CONF-900833--13

PNL-SA--17704

DE91 004078

NOV 26 1990

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August/September 1990

Presented at the
ACEEE 1990 Summer Study on Energy
Efficentcy on Buildings
Pacific Grove, California
August 26-September 1, 1990

Work supported by
the U. S. Department of Energy
under Contract DE- AC06-76RLO 1830

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Richland, Washington 99352

ACEEE 90

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SYNOPSIS

A simple residential heating load calculation method that explicitly accounts for solar gain utilization and closely reproduces DOE-2 simulation results is presented here.

ABSTRACT

A simple and well known method of estimating residential heating loads is the variable base degree-day method, in which the steady-state heat loss rate (UA) is multiplied by the degree-days based from the balance temperature of the structure. The balance temperature is a function of the UA as well as the average rate of internal heat gains, reflecting the displacement of the heating requirements by these gains. Currently, the heat gains from solar energy are lumped with those from appliances to estimate an average rate over the day. This ignores the effects of the timing of the gains from solar energy, which are more highly concentrated during daytime hours, hence more frequently exceeding the required space heat and less utilizable than the gains from appliances. Simulations or specialized passive solar energy calculation methods have previously been required to account for this effect.

This paper presents curves of the fraction of the absorbed solar energy utilized for displacement of space heat, developed by comparing heating loads calculated using a variable base degree-day method (ignoring solar gains) to heating loads from a large number of detailed DOE-2 simulations. The difference in the loads predicted by the two methods can be interpreted as the utilized solar gains. The solar utilization decreases as the thermal integrity increases, as expected, and the solar utilizations are similar across climates. They can be used to estimate the utilized fraction of the absorbed solar energy and, with the load predicted by the variable base degree-day calculation, form a modified degree-day method that closely reproduces the loads predicted by the DOE-2 simulation model and is simple enough for hand calculations.

INTRODUCTION

Space heating loads in residential buildings can be calculated by various techniques with varying degrees of detail. Complex hourly simulation models such as DOE-2 [York et al. 1980] can produce a wide variety of information on the performance of a building. Their drawback is that detailed input information on materials, construction, and operating conditions are needed along with hourly weather data, and the results are only as accurate as the input information.

A simpler, hand calculation method is the variable base degree-day method (VBDD) [ASHRAE 1985], which uses the steady-state heat loss coefficient (UA) and the heating degree-hours (HDH), a measure of the inside-outside temperature difference. The seasonal HDH are determined by integrating the positive hourly differences of a constant indoor air temperature known as the balance temperature minus the outside temperature. If the outside temperature is above the balance temperature, supplemental heating is not required to maintain the setpoint temperature because the heating requirements are met by "free" internal and solar heat gains. Internal gains are from heat sources such as lighting and appliances, while solar gains are insolation through both windows and opaque surfaces.

In the VBDD, the average levels of internal gains and solar gains are lumped together in the calculation of the balance temperature. Specifically, the balance temperature is the indoor air temperature less the average level of internal and solar gains divided by the UA.

The use of a seasonal average balance temperature is a key simplification of the VBDD. However, the balance temperature constantly changes as the solar and internal gains change. In reality, all solar gains occur during the daytime, the period with both the highest internal gains and highest outside temperature. Therefore, the solar gains tend to be less utilizable than the internal gains, on the average. (Utilizable gains offset heating loads; unutilizable gains are "lost" through internal temperature float above the heating setpoint or venting of unwanted heat.)

The method developed here implicitly accounts for the utilizability of internal gains in the calculation of degree-hours, as is done in the VBDD. The key product from this research is the determination of the utilizable solar gains, which allows a more accurate treatment of the effects of solar radiation in seasonal space heating load calculations. The utilization of solar gains has been extracted from an extensive DOE-2 energy data base and can be explicitly calculated based on climate parameters and the building characteristics. The technique presented here is thus an improved degree-day method for lightweight structures that produces results that are in close agreement with DOE-2.

METHODOLOGY

Figure 1 illustrates how the internal and solar gains are typically distributed in a day. Daily patterns of internal gains, solar gains, and outside air temperature are shown. The internal gain pattern is the schedule used in the DOE-2 simulations upon which this work is based. The solar gains and the outside air temperatures are examples taken from actual weather data.

The solar gains are much more concentrated in the daytime than are the internal gains. The internal gains do show some variation, but are relatively constant. Also, the solar gains are at a maximum when the outside temperature is near its maximum and thus the envelope heat loss is at a minimum, reducing their utilizability.

