Direct-Gain Reference Designs

Designation	Thermal Storage Capacity* (Btu/ft² · °F)	Mass Thickness** (in.)	Mass-to-Glazing-Area Ratio	No. of Glazing Layers	Night Insulation
High-Mass					
DGA1	30	2	6	2	no
DGA2	30	2	6	3	no
DGA3	30	2	6	2	yes
DGB1	45	6	3	2	no
DGB2	45	6	3	3	no
DGB3	45	6	3	2	yes
DGC1	60	4	6	2	no
DGC2	60	4	6	3	no
DGC3	60	4	6	2	yes
Suntempered					
SUNTEMP 1	10.8	0.5	20	2	no
SUNTEMP 2	10.8	0.5	20	2	yes

*Per unit of projected area
**Based on volumetric heat capacity of 30 Btu/ft³ · °F

Water Wall Reference Designs

Designation	Thermal Storage Capacity* (Btu/ft² · °F)	Wall Thickness (in.)	No. of Glazing Layers	Wall Surface	Night Insulation
WWA1	15.6	3	2	normal	no
WWA2	31.2	6	2	normal	no
WWA3	46.8	9	2	normal	no
WWA4	62.4	12	2	normal	no
WWA5	93.6	18	2	normal	no
WWA6	124.8	24	2	normal	no
WWB1	46.8	9	1	normal	no
WWB2	46.8	9	3	normal	no
WWB3	46.8	9	1	normal	yes
WWB4	46.8	9	2	normal	yes
WWB5	46.8	9	3	normal	yes
WWC1	46.8	9	1	selective	no
WWC2	46.8	9	2	selective	no
WWC3	46.8	9	1	selective	yes
WWC4	46.8	9	2	selective	yes

*Per unit of projected area

Sunspace Reference Designs

Designation					
No Night Insulation	R9 Night Insulation	Type	Tilt (deg)	Common Wall	End Walls
SSA1	SSA2	attached	50	masonry	opaque
SSA3	SSA4	attached	50	masonry	glazed
SSA5	SSA6	attached	50	insulated	opaque
SSA7	SSA8	attached	50	insulated	glazed
SSB1	SSB2	attached	90/30	masonry	opaque
SSB3	SSB4	attached	90/30	masonry	glazed
SSB5	SSB6	attached	90/30	insulated	opaque
SSB7	SSB8	attached	90/30	insulated	glazed
SSC1	SSC2	semienclosed	90	masonry	common
SSC3	SSC4	semienclosed	90	insulated	common
SSD1	SSD2	semienclosed	50	masonry	common
SSD3	SSD4	semienclosed	50	insulated	common
SSE1	SSE2	semienclosed	90/30	masonry	common
SSE3	SSE4	semienclosed	90/30	insulated	common

Trombe Wall Reference Designs

Designation		Thermal Storage Capacity* (Btu/ft² · °F)	Wall** Thickness (in.)	ρck Btu²/h · ft⁴ · °F²	No. of Glazings	Wall Surface	Night Insulation
Vented	Unvented						
TWA1	TWF1	15	6	30	2	normal	no
TWA2	TWF2	22.5	9	30	2	normal	no
TWA3	TWF3	30	12	30	2	normal	no
TWA4	TWF4	45	18	30	2	normal	no
TWB1	TWG1	15	6	15	2	normal	no
TWB2	TWG2	22.5	9	15	2	normal	no
TWB3	TWG3	30	12	15	2	normal	no
TWB4	TWG4	45	18	15	2	normal	no
TWC1	TWH1	15	6	7.5	2	normal	no
TWC2	TWH2	22.5	9	7.5	2	normal	no
TWC3	TWH3	30	12	7.5	2	normal	no
TWC4	TWH4	45	18	7.5	2	normal	no
TWD1	TWI1	30	12	30	1	normal	no
TWD2	TWI2	30	12	30	3	normal	no
TWD3	TWI3	30	12	30	1	normal	yes
TWD4	TWI4	30	12	30	2	normal	yes
TWD5	TWI5	30	12	30	3	normal	yes
TWE1	TWJ1	30	12	30	1	selective	no
TWE2	TWJ2	30	12	30	2	selective	no
TWE3	TWJ3	30	12	30	1	selective	yes
TWE4	TWJ4	30	12	30	2	selective	yes

