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A METHOD FOR ESTIMATING THE UTILIZATION OF SOLAR GAIN THROUGH WINDOWS

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RÉSUMÉ

On peut, par un simple calcul, estimer l'énergie nécessaire au chauffage des habitations en faisant appel à la notion de facteurs saisonniers d'utilisation de l'énergie solaire dérivés d'une simulation sur ordinateur qui tient compte, chaque heure, des données météorologiques de cinq villes du Canada. Ces facteurs d'utilisation sont présentés pour divers niveaux de stockage thermique comme une fonction du rapport des apports saisonniers de chaleur solaire à la charge saisonnière du bâtiment. Les courbes sont tracées pour des températures intérieures constantes et des écarts de température de l'ordre de 2,75°C et de 5,5°C. Les données expérimentales, obtenues de l'installation d'essai de chauffage solaire passif, correspondent aux données calculées à partir des facteurs d'utilisation.

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A Method for Estimating the Utilization of Solar Gain through Windows

D.M. Sander **S.A. Barakat**

ABSTRACT

The heating energy requirements for houses may be estimated by a simple calculation using the concept of seasonal solar utilization factors derived from hour-by-hour computer simulation of actual weather data for five Canadian locations. These utilization factors are presented for various levels of thermal storage as a function of the ratio of seasonal solar gain to seasonal building load. Curves are presented for conditions of constant room temperature and for temperature swings of 2.75°C and 5.5°C. Experimental data obtained from the Passive Solar Test Facility are shown to agree with calculations using the utilization factors.

INTRODUCTION

The need for a simple method of estimating the heating energy requirements of houses is widely recognized. Such a technique could be used for comparing alternatives in the design process and for evaluating house designs to determine their compliance with energy standards. An important component would be the estimation of the amount of solar energy collected through the windows of houses and utilized to offset heat losses. It has been shown that south-facing double- and triple-glazed windows can be net suppliers of energy during the heating season for all locations in southern Canada, provided that all of the solar gains are utilized.[1] In reality, however, it is possible to use only a fraction of the solar gains. The magnitude of this fraction, which will be referred to as the utilization factor, depends upon several parameters including geographical location, size and type of glass, over-all building heat loss, thermal storage properties of the house, and the allowable indoor temperature swing.

A number of methods have been developed to estimate the net solar contribution to space heating for direct-gain passive solar designs.[2-4] One that is widely used in Canada and the USA is the solar load ratio (SLR) method developed by the Los Alamos Scientific Laboratory. It has been applied extensively to all types of buildings, despite the caution that "the method is not applicable to the analysis of low-mass sun-tempered buildings."

It was the objective of the present study to develop a method of quantifying the useful solar gain through windows that would be applicable to all types of houses in all climatic regions of Canada. As the scope of the method was not to be limited to passive solar houses, it was necessary to consider solar heat gains through all windows (not only those facing south) as well as houses with different amounts of thermal mass. The most important application, however, will be the evaluation of energy consumption in the lightweight wood-frame houses prevalent in Canada. In addition, it was deemed desirable to base the method on seasonal rather than monthly consumption to make it easier to estimate the seasonal heating energy required for a house. This seasonal approach has, in fact, resulted in a calculation procedure only slightly more difficult to apply than the degree-day method.

This paper describes the development of the method and presents the solar utilization factors for various amounts of thermal storage and three values of indoor temperature swing.

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THE UTILIZATION FACTOR CONCEPT

Instantaneous Heat Balance

The instantaneous (hourly) heat balance for a house is given by:

$$h = l_t + l_a + l_b - g_i - g_s \tag{1}$$

where

- h = instantaneous heating required
- l_t = instantaneous heat loss due to transmission through exterior walls, windows, ceilings, etc.
- l_a = instantaneous heat loss due to air change with outdoors (infiltration plus ventilation)
- l_b = instantaneous below-grade heat loss
- g_i = instantaneous heat gain from internal sources (lights, equipment, people, etc.)
- g_s = instantaneous solar heat gain through windows

There will be times when gains exceed losses. Under these conditions, the excess heat will be stored in the mass of the room, causing the room temperature to rise. In order to prevent it from rising above an acceptable limit, the excess heat gain must be eliminated. This may be done by closing the blinds, opening the windows, or operating a ventilating or air-conditioning system. A portion of the stored heat will become available as useful heat when the room temperature drops to the thermostat setting. The remainder of the stored heat will have been wasted in the form of increased transmission heat loss through the walls owing to the rise in room air temperature.