Figure 2 illustrates the definition of utilizability of gains. For this example, assume that, neglecting internal gains, a constant 4500-Btu/hr supply of heat is needed to heat the house. The large triangular shape is the same daily solar gain distribution seen in Figure 1. The solar heat gains below the 4500-Btu line are utilized in meeting the heating demand, with the remainder of the heating requirements supplied by the heating system. All

FIGURE 1. Typical Daily Heat Gain and Outdoor Temperature

FIGURE 2. Simplified Example of Solar Utilizability

solar gains above the 4500-Btu line are not useful (assuming no heat is stored in thermal mass). This example illustrates how not all gains are utilizable, as well as the dependence of the utilization on the timing of the gains. Utilizability is defined as the fraction of the gains that is used to displace heating loads. The utilizability concept has been successfully used for passive solar design methods [Monsen et al. 1981]. Note that if the internal gain distribution from Figure 1 instead of the solar gains were plotted in this example, all internal gains would be utilized.

Figures 1 and 2 show that internal gains, on average, tend to be more useful in contributing to heating requirements on a daily level. On a seasonal level, for many climates, daily solar gains are much greater in the spring and fall than in the winter, compounding the lower utilizability of solar gains. This indicates that, if all solar gains were averaged across the entire heating season (to calculate the balance temperature), their value will be overrated. The low solar gains in the dead of winter are offset to some degree by the seasonal variation of internal gains, which will tend to be highest in the winter.

Internal gains vary hourly, and some inaccuracy will result from the assumption of constant internal gains. The error of assuming constant internal gains is illustrated in Figure 3 relative to the overall gain pattern. The solid line shows the solar gains plus a constant internal gain over the day. The line with the large dashes is the solar gains plus the

FIGURE 3. Effect of Constant Internal Gain Assumption

varying internal gains (the dotted line) assumed in the DOE-2 simulations. Although the solar with constant internal gains differ somewhat from the solar with internal gains that vary by time of day, the error is relatively small.

SOLAR UTILIZABILITY CALCULATION

The seasonal heating load can be written as

$$HL = [\ (UA)\ HDH_{Tr} - \Phi_i\ I\ ] - \Phi_s(\ SF\ A_g\ S_g + e_w\ A_w\ S_w + e_r\ A_r\ S_r + e_f\ A_f\ S_f\ ) \qquad (1)$$

where
- HL = seasonal heating load (Btu)
- UA = heat loss coefficient for envelope & infiltration ($Btu/hr \cdot ft^2 \cdot {}^\circ F$)
- HDH_{Tr} = heating degree-hours based on the room temperature ($hr \cdot {}^\circ F$)
- Φ_i = seasonal utilizability of internal heat sources
- Φ_s = seasonal utilizability of solar heat sources
- I = internal heat generation (Btu)
- SF = shading fraction (for external shading, sash, glass, and curtains)
- e_n = average solar efficiency of nth opaque surface
- A_n = area of nth building component (ft^2)
- S_n = solar radiation incident on nth building component (Btu/ft^2)

The subscripts g, w, r, and f represent the glazing, wall, roof, and foundation, respectively. Average heating season incident solar radiation can be obtained from monthly weather data and should account for the orientation of each envelope component. The opaque surface efficiency, e, is the fraction of the incident solar energy that is absorbed and transferred inside the building for each surface:

$$e = a\ R_o\ /\ (\ R_w + R_o\ ) \qquad (2)$$

where a is the absorptance of the surface (related to color), R_o is the outside air film resistance, and R_w is the resistance of the envelope component.

If the rate of internal heat generation is considered to be uniform over the heating season, then the first two terms can be combined using the balance temperature concept to form

$$[\ (UA)\ HDH_{Tr} - \Phi_i\ I\ ] = (UA)\ HDH_{Tb} \qquad (3)$$

where the balance temperature $T_b = T_r - I\ /\ (UA)$, and HDH_{Tb} is the heating season degree-hours based on the balance temperature.

The seasonal utilizability of the (assumed constant) internal gains is implicitly accounted for in the change in heating degree-hours resulting from changing the reference temperature from the room temperature to the balance temperature. Combining all solar gains terms, Equation (1) becomes

$$HL = (UA)\ HDH_{Tb} - \Phi s\ SG \qquad (4)$$

where SG (the total solar heat gain into the building) = $SF\ A_g\ S_g + e_w\ A_w\ S_w + e_r\ A_r\ S_r + e_f\ A_f\ S_f$.

