COMPARISON OF SLR PREDICTIONS TO MONITORED PERFORMANCE
OF SIX VIRGINIA PASSIVE SOLAR HOUSES/

by

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I would like to sincerely thank my thesis committee for their guidance and patience with my work.
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ABSTRACT
I. INTRODUCTION

"the sunshine is a glorious birth;
but yet I know, where'er I go,
that there hath past away a glory from the earth."
- William Wordsworth

Each age has tried to develop buildings that capture the sun's energy through the use of the available technology and materials. The Greeks, in the fifth century before Christ, were troubled by local fuel wood shortages so severe that the use of wood for fuel was restricted and taxed. Many parts of Greece were almost totally devoid of trees, and the supply lines for wood stretched across the Aegean Sea as far as the shores of the Black Sea. The Greeks eventually learned that massive masonry buildings could be kept cool in the summer, and more importantly, warm in the winter by orienting the openings of the building toward the south. In fact, entire communities were planned and built with this principle as a guide.

Fuel wood shortages also plagued the Romans. Heavy demand was placed on available wood supplies by wasteful systems used to heat private villas. These "hypocaust systems" could burn more than two cords per day. The Romans were transporting wood over a thousand miles, which influenced them to adopt the Greek lessons of passive solar
buildings. One technological advance, however, allowed the Romans to make more efficient use of the sun's energy: the use of glass.\textsuperscript{1}

In North America, the use of passive solar energy for space heating was first developed around the year 1000 A.D., in what is now the American desert Southwest. The Anasazi Indian culture had quite possibly met the same fate that had befallen the ancient Greeks and Romans.\textsuperscript{2} The immediate fuel sources had been exhausted and sources such as solar energy were exploited. The result was a cultural and architectural diversity unknown previously by that civilization.\textsuperscript{3}

The American post-industrial society history has run much the same course as previous civilizations. The inexpensive, easier to obtain fuel sources that were so abundant earlier in this century have proven themselves exhaustible. By most predictions, most sources of fossil fuel other than coal will be exhausted in the 21st century, forcing designers to turn to renewable resources, including direct energy from the sun. Some think this society's very survival is at stake.

Some attempts in the 20th century have been made to use the direct energy from the sun for space heating. During the 1930's and 1940's, Frank Lloyd Wright, among others, argued a return to architecture that was responsive to it's natural surroundings, including the climate in which the building was located. Wright's second Jacobs residence in
Madison, Wisconsin, for example, incorporates features that include large south facing windows, concrete slabs for storing and distributing radiant heat, open floor plans for easy circulation of heated air, and a north wall that is mostly underground to offer shelter from the wind. These features are often used in passive solar residences today. However, two factors caused all interest to be lost in using direct energy from the sun for space heating by the 1950's: 1) the end of World War II conservation measures, and 2) the discovery of plentiful energy supplies, notably in the Middle East.

It was not until the late 1960's that a small resurgence was begun by people concerned with the possible side-effects the heavy use of fossil fuels was having on the environment. Some had decided to work toward a return to a more appropriate technology, and it was in this atmosphere that the latest interest in passive solar technology was born. But these were only small scale projects, conceived by individuals often working alone. To these enthusiasts, the economic payback of this technology was not as important as was the feeling of conservation of limited resources and protection of the environment.

Recent world-wide political events have pointed to the dependence of American society on energy resources. Recent temporary blocks in the normally smooth flow of energy
have shown that any interruption in energy supplies could have harmful results on the national economy, and establishing energy independence from the oil cartels became a national priority. It was this concern that led the government at all levels to fund research, study pilot projects, and provide tax incentives to homeowners and businesses to conserve and collect energy from the sun.

The U.S. Department of Energy (U.S.D.O.E.) funded a research project at Los Alamos Scientific Laboratory (LASL), later referred to as Los Alamos National Laboratory (LANL) conducted by J. Douglas Balcomb, Robert McFarland, Robert Jones, William Wray, and others to develop methodology for the design of passive solar residences and small commercial buildings. Their approach was to construct test cells in which solar elements could be tested under controlled conditions. Computer programs were written that could very accurately predict the temperature histories of these cells through simulation analysis techniques developed by LASL. Further, full scale occupied buildings were monitored to provide validation for the simulation analysis. The research addressed established passive solar design approaches - 1) the water wall, 2) the Trombe wall, 3) direct gain, and 4) the sunspace.5

Hour-by-hour nodal analyses were run using as input parameters building loads, solar radiation, air temperature, auxiliary fuel, internal gain, mass thickness and thermal
storage capacity, and glazing sizes and numbers. The simulation results were compared with actual performance in the test cells, and the predictions of temperature were reported to be generally within 2%. These simulations were then operated using data from the 26 SOLMET (SOLar METeorological) cities for which reliable radiation and weather data existed. 6

These simulations were then used to define a single dimensionless correlation parameter known as the Solar Load Ratio (SLR), defined as:

\[
SLR = \frac{Q_s}{Q_{\text{load}}} = \frac{\text{monthly solar energy absorbed on the storage wall surface}}{\text{monthly building load (including the wall steady-state losses in the absence of solar gains)}}
\]

These correlation values were published in The Passive Solar Design Handbook, Vol. II (hereafter referred to as Vol. II) for most major cities in the U.S. and Canada for water walls, Trombe walls, and direct gain systems, but were of limited value to designers since only a small number of reference designs were used. If a designer were to change parameters from the given reference design, then the procedure became more unreliable. The work, however, represented a major advance in treating the passive solar design process as a quantifiable procedure.

