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Mass & Glass. How Much? How Little?

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ABSTRACT

The energy performance of a house employing south-facing windows depends upon the amount and type of glass and on the thermal mass of the building. A simple graphical procedure is presented that can be used to determine the effects of changes in these parameters on heating energy consumption.

RÉSUMÉ

La performance énergétique d'une maison dont les fenêtres sont orientées vers le sud est fonction de la surface vitrée, du type de verre et de la masse thermique du bâtiment. Une méthode graphique simple permettant de déterminer l'incidence des variations de ces paramètres sur la consommation d'énergie de chauffage est décrite.

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THE NEED for a simple method of estimating the heating energy requirement of a house is widely recognized. Most computer programs for this purpose[1] are too complicated; they are difficult and too expensive to be used for comparing alternatives at the design stage or for determining whether designs comply with energy standards. Current interest in the construction of low energy houses has increased the need for a simple, readily available calculation method.

Two philosophies have emerged for low-energy house design. Traditional passive solar design,[2] sometimes known as the "mass and glass" approach, advocates the use of large areas of south-facing glass to collect solar energy and heavy internal construction to store the excess heat collected during the day for later use at night. The other, known as the "light and tight" approach and typified by the Saskatchewan low energy houses,[3] is to minimize the heat loss of the house by means of high levels of insulation, small glass areas, and air-tight construction.

An evaluation method for low energy houses must, therefore, be applicable to both philosophies. The graphical technique to be described not only shows sensitivity to changes in parameters, but also permits determination of the thermally optimum glass area (i.e., that which will result in minimum annual heating energy). It is a technique that could easily be extended to economic optimization.

Determining "useful" solar gain

An important component of any energy calculation method is the ability to estimate the amount of solar energy collected through the windows of a house and utilized to offset heat losses. A number of methods of estimating the net solar contribution to space heating for direct-gain passive solar designs have been developed. The "solar-load ratio" (SLR) method developed by the Los Alamos Scientific Laboratory[4] and the "un-utilizability" method developed by the University of Wisconsin[5] are well known. Both involve calculations performed on a monthly basis.

More recently, a method based on the concept of the solar utilization factor was developed at the National Research Council Canada.[6,7] It is simple to use and is applicable to a complete range of houses, from high-mass, direct-gain passive solar designs to conventional lightweight wood-frame construction. The calculation can be performed once for the entire heating season, making it practical to perform manually.

A computer program that utilizes the method on a monthly basis[8] is also available.

The graphical procedure is based on a variation of this utilization factor method. The seasonal heating energy required for a house, H, can be expressed as

$$H = F_h L$$

where L, the net seasonal heating load for the building, is the amount of heating that would be required in the absence of solar gain, and F_h, the purchased heating fraction, is the fraction of this net heating load that must be supplied by the heating system. The remaining fraction $(1 - F_h)$ is the useful

Table 1-Sample house weights

Thermal capacity per unit floor area (MJ/m^{2}K)	Construction
0.060	Light - Standard frame construction, 12.7 mm gypsum board finish on walls and ceilings, carpet over wooden floor
0.153	Medium - As above, but 50.8 mm gypsum board finish on walls and 25.4 mm on ceiling
0.415	Heavy - Interior wall finish of 101.6 mm brick, 12.7 mm gypsum board finish on ceiling, carpet over wooden floor
0.810	Very heavy - Commercial office building, 304.8 mm concrete floor

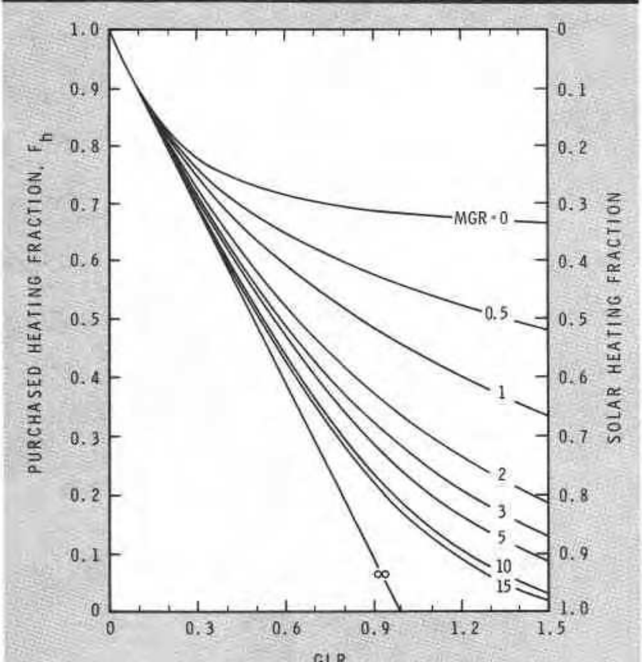

Figure 1 — Seasonal purchased heating fraction (room temperature swing 5.5°C)