A national data base of annual residential heating requirements has been generated with the DOE-2 simulation model for the use in the U.S. Department of Energy (DOE) Voluntary Residential Standards (these simulations will be explained in a forthcoming DOE report, Technical Documentation for a Residential Energy Use Data Base Developed in Support of ASHRAE Special Project 53.) This data base is incorporated in the software ARES, which produces location-specific compliance forms for the DOE energy standard [Pacific Northwest Laboratory 1989]. The heating loads (HL) in Equation (3) can be obtained from the DOE-2 data base as a function of climate, several prototypical building designs and level of energy conservation measures such as insulation levels, number and type of glazing, etc. Building UAs can be calculated from building characteristics, and solar gains (SG) can be reasonably estimated from weather data. HDH_{Tb} can also be determined from weather data, the UA, and the average level of internal gains. The only remaining unknown in Equation (4), the solar utilizability, can then be calculated:

$$\Phi_S = [\, HL_{DOE2} - (UA)\, HDH_{Tb} \,] \,/\, SG \qquad (5)$$

To date, only a single basic house design has been studied to determine solar utilizabilities. The prototype modeled is a one-story ranch house with a crawlspace foundation. Weather Year for Energy Calculations (WYEC) data were used by the DOE-2 simulation to represent typical climate conditions, and therefore were used also to calculate HDH and SG. Table 1 shows additional basic information on the DOE-2 simulation prototype. It is important to note that, although a specific prototypical building was simulated, the technique developed here relies on it only to properly account for the utilization of gains as a function of building and climate parameters.

Table 1. DOE-2 Prototype Parameters

Parameter	Simulation Assumption
Floor Area	1540 ft^2
Interior Mass	6.87 lb/ft^2 of floor area
Window Area	10% of floor area
Window Distribution	25% north, east, south, and west
Interior Shading Coefficient	0.80 for heating, 0.63 for cooling
Infiltration	Sherman-Grimsrud model
Internal Gains	2338 Btu/h (average)
Internal Setpoint	70°F, no setback

The assumptions used in the creation of the DOE-2 data base had to be matched closely to accurately extract the utilizabilities. The DOE-2 data base contained detailed input information and an effort was made to match these assumptions whenever possible in the calculations for the shell UA, internal gains, and solar gains. For example, solar gains through opaque surfaces were accounted for and were found to be a significant fraction of the window solar gains. The infiltration into the house was simulated with the Sherman-Grimsrud method, and the simulated air change rates were readily available from compiled information on the data base. Infiltration air flow into the crawlspace was not available and was estimated using Equation (25) in the 1985 ASHRAE Handbook--Fundamentals (p22.16-22.17.) Note that the DOE-2 assumptions were required only to extract the solar utilizabilities; other assumptions can be used when applying the technique developed here to predict heating loads.

In the DOE-2 data base, a wide range of building UAs was studied by incrementally changing energy conservation measures to increase the thermal resistance. This simulation scheme was followed in the utilizability calculations, with 14 specific UA levels ranging from about 230 Btu/hr·°F to 100 Btu/hr·°F examined. The loosest design had insulation only in the ceiling, single glazing, and high infiltration. The tightest design had R-49 ceiling, R-34 walls, and R-30 crawlspace insulation levels, triple glazing, and very low infiltration.

The generated solar utilizabilities were examined as a function of the solar load ratio (SLR), a common parameter in passive solar design [Monsen et al. 1981; Jones et al. 1982]. The SLR is the ratio of the yearly total solar gains divided by the conductive heating requirements neglecting solar gains:

$$SLR = SG \;/\; [\; (UA_{cond})\; (HDH_{Tb})\;] \qquad (6)$$

Complete utilization of all solar gains in offsetting heating requirements is a utilizability of 1. A high SLR indicates a tight building with low conductive heat losses in a sunny climate. As the building thermal integrity increases for a climate, the SLR increases and the utilizabilities will decrease. This is because the buildings have more solar gains relative to heating needs, and therefore can make less use of the available insolation.

A total of 15 cities across the U.S. were examined. These cities cover a diverse range of climates, from mild climates such as Lake Charles, LA, to cold climates such as Bismarck, ND. Table 2 lists these cities.

Table 2. Cities Studied

Albuquerque, NM	Chicago, IL	Nashville, TN
Bismarck, ND	El Paso, TX	New York, NY
Boise, ID	Fort Worth, TX	Omaha, NE
Boston, MA	Lake Charles, LA	Seattle, WA
Charleston, SC	Medford, OR	Washington, D.C.

RESULTS

Figure 4 shows the utilizabilities versus the SLR for all scenarios examined. All solar heat gains throughout the year are included in the total solar gains. Each point represents one of the fourteen thermal integrity levels for one of the 15 climates. The curve through the center of these points is a lowess curve (*lowess* stands for locally-weighted regression scatter plot smoothing), which is determined by a robust regression, and roughly approximates the median utilizability at any SLR. As a whole, the solar utilizabilities are low because most insolation occurs in the cooling and swing seasons when there is typically no or very little heating load. As expected, the yearly solar utilizability was much lower for mild climates, which have short heating seasons and high SLRs.