The procedure was updated in the publication of The Passive Solar Design Handbook, Vol. III (hereafter referred
to as Vol. III) to include sunspaces and more reference designs for the previously published system types. Ninety four design options were referenced in all, representing a large increase in freedom for the designer. Also, new features for determining the actual solar radiation absorbed in the building were introduced to give more accuracy to the procedure.

Unfortunately, this increase in accuracy brought with it an increase in complexity. The manual was so cumbersome to use and so poorly organized, it led one well known writer in the solar field to write a "user's guide" to Vol. III. The use of microcomputers in the design field had become increasingly feasible, however, and many turned to commercially available software or wrote programs of their own based on the correlations from Vol. III. The Solar Load Ratio method, despite its flaws, remains the most widely used design tool for predicting performance in use today.

Two major evaluations of the SLR method, along with several studies of small groups or individual houses, have been undertaken. During the 1979-1980 heating season, over 300 houses were monitored under the U.S.D.O.E.'s "Class C" program. Class C program monitoring involved on-site audits to record building parameters, such as the solar aperture sizes, and measurements leading to building load coefficients. Homeowners were asked to estimate thermostat
settings, internal temperatures, and other factors that could affect energy use. Radiation and weather data were obtained from the regional Solar Energy Centers, and fuel bills were obtained from the utility companies.  

M.W. Fanning compared the actual heating requirements of 137 houses to the predicted requirements using the earlier version (Vol. II) of SLR. Fanning used the computer program "FCHART/SLR" to speed the computations and comparisons. Fanning states:

this study is an evaluation of a commonly used design process. It is not an attempt to validate the FCHART/SLR design tool; the nature of the data gathered in the Class C program precludes such a validation effort. For example, two factors seriously affecting the prediction (internal gain and interior set temperatures) were estimated, not measured. This does not invalidate the prediction, but it places constraints on the interpretation of the results. The Class C data approximate the type of information available to a designer; the purpose of the study reported here was to evaluate the usefulness of that information in the design.

Fanning concludes that SLR overpredicted auxiliary heating requirements by 103% with a standard deviation of 118%.

In an attempt to quantify the various unknowns in earlier passive monitoring, the U.S.D.O.E. undertook a Class B monitoring program in which automated data acquisition systems were used to record interior temperature, exterior ambient temperature, internal gains, auxiliary energy delivered to the heated zones, and radiation on the horizontal plane and on the plane of the major solar system.
J.J. Duffy evaluated fifty four different sites, monitored during the 1981-1982 and 1982-1983 heating seasons for a total of sixty nine site years. Duffy was able to utilize the expanded SLR version of Vol. III, and used the computer program "Design Tool Comparison" (DTC) to simplify and speed results. Duffy concludes that although the difference between the predicted and measured auxiliary energy averaged 10% over all of the houses monitored, the root mean square difference was 53%. Further, he reports a tendency toward underprediction for houses with relatively small auxiliary energy consumption, and toward overprediction for houses with relatively large auxiliary energy consumption.\textsuperscript{10}

Duffy addressed the ability of SLR to "document" auxiliary energy use if all of the values of the parameters used in making the SLR predictions are known, but he did not address the ability of SLR to predict auxiliary energy use from information typically known during the design phase. Fanning did address the ability of SLR to predict auxiliary energy use from information known during the design phase, but most of the parameters used to make the SLR predictions for her study were not actually monitored. There was no way to compare the estimations of the parameters used to the actual values. Some of the error attributed to the SLR predictions could have been associated with inaccurate estimations of the parameters used in the SLR predictions.
Further, Fanning was able to use only the earlier correlations of Vol. II. The differences that exist between these two studies suggested the research areas and questions to be addressed by this thesis.
II. SCOPE AND OBJECTIVES

This thesis examines the usefulness of SLR in enabling designers to predict auxiliary heating energy consumption from the information reasonably available during the design phase. In this respect, this study is much like the Fanning study with one major difference: the expanded correlations of Vol. III are used to make the SLR predictions.

Like the Duffy study, this study uses data monitored on-site for two reasons: 1) to correct the SLR predictions by using the recorded values for the rate of infiltration, thermostat set-point, and weather data, and 2) to examine errors in the prediction of those parameters.

This study has three objectives: 1) to identify the range of error expected from SLR predictions made during the design of passive solar buildings, 2) to examine errors in the prediction of parameters used in making SLR predictions, and 3) to identify parameters needing better predictive methods and/or needing further research.
III. METHODOLOGY

The data for this study was acquired from The Virginia Passive Solar Study (VIRPASS) for the months of December 1983 through April 1984. The methods of site selection, data recording and preparation, and SLR predictions are described in the following paragraphs.

A. Site Selection

Sites were selected in each of the four climate zones within the state: two houses in Tidewater Virginia (Virginia Beach), Northern Virginia (Alexandria), and Southwestern Virginia (Blacksburg), as well as four houses in Central Virginia (Richmond) that were involved in previous monitoring studies. Telephone interviews were conducted with the homeowners to determine that their passive solar house approximated one of the ninety four system types (or combinations thereof) in the SLR model. Out of the ten original sites, only six produced data that is considered reliable, and only those six are used for the remainder of the project.

B. Data Recorded

The following data was recorded at each site:

1. Dry bulb temperature, as well as relative humidity, was recorded by the homeowners using Weathertronics 5020 Hygrothermographs placed in the main living room of the house. The instruments were calibrated on site with a mercury
thermometer and a sling psychrometer at the time of installation. Charts were changed weekly and sent to the project each month.