Seasonal Heat Balance

The heat balance equation may be written for a longer time period, such as the heating season, by including a utilization factor to account for the usable portion of internal and solar gains.

$$H = L_t + L_a + L_b - \eta_i G_i - \eta_s G_s \tag{2}$$

where

- H = total heating required for season
- L_t = seasonal total of heat losses due to transmission through exterior walls, windows, ceilings, etc.
- L_a = seasonal total of heat losses due to indoor-outdoor air exchange (infiltration plus ventilation)
- L_b = seasonal total below-grade heat loss
- G_i = seasonal total of heat gains from internal sources (lights, equipment, people, etc.)
- G_s = seasonal total of solar heat gains through windows
- η_i = utilization factor for internal gains
- η_s = utilization factor for solar gains

Utilization of Internal Gains. Since, in most situations, the internal gains are small relative to the sum of loss terms (less than 25%), a utilization factor of one may be assumed.

Utilization of Solar Gains. The solar utilization factor can be 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 defined as:

$$GLR = \frac{G_s}{L_t + L_a + L_b - \eta_i G_i} \tag{3}$$

The gain-load ratio is the ratio of the solar gain through windows to the net heating load, where the net heating load is the amount of heating energy required in the absence of solar gains to maintain the room temperature at the heating thermostat setting.

This gain-load ratio differs from the solar load ratio (SLR) as defined in Ref 2 in that the GLR includes heat losses through the windows while the SLR does not. Moreover, the GLR includes solar gains through all the windows, not only those facing south.

For locations in southern Canada, a house built to pre-1975 standards would have a GLR of less than 0.2, while a well-insulated passive solar house (with a south-facing window area equal to 20% of the floor area) would have a GLR on the order of 0.4 to 0.6.

The thermal mass-gain ratio is defined as:

$$MGR = C/\bar{g}_s \tag{4}$$

where

C = thermal capacity of the building interior (MJ/ K)
$\bar{g}_s$ = average hourly solar gain for season (MJ/h)
($\bar{g}_s = G_s$/hours in heating season)

Thermal capacity, C, is calculated as the "effective mass" of the building multiplied by its specific heat. The effective mass is the mass actually available to store heat from direct solar gains or close contact with room air, so that any change in the room air temperature affects the mass temperature. This normally includes the mass inside the insulating layer of the walls and ceilings but excludes the exposed concrete of uninsulated basement walls and floors.

The mass-gain ratio reflects the thermal storage characteristics of the building as well as the area, type, and orientation of the glazing. Typical houses of lightweight construction with window areas equal to 10% to 20% of the floor area have a mass-gain ratio of approximately 1 h/K. The medium and heavy constructions described in Tab. I have mass-gain ratios of approximately 3 and 7.5 h/K, respectively. These mass-gain ratios increase as the window area decreases and vice-versa.

Figs. 1 to 3 show the seasonal solar utilization factor plotted against the GLR for various values of MGR. Fig. 1 is based on the assumption that the room temperature is maintained constant, while Figs. 2 and 3 are for cases in which room temperature rises of 2.75°C and 5.5°C, respectively, are permitted. The development of these solar utilization factors will be described.

DEVELOPMENT OF SOLAR UTILIZATION CURVES

Computer Simulation

The solar utilization curves shown in Figs. 1 to 3 were derived from a large number of computer simulations. The computer program performed hour-by-hour calculations, using measured weather data for an actual year, to determine heat gains and losses, the heating energy required to maintain room temperature at the thermostat setting, and the room temperature resulting from excess heat gains. The solar radiation incident on glazed surfaces is calculated from hourly values of measured horizontal radiation using the correlation developed by Hay.[5] Solar gain is calculated by applying the transmission characteristics for standard glass and the shading coefficient of the appropriate glazing type.[6]

The thermal storage effects are simulated according to the ASHRAE thermal response method.[7] The response factors given in the ASHRAE Handbook, however, are not appropriate for the type of construction used in houses. Consequently, for this study new values corresponding to three different weights of house construction (light, medium, and heavy) were obtained using the room thermal response factor program. For reference purposes, very heavy construction was defined by the coefficients given in the ASHRAE Handbook. In addition, the thermal response factors of the three weights of house construction were confirmed experimentally in the NRC passive test facility. The construction features of each house weight are described in Tab. 1.

House Models

Twenty house models, each with a different level of insulation so as to provide a wide range of gain-load ratios, were defined; the window area was fixed in order to maintain a constant mass-gain ratio. Each model was simulated for five locations representing different Canadian climatic regions: Vancouver (B.C.), Summerland (B.C.), Edmonton (Alta.), Ottawa (Ont.), and Halifax (N.S.). This procedure was repeated for each of the constructions described in Tab. I, as well as for an infinitely light construction established for reference purposes.