As most data points occur at low SLR ratios, it is informative to examine a subset of the data in Figure 4 in more detail. Figure 5 shows four of the

FIGURE 4. Relationship Between Solar Utilizability and the Solar Load Ratio at 15 Locations and 14 UA Levels

FIGURE 5. Sample Solar Utilizability Curves with Logarithmic Axes

individual climates on a plot with logarithmic axes. These lines illustrate the typical degree of "non-smoothness" or "noise" that is apparently caused from inaccuracies in matching the DOE-2 data base with the degree-day-based heat loss calculation and solar gain calculation used here. On any line, each positive increment in the SLR indicates a building with a lower heating load that should have a slightly lower utilizability (this can be seen on Figure 2, as unutilized gains increase if the heating load is lowered). This general trend is not always the case because of the noise in the results.

From Figure 4, the utilizability is clearly a function of the SLR, but there is a considerable scatter of utilizabilities about any given SLR. A more detailed examination of climate attributes revealed that much of this scatter could be explained. The SLR is based on only the absolute solar gains and degree-hours, and no consideration is given to the distribution of these parameters throughout the heating season. For example, Seattle has a long but mild heating season while Chicago has a shorter but more severe season. Similarly, Seattle has very little solar radiation in the depth of winter while Albuquerque is very sunny at that time of year. Much of the scatter in the utilizabilities can be explained by the solar and temperature patterns across the year for each climate.

Figure 5 indicates that the set of data points for each climate can be reasonably approximated by a line in a log-log plot. A linear regression of the form produces two coefficients defining each line,

$$\log(\Phi_s) = a + b\ (\log(\mathrm{SLR})) \qquad (7)$$

This equation can be rewritten as

$$\Phi_s = \exp(a)\ (\mathrm{SLR})^b \qquad (8)$$

The coefficients a and b were produced from regressions for each of the 15 climates. A multivariate regression analysis was then conducted to correlate both the coefficients to the seasonal characteristics of the various climates. The most significant parameters were (1) the ratio of January HDHs to yearly HDHs (base 60°F), and (2) the ratio of January horizontal solar radiation ($\mathrm{Btu/day \cdot ft^2}$) divided by January HDHs (°F·hr, base 60°F).

The ratio of January to yearly heating degree-hours is a measure of how harsh the heating season is relative to its length. The utilizability decreases as this ratio increases, because a deep but short winter climate can make less use of swing season solar gains than can a more extended heating season climate. The January horizontal solar radiation to heating degree-hour ratio accounts for the mid-winter solar gains relative to mid-winter outside temperatures. The utilizability tends to be higher when this ratio is larger because solar gains are relatively high in the depth of winter, when they can be best utilized.

The coefficients for each climate were regressed against the two significant climate parameters to determine functional relationships:

$$a = 0.443 - 8.149\ (HDH_{jan}/HDH_{year}) + 0.332\ (sol_{jan}/HDH_{jan}) \qquad (9)$$

$$b = -0.981 + 3.396\ (HDH_{jan}/HDH_{year}) + 0.321\ (sol_{jan}/HDH_{jan}) \qquad (10)$$

where HDH_{jan} = January heating degree-hours, base 60°F
HDH_{year} = yearly heating degree-hours, base 60°F
sol_{jan} = January horizontal solar

With Equations (8), (9), and (10), utilizabilities can be readily determined for any climate where monthly weather data is available. The difference between the utilizabilities generated from the DOE-2 data and the utilizabilities calculated from Equations (8), (9), and (10) for each of the 15 climates studied is the residual error of the hand calculation method. Figure 6 shows this residual error, about the same lowess curve (the solid curve) from Figure 4, to illustrate the scatter that still exists after the DOE-2-based utilizabilities are corrected for the two significant climate variables. All data points would lie on the lowess curve if the hand-calculated utilizabilities perfectly matched the DOE-2-generated utilizabilities. The mean absolute difference of the utilizabilities of all data points from the median curve is reduced from 0.129 in Figure 4 to 0.034 in Figure 6. This indicates that the two most significant climate parameters account for much of the scatter about the median utilizability in the original results. Note that about a third of the remaining error is attributable to inexact matching of the DOE-2 assumptions (the noise about the linear regression for each city, illustrated in Figure 5).

FIGURE 6. Solar Utilizabilities Adjusted by Climate Correctors. There is Less Scatter Compared to the Unadjusted Utilizabilities in Figure 4.

APPLICATION OF UTILIZABILITY METHOD

The method developed here is a simple-to-use enhancement of the VBDD. A sample application of the solar utilizability concept is shown below for Chicago.

Assume for this example that UA = 600 Btu/hr·°F, T_b = 60°F, and SG = 30e6 Btu. The yearly solar gain (SG) can be calculated using equations (1) and (2), with published weather data, for example, Olsen [1984].

From WYEC data, HDH_{janH}/HDH_{year} = 0.2044, sol_{jan}/HDH_{jan} = 0.5764, and HDH_{Tb} = 122832°F·hr.

