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TITLE: A PASSIVE-SOLAR DESIGN MANUAL FOR THE UNITED STATES NAVY

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A PASSIVE SOLAR DESIGN MANUAL FOR THE UNITED STATES NAVY

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ABSTRACT

A passive solar design manual for single-family detached residences and dormitory-type buildings is being developed at Los Alamos National Laboratory for the United States Navy. The design procedure employed in the manual is a simplification of the original monthly solar load ratio (SLR) method. The new SLR correlations involve a single constant for each system. The correlation constant appears as a scale factor permitting the use of a universal performance curve for all passive systems. Furthermore, by providing location-dependent correlations between the annual solar heating fraction (SHF)* and the minimum monthly SHF, we have eliminated the need to perform an SLR calculation for each month of the heating season.

1. BACKGROUND

This work began in FY 1981 with a contract from the U.S. Navy to study the retrofit potential of concrete-block buildings. The results of that investigation showed that both direct gain and thermal storage wall retrofits are quite appropriate for concrete-block buildings, because of their inherently massive character.[1,2] In FY 1982 the Navy decided to continue the work at Los Alamos by supporting the development of a passive solar design manual that would include design methods for new construction as well as retrofits. It was also decided that treatment of single family detached residences, which are typically much less massive than the larger concrete block structures, should be included in the manual.

The Navy further stipulated that the new design manual be an extension of "Design Calculation Procedure for Passive Solar Houses of Navy Installations, Vol. I - Vol. V,"[3] a set of design manuals developed for the Navy by Monika Lumsdaine at New Mexico State University (NMSU). Consequently, much of the character of the NMSU document will be retained, including the use of a universal performance curve to characterize the behavior of passive systems.

*The reader is advised to note that, in this paper, we use SHF rather than solar savings fraction (SSF), which appears in the standard SLR correlations. Also note that, in contrast to recent SLR practice, our thermal storage wall correlations employ nonzero values of G, a correlating parameter that may be interpreted as an effective aperture conductance.

2. THE FAST SOLAR LOAD RATIO METHOD

The new performance calculation procedure developed for the Navy design manual is called the fast solar load ratio (FSLR) method; this method relates the monthly solar heating fraction to the monthly solar load ratio through a scaling law. The new procedure is a direct extension of the original solar load ratio (SLR) method developed for passive solar buildings by Balcomb and McFarland.[4] This scaling law is then combined with a weather-dependent correlation between the annual solar heating fraction and the minimum monthly solar heating fraction, which usually occurs in January. Thus, the annual auxiliary heat requirements are obtained directly from a simple equation involving the solar load ratio for a single month.

2.1 Scaling Law for Monthly Performance

Monthly performance correlations for the FSLR method are developed in the following form:

$$SHF = 1 - e^{-SLR^*} \qquad (1)$$

where

$$SLR^* = f \cdot SLR \qquad (2)$$

is the scaled solar load ratio.

The parameter, f, is a system or design dependent scale factor, SLR is the monthly solar load ratio, and SHF is the monthly solar heating fraction. It will be recalled that the SLR is defined as

$$SLR = \frac{S/DD}{LCR + G} , \qquad (3)$$

where S (Btu/ft^2) is the monthly solar radiation absorbed by the system per square foot of collection area, DD (°F day) is the monthly heating degree days, G ($Btu/DD\ ft^2$) is the effective aperture conductance, and LCR ($Btu/DD\ ft^2$) is the load collector ratio of the building. The LCR is obtained by dividing the building-load coefficient, BLC (Btu/DD), by the solar collector area, A_c (ft^2). The BLC is defined as the amount of heat that would be required to maintain the air temperature in a building one degree Fahrenheit above the outdoor ambient temperature for a period of one day if no heat losses or gains were allowed through the solar aperture.

The monthly solar heating fraction is the fraction of the monthly reference heat load experienced by a building that can be met by solar energy transmitted through the collection apertures. Thus,

$$SHF = 1 - \frac{Q_A}{Q_L} , \qquad (4)$$

where

$$Q_L = (BLC + G \cdot A_c)DD \qquad (5)$$

is the monthly reference heat load, and Q_A is the monthly auxiliary heat.