2. The monthly reading was taken from the utility company's watt-hour meter on the first day of each month by the homeowners, or in Richmond, by paid staff.

3. The homeowners weighed their firewood as it was consumed on ordinary bathroom scales issued by the project, and recorded on a daily basis. All homes that recorded wood use had "air tight" woodstoves.

4. Infiltration tests were completed during February and early March 1984 with a Harmax blower door. The houses were pressurized from 12.5 Pascals (Pa) to 62.5 Pa. At least two readings at intervals of 12.5 Pa were taken in order to assure an accurate measurement. The fan was then reversed and the same procedure followed to depressurize the house. All vents leading to the outside, as well as the blower door itself, were sealed with plastic to prevent leakage. Indoor and outdoor temperatures were recorded, and windspeed was estimated by visual methods. This was a one time test for each site.

Solar radiation was measured within a few miles of the
Tidewater and Central Virginia sites using Hollis Geosystems insolometers, and the total global radiation on a horizontal plane was recorded monthly. Radiation data for the Northern Virginia site was obtained from the Smithsonian Radiation Lab in Rockville, M.D. This data was recorded using an Eppley pyranometer. The radiation data for the Southwestern Virginia site was obtained from the Turfgrass Research Station at Virginia Tech. This data was recorded using an Eppley pyranometer. A Hollis Geosystems insolometer was also used to record radiation data within a few miles of the Turfgrass Research Station in order to verify the insolometer data at other sites. The Eppley pyranometer was considered to be more accurate than the insolometer, and the Eppley pyranometer monthly radiation totals were 25% lower than the radiation recorded using the insolometers. The insolometer data was corrected by a 25% reduction at all sites.

C. Data Preparation

The data collected in the above manner was prepared for use in the following ways:

Temperature

The temperature data was reduced manually by recording values at 6:00 A.M., 12:00 Noon, and 8:00 P.M., times chosen to avoid the unrepresentative temperature spikes of the day. The values were read for only the five week days,
and the values were averaged for the month, as well as for the entire study period.

**Watt-hour Meter Reading**

The electric watt-hour meter readings were subtracted from the previous monthly reading to calculate the monthly kWh used. This figure was then multiplied by 3413 to calculate the number of BTUs produced. This assumed that all electric use ultimately went into producing heat, either directly as resistance heat, or as internal gain.

**Firewood**

The weight of the wood burned was totaled for each month. This weight was multiplied by 6400 BTU/lb to give the available heat, assuming a 20% moisture content of the wood. The woodstoves were assumed to have an average operating efficiency of 55%, and the monthly figures were multiplied by .55 to reflect the total delivered energy.

**Infiltration**

A regression analysis was performed on the fan speed data collected during pressurization and depressurization to predict flow rates at 4 Pa. and at 50 Pa. using the equation:

\[ Q = K\Delta p^n \]

where

- \( Q \) = flow rate, \( m^3/hr \)
- \( \Delta p \) = pressure difference, Pascal
- \( K, n \) = empirical constants from regression analysis

One model that equates these pressure readings to
infiltration rates is the Lawrence Berkeley Laboratory (LBL) model, and this model has been accepted as an ASTM standard for such tests. The effective leakage area is then calculated using 4 Pa. as the reference pressure, as this is typical of a weather induced pressure that causes infiltration:

\[ L = K \sqrt{\frac{\rho}{2}} (\Delta P_r)^{n-\frac{1}{2}} \]

where \( L \) = the effective leakage area (m)
\( K \) = the calculated constant
\( \rho \) = the density of air (kg/m³)
\( \Delta P_r \) = the reference pressure (Pa.)
\( n \) = the calculated exponent

Infiltration is then computed from the equation:

\[ Q = L \left( \frac{f_s^2 \Delta T + f_w^2 v^2}{f_s} \right) \]

where \( Q \) = the infiltration (m³/s)
\( \Delta T \) = indoor-outdoor temperature difference (K)
\( f_s \) = the stack parameter
\( f_w \) = the wind parameter
\( v \) = the wind speed (m/s)

The wind parameter is then calculated from the equation:

\[ f_w = C' \left( \frac{1}{1 - R} \right)^3 \left[ \frac{\alpha \frac{H}{10} \gamma}{\alpha' \frac{H'}{10} \gamma'} \right] \]

where \( C' \) = the generalized shielding coefficient
\( R \) = the fraction of leakage on horizontal surfaces
\( H \) = the height of the structure (m)
\( H' \) = the height of the wind measurement (m)
\( \alpha, \gamma \) = terrain parameters

\( R \) is calculated as a ratio of the horizontal surface leakage area to the total leakage area to account for shielding from the wind:

\[ R = \frac{L_{Ceiling} + L_{Floor}}{L} \]

The generalized shielding coefficient \( C' \) is listed in the
following table:

Table I Generalized Shielding Coefficients

<table>
<thead>
<tr>
<th>Shielding Class</th>
<th>C'</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.32</td>
<td>No obstructions whatsoever</td>
</tr>
<tr>
<td>II</td>
<td>0.28</td>
<td>Light local shielding with few obstructions</td>
</tr>
<tr>
<td>III</td>
<td>0.24</td>
<td>Some obstructions within two house heights</td>
</tr>
<tr>
<td>IV</td>
<td>0.18</td>
<td>Obstructions around most of perimeter</td>
</tr>
<tr>
<td>V</td>
<td>0.10</td>
<td>Large obstructions surrounding perimeter within two house heights</td>
</tr>
</tbody>
</table>