UA x HDH_{Tb} = 73.7e6 Btu
SLR = SG/ (UA x HDH_{Tb}) = 0.407
From Equation (9) and (10), a = -1.031, b = -0.102
From Equation (8), Φ_s = 0.391
From Eq. 4, HL = 73.7e6 - 0.391 (30e6) = 62.0e6 Btu

Recalculating the heating load using the standard VBDD with solar gains included in balance temperature calculation yields

SG = 30e6 Btu/year = 3424 Btu/hr
$T_b = T_b - Q_s/UA$ = 60 - 3424/600 = 54.3°F
HDH at 54.3°F ≈ 93480°F·hr, and HL = 600 x 93480 = 56.1e6 Btu [or Φ_s = 0.59]

Using a SG reduced by 17% to represent the average of non-summer months (instead of the yearly average) produces only slightly different results: SG = 2860 Btu/hr, Tb = 55.2°F, HDH ≈ 95066°F·hr, and HL = 57.0e6 Btu

The heating load determined by the solar utilizability technique is 10.5% higher than the standard VBDD. The lower load obtained when the solar gains are included in the balance temperature calculation can be attributed to two factors: (1) primarily, the averaging of solar gains over the day overrates the utilization of the solar heat gains, and (2) secondarily, the heating season solar gain rate is less than the yearly average solar gain rate.

The mean absolute difference between the utilizabilities calculated by Equations (8) through (10) and the DOE-2-based utilizabilities is 0.034. The calculation below shows the effect of adding this average uncertainty to the calculated utilizability (0.391) on the heating load for the Chicago example:

Assume Φ = 0.425 -> HL = 73.7e6 - 0.425 (30e6) = 61.0e6 Btu

This change in the utilizability resulted in only a 1.6% change in the seasonal heating load.

CONCLUSIONS

The use of the DOE-2 data base to produce utilizabilities for a wide range of climates has allowed the calculation of solar gain utilizability as a function of climate and building UA. This utilizability can be calculated from commonly available meteorological data. Good agreement is obtained when comparing the results of this method back to the DOE-2 data base: the heating loads differ by only a few percent.

The heating load calculation method presented here is a significant advancement of the VBDD. The results indicate that the usefulness of solar gains is greatly exaggerated by the balance temperature concept. Furthermore, a key improvement from the utilizability method is that the average heating season hourly solar heat gain rate is no longer needed. This eliminates one source of uncertainty and error in the VBDD.

This research examined only one basic, generic housing structure, with the building UA the only parameter being varied. The solar utilizability is not expected to change significantly with the geometric shape, but other building parameters including internal mass, ground mass coupling, and window area and distribution will affect the utilizability. In addition, the effect of operating conditions such as thermostat setbacks has not been examined. Further work to study the impact of these building parameters and operating conditions on the solar utilizability is suggested to make the technique more general.

ACKNOWLEDGMENTS

We would like to thank Joe Huang of Lawrence Berkeley Laboratory for his assistance.

Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

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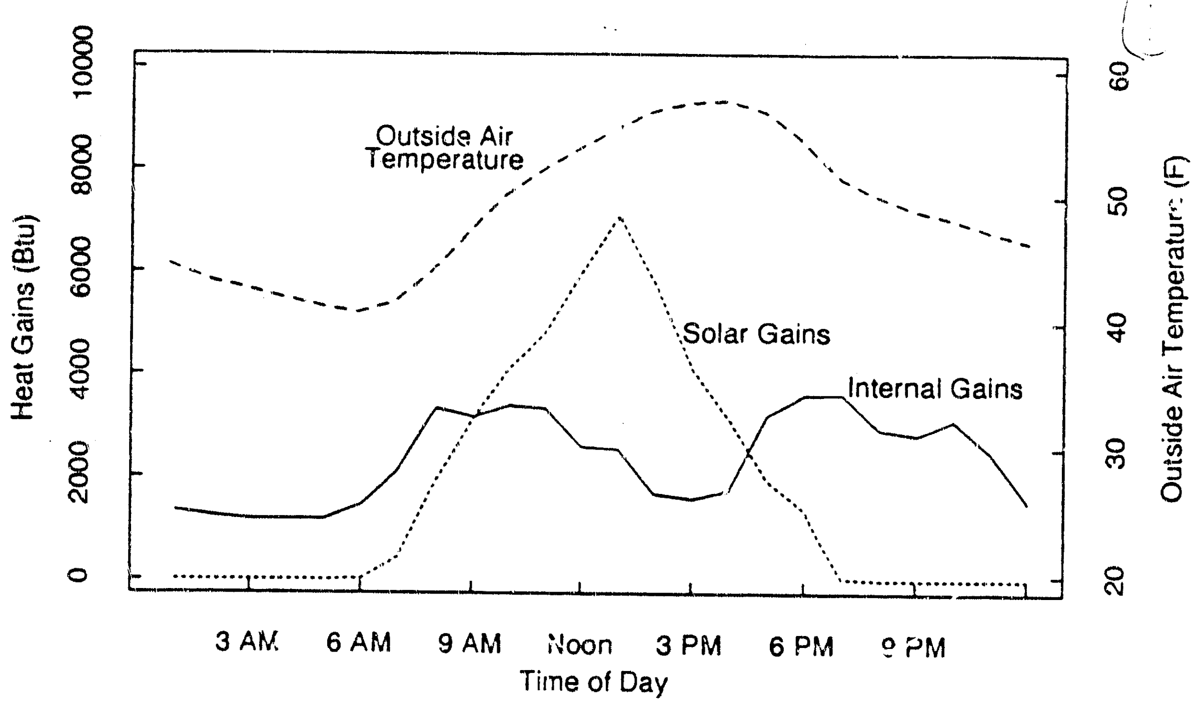
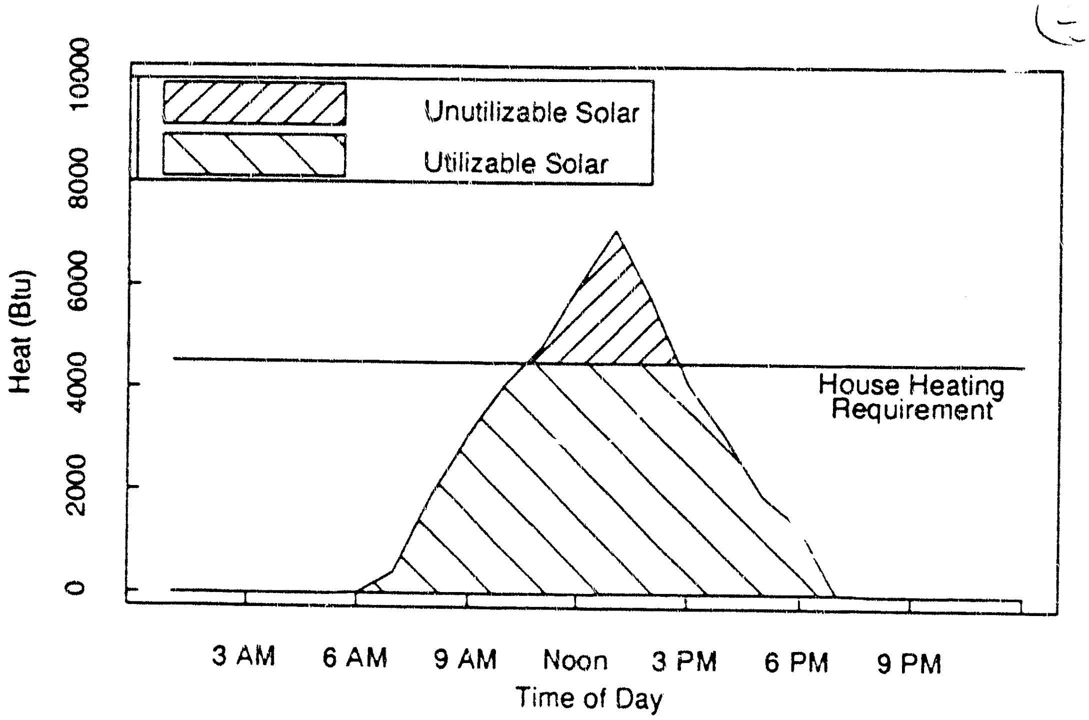
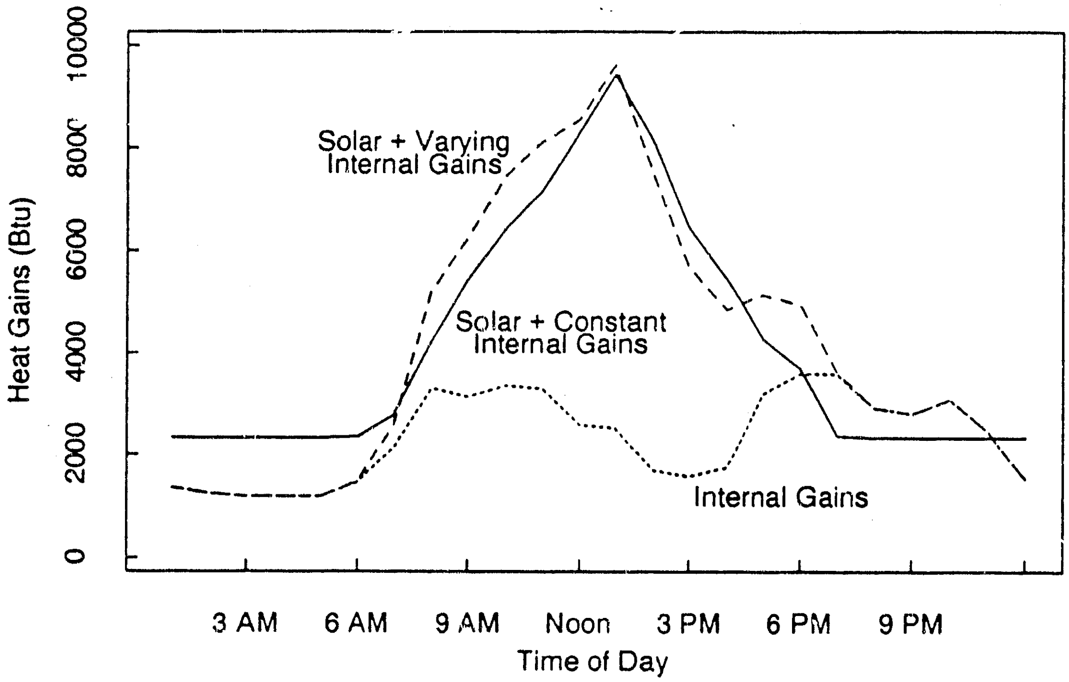


