MASTER

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**Supplementary Material on Passive
Solar Heating Concepts—A
Compilation of Published Articles**

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best
available copy to permit the broadest
possible availability.

May 1979

**Presented in Conjunction with a Series of
Passive Solar Heating Seminars
Sponsored by the
Solar Energy Technology Transfer Program**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SUPPLEMENTARY MATERIAL ON
PASSIVE SOLAR HEATING
CONCEPTS - A COMPILATION
OF PUBLISHED ARTICLES

May 1979

Presented in conjunction with a series
of Passive Solar Heating Seminars
sponsored by the Solar Energy
Technology Transfer Program

Work Supported by
the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

This booklet is a compilation of published articles and reports dealing with passive solar energy concepts for heating and cooling buildings. The booklet has been assembled as part of the Pacific Northwest Laboratory's Solar Energy Technology Transfer Program, sponsored by the U.S. Department of Energy, and is intended to supplement the passive solar seminars being presented by the Pacific Northwest Laboratory throughout the Pacific Northwest.

CONTENTS

A. Fundamentals of Passive Systems

1. ERDA, "Passive Solar Heating Uses the Sun's Energy Naturally."
2. D. Wright, "Passive Art" (from Solar Age Catalog).
3. S. Baer, "Movable Insulation."
4. Solar Age Catalog, "Glossary."

B. Applications and Technical Analysis

1. J.D. Balcomb, et al., "Passive Solar Heating of Buildings."
2. E. Mazria, et al., "Predicting the Performance of Passive Solar Heated Buildings."
3. E. Mazria, "The Performance of Passive Solar Heated Buildings in the Pacific Northwest."
4. W. Yanda, "Considerations for Retrofitting an Attached Solar Greenhouse."
5. J.D. Balcomb, et al., "A Simple Technique of Estimating the Performance of Passive Solar Heating Systems."
6. W.D. Wray, et al., "A Semi-Empirical Method for Estimating the Performance of Direct Gain Passive Solar Heated Buildings."

C. Graphic Tools - Solar Guide and Calculator (University of Oregon)

D. Information Sources - Highlights

FUNDAMENTALS

Information from

ERDA
Washington, D.C. 20545

NF-77-23

FOR IMMEDIATE RELEASE
(Friday, September 30, 1977)

**"PASSIVE" SOLAR HEATING USES
THE SUN'S ENERGY "NATURALLY"**

Solar energy has been around as long as the sun, but solar heating for homes and other buildings has become a popular subject in just the last few years. And already many people have come to think of solar energy in terms of the pipes, pumps, tanks, and flat-plate collectors that equip most solar-heated buildings.

But a more simple "built-in" approach to solar heating has been demonstrated to be as economical and effective as systems that use collectors mounted on rooftops.

This approach is called "passive" solar heating. In a passive system, the house itself collects and stores the sun's radiant energy in the form of heat. The heat is distributed throughout the building by natural processes. "Active" heating systems, on the other hand, use special collectors to capture the sun's energy in heated air or liquid, which is distributed by fans, pumps, or other mechanical devices.

How can a building be its own solar collector? It has to be designed that way. Architects, designers, and engineers throughout the country have come up with some innovative designs, featuring greenhouses, roof ponds, and massive thermal storage walls. All are meant to provide a comfortable living environment with minimal consumption of energy.

The basic ideas behind passive solar heating were in fact developed hundreds and even thousands of years ago. The Pueblo Indians of the American Southwest designed dwellings with thick adobe walls which absorbed solar heat during the day, and radiated heat into the living space during the cold desert night. Indians in what is now Arizona built cliff dwellings in 1100 A.D., using the cliff as a natural overhang to block the summer sun.

(MORE)

With this very early use of solar energy in the Southwest, it's not surprising that the passive solar energy movement is quite active in New Mexico. It is also popular in New England, where cold winters, high fuel bills, and "Yankee" self-reliance make solar heating look attractive.

New Mexico residents benefit from a state income tax credit that applies to both passive and active solar systems. There are about 150 passive solar homes in New Mexico, according to Dr. J. Douglas Balcomb of the Los Alamos (N.M.) Scientific Laboratory, a facility of the Energy Research and Development Administration (ERDA). The homes in New Mexico represent about ten percent of the total number of passive solar homes in the U.S., said Balcomb, even though the state has only two percent of the Nation's population.

Analysis of passive systems at Los Alamos is the core of an expanding program to learn more about passive heating and cooling systems and how they can save energy and money. The program is funded by ERDA's Division of Solar Energy, Research and Development Branch. ERDA spent about \$300,000 in Fiscal Year 77 on passive solar research and development, mostly for work at Los Alamos. In Fiscal Year 78, plans are to spend about \$1.4 million, with contracts to be awarded to small businesses, universities, government laboratories, and individuals throughout the country. Some of the projects will involve design, construction, and instrumentation of buildings with innovative passive heating and cooling systems. Data from these buildings will provide a "quantitative basis" for designing passive systems for other buildings.

"The architectural, engineering, and building community needs an accurate way to predict the amount of energy that can be supplied by a passive heating and cooling system," said ERDA program manager Michael W. Maybaum. "They also need simple but accurate tools and techniques for designing such systems. We hope to make these available in the next year."

As part of this effort to develop a "quantitative basis for design," a series of 14 "test modules" has been set up at the Los Alamos laboratory. Each module is a tiny one-room building using a different passive solar concept. By taking careful measurements over many months, the Los Alamos group has developed a computer modeling technique to predict the performance of passive solar heating concepts in different climates and under different conditions.

(MORE)

The results look encouraging. According to a Los Alamos study published in July, a passive system could provide practically all the heat needed in a Los Angeles residence -- 99.9 percent -- and 60 percent in New York, 57 percent in Boston, 52 percent in Seattle, and 42 percent in Madison, Wisconsin.

The test modules illustrate the four main passive solar concepts. The simplest is the "direct gain" approach, in which a building's south wall is a large expanse of double-pane glass. The low-altitude winter sun illuminates the south wall most of the day, but the high-altitude summer sun is prevented from reaching the wall by an overhang.

During the winter, the glass wall lets the sunshine in, and solar heat is stored in the building's massive masonry or concrete floor and north-facing wall. This design makes the whole building a live-in solar collector. Stored heat radiates throughout the living space on cold days and nights.

Insulation is used in all passive solar designs, not only on the inside, but in some cases on the outside of walls and roofs as well. Moveable insulating shutters are used at night to cover the south wall in order to prevent heat loss. Some buildings use a unique "beadwall" system, which fills the air space between the two panes of glass with tiny styrofoam beads. During the day the beads are vacuum-pumped out and stored until needed.

Another basic approach to passive solar heating is the thermal storage wall -- a thick south-facing concrete wall covered with glass, with an air space between the glass and the wall to prevent heat loss. Sunshine enters through the glass and is immediately stored in the wall. The stored heat radiates throughout the building at night.

A thermal storage wall is usually made of concrete, up to two feet thick. But it doesn't have to be concrete. A home in Albuquerque uses a row of 55-gallon water-filled drums as a thermal storage "wall." At night the outside of this "drumwall" is covered with insulating shutters. During the day, the shutters are kept flat on the ground to reflect additional sunlight onto the wall.

Another variation of the thermal storage wall concept is the Trombe wall, first used in the Felix Trombe house

(MORE)

in Odeillo, France. It is a thick concrete or masonry wall with vents at the top and bottom of the room. Cold air from the room enters the bottom vents, and rises through the space between the wall and its glass glazing. As it becomes warmer, the air rises to the top of the space, where it re-enters the room through the top vents. This way a natural "thermocirculation" pattern is established, using convection to continually replenish the supply of warm air in the building.

A greenhouse added to the outside of a thermal storage wall can collect additional heat. Solar energy not only provides all the heat needed by the greenhouse but provides substantial heat for the house itself as well.

The last major design concept is the roof pond, which can be an open pond or can consist of water-filled plastic bags on the roof. California scientist Harold Hay designed a roof pond system, which he calls "Skytherm," for his house in Atascadero and for other homes as well. The flat roof is covered with large plastic bags of water which absorb solar heat and radiate it through a metal ceiling to the rest of the house. On cold nights, moveable insulation panels cover the pond to prevent heat loss. In hot weather, the pond is covered during the day, and is opened at night so it can radiate heat from the house to the night sky.

Will these unusual home designs become commonplace in the future? Much of passive solar heating's potential success depends on cost. Passive solar systems are still more expensive than conventional heating systems, and ERDA scientists say that more research is needed to compare the cost-effectiveness of passive and active systems. However, passive systems generally last the life of the building, and require little upkeep, according to ERDA's Maybaum. "If we consider the life-cycle cost of passive and active systems," he said, "passive appears even more economically viable."

Right now, passive systems are used mainly in custom-built homes, which represent only five to eight percent of the nation's total housing volume. But one of the ERDA projects to be conducted in 1977-78 will test the feasibility of "retrofitting" an older masonry home with a Trombe wall passive solar system. And ERDA's Los Alamos scientists have just begun testing a prototype modular home that might prove the feasibility of making passive solar systems available in manufactured housing.

(MORE)

The potential success of all solar energy systems will depend on many factors, including the future cost of gas, oil, and electricity. Basically, passive solar heating will catch on if builders can sell it, according to Baltimore architect Peter Powell. "We're already seeing a surge of demand for energy conservation features in homes," Powell said, "and this demand may eventually extend to passive solar if we can show how well it works."

For more information about solar heating and cooling, write to the National Solar Heating and Cooling Information Center, P.O. Box 1607, Rockville, Maryland 20852.

#

News Media Contact: Leslie Braunstein
Tel.: 202/376-4058

PASSIVE SOLAR HEATING CONCEPTS

(Shaded Areas Are Main Solar Heat Storage Areas.)

DIRECT GAIN

South Wall Is Double-Pane Glass

THERMAL STORAGE WALL

Heat Is Stored in Wall
With Glass Glazing

TROMBE WALL

Vents at Top and Bottom of Thermal
Storage Wall Permit Natural
Thermocirculation Pattern

SOLAR GREENHOUSE

Greenhouse Admits Solar Energy;
Heat Is Stored in Thermal Storage Wall

ROOF POND

Heat Is Stored in Water on Roof

DIRECT GAIN WITH CLERESTORY WINDOWS

Windows Admit Solar
Energy to Back Rooms

Passive: when applied to solar energy, a method of collection that uses building design and materials rather than store solar heat (or cool), rather than special hardware, machinery, or energy-consuming equipment.

The state—and state-of-mind—of THE PASSIVE ART

By David Wright and Barbara Wright

Man has devised ingenious systems using stored solar energy in the form of coal, oil, gas, uranium and the like to assist his life support techniques. We are discovering that these systems, while logical for a short term, are not sufficient for the long range scheme of things.

Nature manages to accomplish the miracles of life on a low temperature scale. Virtually all of our natural earthly processes are sustained by diffused energy. Photosynthesis, body metabolism, and weather cycles make use of low grade conversion of energy to produce the forces which power our earth's systems. The main power input, that great fusion reactor called the sun, is the only necessary driving force. Man, on the other hand, has created high energy techniques of coping with his environment, and we call this progressive. This quest for progress has driven us to overdependency on high temperature and relatively inefficient thermal processes to accomplish a myriad of tasks that at this time we consider necessary for our quality of life.

In many cases, we are finding that high energy active methods are not the most efficient means of using our technology. Certainly space conditioning, food production, water heating, desalinization, and crop drying, among other things, are easily accomplished using primarily the incoming solar resource. Imagine a design that would make efficient use of all energy and

materials. This involves thinking on both major and minor scales. Passive systems that do not require high temperature thermal processes to function are probably our most readily available and even our best long range solution to many of today's energy problems. In order to succeed in the implementation of passive processes in our houses, offices, and factories, we must reevaluate all of our systems, and draw from history, nature and technology at many different levels.

The first step toward this goal is to ascertain what forms of energy are being wasted. We need to know how many units of heat energy are required to do a job, and then use our knowledge to do that job in the most efficient practical manner. Once the task has been singled out and objectively reviewed, we can get on with creating the mechanisms for implementation.

Today the state of the art of passive systems is evolving rapidly. We now are aware that many tasks formerly requiring the combustion of fuels can be accomplished by much lower temperature means. In the forefront are the heating, cooling, and ventilation of the buildings in which we live, learn and work. This is just the tip of the iceberg. Many creative minds and hands are exploring avenues of solving both short and long range problems through passive techniques. The simple reminder that enough usable solar energy falls on the surface of the earth to provide all of our energy requirements as long as the

Wright is an environmental architect based at the Sea Ranch, Calif., and a member of the Solar Age advisory board. Barbara Wright translates.

THE PASSIVE ART continued

Phase change material: a substance that changes from one phase (for instance, a solid) to another (for instance, a liquid) with a change in temperature, and that with each change either stores or releases heat.

sun will shine, is enough to stimulate this long overdue research and development.

Basically, the approach today falls into three categories. The first and most evident is to use what we have and know about already to the best advantage. The use of commercially made or homemade materials and devices for new tasks involves looking around in our environment for things that can be used in different and better ways. Junkyards, hardware stores, the yellow pages, and many other places hold untapped reserves. Steve Baer's discovery that steel drums, once used to transport oil or chemicals, could be filled with water and used to collect and store energy to heat and cool without electricity or any fuels, was a remarkable reevaluation of a material and man's needs. The Harold Hay experiment—an insulated ice chest, filled with water and covered and uncovered systematically—taking advantage of direct solar gain, deep space radiation, and evaporation to heat and cool the contents, led to the "Skytherm," another example of how the laws of physics and existing materials can effect man's

needs. Both have led to further innovative speculation on how and why we do things with what we've got.

The building materials industry currently markets numerous materials and devices that can be adapted to passive solar designs. Large transparent and sloped solar collection surfaces can be made using sliding glass door replacement units. These factory sealed, double tempered, altitude adjustable glass units, which come in four basic sizes, are exceptionally durable and high quality transmission surfaces. They usually can be purchased quite reasonably in orders of ten or more. Other industrial materials such as fireproof wood fiber insulations with "R" values up to 7.0 per inch, neoprene windshield glazing gaskets, ultraviolet resistant greenhouse fiberglass, flexible high temperature hose, and other such items can aid solar designers with a ready-made pallet of suitable materials.

The other approach to passive systems is to create new tools and materials to accomplish tasks that appear feasible. Here, we step beyond the adaptation of existing ideas and products to reach for the means to solve specific problems with new ideas and products. Take, for example, the work of Suntek (Day Chahroudi and others)—the sandwiching of clear gel, which becomes opaque at higher temperatures, between transparent sheets to create a self governing solar gain surface and prevent excess absorption, is an instance of finding a low-key solu-

tion to a problem that exists in greenhouses and direct solar gain structures. They and other groups are working on the capacity to store passive or ambient heat in new and existing structures, another problem. Today development is being done on encapsulating phase change materials in concrete masonry units, wall and ceiling tiles, plasterboard, etc. This will allow the fabric of our buildings to use the latent heat of phase change in order to maintain equalized temperature in spaces at all times. Within a temperature range of a couple of degrees, a building will have enough heat capacity to accept or give off energy to sustain comfort, equalizing the normal daily and seasonal loss gain demands.

Now our focus on passive applications will intensify. With a sustained effort, we will undoubtedly become aware of the solutions which now elude us. The products and systems contained in this catalog are the starting point.

From now on, it is eminently important to search out and use all of the methods available to better use the energy of the sun. We must, however, at the same time beware of half baked solutions, fast buck artists whether corporate or individual, and even the entrepreneur hiding under alternative energy slogans who is marketing a good product at an outrageous price.

May we all become more active passive in our attitudes towards energy consumption. ☉

MOVEABLE INSULATION

by

Stephen C. Baer

ABSTRACT

It is difficult to seal for air leaks around the edges of a moveable insulating panel. Moveable insulation is most useful if it can be used to prevent both heat gain and heat loss and also act as a reflector to increase winter heat gain.

I. INTRODUCTION

The great problem with moveable insulation is cracks. A door, shutter, or curtain is placed in front of a window to stop heat loss. The optimist notes the R value of the material and predicts success but, in fact, he does not achieve it. Unfortunately, it is difficult to discover the exact problems and their solutions.

The effect of clothes and blankets on heat loss is naturally investigated by everyone. You can feel where you are cold and the results of tucking this or that in or adding another layer of cloth, but we aren't in such close touch with temperatures of a window or skylight. A sniper scope or camera of some kind that shows different temperatures as different colors would be an enormous help to the investigator. 30 minutes with such a tool could be as valuable as a week's work done without it. Occasionally nature treats you to such a

view of the window or skylight with a pattern of frost. The fussy problem of seals is the entire problem. The problem resists solutions because it is not easy to quickly determine success or failure.

CRACKS

A crack size of $2 \text{ in}^2/\text{ft}^2$ between an insulating panel and a single glazed window can conduct $1/3 \text{ Btu}/\text{ft}^2 \text{ hr}^\circ \text{F}$. If you are likely to have cracks, plan to torture any air that dares to pass through them. This can be done by pressing the insulating panel directly against the glass - any air leak around the edges must then spread out in a thin film in order to warm the glass. Experimenting with smoke introduced in thin films behind glass, you find that once this layer is less than $1/16$ " in thickness, it is slowed by enormous resistance and acts almost like syrup. Treat a glass area like a ship - break it into separate compartments so that a leak in one

This paper presented at the Passive Solar Heating and Cooling Conference, May 1976, Albuquerque, New Mexico.

place won't be fatal.