The terrain parameters are found in the following table:

Table II Terrain Parameters

<table>
<thead>
<tr>
<th>Class</th>
<th>γ</th>
<th>α</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.10</td>
<td>1.30</td>
<td>Ocean or other body of water with at least 5 km of unrestricted expanse</td>
</tr>
<tr>
<td>II</td>
<td>0.15</td>
<td>1.00</td>
<td>Flat terrain with some isolated obstacles (e.g. buildings or trees) well separated from each other</td>
</tr>
<tr>
<td>III</td>
<td>0.20</td>
<td>0.85</td>
<td>Rural areas with low buildings, trees, etc.</td>
</tr>
<tr>
<td>IV</td>
<td>0.25</td>
<td>0.67</td>
<td>Urban, industrial, or forest areas</td>
</tr>
<tr>
<td>V</td>
<td>0.35</td>
<td>0.47</td>
<td>Center of large city</td>
</tr>
</tbody>
</table>

The stack parameter is calculated with the equation:

\[
f_S = \left( \frac{1 + R/2}{3} \right) \left[ 1 - \frac{X^2}{(2-R^2)} \right]^{1/2} \sqrt{\frac{gH}{T}}
\]

where:
- \( f_S \) = the stack parameter
- \( g \) = the acceleration of gravity (9.8 m/s\(^2\))
- \( T \) = the inside temperature (K)
- \( X \) = estimated ratio of difference between floor and ceiling leakage area to the total leakage area
X is calculated by:
\[ X = \frac{L_{\text{Ceiling}} - L_{\text{Floor}}}{L} \]

The values for X and R were not actually calculated for this study. The measurement of infiltration cannot be localized by any simple procedure, therefore, the value for X was set at .15 and the value for R was .65.

Average wind speed and temperature for the house sites were obtained from the National Climatic Center (N.C.C) of the National Oceanic and Atmospheric Administration (N.O.A.A) monthly summaries for the airports nearest to the sites. The wind speed and temperatures for the Southwest Virginia site were obtained from the Turfgrass Research Station at Virginia Tech. A seasonal infiltration rate was then calculated for each house.

Weather Data

The total insolation measured was averaged over the number of days in each month, and defined as the daily average horizontal radiation (HS) for that month. The clearness ratio (KT) was calculated for each month:

\[ KT = \frac{Q_h}{Q_{he}} \]

where
- KT = the clearness ratio
- \( Q_h \) = the total horizontal radiation
- \( Q_{he} \) = the calculated extraterrestrial horizontal radiation

The total horizontal radiation \( Q_h \) was calculated by:

\[ Q_h = N \times HS \]

The extraterrestrial radiation was calculated from the known
latitude by:

\[ Q_{he} = N \times I \times Y \]

where \( Q_{he} \) = the extraterrestrial radiation total for the month
\( N \) = number of days in the month
\( Y = (24/\pi) \times (\cos L \times \cos D \times \sin H_S + H_S \times \sin L \times \sin D) \)

where \( Y \) = the integral of the sine of the solar altitude from sunrise to sunset
\( H_S = \cos (-\tan L \times \tan D) \)

where \( H_S \) = the sunset angle in radians
\( D = 23.45 \times \sin(360 \times (284 + n)/365) \)
\( I = I_S \times (1 + .033 \cos (360n/365)) \)

where \( L \) = the latitude
\( n = \) the day of the year, mid point of each month
\( D \) = the solar declination at mid month
\( I_S \) = the solar constant, 428 BTU/hr

The average radiation on a vertical plane is calculated from the measured horizontal radiation (HS) by:

\[ V_S = HS \times (.6866 - .6623 \times Z + 1.3269 \times Z^2 + \]
\[ KT \times (-.4458 + .3090 \times Z + 4.7776 \times Z^2)) \]

where \( V_S \) = the average daily radiation on a vertical plane
\( Z = \) the calculation of \( L-D/100 \)
\( L = \) the latitude of the site
\( D = \) the mid-month solar declination

Outdoor ambient temperatures were averaged over the month from daily maximum and minimum temperatures to give a daily normal temperature.

D. SLR Predictions

Auxiliary energy use was predicted using SOLPAS - Passive Solar Design Program, written by, and commercially available from, the author of this thesis. Except where
noted, the algorithms were taken strictly from the Passive Solar Design Handbook, Vol. II and Vol. III. Building heat Loss Coefficients (BLC) were estimated using equations from Vol. II. The method involved calculating the BLC from the construction drawings using standard ASHRAE derived formulas. These formulas produce an estimated BLC since only gross areas, as well as homogeneous building sections, are used. The formulas for calculating the estimated BLC are:

Walls
\[ L_w = \frac{24 \times \text{wall area}}{R \text{ value of walls}} \]

Non-South Window
\[ L_g = \frac{26 \times \text{non-south window area}}{\text{number of glazings}} \]

Perimeter (slab on grade)
\[ L_p = \frac{100 \times \text{length of perimeter foundation}}{R \text{ value of perimeter insulation} + 5} \]

Floor (over vented crawl space)
\[ L_f = \frac{24 \times \text{area of ground floor}}{R \text{ value of floor}} \]

Basement
\[ L_b = \frac{256 \times \text{length of wall}}{R \text{ value of wall insulation} + 8} \]

Roof
\[ L_r = \frac{24 \times \text{roof area}}{R \text{ value of roof}} \]