A heating thermostat setting of 21°C was assumed. As occupant preference would determine the allowable rise in room temperature, three different assumptions were considered, namely, a constant room temperature and two allowable rises in room temperature, one of 2.75°C and the other of 5.5°C. In this simulation it was also assumed that the room temperature was prevented from rising above the allowable limit by ventilation using outside air.

Seasonal Solar Utilization

The heating season for all locations was assumed to consist of the months October to April, inclusive. Seasonal values of solar utilization factor, gain-load ratio, and mass-gain ratio were determined for this time period. Curves of solar utilization factor as a function of GLR were obtained for each of light, medium, heavy, and very heavy constructions (MGR equal to 1.0, 2.6, 7.2, and 14.0 h/K, respectively) using the method of least squares. The data points obtained for Edmonton, Ottawa, and Halifax produced well-defined curves of solar utilization factor against GLR for all cases. The root mean square (rms) error between these data points and curve fit is less than 0.015. Data and corresponding curve fits, for light, medium, and heavy constructions only, are illustrated in Figs. 1 to 3. Figs. 4 to 6 were then obtained by interpolation between these curves for other values of MGR.

The solar utilization factors obtained for Vancouver and Summerland, B.C., are somewhat lower than those for the other locations. This was attributed to the characteristic of the climatic pattern of the West Coast region. Even for Vancouver, however, which probably typifies the extreme of this type of winter weather for Canada, maximum error in utilization factor is only about 0.08. For a house with a GLR of 0.6, this corresponds to a maximum error of 5% in estimating heating energy requirements.[8]

The information contained in the utilization factor curves can also be presented as the ratio of purchased heating energy to load (Purchased Heating Fraction) or as the ratio of solar contribution to load (Solar Heating Fraction). Curves presenting the data in this form are given in Figs. 7 to 9. In addition to seasonal values, calculations can also be performed using solar utilization factors on a monthly basis.[8]

COMPARISON WITH EXPERIMENTAL DATA

The measured energy consumption for the NRC passive test units during the 1981-82 heating season was compared with the corresponding consumption calculated using the solar utilization factor concept. The NRC test facility[9] consists of four two-room test units and four single-room units. Three of the four two-room units (Units 1, 2, and 3) are of the direct-gain type and differ only in their thermal mass: Unit 1 is classified as light, Unit 2 as medium, and Unit 3 as heavy construction (see Tab. 1). The south room of each unit has a south-facing window with a 2.6 m^2 glass area; the north room has a 1 m^2 window facing north. The four single-room units have the same thermal mass as Unit 1. Each unit has a 2.6 m^2 window facing one of the cardinal directions.

The two-room units were operated in two modes that were alternated every two weeks. In the first mode, each unit was monitored as two separate rooms; in the second, air was circulated between the south and north rooms, and the whole unit was treated as a single space. All the rooms were operated with an allowable indoor air temperature swing of 7°C. Solar gain values were obtained by measuring the solar radiation on the vertical surfaces. The load values were determined by multiplying the heat-loss coefficient by the sum of the differences between the heating set point and the measured outdoor temperature.

Comparison of measured and calculated energy consumptions is presented in Tab. 2 for both modes of operation. The corresponding seasonal solar utilization factors were obtained from Fig. 3 by interpolating between the curves for the appropriate value of the MGR. The calculated values show close agreement with measured results; maximum difference between the calculated and measured space-heating energy is less than 5%.

USE AND LIMITATIONS

The use of solar utilization factor curves to estimate the heating energy requirement of houses can be summarized in the following steps:

- Calculate each of the loss and gain components of Eq 2.
- Calculate the GLR from Eq 3.
- Calculate the MGR from Eq 4 (or assume 1 for standard lightweight construction).
- Obtain the utilization factor corresponding to the GLR and MGR by interpolation from Fig. 1, 2, or 3 (depending on the desired allowable temperature rise).
- Substitute this utilization factor in Eq 2 to obtain the heating energy requirement.

The utilization factors are based upon a number of assumptions, some of which impose limitations on the use of the factors. They apply only to simple direct-gain buildings that do not use night insulation systems on the windows. They should not be used for mass-walls, attached sun spaces, or systems utilizing active thermal storage.

The calculation method assumes that all of the loss components can be offset by solar gains whenever and wherever the latter occur. This is a valid assumption for small open spaces or where forced-air circulation is provided; if an area (such as a basement or a north-facing room) is remote from or thermally separated from the windows providing the solar gains, however, the loss from such an area should not be included in the "load" used to calculate the gain-load ratio. Furthermore, the mass in this area should not be included in the calculations of the MGR. These considerations are especially important when estimating the energy requirements of houses with zone-controlled heaters.