Tests done at the Illinois Institute of Technology(1) during 1974 on conventional window shades showed the following:

- 1) A roller shade inside a casement window with 1/4" gaps at the sides of the shade reduced heat loss through a single glazed window by about 28%.
- 2) A drape drawn in front of the single glazed window reduced heat loss by about 6%.
- 3) A venetian blind reduced heat loss by 7%.

During the summer the shading devices reduced heat gain by the following amounts:

- 1) white, opaque roller shade 50%
- 2) venetian blinds(slats at 45%) 18%
- 3) venetian blinds(slats closed) 29%

Tests we have done at Zomeworks on 45° sloped skylights with our insulating Skylids installed beneath a single pane of glass show a reduction in heat loss of about 75% when the louvers are closed. The louvers average 3" thick, have aluminum skins and are filled with fiberglass - most of the heat loss occurs through air leaks around and between the louvers.

We have not tested the Beadwall for heat loss, but have used the manufacturer's figure of a resistance of 3 per inch for the styrofoam beads. The Beadwall seems to be the perfect answer for superior insulation against heat loss.

Tests done by thermal decay of a glass aquarium show a U factor of the naked glass of about 1.1/3 and of the glass covered

with Nightwall, of about 1/3.

Moveable insulation can also be used to prevent heat gain. In this case, the best position for it is outside the glass rather than inside.

A particularly attractive use of insulating panels is to have them double as reflectors - during the day they bounce additional energy through the same window they will insulate at night. Often it is most cost-effective to have a moveable reflector outside a south window or skylight that is changed seasonally, but not daily.

SUMMARY

- 1) It is best to have a way to prevent both heat gain and heat loss.
- 2) Be skeptical of mechanical seals.
- 3) Do not use single glazing unless it is a mild climate or the moveable insulation is controlled by reliable automatic means.
- 4) Do not install anything you cannot fix.
- 5) Look for two uses for one material.
- 6) Break the area to be insulated into pieces so that an air leak in one area will be isolated.
- 7) Always use strong, durable materials outside.

REFERENCE

1. Rollin C. Dix, Zalman Lavan, "Window Shades and Energy Conservation," Illinois Institute of Technology, 1974.

GLOSSARY

*Short definitions of some of the names and terms that crop up in solar energy **

Absorbent—the less volatile of the two working fluids used in an absorption cooling device.

Absorber—the blackened surface in a solar collector that absorbs the solar radiation and converts it to heat energy.

Absorptance—the ratio of solar energy absorbed by a surface to the solar energy striking it.

Active system—a solar heating or cooling system that requires external mechanical power to move the collected heat.

Air-type collector—a solar collector that uses air as the heat transfer fluid.

Altitude—the angular distance from the horizon to the sun.

ASHRAE—abbreviation for the American Society of Heating, Air-conditioning and Refrigerating Engineers.

Auxiliary heat—the extra heat provided by a conventional heating system for periods of cloudiness or intense cold, when a solar heating system cannot provide enough.

Azimuth—the angular distance between true south and the point on the horizon directly below the sun.

Btu. or British thermal unit—the quantity of heat needed to raise the temperature of 1 pound of water 1°F.

Caloric—the quantity of heat needed to raise the temperature of 1 gram of water 1°C.

Coefficient of heat transmission, or U-value—the rate of heat loss in Btu per hour through a square foot of a wall or other building surface when the difference between the indoor and outdoor air temperatures is 1°F.

Collector—any of a wide variety of devices (flat-plate, concentrating, vacuum tube, greenhouse, etc.) used to collect solar energy and convert it to heat.

Collector efficiency—the ratio of heat energy extracted from a collector to the quantity of solar energy striking the cover, expressed in percent.

Concentrating collector—a device that uses reflective surfaces to concentrate the sun's rays onto a smaller area, where they are absorbed and converted to heat energy.

Conductance—a property of a slab of material equal to the

quantity of heat in Btu per hour that flows through one square foot of the slab when a 1°F temperature difference is maintained between the two sides.

Conduction—the transfer of heat energy through a material by the motion of adjacent atoms and molecules.

Conductivity—a measure of the ability of a material to permit conduction heat flow through it.

Convection—the transfer of heat energy from one location to another by the motion of fluids that carry the heat.

Cover plate—a sheet of glass or transparent plastic that sits above the absorber in a flat-plate collector.

Degree-Day—a unit that represents a 1°F deviation from some fixed reference point (usually 65°F) in the mean daily outdoor temperature. If the outdoor temperature is 40°F for one day, then twenty-five (65° minus 40°) Degree Days result. Used to determine the demand of a heating season for different locales.

Design heat load—the total heat loss from a house under the most severe winter conditions likely to occur.

Design temperature—a temperature close to the lowest expected for a location, used to determine the design heat load.

Diffuse radiation—sunlight that is scattered from air molecules, dust, and water vapor and comes from the entire sky vault.

Direct methods—techniques of solar heating in which sunlight enters a house through the windows and is absorbed inside.

Direct radiation—solar radiation that comes straight from the sun, casting shadows on a clear day.

Double-glazed—covered by two panes of glass or other transparent material.

ERDA—U.S. Energy Research and Development Administration, responsible for commercial, institutional, and industrial solar demonstration program; and for general coordination of federal solar energy research and development.

Emissance—a measure of the propensity of a material to give off thermal radiation.

Continued

GLOSSARY *continued*

Eutectic salts—a group of materials that melt at low temperatures, absorbing large quantities of heat and then, as they re-crystallize, release that heat. One method used for storing solar energy as heat.

FEA—Federal Energy Administration, responsible for federal energy policy.

Flat-plate collector—a solar collection device in which sunlight is converted to heat on a plane surface, usually made of metal or plastic. A heat transfer fluid is circulated through the collector to transport heat to be used directly or to be stored.

Forced convection—the transfer of heat by the flow of warm fluids, driven by fans, blowers, or pumps.

Glaubers salt—sodium sulfate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), a eutectic salt that melts at 90°F and absorbs about 104 Btu per pound as it does so.

Gravity convection—the natural movement of heat through a body of fluid that occurs when a warm fluid rises and cool fluid sinks under the influence of gravity.

HUD—U.S. Department of Housing and Urban Development, responsible for residential solar demonstration program.

Header—the pipe that runs across the top (or bottom) of an absorber plate, gathering (or distributing) the heat transfer fluid from (or to) the grid of pipes that runs across the absorber surface.

Heat capacity—a property of a material, defined as the quantity of heat needed to raise one cubic foot of material 1°F.

Heat exchanger—a device, such as a coiled copper tube immersed in a tank of water, that is used to transfer heat from one fluid to another through an intervening metal surface.

Heating season—the period from about October 1 to about May 1, during which additional heat is needed to keep a house warm.

Heat pump—a mechanical device that transfers heat from one medium (called the heat source) to another (the heat sink), thereby cooling the first and warming the second.

Heat sink—a medium or container to which heat flows (see heat pump).

Heat source—a medium or container from which heat flows (see heat pump).

Heat storage—a device or medium that absorbs collected solar heat and stores it for periods of inclement or cold weather.

Heat storage capacity—the ability of a material to store heat as its temperature increases.

Indirect system—a solar heating or cooling system in which the solar heat is collected outside the building and transferred inside using ducts or piping and, usually, fans or pumps.

Infiltration—the movement of outdoor air into the interior of a building through cracks around windows and doors or in walls, roofs, and floors.

Infrared radiation—electromagnetic radiation, whether from the sun or a warm body, that has wavelengths longer than visible light.

Insolation—the total amount of solar radiation—direct, diffuse and reflected—striking a surface exposed to the sky.

Insulation—a material with high resistance or R-value that is used to retard heat flow.

Integrated system—a solar heating or cooling system in which the solar heat is absorbed in the walls or roof of a dwelling and flows to the rooms without the aid of complex piping or ducts.

Langley—a measure of solar radiation, equal to one calorie per square centimeter.

Life-cycle costing—an estimating method in which the long-term costs such as energy consumption, maintenance, and repair can be included in the comparison of several system alternatives.

Liquid-type collector—a collector with a liquid as the heat transfer fluid.

Natural convection—see gravity convection.

Nocturnal cooling—the cooling of a building or heat storage device by the radiation of excess heat into the night sky.

psi—pounds per square inch (pressure).

Passive system—a solar heating or cooling system that uses no external mechanical power to move the collected solar heat.

Percentage of possible sunshine—the percentage of daytime hours during which there is enough direct solar radiation to cast a shadow.

Photosynthesis—the conversion of solar energy to chemical energy by the action of chlorophyll in plants and algae.

Photovoltaic cells—semi-conductor devices that convert solar energy into electricity.

Radiant panels—panels with integral passages for the flow of warm fluids, either air or liquids. Heat from the fluid is conducted through the metal and transferred to the rooms by thermal radiation.

Radiation—the flow of energy across open space via electromagnetic waves, such as visible light.

Reflected radiation—sunlight that is reflected from surrounding trees, terrain or buildings onto a surface exposed to the sky.

Refrigerant—a liquid such as freon that is used in cooling devices to absorb heat from surrounding air or liquids as it evaporates.

Resistance, or R-value—the tendency of a material to retard flow of heat.

Retrofitting—the application of a solar heating or cooling system to an existing building.

Risers—the flow channels or pipes that distribute the heat transfer liquid across the face of an absorber.

R-value—see resistance.

Seasonal efficiency—the ratio of solar energy collected and used to that striking the collector, over an entire heating season.

Selective surface—an absorber coating that absorbs most of the sunlight hitting it but emits very little thermal radiation.

Shading coefficient—the ratio of the solar heat gain through a specific glazing system to the total solar heat gain through a single layer of clear, double-strength glass.

Shading mask—a section of a circle that is characteristic of a particular shading device. This mask is superimposed on a circular sun path diagram to determine the time of day and the months of the year when a window will be shaded by the device.

Solar house, or solar tempered house—a dwelling that obtains a large part, though not necessarily all, of its heat from the sun.

Solar radiation—electromagnetic radiation emitted by the sun.

Specific heat—the quantity of heat, in Btu, needed to raise the temperature of 1 pound of a material 1°F.

Sun path diagram—a circular projection of the sky vault, similar to a map, that can be used to determine solar positions and to calculate shading.

Thermal capacity—the quantity of heat needed to warm a collector up to its operating temperature.

Thermal mass, or thermal inertia—the tendency of a building with large quantities of heavy materials to remain at the same temperature or to fluctuate only very slowly; also, the overall heat storage capacity of a building.

Thermal radiation—electromagnetic radiation emitted by a warm body.

Thermosiphoning—see gravity convection.

Tilt angle—the angle that a flat collector surface forms with the horizontal.

Trickle-type collector—a collector in which the heat transfer liquid flows down open channels in the front face of the absorber.

Tube-in-plate absorber—an aluminum or copper sheet metal absorber plate in which the heat transfer fluid flows through passages formed in the plate itself.

Tube-type collector—a collector in which the heat transfer liquid flows through metal tubes that are wired, soldered, or clamped to the absorber plate.

Ultraviolet radiation—electromagnetic radiation, usually from the sun, with wavelengths shorter than visible light.

Unglazed collector—a collector with no transparent cover plate.

U.S. Department of Energy—proposed cabinet department that will take over U.S. energy programs, including the functions of ERDA and FEA.

U-value—see coefficient of heat transmission.

APPLICATIONS AND ANALYSIS

TITLE: PASSIVE SOLAR HEATING OF BUILDINGS

AUTHOR(S): J. Douglas Balcomb
James C. Hedstrom
Robert D. McFarland

SUBMITTED TO: Workshop on Solar Energy Applications
Associated Universities, Inc.
June 27-July 31, 1977

By acceptance of this article for publication, the publisher recognizes the Government's (license) rights in any copyright and the Government and its authorized representatives have unrestricted right to reproduce in whole or in part said article under any copyright secured by the publisher.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the USERDA.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

PASSIVE SOLAR HEATING OF BUILDINGS*

by

J. D. Balcomb, J. C. Hedstrom and R. D. McFarland
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

Passive solar heating concepts--in which the thermal energy flow is by natural means--are described according to five general classifications: direct gain, thermal storage wall, solar greenhouses, roof ponds, and convective loops. Examples of each are discussed. Passive test rooms built at Los Alamos are described and results are presented. Mathematical simulation techniques based on thermal network analysis are given together with validation comparisons against test room data. Systems analysis results for 29 climates are presented showing that the concepts should have wide applicability for solar heating.

INTRODUCTION

Solar gains through windows, walls, modified walls, skylights, clerestory windows, and roof sections provide an opportunity to dramatically reduce the total heating energy requirements of a building. When the thermal energy flow is wholly by natural means, such as radiation, conduction, and natural convection, and when solar energy contributes more than half of the total outside energy requirements, then the building is referred to as a passive solar heated structure.

Passive solar heating works very well. This has been demonstrated time and again in a wide variety of buildings located in a wide variety of climates. The occupants of these buildings testify to their comfort, to the ease of their natural operation, and especially to their low fuel bills. A principal problem, however, has been the lack of a quantitative basis for incorporation of the basic concepts into architectural design.

The ERDA Los Alamos Scientific Laboratory has been evaluating passive solar heating for one year under the cognizance of the Division of Solar Energy Heating and Cooling Research and Development Branch. The purpose of the two-year LASL program is to provide the needed quantitative basis for design.

Test rooms have been set up at Los Alamos to study the behavior of passive solar heating elements under carefully controlled conditions. One year of test data have been obtained on a pair of test rooms which utilize thermal storage walls concepts, one with cylindrical water storage tubes and the other with a thick masonry wall. The storage walls are located behind a vertical double-glazed wall. During the mid-winter months each of these rooms has an average inside temperature 60 to 70°F above the ambient temperature. The temperature histories in these rooms are very accurately predicted by simulation analysis techniques developed at LASL.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

Eleven different buildings have been instrumented in order to study passive solar heating elements within these buildings. These are the Doug Kelbaugh residence in Princeton, NJ, the Benedictine Monastery Dove Publications Building in Pecos, NM, four small buildings at the Ghost Ranch in New Mexico, the Bernardo Chavez solar greenhouse in Anton Chico, NM, the Santa Fe First Village Unit #1, and the residences of Bruce Hunn, Carl Newton, and Tom Shankland in Los Alamos, NM. Data from these installations will be used to validate the simulation analysis technique.

A comprehensive simulation analysis computer code has been written to predict the performance of passive solar heated buildings. The code has been partially validated against test room results and has been used to predict the performance of numerous building geometries. The results of geographic studies done with this code demonstrate that passive solar heating systems can be expected to work effectively in all U.S. climates.

Types of Passive Systems

The first and simplest type of passive system is the *direct gain* approach in which one simply has an expanse of glass, usually double glass, facing south. The building should have a considerable thermal mass, either a poured concrete floor or a massive masonry construction with insulation on the outside. The building becomes a live-in solar collector. The characteristic sun angles result

DIRECT GAIN

in a good situation since the south face is exposed to a maximum amount of solar energy in the cold winter months when the sun angles are low and a minimum amount of solar energy in the summer when the sun angles are high. Thus the basic seasonal characteristic of control is automatic. An example of this direct gain system is the Wallasey school.¹

This is certainly the largest passive solar heated structure in the world and one of the first. It was built in 1962, but it is little known. It is a large building of concrete construction with 7 to 10 in. of concrete forming the roof, the back wall the floor and side walls with 5 in. of expanded polystyrene as the insulation outside of that. The solar wall is an expanse of glass, 27 ft tall and ~230 ft long facing south. There are two sheets of glass, the one on the outside is clear and about 2 ft inside of that is a diffusing layer of glass. It is a figured glass, so called, which refracts sun's rays, so that it irradiates the roof and the floor fairly uniformly. This structure is heated to about 50% by the sun, the remaining energy for heating the building comes from the lighting and from the students. The auxiliary system which originally installed has not been needed. The school is located in Liverpool, England near the sea at a latitude of 53° north.

Another direct gain system is the David Wright house in Santa Fe, New Mexico which uses adobe or earth brick construction with insulation on the outside and has a system of shutters which drop down at night when needed to reduce heat losses.

THE DAVID WRIGHT HOUSE

The direct gain approach can take more complicated forms as shown in this sketch by Mark Chalom with the use of clerestory windows or sky lights to provide energy in back rooms.²

The second type of system is the thermal storage wall in which the thermal storage is in a wall which blocks the sun after it comes through the glazing and stores the heat energy. The wall in this case is usually painted black or a dark color to be a good absorber. It can be water in containers or masonry. A small section of thermal storage wall was used in the Wallasey school discussed earlier.

THERMAL STORAGE WALL

An example is the Steven Baer house in Albuquerque, NM in which the thermal storage wall consists of 55 gallon drums filled with water, laid on their side providing a massive thermal storage. A system of

South wall

THE BAER HOUSE

movable insulation is used in which a door forming the south wall lowers during a winter day to allow the sun in and actually reflect some sun onto the storage. There is a single layer of glass. The door can then be raised at night to reduce heat loss.

A very well known implementation of the storage wall concept is the Trombe house in Odeillo, France in which the wall is concrete.³ In the houses that were built in 1967 the wall is about 2 ft thick. The primary mechanism for heating the house is by radiation and convection from the face of the wall with the thermal energy diffusing through this thick wall. About 30% of the energy is by a thermocirculation path which operates during the day only by natural convection with ports at the bottom and top. Some data taken on this system for a period of four days in December of 1974 are for situations in which the ambient temperature is only slightly above freezing and there are two sunny days, a cloudy day and then another sunny day.⁴ The outside surface of the concrete heats up to about 140°-150°F during the day. The inside temperature remains at about 85°F fairly uniform, providing radiant and convective heat to the room.

