PASSIVE SOLAR HEATING ANALYSIS

SUPPLEMENT ONE

THERMAL MASS EFFECTS AND ADDITIONAL SLR CORRELATIONS

J. Douglas Balcomb
William O. Wray

CONTRIBUTORS

Robert W. Jones
Elaine D. Best
Claudia Peck

Los Alamos National Laboratory

TECHNICAL WRITERS

Jim Ohi
Murrey Goldberg
Barbara Glenn
Grace Griego

Solar Energy Research Institute

American Society of Heating, Refrigerating and Air-Conditioning Engineers
1791 Tullie Circle, NE, Atlanta, GA 30329

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NOMENCLATURE

Symbol		Units
A_g	area of glazing	ft^2
A_m	area of mass surface	ft^2
C	correlation coefficient	
c	specific heat	Btu/lb·°F
D	correlation coefficient	
DD	number of degree-days	°F·day
DHC	total diurnal heat capacity	Btu/°F
dhc	diurnal heat capacity	Btu/°F·ft^2
dhc_∞	dhc of an infinitely thick wall	Btu/°F·ft^2
EF	enhancement factor	
EHC	total effective heat capacity	Btu/°F
ehc	effective heat capacity	Btu/°F·ft^2
f	fraction of daylight hours	
H	correlation coefficient	
HDHC	total hexdiurnal (6-day) heat capacity	Btu/°F
hdhc	hexdiurnal (6-day) heat capacity	Btu/°F·ft^2
k	thermal conductivity	Btu/ft·°F·h
LCR	load collector ratio	Btu/°F·day·ft^2
LCRs	load collector ratio for sunspaces	Btu/°F·day·ft^2
NLC	net load coefficient	Btu/°F·day
Q_i	daily internal heat (assumed uniform)	Btu/day
Q_{int}	internal heat generation	Btu/day
Q_s	daily solar gain	Btu/day
Q_{sav}	solar savings	Btu
q	daily solar gain per unit area	Btu/ft^2·day
S	monthly solar gain	Btu/ft^2
SC	shading coefficient	
SLR	solar load ratio	
SSF	solar savings fraction	

NOMENCLATURE (continued)

Symbol		Units
TLC	total load coefficient	Btu/°F-day
T_a	daily average ambient temperature	°F
T_{av}	time weighted average thermostat setting	°F
T_b	base temperature	°F
T_{ec}	equivalent thermostat setpoint	°F
T_r	daily average space temperature	°F
T_{set}	thermostat setpoint	°F
t_1	characteristic thickness	ft
U_c	heat transfer coefficient	Btu/h°-F-ft^2
V	volume of mass	ft^3
X	mass thickness	ft
α	absorptance of material	°F
ΔT	peak-to-peak variation in room temperature (swing)	°F
λ	building time constant	h
ρ	density	lb/ft^3
τ	dimensionless thickness, X/t_1	

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ASHRAE FOREWORD

This is *Supplement One* to the publication, *Passive Solar Heating Analysis: A Design Manual*, written by members of the Solar Energy Section at Los Alamos National Laboratory and published by ASHRAE in 1984. This supplement includes additional solar load ratio (SLR) correlations, as well as discussion of and means of analyzing the effect of thermal storage in passive solar buildings.

The experimental and theoretical studies to develop the information contained in the supplement were similar to those used for the data contained in the basic manual.

The analytical methods and data presentation are also the same as those in the original manual, and it is hoped they will be helpful to both experienced and first-time designers of passive solar heated buildings.

The Solar Energy Research Institute of Golden, Colorado, edited and produced this supplement in cooperation with the Los Alamos Solar Energy Section.

ASHRAE members have been involved in the organization and review of *Supplement One* to help ensure its usefulness to designers and engineers. This supplement has been scrutinized by these members and deemed to be useful and technically responsible. The manual has been formally approved by the ASHRAE technical committee on Solar Energy Utilization (TC 6.7).

The Passive Solar Heating Analysis Subcommittee of TC 6.7 consists of Herman G. Barkmann, Chairman (Consulting Engineer); Bion D. Howard (National Association of Home Builders); and Benjamin T. Rogers (Consulting Engineer).

HOW TO USE THIS BOOK IN DESIGN

The design of buildings is customarily separated into four phases. In the first phase, programming, facts are accumulated that will determine the design outcome, such as site and budget constraints, user requirements, and weather data. In the second phase, schematic design, the rough form of the building is defined and sketched. These first two phases are the most important to the successful incorporation of passive solar elements into the building. In the third phase, design development, more particulars are defined, such as window placement and wall sections. During the fourth phase, construction documents, detailing is completed and specifications finalized. Schematic design and (to a lesser extent) design development are iterative phases in which various concepts are tried and modified as the design converges to final form.