*Per unit of projected area
**For the particular case of ρc = 30 Btu/ft³ · °F

PASSIVE SOLAR HEATING ANALYSIS

A DESIGN MANUAL

J. DOUGLAS BALCOMB
ROBERT W. JONES
ROBERT D. McFARLAND
WILLIAM O. WRAY

CONTRIBUTORS:

Dennis Barley
Claudia Kosiewicz
Gloria Lazarus
Joseph Perry
Greg Schoenau

TECHNICAL WRITER:

Edwin Nelson, Tech. Reps., Inc.

Los Alamos National Laboratory



ISBN 0-910110-38-7



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

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ACKNOWLEDGMENTS

Passive Solar Heating Analysis is the result of work at the Los Alamos National Laboratory during the period 1977-1983, performed under the auspices of the U.S. Department of Energy, Office of Solar Heat Technologies. It builds on the extensive work of Volumes II and III of the *Passive Solar Design Handbook* (subtitled *Passive Solar Design Analysis*) and the large supporting effort of the many people involved. The authors of Volume II are Douglas Balcomb; Dennis Barley; Robert McFarland; Scott Noll; Joseph Perry, Jr.; and William Wray; the authors of Volume III are Robert Jones, editor; Douglas Balcomb; Claudia Kosiewicz; Gloria Lazarus; Robert McFarland; and William Wray. Assistance in the preparation of Volumes II and III was provided by Della Baldock, Mary Beckett, Mary Blackwell, Kirk Collier, Lee Dalton, Jared Dreicer, Derrick Grimmer, James Hedstrom, Jack Hyde, Charlene McHale, Ike Meissner, Stan Moore, Lois Murray, Jan Sander, Peter Stromberg, Robert Sutton, Mark Thayer, Michael Ulibarri, and Kai Zinn. Reviewers of these volumes included Donald Abrams, Bruce Anderson, William Ashton, Bruce Baccei, Duncan Bremer, Matt Crosby, Harrison Fraker, Greg Franta, Drew Gillett, Harry Gordon, Daniel Hagan, John Hill, Mike Holtz, Bruce Hunn, Terry Ingersol, Bruce Johnson, Tim Johnson, Ove Jorgensen, Ron Judkoff, Doug Kelbaugh, William Kolar, Andrew Lau, Vivian Loftness, Fuller Moore, David Odegard, Larry Palmiter, Wayne Place, Greg Schoenau, and John Yellott.

Work on an ASHRAE book, combining and rewriting the previous work, was initiated by Michael Maybaum at the U.S. Department of Energy. Sherry Reisfeld at Los Alamos aided in obtaining a contract with Tech. Reps., Inc., of Albuquerque, New Mexico, to do the technical writing for the project.

Ed Nelson was the principal technical writer and production manager for Tech. Reps. Bruce Howden was the copy editor.

Los Alamos worked with ASHRAE from the beginning. With the assistance of Herman Barkmann and Stanley Mumma, a special ASHRAE subcommittee was formed to oversee the work, from the development of an outline through detailed review of three drafts of the manuscript. The authors are particularly indebted to the members of this subcommittee—Bruce Novell, Chairman; Steven Heibein; and Benjamin Rogers—for their diligent and thoughtful dedication to a quality product.

During the writing and editing process, Robert Jones provided liaison between Los Alamos, ASHRAE, and Tech. Reps., aided by Douglas Balcomb. Reviewers of *Passive Solar Heating Analysis* are Bruce Hunn, Harold Lorsch, Alwin Newton, and Bud Wildin. Valuable suggestions were received from William Shurcliff, based on Volumes II and III. We are especially grateful to Byron Winn who provided a detailed review of the entire manual during the last stages of its preparation.

Lastly, the authors wish to thank Donald Neeper for his help and his leadership of the Los Alamos Solar Energy Group during these years.

