LIVING INSIDE A SOLAR COLLECTOR

T. Yamaguchi
University of Queensland

SUMMARY A computer program : SOUP has been developed for performance prediction of mixed systems with direct-gain and Trombe wall, and is used to analyse the effects of geometries of window and a massive floor-slab on the monthly solar energy absorbed. Design recommendations for geometries of main components in a direct-gain system are given. A simple graphical design tool for a condition in Canberra is produced.

1 INTRODUCTION

Heating buildings using passive solar systems has been attracting the attention of energy-concerned people. Its main features are the simplicity of the system and the art of the harmony of a building with environment.

Even some conventional buildings may owe great benefit from the sun by using the energy for a space heating with direct-gain system, often without the user's notice, if they have the following components:

equator-facing windows, which allow solar radiation to be transmitted into a room as well as the visual role;

massive elements, such as walls and floor-slab, which absorb and store the transmitted solar radiation, then later re-emit heat into the interior.

If architects or solar engineers attempt to design a passive solar heated house, or if a resident intends to reconsider the possibility of his/her house to utilize solar energy for space heating, the following fundamental factors have to be rationalised as the first step:

position of windows on equator-facing wall;
size and proportion of windows;
position of massive elements;
size and proportion of massive elements.

The argument is focused on the situation of massive floor as a collector/storage/emitter for heating, because the system is more general and it may also apply to existing conventional houses to a great extent.

2 COMPUTER SIMULATION PROGRAM FOR PASSIVE HEATING SYSTEM

In the past four years, a number of computer programs have been developed for the prediction of performance of passive solar heating systems in various degrees of sophistication.

The methods range from simple rule-of-thumb aimed at builders and architects as a tool for sketch design stage to highly sophisticated simulation programs to be used by researchers.

Some simple programs use empirical formulae originally derived from a detailed hour-by-hour simulation program, or thermal network method with limited number of nodes and with an assumption that all variables are time-independent. These programs, such as TEANET, PEGFIX(1), PSP(2), do not require much computer memory capacity and they are available on desk-top calculators.

Sophisticated programs such as FREHEAT, PASOLE, SUNSPOT, use thermal network algorithms with 20 to 50 nodes. Since the computer memory required is generally in proportion to the square of the number of nodes, they are primarily developed on main-frame computers, which are usually not available for designers.

Under the current situation, most of designers do not have a direct access to any tools to check and finalize their detailed design yet. To fill the gap between the two types of simulation programs, the SOUP program is developed to do a simulation of passive solar heated buildings on a mini-computer, which is rapidly becoming popular and being used by architects and engineering firms.

SOUP is a user oriented program, particularly designed for mixed systems with massive walls and a massive floor-slab, based on hour-by-hour calculations for one average day in each month. The model of SOUP uses a general thermal network method with maximum of 40 nodes. Fig-1 shows a diagram of the model.

The program is written in FORTRAN for a PDP-11/03 mini-computer using the RT-11 operating system, and the current version requires a computer memory of 24k words using overlaying technique. It may fit on any other mini-computer with minor modifications. Some subroutines of SOUP are primarily implemented from those of the PASOLE program (3), however, SOUP is modified and improved, without losing the sophistication of the original program.

SOUP also considers the thermal capacity of non-massive building components, the effect of both horizontal and vertical shading, and includes the detailed calculation of solar radiation absorbed on massive floor and radiative heat transfer between internal surfaces.

SOUP requires the user to input the following non-environmental data:

1. building orientation;
2. three dimensions of a room;
3. thickness and thermal properties of roof, walls, floor, glazing, night insulation, mass walls and mass floor-slab.
   To allow the effect of the positioning of insulation layer, two thermal resistances of inside and outside of major layer of elements must be input;
4. dimensions of equator-facing windows, massive components;
5. absorptance, reflectance and emittance of internal surfaces;
6. control parameters; room temperature setting, infiltration rate, time of night insulation usage;
7. internal heat generation;
8. the number of nodes in massive elements.

The output format of the results are user controlled and may include graphic output as well as numerics.

The current version of SOUP takes 25 minutes of execution time per month on the PDP-1103, however, the program has an auto-starting facility which allows users to pre-set maximum 10 different alternative designs with arbitrary combinations of parameters per execution of the program. This is suitable for the use of a computer during the night.

3 SOLAR RADIATION ON MASSIVE FLOOR

The method of separating hourly horizontal radiation into beam and diffuse radiation is based on Spencer and Bugler's method (4). Transmittance of glazing is calculated using Fresnel's equation (5).

