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UTILIZATION OF SOLAR GAIN THROUGH WINDOWS FOR HEATING HOUSES

by

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ABSTRACT

The heating energy requirements for houses may be estimated by a simple calculation using the concept of a seasonal solar utilization factor. Solar utilization factors were derived using an hour-by-hour computer simulation with 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 gains to seasonal building loads. Curves are presented both for conditions of constant room temperature and for temperature swings of 2.75 and 5.5 C°. Experimental data obtained from the NRC Passive Solar Test Facility are shown to agree with calculations using the utilization factors.

1. INTRODUCTION

The need for a simple method to estimate the heating energy requirements of houses is widely recognized. Such an estimating 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 of this method 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[1] that south-facing double- and triple-glazed windows can be net suppliers of energy over the heating season for all locations in southern Canada, provided that all of the solar gains are utilized. In reality, only a fraction of the solar gains can be utilized. The magnitude of this fraction, which will be referred to as the utilization factor, depends upon several parameters including the geographical location, the size and type of glass, the overall building heat loss, the thermal storage properties of the house, and the allowable indoor temperature swing.

A number of methods[2,3,4] have been developed to estimate the net solar contribution to space heating for direct-gain passive solar designs. One of the methods widely used in Canada and the USA is the solar load ratio (SLR) method developed by the Los Alamos Scientific Laboratory. This method has been extensively applied to all types of buildings, despite the author's caution that "the method is not applicable to the analysis of low-mass sun-tempered buildings".

The objective of this study was to develop a method for quantifying the useful solar gain through windows that would apply to all types of houses in all climatic regions of Canada. Since the scope of this 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 of this method, 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 that is only slightly more difficult to apply than the degree-day method.

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

2. 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 + 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 the gains exceed the 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 the room temperature 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 ventilation or air-conditioning system. A portion of the stored heat will become available as useful heat once 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 due 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 + 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

It has been found that 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:

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

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 Reference 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 in the order of 0.4 to 0.6.

The thermal mass-gain ratio is defined as:

$$MGR = C/\bar{g}_s \qquad (4)$$

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

The thermal capacity, C, is calculated as the "effective mass" of the building multiplied by its specific heat. The effective mass is the mass actually available to store heat as a result of direct solar gains or of close contact with the 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 hr/K. The medium and heavy constructions described in Table I have mass-gain ratios of approximately 3 and 7.5 hr/K, respectively. These mass-gain ratios increase as the window area decreases and vice versa.

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

3. DEVELOPMENT OF SOLAR UTILIZATION CURVES

COMPUTER SIMULATION

The solar utilization curves shown in Figures 1 to 3 were derived from a large number of computer simulations. To produce these curves, the computer program performs 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]. The 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[8]. 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[9]. The construction features of each house weight are described in Table 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; their 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 Table I, as well as for an infinitely light construction established for reference purposes.

A heating thermostat setting of 21°C was assumed. Since 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 last from October to April inclusive. The seasonal values for the solar utilization factor, the gain-load ratio, and the mass-gain ratio were determined for this time period. Following this, curves of the solar utilization factor as a function of the GLR were obtained for each of the light, medium, heavy, and very heavy constructions (MGR equal to 1.0, 2.6, 7.2, and 14.0, respectively) using the method of least squares. Figures 1 to 3 were then obtained by interpolation between these curves for other values of the MGR. The data and corresponding curve fits are presented in Appendix A.

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 alternatively, as the ratio of solar contribution to load (Solar Heating Fraction). Curves presenting the data in both of these forms are given in Figures 4 to 6.

In addition to seasonal values, calculations can also be performed using solar utilization factors on a monthly basis. This is discussed in Appendix B.

4. COMPARISON WITH EXPERIMENTAL DATA

The measured energy consumption for the NRC passive test units during the 1981-82 heating season[10], was compared with the corresponding consumption calculated using the solar utilization factor concept.

The NRC test facility[11], described in Reference 11, consists of four 2-room test units and four single-room units. Three of the four 2-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 Table I). 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 2-room units were operated in two modes, which 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°. The 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.

The comparison between the measured and the calculated energy consumptions is presented in Table II for both modes of operation. The corresponding seasonal solar utilization factors were obtained from

Figure 3 by interpolating between the curves for the appropriate value of the MGR. The calculated values show close agreement with the measured results; the maximum difference between the calculated and measured space heating energy is less than 5%.

5. USE AND LIMITATIONS

The use of solar utilization factor curves to estimate the heating energy requirement of houses is described in detail in Reference 12. The steps involved can be summarized as follows:

- calculate each of the loss and gain components of Equation 2,
- calculate the GLR from Equation 3,
- calculate the MGR from Equation 4 (or assume 1 for standard lightweight construction),
- obtain the utilization factor corresponding to the GLR and MGR by interpolation from Figure 1, 2 or 3 (depending on the desired allowable temperature rise),
- substitute this utilization factor into Equation 2 to obtain the heating energy requirement.

The utilization factors presented here are based upon a number of assumptions, some of which impose limitations on the use of the factors.