TROMBE HOUSE

The data taken over a period of one year indicate that about 36% of the total energy incident on the wall is effective in heating the building during the winter months which is typical of a ge active solar heating system. About 70% of the thermal energy required by the building (which is controlled at a temperature of 68°F) was provided by solar energy over this one year period.

Efficiency of the solar wall of the 1957 Trombe house. Each point represents an average over one month of data.

A mix of these two concepts is the *solar greenhouse* house in which one builds a greenhouse onto the south side of a building with some kind of thermal storage wall between the greenhouse and the house. The temperature in the greenhouse does not require very good control as long as the plants do not freeze. Solar energy provides, typically, all of the heat required for the greenhouse as well as providing substantial energy for heating the house.⁵

The fourth type of design is the *roof pond* in which the thermal storage is in the ceiling of the building. In this case movable insulation is needed because the sun angles are altogether wrong. The sun provides large inputs in the summer and small inputs in the winter. It is a good natural cooling system because by using movable insulation one can take advantage of night time radiation. This concept has been implemented in the Atascadero, CA house which uses the Harold Hay skytherm concept.

SOLAR GREENHOUSE

ROOF POND

THE HAROLD HAY HOUSE

A system of insulating panels on the roof are is used which slide back and forth on tracks.⁶ The water bags are left exposed to the sky during the day in the winter and during the night in the summer. This provides heat input in the winter and heat loss on a summer night. The insulation is put in place during a winter night to conserve heat and during a summer day in order to exclude the sun which is reflected from the top of the white panels. This system has worked very well and has operated without any backup in the rather mild climate of Atascadero providing good thermal comfort in a small building.

The fifth type of passive system is a natural convective loop. The classic thermosiphon water heater fits into this category. Natural convective loops which use air as the heat transport fluid have been built and work well. A good example is the Paul Davis house in Corrales, NM.

MATHEMATICAL SIMULATION ANALYSIS

Thermal network analysis techniques can be used to predict the performance of passive solar heated buildings. The building temperature state is characterized by 6 to 11 temperatures at various locations--such as air temperature, surface temperatures, glass temperatures, and the temperature of various thermal storage materials at various depths. Energy balance equations are set down for each location accounting for thermal energy transport by radiation, conduction and convection, energy sources from the sun, lights, people, and auxiliary heaters, and sensible thermal energy storage in the material. The temperature history of each location is then simulated by solving these equations for given inputs of solar radiation, ambient air temperature

and wind. A one-hour time step is used through a one year time period. Energy flows are accumulated on a monthly basis. This technique is used to characterize the performance of various passive solar systems which use solar gain through windows and thermal storage mass walls. The influence of various parameters is studied by successive computations of different parameters.

Building Model

The type of thermal network model used in the analysis is shown in Fig. 1. This represents a building with a concrete thermal storage wall located behind vertical double glazings. Node 5 represents the temperature of the air between the inner glazing and the wall. Nodes 6 and 11 represent the wall outer and inner surface temperature. The mass of the wall is equally divided between Nodes 7, 8, 9 and 10 which represent the temperatures within the wall at distances of $1/8$, $3/8$, $5/8$, and $7/8$ of the wall thickness from the outer surface. Node 2 represents the room (globe) temperature and Node 1 represents the outside ambient air temperature.

Solar radiation on a horizontal surface, ambient air temperature, and wind velocity are the input variables to analysis, given at hourly intervals. Solar radiation on a vertical surface is calculated by separating the horizontal surface data into direct and diffuse components and applying the proper geometrical transformation as described by Liu and Jordan.⁸ A ground reflectance of 0.3 is assumed. The separation of solar radiation into components is done using the technique described by Boes.⁹ The transmittance of the glass is calculated as a function of incidence angle using the Fresnel relations and accounting for glass absorptance. The transmittance at normal incidence is 85% per glass layer. The radiation transmitted through the glass is all absorbed at Node 6.

At each hour, node temperatures are calculated as required to achieve an energy balance at the node. Energy storage occurs at only Nodes 7, 8, 9, and 10.

The thermal energy flow between nodes is calculated based on the temperature difference and the appropriate U-value. The values of U_2 , U_4 , and U_5 include non-linear radiation terms. All emittances are set at 0.8. The value of U_2 includes a

Fig. 1. Simulation schematics of the test rooms.

wind-velocity-dependent convective term. The values of U_3 , U_5 , and U_7 are a constant $1.0 \text{ BTU/hr-}^\circ\text{F ft}^2$. The values of U_8 , U_9 , U_{10} , U_{11} , and U_{12} represent thermal conduction through the concrete.

In the original version of the masonry thermal storage wall, as developed by Felix Trombe and his colleagues, vent holes are left at the bottom and top of the wall to allow a natural convection air flow from the room floor level up through the space between the inner glass and the wall and return to the room at the ceiling level. This "thermocirculation" provides a mechanism for instantaneous flow of heat into the room during the day. The conductance U_{13} represents this energy flow path. The volumetric air flow is determined from the following relationship:

$$C_d A_v \sqrt{9.8(T_5 - T_2)/H}$$

where C_d vent discharge coefficient = 0.3,
 A_v = vent opening area per unit width,
 $= 0.074 \text{ ft}^2/\text{ft}$
 H = wall height = 8 ft
 $\beta = 1/T_5$

Various options are possible as follows:

- 1) Solid Wall: No thermocirculation is allowed.
- 2) Trombe Wall: Thermocirculation is allowed only in the normal direction as previously described. Reverse thermocirculation, as would normally occur at night, is not permitted. (This can be implemented with thin plastic film passive damper draped over the inside of the top opening.) It was determined

that if reverse thermocirculation is not prohibited then the vents are a net thermal disadvantage to the building.

3) Trombe Wall with Control: The results of the normal thermocirculation frequently is to overheat the building during the day. In this option, the vents are closed whenever the building temperature is 75°F or greater. This greatly reduces the required cooling. This presumably would require some passive or active mechanism.

Another configuration analyzed is the "water wall." This might consist of cans or drums of water stacked to form a thermal storage wall. Alternatively, vertical free-standing cylindrical tubes could be used or any other means of containing water in a

thermal storage wall. When heated by the sun on one side the water will freely convect to transport the heat across the wall horizontally and thus temperature gradients across the wall will be very small. The water wall has been analyzed by replacing Nodes 6,7,8,9,10 and 11 in Fig. 1 with a single Node 6 which represents all of the water mass.

In the analysis the room temperature (Node 2) is always maintained within bounds, $T_{\min}$ and $T_{\max}$, which are set at 65°F and 75°F , respectively. In the solution of the equations, two possible situations can result:

- 1) The calculated room temperature falls within the prescribed bounds $T_{\min}$ and $T_{\max}$.
- 2) The calculated room temperature is above $T_{\max}$ or below $T_{\min}$.

In the first situation, the room temperature assumes the calculated value. The second situation results in two further possibilities:

- 1) The calculated room temperature is less than $T_{\min}$. In this instance auxiliary energy is calculated as required to hold the room at $T_{\min}$.
- 2) The calculated room temperature is greater than $T_{\max}$. In this instance excess heat is dumped (to the environment, presumably by ventilation) in order to hold the room at $T_{\max}$.

The form of the solution is different depending on whether the room temperature is constrained to a bound or floating in-between. In the cases where a transition between operating modes occurs during the hour, the hour is partitioned and the appropriate equations used in each segment.

COMPARISON WITH TEST ROOM RESULTS

The validity of the simulation analysis techniques for two simple concepts is established by demonstrating that they adequately predict the temperature behavior of several small passive test rooms located in Los Alamos, NM. These test rooms are small insulated structures measuring five feet wide by eight feet deep by ten feet high. The south five foot by ten foot exposure is glazed with two sheets of Plexiglas. One test room contains four twelve inch-diameter fiberglass tubes which stand eight feet high directly behind the glass. The tubes are blackened to absorb solar radiation and filled with 123 gallons of water. A second test room contains a 16-inch concrete wall made of stacked cast blocks. Vents at the top and bottom can be opened to allow natural thermocirculation of air. The test rooms are virtually massless except for the thermal storage walls.

On a typical mid-winter clear day (Jan. 11) with an average ambient temperature of 23°F, the water temperature at mid-height varied from 82°F to 101°F and the room interior globe temperature varied from 74°F to 94°F. Stratification of water temperature of up to 32°F was observed from the bottom of the tube to the top of the tube. In the second test cell, the exterior wall surface temperature varied from 93°F to 153°F, the interior wall surface temperature varied from 84°F to 96°F, the top vent temperature varied from 84°F to 132°F, and the room interior globe temperature varied from 74°F to 93°F. During the longest stormy period of the winter, for which the ambient temperature held at roughly 20°F, the interior temperature of both cells dropped to the yearly minimum of 43°F.

The thermal behavior of both cells is simulated mathematically using a thermal network of 6-11 interconnected points each of which represents a characteristic location within or outside the test cell such as air temperature, surface temperature, glazing temperature, or the temperature of the thermal storage material at some depth within the material. Energy balance equations are written for each location and solved for the hourly observed ambient temperature, solar radiation, and wind conditions. The performance of both test cells can be predicted within roughly $\pm 2^\circ\text{F}$ under most conditions and about 8°F at the extremes.

An additional 12 test rooms have been completed for evaluating various passive systems. Simulation analysis of these will be carried out for comparison with observed temperatures.

Test Room Construction

A plan view of the pair of test rooms is shown in Fig. 2. The walls, floor, and ceiling are 2" x 4" stud-wall construction with 3-1/2" fiberglass insulation. The exterior is covered with plywood sheathing and the interior is lined completely with one-inch polystyrene insulation and all seams are well caulked. Thus the building interior mass is negligible compared with that of the various thermal storage elements added for the tests. The net calculated thermal conduction coefficient (exclusive of the south wall and the common wall) between the building interior and the ambient exterior temperature is 0.23 BTU/°F-hr per square foot of south glazing.

The entire 50 square-foot south wall of each test room is glazed with two sheets of 1/8" Plexiglas sheet separated by a 1/2" air gap. The rooms are actually oriented with the south wall facing 13° east of due south.

Storage Walls

Two different thermal storage wall concepts have been evaluated in the test rooms. The "water wall" consists of four 12"-diameter fiberglass tubes which are free standing behind the glazing separated by 2.4" from one another and the side walls. During most of the winter, these spaces and the two-foot space above the tubes were blocked with 2"-thick polystyrene insulation cut to fit.

The second test room contained a thermal storage wall. An original wall consisting of 8" solid blocks of cinder block was replaced for most of the winter with a 16" wall stacked from 6"x3"x16" blocks of solid cast concrete. Three 3"x3" holes were left open near the bottom and also near the top to allow air to thermocirculate from the room floor level up through the 6" space between the wall and the glazing and return at the room ceiling level. The holes were blocked during portions of the test year, left open day and night during other times, and opened during the day only at other times.

Fig. 2. Plan view of passive test rooms.

Storage masses were as follows:

	Thermal Storage/Glazed Area BTU/°F-ft ² _g
Water-wall	35
Masonry wall	32.5

General Results

The test rooms were very well heated by the sun. Average room temperatures were 60 to 70°F above the ambient average temperature during typical sunny midwinter days. The minimum temperature in the one room was very nearly equal to the minimum temperature in the other room each night throughout the winter. Daily room temperature variations were approximately as follows:

Water wall:	20°F
Masonry wall:	
Vents closed	11°F
Vents open	24°F

Thus the main effect of the thermocirculation vents is to provide direct heat to the room during the day. This increases the daily swing and although the daily average room temperature is larger by about 5°F, it does not noticeably change the minimum room temperature. The maximum inside wall surface temperature occurs at roughly 4:00 p.m. on the water wall and at 8:00 to 10:00 p.m. on the masonry wall.

Simulation Model

Thermal network models of the two test-room configurations are shown in Fig. 1. The thermal conductances used in the analysis are as follows (all values are normalized to one square foot of glazing, ft²_g): Water wall and masonry wall:

$$U_1 = \text{"load"} = 0.23 \text{ BTU/hr}^\circ\text{F ft}_g^2$$

$$U_2 = \text{radiation} + \text{exterior film conduction}$$

$$\text{radiation} = \frac{(T_1^2 + T_3^2)(T_1 + T_3)}{1/\epsilon_1 + 1/\epsilon_3 - 1}$$

$$\text{exterior film conduction} = 4 \text{ BTU/hr}^\circ\text{F ft}_g^2$$

(for an average wind speed of 7.5 mph)

$$\alpha = \text{Stefan-Boltzmann Constant} = 1.713 \times 10^{-9} \text{ BTU/hr ft}^2\text{F}^4$$

$$\epsilon_1 = 0.8 \text{ (Plexiglas)}$$

$$\epsilon_3 = 0.8 \text{ (ambient)}$$

$$U_3 = U_6 = U_7 = 1.0 \text{ BTU/hr }^\circ\text{F}^2 \text{ ft}_g$$

$$U_4 = \text{radiation} + \text{conduction}$$

$$\text{radiation similar to } U_2 \text{ with } \epsilon_2 = \epsilon_5 = 0.8$$

$$\text{conduction} = 0.35 \text{ BTU/hr }^\circ\text{F ft}_g^2, (1/2" \text{ space})$$

$$U_5 = \text{radiation similar to } U_2 \text{ with } \epsilon_5 = \epsilon_6 = 0.8$$

Masonry Wall:

$$U_8 = U_{12} = 4.7 \text{ BTU/}^\circ\text{F ft}_g^2 \text{ (2" concrete)}$$

$$U_9 = U_{10} = U_{11} = 2.35 \text{ BTU/}^\circ\text{F hr ft}_g^2 \text{ (4" concrete)}$$

The mass heat capacity of all nodes is zero except as follows:

$$\text{Water Wall: Node 6 heat capacity} = 35 \text{ BTU/}^\circ\text{F ft}_g^2$$

$$\text{Masonry Wall: Nodes 7, 8, 9 and 10 heat capacity} = 8.1 \text{ BTU/}^\circ\text{F ft}_g^2$$

Input to the simulation model are instantaneous hourly values of measured ambient temperature (Node 1) and also the solar radiation measured on a vertical surface parallel to the glazing, integrated over one hour.

Solar transmittance through the glazing is calculated accounting for both Fresnel reflections and for absorption in the glazing based on the calculated incidence angle. This leads to an energy

Figure 3. Comparison for a Period with the Thermocirculation Vents Open.

Figure 4. Comparison for a Period with Thermocirculation Vents Closed.

source term into Node 5. For the water wall, 30% of the transmitted solar radiation is reflected out by the light polystyrene blocks between and above the tubes. For the masonry wall this is 20%.

When the vents are open the air flow rate due to thermocirculation is estimated assuming the major flow resistance to be in the vents. The temperature distribution in the wall-glass air space is assumed to be linear so that T_5 is the arithmetic average of the inlet and outlet air space temperatures. The room temperature is assumed to be constant, so the inlet air space temperature is the room temperature, T_2 .

When the vents are closed there is no thermocirculation accounted for and all the solar heat transfer to the room is by conduction through the wall.

Temperatures are calculated each hour as required to achieve an energy balance at each node point. Since the thermal conductances are non-linear, this is done by iteration around a linear equation solving routine.

Comparison

Comparison of calculated and measured temperatures have been made for the period December 31, 1976 to January 6, 1977 during which the thermocirculation vents were open and during the period January 13 to 21 when the vents were blocked. The first interval is a period of erratic weather with three separate snowfalls and some bright sunny intervals. The second period starts with a sunny day followed by three days of partial sun.

The simulation model quite accurately predicts the temperature during most of the time--generally within $\pm 2^\circ\text{F}$. The largest errors occur during strong heating periods when discrepancies up to 8°F are observed.

The comparisons are shown on Figs. 3 and 4. For each graph, the symbols * represent the measured quantity and the solid line represents the value calculated by the simulation model.

It is concluded that these particular passive collector-storage elements are quite amenable to accurate representations using the type and level of simulation models employed.

SIMULATION ANALYSIS FOR LOS ALAMOS

For much of the preliminary work, the solar and weather data were for Los Alamos year September 1972. For this year, the total radiation on the surface was $518,000 \text{ BTU/ft}^2$ and the solar load (base: 65°F) was $7350 \text{ degree hr/ft}^2$ (less than normal for Los Alamos). This is less than normal for Los Alamos. For these initial studies the glass is characterized by a single constant term, but the non-linear, two-term representation shown in Fig. 1. The results are useful to determine general effects but the simple model over-predicts total performance by about 12%. Five different cases have been studied as follows: (see Fig. 5 designation of symbols).

Case 0: The room and storage are the same temperature. (U_i is infinite.)

Case 1: Storage is coupled thermally only to the room. This case would represent massive internal walls or furniture placed out of the direct sunlight ($U_{gs} = 0$, $U_{ws} = 0$).

Case 2: Storage is placed directly in front of the glass. The sun shines on and is absorbed by storage. Storage is thermally coupled to the environment through the glass and also to the room. ($U_{gr} = 0$, $U_{ws} = 0$).

Case 3: Storage is placed against the back wall out of the direct sun. This case would represent massive walls or roof insulation on the outside. ($U_{gs} = 0$, $U_{gr} = 0$).

Case 4: Storage is placed in the room in the direct sun but loses heat only to the room. ($U_{gs} = 0$, $U_{ws} = 0$).

Fig. 5. Passive Solar Heating Model.

These cases are intended to represent extremes. Any real design may tend toward one or another case but will actually be a mixture. For the preliminary study the U values were held constant although in reality, they will vary with temperature difference, wind, and other influences. The glass was assumed to be vertical, to face due south, and to be unshaded. Three glazings were studied:

- 1) Single glazing: $U_g = 1.1 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$.
- 2) Double glazing: $U_g = 0.50 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$.
- 3) Night insulated double glazing: $U_g = 0.1$, 5 p.m. to 8 a.m.