Outside Air Temperature
Solar Gains
Internal Gains
Heat Gains (Btu)
Outside Air Temperature (F)
3 AM
6 AM
9 AM
Noon
3 PM
6 PM
9 PM
Time of Day



Unutilizable Solar
Utilizable Solar
House Heating Requirement
Heat (Btu)
3 AM
6 AM
9 AM
Noon
3 PM
6 PM
9 PM
Time of Day


Heat Gains (Btu)
0
2000
4000
6000
8000
10000
Solar + Varying
Internal Gains
Solar + Constant
Internal Gains
Internal Gains
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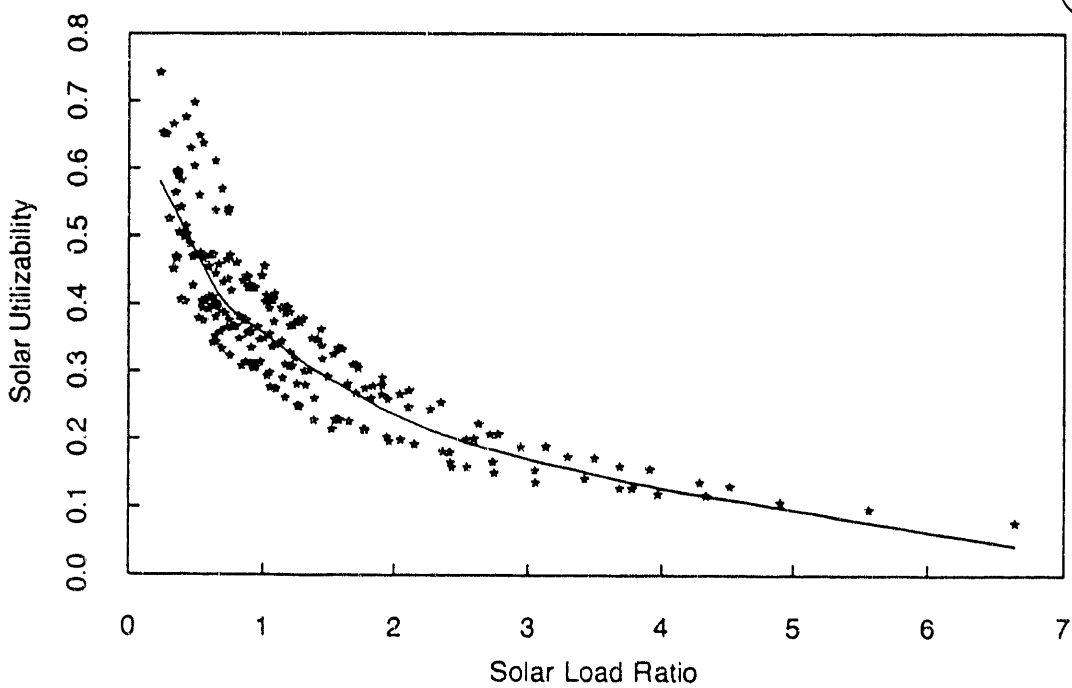
9 AM
Noon
3 PM
6 PM
9 PM
Time of Day