Beam and diffuse solar radiation (Gbf,Gdf) are calculated as follows:

$$\mathrm{Gbf} = \mathrm{Gbw}\ \mathrm{Asunlit}\ \cos(\mathrm{INC})\ a \qquad [1]$$

$$\mathrm{Gdf} = \mathrm{Gdw}\ \mathrm{Afloor}\ \mathrm{SF}\ a \qquad [2]$$

where

Gbw : beam radiation transmitted through glazing.
Gdw : diffuse radiation transmitted through glazing.
Asunlit : net sunlit area on a given rectangular floor-slab.
Afloor : area of the floor-slab.
INC : incident angle on floor.
a : absorptance of floor surface.
SF : shape factor of the rectangular floor-slab viewed from windows.

Canberra is chosen for the location of simulation model. Hourly climatic data at Wagga Wagga (latitude = -35.2) given by Roy et al (6) is used.

4 POSITIONING OF WINDOW AND FLOOR SLAB

To maximise the absorption of solar radiation on a floor, the receiver surface has to be cleared from any obstructions. This gives residents a restriction on the use of the internal space.

It is desirable to position a window and a floor-slab so that daily and monthly distribution of solar radiation on a floor will be concentrated on as small a section as possible, in order to minimize the receiver surface and to maximize usable space in a room. From the thermal point of view, this may not be the most desirable pattern, because a high temperature surface may more easily lose heat to outside of a building by conduction through the slab to ground then to the outdoor, and by radiative heat transfer mainly through glazing. As the thermal response of the building depends on numerous parameters, to simplify the optimization methods of the window and floor-slab configuration, the monthly solar radiation absorbed on the floor is taken as a criterion. Wray et al (7) suggest that three times the glazing area for the mass floor surface substitutes the solar radiation collector on Trombe wall, however, no further analysis of the geometry is given by them. In the following sections, detailed analysis of the effect of the configuration is presented.

Fig.2 shows the sunlit areas on a floor at various times on 22 June. In the case (a), the window is 1 unit high and the window width and height are both 1 unit. In (b) the window sill is at the floor level. These two types indicate a distinctive difference in the distribution of the sunlit areas, obviously (a) is spread around the room and regarded as a worse case. It is apparently the ideal solution to install windows at the floor level and the mass floor-slab as close as possible to the windows.

5 THE EFFECT OF WALL THICKNESS

Wall thickness has often been ignored in the calculations of incident solar radiation on glazing or on internal surfaces. It is valid only when the perimeters of glazing are sufficiently tapered in both inside and outside, but practically this is impossible. The influence of wall thickness is not negligible when the solar incident angle on the window is large.

Fig.3 shows the vertical/horizontal factor for single and double glazing, taking into account the wall thickness. The vertical/horizontal factor is the ratio of the monthly solar irradiation transmitted through vertical north-facing glazing to the monthly total horizontal solar irradiation. It is assumed that the glazing is installed at the inner surface of the wall.

The value of (L-D) during the heating season in Canberra is in the range of 35 to 58 degrees. It can be noticed that the effect of wall thickness is significant in winter. This is because in Winter, a large amount of solar radiation incidence on northern walls is expected in the early morning and late afternoon when incident angles are great and the sides of windows cast shadows on the glazing surfaces.

6 THE EFFECT OF WINDOW PROPORTION

The question is whether a vertically long window is better than a horizontally elongated one.

If the wall thickness is taken into account, the face of the window head acts as projected shading on the glazing. From the fact that the intensity of solar radiation normal to its direction is highest at noon due to the least length the sunlight passes through in the atmosphere, a vertically long window seems to be desirable. However, in Canberra during winter the solar altitude at noon is below 50 degrees and the azimuth before 9am and after 3pm is greater than 45 degrees. The shading effect of the horizontal projection on glazing is less than that of side vertical projections.

Fig.4 shows the total solar radiation transmitted through an equator-facing vertical single glazing from May to September in Canberra. As the window ratio of width/height decreases below 1.0, the effect of shadowing by wall thickness becomes dominant.

Another effect of the window proportion, the sun penetration into a room, has to be considered. Fig.5 shows the sunlit area on the floor at the winter solstice in Canberra. Both windows have the same aperture area, but in different proportions. The ratio of window width to window height is 2 in (a) and 0.5 in (b). The sunlit area in (a) is more condensed than in (b), which means the required area of massive floor in (a) is less than in (b).

Therefore it is suggested that the required window area be wider and shorter, and, if possible, it is more desirable to have one large window rather than a number of small windows. The ratio of window width to window height of greater than 2 is recommended. Namely:

$$\text{Window width} \geq 2 \times \text{window height} \qquad [3]$$

7 THE EFFECT OF WINDOW/FLOOR-SLAB GEOMETRY

The distributions of sun penetration through an equator-facing window are concentrated at near the window around mid-day, but they are long and divergent from the centre of the window in early morning and in late afternoon. It is not ideal to have a large mass-floor to cover these areas, because the solar radiation on a horizontal surface before 9am and after 3pm is considerably less than that of other periods. Fig.6 shows the extent of the aggregate sunlit area between 9am and 3pm in Canberra for various window proportions. The ratios of width to height of (a), (b) and (c) are 1, 2 and 4 respectively. The higher the window proportion, the less the required floor surface per unit area of the window, and the shape of the aggregate sunlit area becomes close to a trapezoid, having the same height in all three cases. To simplify the calculation, a rectangular massive floor-slab is used, and the percentages of solar radiation reaching the floor to that transmitted through glazing are compared by using the following factors:

The Floor/Window Factor is defined as:

$$\text{F/W Factor} = \frac{\text{the monthly total solar irradiation absorbed on floor-slab}}{\text{the monthly total solar irradiation transmitted through glazing}} \qquad [4]$$

Fig.7 shows the F/W Factor for various window and floor geometries for June in Canberra. Under a given window proportion, the F/W Factor increases sharply as the ratio of the floor-slab width to window height (call it floor-width ratio) increases up to the same value as that of window proportion (width/height), and the slope becomes gentle when the floor-width ratio is greater than window proportion plus 1. Therefore, the desirable relationship between window proportion and the width of floor-slab is:

$$\text{floor width ratio} = \text{window proportion} + 1$$

$$\frac{\text{floor width}}{\text{window height}} = \frac{\text{window width}}{\text{window height}} + 1$$

from which

$$\text{floor width} = \text{window width} + \text{window height} \qquad [5]$$

Fig.8 shows the effect of the depth of a floor-slab on the solar radiation absorbed on the floor. The following ratios are used, as earlier concluded [eq. 3 and 5]:

$$(\text{window width})/(\text{window height}) = 2$$

$$(\text{floor width})/(\text{window height}) = 3$$

The reach of sunlight on floor at noon (L_0) is expressed as:

$$L_0 = H \cot(ANG) \qquad [6]$$

where

H : window height
ANG : solar altitude angle at noon
ANG=90.-(LAT+DEC)
LAT : absolute value of latitude
DEC : declination angle

The Floor-Depth Ratio and Floor-Depth Factor are defined as follows:

$$\text{FD ratio} = \frac{\text{floor-slab depth}}{L_0} \qquad [7]$$

$$\text{FD factor} = \frac{\text{Floor/Window Factor for a given floor depth}}{\text{Floor/Window Factor for the FD ratio of 1}}$$

$$= \frac{\text{the monthly total radiation absorbed on floor for a given floor depth}}{\text{the monthly total radiation absorbed on floor for FD ratio of 1}} \qquad [8]$$

Under the above-mentioned desirable geometry of window and floor width, the F/D Factor increases almost linearly with FD ratio increasing from 0 to 1, but almost constant above the FD ratio of 1. If the floor width is greater, the radiation in early morning and in late afternoon may be also received on the rectangle. However, judging from Fig.7, even in the case of window width/height = 2 and floor width/window height = 5, there is not much increase in the absorbed radiation. This means that the radiation received during these periods does not contribute a lot to the daily total.

Therefore, it can be concluded that there is no need to have the floor-slab depth more than L_0 on winter solstice. It is also found that the FD Factor is independent of the month.

8 A SIMPLE DESIGN TOOL

In the sketch design stage, prediction of a required area of window aperture and massive floor is the first task. A quick method without using computer programs is a convenient tool.

Balcomb and McFarland (8) established a simple method, Solar Load Ratio method, for Trombe wall and water wall, then Wray et al (7) did the same for direct-gain systems using PASOLE and SUNSPOT respectively.
The Solar Load Ratio (SLR) is defined as:

$$SLR = \frac{MET}{MBL} \qquad [9]$$

$$MET = Gw\ Aw \qquad [10]$$

$$MBL = DD\ 24.\Sigma UA \qquad [11]$$

where

MBL : the steady-state monthly building load including infiltration and the conduction loss through thermal storage elements and glazing for the solar energy collection

MET : the monthly energy transmitted through glazing. It is assumed that 80% of the transmitted radiation is absorbed on massive floor, and 20% in the room air

Gw : the monthly solar radiation transmitted through glazing of unit area

Aw : area of equator-facing windows

DD : the monthly heating degree days

ΣUA : the building heat loss coefficient

In the real situation only a portion of the transmitted radiation is absorbed on a massive floor and the rest is partly absorbed by walls, room air and/or furniture, and partly reflected to the outdoors. If the solar radiation received by the actual mass-floor area is only taken into account, and the contribution of energy absorbed in other surfaces is negligible, the MET must be altered to the Monthly total Energy received by a massive Floor surface (MEF), then

$$SLR' = \frac{MEF}{MBL} \qquad [12]$$

$$MEF = Gf\ Af \qquad [13]$$

where

Gf : the monthly solar radiation incident on massive floor of unit area

Af : the area of massive floor surface

To couple the above steady-state parameters and results obtained from hourly unsteady-state calculations, Solar Heating Factor (SHF) is introduced as a solar contribution indicator by Balcomb et al (8).

$$SHF = 1 - \frac{AUX}{MBL} \qquad [14]$$

where

AUX : the auxiliary heat to maintain the room air temperature above setting temperature, calculated by a finite-difference method.