A value of U_{wr} of $0.5 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$ was chosen initially.

A storage mass of $30 \text{ BTU/ft}^2\text{-}^\circ\text{F}$ was chosen. This is equivalent to 30 lbs of water per sq ft of glass or 150 lbs of concrete.

Lastly the room temperature was allowed to vary 5°F around a desired value of 70°F . Therefore $T_{\min} = 65^\circ\text{F}$ and $T_{\max} = 75^\circ\text{F}$.

Simulation Results for a Case with Isothermal Storage

It is instructive to observe the simulation results for a few days of cold weather. Figure 6 shows the 7-day interval between the 31st of December and the 6th of January. Case 2 was chosen for this calculation with a value of $U_g = 1.0 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F}$. There was snow on New Year's Eve followed by two days of cloudy weather and then cold but sunny weather.

Fig. 6. Seven days in winter, simulation results.

SOLAR PERFORMANCE SUMMARY (CASE 2)

BTU/ft² of Glass							
Month	Building Load	Incident Solar Energy on Glass Wall	Solar Energy Transmitted Through Glass Wall	Excess Energy Ventilated	Auxiliary Energy Required	Degree-days (F)	Percent of Solar Heating
9	6073	36932	25311	6183	48	203	99.20
10	8447	31623	22044	3479	2149	505	74.56
11	13617	40103	29331	633	4300	1032	68.42
12	15005	39693	29638	752	5788	1144	61.43
1	15865	45150	34353	817	4573	1202	71.17
2	13066	38330	27955	961	4053	932	68.93
3	12650	34902	23904	472	5377	980	57.49
4	10451	34288	22632	650	3031	759	70.52
5	6961	30510	19356	2593	842	366	87.72
6	4147	33956	22162	8321	1	123	99.96
7	3520	23393	18686	7413	0	28	100.00
8	2252	31293	20550	8373	0	16	100.00
Yearly Summary							
	112954	426547	295532	41152	36214	7350	73.25

In the following discussion the effect of variations in various parameters will be shown. In each case the simulation model was run repeatedly varying one parameter at a time while holding the others constant at the nominal values given above. The circled point on each graph represents the nominal case.

Figure 7 shows the yearly results for all five cases as a function of the room-to-storage thermal coupling factor, U_1 . All cases become equivalent for large values of U_1 . Cases 2 and 4 are observed to be appreciably better in performance than the others. These two cases are for a wall directly heated by the sun. Clearly this is an enormous advantage. Case 4 is unrealistic for low values of U_1 because the sun must shine through the room to reach storage and this implies transparent insulation. Case 2 is fairly representative of a "drum-wall," in which the thermal storage is in water contained in cans placed in front of the glass wall.

It is significant to note that there exists an optimum value of U_1 for Case 2. The optimum value is approximately $1.5 \text{ BTU/hr} \cdot ^\circ\text{F} \cdot \text{ft}_g^2$. The reason for the optimum is as follows. At higher values of U_1 , storage loses too much heat to the room during charging periods. This prevents storage from attaining higher temperatures and storing greater amounts of heat. At lower values of

Fig. 7. Effect of thermal coupling between room and storage.

U_1 , storage attains such high temperatures during charging periods that it loses too much heat through the glass to the environment. The optimum value of U_1 will depend on the storage heat capacity.

The effect of varying storage heat capacity and glass insulation is shown in Fig. 8. The benefits of storage are obtained at a value of $30 \text{ BTU/}^\circ\text{F} \cdot \text{ft}_g^2$. The improvement obtained with glazing is very dramatic. In fact, a single glass wall without night insulation can hardly be considered a viable passive solar heating element since only 30% solar heating can be achieved even with large storage and the glass is a net loser at low storage. The increased effectiveness of insulating the glass at night (for example, as in a beadwall) is impressive. The cost-effectiveness of this approach needs further study. Night insulation can be seen to be far more important with single glazing than with double glazing. Single glazing becomes viable only with night insulation. A strategy of placing night insulation based on observed conditions rather than a timeclock would result in only a small increase in performance ($\sim 2\%$).

The effect of varying the glass area is inverse to the effect of varying the building thermal load U_w . This is shown in Fig. 9.

Fig. 8. Effect of storage mass.

Fig. 9. Effect of glass area.

The effect of the allowable temperature swing is shown in Fig. 10. A variation of $\pm 5^\circ\text{F}$ may be reasonable for a residence whereas a much larger variation may be tolerable in other buildings such as a warehouse or greenhouse. The effect of mass is also shown for both Cases 2 and 4.

Simulation with a masonry wall

The example of Case 2 is somewhat representative of the concept developed at Odeillo, France by Trombe and his colleagues utilizing a masonry wall, specifically a concrete wall. In the French concept, a thermocirculation path was provided by perforations extending through the wall at the top and bottom. The value of these perforations had not yet been established and this effect was not simulated.

In order to study the basic performance characteristics of such a wall, as compared to the case of an isothermal wall studied earlier, the mathematical model was modified to describe the time and one-dimensional space dependent thermal transport of heat through the wall. This was done by simulation of the masonry temperature at the wall surfaces and at several different distances into the wall.

The thermal properties used for the masonry were as follows (typical of dense concrete):

Fig. 10. Effect of allowable room temperature variation.

Heat Capacity: $30 \text{ BTU/ft}^3 \text{ }^\circ\text{F}$

Thermal Conductivity: $1 \text{ BTU/ft }^\circ\text{F hr}$

The calculated wall temperatures are shown on Fig. 11a, 11b, and 11c for the same seven-day period shown in Fig. 6 for three different wall thicknesses--0.5 ft, 1 ft, and 2 ft. The daily fluctuations felt on the inside wall surface are markedly different for the three cases, being very pronounced ($\sim 45^\circ\text{F}$) for the thin wall and almost non-existent for the thick wall. The longer-term effect of the storm is observed on the inside of the thick wall as a 10°F variation.

The net annual results of several such calculations are summarized in Fig. 12. The net annual thermal contribution of the three different thicknesses of walls are not markedly different. In fact the 1 ft thick wall is the best of the three--giving an annual solar heating contribution of 68%. This compares with a value of 73% for an isothermal wall with the same heat capacity. In each case auxiliary cooling or heating was assumed to maintain the room temperature within the bounds given previously. Although the net thermal contribution of the thin wall and thick wall cases are nearly the same, the amount of control required for the thick wall is much less and the variation in room temperature within the set bounds is much less.

Fig. 11. Time response of a masonry wall for a one-week period.

Fig. 12. Yearly performance of a passive masonry wall as a function of thickness for various thermal conductivities.

The effect of variations in wall thermal conductivity is also shown in Fig. 12. The isotherms wall corresponds to the infinite conductivity case. It can be seen that for each conductivity there exists a thickness which will give a maximum yearly solar energy yield. The optimum thickness decreases as the thermal conductivity decreases. Annual heating performance, of course, is only one consideration in the selection of wall materials and wall thickness.

Results for Other Climates

In the analysis for other climates, the more detailed simulation model of the glazing layers was used as shown in Fig. 1. This more accurate representation makes a significant difference--the annual solar heating fraction for Los Alamos was reduced from 69% to 55% in one case. Since the more complex model has been validated against the test room data, it is more to be believed. Several changes in the model are responsible for the change. Probably the most significant is a more detailed accounting of the transmission of diffuse and reflected solar energy.

Hourly values of solar radiation and weather data were obtained from the National Weather Service. A specific one-year period is selected for the hour-by-hour simulation analysis. For Madison, Wisconsin the year chosen is July, 1961 through June, 1962. The results of a parametric study of the effect of thermal storage mass is shown in Fig. 13 for the four cases studied. As had been noted in a previous preliminary analysis, there is an optimum thickness of about one foot for the masonry wall. From calculations done for other locations it is determined that this optimum does not depend on climate.

A study of the effect of climate on performance is given in Table I. These calculations are all for a thermal storage mass of $45 \text{ BTU/}^\circ\text{F ft}^2_g$ ($\sim 13"$ of concrete or $8.6"$ of water). Although some cases are clearly better than others, all seem to be viable approaches to solar heating in all the climates studied. The effectiveness of the thermocirculation vents is pronounced in the colder climates.

The ultimate measure of cost-effectiveness of these concepts will be the heating energy delivered to the building by the solar wall. These annual values are given in Table II for the particular case of the 18" Trombe wall.

TABLE I
ANNUAL RESULTS FOR THERMAL STORAGE
 $= 45 \text{ BTU/}^\circ\text{F ft}^2_g$

City	Annual Percent Solar Heating				
	WW	SW	TW	TW(A)	TW(B)
Santa Maria	99.0	98.0	97.9	97.3	93.0
Dodge City	77.6	69.1	71.8	62.8	73.6
Bismarck	49.8	41.3	46.4	31.1	47.6
Boston	60.0	49.2	56.8	44.9	56.7
Albuquerque	90.8	84.4	84.1	81.8	87.5
Fresno	85.5	82.4	83.3	78.0	83.4
Madison	43.1	35.2	41.6	24.7	42.0
Nashville	63.2	60.7	65.2	54.1	65.4
Medford	59.0	53.3	56.1	42.2	56.8

WW: Water Wall
SW: Solid Wall (no vents)
TW: Trombe Wall (no reverse vent flow)
TW(A): Trombe Wall with vents open at all times
TW(B): Trombe Wall with thermostatic vent control

Fig. 13. Effect of storage mass and wall type on the performance of a thermal storage wall passive solar heating system in Madison, Wisconsin. The weather data used are for 1961-62 (7838 degree-days). Load = $0.5 \text{ BTU/hr } ^\circ\text{F ft}^2_g$.

TABLE II
ANNUAL SOLAR HEATING RESULTS FOR 29 VARIOUS CLIMATES

Case: 18 in. Trombe Wall

Thermal Conductivity = 1 BTU/ft hr °F

Heat Capacity = 30 BTU/ft³ °F

Vent Size = 0.074 ft²/ft of length (each vent)

No reverse thermocirculation

Load (U_l) = 0.5 BTU/ft² °F hr

Temperature band = 65°F to 75°F

City	Year Starting	Heating Degree- Days	Latitude	Solar Heating, BTU/ft ² *	Solar Heating Fraction, Percent
Los Alamos, NM	9/1/72	7350	35.8	60,200	56.5
El Paso, TX	7/1/54	2495	31.8	50,000	97.5
Ft. Worth, TX	7/1/60	2457	32.8	38,200	80.8
Madison, WI	7/1/51	7838	43.0	44,900	41.6
Albuquerque, NM	7/1/62	4253	35.0	63,600	84.1
Phoenix, AZ	7/1/62	1278	35.5	38,300	99.0
Lake Charles, LA	7/1/57	1694	30.1	34,300	90.5
Fresno, CA	7/1/57	2622	36.8	43,200	83.3
Madford, OR	7/1/51	5275	42.3	47,400	55.1
Bismarck, ND	7/1/54	8238	46.8	53,900	46.4
New York, NY	6/1/58	5254	40.6	48,000	60.2
Tallahassee, FL	7/1/59	1788	30.3	40,700	97.3
Dodge City, KS	7/1/55	5199	37.8	58,900	71.8
Nashville, TN	7/1/55	3805	36.1	39,500	65.2
Santa Maria, CA	7/1/55	3065	34.8	69,800	97.9
Boston, MA	7/1/57	5535	42.3	47,100	55.0
Charleston, SC	7/1/63	2279	32.8	47,900	89.3
Los Angeles, CA	7/1/63	1700	34.0	53,700	90.0
Seattle, WA	7/1/63	5204	47.5	42,400	52.2
Lincoln, NE	7/1/58	5995	40.8	53,500	59.1
Boulder, CO	1/1/55	5671	40.0	62,500	70.0
Vancouver, BC	1/1/70	5904	49.1	46,000	52.7
Edmonton, ALB	1/1/70	11679	53.5	37,700	24.7
Winnipeg, Man	1/1/70	11490	49.8	33,700	22.6
Ottawa, Ont.	1/1/70	8838	45.3	37,900	31.9
Fredericton, NB	1/1/70	8334	45.8	40,100	33.9
Hamburg, Germany	1/1/73	6512	53.2	24,900	27.5
Denmark	?	6243	56	43,100	43.8
Tokyo, Japan	?	3287	34.6	50,300	85.8

* The values in the solar heating column are the net energy flow through the inner face of the wall into the building.

References:

1. M. G. Davies, "The Contribution of Solar Gain to Space Heating," Paper 47-1 in Extended Abstracts of the 1975 International Solar Energy Congress and Exposition, UCLA, Los Angeles, CA, July 23 to August 1, 1975 (unpublished). To appear shortly in Solar Energy (Journal of the International Solar Energy Society). Also see: J. E. Perry, Jr., "The Wallasey School," to be published in the Proceedings of the Workshop and Conference on Passive Solar Heating and Cooling, Albuquerque, NM, May, 1976.
 2. P. VanDresser, "Energy Conserving Folk Architecture in Rural New Mexico," ASC/AIA Forum 75 on Solar Architecture, Arizona State University, 1975, pp 12.1-42.
 3. F. Trombe, Maisons Solaires, Techniques de l'Ingenieur (3), 1974, C777.
 4. F. Trombe, J. F. Roberts, M. Cabanat and B. Sasolis, "Some Performance Characteristics of the CHRS Solar House Collectors," to be published in the Proceedings of the Passive Solar Heating and Cooling Workshop and Conference, Albuquerque, NM, May, 1975.
 5. R. Fisher and W. F. Yanda, "Solar Greenhouses," John Muir Press, Santa Fe, NM. (1976).
 6. "Research Evaluation of a System of Natural Air Conditioning," Cal. Poly. State Univ., Jan., 1975.
 7. P. Davis, "To Air is Human," Proceedings of the Workshop and Conference on Passive Solar Heating and Cooling, Albuquerque, NM, May 1976.
 8. B.Y.H. Liu and R.C. Jordan, "Availability of Solar Energy for Flat-Plate Solar Heat Collectors," ASHRAE, Low Temperature Engineering Application of Solar Energy, 1967.
 9. E. C. Boes, "Estimating the Direct Component of Solar Radiation," paper presented at ISES Congress, Los Angeles, CA, July, 1975.
-

PREDICTING THE PERFORMANCE OF PASSIVE SOLAR HEATED BUILDINGS

E. Mazria
M.S. Baker
Dept. of Architecture
University of Oregon
Eugene, OR 97403

F.C. Wessling
Dept. of Mech. Engineering
University of New Mexico
Albuquerque, NM 87106

Rising energy costs have provided the incentive to reduce energy consumption through the design and application of alternative energy sources. In order to have widespread (global) application, it is necessary that this technology be inexpensive and simple in concept. Passive solar energy systems offer such an alternative.

There are many types of passive solar heating systems being built today, but the simplest and most efficient is commonly referred to as a "direct gain" system. Solar energy admitted into a space through windows, clerestories, and/or skylights is absorbed and stored within the walls or floor of the space for use during the evening. The walls and/or floors are constructed of materials capable of storing heat such as brick, concrete, adobe and water (contained). In effect, the entire space becomes the solar heating system. There are no separate collector panels, storage units, or mechanical equipment. By properly designing and integrating all the architectural elements within each space (doors, windows, walls, floor and roof), a passive solar heating system is able to utilize most of the solar radiation admitted into a space for winter heating.

Our present knowledge of passive solar heating is a result of the determined efforts of a group of designers and builders. To date, relatively little scientific research support has been allocated for passive solar heating projects. In the absence of such research, most of our present information has

This paper presented at the 1977 Annual Meeting of the American Section of the International Solar Energy Society, Orlando, Florida.

been learned through the performance of various existing projects.

Solar gain through south-facing glass is easily calculated. However, predicting the performance of thermal mass materials in a space is beyond the capability of most building designers. An analytical solution has been developed for a simplified model of passive solar heating systems to establish usable performance criteria for their design. This model is presently being used to develop rules-of-thumb and other analytical and graphic tools for designers of passive solar heated buildings. Our studies indicate that passive solar heating systems can supply a significant portion of a building's winter space heating requirements and maintain relatively stable indoor air temperatures. The preliminary conclusions presented in this article for the design of "direct gain" passive systems have considerable implications for future building design.

ANALYTICAL MODEL

A graphic description of the analytical model used in this study is represented in Figure 1. Indoor air temperature is represented by T_i ; outdoor air temperature by T_o . Solar energy enters the space through glazing and strikes the interior face of a thermal mass wall which has a thickness L . The value Q_s equals the solar energy incident per unit area of mass wall. The portion of incident solar energy absorbed by the mass wall is determined by the surface absorptivity α . Solar energy reflected from the face of the wall is either lost to the outside (reflected back out through the glazing) or reflected onto other non-massive interior surfaces which act as a heat source Q_f to the room air. In this paper, it is assumed that any reflected sunlight is added as heat directly to the room air.

The thermal storage wall loses heat to the outside by two paths. The first path is through the insulation on the exterior surface of the storage material. The thermal conductance of the insulation is represented by U_o . The second path is heat transfer from the surface of the mass to room air, and from room air through the exterior skin of the building to the outside. This heat transfer depends on the following thermal conductances: U_w , from the wall surface to room air, and U_h , from the room air to the outside.

Figure 1: Analytical Model

The model represents temperatures that would occur after several consecutive near-identical days; such as several clear or cloudy days in a row. The results for consecutive clear days are presented here since this has a greater influence on system design.

The analytical model with minor changes can also be used to analyze other passive solar heating systems such as the Trombe Wall and solar greenhouse/housing combinations. This is being investigated and will be presented in a future paper.