The advantage of the form of the performance correlation given by Eq. (1) is that the behavior of all passive solar systems is represented by a single universal curve as depicted in Fig. 1. The algebraic simplicity of Eq. (1) makes it possible to develop a simple analytic expression for the annual auxiliary heat requirement as discussed in the next two subsections.

2.2 Correlation for Annual Performance

Employing functional analysis, Subbarao[5] demonstrated the existence of city dependent correlations between annual SHF and January SHF for all passive systems obeying a scaling law on the SLR. He also showed empirically that double glazed Trombe walls, water walls, and direct gain buildings, taken with or without night insulation, all satisfy annual performance correlations of the following form in 11 selected cities:

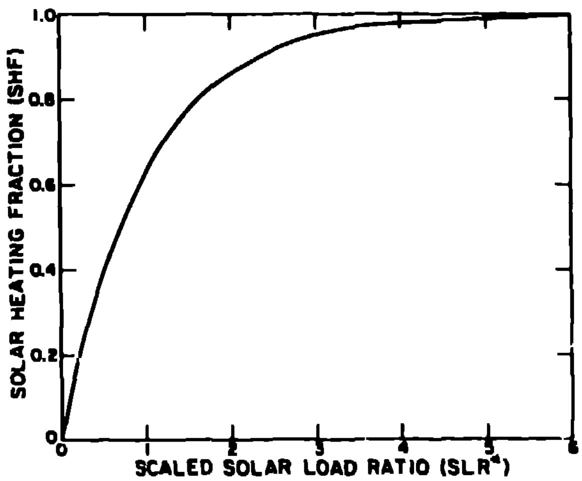

Fig. 1. Universal performance curve for passive solar buildings.

$$SHF_Y = SHF_J + SHF_J (1 - SHF_J) \cdot [a + b(0.7 - SHF_J)], \qquad (6)$$

where SHF_Y is the yearly SHF, SHF_J is the January SHF, and a and b are city-dependent constants. This is, of course, a potentially powerful concept and we have, therefore, investigated its practical applications.

We find that annual performance correlations similar to those suggested by Subbarao can, in fact, be obtained for any city for which monthly weather data are available. Consequently, such correlations have been developed for all 209 typical meteorological year (TMY)[5] cities in the continental United States. Our correlations differ from those suggested by Subbarao in three respects.

(1) Rather than correlating the yearly SHF to the January SHF, we correlated to the minimum monthly SHF, which does not always occur in January.

(2) Instead of the two-parameter form suggested by Subbarao in Eq. (6), we used the following single parameter equation:

$$SHF_Y = SHF_M [1 + a(1 - SHF_M)], \qquad (7)$$

where SHF_M is the minimum monthly SHF and "a" is the city dependent correlation parameter. The single parameter form was chosen for its algebraic simplicity and because it yielded acceptable accuracy. Standard deviations of less than 0.02 were obtained in all cases. A schematic representation of Eq. (7) is presented in Fig. 2. Note that SHF_Y limits to zero and unity when SHF_M is zero and unity, respectively. Also note that the difference between SHF_Y and SHF_M is at a maximum of a/4 when SHF_M is equal to 0.5.

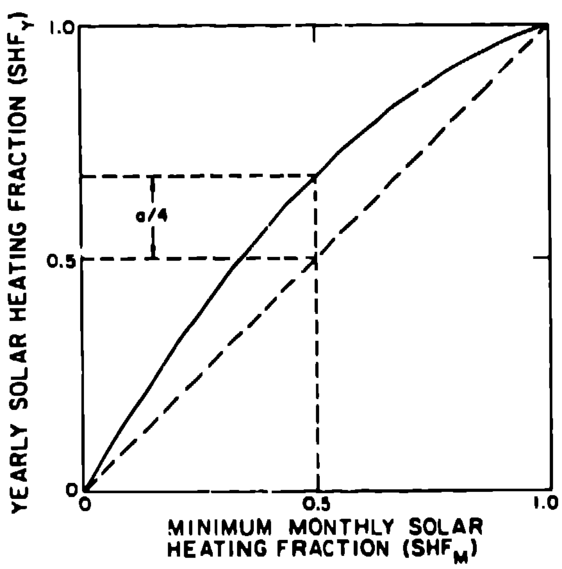

Fig. 2. Schematic of annual performance correlation.