Table 2 - Sample calculation for Ottawa houses

Parameter	House 1 Case 1	House 1 Case 2	House 1 Case 3	House 2 Case 1	House 2 Case 2	House 2 Case 3
Floor area, m^2	207	207	207	207	207	207
Thermal capacity, MJ/K	12.4	49.6	12.4	12.4	49.6	12.4
Wall thermal resistance, m^{2}K/W	3.5	3.5	3.5	6.4	6.4	6.4
Ceiling thermal resistance, m^{2}K/W	5.2	5.2	5.2	10.5	10.5	10.5
Glazing type	Double	Double	Triple	Double	Double	Triple
South solar gain, MJ/m^2	1814	1814	1670	1814	1814	1670
Basement heat loss, GJ	20	20	20	17	17	17
Internal gains, GJ	15	15	15	15	15	15
Air change rate, 1/h	0.25	0.25	0.25	0.1*	0.1	0.1
Heat loss coefficient (at $A_{south} = 0$), m^{2}K/W	206	206	197	120	120	116
Optimum south window area, m^2	16	32	24	7	18	10
Minimum purchased heating, GJ	81	75.5	69	48	47	38

**Equivalent to 0.5 air changes per hour using an air-to-air heat exchanger of 0.8 effectiveness.*

energy obtained from solar gain through windows; this is often referred to as the solar heating fraction.

F_h is expressed as a function of two normalized parameters, namely the "gain-load ratio" (GLR) and the "thermal mass-gain ratio" (MGR).

The gain-load ratio is the ratio of the seasonal solar gain through windows, G_s, to the net heating load, L, or,

$$GLR = \frac{G_s}{L}$$

The mass-gain ratio reflects the thermal storage characteristics of the building as well as the area, type, and orientation of the glazing. It is defined as*

$$MGR = C/g_s$$

where C = thermal capacity of the building interior (MJ/K),
g_s = average hourly solar gain for heating season (MJ/hr)
(g_s = G_s/hours in heating season)

The thermal capacity, C, is calculated as the "effective mass" of the building multiplied by its specific heat. Examples of thermal capacity values for four types of construction are given in *Table 1.*

Figure 1 shows F_h plotted against GLR for various values of MGR for the case in which a room temperature rise of 5.5°C is permitted. (Curves for the cases of 0 and 2.75°C temperature rise are also available.[6])

**The units of MGR (hours/K) are arbitrarily chosen to give values generally in the range of 1 to 10.*

The net heating load, L, is calculated as

$$L = L_t + L_a + L_b - n_i\, G_i$$

where

- L_t = total seasonal heat loss due to transmission through exterior walls, windows, ceilings, etc.,
- L_a = total seasonal heat loss due to indoor-outdoor air exchange (infiltration + ventilation),
- L_b = total seasonal below-grade heat loss,
- G_i = total seasonal heat gain from internal sources (lights, equipment, people, etc.),
- n_i = utilization factor for internal gain

Above-grade losses, L_t and L_a, can be calculated using the seasonal average outdoor temperature, which may be obtained from weather data records.[9] The below-grade heat loss, L_b, can be calculated using a procedure recently developed by Mitalas.[10]

The magnitude of the internal gains, G_i, depends on the occupancy of the house. Although data concerning rate of heat release by various appliances are available, it is always necessary to make arbitrary assumptions regarding occupant behavior and, therefore, total internal gain. For most situations (in which G_i is less than 25 percent of heat losses) all the internal gains can be assumed to be useful (n_i = 1).

The net heating load, L, is then obtained from equation (4). The seasonal solar gain through windows can be calculated using tabulated values of solar radiation incident