These utilization factors 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 sunspaces, 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 when forced air circulation is provided; however, 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, 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.

It should be noted that the accuracy of the heating energy estimate is more dependent on the calculation of heat losses and gains than it is upon the limitations of the solar utilization curves themselves. The heat loss and gain calculations must allow for factors such as the lowering of the thermostat setting at night; the exterior shading of windows by trees, buildings, overhangs, etc.; the use of blinds and drapes by the occupant; and the 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 to limit the 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 for calculating the contribution of solar heat gains for direct-gain passive solar designs as well as for houses of conventional and super-insulated construction.

REFERENCES

1. Barakat, S.A. Solar Heat Gains Through Windows in Canada, National Research Council of Canada, Division of Building Research, NRCC 18674, Ottawa, 1980.

2. Wray, W.O. Design and Analysis of Direct Gain Solar Heated Buildings, Los Alamos Scientific Laboratory, LA-8885-MS, 1981.

3. Cuplinskas, E.L. Residential Passive Solar Heating: Review of Development of Design Aids, Report to Ministry of Energy, Province of Ontario, February 1980.

4. Monsen, W.A., S.A. Klein, and W.A. Beckman. Predicting of Direct Gain Solar Heating System Performance, Solar Energy, Vol. 27, No. 2, pp. 143-147, 1981.

5. Hay, J. A Study of Shortwave Radiation of Nonhorizontal Surfaces, Canadian Climate Centre Report 79-12, Atmospheric Environment Service, Downsview, Ont., 1979.

6. ASHRAE Handbook of Fundamentals, Chapter 26, American Society of Heating, Refrigeration and Air Conditioning Engineers, New York, 1977.

7. ASHRAE Handbook of Fundamentals, Chapter 22, American Society of Heating, Refrigeration and Air Conditioning Engineers, New York, 1977.

8. Mitalas, G.P. Room Thermal Response Factors (in progress).

9. Barakat, S.A. and D.M. Sander. Thermal Response of Houses (in progress).

10. Barakat, S.A. DBR/NRC Passive Solar Test Facility, 1980/81 Thermal Performance (in progress).

11. Barakat, S.A. A Canadian Facility for Investigating Passive Solar Heating, presented at International Symposium on Experimental Research with Passive Solar Houses, Nice, France, December 1980.

12. Sander, D.M. et al. A Simple Method of Estimating Heating Requirements of Houses (in progress).

TABLE I

HOUSE WEIGHTS FOR COMPUTER SIMULATION		
	Thermal Capacity $MJ/\cdot Km^2$ 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 II

COMPARISON WITH EXPERIMENTAL RESULTS

Description	No. of days	Storage Capacity MJ/K	Ref. Load MJ	Solar Gain MJ	GLR	MGR hr/K	Seasonal Utilization Factor, η_s	Heating energy Measured MJ	Heating energy Calc. MJ	% Difference
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

Appendix A

SIMULATION RESULTS: SEASONAL SOLAR UTILIZATION

The data points obtained for Edmonton, Ottawa, and Halifax produced well-defined curves of solar utilization factor versus GLR for light, medium, heavy, and very heavy constructions (MGR equal to 1.0, 2.6, 7.2 and 14.0 hr/K, respectively), as well as for the zero-mass case. The root mean square (rms) error between these data points and the curve fit is less than 0.015. The data and corresponding curve fits are illustrated in Figures A1 to A3 for light, medium and heavy constructions only.

These figures also show that 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 characteristics of the climatic pattern for the West Coast region. Vancouver weather has long, cloudy and relatively cold periods with intermittent short, sunny and warmer periods. Even with high levels of thermal storage, the building load during such warm, sunny periods is very small, causing the excess gains to be eliminated once the room temperature has risen to the allowable limit. Consequently, the utilization factor is reduced.

Although the curves shown in Figures 1, 2 and 3 are directly applicable to the type of climate found in most of Canada, they will overestimate the solar utilization for regions with very overcast winter conditions. This indicates that another parameter may be needed to account for climatic variations. Further study is necessary to identify this parameter and the corresponding correction. In any case, the maximum error in the utilization factor is only about .08, even for Vancouver, which probably typifies the extreme of this type of winter weather for Canada. For a house with a GLR of 0.6, this would cause a maximum error of 5% in estimating heating energy requirements.

Appendix B

SIMULATION RESULTS: MONTHLY SOLAR UTILIZATION

Calculations may be performed using solar utilization on a monthly rather than on a seasonal basis. The values of the solar utilization factor and the gain-load ratios for each month of the heating season for all five locations are plotted in Figures B1 to B3, together with the curve showing seasonal solar utilization. Since the monthly utilization factors do not differ greatly from those for seasonal utilization, the rms error between the monthly data points and the curves, being in the order of 0.05, the seasonal utilization factor curves of Figures 1 to 3 could be applied on a monthly basis.