Solar Utilizability
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0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
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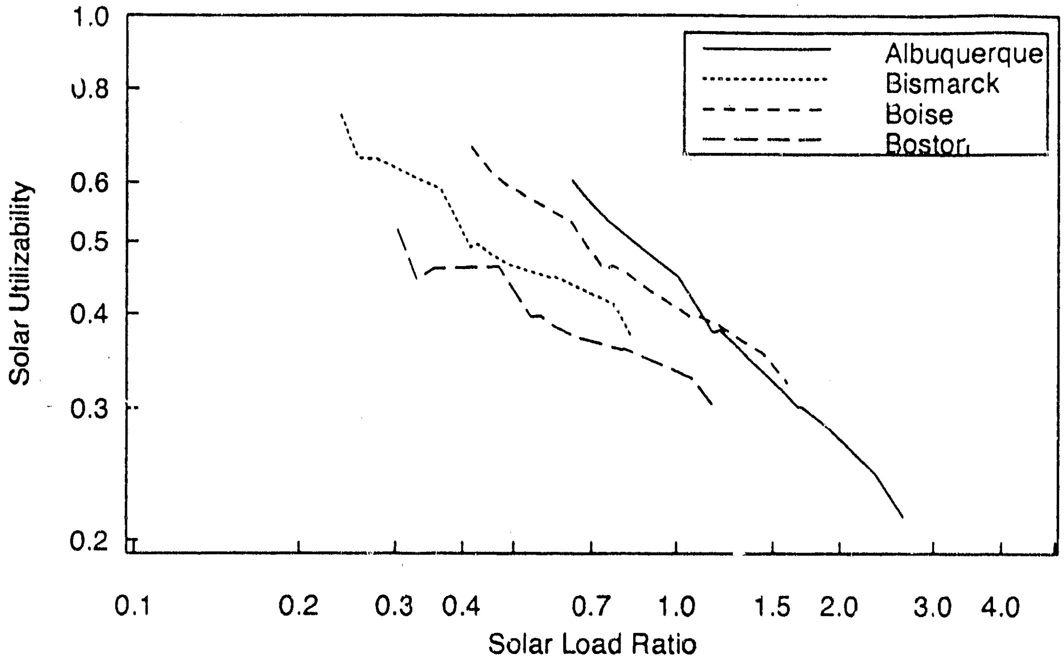
2
3
4
5
6
7
Solar Load Ratio



1.0
0.8
0.6
0.5
0.4
0.3
0.2
Solar Utilizability
Albuquerque
Bismarck
Boise
Boston
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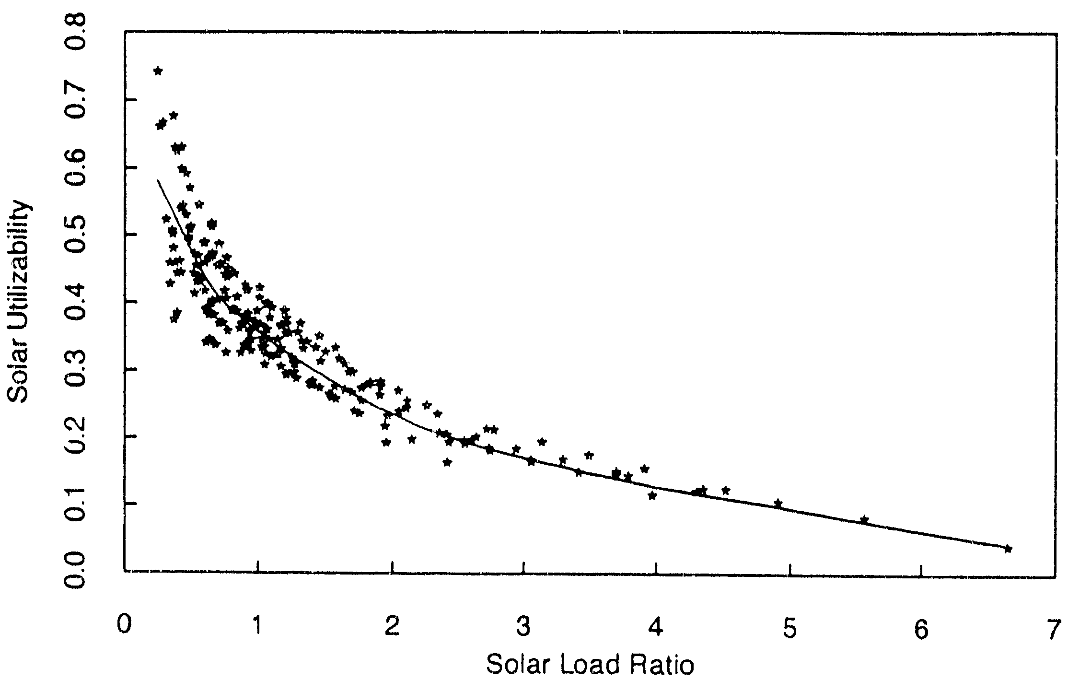
0.2
0.3
0.4
0.7
1.0
1.5
2.0
3.0
4.0
Solar Load Ratio



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0.2
0.3
0.4
0.5
0.6
0.7
0.8
Solar Utilizability
0
1
2
3
4
5
6
7
Solar Load Ratio

END

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