SYSTEM DESCRIPTION

In a "direct gain" system, because the building configuration used in coupling solar radiation with a thermal mass greatly influences system performance, three different systems are presented for investigation.

System 1: Thermal storage mass is placed against the rear wall in direct sunlight. The surface area of mass exposed to direct sunlight over the day is 1.5 times the area of the glazing. This system represents a space with a horizontal band of south-facing windows or clerestories coupled directly to a thermal mass which is insulated on the exterior face (Figure 2).

Figure 2: System 1

System 2: Thermal storage mass is placed against the rear wall in direct sunlight. The surface area of mass exposed to direct sunlight over the day is 3 times the area of the glazing. This system represents a space with vertical windows (evenly spaced) or translucent (diffusing) glazed openings (Figure 3).

Figure 3: System 2

System 3: The space (walls and floor) becomes the thermal storage mass. The surface area of mass exposed to direct sunlight is 9 times the area of the glazing. This system represents a space constructed of masonry materials with translucent glazed openings or clear glazed openings coupled initially with light colored interior surfaces (Figure 4).

Figure 4: System 3

COMPUTER SIMULATION

Each system is analyzed by computer for different parameters of outdoor air temperatures, latitude, thermal storage material, thickness and surface color. The building is considered to be well insulated with a space heat loss (U_h) of 0.35 Btu/hr ft^2 (floor area) $^{\circ}\text{F}$. Heat loss from the thermal storage mass to the exterior is calculated separately ($U_o = 0.08 \text{ Btu/hr ft}^2$ $^{\circ}\text{F}$) and is additional to the space heat loss. The overall U value of the building (U_h , space heat loss + U_o , storage mass heat loss) is 0.39 Btu/hr ft^2 (floor area) $^{\circ}\text{F}$ for System 1, 0.41 Btu/hr ft^2 $^{\circ}\text{F}$ for System 2, and 0.53 Btu/hr ft^2 $^{\circ}\text{F}$ for System 3.

An analysis using January clear-day insolation values and outdoor temperatures for Portland, Oregon (45°NL) is presented in this paper to illustrate the computer results. All systems assume 75% solar absorption by the thermal mass, with the remaining 25% supplied directly to the air in the space as heat. South-facing glass is 25% of the building's floor area. This percentage is determined by the amount of solar gain needed to offset the building's heat loss for an average clear January day with an indoor design temperature of 70°F . System performance is measured using indoor air temperatures. In reality system performance and human comfort are determined by a complex set of interior conditions (air temperature, mean-radiant temperature, relative humidity and air movement).

SIMULATION RESULTS: Thermal Storage Thickness

Design Parameters

Systems 1, 2, and 3 are analyzed for a concrete thermal storage mass of different thickness.

System 1: During a clear day, an increase in mass thickness beyond 8" results in little improvement in system performance. Figure 5 illustrates the indoor air temperatures (over a day) for mass thickness of 4", 8", and 16". By increasing the mass (thickness) from 4" to 8", maximum air temperatures are relatively unchanged, while minimum air temperatures are changed significantly; the 8" mass wall increases the minimum room air temperature 5°F. Increasing mass thickness to 16" has little impact on air temperatures. In fact, maximum temperatures in the space are increased slightly (poorer performance) with mass thickness greater than 8".

Figure 5: Computer Model-System 1

System 2: An increase in mass thickness beyond 8" results in little change in system performance. Figure 6 illustrates room air temperatures for a mass wall thickness of 4", 8", and 16". The major temperature difference occurs by increasing mass thickness from 4" to 8"; maximum room air temperature remains unchanged while minimum air temperature is raised 2°F. Beyond an 8" thickness, there is very little variation in room temperatures.

Figure 6: Computer Model-System 2

System 3: An increase in mass thickness beyond 4" results in little change in system performance. For all three thicknesses, room air temperatures are very similar.

Figure 7: Computer Model-System 3

COMPARISON OF SYSTEMS 1,2, and 3

By spreading solar radiation over a larger mass surface, room air temperature fluctuations are decreased (see Figure 8 and Table 1). For residential use, where relatively stable indoor air temperatures are desired, System 3 is preferable. System 3 maintains the highest minimum air temperatures and smallest daily temperature fluctuations of $\pm 6.5^{\circ}\text{F}$. Both System 1 and 2 would require some ventilation to prevent overheating during the day. Ventilation lowers system performance by disposing of excess heat which could be utilized for space heating during evening hours. System 1, with a maximum room air temperature of 95°F requires a significant amount of daytime ventilation.

By spreading solar radiation over a larger mass surface area, a greater percentage of solar heat is stored in the mass at the end of the day, at 5 p.m. (see Table 1). System 3 stores the largest percentage of solar heat admitted into the space (61%). The efficiency of stored solar energy in the mass wall (including a glass transmissivity of 75% over the day) is 46%. This does not include heating provided during the daytime hours (7 a.m. to 5 p.m.). The efficiency of System 3 with this taken into account becomes 64% of the solar radiation incident on the glass (the energy used to maintain indoor temperatures above 70°F is discounted). As can be seen from Figure 8, the highest and lowest indoor air temperatures occur at approximately the same time. The lows occur at 7 a.m., one hour before sunrise, and the highs at 1 p.m., except for System 3 which peaks one hour later at 2 p.m.

The greatest difference between the surface temperature of the thermal mass and indoor air temperature occurs during the late evening and early morning hours. In early morning, even though the indoor air temperature is low, the mean radiant temperature of the space is higher, providing greater environmental comfort than registered by the air temperature alone.

Figure 8: Comparison of Systems

SIMULATION RESULTS: Thermal Storage Materials

Design Parameters

System 2 is analyzed for different thermal storage materials of 8" thickness. These materials include Concrete (stone), Brick (common), Brick (magnesium additive), Adobe and Water contained in cans (represented as an isothermal mass). These materials have the physical properties listed in Table 2.

Results

The major impact on system performance occurs with a change in the conductivity of the material. By using a thermal mass of higher conductivity the air temperature fluctuations in the space are minimized. The largest temperature fluctuations occur using adobe which has the poorest conductivity (max. 93°F and min. 53°F). The best performance (smallest temperature fluctuations) occur with brick which has a magnesium additive (max. 81°F and min. 57.5°F). When using masonry materials, higher conductivity produces substantially reduced maximum and slightly increased minimum space air temperatures. A comparison of masonry with water storage (same thickness and modeled as an isothermal wall) shows that for System 2, water storage produces the best results or smallest space air temperature fluctuations (max. 75°F and min. 62°F). It should be noted that System 3 with 4" of concrete mass achieves similar results as System 2 with an 8" water wall. This analysis does not take into account sizing for cloudy day storage which will affect mass thickness and area of glazing.

Figure 9: Comparison of Materials

CONCLUSION

Our studies indicate that passive solar heating systems can supply a significant portion of a building's winter space heating requirements and maintain relatively stable indoor air temperatures. Through careful design this can be accomplished without the use of excessive amounts of thermal mass material and glazing.

TABLE 1: COMPARISON OF SYSTEMS

	System 1 (8" thickness)	System 2 (8" thickness)	System 3 (4" thickness)
Max. space air temperature	95°F (35°C)	84°F (29°C)	71°F (22°C)
Min. space air temperature	53°F (12°C)	57°F (14°C)	59°F (15°C)
Space air temperature fluctuation	41°F (23°C)	26°F (14°C)	13°F (7°C)
Thermal mass temperature at 7 a.m. (average)	70°F (22°C)	67°F (19°C)	61°F (16°C)
Thermal mass temperature at 5 p.m. (average)	90°F (32°C)	78°F (26°C)	70°F (21°C)
Percentage solar stored (at 5 p.m., sunset)*	49%	55%	61%

*percentage of solar radiation admitted into the space.

TABLE 2: THERMAL STORAGE MATERIAL PROPERTIES

	Conductivity(k) Btu/hr ft ² °F (W/m ² °C)	Specific Heat (C) Btu/lb. °F (kJ/kg °C)	Density(ρ) lb/ft ³ (kg/m ³)
Concrete (stone)	12.0 (1.70)	0.20 (0.84)	140.0 (2,240)
Brick (common)	5.0 (0.72)	0.20 (0.84)	120.0 (1,920)
Brick (magnesium additive)	26.4 (3.80)	0.20 (0.84)	120.0 (1,920)
Adobe	3.6 (0.52)	0.24 (1.00)	106.0 (1,700)
Water (isothermal)	----	1.00 (4.19)	62.4 (1,000)

THE PERFORMANCE OF PASSIVE SOLAR HEATED BUILDINGS IN THE PACIFIC NORTHWEST

Edward Mazria
Department of Architecture
University of Oregon
Eugene, Oregon 97403

INTRODUCTION¹

Rising energy costs have provided the incentive to reduce energy consumption through the design and application of alternative energy sources. In order to have widespread (global) application, it is necessary that this technology be inexpensive and simple in concept. Passive solar energy systems offer such an alternative.

There are many types of passive solar heating systems being built today, but the simplest and most efficient is commonly referred to as a "direct gain" system. Solar energy admitted into a space through windows, clerestories, and/or skylights is absorbed and stored within the walls or floor of the space for use during the evening. The walls and/or floors are constructed of materials capable of storing heat such as brick, concrete, adobe, and water (contained). In effect, the entire space becomes the solar heating system. There are no separate collector panels, storage units, or mechanical equipment. By properly designing and integrating all the architectural elements within each space (doors, windows, walls, floor, and roof), a passive solar heating system is able to utilize most of the solar radiation admitted into a space for winter heating.

Our present knowledge of passive solar heating is a result of the determined efforts of a group of designers and builders. To date, relatively little

¹from Mazria, Baker, and Wessling, Predicting the Performance of Passive Solar Heated Buildings. Paper presented at the International Solar Energy Society Conference, Orlando, Florida (1977).

scientific research support has been allocated for passive solar heating projects. In the absence of such research, most of our present information has been learned through the performance of various existing projects.

Solar gain through south-facing glass is easily calculated. However, predicting the performance of thermal mass materials in a space is beyond the capability of most building designers. An analytical solution has been developed for a simplified model of passive solar heating systems to establish usable performance criteria for their design. This model is presently being used to develop rules-of-thumb² and other analytical and graphic tools for designers of passive solar heated buildings. Our studies indicate that passive solar heating systems can supply a significant portion of a building's winter space heating requirements and maintain relatively stable indoor air temperatures. The results presented in this paper have considerable implications for future building design.

SYSTEM ANALYSIS

Passive solar heating systems have been analyzed for various locations in the Pacific Northwest. The performance of a building designed with a south-facing Thermal Storage Wall is presented below. The building used is considered to be well insulated with a space heat loss of $8.4 \text{ Btu/hr-ft}^2_{\text{fl}}$. The thermal storage wall is a solid concrete mass, one foot thick with double glazing on the exterior face. The exterior surface of the wall is painted black (solar absorption of 95%). The ratio of thermal wall to building floor area is 1:2. This corresponds to a building 20' x 40' with a 10' x 40' solar wall. This system differs from a Trombe Wall since thermocirculation vents are not used. In cold climates, wall vents with reverse flow controls can increase system performance up to 6%. In

² Rules-of-thumb for passive solar heating in the Pacific Northwest are currently being prepared by Edward Mazria and Mark Steven Baker under a research grant from the Pacific Northwest Regional Commission.

THERMAL STORAGE WALL - Seattle, Washington

Solar Performance ¹

Btu/ft²
fl area

<u>Month</u>	<u>Degree- Days/Month</u>	<u>Building Load</u>	<u>Incident Solar Radiation on Glass³</u>	<u>Solar Radiation Transmitted Through Glass²</u>	<u>Percent Solar Heat</u>
Oct.	412	3460	15174	10958	100
Nov.	633	5317	10245	7755	57
Dec.	781	6560	6711	5053	30
Jan.	862	7240	7486	5487	29
Feb.	675	5670	11340	8344	57
Mar.	636	5342	15732	10804	80
Apr.	477	4006	14565	9330	91
May	307	2578	14725	8695	100
Yearly Totals	4783	40173	95972	66426	50%

1. System performance will be slightly less as heat is ventilated from the building.
2. Assumes a 5% direct beam absorption loss.
3. Ground reflectance 20%.

temperate cloudy climates the increase in performance is slight since entering the building on mild and cloudy days is mainly by conduction through the solar wall.

THERMAL STORAGE WALL - Pacific Northwest Locations

Solar Performance

	<u>Degree Days/yr.</u>	<u>Percent Solar Heating</u>
Eugene, Ore.	4357	59
Medford, Ore.	4401	71
Seattle, Wash.	4783	60
Spokane, Wash.	6456	61
Boise, Idaho	5663	71
Annette, Alaska	7096	66
Edmonton, Alberta	9830	55

CONSIDERATIONS FOR RETROFITTING AN ATTACHED SOLAR GREENHOUSE

by

William F. Yanda

ABSTRACT

A passive, attached greenhouse can contribute substantial heat and energy savings to a home. The retrofitted greenhouse lends itself to custom design and presents unique problems in each separate application. Criteria for operating the home greenhouse are quite different from commercial units and will vary for every family. Seed to table food production in the greenhouse represents a measurable energy savings nationally.

Fig. 1. Part of Phase II project building.

Fig. 2. Exterior - Yanda greenhouse, Nambe, NM.

This paper presented at the Passive Solar Heating and Cooling Conference, May 1976, Albuquerque, New Mexico.

The attached thermally designed greenhouse is an economically attractive retrofit to a residence. Four benefits that the home will derive from the addition are:

- 1) Direct gain of winter heat;
- 2) Insulation (buffer area) for a wall that would normally be exposed to outside night air;
- 3) Raised humidity in winter;
- 4) CO_2 -- O_2 exchange by the plants.

The main challenge of retrofitting a greenhouse to a home is that the site will never be exactly right in all categories. It will usually not face due south, therefore a partially opaque side wall is possible. The greenhouse can be as much as 40° east or west of true south and still function properly. It might even be built around a corner.

The solar greenhouse must be light-efficient as well as thermally efficient. Vegetables, especially fruiters, require a maximum length of photoperiod all times of the year. Careful planning of the interior layout of the structure should determine the varying light and heat requirements for the plants and situate the growing areas accordingly. A home greenhouse growing a wide variety of plants has different operational criteria from commercial units specializing in one or two crops. There will never be optimal conditions for all varieties. Generally plants are more cold-tolerant (comfortable between 35° and 90° completely naked) than humans, and this gives the passive greenhouse an edge over

the passive home. However, plants are not nearly as light-tolerant as humans, naked or otherwise. It makes sense that only materials that have thermal storage capability be painted dark and all other surfaces, such as insulated walls and exposed framing members be a light color. Flat black and bright white would be the most efficient, but there is a wide range of earth colors that are more conducive to a pleasant growing environment.

The ventilation between the home and the greenhouse may not be perfect in a retrofit. Large openings near the apex of the addition and slightly smaller openings at the bottom are optimal for a gravity convection cycle. However, a standard size door and window combination will do fine while the builder decides if it's necessary to punch holes in the wall.

Totally integrated house/greenhouse designs are coming into vogue. One drawback to this concept is that greenhouses and bugs are a matched pair. Unless the owner can (1) afford a part-time greenhouse manager, (2) plans to spend much time insect tending or (3) relies on heavy duty insecticides, he may have to get used to white fly in the scrambled eggs or at least periods of house plant infestation. An advantage of a contiguous, but not integral retrofit is that the greenhouse can be shut off during its depressing periods.

An important consideration that makes the custom design retrofit superior to any possible pre-fab is the micro-climate of a given area. For instance, in northern New Mexico a clear winter morning is the

rule and late afternoon high cloudiness is common. For that reason and also for getting the morning sun into the greenhouse, a clear eastern wall would be designed into the plans. A partially opaque western wall will serve to insulate from prevailing winter winds out of the northwest. The exterior greenhouse door is designed to open away from the cold zephyrs. And, of course, two places next door to each other can have different terrain configuration and micro-climates which would lead to different designs.

Cost is always a major factor in any project. The original Solar Sustenance Project built eleven greenhouses in 1974 for a material cost of \$1.86 a square foot. This included paint, plaster and shelves. An updated estimate for the same buildings today would be \$2.50 a square foot -- but a good scavenger who used recycled and rough materials could probably build one for around \$1.00 a square foot. It would be difficult to spend more than \$5.00 a square foot on the greenhouse.

There are a multitude of ways to run an attached greenhouse even in a purely passive mode. Movable interior or exterior insulating panels greatly improve performance in the coldest months and are inexpensive to construct. Increasing thermal storage in enclosed water containers will raise nighttime temperatures. You might choose to back up the system with a wood-burning stove for the few extra cold nights in January. In a passive greenhouse, planning for seasonal planting is necessary. Take the warm weather crops such as tomatoes, chile and

cucumbers as far as they go, but plan on raising cold weather crops and hardy plants during the hard winter months. Seasonal planting is important for people who have interests beyond the greenhouse and do not wish to be tied to it.

The well sealed passive attached greenhouse with 80 pounds of concrete or 2 gallons of water storage per square foot of south-facing glazing will give a "cool range" environment (lows of 50°+) for about 9½ to 10 months in the Santa Fe area. Without any movable insulation it will add to the heat of the home in the ratio of two to three times the square footage of its southern glazed area. The above numbers are estimates and will vary enormously according to the considerations previously mentioned and an infinite number of other variables.