The scatter of points is considerably greater for monthly values than for seasonal values. This may be partially explained by the fact that the value of the MGR varies from month to month. In addition, the influence of the monthly climatic variation must be considered, as well as the effect of carry-over of stored energy in heavy constructions from one month to the next. All these factors may lead to significant errors in estimating the solar contribution for a particular month.

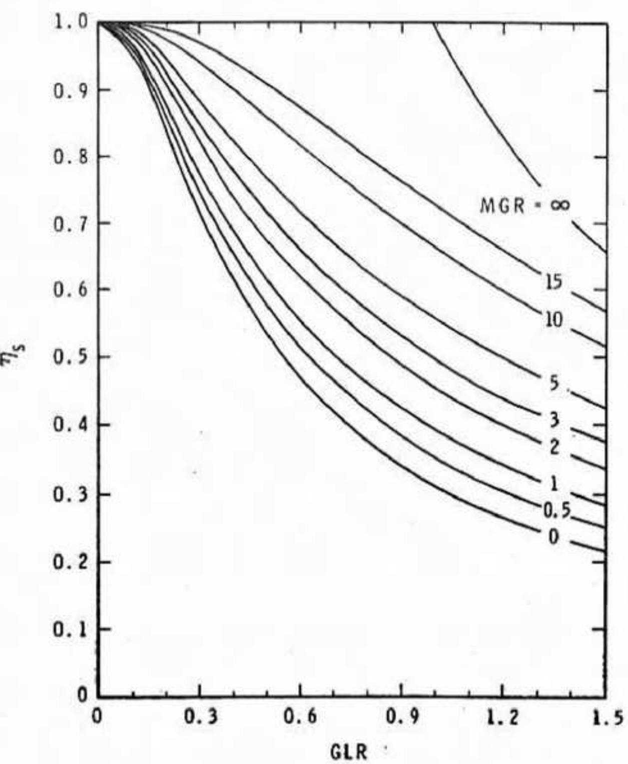


FIGURE 1

SEASONAL SOLAR UTILIZATION FACTOR
(CONSTANT ROOM TEMPERATURE)

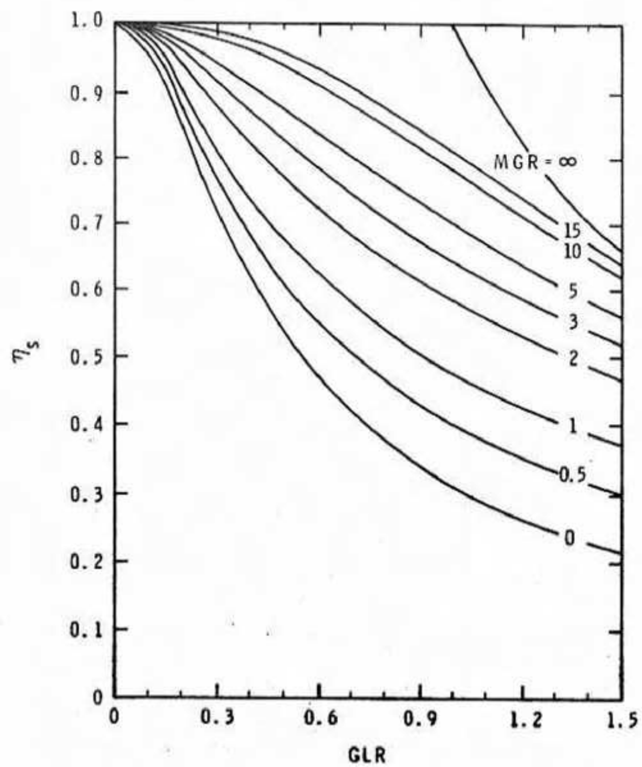


FIGURE 2

SEASONAL SOLAR UTILIZATION FACTOR
(ROOM TEMPERATURE SWING = 2.75°C)

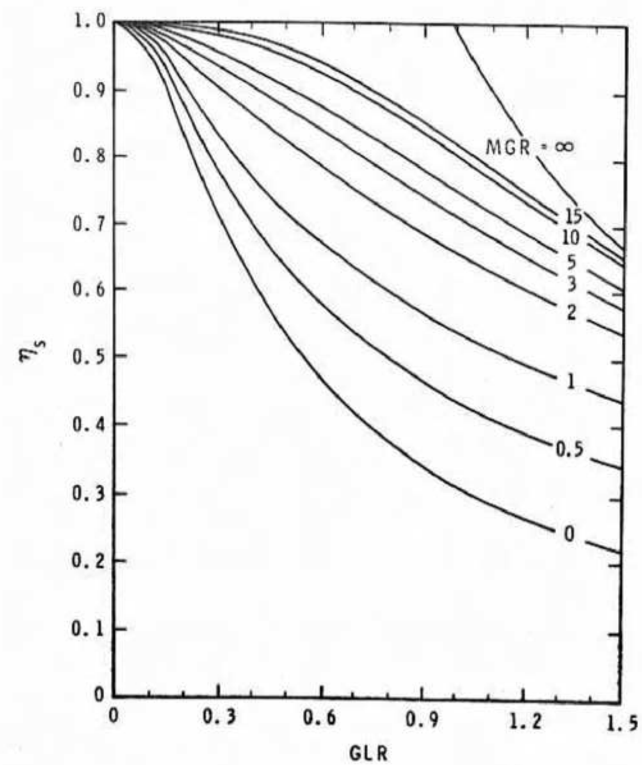


FIGURE 3

SEASONAL SOLAR UTILIZATION FACTOR
(ROOM TEMPERATURE SWING = 5.5°C)