Fig.10 shows the correlations between SLR and SHF for direct-gain systems derived by Wray et al (7). Similar correlations are expected from SOUP after validation, but in the meantime, the correlations of Wray et al are adopted, based on an assumption that 20% of incident radiation on the floor is reflected and absorbed by the room air. The broken lines in Fig.10 are expected correlations for single glazed direct-gain systems with and without night insulation.

The correction factors mentioned in the previous sections can be applied to the SLR method. The modified SLR method for massive floor direct-gain systems may be performed as follows:

Step 1. Obtain the monthly horizontal total solar radiation.

Step 2. Calculate (LATitude - DEClination angle) for each month.

Month	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT
DEC	0.	11.7	20.3	23.5	20.3	11.7	0.	-11.7

Step 3. Read Vertical/Horizontal factor for the (LAT-DEC) from Fig.3.

Step 4. Calculate the monthly total solar radiation transmitted through glazing Gw.

$$Gw = Gh\ (V/H\ factor) \qquad [15]$$

Step 5. Read Floor/Window Factor (Fig.7), Floor-Depth Factor (Fig.8) and Month Factor (Fig.9), then calculate the monthly total radiation received on a massive floor [Eq. 13].

$$Gf = Gw\ (FW\ factor/0.8)(FD\ factor)\ (month\ factor) \qquad [16]$$

where 0.8 : absorptance of floor surface. Convert the absorbed radiation into the incident value.

Step 6. Calculate the building heat loss coefficient including infiltration and equator-facing glazing.

Step 7. Obtain the monthly heating degree days (ref 18 deg.C)

Step 8. Calculate MBL [Eq. 11]

Step 9. Calculate SLR' [Eq. 12]

Step 10. Read SHF for the SLR from Fig.10.

The following section presents a method of rule-of-thumb to predict the required window area for Canberra. To make the process simpler, let's decide the target SHF, say 0.6 for July and estimate the window area.

From Table 1 the monthly total horizontal radiation and the heating degree days are 93713 (Wh/m^2.month) and 335 (deg.day) respectively.

Assume that

a) 30% of the radiation transmitted through glazing will be directly received on the massive floor;

b) 20% of that is received on other elements, furniture and substitutes for heating, in the same manner as the massive floor;

c) the rest does not contribute to heating at all.

Therefore,

$$\begin{aligned} \mathrm{MEF} &= \mathrm{Gh}\ (\mathrm{V/H\ factor})\ \mathrm{Awindow}\ (0.3+0.2) \\ &= 93713 \times 0.75 \times \mathrm{Awindow} \times 0.5 \end{aligned}$$

$$\begin{aligned} \mathrm{MBL} &= \mathrm{DD}\ 24\ \Sigma \mathrm{UA} \\ &= 335 \times 24 \times \Sigma \mathrm{UA} \end{aligned}$$

If double glazing with no night insulation is used, the required SLR for the target SHF of 0.6 is 0.78 (Fig.10). Substituting these values into Eq. 12

$$0.78 = \frac{93713 \times 0.75 \times \mathrm{Awindow} \times 0.5}{335 \times 24 \times \Sigma \mathrm{UA}}$$

then

$$\mathrm{Awindow} = 0.178 \Sigma \mathrm{UA}$$

Because the ΣUA value includes the window, the calculation must be repeated several times. However, the required window area will be obtained after a few iterations.

9 CONCLUSION

As a general design guide for the geometry of direct-gain passive heating systems with a rectangular mass floor-slab, the following are recommended (see Fig.11):

1. Windows are positioned as low as floor level.
2. A massive floor-slab should be adjacent to the window.
3. Window aperture width is greater than the window height.
4. Width of floor slab = width of window aperture + window height.
5. Depth of the floor-slab = the reach of the sun-penetration at noon on winter solstice (i.e. 1.63 x window height in Canberra).

With these dimensions, in June, 38% of transmitted solar radiation through glazing will be absorbed on the massive floor, and average 32% during heating season in Canberra.

Further study is necessary to analyse the effect of the window/floor geometry on the thermal performance of buildings in terms of heat flow from a massive floor to outdoors through windows.

TABLE I

THE MONTHLY HEATING DEGREE DAYS AND HORIZONTAL TOTAL SOLAR RADIATION IN CANBERRA

Month	DD	Gh (Wh/m^2.month)	(Wh/m^2.day)
APR	72.	82710.	3814.
MAY	235.	68758.	2757.
JUN	309.	69660.	2217.
JUL	335.	93713.	2332.
AUG	295.	138694.	3023.
SEP	237.	174600.	4476.
OCT	117.	180420.	5820.
NOV	30.	211260.	7042.

Extensive examination of the contribution of energy absorbed on non-massive elements to the heating is also required to establish accurate SLR:SHF correlations. Simulations with various parameters should be carried out to derive correlation factors for more general alternative designs.