Just as an increasing number of people are realizing the economic and ecological benefits of solar utilization in heating and cooling homes, a growing number are becoming aware of the same benefits in extended vegetable gardening at home through use of greenhouses. A quick look at almost any geographical location in the United States will document the dependence of the area on outside food sources for fresh or processed vegetables. For example, the northeastern United States in 1970 had a per capita consumption of 201.8 pounds of vegetables while it produced only 41.3 pounds in the same period.¹ The 80% it did not produce went through an intricate process that consumes

¹U.S. Department of Agriculture, 1974: Statistics of vegetables and melons. Agricultural Statistics, 1973, p. 149-253, 564-567.

approximately 12% of the total energy in the country and 20% of all electricity used.² Surprisingly, the largest percentage is not in transportation, but in storing and processing.

The conservational benefits derived from increased home vegetable production are obvious. One might look at a December home grown tomato not as a fruit worth 35 cents, but as a quarter's worth of oil that did not get depleted in "the process". In an organically operated attached greenhouse, seed-to-table vegetables might only rely on water and the

energy involved to move it as outside energy requirements.

The combined usefulness of a solar greenhouse-- supplemental heat and food -- makes it unique in solar applications. Poorly run, it can pay itself off in three years. Operated efficiently, it will return the original materials investment in one year.

²Hirst, Eric, "Food-related Energy Requirements," Science, 184, 134-138 (1974).

APPENDIX A

PHOTOGRAPHS

Fig. 3 Fisher - El Valle greenhouse, 8000'.

Fig. 4. Greenhouse with direct gain south wall--(to earth bed behind) single glazed--140°F in winter.

A SIMPLE TECHNIQUE OF ESTIMATING
THE PERFORMANCE OF PASSIVE SOLAR
HEATING SYSTEMS

by

J. D. Balcomb and R. D. McFarland
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

ABSTRACT

A method is presented for estimating the annual solar performance of a building using a passive thermal storage wall of the Trombe wall or water wall type with or without night insulation. Tables of performance parameters are given for 84 cities. The method is accurate to $\pm 3\%$ as compared with hour-by-hour computer simulations.

PROCEDURE

A simple procedure has been devised for predicting the performance of solar heated structures of the thermal storage wall type. The method was originally developed for estimating performance of active systems [1] but proves to be even more accurate for the analysis of passive systems.

The correlation procedure used, called the monthly solar load ratio method, is based on the premise that the monthly solar heating fraction can be correlated with the ratio of monthly solar energy absorbed by the solar wall to the total building monthly thermal load. The correlation procedure is described in detail in Ref. [2].

Data have been obtained for 84 cities for the monthly solar radiation on a horizontal surface and for the monthly heating degree-days. Based on these data and on the correlations of the monthly solar load ratio method, tables of solar heating performance have been prepared for the 84 cities. The tables have been prepared for a specific set of reference passive solar systems as follows:

Vertical, south-facing glass
Wall absorptance = 1.0
Ground reflectance = 0.3
No shading
Thermal Storage = $45 \text{ BTU/}^\circ\text{F ft}^2$ of glazing
Trombe wall has vents with back draft dampers
Double Glazing (normal transmittance = 0.747)
Temperature range in building = 65 to 75°F
Other building mass is negligible
Night insulation (when used) is R9;
5:00 p.m. to 8:00 a.m.
Wall to room conductance = $1.0 \text{ BTU/hr } ^\circ\text{F ft}^2$
Trombe wall properties: $K = 1.0 \text{ BTU/ft hr } ^\circ\text{F}$
 $\rho C = 30 \text{ BTU/ft}^3 ^\circ\text{F}$

Step 1

Estimate the Building Loss Coefficient (BLC) in BTU/degree-day. This is the sum of the building skin conductance plus infiltration. It is the extra energy required (BTU) per day for each additional 1°F increase in temperature difference between the building interior and outside. It can be calculated from the sum of the UxA values for the exterior areas of the building plus infiltration. IMPORTANT--in calculating the Building Loss Coefficient, the passive thermal storage wall should not be included in the load.

Step 2

Calculate the building Load Collector Ratio (LCR) defined as follows:

$$\text{Load Collector Ratio} = \frac{\text{Building Loss Coefficient (BTU/DD)}}{\text{Solar Collection Area (ft}^2\text{)}}$$

In calculating the Load Collector Ratio the solar collection area used should be the net glazed area (the actual solar collection aperture) and not the gross area of the solar wall.

Step 3

Go to Table 1 and locate the city of interest and the wall type of interest. If the Load Collector Ratio determined in Step 2 corresponds exactly to one of the values of Solar Heating Fraction (SHF) listed in the table, then this is the desired answer. If not, one needs to interpolate in the table. The meaning of a Solar Heating Fraction is ambiguous when applied to a passive solar building. What is the building being compared with? As used herein, the SHF is the fraction of the degree-days times the Building Loss Coefficient) which is supplied by the solar wall. The wall is not credited with the heat used to supply its own steady-state load since a "normal" south wall would presumably have a much lower loss coefficient and would inevitably benefit from solar gains, even if they are unintentional.

The auxiliary used is a less ambiguous peg point, leaving the basis of comparison up to the user.

This paper presented at the 1978 Annual Meeting of the American Section of the International Solar Energy Society.

Step 4

The annual auxiliary energy required to maintain the building at a minimum temperature of 65°F can be estimated from the following equation:

$$\text{Auxiliary Energy, BTU/yr} = (1 - \text{SHF}) \times \left(\frac{\text{Annual Heating Degree-Days}}{\text{Day}} \right) \times \left(\frac{\text{Building Loss Coefficient, BTU/Degree-Day}}{\text{Day}} \right)$$

EXAMPLE

A 72' x 24' building in Dodge City, Kansas is to be constructed with a 309 sq ft water wall on the south side. The water wall will contain 45 lbs of water per sq ft of south glazing for a total of 13,500 lbs of water or 1618 gallons. The wall is double glazed with normal sealed glass units which have a net transmittance of 0.74 for sunlight striking the glass perpendicularly. Other than the thermal storage wall, the building is of light frame construction with little additional mass. It is desired to estimate the annual solar heating contribution.

(Step 1) The Building Loss Coefficient is estimated as follows:

Skin Conduction:

Surface Type	Area ft ²	U-Value BTU/ft ² °F hr	UxA BTU/°F hr
Water Wall	309	(not included in BLC)	
Opaque Walls	1107	0.07	77.5
Windows (E,W,N)	120	0.55	66.0
Roof	1728	0.05	86.4
Floor	1728	0.05	86.4

Building Skin Conductance = 316.3

Infiltration:
(12320 ft³) (1/2 ACH) (0.018) = 110.9

Total: Building Loss Coefficient = 427.2 BTU/hr°F
= 10250 BTU/DD

The building is tightly sealed and equipped with an air-lock entry and thus the infiltration can probably be held to the minimum recommended level of 1/2 air change per hour.

(Step 2) The building south wall is glazed with 18 standard patio door size sealed double glass units each with a net effective exposed area of 75 x 33 in. for a total of 309 sq ft of collection area. Thus the Load Collector Ratio is 10250/309 = 33.2 BTU/degree-day-sq ft.

(Step 3) In the table for Dodge City, Kansas we find the following entries for the case of a water wall without night insulation:

GHT	0.30	0.40	0.50	0.60
LCR	61	43	31	23

Our Load Collector Ratio of 33.2 lies between the two values of 0.40 and 0.50 Solar Heating Fraction

$$\text{SHF} = 0.48$$

The energy saved by the installation of the solar wall is estimated as (0.48)(10250)(4986) = 24.5 MBTU/yr. The energy actually supplied by the solar wall will be greater than this since the room temperature will frequently be above 65°F.

(Step 4) The auxiliary energy can be estimated as:

$$\text{Auxiliary Energy} = (1 - 0.48)(10250)(4986) = 26.6 \text{ MBTU/yr}$$

VARIATIONS FROM THE ASSUMED REFERENCE SYSTEMS

The monthly solar load ratio curves which have been determined are for the specific reference systems as defined. If it is desired to estimate the performance of a system which is different than one of these reference systems, then it is necessary to make a correction. The most reliable way of doing this is to refer to results of hourly-by-hour calculations which are made for a specific system varying only the parameter of interest. Quite a few such calculations have been made by LASL and have been published. [3,4] These describe the effect of water mass in a water wall, the effect of using or not using the vents in the Trombe wall, the effect of thickness of a Trombe wall, and the effect of different thermal conductivities of the material.

The recommended procedure is to make a calculation for the reference case and then to adjust that value up or down.

REFERENCES

1. J. D. Balcomb and J. C. Hedstrom, "A Simplified Method for Calculating Required Solar Collector Array Size for Space Heating," Proceedings, 1976 ISES Annual Meeting, Vol. 4, Winnipeg, Canada, Aug. 15-20, 1976. See also: ERDA's Pacific Regional Solar Heating Handbook, Nov. 1976.
2. J. D. Balcomb and R. D. McFarland, "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type," Proceedings of the 2nd National Passive Solar Conference, Philadelphia, PA, March 16-18, 1978.
3. J. D. Balcomb, et al., "Simulation Analysis of Passive Solar Heated Buildings--Preliminary Results," Solar Energy, Vol. 19, pp 277-282 (1977).
4. J. D. Balcomb, J. C. Hedstrom and R. D. McFarland, "Passive Solar Heating of Buildings," Printed in SAND-77-1204 and also Solar Architecture, Ann Arbor Science (1977).

TABLE 1: PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS
Load Collector Ratio (BTU/DD-ft²) for particular values of Solar Heating Fraction (SHF)

Page, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Apacheville, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
6632 DO	WW	196	88	54	37	27	19	13	7		1308 DO	WW	700	322	204	145	110	85	65	48	32
	WWNI	312	145	91	65	49	38	29	22	15		WWNI	956	444	287	203	155	123	97	75	53
	TW	195	94	56	37	25	17	11	6			TW	635	313	194	133	95	70	51	36	24
37°N	TWNI	304	141	89	63	46	35	26	18	12		TWNI	906	240	266	189	142	108	82	61	42
Phoenix, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Gainesville, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1765 DO	WW	626	294	188	135	102	78	60	44	29	1239 DO	WW	731	333	212	152	116	90	69	51	35
	WWNI	863	407	261	189	145	114	90	69	49		WWNI	1000	457	292	211	162	129	102	79	56
	TW	577	287	179	123	88	64	47	33	21		TW	662	326	202	139	100	73	54	39	25
33°N	TWNI	819	386	247	176	132	101	76	56	38		TWNI	943	435	276	197	148	113	86	64	44
Tucson, Arizona	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Tallahassee, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1800 DO	WW	631	291	184	132	100	77	59	43	29	1485 DO	WW	621	285	179	128	97	75	57	42	28
	WWNI	871	403	256	185	142	112	89	68	49		WWNI	857	397	249	180	138	109	87	67	48
	TW	578	284	176	121	87	63	46	33	21		TW	563	279	172	117	84	61	45	32	21
32°N	TWNI	825	383	243	173	130	99	75	56	38		TWNI	809	376	237	169	127	97	73	54	37
Little Rock, Arkansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Tampa, Florida	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
3219 DO	WW	239	108	66	46	33	24	17	11		683 DO	WW	7147	573	374	272	210	166	129	98	69
	WWNI	365	172	107	76	57	44	35	26	18		WWNI	1520	760	500	365	283	227	182	141	102
	TW	232	112	67	44	30	21	14	9			TW	1059	548	351	245	179	134	100	73	49
35°N	TWNI	356	165	103	73	54	40	30	22	14		TWNI	1443	717	467	339	258	199	152	114	80
Davis, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Atlanta, Georgia	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2502 DO	WW	409	187	115	79	57	42	30	21	11	2961 DO	WW	301	136	83	58	43	31	23	15	8
	WWNI	585	272	170	120	89	68	52	39	26		WWNI	448	207	129	91	69	54	42	32	22
	TW	376	183	111	74	51	36	25	16	9		TW	286	138	83	55	38	27	18	12	7
39°N	TWNI	556	259	161	112	82	61	45	32	21		TWNI	431	198	123	87	64	48	36	26	17
El Centro, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Boise, Idaho	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1458 DO	WW	1028	482	301	214	161	125	97	72	50	5809 DO	WW	185	83	48	31	20	12	6		
	WWNI	1375	649	407	290	221	175	139	107	77		WWNI	299	139	86	59	43	31	23	16	10
	TW	916	458	284	194	140	103	75	54	36		TW	182	86	50	31	20	12	6		
33°N	TWNI	1294	608	382	270	202	154	117	87	60		TWNI	290	135	83	56	40	29	21	14	8
Fresno, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Lemont (ANL) Illinois	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2492 DO	WW	405	186	113	77	55	40	29	19	10		WW	120	51	29	18	11				
	WWNI	577	271	168	117	87	66	50	37	25		WWNI	219	100	61	42	31	24	18	13	8
	TW	370	181	109	72	49	34	24	15	8		TW	129	59	33	20	12	7			
37°N	TWNI	550	257	159	110	79	59	43	31	20		TWNI	216	99	61	42	30	22	16	11	7
Inyokern, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Indianapolis, Indiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
3528 DO	WW	453	209	129	90	66	50	37	26	16		WW	136	58	33	21	14	7			
	WWNI	641	300	188	132	100	77	60	46	32		WWNI	239	109	67	46	34	26	19	14	9
	TW	419	204	124	84	59	42	30	20	12		TW	142	65	37	23	14	8			
36°N	TWNI	613	284	177	124	92	69	52	38	25		TWNI	235	107	66	45	33	24	17	12	7
Los Angeles, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Ames, Iowa	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2061 DO	WW	763	362	225	158	118	91	70	52	35		WW	117	50	29	18	11				
	WWNI	1032	498	310	219	165	131	103	80	57		WWNI	215	99	61	42	31	23	18	12	8
	TW	687	344	213	145	103	75	55	39	26		TW	127	58	33	20	12	6			
34°N	TWNI	979	464	291	205	153	116	88	65	45		TWNI	213	98	60	41	30	22	16	11	7
Riverside, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Dodge City, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1803 DO	WW	767	356	224	160	121	94	72	53	36		WW	214	99	61	43	31	23	16	10	
	WWNI	1039	488	308	221	169	134	106	82	58		WWNI	335	160	101	72	54	42	33	25	17
	TW	692	344	214	146	105	77	56	40	26		TW	214	104	63	41	28	20	13	8	
34°N	TWNI	984	459	290	207	155	118	90	67	46		TWNI	327	154	97	69	51	38	29	21	14
Santa Maria, California	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Manhattan, Kansas	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2967 DO	WW	544	272	176	126	96	74	56	41	27		WW	165	74	44	30	21	14	8		
	WWNI	752	376	247	179	137	108	86	66	45		WWNI	274	128	80	56	42	32	25	18	12
	TW	514	264	167	115	83	61	44	31	20		TW	169	80	47	30	20	13	8		
35°N	TWNI	720	358	231	166	126	96	73	54	36		TWNI	259	125	78	54	40	30	22	15	10
Grand Junction, Colorado	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Lexington, Kentucky	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
5641 DO	WW	199	92	56	39	28	20	13				WW	143	63	36	24	16	10			
	WWNI	317	150	95	67	51	39	30	22	15		WWNI	246	114	70	49	36	28	21	15	10
	TW	201	97	58	38	26	17	11	6			TW	148	70	40	25	16	10	5		
39°N	TWNI	310	145	91	64	48	36	26	19	12		TWNI	242	112	69	48	35	26	19	13	8
Washington, D. C.	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Lake Charles, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
4224 DO	WW	179	79	47	32	22	15	9				WW	522	239	152	109	82	63	48	35	23
	WWNI	292	135	83	58	44	33	25	18	12		WWNI	730	338	214	155	119	94	74	57	40
	TW	180	85	50	32	21	13	8				TW	481	237	146	100	71	52	38	26	17
39°N	TWNI	285	131	81	57	41	31	22	16	10		TWNI	695	322	204	146	109	83	63	46	32
											Shreveport, Louisiana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
												WW	361	166	104	74	65	42	31	22	14
												WWNI	524	245	154	111	85	67	53	40	28
												TW	340	167	103	69	49	35	25	17	10
												TWNI	500	234	148	105	79	60	45	33	22

TABLE I: PERFORMANCE PARAMETERS FOR PASSIVE SOLAR HEATING SYSTEMS USING THERMAL STORAGE WALLS (Cont.)
Load Collector Ratio (BTU/DD-ft²) for particular values of Solar Heating Fraction (SHF)