Infiltration
\[ L_i = (0.432) \times \text{ACH} \times \text{Air Density Ratio} \times \text{Volume} \]

The equations from Vol. III are:
\[ S = N \times HS \times \left(\frac{T}{Q_h}\right) \times \left(\frac{S}{T}\right) \]

where
- \( N \) = number of days in the month
- \( HS \) = average daily value of total radiation incident on a horizontal surface, BTU/ft\(^2\) day
- \( T/Q_h \) = ratio of monthly total solar radiation
transmitted through a unit area of horizontal surface

\[ S/T = \text{ratio of monthly total solar radiation absorbed in the building per unit of projected area to that transmitted through a unit of glazing} \]

\[ X = \frac{(S/DD - LCR_S \times H)}{(LCR \times K)} \]

where \( K = 1 + G/LCR \)

\[ DD = \text{degree days as calculated from a temperature base defined by the thermostat setpoint - internal gain divided by the total building loss} \]

\[ LCR = \text{load collector ratio (solar aperture / Building Load Coefficient)} \]

\( G, H, LCR_S = \text{correlation values for system type} \)

\[ F(X) = \begin{cases} A \times X, & \text{if } X < R \\ B - C \exp(-D \times X), & \text{if } X \geq R \end{cases} \]

where \( A, B, C, D, R = \text{correlation values for system type} \)

\[ SSF = 1 - K \left[1 - F(X)\right] \]

Monthly \( Q = (1 - SSF) \times BLC \times DD \)

where \( Q = \text{the auxiliary heat requirement} \)

One notable difference involves the computation of degree days (DD). Vol.III suggests interpolation between tables, where the method used for this study involves a correlation procedure using the DD base 65. The use of this procedure probably slightly increases accuracy, and greatly speeds computation. The equation reads:17

\[ DD = N \left(T_b - \bar{T}_a + C\right) \]

where \( N = \text{number of days in the month} \)

\( T_b = \text{the degree day base (65 was used)} \)

\( \bar{T}_a = \text{the monthly ambient average} \)

\( C = \text{a correction factor significant in mild months given} \)
as:

\[ C = (1.339 + 0.00387 \frac{D_a}{10^6} - \frac{0.277 D_a^2}{16.23}) \times e^{-\left[ \frac{T_b - T_a + 20}{16.23} \right]^2} \]

where \( D_a \) = the 65F degree base annual degree day total
(use 7200 if DD exceeds 7200)

Internal gains were assigned as recommended by Vol. II and Vol. III as 20,000 BTU/day per occupant. This was considered a predicted value, and 5000 BTU/day of that was attributed to heat given off by the occupant. The remaining 15,000 BTU/day was attributed to "purchased" energy from appliances, water heaters, and etc. The entire 20,000 BTU/day was used to compute the solar base temperature, as in the above degree day calculations.

One other clarification should be noted. Vol. III offers a choice of procedures when two or more passive system types are used in the same building. The method used is the preferred method, that is, the SSF for each month is a weighted average of the SSFs for the individual systems, and this SSF is applied as for a single system to obtain the auxiliary heat \((Q)\).

No solar gains were attributed to east, west, or north facing glass as none of the sites had glazing of significant size other than that facing south. Further, no calculations were done to account for loss of radiation due to shading of the site or building.
IV. RESULTS OF SLR PREDICTIONS

Base Case

SLR predictions were made for the six houses for auxiliary fuel requirements and compared to the recorded energy consumed. Data was taken from the construction documents, and some design assumptions were based on typically accepted values. Specifically, the infiltration rate was set at .5 ACH\textsuperscript{19}, the thermostat set-point was 68 degrees F, and the internal gain rate was assumed to be 20,000 BTU\textsuperscript{20} for computing the solar base temperature. For the predicted column, however, only the internal gain less the body heat (20,000 BTU - 5,000 BTU = 15,000 BTU) was added. These predictions were the base case, that is, those predictions made with information typically known during the design phase.

The electric consumption was assumed to be at 3413 BTU/kWh at 100% efficiency (3413 BTU/kWh), and the wood was 6400 BTU/lb at 55% efficiency (3520 BTU/lb). The predicted auxiliary energy consumption was compared to the recorded auxiliary energy from each site and the results are in Table 1.

Infiltration Adjusted

The SLR predictions were made with the infiltration rate adjusted to reflect the actual measured value and compared to the recorded auxiliary energy consumed. The results are in Table 2.
Thermostat Set-Point Adjusted

The SLR predictions were made with the thermostat set-point adjusted to reflect the actual measured value and compared to the recorded auxiliary energy consumed. The results are in Table 3.

Weather Adjusted

The actual recorded weather parameters of monthly average temperature, horizontal radiation, KT (clearness ratio), and calculated vertical radiation were used to make SLR predictions in order to examine the differences in the predictions caused by the use of the average weather tables of Vol. III and the actual weather. SLR predictions were compared to the recorded auxiliary energy consumed. The results are in Table 4.