(3) We observed that the parameter "a" depends not only on location, but also on any system variable that affects S (such as overhang dimensions, number of glazings, orientation, and tilt) or DD (such as the thermostat set point or the rate of heating by internal sources). We, therefore, determined appropriate values of "a" for systems with reference temperatures ranging from 40-70°F, with one, two, or three glazings and with azimuths varying from 60° east to 60° west of due south. Variations of "a" with the number of glazings were insignificant (half a percent at most) and, therefore, only the values calculated for double-glazed systems were retained. All systems were assumed to have no overhang and to have vertical apertures.

In summary, we now have available annual performance correlations for 209 TMY cities that are applicable to those single-glazed, double-glazed or triple-glazed systems that have azimuths within 60° of due south and reference temperatures between 40 and 70°F.

2.3 Combined Scaling Law and Annual Performance Correlation

The scaling law given by Eq. (1) may be combined with the annual performance correlation given by Eq. (7) to obtain a single expression for the annual auxiliary heat requirements. First, we write Eq. (1) for the month with the minimum solar heating fraction

$$SHF_M = 1 - e^{-SLR_M^*}, \tag{8}$$

where SLR_M^* is the minimum monthly solar load ratio. Then, substituting Eq. (8) into Eq. (7) yields

$$SHF_Y = \left(1 - e^{-SLR_M^*}\right)\left(1 + ae^{-SLR_M^*}\right). \tag{9}$$

Equation (4) may be employed to express SHF_Y directly in terms of the yearly auxiliary heat. Substituting Eq. (4) into Eq. (9) produces the desired relation.

$$\left(\frac{Q_A}{Q_L}\right)_Y = e^{-SLR_M^*}\left[a\left(e^{-SLR_M^*} - 1\right) + 1\right]. \tag{10}$$

Equation (10) is plotted in Fig. 3, which we refer to as the yearly heat-to-load ratio nomogram. One has only to calculate the minimum monthly solar load ratio and multiply by the appropriate system scale factor, F, a tabulated quantity, to obtain the appropriate scaled solar load ratio. A vertical line is then extended upward until the performance curve with the appropriate value of the city parameter "a" is intercepted. (The parameter "a", a tabulated quantity, depends on the city as well as certain other system parameters as previously noted.) Some interpolation may be required. Having intercepted the appropriate performance curve, we then extend a horizontal line from that point to the vertical axis and read the annual ratio of auxiliary heat to building load. Multiplication of this quantity by the annual load,

$$(Q_A)_Y = (BLC + G \cdot A_c)DD_Y, \tag{11}$$

where DD_Y is the annual degree day sum, yields the auxiliary heat required yearly.