The accuracy of the heating energy estimate is more dependent on the calculation of heat losses and gains than it is on the limitations of the solar utilization curves themselves. Heat loss and gain calculations must allow for such factors as the lowering of the thermostat setting at night; exterior shading of windows by trees, buildings, overhangs, etc.; use of blinds and drapes by the occupant; and correct estimation of a seasonal average air-change rate.

One should also keep in mind that the utilization factors permit calculation of heating energy on the assumption that the designer has provided some means of limiting rise in room temperature. At high gain-load ratios it is quite possible that problems with interior comfort could arise as a result of overheating and glare.

Despite all the indicated limitations, the solar utilization factor does provide a simple method of calculating the contribution of solar heat gains for direct-gain passive solar designs as well as for houses of conventional and superinsulated construction.

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TABLE 1

House Weights for Computer Simulation

	Thermal Capacity $MJ/K{\cdot}m^2$ Floor Area	Description
Light	0.060	Standard frame construction, 12.7 mm gyproc walls and ceilings, carpet over wooden floor.
Medium	0.153	As above, but 50.8 mm gyproc walls and 25.4 mm gyproc ceiling.
Heavy	0.415	Interior wall finish of 101.6 mm brick, 12.7 mm, gyproc ceiling, carpet over wooden floor.
Very heavy	0.810	Very heavy commercial office building, 304.8 mm concrete floor.

TABLE 2

Comparison with Experimental Results

Description	No. of days	Storage Capacity MJ/K	Ref. Load MJ	Solar Gain MJ	GLR	MGR hr/K	Seasonal Utili-zation Factor, η_s	Heating energy Measured MJ	Heating energy Calc. MJ	% Differ-ence
Single-room unit, (south window)	154	0.75	5785	3103	0.54	0.9	0.62	3996	3820	-4.4
Single-room unit, (east window)	154	0.75	5598	1868	0.33	1.4	0.82	4090	4086	0.1
Single-room unit, (west window)	154	0.75	6448	1872	0.30	1.4	0.87	4810	4770	-0.8
Single-room unit, (north window)	154	0.75	6257	1029	0.16	2.7	0.97	5252	5256	-0.1
South room of Unit 1*	66	0.75	2891	1318	0.46	0.9	0.70	1915	1966	2.7
Full Unit 1**	51	1.53	3852	1109	0.29	1.7	0.90	2837	2815	-0.6
South room of Unit 2*	66	2.03	2826	1318	0.47	2.5	0.81	1732	1753	1.2
Full Unit 2**	51	4.13	3542	1109	0.31	4.6	0.94	2506	2516	0.4
South room of Unit 3*	66	6.33	2851	1318	0.46	7.7	0.92	1606	1652	2.9
Full Unit 3**	51	11.55	3694	1109	0.30	12.8	0.97	2617	2621	0.2

* Mode 1 = south and north rooms separate
** Mode 2 = south and north rooms joined

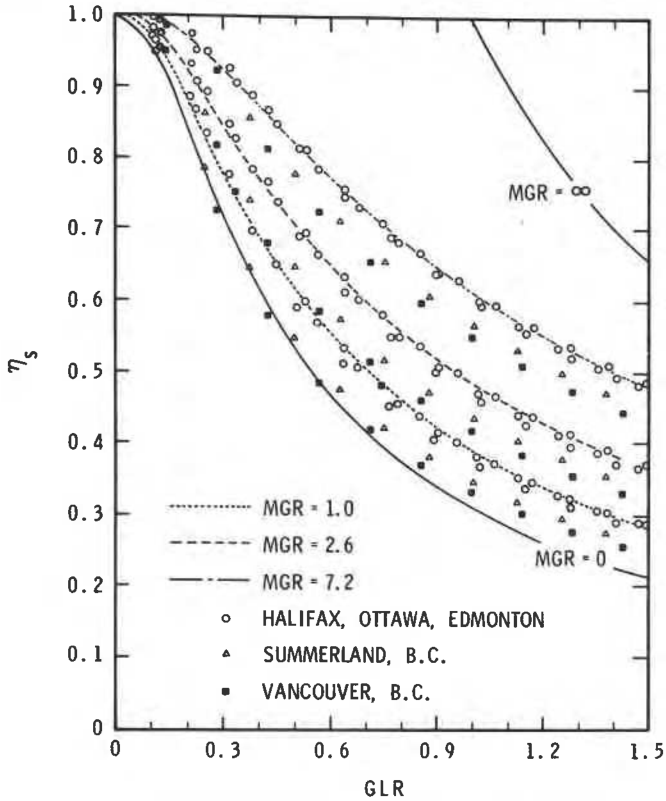

Figure 1. Seasonal solar utilization curves and actual data points for five locations (constant room temperature)