The design tools presented in *Passive Solar Heating Analysis* (*PSHA*) and *Supplement One* can provide essential information at key points during this process, as shown in the schematic, Figure 1:

1. Based on only the size of the building and the climate, guidelines for conservation levels, total passive solar aperture, and orientation can be determined (Chapter 2, *PSHA*). This is useful input at the very beginning of schematic design.

2. During schematic design, load calculations (Chapter 3, *PSHA*) and performance estimates can be made using the annual load collector ratio (LCR) method (Chapters 4-5, *PSHA*) and temperature swing estimates made using the diurnal heat capacity (DHC) method (*Supplement One*, Chapter 2). These methods can be useful during schematic design iterations and/or as a sign-off before proceeding to design development. Other guidelines in *PSHA* and *Supplement One* will also be useful as the design evolves.

3. During design development, monthly SLR calculations can be performed using correlations from *PSHA* or the new correlations in *Supplement One*, facilitated, in the case of direct-gain systems, by calculating a total effective heat capacity (EHC) to better characterize the total heat storage potential of the building (*Supplement One*, Chapter 3). These calculations may be used to account for effects not included in the annual method (such as shading, which changes from month to month) or to estimate the performance of new systems, such as hollow block Trombe walls, thermosiphoning air heaters, or solar radiant panels.

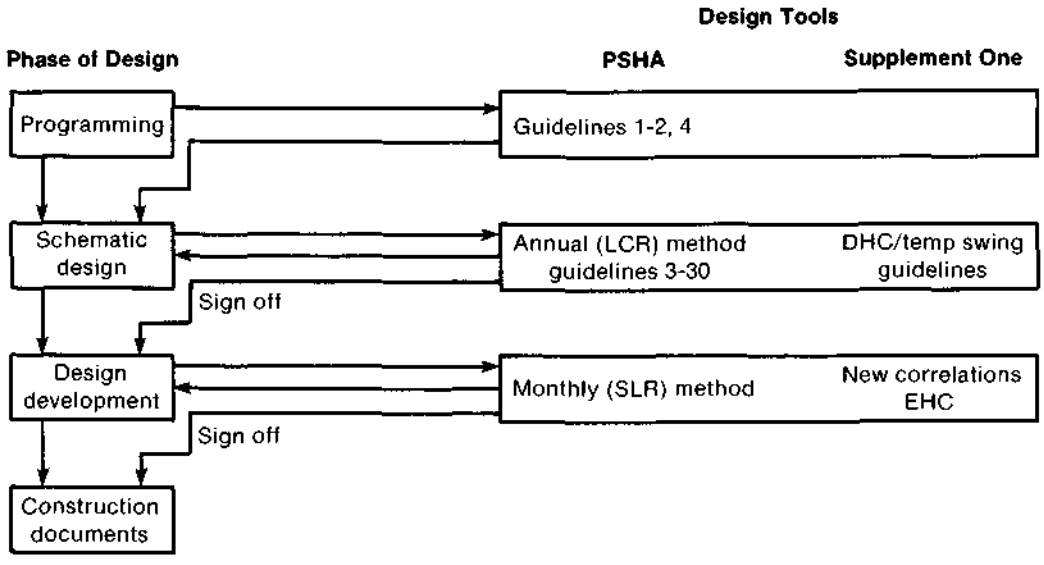


Figure 1. Schematic Showing the use of Design Tools in the Design Process. *PSHA* refers to *Passive Solar Heating Analysis* and *Supplement One* refers to this book.

CHAPTER 1
INTRODUCTION

This volume is *Supplement One* to *Passive Solar Heating Analysis: A Design Manual* (*PSHA*) (Balcomb et al. 1984). *PSHA* provides quantitative methods to analyze the performance of passive solar heating systems during the schematic design and design development phases of passive solar buildings. The methods are based on the solar load ratio (SLR) method developed at Los Alamos National Laboratory (LANL). In this method, performance estimates are made using monthly mean values of solar radiation and heating load. The method is developed using least-squares regression based on performance estimates derived from hour-by-hour computer simulations. Based on the performance analysis, *PSHA* permits a designer to estimate the annual and monthly energy required to maintain comfort during the heating season and the energy savings attributable to the passive solar design. The methods to analyze performance refer to specific passive system configurations, or reference designs, for which all design parameters are given.