ASHRAE FOREWORD

This manual is a condensation of passive solar heating analysis methods developed at the Los Alamos National Laboratory. It represents a current state of the art in evaluating passive solar heating systems and is a significant addition to previously available methods.

Extensive experimental and theoretical studies were required to develop these methods, including building and testing passive "test cells," studying the dynamic behavior of these units, developing detailed hourly simulation codes to predict their behavior, and then using these to generate simpler monthly and annual analysis tools. The methods presented herein are straightforward, easy to use, and well matched to the designer's design process and required accuracy. These methods allow the building designer to choose from multiple passive system types for various types of buildings and to combine several passive systems on the same building. The designer can evaluate the effects of varying virtually all of the major passive design parameters to determine their effect on auxiliary heat savings. Design guidelines in this manual give design direction for passive solar features in buildings. Methods and recommendations are also given to optimize the balance between energy conservation and passive solar systems. Tabulated values for 223 locations in the U.S. and Canada make the methods useful virtually anywhere in the U.S. Furthermore, generalized techniques are presented that allow passive solar systems to be evaluated at any location where solar radiation and ambient temperature data are available.

The work of organizing and writing this manual was performed by Tech. Reps., Inc., of Albuquerque, New Mexico, in cooperation with the Los Alamos Solar Energy Group. The manual is written so that it is useful to building designers experienced in passive solar design and designers considering their first passive solar building. Analysis methods and data are presented in tables, graphs, and equations so that they can be used manually (with worksheets provided) or computerized.

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

Passive Solar Heating Analysis Subcommittee
of the Solar Energy Utilization
Technical Committee, TC 6.7

Bruce Novell, Chairman
Alabama Solar Energy Center

Stephen Heibein
Innovative Design

Benjamin Rogers
Consulting Engineer

PREFACE

Passive Solar Heating Analysis represents the product of several years work at the Los Alamos National Laboratory. The object has been the development of simplified methods of analysis for passive solar heated buildings. The primary result is the solar load ratio method, which has now been applied to a variety of direct-gain, Trombe wall, water wall, and sunspace configurations. A large number of performance sensitivity curves for these systems supplement the method. Procedures for their use have been carefully tailored to integrate smoothly into the normal design process, specifically into the formative schematic design and design development phases.

The precursors to *Passive Solar Heating Analysis* are Volume Two and Volume Three of the *Passive Solar Design Handbook*, written at Los Alamos for the U.S. Department of Energy. Volume One of this series concerns passive solar design concepts. These books have served an important interim function in the evolution of passive solar practice and analysis and have been used by many designers. Volume Two, issued in January 1980, presents the solar load ratio methodology and gives results for six reference designs, specifically, direct-gain, Trombe wall, and water wall designs, both with and without night insulation. Volume Three, issued in July 1982, is a major addendum to Volume Two, expanding and modifying the original 6 reference designs to 66 and adding 28 sunspace reference designs. A procedure for balancing conservation and solar strategies is also included.

Passive Solar Heating Analysis is a complete rewrite of Volumes Two and Three by a professional technical editor. This step was taken because it was felt that the work is mature and that it deserves better presentation. The result is a smooth and consistent development with step-by-step procedures given at each stage together with convenient worksheets as appropriate. All tables and graphs required are included so that the book is self-contained, at least for users in the contiguous 48 United States and southern Canada. Acceptance within the building analysis community was assured by working closely with a special committee appointed by ASHRAE.

With minor exceptions, *Passive Solar Heating Analysis* is completely consistent with Volume Three. The solar load ratio correlation form and correlation constants are identical. The solar radiation and transmittance correlations are also identical except that azimuths north of east and west and overhang shading for vertical south-facing windows are included. A major addition is the incorporation of Chapter 2, "Passive Solar Design Guidelines," which provides specific, quantitative design guidance very early in the design process. Thirty guidelines are given that range from general rules relating to conservation, solar area, and orientation, to specific rules for the various passive solar system types. Also included are new correlations useful for estimating average inside temperature during clear days.

Designers may still wish to refer to Volume Two for some specific topics that are not covered in this book. These are chapters that pertain to design of fan-forced rock beds, diurnal heat capacity and temperature swing calculations, and economics.