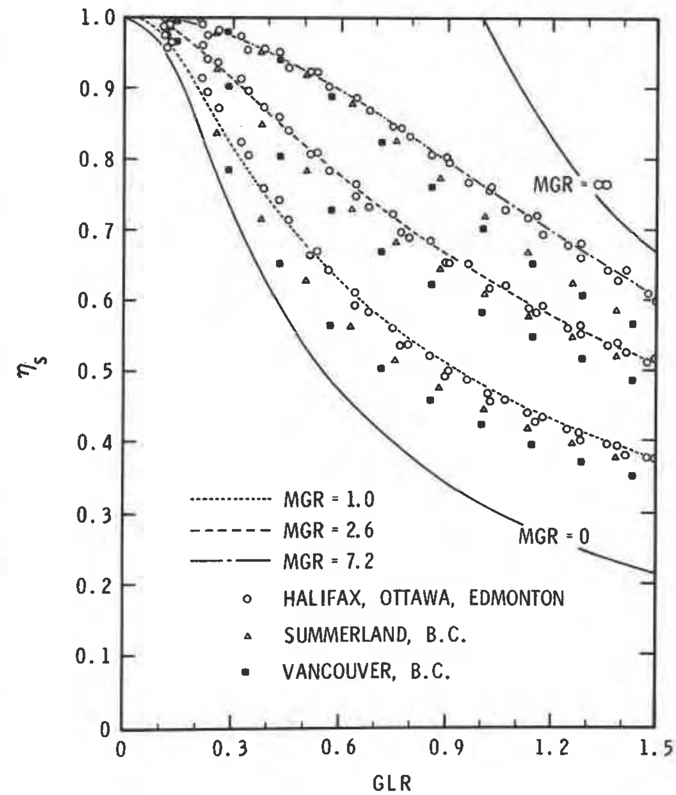

Figure 2. Seasonal solar utilization curves and actual data points for five locations (room temperature swing = 2.75°C)

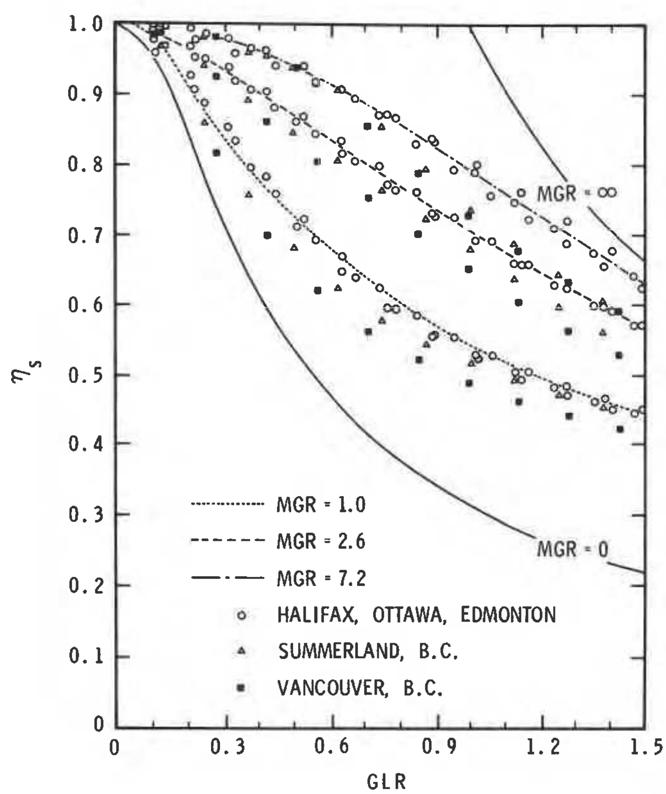

Figure 3. Seasonal solar utilization curves and actual data points for five locations (room temperature swing = 5.5°C)