This supplement provides additional reference designs for direct gain systems and for three systems not treated in *PSHA*: concrete block Trombe walls, thermosiphoning air panels, and solar radiant panels. A set of correlation coefficients for each reference design is provided.

This supplement extends the treatment of heat storage in passive solar buildings given in *PSHA* by including methods to calculate diurnal heat capacity (DHC) of both uniform and layered wall sections and methods to estimate diurnal temperature swings in a direct-gain room. *Supplement One* also develops an analytical expression for the total effective heat capacity (EHC) of buildings. By using this approach, it is possible to generalize the thermal storage capabilities of direct gain systems using different thermal storage media in different geometric arrangements. EHC provides a single thermal mass parameter that best characterizes the building mass relative to annual passive solar heating performance.

Supplement One also includes a procedure to account for night thermostat setback within the context of SLR analysis. This procedure determines an effective setpoint by a nonlinear interpolation between daytime and nighttime setpoints involving hours of setback and the building time constant.

The Naval Civil Engineering Laboratory (NCEL) at Port Hueneme, California, has worked with LANL to extend the technology developed with the support of the U.S. Department of Energy (DOE). The first of these efforts developed strategies for passive retrofit of concrete block and metal buildings. The results of this effort are the correlations found in this supplement. NCEL also sponsored work to combine the SLR method with the universal curve method to form the fast solar load ratio method. LANL and NCEL also developed methods to evaluate the effects of night thermostat setback and to calculate the EHC of buildings. The results of these efforts are included in *Passive Solar Design Procedures for Naval Installations* (Wray and Peck 1987).

CHAPTER 2
THERMAL STORAGE IN PASSIVE BUILDINGS

Time-Phased Heat Storage and Release

Necessity for Thermal Storage

A key element in passive solar design is the use of dense materials in building interiors to match the solar gain of occupied space with the comfort requirements of the occupants. Solar gain is primarily controlled by the location, orientation, and shading of building apertures (windows and skylights), and heat is distributed throughout the space by the natural processes of radiation and convection. The presence of massive materials that can store excess heat for later release is essential to achieving a proper balance between the large variations over time in solar gain and the more nearly constant indoor temperature needs of people.

Direct gain is the most widely used passive solar strategy and occurs to some degree in most buildings. All windows contribute to solar gain, and all interior building materials store the heat received to some degree. For lightweight materials, storage is usually quite temporary, with rapid transfer of received heat to room air. For massive materials, heat transfers into the material interior and is released to the air later as room temperature drops.

Heat distribution in an enclosed direct-gain space is complex but is well enough understood for an adequate picture of how storage occurs. When sunlight shines on a particular area of a room, some energy is absorbed and converted to heat, and some is reflected. For dark receiving surfaces, conversion of light to heat is concentrated in the region of solar incidence. If receiving surfaces are light in color, heat is distributed more uniformly. When sunlight angles are acute and surfaces are light, reflection to areas deep within the room facilitates both heat distribution and natural lighting. Once short-wave sunlight is converted to heat at an interior surface, three actions occur: (1) heat conducts into the material, (2) heat is transferred to room air by convection, and (3) heat is reradiated as long-wave (infrared) energy to all room surfaces within direct sight. Most heat leaves the surface as infrared radiation; convection to air is usually the smallest of the three effects. Thus, each room surface is continually receiving infrared radiation from all surfaces within "view." This radiant flux is the main source of heat to surfaces not in the direct sun, and its dominance is the primary reason for the viability of direct gain as a solar heating strategy.

Depending on sun angle, only an area approximately equal to window size receives direct-beam solar radiation. Energy inflow at this point is generally greater than the absorptive capacity of most masonry materials, so much of the energy is redistributed by infrared radiation and convection. Therefore, it is better to distribute the energy uniformly over a large surface area rather than to attempt to absorb it at the point of incidence. This reduces temperature swings within the space. Although surfaces in the direct sun may temporarily be warmer than other surfaces, most will have nearly the same temperature within a few hours. Heat diffusion into massive materials can be slow and is little affected by short-term variations in incident energy. The reader should be concerned with the behavior of storage materials over a period of a day or more and not with short-term transient effects near the surface.