All this is only a question of time as the model developed (see Fig.1) is sufficiently flexible to facilitate the examination of all these factors.

10. ACKNOWLEDGEMENTS

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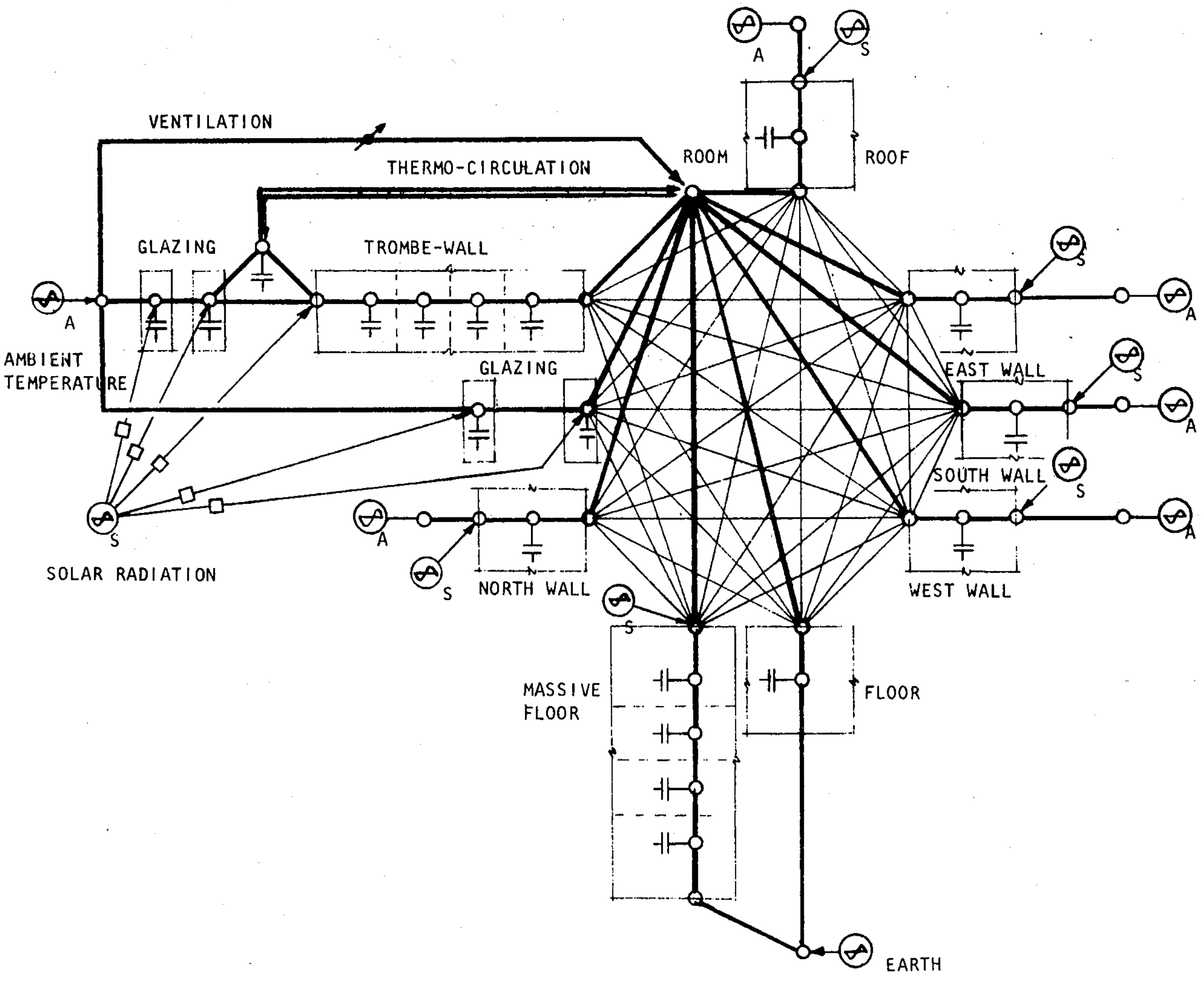