Infiltration, Thermostat Set-Point, and Weather Adjusted

SLR predictions were made using recorded values for infiltration, thermostat set-point, and weather. The predictions were compared to the recorded auxiliary energy consumed, and the results are in Table 5.
Table 1
Base Case SLR Predictions
Compared to Recorded Auxiliary Energy Consumed

<table>
<thead>
<tr>
<th>SITE</th>
<th>1 PREDICTED (auxiliary + internal gain)</th>
<th>2 RECORDED (electric + wood)</th>
<th>3 DIFFERENCE 2-1 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA</td>
<td>13,188,844</td>
<td>14,010,365</td>
<td>6</td>
</tr>
<tr>
<td>CVB</td>
<td>20,583,706</td>
<td>28,824,978</td>
<td>29</td>
</tr>
<tr>
<td>CVC</td>
<td>11,375,567</td>
<td>22,062,528</td>
<td>48</td>
</tr>
<tr>
<td>EVA</td>
<td>27,411,517</td>
<td>52,459,759</td>
<td>48</td>
</tr>
<tr>
<td>NVA</td>
<td>34,893,068</td>
<td>31,818,105</td>
<td>-10</td>
</tr>
<tr>
<td>SWA</td>
<td>30,113,584</td>
<td>39,450,609</td>
<td>24</td>
</tr>
<tr>
<td>MEAN ERROR</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td></td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>
Table 2

SLR Predictions With Recorded Infiltration
Compared to Recorded Auxiliary Energy Consumed

<table>
<thead>
<tr>
<th>SITE</th>
<th>PREDICTED (auxiliary + internal gain)</th>
<th>RECORDED (electric + wood)</th>
<th>DIFFERENCE 2-1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA</td>
<td>13,522,702</td>
<td>14,010,365</td>
<td>3</td>
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<td>CVB</td>
<td>22,432,122</td>
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<td>22</td>
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<td>CVC</td>
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<td>22,062,528</td>
<td>46</td>
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<tr>
<td>EVA</td>
<td>25,715,277</td>
<td>52,459,759</td>
<td>51</td>
</tr>
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<td>NVA</td>
<td>48,358,071</td>
<td>31,818,105</td>
<td>-52</td>
</tr>
<tr>
<td>SWA</td>
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<td>39,450,609</td>
<td>15</td>
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</table>

MEAN ERROR..................................................14

STANDARD DEVIATION........................................34
Table 3
SLR Predictions with Recorded Thermostat Set-Point
Compared to Recorded Auxiliary Energy Consumed

<table>
<thead>
<tr>
<th>SITE</th>
<th>Predicted (auxiliary + internal gain)</th>
<th>Recorded (electric + wood)</th>
<th>Difference ((%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA</td>
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<td>23</td>
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<td>CVB</td>
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<td>EVA</td>
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<td>52,459,759</td>
<td>51</td>
</tr>
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</tr>
<tr>
<td>SWA</td>
<td>30,683,755</td>
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</table>

MEAN ERROR: .......................................................... 26

STANDARD DEVIATION: ............................................. 19
Table 4
SLR Predictions with Recorded Weather Compared to Recorded Auxiliary Energy Consumed

<table>
<thead>
<tr>
<th>SITE</th>
<th>PREDICTED (auxiliary + internal gain)</th>
<th>RECORDED (electric + wood)</th>
<th>DIFFERENCE 2-1 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA</td>
<td>13,794,706</td>
<td>14,010,365</td>
<td>2</td>
</tr>
<tr>
<td>CVB</td>
<td>21,559,790</td>
<td>28,824,978</td>
<td>25</td>
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<tr>
<td>CVC</td>
<td>11,897,169</td>
<td>22,062,528</td>
<td>46</td>
</tr>
<tr>
<td>EVA</td>
<td>26,034,409</td>
<td>52,459,759</td>
<td>50</td>
</tr>
<tr>
<td>NVA</td>
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<td>-5</td>
</tr>
<tr>
<td>SWA</td>
<td>29,385,822</td>
<td>39,450,609</td>
<td>26</td>
</tr>
<tr>
<td>MEAN ERROR</td>
<td>..................................</td>
<td>..................</td>
<td>24</td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td>......................</td>
<td>..................</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 5

SLR Predictions with Recorded Rate of Infiltration, Thermostat Set-Point, and Weather Data

Compared to Recorded Auxiliary Energy Consumed

<table>
<thead>
<tr>
<th>SITE</th>
<th>1 PREDICTED (auxiliary + internal gain)</th>
<th>2 RECORDED (electric + wood)</th>
<th>3 DIFFERENCE 2-1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVA</td>
<td>13,801,120</td>
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<tr>
<td>CVB</td>
<td>28,740,156</td>
<td>28,824,978</td>
<td>0</td>
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<td>CVC</td>
<td>12,223,595</td>
<td>22,062,528</td>
<td>45</td>
</tr>
<tr>
<td>EVA</td>
<td>27,017,918</td>
<td>52,459,759</td>
<td>48</td>
</tr>
<tr>
<td>NVA</td>
<td>37,782,124</td>
<td>31,818,105</td>
<td>-19</td>
</tr>
<tr>
<td>SWA</td>
<td>28,912,199</td>
<td>39,450,609</td>
<td>27</td>
</tr>
<tr>
<td>MEAN ERROR</td>
<td></td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>STANDARD DEVIATION</td>
<td></td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>
V. DISCUSSION OF SLR MODEL RESPONSE

The Base Case SLR predictions for auxiliary energy use, recorded auxiliary energy consumed, and the differences are reported in Table 1. These predictions were made using typically accepted design values for infiltration, thermostat-set point, internal gain, and weather data from The Passive Solar Design Handbook, Vol. III. The predictions were compared to the recorded auxiliary energy use for each site, and the differences ranged from an overprediction of 10% to an underprediction of 48%. The mean error was a 24% underprediction with a standard deviation of 24%. This result is quite impressive when one considers: 1) all of the unknowns built into the SLR prediction process, and 2) the range of error found in other engineering models.21

SLR predictions might reasonably be expected to increase in accuracy as one deviates from the Base Case by adjusting the predictions with actual monitored data from the houses. When the actual infiltration rates, thermostat set-points, and weather data are used in the SLR predictions (Table 5), the mean error becomes an underprediction of 17%, with a standard deviation of 25%. This effort approximates the J.J. Duffy study, and the range of error is quite similar, however, with Duffy reporting an overprediction of 10% with a standard deviation of 53%.