Although it is usually best to maintain collected solar energy as radiant energy or as stored heat, some inevitably is transferred to room air, causing a temperature increase. Air has low heat capacity (typically about 1/1400, on a volumetric basis, of solid materials) and tends to rise as heating decreases its density. Cooler air elsewhere in the building is displaced, and convective loops are established. Hot air may simply collect near the ceiling, resulting in temperature stratification.

About one-third of entering solar gain usually heats room air. Warmed air either convects to cooler spaces within the building, exfiltrates from the building (replaced by cooler infiltrating air), or increases in temperature until energy flows balance. Control of this temperature rise is a key factor in maintaining building comfort. Room day and night temperature swings are a frequent measure of passive design success. A swing of more than 10°F is generally considered uncomfortable.

Daytime heat convection to cooler areas of the building is a major heat distribution mechanism and a major source of heat for storage within remote area surfaces. Normally the heat flux at these remote mass

surfaces is substantially less than fluxes at surfaces within the direct-gain space. It is therefore convenient to distinguish between surfaces radiatively coupled to the source and those convectively coupled. Radiative coupling is very effective and is dominant at surfaces within the direct-gain space; convective coupling is the primary mechanism for heat transport to remote spaces. Convective-coupled heat storage is usually the lesser of the two, but it is nonetheless an important part of building heat storage.

In a passive solar sunspace, convection through doorways and other apertures is usually the major energy transport mechanism to the attached building. Sunspace temperature swings are large because the ratio of mass surface to glass surface is small (typically 3:1). Accentuated temperature differences between the sunspace and other space drive convective exchange to the rest of the building. Because building living spaces have large interior surface areas, there can be extensive heat storage in these rooms even though surface heat fluxes are relatively small.

For a wall to be effective as a heat storage element, it should have the following characteristics:

- High thermal capacity, i.e., the product of density, ρ, and specific heat, c, should be large.

- High thermal conductivity, k. Deep portions cannot participate in the charge and discharge cycle if they are isolated from the room by a layer of material with low thermal conductivity.

Thus a wall material with a low (ρck) product will have low heat-storage capacity, even though it may be quite thick. Because high-density materials usually have high thermal conductivity (and vice versa), typical wall insulation materials are not good heat storers. For example, expanded polystyrene and fiberboard are very poor for heat storage; wood is moderately poor; and concrete, rock, brick, and adobe are relatively good. Thus, the very properties that make a wall perform well as an interior thermal storage element make it perform poorly as an exterior envelope insulating element. It is, however, common construction practice to build interior partitions and inside elements of exterior walls of lightweight frame construction and to place more massive materials, if used at all, outside the insulation. This is unfortunate from a thermal storage standpoint, since it is desirable to locate mass inside the insulated thermal envelope. Also, widespread use of thin layers of sheetrock as an interior material in construction in this country is not helpful to passive design.

Importance of Diurnal Heat Storage

For analytical purposes, it is convenient to distinguish three heat storage time domains:

- Short-term — the period of a few hours that is characteristic of the storage capacity of low-density materials.

- Diurnal — the 24-hour cycle of daytime heat storage and nighttime heat release.

- Long-term — storage durations greater than diurnal.

Of the three, diurnal heat storage is most significant to passive solar heating design. It will be treated extensively in the remainder of the discussion.

The observed strong diurnal response of passive solar buildings is, of course, a reflection of the 24-hour natural harmonic content of the daily cycle of solar input and the daily variation of outside temperature. Observation of the temperature change with time in the interior of a passive solar building shows the effect simply. Figure 2-1 shows temperatures measured at two points in a solar house over a week's time, as well as the associated outside temperature and solar radiation. Figures 2-1 through 2-4 are taken from measurements made in Unit One, First Village solar house in Sante Fe, New Mexico.

Temperature swings in the greenhouse are much larger than those in the house interior, but both show a strong diurnal component. Temperatures measured at various depths in the adobe wall between the house and greenhouse are shown in Figure 2-2. The marked diurnal response on the outside surface results from strong direct solar heating. At the six-inch depth, the temperature response is nearly sinusoidal except for a long-term drift, due to the overall interaction of house and climate.

A plan view of the ground floor and a section of Unit One, First Village, are shown in Figure 2-3. The section clearly shows the two-zone design, with an adobe thermal storage wall as a separator, and the air ducts and two fan-forced rock beds. The house is heavily instrumented and has been monitored and analyzed in great detail. Results pertinent to an understanding of the time history of the building's heat storage are used here. Hourly data measured in different rooms throughout the house were used to drive hour-by-hour simulation models that characterize the various storage elements.

From data collected through the heating season, it is clear that the most important mechanism for energy