Fig.1 Thermal Network Diagram of SOUP

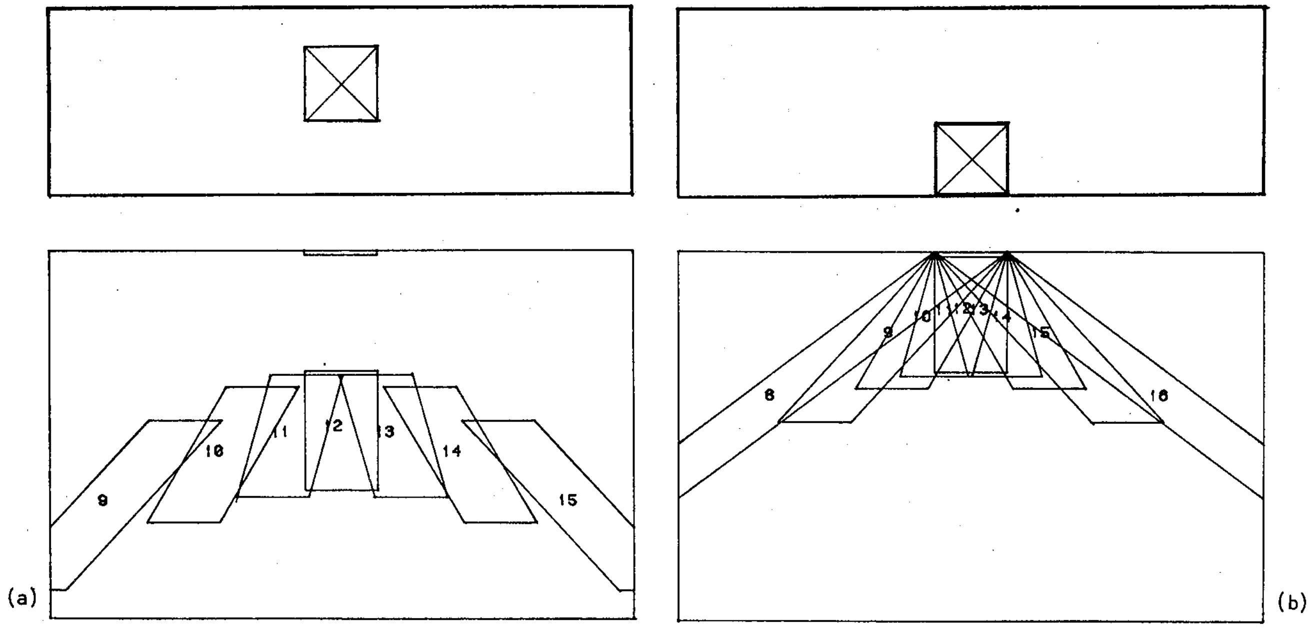

Fig.2 The comparison of sun penetration between two different window positions on 22 June in Canberra. (output of SUNLIT program)

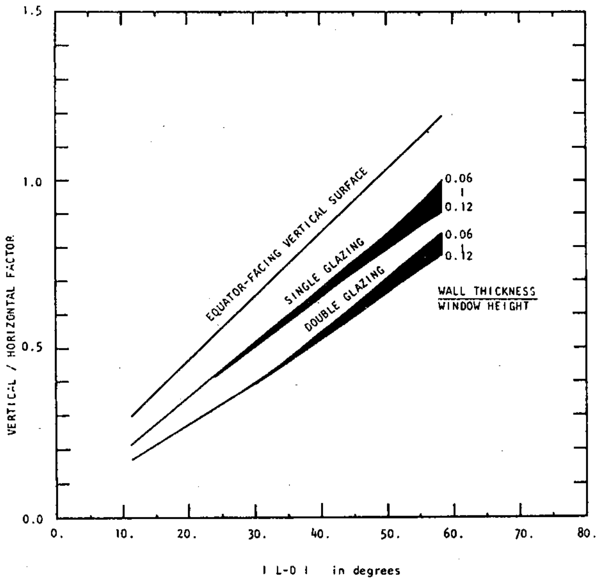

Fig.3 The Vertical/Horizontal Factor vs absolute value of (latitude minus mid-month declination angle). Ground reflectance = 0.3, window width/ window height = 5, refractive index of glazing = 1.526.

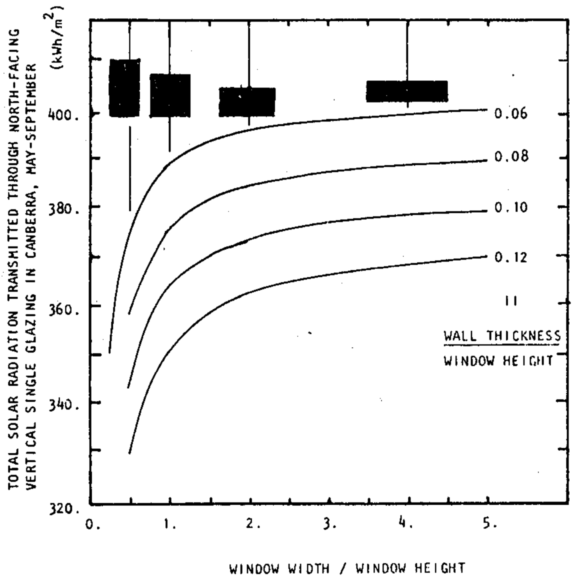

Fig.4 The solar radiation transmitted through glazing vs window proportion ratio for various wall thickness ratios.