It is useful to look at each of the parameters -
infiltration, thermostat set-point, and weather data - separately to examine the effect each has on the mean error of the prediction. Comparing the results of adjusting the infiltration rates (Table 2), the mean error is an underprediction of 14% with a standard deviation of 34%. Adjusting the predictions with the actual thermostat set-points (Table 3), the mean error is an underprediction of 26%, with a standard deviation of 19%. The mean error, when adjusting the predictions with the actual weather data (Table 4), is an underprediction of 24%, with a standard deviation of 20%. Quite clearly, the infiltration rate is the variable that affects the accuracy of the prediction the greatest. It introduces the largest change in mean error toward more accurate predictions, but also increases the standard deviation.

It is difficult for designers to accurately predict the rate of infiltration. The use of infiltration barriers, double entry air locks, caulked sill plates, tight windows, magnetic door seals, and other building products reduces the rate of infiltration. The amount of reduction is not known. The tools available from ASHRAE and others, however, give only such gross estimates (as with the air change method) as to render them unusable, or too cumbersome for actual use (as with the crack method). A simple tool is needed that can accurately predict infiltration rates during the design phase.
Part of the rate of infiltration is not within the control of the designer. Personal lifestyle of the occupant, it is estimated, will add .10 to .20 Air Changes / Hour (ACH). One time blower-door tests do not measure this increase in the infiltration rate, and may account for some error in this study.\textsuperscript{22}

The thermostat set-point may produce errors in the predictions, and those errors cannot be controlled by the design process. Although the occupant does ultimately control the thermostat set-point, this variable had little effect on predictions in the group of houses as a whole. In the predictions of an individual house, however, the difference in the prediction of 68 degrees and the actual thermostat set-point could cause an error of approximately 8% of auxiliary energy required for each degree (F) difference.

The use of averaged weather data when compared to recorded weather data accounted for little error in the predictions for the group as a whole or for individual houses. J.J. Duffy also reports little error attributed to the use of averaged weather data for the heating seasons of 1981-1982 and 1982-1983.

Some parameters are chosen at the discretion of the designer, but the methods used in design may introduce some unexplained, as well as unpredictable, differences in the
accuracy of the SLR predictions. One variable that may introduce some uncertainty in the prediction is the heat loss due to building skin conductance (referred to as UA). As an important part of the SLR prediction process, the UA is normally calculated using ASHRAE heat loss equations, and added to a calculated loss due to infiltration, in order to calculate an overall Building Load Coefficient (BLC). The comparison of calculated values and measured values of UA produces some interesting results.

An accepted way of measuring the BLC is to perform an electric co-heating test of the building. In this test, usually small electric resistance heaters are placed throughout the building with their thermostats pre-set at some temperature that might be reasonable for occupancy, usually 70 degrees F. The heaters are individually metered, and all appliances are turned off in order to give a true reading of kWh consumed for maintaining the set-point temperature. The exterior temperature is monitored in order to calculate a temperature difference through the building skin. If the infiltration is known, then a loss due to conductance through the building skin (UA) can be measured. However, the results of electric co-heating tests have been questioned by some researchers for buildings containing large amounts of mass (as is often found in passive solar houses).

The use of a calculated UA rather than a measured UA
in SLR predictions produces some error, as reported by several researchers. Results from a joint study by the Southern Solar Energy Center and the National Association of Home Builders show that measured values are less in the range of 20-22%. This study included only two houses that both values were measured and calculated. A 1982 study of eleven California Class B monitored houses tend to confirm this result, but showed four houses where the measured value was greater by a range of 1-12%, one was equal, and six where the calculated UA was greater than the measured by a range of 1-28%.25

The possibility of error where the measured value is greater than the calculated value is substantiated by a 1983 study by Tsongas using class B monitored data, where the infiltration was measured by a blower door test corrected for wind speed and temperature at the time of the electric co-heating tests. Tsongas reports a 31% higher measured UA over a calculated figure. Given the above supporting evidence, the assumption can be made that the calculated figures for the UA for VIRPASS are correct, within + or - 30%.

It is useful to examine the effect a 30% error in UA can have on predicted auxiliary energy. To study this effect, a "standard house" was selected with 1500 sq.ft. floor space, single story of 8 ft., with insulation R
values, glazing sizes, mass heat storage capacity, Load Collector Ratios, etc.—in short—a similar house to an average of the VIRPASS monitored houses. The house was sited in Richmond with an infiltration of .5 ACH, thermostat set-point of 68, and an occupancy of two. SLR predictions were made using a base case, and then varying the UA by 30%. This 30% range in UA produced an approximately corresponding 30% range in auxiliary energy predictions. The effect this range of predictions of auxiliary energy has on the SLR predictions made for this study is unknown, but could account for a portion of the error.