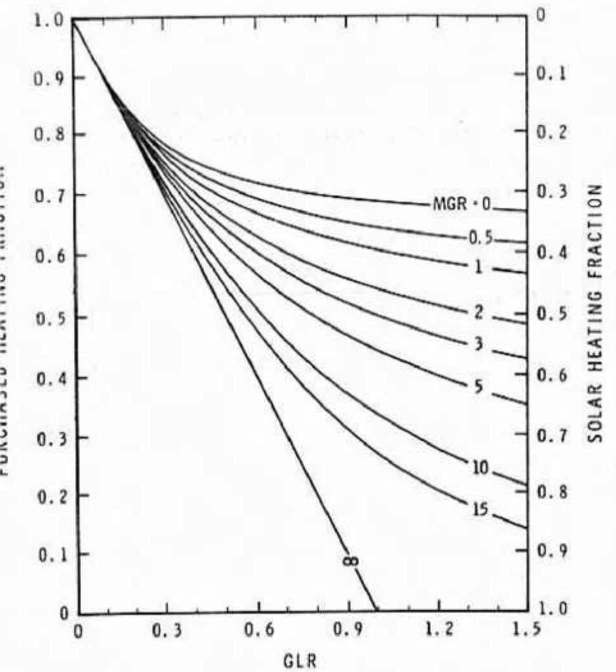


FIGURE 4
SEASONAL PURCHASED HEATING FRACTION
(CONSTANT ROOM TEMPERATURE)

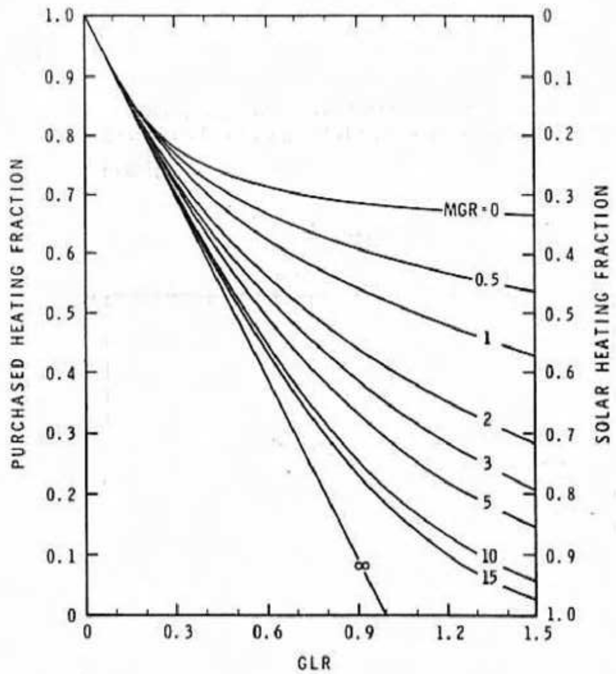


FIGURE 5
SEASONAL PURCHASED HEATING FRACTION
(ROOM TEMPERATURE SWING = 2.75°C)

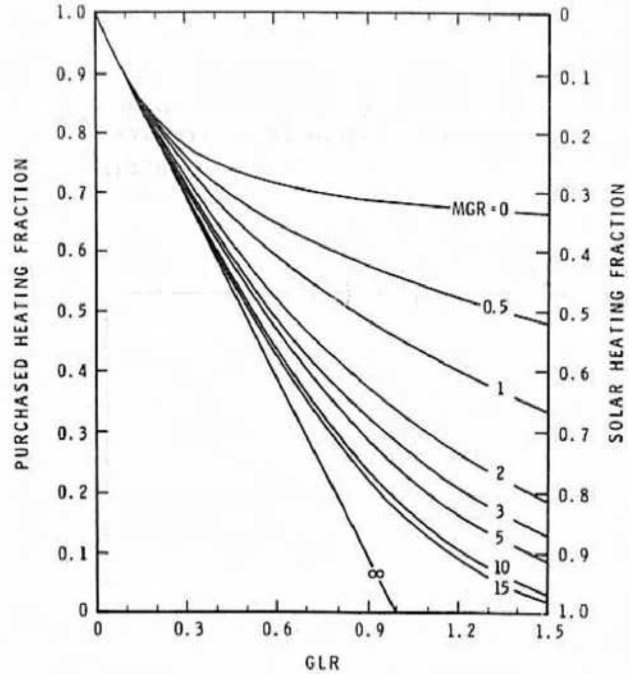


FIGURE 6
SEASONAL PURCHASED HEATING FRACTION
(ROOM TEMPERATURE SWING = 5.5°C)