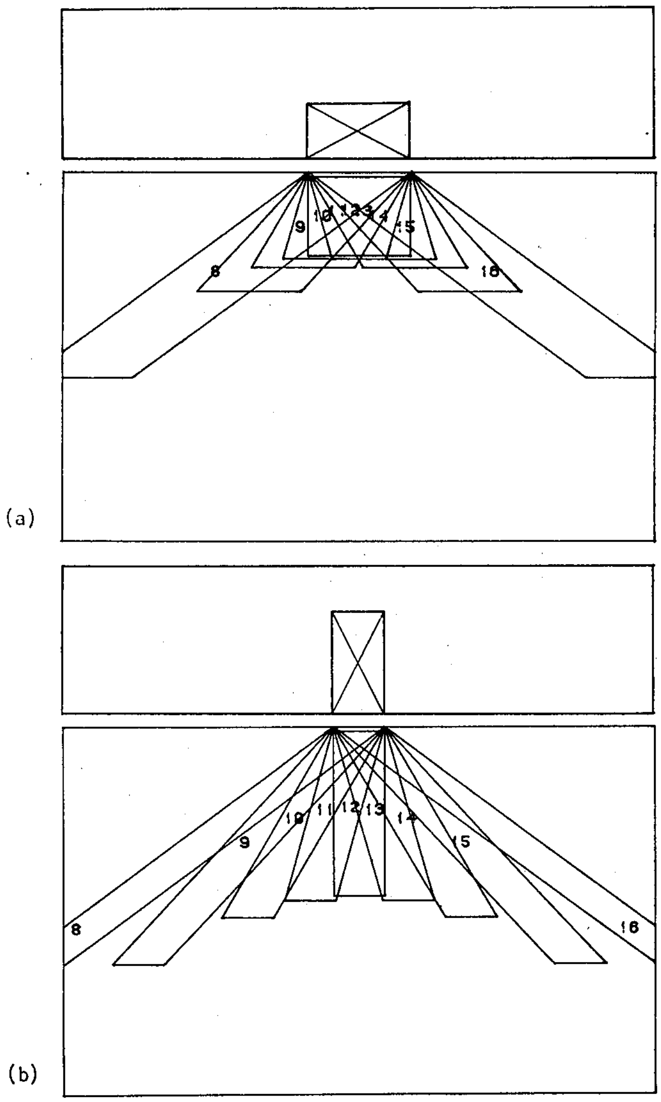

Fig.5 The comparison of sun penetration between two different window proportions, having same window area, on 22 June in Canberra

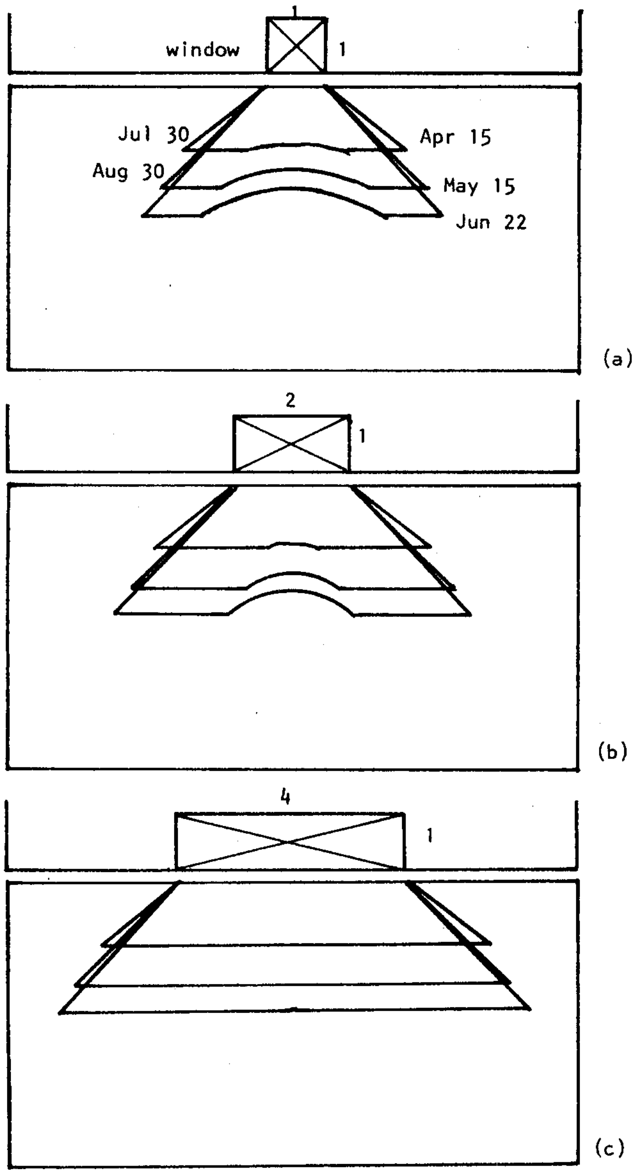

Fig.6 The comparison of sun penetration between three different window widths from 9am to 3pm