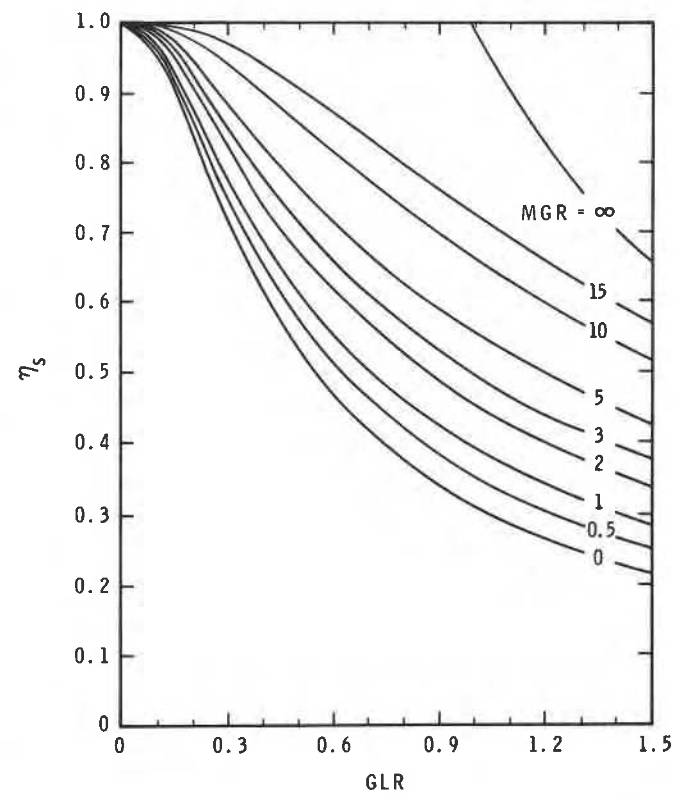

Figure 4. Seasonal solar utilization factor (constant room temperature)

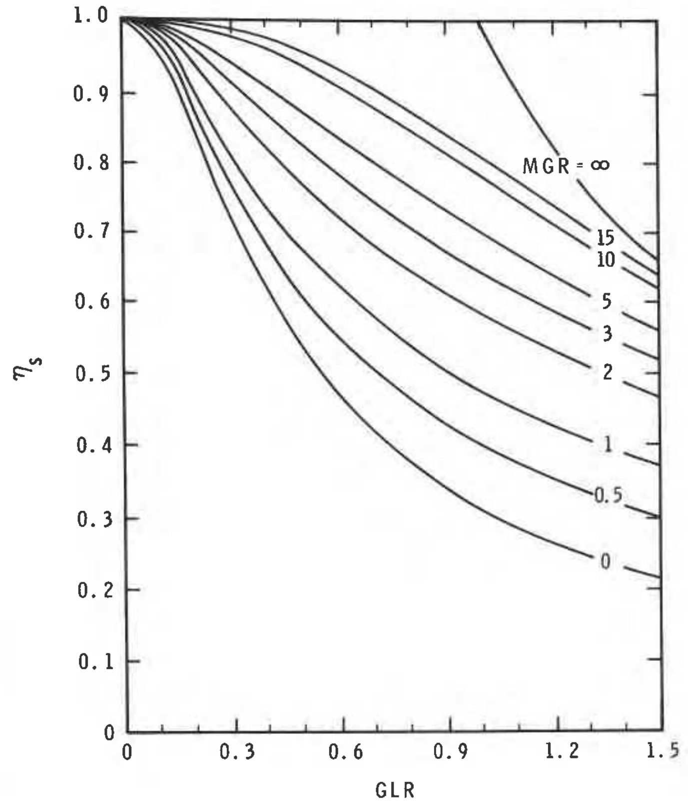

Figure 5. Seasonal solar utilization factor (room temperature swing = 2.75°C)