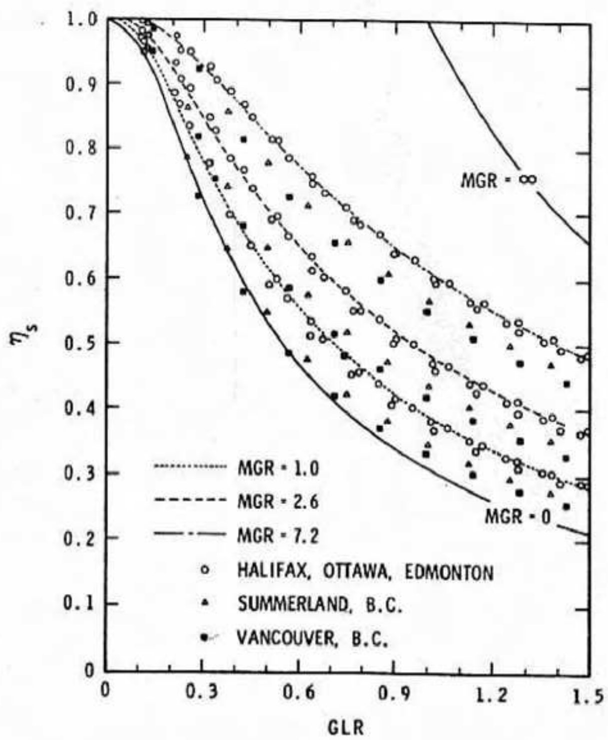


FIGURE A.1

SEASONAL SOLAR UTILIZATION CURVES, AND ACTUAL DATA POINTS FOR 5 LOCATIONS (CONSTANT ROOM TEMPERATURE)

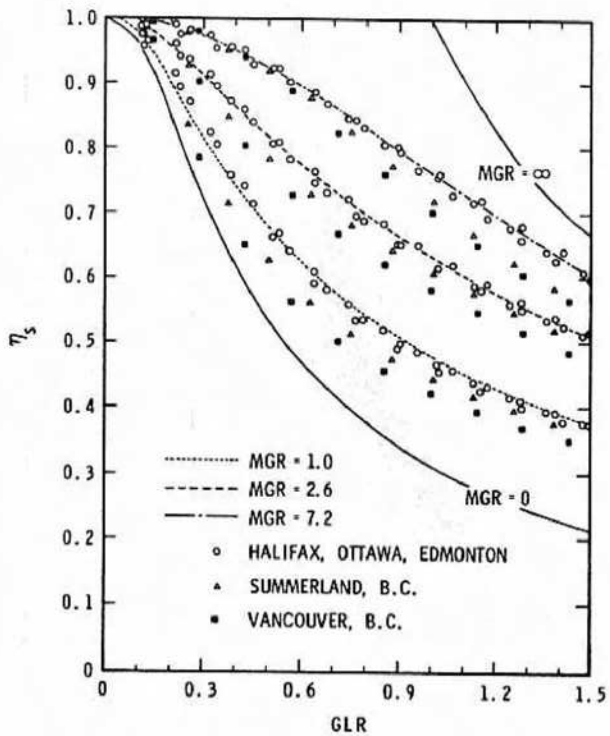


FIGURE A.2

SEASONAL SOLAR UTILIZATION CURVES, AND ACTUAL DATA POINTS FOR 5 LOCATIONS (ROOM TEMPERATURE SWING = 2.75°C)