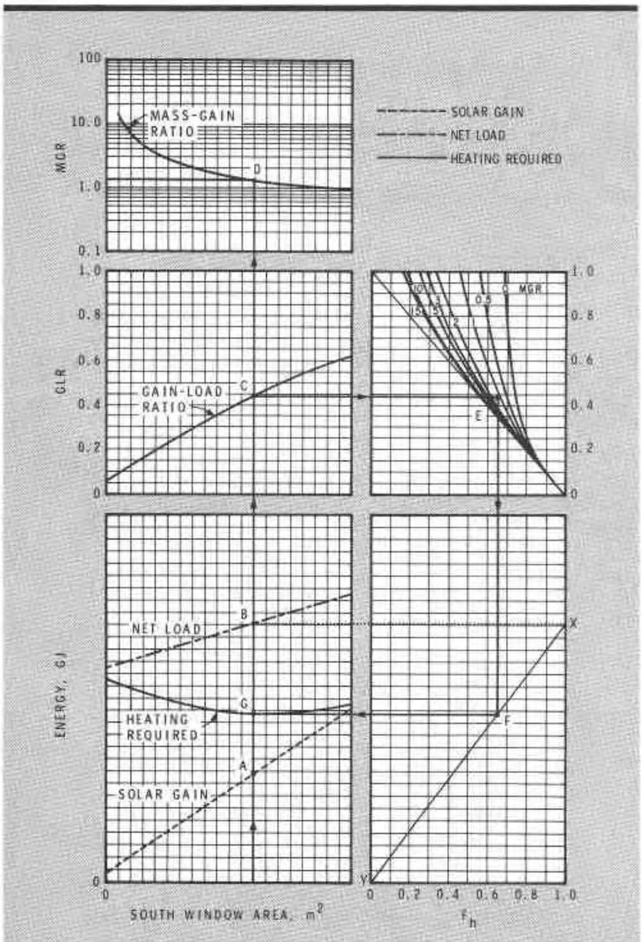

Figure 2 — Graphical procedure

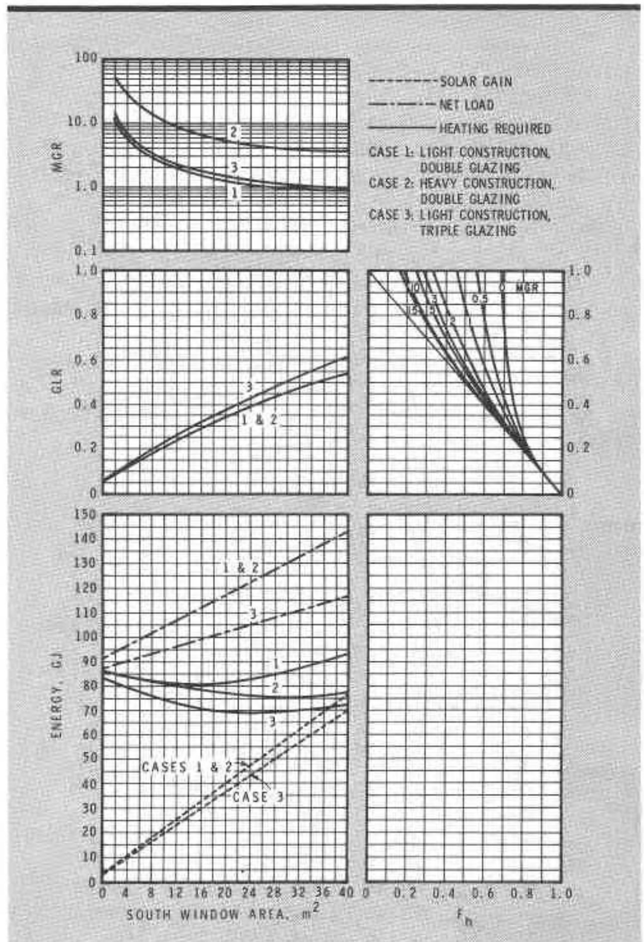

Figure 3 — Sample calculation, House 1

on surfaces of different orientation.[11] The gain-load ratio (GLR) and mass-gain ratio (MGR) can be determined using equations (2) and (3). F_h can then be obtained from the graph of *Figure 1* and the heating requirement from equation (1).

Graphical method

The effect of varying the south-facing glass area can be studied by repeating the foregoing calculation for different glass areas. This effect can be shown more easily, however, by a direct graphical procedure. The purchased heating fraction plot may be reformatted as shown in *Figure 2*. For a particular house design the following can then be plotted against south-facing window area:

- Solar gain, G_s, is a linear function of south-facing window area. It can therefore be plotted by calculating G_s for two different areas and drawing a straight line through these points. (It is normally convenient to use zero south-facing area as one of the points.) This is represented by the line for solar gain.
- Net load, L, is also a linear function of window area and has been plotted in a similar fashion.
- The gain-load ratio, GLR, is a non-linear function of window area and can be calculated (using values of G_s and L from the above plots) at a number of points. A curve can be drawn through these points.
- The mass-gain ratio, MGR, is also non-linear with window area, but can be calculated at a number of points to produce a characteristic curve.