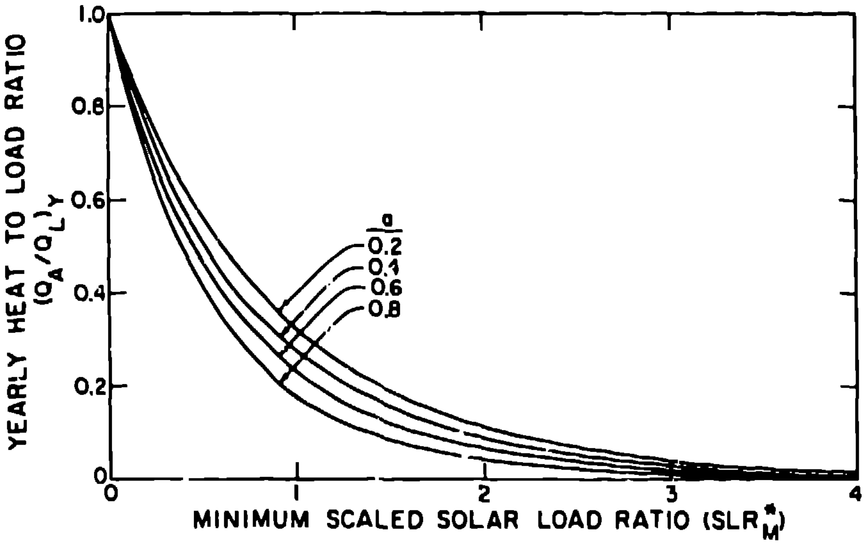

Fig. 3. Yearly heat-to-load ratio nomogram.

2.4 Yearly Heating-Cost Nomogram

In order to simplify the task of determining the economic consequences of various design decisions, one or more yearly heating cost nomograms will be included in the Navy design manual. The concept is illustrated in Fig. 4. The upper right quadrant in Fig. 4 is identical to the nomogram in Fig. 3 and serves to provide an estimate of the yearly heat-to-load ratio. (For clarity, only one of the performance curves is included in

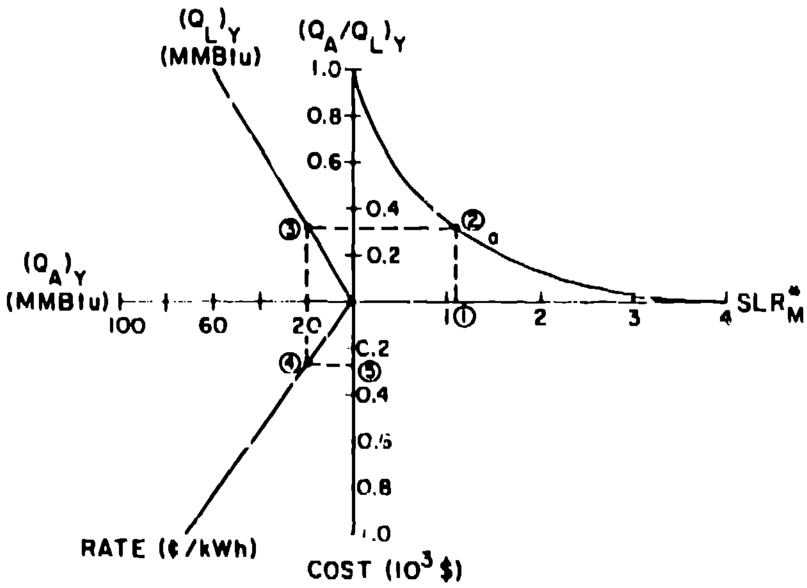

Fig. 4. Schematic of yearly heating cost nomogram.

Fig. 4.) The upper left quadrant contains a family of radial lines representing various values of $(Q_L)_Y$ (only one such line is shown) and the lower left quadrant contains a family of lines (only one is shown) representing various rates per kWh. The nomogram is used in the following manner.

(1) Calculate the minimum scaled solar load ratio and enter the value on the abscissa at point ①.

(2) Extend a vertical line from point ① until the curve with the appropriate value of "a" is intercepted. This procedure locates point ②.

(3) Draw a horizontal line left from point ② until the line with the appropriate value of $(Q_L)_Y$ is intercepted. The intercept is point ③.

(4) Drop a vertical line from point ③ into the lower left quadrant until the line indicating the appropriate rate is intercepted at point ④.

(5) Extend a horizontal line from point ④ to the ordinate. The intercept at point ⑤ gives the yearly cost of heating the building.

The procedure described above can be repeated for a series of designs that may then be evaluated on the basis of their cost effectiveness. Or, individual design decisions can be weighed by determining the resulting annual cost savings. The user must, of course, provide his own estimate of any marginal costs associated with passive solar features in order to determine if associated heating cost savings are sufficient to provide rapid payback.