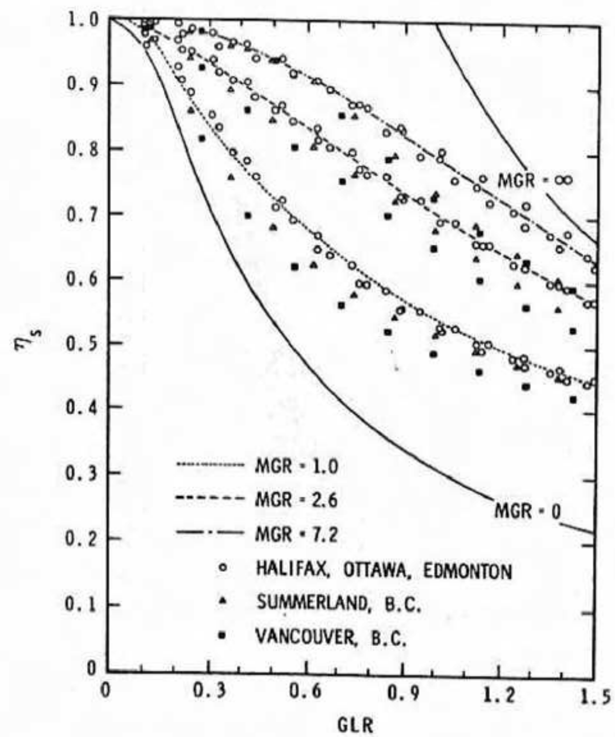
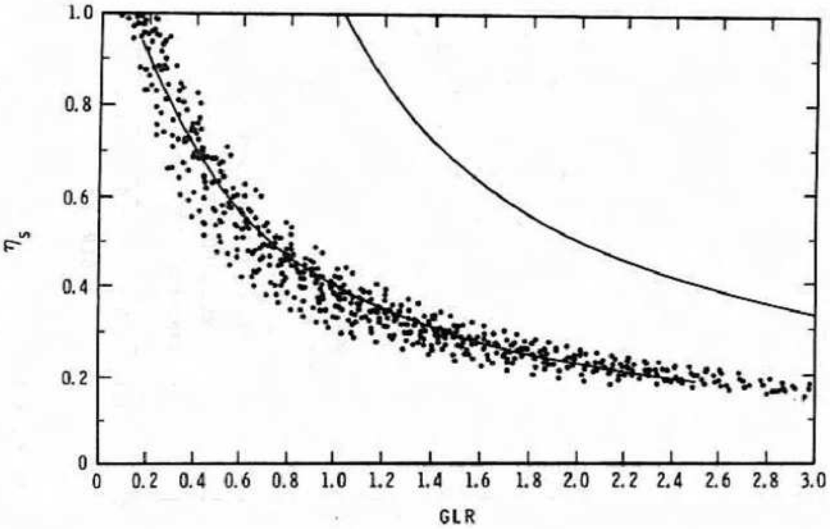
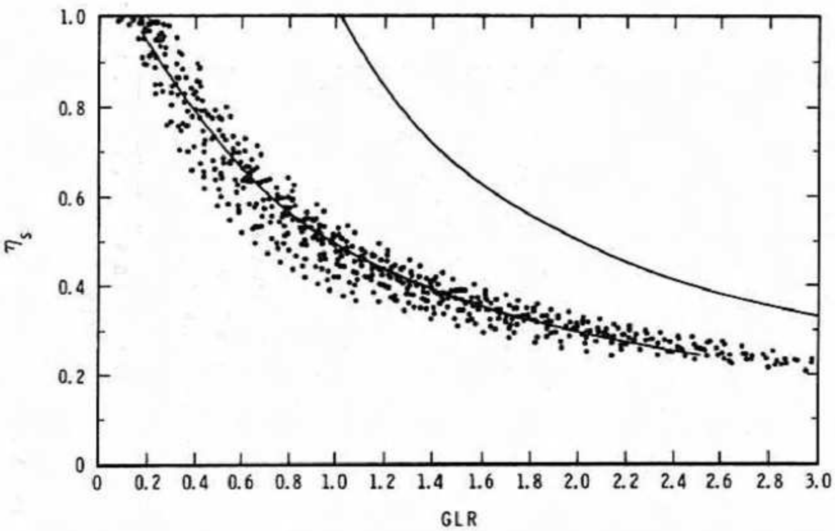


FIGURE A.3

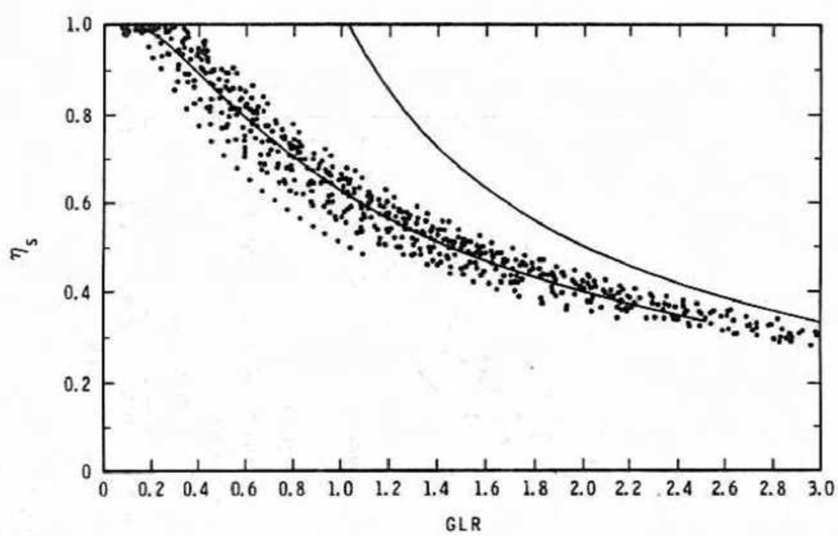
SEASONAL SOLAR UTILIZATION CURVES, AND ACTUAL DATA POINTS FOR 5 LOCATIONS (ROOM TEMPERATURE SWING = 5.5°C)



(a) LIGHT CONSTRUCTION (MGR = 1)