Buildings cannot be engineered in the same way that a power plant, a satellite, or a ship is designed. Fine-honed precision is not justified either by the accuracy required or the design budget. This is especially true of small buildings that are normally designed using rules-of-thumb gained through experience. It is this smaller building, both residential and commercial, that is the primary target of this book, and the analysis methods given are geared principally to these applications. Little time or mathematical expertise is needed to apply the methods, especially those that are used during the critical early phases of design. Worksheets, pencil, and a handheld calculator are all that are required. It is expected that some readers will use only the simplest methods given in Part I. Others will continue to the more complex procedures in Part II.

Simplicity and speed in an analytical method necessarily involve some compromises in accuracy and generality. This is true of the methods presented here. First, the methods are based on simple correlations of complex data that are themselves estimates of building performance by computer simulation. Nevertheless, the user can expect accuracy in the 10% to 15% range, which is suitable for design estimates. Second, the methods apply to specific building configurations called reference designs. Even though there are many configurations to choose from and a large amount of sensitivity data with which to estimate the effect of modifying the principal design variables, most buildings to be analyzed will not exactly match the analytical assumptions. The designer must then use clear judgment in applying the results and candor in representing their applicability to a client.

The designer and client should understand that analytical results are not a prediction of building energy performance. And this fact is not necessarily because of shortcomings in the analytical procedure but rather because of the nature of design analysis. There are three principal reasons. First, the assumptions about the characteristics of the building cannot be expected to match the actual building. This is because of the uncertainty and variability in the properties of the building materials and in the quality of the construction. For example, the building heat loss characteristics are very sensistive to the care taken during construction to seal cracks. Second, the performance of a building depends on the actual weather rather than the long-term normals used in the analysis: the weather during any particular period will differ from the normal for that period, and the weather at a particular site will differ from that at the nearest weather station. Third, the manner in which the building is occupied and operated has a strong influence on performance and is not entirely predictable.

Often the assumptions most difficult to match are not directly related to the building design but to its operation. Important factors are the operation of vents, doors, and windows; the thermostat settings; and the rates of internal heat generation by lights, appliances, machinery, and people. The assumptions in this book are as follows. Vents in Trombe walls and sunspaces are assumed to never permit reverse flow of heat from the heated building back to the Trombe wall air space or the sunspace. The heat loss characteristics of the nonsolar parts of the building are assumed to be represented by a constant heat loss coefficient so that the building heat loss is proportional to the difference between the indoor and outdoor temperatures. (This is called a degree-day load.) The thermostat settings and the rate of internal heat generation (not including the deliberate generation of heat by space heating equipment) are assumed to be constant. A difficulty often arises with this last assumption, especially in the case of certain types of commercial buildings where a predominantly daytime occupancy leads to varying thermostat settings and internal heat generation.

Despite the importance of space heating in most U.S. locations and for most types of buildings, it is certainly not the only energy issue in a building. Space cooling is the major concern in many locations, especially in buildings with a large rate of internal heat generation. Nevertheless, this book deals only with passive solar heating. Here, there is a well-established quantitative basis, whereas natural solar cooling is less well understood. It is not that passive cooling techniques are felt to be ineffective; quite the contrary. As quantitative procedures are developed, the need for a follow-up to this book dealing with passive cooling will be evident. It should be noted, however, that the most important factor in cooling a building is not to heat it. Thus, solar gains of all kinds must be very carefully controlled during the cooling months by shades, overhangs, or vegetation.

A balanced thermal design begins from an awareness of the total energy needs of the building. But the analytical methods in this book are applicable to the passive solar heating system design even when the space heating requirement turns out to be small, provided the analytical assumptions are met. The applicability of the methods to commercial buildings is discussed further in Chapter I, "Introduction."

A difference in the analysis approach used in this book and that used in Volumes Two and Three is the comparison with a nonsolar reference building. The procedures used in the earlier volumes required defining a different degree-day base for the solar and nonsolar building. This proved awkward, confusing, and of questionable value. In this book, a single base temperature is used, defined for the solar building. The analyst can either use the simple formulation of solar savings developed, which is usually reasonably accurate, or perform two

complete, separate calculations, one for the solar building and one for any arbitrarily defined nonsolar building, and then compare the auxiliary heat required by each.