Caribou, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Albuquerque, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	83	34	17	8							WW	278	133	83	59	44	33	24	16	9
9769 DO	WWNI	172	78	48	33	24	17	13	8		4348 DO	WWNI	414	201	128	92	70	55	43	33	23
	TW	97	43	23	12	5						TW	271	135	83	56	39	28	19	13	7
47°N	TWNI	172	79	48	33	23	17	12	8	4	35°N	TWNI	402	193	123	87	65	49	37	27	18
Portland, Maine	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Los Alamos, New Mexico	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	125	54	31	20	13	7					WW	179	84	52	36	26	18	12	7	
7511 DO	WWNI	223	103	64	45	33	25	19	14	8	6604 DO	WWNI	288	139	89	64	48	37	29	21	14
	TW	133	62	35	22	14	8					TW	183	89	54	36	24	16	11	6	
44°N	TWNI	221	102	63	44	32	23	17	12	7	36°N	TWNI	283	136	86	61	45	34	25	18	12
Boston, Massachusetts	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Ithaca, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	137	60	35	23	15	9					WW	93	36	18	9					
5634 DO	WWNI	241	110	68	48	36	27	21	15	9	6914 DO	WWNI	189	83	50	34	24	18	13	9	5
	TW	145	67	39	24	15	9	5				TW	106	46	24	13	6				
42°N	TWNI	238	108	67	47	34	25	18	13	8	42°N	TWNI	188	83	50	34	24	17	12	8	4
East Lansing, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	New York City, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	111	46	25	15	8						WW	147	64	38	25	17	11	5		
6909 DO	WWNI	208	94	57	39	29	22	16	11	7	4871 DO	WWNI	250	117	72	51	38	29	22	16	10
	TW	120	54	30	18	10	4					TW	152	71	42	26	17	11	6		
43°N	TWNI	206	93	57	39	28	20	15	10	6	41°N	TWNI	247	114	71	49	36	27	20	14	9
Sault St. Marie, Michigan	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Sayville, L.I., New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	100	40	21	11							WW	165	74	45	30	21	14	9		
9048 DO	WWNI	193	87	53	36	26	19	13	9	5	4811 DO	WWNI	272	129	80	57	43	33	25	18	12
	TW	110	49	26	15	7						TW	169	81	48	31	20	13	8	4	
46°N	TWNI	192	87	53	36	25	18	13	8	4	41°N	TWNI	268	125	78	55	40	30	22	16	10
St. Cloud, Minnesota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Schenectady, New York	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	96	39	21	11							WW	84	34	18	9					
8879 DO	WWNI	189	85	52	36	26	19	14	9	5	6650 DO	WWNI	174	79	48	33	24	18	13	9	5
	TW	108	48	26	15	7						TW	98	43	23	13	6				
46°N	TWNI	189	86	52	36	25	18	13	8	5	43°N	TWNI	175	79	49	33	24	17	12	8	5
Columbia, Missouri	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Greensboro, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	46	31	21	14	8				WW	237	107	66	46	33	24	17	11	
5046 DO	WWNI	287	133	82	57	43	33	25	18	12	3805 DO	WWNI	267	120	75	57	44	35	26	18	
	TW	177	83	49	31	20	13	8				TW	231	112	67	44	30	21	14	9	
39°N	TWNI	281	129	80	55	41	30	22	15	10	36°N	TWNI	254	165	103	72	54	40	30	22	14
Glasgow, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Hatteras, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	168	75	44	29	19	12	6				WW	412	189	118	82	61	46	34	24	15
8956 DO	WWNI	277	130	81	56	41	31	23	17	10	2612 DO	WWNI	588	274	173	123	93	71	57	43	30
	TW	171	80	47	30	19	12	7				TW	381	187	115	77	54	39	28	19	11
48°N	TWNI	272	126	78	54	39	29	21	14	9	35°N	TWNI	560	261	164	115	86	65	49	36	24
Great Falls, Montana	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Raleigh, North Carolina	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	143	63	37	23	14	8					WW	256	117	71	50	37	27	19	12	7
7750 DO	WWNI	246	115	71	49	36	27	20	14	8	3393 DO	WWNI	391	182	114	80	61	48	37	28	19
	TW	149	69	40	25	15	9					TW	249	120	72	48	33	23	16	10	5
47°N	TWNI	243	112	69	48	34	25	18	12	7	36°N	TWNI	378	175	109	77	57	43	32	23	15
Lincoln, Nebraska	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Bismarck, North Dakota	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	175	77	45	30	21	14	8				WW	111	46	25	14	6				
5864 DO	WWNI	288	133	82	57	42	33	25	18	12	8851 DO	WWNI	208	94	57	39	28	21	15	10	6
	TW	176	83	48	31	20	13	8				TW	120	54	30	17	9				
41°N	TWNI	280	129	79	55	40	30	22	16	10	47°N	TWNI	207	94	57	39	27	20	14	9	5
Ely, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Cleveland, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	172	80	50	35	25	18	12	6			WW	103	41	22	12					
7733 DO	WWNI	282	134	85	61	47	36	28	21	14	6351 DO	WWNI	202	89	53	36	25	20	14	10	6
	TW	178	86	52	34	23	16	10	6			TW	114	50	27	15	8				
39°N	TWNI	277	131	83	59	44	33	25	18	11	41°N	TWNI	200	89	53	36	26	19	13	9	5
Las Vegas, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Columbus, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	448	209	130	92	68	52	39	28	17		WW	120	51	29	18	11				
2709 DO	WWNI	632	300	188	134	102	80	63	48	33	5211 DO	WWNI	218	100	61	42	31	23	17	12	7
	TW	414	205	126	85	60	43	31	21	13		TW	128	59	33	20	12	6			
36°N	TWNI	603	284	179	126	94	71	53	39	26	40°N	TWNI	216	99	61	42	30	22	16	11	6
Reno, Nevada	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Put-in-Bay, Ohio	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	192	88	54	37	26	18	12	6			WW	102	39	20	9					
6332 DO	WWNI	307	145	91	65	49	37	28	21	13	5796 DO	WWNI	199	88	52	35	25	18	13	8	
	TW	192	93	55	36	24	16	10	5			TW	112	48	26	14	6				
39°N	TWNI	298	141	89	62	46	34	25	18	11	42°N	TWNI	199	87	52	35	25	18	12	8	4
Seabrook, New Jersey	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Oklahoma City, Oklahoma	SHF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	WW	163	72	43	29	20	13	8				WW	250	115	70	49	36	26	19	12	6
4812 DO	WWNI	271	126	78	55	41	31	24	17	11	3725 DO	WWNI	382	179	112	80	60	47	37	28	19
	TW	167	78	46	29	19	12	7				TW	243	118	71	47	32	23	15	10	5
39°N	TWNI	267	123	76	53	39	29	21	15	9											

A SEMI-EMPIRICAL METHOD FOR ESTIMATING THE PERFORMANCE
OF DIRECT GAIN PASSIVE SOLAR HEATED BUILDINGS

W. O. Wray, J. D. Balcomb and R. D. McFarland
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

The SUNSPOT code for performance analysis of direct gain passive solar heated buildings is used to calculate the annual solar fraction for two representative designs in ten American cities. The two representative designs involve a single thermal storage mass configuration which is evaluated with and without night insulation. In both cases the solar aperture is double glazed. The results of the detailed thermal network calculations are then correlated using the monthly solar load ratio method which has already been successfully applied to the analysis of both active solar heated buildings and passive thermal storage wall systems. The method is based on a correlation between the monthly solar heating fraction and the monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the monthly solar energy transmitted through the glazing aperture to the building's monthly thermal load.

The procedure using the monthly method for any location is discussed in detail. In addition, a table of annual performance results for 84 cities is presented, enabling the designer to bypass the monthly method for these locations.

1. Introduction

The solar load ratio method for estimating the performance of solar heated buildings was originally developed as a design tool for active systems.⁽¹⁾ Later the technique was modified slightly by Balcomb and McFarland⁽²⁾ and applied to passive solar heated buildings of the thermal storage wall type. In this paper, the technique of Balcomb and McFarland, as described in Ref. 2, is extended to include direct gain passive solar heated buildings.

The solar load ratio method involves the use of a correlation between monthly solar heating fraction and monthly solar load ratio. The monthly solar load ratio is defined as the ratio of the solar radiation transmitted through the glazing of the solar aperture during a one month period

to the total building heating load during the same one month period. Simulation results on which to base the correlation for direct gain buildings were obtained from a series of calculations performed with the PASOLE/SUNSPOT⁽³⁾ thermal network code. SUNSPOT has been validated on the basis of experimental data from the direct gain test cell at the Los Alamos Solar Laboratory and although it is quite a simple model it is considered a reasonably accurate representation of actual direct gain buildings.

In the following sections we describe the procedure used to correlate the monthly solar heating fraction for direct gain buildings with the monthly solar load ratio. Limitations and accuracy of the resulting correlation are discussed. Finally a step-by-step procedure for estimating the annual performance of an arbitrarily located direct gain building on the basis of the solar load ratio correlation is presented.

2. The Reference Direct Gain Design

A single reference design is used in this study. It is, of course, desirable to have several reference designs available for analysis by the solar load ratio method and studies involving other configurations are therefore planned for the near future. At present, however, the performance of direct gain systems other than the reference design must be estimated by scaling the results based on parametric studies as will be discussed later.

The characteristics of the direct gain reference design are matched to corresponding characteristics of the previously reported solar load ratio analysis of thermal storage wall systems⁽⁴⁾ wherever possible. For example, the direct gain design has a six inch thick layer of high density concrete distributed on the floor and north, east and west walls of the enclosure. The mass surface area is three times the glazing area. Thus the total volume of concrete thermal storage mass is equal to that available in an 18

*Work performed under the auspices of the U.S. Department of Energy, and funded by the Research and Development Branch for Solar Heating and Cooling, Office of the Assistant Secretary for Conservation and Solar Applications.

This paper presented at the 3rd National Passive Solar Conference, January 1979, San Jose, California.

inch Trombe wall whose surface area equals the glazing area. The remaining characteristics of the reference direct gain design are:

Thermal Storage: 45 Btu/°F-ft² of glazing

Mass Distribution: 6 in. thick layer of concrete on floor and north, east or west walls. Mass surface area is three times the glazing area.

Other Building Mass: Negligible

Double Glazing: Normal solar transmittance = 0.747

Air Temperature Range in Building: 65°F to 75°F

Night Insulation: R9 when used. Insulation in place from 5 p.m. to 7 a.m.

Mass-surface-to-room air conductance: 1.0 Btu/hr·ft²·°F

Storage Mass Properties:

thermal conductivity = 1.0 Btu/hr ft °F
heat capacity = 30 Btu/ft³ °F

Glazing Orientation: Vertical and south facing

Mass Surface Solar Absorptance: 0.8

Ground Reflectance: 0.3

Overhang: None

The above design is not as constrained as first appearances might indicate. Although the thickness and surface area of the thermal storage mass are fixed, the distribution of the mass along the interior surfaces of the enclosure is arbitrary except that the ceiling is excluded. During the course of validating the SUNSPOT model it was determined that the performance of direct gain enclosures is not very sensitive to variations of mass or solar radiation distribution within the enclosure. However, all non-massive surfaces are modeled as perfect reflectors representing the use of light colors on all light weight elements of the building shell. In order to account for the presence of furniture, rugs and other low thermal capacity objects in the direct gain enclosure, it is assumed that 20% of the transmitted solar flux was absorbed directly into the room air. This procedure synthesizes the absorption of solar radiation by objects which heat up rapidly due to their low heat capacity and subsequently lose thermal energy to the room air with very little lag time.

3. The Solar Load Ratio Correlation

A data base for the solar load ratio correlation was generated by performing a one year SUNSPOT calculation for the reference direct gain design (with and without night insulation) in each of ten American cities. The ten cities were selected on the basis of obtaining a variety of different types of climates. A list of the ten cities is presented in Table I as are the latitude, longitude, annual heating degree days and annual insolation at each site. The beginning date of the "typical year" historical weather file used for each city is also listed. The typical years were determined for each city on the basis of past work on active system simulation as the year which gives an annual performance closest to the average annual performance over a ten year period. Calculations in each city were run with and without night insulation for four different glazing area to building load ratios. Thus a total of $10 \times 2 \times 4 = 80$ annual calculations were performed. The monthly data points obtained with and without night insulation are plotted in Figs. 1 and 2 respectively. In each figure, the monthly solar heating fraction is plotted as a function of the monthly solar load ratio. The grouping of the data points indicates that a correlation does exist and, as shown in Figs. 1 and 2, we have fit analytic curves to both sets of data. The functional relationship is given by:

$$SHF = a_1(SLR), \quad SLR \leq R$$

$$SHF = a_2 - a_3 \exp[-a_4(SLR)] \quad , \quad SLR > R$$

The coefficients selected are those which yield a least squares fit to annual solar heating fraction for the whole data set. The coefficients are given in Table II along with the standard deviation, σ , of the annual data.

The correspondence between annual solar heating fraction by the monthly solar load ratio method as compared with the hour-by-hour results is given in Figs. 3 and 4.

Table I
American Cities used in Solar Load Ratio Correlation

City	Latitude	Longitude*	Annual Heating Degree Days	Annual Insolation (10 ³ Btu/ft ²)	Typical Year Start Date
Albuquerque	35.0	1.6	4253	688	7/1/62
Los Alamos	35.8	1.3	7350	518	9/1/72
Madison	43.0	-0.7	7838	513	7/1/61
Medford	42.3	2.9	5275	527	7/1/61
Boston	42.3	6.7	5535	444	7/1/57
Santa Maria	34.8	0.4	3065	649	7/1/56
Nashville	36.1	-3.3	3786	513	7/1/55
Charleston	32.8	5.0	2255	554	7/1/63
Bismark	46.8	10.8	8234	484	7/1/54
Lake Charles	30.1	3.2	1694	546	7/1/57

*Relative to local time meridian

Table II

Coefficients for Solar Heating Fraction Correlation Function

	Direct Gain (DG)	Direct Gain with Night Insulation (DGNI)
R	0.100	0.600
a ₁	0.6182	0.8865
a ₂	1.0097	1.0028
a ₃	1.0710	1.2646
a ₄	1.2208	1.6467
σ	.025	.030

Fig. 1. Monthly Solar Heating Fraction vs Monthly Solar Load Ratio for reference direct gain design with no night insulation.

Fig. 2. Monthly solar heating fraction vs monthly solar load ratio for reference direct gain design with R9 night insulation.

Fig. 3. Comparison of Annual Solar Heating fractions obtained from SUNSPOT calculations and by the solar load ratio method for the Reference Direct gain design with no night insulation.

Fig. 4. Comparison of Annual Solar Heating Fraction obtained from SUNSPOT calculations and by the solar load ratio method for the reference direct gain design with R9 night insulation.

4. Estimating the Performance of Direct Gain Buildings

In this section we present a method for estimating the annual performance of direct gain solar buildings of the reference type at arbitrary locations. The only weather data required are total monthly insolation on a horizontal surface and monthly heating degree days. Extension of the results to non-reference designs is discussed in the following section.

Monthly Transmitted Solar Radiation

Step 1: Obtain the total monthly solar radiation on a horizontal surface, Q_H (Btu/ft²), from weather data at the location of interest. Repeat for all 12 months.

Step 2: Calculate $(L - \delta)$ for each month where

$$L = \text{latitude (deg)} \\ = 23.3^\circ \cos(30^\circ M - 187^\circ), \text{ solar declination at mid-month (M = month number, i.e. M = 1 for January)}$$

Step 3: From Fig. 5, determine a value of Q_T/Q_H for each of the monthly values of $(L - \delta)$.

Then calculate

$$Q_T = \left(\frac{Q_T}{Q_H} \right) \cdot Q_H \quad (1)$$

where Q_T is the monthly solar radiation transmitted through each square foot of vertical double glazing facing due south. (The data presented in Fig. 5 is the result of hour by hour simulations in 21 U.S. cities. The Boes correlation⁽⁵⁾ was used to determine hourly direct normal and diffuse solar radiation from hourly total horizontal radiation). The analytic form of the function presented in Fig. 5 is:

$$\frac{Q_T}{Q_H} = .226 - .00251 (L - \delta) + .000308 (L - \delta)^2 \quad (2)$$

The standard deviation is 0.060.

Fig. 5 Ratio of solar flux transmitted through double glazing to solar flux incident on horizontal surface vs latitude minus mid-month solar declination.

Step 4: The relationship represented in Equation (2) is based on an assumed ground reflectance

of 0.3. In some cases a designer may wish to use a horizontal specular reflector on the ground in front of the solar aperture. If the reflector is equal in area to the glazing aperture and has a reflectance of 0.8, the monthly transmitted solar radiation is enhanced as illustrated in Fig. 6. The enhanced monthly transmitted solar radiation is given by

$$Q'_T = Q_T \cdot EF$$

where EF is the enhancement factor and Q_T is the transmitted solar radiation obtained in Step 3 above. The correlation in Fig. 6 was obtained from hour by hour simulations in ten American cities. The standard deviation is 0.0197. The analytic form of the function in Fig. 6 is:

$$EF = 1.008 - .0179 (L - \delta) + .00192 (L - \delta)^2 \\ - 4.03 \times 10^{-5} (L - \delta)^3 \\ + 2.47 \times 10^{-7} (L - \delta)^4 \quad (3)$$

Q'_T is the desired monthly transmitted solar radiation.

Fig. 6. Specular reflector enhancement factor vs latitude minus mid-month solar declination.

Monthly Thermal Load

Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. The BLC is the sum of the building skin conductance (including the south facing glazing) and the infiltration.

Step 2: Determine the monthly heating degree days, DD, from weather data at the site of interest.

Step 3: Determine the monthly thermal load, MTL, by taking the product of the

building loss coefficient and the monthly heating degree day values.

$$MTL = BLC \cdot DD$$

Monthly Solar Load Ratio

The monthly solar load ratio is

$$SLR = Q_T / MTL$$

Monthly Solar Heating Fraction

Each previously calculated monthly solar load ratio corresponds to a unique monthly solar heating fraction, SHF, which can be obtained from the solid lines graphed in Figs. 1 and 2 for designs without and with night insulation, respectively.

Monthly Auxiliary Energy Required

The auxiliary heating energy, AUX, required each month is calculated as follows:

$$AUX = (1 - SHF) \cdot BLC \cdot DD$$

Annual Auxiliary Energy Required

Simply sum the monthly AUX's to get the annual total.

$$ANNUAL\ AUX = \sum_{i=1}^{12} AUX_i$$

Annual Solar Heating Fraction

Sum monthly heating degree days to get ANNUAL DD and evaluate the annual solar fraction as follows:

$$ANNUAL\ SHF = 1 - \frac{ANNUAL\ AUX}{BLC \cdot ANNUAL\ DD}$$

5. Variations from the Reference Designs

In the near future solar load ratio curves will be generated for several additional direct gain configurations in order to extend the applicability of the solar load ratio method. In the meantime, the performance of non-reference configurations must be approximated by scaling annual solar fractions obtained for the reference design on the basis of detailed sensitivity study results. The variation of annual solar heating fraction as a function of number of glazings, resistance of night insulation, thickness of thermal storage mass, surface area of thermal storage mass, and allowable room air temperature swing has been determined by performing an extensive matrix of SUNSPOT calculations. The results are reported in another paper in these proceedings.⁽⁶⁾ From the calculated results presented in Reference 6 it is possible to determine the fractional change in annual solar

heating fraction which results from a selected design departure from the reference system. The annual solar heating fraction obtained by the solar load ratio method can be multiplied by the appropriate fractional change in order to determine the performance of the configuration of interest to the designer. Application of this approximation involves the implicit assumption that fractional variations of the annual solar heating fraction due to changes in a single design parameter are insensitive to the values of the remaining design parameters. This implicit assumption is of course not rigorously correct but use of the suggested scaling correction is better than using no correction at all for off-reference configurations.