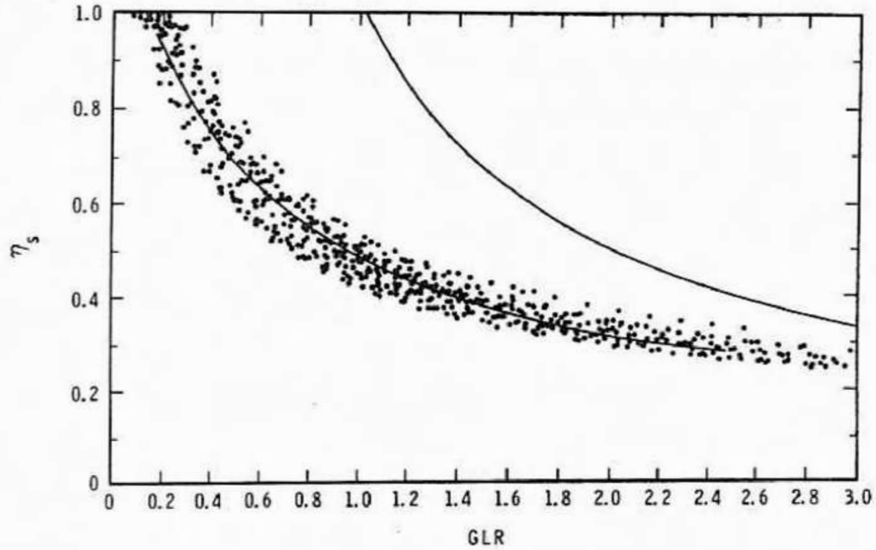
(b) MEDIUM CONSTRUCTION (MGR = 2.6)



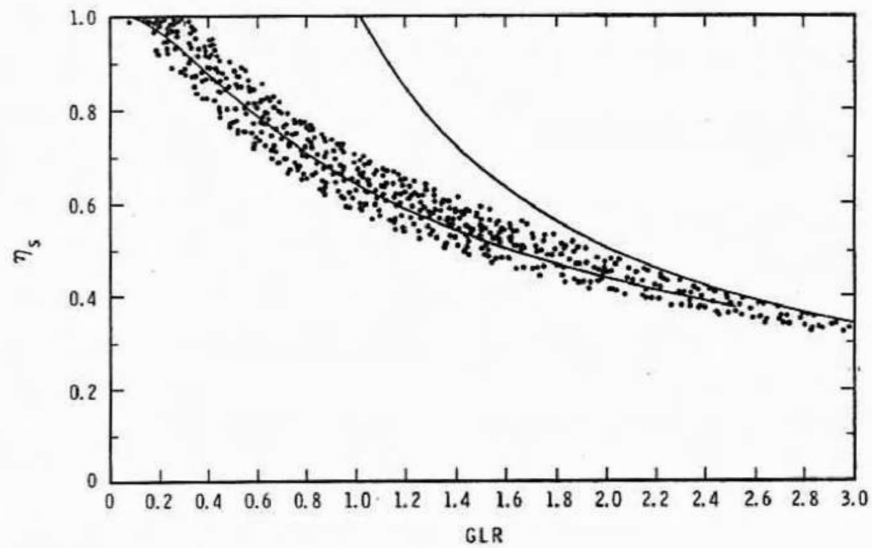
(c) HEAVY CONSTRUCTION (MGR = 7.2)

FIGURE B.1

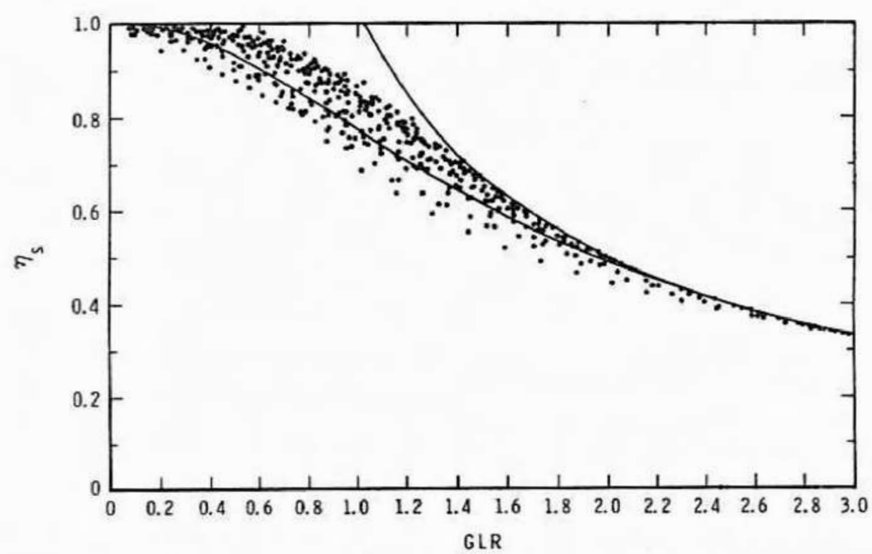
MONTHLY VALUES OF SOLAR UTILIZATION
(CONSTANT ROOM TEMPERATURE)



(a) LIGHT CONSTRUCTION (MGR = 1)