Another notable change is in the terminology of the building load coefficient, termed *BLC* in Volumes Two and Three. This has caused some confusion because most analysts use *BLC* to refer to the *total* load coefficient, whereas, in Volumes Two and Three, *BLC* refers to the building *exclusive of the solar wall.* To alleviate this confusion, the term net load coefficient (*NLC*) is used instead of *BLC*, and a new term, *total* load coefficient (*TLC*), is used to refer to the entire building, including the solar wall. *BLC* is not used.

Passive solar design has become widely recognized as a very effective way to achieve large decreases in the amount of energy required for space conditioning in buildings. It has become generally accepted that these buildings work well and are cost effective. They offer ease of operation, reliability, and enhancement of livability and comfort. The quantitative basis for passive solar design has developed quickly from a rather late start. At the time of the First National Passive Solar Conference, held in Albuquerque in May 1976, there were few people in the country not present at the conference who believed that passive systems would work. This situation has changed markedly. The literature has built up rapidly, reports on the performance of successful buildings across the country have multiplied, and there is now widespread recognition that large energy savings can be obtained.

The purpose of this book is to provide a means whereby performance can be analyzed in advance. Many of the early passive solar builders designed on a rather intuitive basis, hoping for the best. Often their hopes were realized, and the buildings work well. Sometimes they did not. However, these designers represent a small number who are willing to experiment with an investment as large as a building. The vast majority of builders require reliable performance estimates, well founded in experimental observation. This book is intended to fill that need.

There is a growing body of evidence that *correctly designed* passive solar buildings have comfort characteristics that equal or exceed their contemporary counterparts. This is due to several subtle physiological factors. The most important of these is the effect of the thermal radiant environment on comfort.

Under still-air conditions, the radiant temperature is roughly equal to the actual air temperature in the individual's perception of comfort. In a passive building, the enclosing surfaces of a room are usually warmer than in a conventional building. This leads to an increase in radiant temperature. The increase in surface temperature results from two effects: well-insulated walls and multiple glazings (conservation measures) and storage of solar heat (passive solar measures). Thus, the individual can experience an equivalent comfort sensation when the air in a passive building is at 65°F as in a conventional building with a 72°F air temperature. A second effect that enhances comfort is the incredible thermal stability of a well-insulated building with large internal mass. Temperatures change very slowly, resulting in less physical stress than in a building with the same average temperature but with abrupt variations.

The apparent simplicity of passive solar buildings has misled many people into thinking that passive solar design is simple. In fact, it is a complex process, a subtle complexity consisting of consciously designing to take advantage of environmental energies and natural processes. Design decisions must factor in considerations of cost, aesthetics, use of the various spaces in the building, natural lighting, security, code restrictions, and privacy as well as thermal performance. This book provides a basis for quantifying the heating performance side of this complex situation. The procedures have been made as simple as possible without losing the fundamental relationships that influence the result. Even so, they may appear intimidating at first—as is anything new. Time spent in developing a familiarity with the procedures will lead to their comfortable and effective assimilation into the design process.

OVERVIEW

Purpose

The purpose of this book is to provide methods for quantitatively analyzing the performance of passive solar heating systems.

Design decisions must consider cost, aesthetics, function, space allocation, lighting, security, site adaptations, construction code restrictions, and privacy as well as thermal performance. This book provides a basis for quantifying the solar heating performance side of this task. The procedures have been made as simple as possible without losing the fundamental relationships that influence the result. The methods are applicable to both residential and commercial buildings. However, when being applied to commercial buildings, considerable care must be exercised to be sure the assumptions implicit in the method are appropriate to the building being analyzed.

Design Sequence

Traditionally the design process has been divided into the following sequence of steps:

a. Schematic design—review and evaluation of the building requirements and production of drawings and documents to illustrate the initial building concept.

b. Design development—preparation of more detailed drawings and documents to describe the size of the building and its architectural, structural, mechanical, and electrical systems.

c. Construction documents—preparation of finished drawings and specifications suitable for use in negotiation or bid of a construction contract.