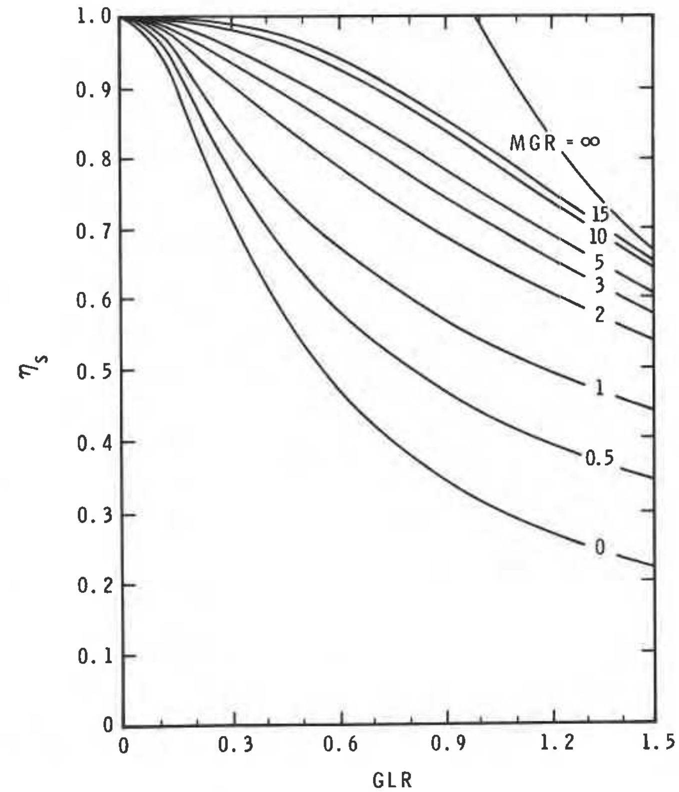

Figure 6. Seasonal solar utilization factor (room temperature swing = 5.5°C)

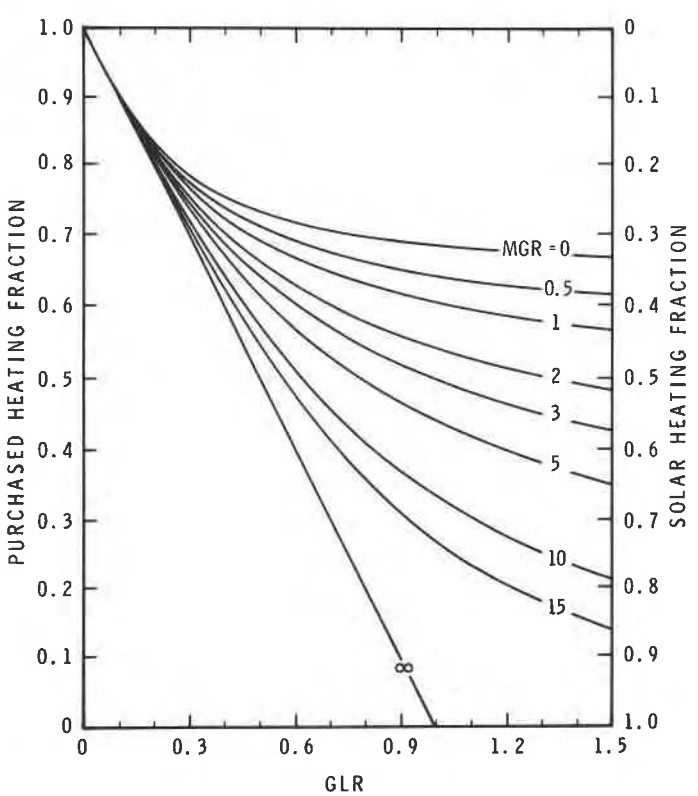

Figure 7. Seasonal purchased heating fraction (constant room temperature)

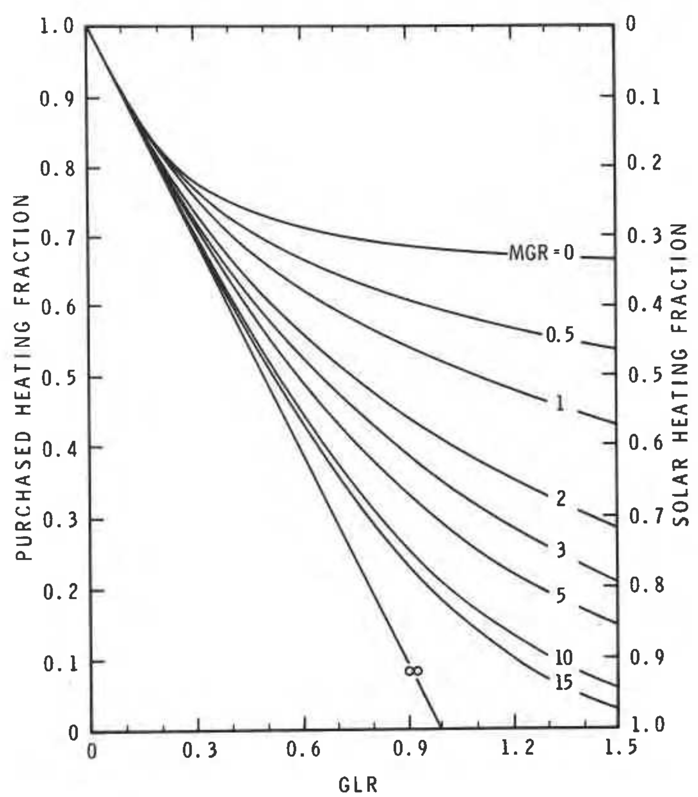

Figure 8. Seasonal purchased heating fraction (room temperature swing = 2.75°C)