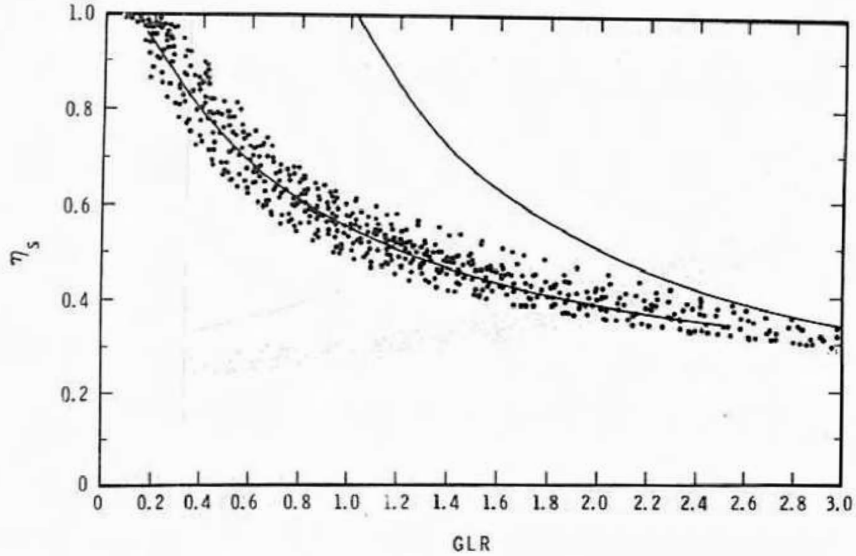
(b) MEDIUM CONSTRUCTION (MGR = 2.6)



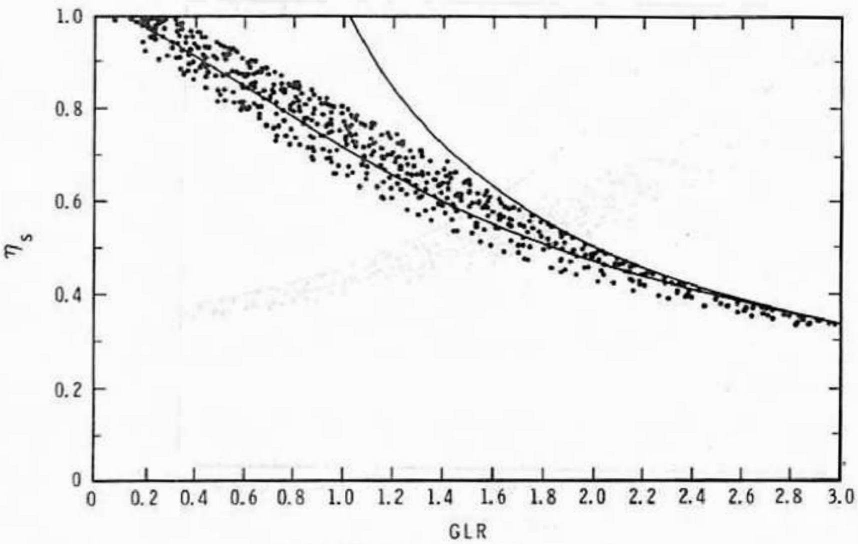
(c) HEAVY CONSTRUCTION (MGR = 7.2)

FIGURE B.2

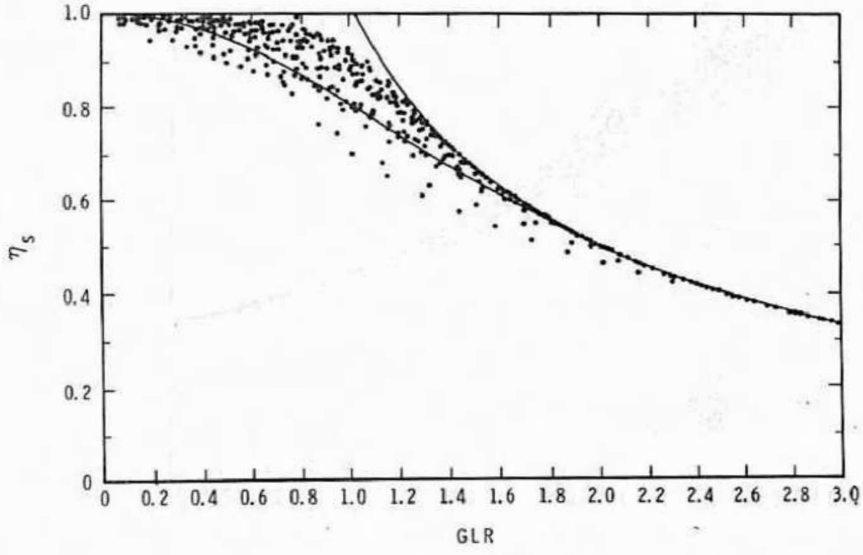
MONTHLY VALUES OF SOLAR UTILIZATION



(a) LIGHT CONSTRUCTION (MGR = 1)



(b) MEDIUM CONSTRUCTION (MGR = 2.6)



(c) HEAVY CONSTRUCTION (MGR = 7.2)

FIGURE B.3

MONTHLY VALUES OF SOLAR UTILIZATION