3. SCOPE OF THE DESIGN MANUAL

3.1 Monthly Performance Correlation Matrix

A total of 109 performance correlations will be included in the Navy design manual. A matrix of 81 correlations for direct gain systems will enable the user to obtain a performance estimate for a wide variety of direct gain buildings by allowing 3 choices for each of the 4 primary design variables. The design options include:

Design options	
THICK = 2 in., 4 in., 6 in., AMOAG = 3, 6, 9, NGL = 1, 2, 3, RESNI = 0, 4, 9,	81 designs

where THICK is the thermal storage mass thickness, AMOAG is the ratio of thermal storage mass surface area to glazing area, NGL is the number of glazings, and RESNI (ft^2 F h/Btu) is the night insulation R-value.

Two smaller matrices of correlations for masonry thermal storage walls are to be provided. The two sets of design options are:

Design options	
THICK = 12 in., NGL = 1, 2, ρck = 15, 30, RESNI = 0, 9, VENTS = YES, NO,	16 designs

and

Design options	
THICK = 6 in., 18 in., NGL = 2, ρck = 30, RESNI = 0, VENTS = YES.	2 designs

The quantity ρck ($Btu^2/h\ ft^4\ F^2$) is the density-specific heat-thermal conductivity product of the thermal storage mass, and VENTS indicates the presence or absence of thermocirculation vents.

Six water-wall correlations will be provided. The following configurations are allowed:

Design options	
THICK = 9 in., NGL = 1, 2, RESNI = 0, 9,	4 designs

and

Design options	
THICK = 6 in., 12 in., NGL = 2, RESNI = 0.	2 designs

In this case, THICK refers to the effective thickness of the mass of water as if it were contained in a rectilinear enclosure that completely filled the solar aperture.

Finally, four specialized correlations are included for thermal storage walls made from 8-in. concrete building blocks. The correlation matrix is:

Design options	
THICK = 8 in., RESNI = 0, NGL = 1, 2, FILLED = YES, NO.	4 designs

The term FILLED refers to whether or not the concrete-block cores have been filled with mortar.

A table will be provided in the Navy design manual that gives the scale factor, F, the effective aperture conductance, G, and the effective solar absorptance of each of the 109 designs described above. Furthermore, the performance of any system involving a mixture of two or more of the above designs can be determined from the yearly heat-to-load ratio nomograms by using the area-weighted averages of F and G of the component systems.

3.2 Table of Weather Data and City Parameters

The TMY weather data base, containing 209 cities in the continential U.S., was selected for use in the Navy design manual. All radiation and degree day quantities reported in the design manual will be based on hourly summations of quantities on the TMY tapes.

In order to permit calculation of the annual heat load under a variety of thermostat settings and internal heating situations, annual DD summations for reference temperatures ranging from 40 to 70°F in 5°F increments will be included for each city. Additionally, the monthly summation of VT/DD will be tabulated for one, two, and three glazings, at each of the reference temperatures indicated above for the minimum SHF month in each city. The quantity VT is the radiation transmitted through a vertical south-facing solar aperture and must be multiplied by, α, the effective solar absorptance, to obtain S, the radiation absorbed by the system. Tabulation of VT/DD allows rapid calculation of SLR_M, the minimum monthly solar load ratio, for any system in any of the 209 locations. Furthermore, the values of VT/DD reported in the tables may be adjusted to account for variations in azimuth from 60° east to 60° west of due south by using a simple quadratic formula. The coefficients of the quadratic vary from city to city and will be given in the weather table.

Values of the city parameter, "a", are to be included in the weather table. For each city, the "a" parameter is specified for each reference temperature from 40 to 70°F assuming an orientation of due south. The "a" parameters can be adjusted for azimuths varying from 60° east to 60° west of due south by using a quadratic formula similar to that employed to adjust VT/DD. Again, the coefficients of the quadratic are city dependent and are to be included in the weather tables.

4. SUMMARY

Los Alamos is producing a passive solar design manual for the United States Navy. A new design calculation procedure called the fast solar load ratio method has been developed for use in the manual. The new method enables the user to quickly estimate the performance of 109 reference designs (or mixtures of those designs) in 209 U.S. cities. The speed and simplicity of the FSLR method makes it appropriate for use very early in the design process when potential is greatest for implementation of energy-saving design decisions.

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