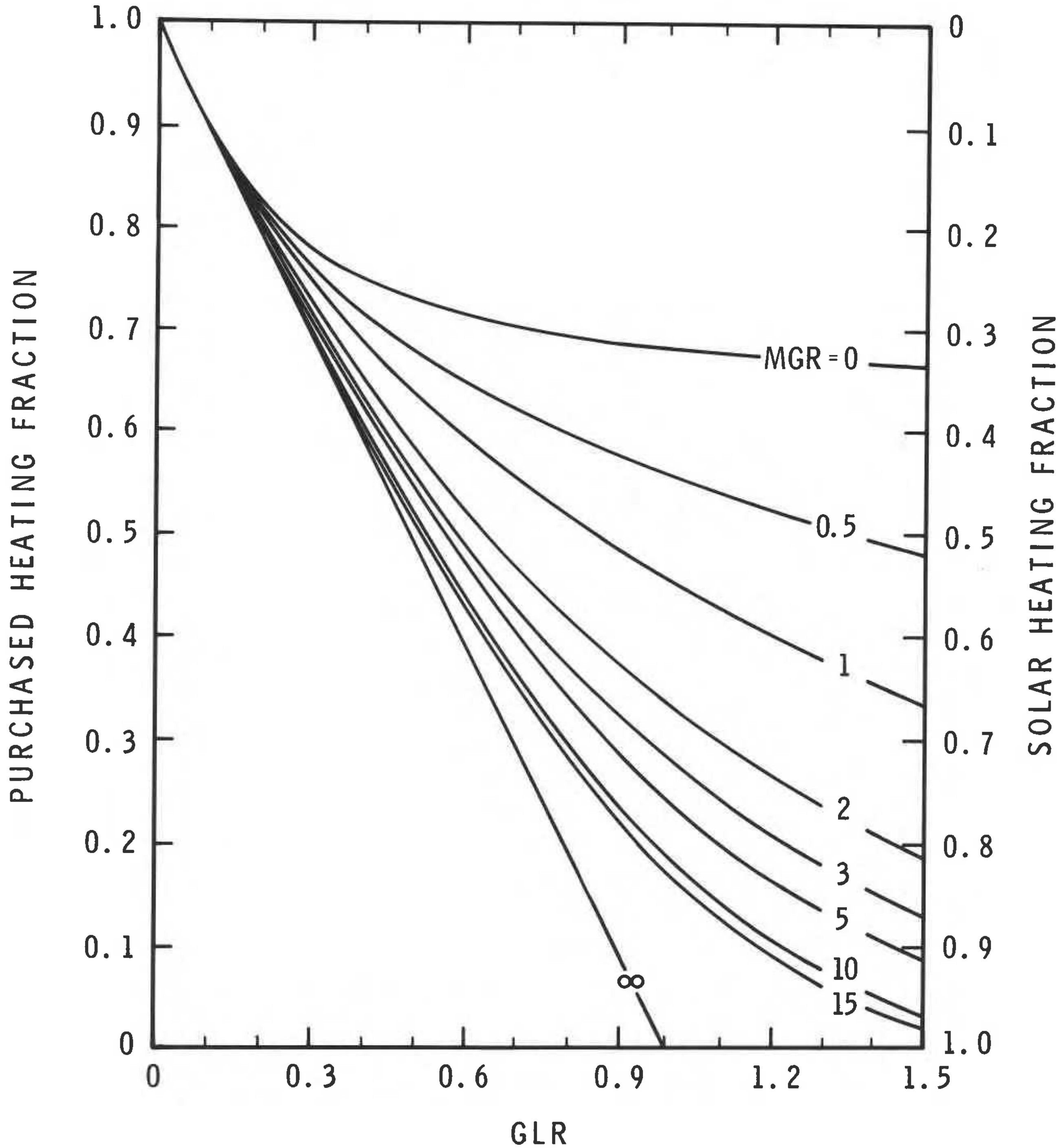

Figure 9. Seasonal purchased heating fraction (room temperature swing = 5.5°C)

DISCUSSION

S.J. Treado, National Bureau of Standards, Washington, DC: Could the authors please comment on the sensitivity of the solar utilization factor calculation to the assumptions which must be made regarding heat loss due to envelope transmission, air exchange, and below-grade transmission?

D.M. Sander: The sensitivity of the solar utilization factor to the heat loss is as shown in the graphs of η_s versus GLR. This is not affected by assumptions made in calculating losses. Any errors in the calculation of losses due to simplifying assumptions will, of course, affect the accuracy of the energy estimate using the utilization factors.