The prediction of internal heat gain, and its subsequent approximation in this study, is likely to produce some errors. The Vol. III SLR method contains a recommended value of 20,000 BTU/day per occupant, and while this seems to be a reasonable figure, very little study has been given to this value. Obviously, this figure is not a constant and can be affected by occupant lifestyle, appliance types and numbers, and usage. The VIRPASS methods separated the internal gain associated with the body heat of the occupants (5000 BTU/day) and reported only the internal gain associated with purchased energy. Further research and validation of the Vol. III recommended value is needed.

This study considered electric use to produce heat as a by-product of any work performed. The measurement of heat production from electric use was considered to be 100% at
3413 BTU/kWh. There is some error of unknown proportion associated with gray-water heat losses and outside ventilation of appliances such as clothes dryers or stoves. These losses were considered to be under 20% of the total internal heat gain. VIRPASS was unable to devise a simple, inexpensive method for actually measuring the internal heat gain. Development of a simple, inexpensive method to measure internal gain is needed.

Finally, although any monitoring study would be advised to monitor houses that use only metered energy sources for heat, it was difficult to find passive solar houses that did not use woodburning devices for supplemental heat. It was for this reason houses with woodstoves were used in this study. The VIRPASS methodology assumed a heat content of wood at 20% moisture to be 6400 BTU/lb to be burned at 55% efficiency. This figure could vary because of the moisture content of the wood, the actual efficiency of the "air tight" stove, or the errors of weighing the wood burned.

One site in particular, EVA, recorded a total figure of 9770 lbs. of wood. In the relatively mild climate of Tidewater, simple ASHRAE heat loss design equations would predict a use of 43.5 million BTU per year for this well insulated house of 1500 sq.ft. Compared to the 52.5 million BTU recorded for only the months of December through April, there appears to be a discrepancy between the amount of
energy recorded and that predicted by the ASHRAE model, which does not account for any solar gains. No heat was supplied by the heat pump as it was shut off during the entire heating season, a figure substantiated by the almost constant electric readings of around 1000 kWh per month. No explanation was obtained either from examination of the construction documents or from occupant interview to account for the obvious discrepancy.
VI. CONCLUSIONS

This thesis has examined the differences between SLR predictions and the recorded energy consumed for six passive solar houses in Virginia. These differences are within the range of error reported in earlier work by Duffy. It is concluded the error of an SLR prediction made during design will be within $\pm 50\%$ of the actual energy use.

This study has examined the following parameters: 1) the prediction of the rate of infiltration, 2) the prediction of the thermostat set-point, 3) the use of averaged weather data, 4) the calculated heat loss due to building skin conductance (UA), and 5) the prediction of internal heat gain. It is concluded that no error in the SLR prediction process can be attributed to the use of averaged weather data contained in The Passive Solar Design Handbook, Vol. III. Further, it is concluded that all of the remaining parameters will result in errors in the SLR predictions. However, no conclusions are reached as to the expected range of errors for these parameters due to the lack of supporting evidence.
VII. RECOMMENDATIONS

Much difficulty has been encountered by researchers trying to separate the errors attributed solely to the SLR model from those errors attributed to the predictive models associated with the individual parameters. As noted earlier, further research is needed to develop better predictive models for parameters used in the SLR process.

The prediction of the rate of infiltration represents the "best guess" by the designer, with the possible error of 100% or more. A simple tool is needed that can accurately predict infiltration rates during the design phase.

Differences in the calculated (using ASHRAE heat loss equations) UA and UA determined by electric co-heating tests have been noted of + or − 30%. The accuracy of SLR predictions are highly dependent on the accuracy of the prediction of UA during design. Duffy states that much of the error in the SLR predictions used in his study could be attributed to the differences in the measurement and calculation of UA. Further research is necessary to determine the more accurate method.

At least part of the difficulty in separating the errors attributed to the SLR model from those errors attributed to the individual parameters may rest in the actual monitoring. While the SLR model rests on a sound theoretical basis, and has been substantiated with empirical
tests under laboratory conditions, the tools used to monitor all parameters in occupied buildings are not accurate enough at this time to match the accuracy of laboratory testing.

Although the methods used in this study can be used effectively in passive solar monitoring, it is suggested that future monitoring studies emphasize accuracy in monitoring the three parameters most difficult to estimate. These parameters are: 1) the rate of infiltration, 2) the internal heat gain, and 3) the quantity of heat delivered by woodburning devices.

Some design tools (i.e. hourly simulation methods) used in predicting passive solar building performance are said to have more accuracy than SLR, but at a high cost of time, skill, and collection of necessary information to make those predictions. The increase in accuracy is somewhat like a carpenter measuring with a micrometer, marking with a crayon, and cutting with an axe.

Although it may be intellectually gratifying to predict precisely, common sense suggests that the tools used to design the building need be no more accurate than the process used to build it. Research resources will be better utilized establishing and validating predictive design tools for the most basic building parameters, rather than refining the tool used for the predictions of auxiliary energy use.
VIII. REFERENCES


19. Percily, pp. 118.


27. Duffy, p. 11.
IX. BIBLIOGRAPHY


The vita has been removed from the scanned document
Six houses heated by passive solar energy were monitored during the 1983 - 1984 heating season to determine auxiliary heating fuel used. Predictions were made using the Solar Load Ratio (SLR) method for the expected use of auxiliary heating fuel. Comparisons were then made between actual performance and predicted performance.

The SLR method is used for predictions because it is a widely used tool in the design of passive solar houses, and questions have been raised as to its usefulness as a predictor of auxiliary heating fuel consumption.

Variables used in the SLR predictions and methodology for monitoring actual energy consumed are examined to explain differences in the predicted and monitored energy used.