The procedure for constructing the relation between window area and purchased heating requirement, using *Figure 2*, is as follows:

1. For any value of south-facing window area draw a vertical line to intersect the solar gain line, the net load line, the GLR curve, and the MGR curve at points A, B, C, and D, respectively.
2. Draw a horizontal line from point C to intersect the purchased heating fraction plot for the appropriate MGR (determined by point D) at point E. The heating requirement, H, is equal to the product of F_h and L, and can be obtained graphically in the next three steps.
3. Draw a horizontal line from point B to intersect the vertical line of $F_h = 1.0$ at X. Connect a line between point X and point Y (the point of intersection of the vertical line through $F_h = 0$ and the horizontal axis).
4. Draw a vertical line from point E to meet the line XY at F.
5. Draw a horizontal line from point F to meet the original vertical line of Step 1 at point G. The energy value at point G represents the purchased heating energy for this south window area.
6. Repeat steps 1 through 5 for other south window areas and draw a curve through the points to construct the relation between south-facing window area and purchased heating energy (solid line designated heating required).

A change in thermal storage for the same house can be simply accommodated by calculating new values of MGR and repeating the procedure. A change in window type requires that the entire procedure be repeated, beginning with recalculation of both G_s and L.

Examples are presented in *Figures 3 and 4* for two different house envelope constructions (thermal resistance) in Ottawa, Canada. For each, three options are evaluated:

1. Light-construction house, all windows double-glazed,
2. Same as 1, but house has four times the amount of thermal storage,
3. Light-construction house, all windows triple-glazed.

The details of the six cases are given in *Table 2* along with the minimum purchased heating required for each case and optimum south window area.

Summary and observations

A simple graphical procedure is presented that can be used to determine, for any house construction, the optimum combination of south-facing window area, window type and

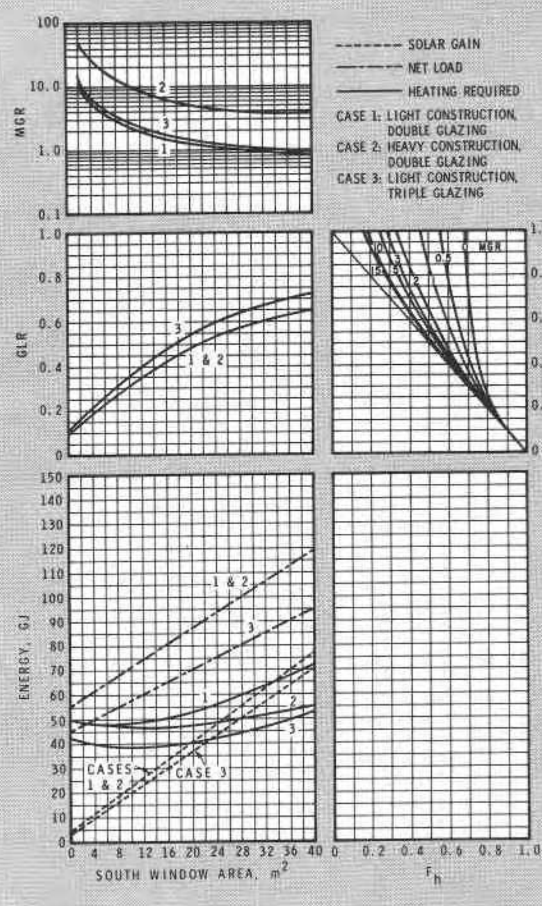

Figure 4 — Sample calculation, House 2

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thermal storage mass. The following observations regarding direct-gain passive solar houses in the Canadian climate were derived by applying this method to a number of house designs for the Ottawa climate.

1. The curves of purchased heating versus south-facing window area are very shallow around the optimum area. In general, a 50 percent change in south window area on either side of the optimum value would result in a small change in purchased energy requirement (a maximum of 4 percent in the six cases presented).

2. The optimum south window area decreases as the house becomes more energy conserving. For double-glazed windows and lightweight construction the optimum area is about 8 percent of floor area for an 80 GJ house (House 1). This reduces to 3.5 percent of the floor area for the more energy-conserving 48 GJ house (House 2).

3. Although an increase in thermal storage allows use of more windows and results in a reduction in purchased energy, a larger reduction would be possible with a smaller area of triple-glazed, rather than double-glazed windows. Taking the optimum double-glazing configuration as reference, a four-fold increase in mass can achieve a 7 percent reduction in purchased heating for House 1 and 2 percent reduction for House 2. Use of triple-glazing could achieve a reduction in purchased heating of 15 and 21 percent for Houses 1 and 2, respectively.

The method is currently being extended to permit determination of the effect of night-time use of insulating shutters on the space heating requirement. It will then be used to develop guidelines for the design of direct-gain passive solar houses in Canada. ■

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