cutting out for grilles/m^2	4.6
Control grilles/m^2	13.89
Weatherstripping/window	1.76
Solar Modulators/m^2	10.85
Saving on curtains and fixings over same windows and others; present value over 25 yrs/m^2	21.70
PCM Tiles	
Cost of tiles/m^2	15.74
Fixing/m^2	4.00
Saving on preparing and finishing ceilings present value over 25 yrs/m^2	3.27
Living-room Window	
Cost of double glazed french doors with heat mirror between/m^2	50.00
Saving on non-solar lounge window/m^2	30.00
Saving on removing wall/m^2	7.20
Saving on quoining up/m	8.35
Saving on plastering/m	4.00
Saving on lintol and strutting + needles and shores	105.15
Bedroom Window	
Weatherstrip/window	1.76
Storm + heat mirror/m^2	36.00
Save on maintenance over 25 yrs/window	5.88
E2	
Double glass + double heat mirror-fixed/m^2 minus proposed in non-solar design	30.00
E3	
Double glared french doors + double heat mirror/m^2 minus proposed in non-solar design	36.00

Component & Breakdown	Assumed Cost(£)/unit
E4	
One layer glass + double heat mirror fixed/m^2	30.00
E1	
Storm + heat mirror/m^2	36.00
Saving on maintenance as on N. windows/window	5.88
South Main Window	
Double special casement + double heat mirror/m^2	81.30
Saving on dining room window/m^2	30.00
Wall removed/m^2	7.20
Salvage on playroom window	4.00
Quoining up/m	8.35
Plastering/m	4.00
Save on maintenance of playroom window and re-pointing of removed wall	26.05
Save on shoring + lintol + needles	105.15
Remove.wall above playroom window/m^2	7.20
Frame up area above playroom window/m^2	25.00
Handrail	
Worked softwood/m	5.00
Playroom	
Facing and plastering end of floor	6.00
Heating	
Saving on central heating system	1100.00
4 storage radiators	200.00
Garden Wall	
Remove garden wall/m^2	2.65
Quoin up/m	8.35
Reflector	
Aluminized mylar/m^2	3.00
Receiver at base of window	4.00

The total cost of additional works, over and above those done in the non-solar design, is £1687.51. The value for the area of the improvement within the Cost Benefit Program will be $1m^2$.

7. Costing Variables.

a. Discount rate. 7% (0.07) was taken as a test discount rate for local authority works (Ch.II,3).

b. Fuel spiral rate. 4% (0.04) was chosen as the real increase in the price of heating fuel.

c. Cost of heating fuel. This is assumed to be £0.0115 per kWh of useful heat supplied. The estimation of the cost of North Sea gas is fairly complex. In March 1977 the cost was £0.0114 per kWh of useful energy supplied (60% efficiency) for the first 914kWh of the building's heating load in each quarter. Further gas consumption (unlikely for domestic consumption) will cost £0.0088 per kWh of useful energy consumed. There has been a price increase since March '77.

d. Borrowing period. The system has the same life-span as the building. Therefore the number of years chosen for this variable is the normal time span of a mortgage (25 years).

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