It should be noted that this design process is a sequence of increasingly more detailed steps. Major decisions are made in the early design steps and the details developed in the later steps. Issues of energy use and energy conservation traditionally have been addressed during design development. Heating and cooling requirements have been dealt with as part of mechanical and electrical system design; insulation has been considered during detailing of wall sections. Since fuel costs were small, energy use and conservation was treated as a relatively minor constraint on overall building design and was appropriately considered during design development.

In recent years, rising fuel costs, prospective fuel shortages, and the imposition of governmental energy performance standards have combined to make energy an extremely important consideration in building design. Energy-related decisions must now be made during schematic design and their implications carried into design development. Energy considerations are no longer a minor constraint on building design that can be deferred to the detailed design stage.

To provide for these circumstances, this book is divided into two parts. Part I begins with a set of guidelines that are useful to the designer at the very beginning of schematic design. Subsequent chapters present a method for building thermal analysis that can be applied during schematic design. The method is called the annual *LCR* method. Only the general characteristics of the building need be known to apply the method. It is quick and easy to apply so that several design concepts can be analyzed for their thermal performance and the results compared before selecting a final concept for design development. Part I also treats the subject of energy conservation and presents a method for determining the optimum balance between conservation measures and solar heating measures.

Part II presents a more detailed method called the monthly *SLR* method, which is suitable for use during the design development stage. In comparison

with the annual *LCR* method, the monthly *SLR* method can accommodate more design variations and evaluates building thermal performance on a month-to-month basis rather than by a single annual figure. The extra effort required is modest. Completion of the monthly *SLR* method thermal analysis is a recommended procedure after completion of design development and prior to initiating the construction documents phase.

The methods in this book lead to estimates of annual and monthly consumption of energy required to maintain comfort during the heating season. This energy will presumably be supplied by a backup or auxiliary heating system that will often be off or be operating at partial power. It is assumed that such a system is installed and that it can supply the required heat energy. Methods for sizing the capacity of this equipment are not discussed in this book. It is expected that most designers will use traditional methods, such as those described in the *ASHRAE Handbook of Fundamentals*, to determine the maximum of design-day capacity requirements.

Passive solar system energy savings estimated using the techniques in this book refer to specific passive system configurations in which all the design parameters are specified. These are called *reference designs.* There are 94 reference designs, 9 for direct gain, 42 for Trombe walls, 15 for water walls, and 28 for sunspaces. Once estimates have been made for one or a combination of these reference designs, the effect on performance of a difference in one or more of the design parameters can be estimated using sensitivity curves.

PART I
SCHEMATIC DESIGN

Scope of Part I

The methods of analysis and the supporting data tables presented in this book were developed at the Los Alamos National Laboratory as a result of a continuing research program. Much of the information has appeared previously in separate Los Alamos National Laboratory reports, conference papers, and the second and third volumes of the *Passive Solar Design Handbook*. This book integrates the previously presented material, using uniform terminology, and includes new material generated exclusively for this book. In Chapter 1, key design elements are discussed, and the physical configurations of the various passive solar systems are described and terminology is defined. Chapter 2 presents a set of design guidelines that are useful in beginning a schematic design, such as conservation levels, the size and orientation of the solar aperture, the amount and location of thermal storage mass, the orientation of the building, and other considerations. Chapter 3 discusses methods of estimating the net load coefficient (*NLC*) of a building before schematic design is completed. The computation of the degree-days (*DD*), given the building internal heat sources and thermostat setting, is discussed in Chapter 4. Chapter 5 describes the annual load collector ratio (*LCR*) method of evaluating the thermal performance of a building. This method is a simple means of estimating annual solar savings and the key parameter, auxiliary heat. Chapter 6 presents information on the optimum mix of conservation and passive solar strategies in building design. Guidance is available here on adjusting the appropriate conservation level for a given location. Chapter 7 is a collection of example problems illustrating the methods described in Part I. The appendices contain the data tables and graphs necessary to exercise the analysis methods.