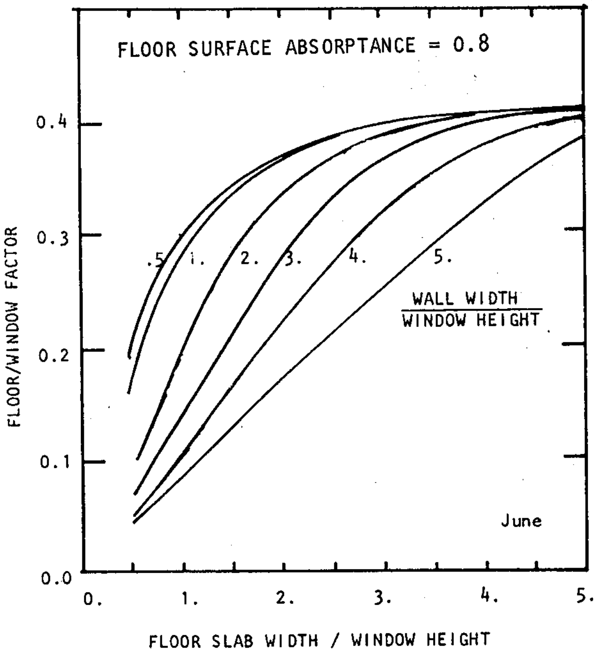

Fig.7 The floor/window factor vs floor width ratio, window width ratio. The absorptance of floor surface is 0.8

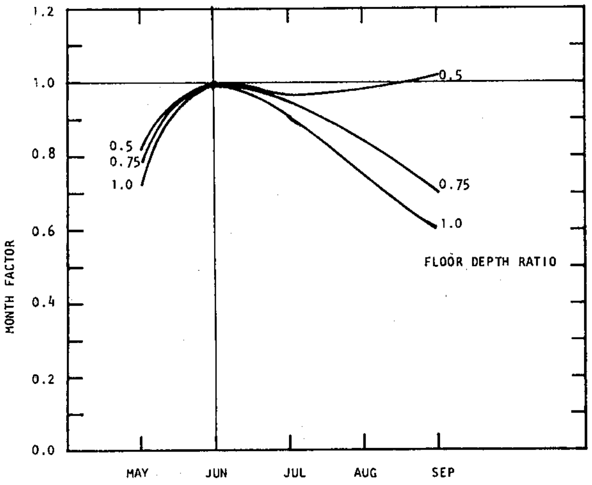

Fig.9 The month factor to be applied to the floor/window factor for other months

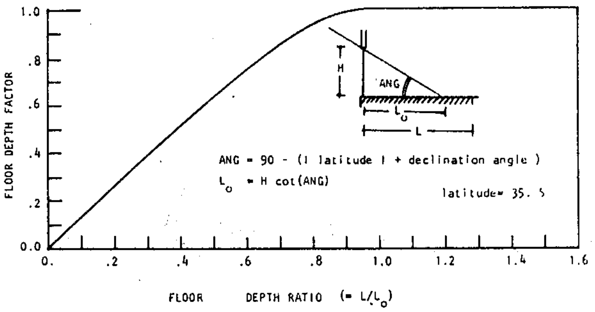

Fig.8 The floor depth factor vs floor depth ratio in June. (window width/height = 2, floor width/window height = 3)

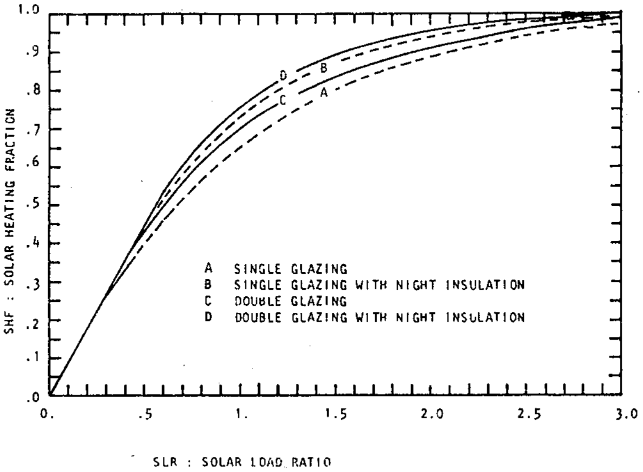

Fig.10 Monthly solar load ratio vs monthly solar heating fraction

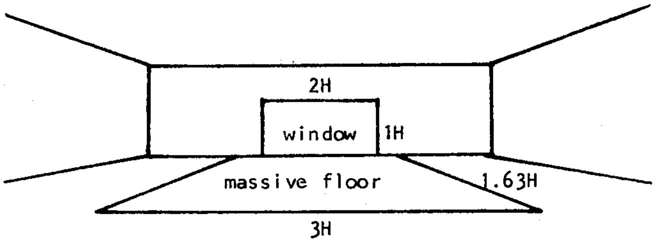

Fig.11 Ideal window/floor geometry for a direct gain system in Canberra