6. Tabular Solution for Annual Solar Heating Fraction in 84 U.S. and Canadian Cities

A variation of the solar load ratio method described in Section 4 has been used to calculate annual solar heating fractions for the reference direct gain designs in 84 U.S. and Canadian cities and the results are presented in Table III. A designer interested in a building site located in one of the cities included in Table III need not perform the month by month calculations required by the solar load ratio method. Instead, the following much simpler procedure may be followed:

- Step 1: Calculate the building loss coefficient (BLC) in Btu/degree-day. This is the sum of the building skin conductance (excluding the south facing glazing) and the infiltration load. Internal heat sources may be subtracted from the building loss coefficient. IMPORTANT: Remember that when using Table III the calculated building loss coefficient should not include the south facing glazing of the solar aperture.
- Step 2: Calculate the building load collector ratio (LCR) defined as follows:

$$LCR = \frac{BLC}{\text{Solar Collection Area (ft}^2\text{)}}_g$$

- Step 3: Locate the city and reference design of interest in Table III. The symbol DG refers to the direct gain design and DGNI is the direct gain design with night insulation. The load collector ratios required to achieve the indicated solar heating fractions, which range from 0.1 to 0.9, appear beneath the solar heating fractions. It will usually be necessary to interpolate in the table in order to determine the correct solar heating fraction.
- Step 4: The annual auxiliary energy required by the building is given by:

$$ANNUAL\ AUX = (1 - SHF) \cdot (ANNUAL\ DD) \cdot (BLC)$$

where, again, the building loss coefficient does not include the solar aperture.

TABLE III: Heating-LOAD/COLLECTOR-AREA RATIO FOR GIVEN SOLAR FRACTIONS
Heating-Load in Btu/DD; Area in Sq. Ft.

Phoenix, AZ				6632 DD				Santa Maria, CA				2967 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	217.0	110.5	64.6	39.1	22.4	0.0	0.0	0.0	0.0	LCR (DG)	660.7	372.7	243.7	170.2	122.4	88.7	63.2	42.7	24.7
LCR (DQNT)	339.0	156.1	97.6	68.6	51.3	38.9	28.7	19.9	11.6	LCR (DQNT)	853.2	426.6	278.5	200.4	152.7	119.8	92.5	68.9	46.6
Phoenix, AZ				1765 DD				Boulder, CO				5509 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	724.5	396.7	256.0	177.7	127.6	92.5	66.0	44.7	26.0	LCR (DG)	211.8	109.4	64.8	39.9	23.5	0.0	0.0	0.0	0.0
LCR (DQNT)	959.8	452.8	289.2	209.3	158.9	123.7	95.8	71.2	48.1	LCR (DQNT)	327.2	152.8	96.8	69.0	52.0	39.8	29.5	20.7	12.3
Tucson, AZ (State Univ.)				1800 DD				Granby, CO				10802 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	724.7	394.6	253.8	175.9	126.3	91.6	65.6	44.6	26.3	LCR (DG)	90.2	39.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	974.3	451.0	286.0	206.3	157.0	123.1	95.4	71.2	48.4	LCR (DQNT)	169.6	84.6	54.6	38.8	28.5	20.8	14.3	8.6	0.0
Little Rock, AR				3219 DD				Grand Junction, CO				5641 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	269.4	140.0	84.0	53.1	33.3	19.3	0.0	0.0	0.0	LCR (DG)	222.1	114.0	67.3	41.0	23.8	0.0	0.0	0.0	0.0
LCR (DQNT)	405.1	188.6	116.2	82.1	61.2	46.7	34.8	24.6	15.0	LCR (DQNT)	341.4	160.6	100.6	70.7	52.6	39.7	29.2	20.2	11.8
Davis, CA				2502 DD				Washington, DC, Silver Hill, MD				4224 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	486.2	249.5	154.6	102.2	69.3	46.4	29.4	15.5	0.0	LCR (DG)	225.5	114.6	66.8	40.2	22.9	0.0	0.0	0.0	0.0
LCR (DQNT)	664.7	307.2	190.7	133.8	98.3	73.5	55.2	39.3	24.5	LCR (DQNT)	351.5	162.3	100.4	70.1	51.8	39.1	28.7	19.8	11.5
El Centro, CA				1458 DD				Apalachicola, FL				1308 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	1211.3	662.5	428.2	298.2	215.8	158.7	116.1	82.2	52.5	LCR (DG)	818.2	446.4	287.3	199.4	143.5	104.5	75.3	52.0	31.4
LCR (DQNT)	1578.6	742.0	464.8	331.4	251.3	197.1	153.3	115.3	79.7	LCR (DQNT)	1093.5	505.9	321.2	229.9	175.0	137.4	106.5	79.7	54.5
Fresno, CA				2403 DD				Gainesville, FL				1139 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	476.9	242.9	149.4	97.9	65.5	43.3	26.7	13.0	0.0	LCR (DG)	857.7	466.8	301.1	209.8	151.6	111.0	80.5	56.0	34.3
LCR (DQNT)	642.3	303.1	186.2	129.5	94.6	70.2	52.5	37.1	22.9	LCR (DQNT)	1146.3	524.3	334.5	240.5	183.9	144.6	112.5	84.4	57.8
Inyokern, CA (China Lake)				3528 DD				Tallahassee, FL (State Univ.)				1495 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	528.6	280.1	176.0	118.5	82.2	57.0	38.3	23.5	0.0	LCR (DG)	701.7	382.9	245.1	169.0	121.0	87.6	62.6	42.5	25.0
LCR (DQNT)	727.4	338.6	210.7	147.8	110.6	84.9	64.7	47.2	31.0	LCR (DQNT)	952.4	439.3	276.4	198.7	151.1	118.8	92.0	68.7	46.8
Los Angeles, CA				2061 DD				Tampa, FL				683 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	892.7	489.1	314.2	216.8	155.1	112.4	80.9	56.0	34.6	LCR (DG)	1403.0	802.6	533.8	380.6	281.0	210.4	156.9	113.6	75.1
LCR (DQNT)	1177.7	563.1	350.1	247.0	186.1	145.6	112.7	84.4	58.1	LCR (DQNT)	1742.7	871.4	570.1	415.6	321.8	255.7	200.7	152.7	107.1
Riverside, CA				1803 DD				Atlanta, GA				2951 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	895.5	488.1	314.8	218.7	157.6	115.1	83.4	58.0	35.7	LCR (DG)	342.3	179.5	110.0	71.8	47.7	30.8	18.1	0.0	0.0
LCR (DQNT)	1182.8	551.7	348.2	249.4	190.2	149.0	115.7	86.8	59.5	LCR (DQNT)	500.5	230.0	142.3	100.2	75.0	57.7	43.4	31.2	19.8
Boise, ID				5809 DD				Portland, ME				7511 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	205.2	98.6	53.5	27.4	0.0	0.0	0.0	0.0	0.0	LCR (DG)	132.2	60.0	27.4	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	328.2	151.1	91.9	61.7	42.6	31.0	21.7	13.6	0.0	LCR (DQNT)	238.5	108.0	66.1	45.4	32.9	24.0	16.7	10.3	0.0
Argonne Nat. Lab., Lemont, IL				6155 DD				Boston, MA				5634 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	124.3	54.2	21.2	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	141.4	65.2	32.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	231.0	103.9	62.6	42.7	30.8	22.3	15.3	9.2	0.0	LCR (DQNT)	250.2	113.2	69.0	47.8	34.8	25.6	18.0	11.4	0.0
Indianapolis, IN				5699 DD				East Lansing, MI				6909 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	142.6	64.7	30.2	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	111.0	44.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	254.7	114.6	68.7	46.8	33.8	24.5	17.0	10.6	0.0	LCR (DQNT)	216.5	96.8	57.6	38.8	27.6	19.5	13.0	7.2	0.0
Ames, IA (State Univ.)				6588 DD				Sault Ste. Marie, MI				9048 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	119.0	51.3	16.7	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	90.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	223.7	101.1	61.0	41.6	29.9	21.5	14.7	8.7	0.0	LCR (DQNT)	194.6	85.9	50.8	33.4	22.6	15.1	8.9	0.0	0.0
Dodge City, KS				4986 DD				Saint Cloud, MN				8679 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	245.0	127.7	76.8	48.4	30.0	16.5	0.0	0.0	0.0	LCR (DG)	93.6	31.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	368.1	174.0	109.1	77.0	57.8	44.3	32.9	23.2	14.1	LCR (DQNT)	158.1	67.5	52.2	34.7	24.0	16.4	10.3	0.0	0.0
Manhattan, KS				5182 DD				Columbia, MD				5046 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	177.6	87.4	48.2	25.8	0.0	0.0	0.0	0.0	0.0	LCR (DG)	188.9	92.5	51.1	27.7	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	290.9	134.7	82.8	57.5	42.4	31.7	22.8	15.3	8.2	LCR (DQNT)	309.0	141.2	86.0	59.4	43.5	32.4	23.3	15.6	8.3
Lexington, KY				4683 DD				Glasgow, MT				8996 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	150.7	70.8	35.7	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	179.0	87.1	47.0	23.3	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	260.8	119.4	72.4	49.7	36.2	26.6	18.8	12.1	0.0	LCR (DQNT)	295.0	136.5	83.6	57.2	41.2	29.9	21.1	13.6	0.0
Lake Charles, LA				1459 DD				Great Falls, MT				7750 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	601.4	325.1	207.7	142.9	101.6	72.8	51.1	33.7	18.3	LCR (DG)	146.2	67.5	32.1	0.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	817.4	477.3	293.2	172.9	131.5	102.3	79.0	58.5	39.2	LCR (DQNT)	255.7	117.6	71.9	48.6	34.3	24.3	16.5	9.7	0.0
Shreveport, LA				2184 DD				Lincoln, NE				3884 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	405.6	218.0	136.9	92.0	63.6	43.8	28.9	16.7	0.0	LCR (DG)	189.9	93.0	51.4	28.0	0.0	0.0	0.0	0.0	0.0
LCR (DQNT)	573.3	266.3	167.4	120.3	91.2	71.2	54.4	39.8	26.2	LCR (DQNT)	310.6	141.8	86.3	59.4	43.7	32.5	23.5	15.8	8.5
Caribou, ME				9767 DD				Ely, NV				7733 DD							
SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	SHP	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
LCR (DG)	76.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	191.1	97.6	56.9	33.9	18.1	0.0	0.0	0.0	0.0
LCR (DQNT)	175.4	78.1	46.9	31.1	21.2	14.2	8.3	0.0	0.0	LCR (DQNT)	299.6	141.4	89.6	63.6	47.8	36.3	26.7	18.4	10.6

Las Vegas, NV										Raleigh, NC										3393 DD									
SIF	0.1	0.2	0.3	0.4	2709 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	513.9	278.1	175.8	119.1	83.0	58.1	39.3	24.6	0.0	0.0	LCR (DG)	290.7	151.7	92.1	59.3	38.4	23.6	11.9	0.0	0.0									
LCR (DQNT)	708.4	333.4	208.4	148.4	111.7	86.2	66.0	48.4	31.9	0.0	LCR (DQNT)	431.8	200.0	124.2	87.4	65.7	50.6	37.9	27.1	17.0									
Reno, NV										Bismark, ND										8851 DD									
SIF	0.1	0.2	0.3	0.4	6332 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	207.8	105.7	61.1	35.9	18.9	0.0	0.0	0.0	0.0	0.0	LCR (DG)	110.3	43.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	325.2	152.4	95.4	66.8	49.1	36.5	26.6	18.0	9.8	0.0	LCR (DQNT)	219.2	97.1	57.6	38.1	26.5	18.4	11.8	5.9	0.0									
Seabrook, ND										Cleveland, OH										6351 DD									
SIF	0.1	0.2	0.3	0.4	4812 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	170.2	82.4	44.5	22.3	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	94.3	30.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	283.9	130.1	79.5	55.2	40.4	30.1	21.5	14.2	0.0	0.0	LCR (DQNT)	203.7	87.8	51.3	34.0	23.7	16.4	10.3	0.0	0.0									
Albuquerque, NM										Columbus, OH (State Univ.)										5211 DD									
SIF	0.1	0.2	0.3	0.4	4348 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	321.9	173.5	108.2	71.6	48.1	31.6	19.0	0.0	0.0	0.0	LCR (DG)	121.7	52.5	17.4	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	457.4	220.4	139.8	99.5	75.5	58.4	44.2	31.9	20.4	0.0	LCR (DQNT)	228.0	102.8	61.9	42.2	30.0	21.4	14.5	8.4	0.0									
Ithaca, NY										Put-In-Bay, OH (Stone Lab.)										5796 DD									
SIF	0.1	0.2	0.3	0.4	6914 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	81.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	95.5	28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	189.2	80.9	47.0	31.0	21.3	14.3	8.5	0.0	0.0	0.0	LCR (DQNT)	207.6	88.8	51.6	34.1	22.8	15.1	8.8	0.0	0.0									
New York, NY (Central Park)										Oklahoma City, OK										3725 DD									
SIF	0.1	0.2	0.3	0.4	4871 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	158.6	76.0	39.9	17.9	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	276.2	144.2	87.2	55.7	35.6	21.3	0.0	0.0	0.0									
LCR (DQNT)	269.4	123.4	75.5	52.4	38.3	28.4	20.2	13.2	0.0	0.0	LCR (DQNT)	411.7	191.7	119.4	84.3	63.1	48.4	36.2	25.7	15.9									
Sayville, NY										Astoria, OR										5186 DD									
SIF	0.1	0.2	0.3	0.4	4811 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	182.3	90.8	51.0	28.3	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	236.9	117.3	67.3	38.5	17.8	0.0	0.0	0.0	0.0									
LCR (DQNT)	294.5	137.3	84.9	59.5	43.9	33.0	23.9	16.1	8.8	0.0	LCR (DQNT)	349.7	169.6	105.4	72.1	51.0	36.2	25.0	15.7	0.0									
Schenectady, NY										Corvallis, OR (State College)										4726 DD									
SIF	0.1	0.2	0.3	0.4	6650 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	78.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	252.5	118.7	66.5	37.5	17.3	0.0	0.0	0.0	0.0									
LCR (DQNT)	177.9	79.0	47.1	31.6	22.0	15.1	9.3	0.0	0.0	0.0	LCR (DQNT)	389.7	172.4	104.6	70.8	50.1	35.8	25.1	16.0	0.0									
Greensboro, NC										Medford, OR										5008 DD									
SIF	0.1	0.2	0.3	0.4	3805 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	264.0	136.6	81.9	51.7	32.5	18.6	0.0	0.0	0.0	0.0	LCR (DG)	201.9	94.5	50.6	24.8	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	398.9	184.1	114.4	80.5	60.2	46.0	34.3	24.2	14.8	0.0	LCR (DQNT)	324.0	146.7	89.6	60.4	42.4	29.8	20.4	12.4	0.0									
Batteras, NC										State College, PA										5934 DD									
SIF	0.1	0.2	0.3	0.4	2612 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	463.4	249.1	156.3	105.1	72.7	50.2	33.5	20.0	0.0	0.0	LCR (DG)	120.5	52.1	17.8	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	651.9	301.5	189.9	133.7	100.5	77.9	59.4	43.4	28.4	0.0	LCR (DQNT)	225.9	102.2	61.6	41.9	30.1	21.6	14.7	8.7	0.0									
Newport, RI (Bapley Lab.)										Flaming Gorge, UT										6929 DD									
SIF	0.1	0.2	0.3	0.4	5804 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	157.3	75.6	40.1	18.9	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	189.7	96.6	55.6	32.4	16.1	0.0	0.0	0.0	0.0									
LCR (DQNT)	267.2	121.9	75.0	52.3	38.7	28.9	20.8	13.8	0.0	0.0	LCR (DQNT)	299.7	141.3	89.0	62.7	46.7	35.2	25.7	17.6	9.9									
Charleston, SC										Salt Lake City, UT										6052 DD									
SIF	0.1	0.2	0.3	0.4	2033 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	507.2	275.5	174.2	118.2	82.8	58.2	40.0	25.4	0.0	0.0	LCR (DG)	212.4	106.5	60.7	34.9	17.2	0.0	0.0	0.0	0.0									
LCR (DQNT)	703.2	329.0	205.1	146.5	111.0	86.7	66.6	49.2	32.9	0.0	LCR (DQNT)	336.8	155.5	96.0	66.3	48.3	35.6	25.7	17.2	9.2									
Rapid City, SD										Burlington, VT										8269 DD									
SIF	0.1	0.2	0.3	0.4	7345 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	159.8	77.3	40.9	18.7	0.0	0.0	0.0	0.0	0.0	0.0	LCR (DG)	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	269.5	124.5	76.8	53.0	38.8	28.6	20.3	13.2	0.0	0.0	LCR (DQNT)	169.1	72.4	42.4	27.9	19.2	12.7	7.1	0.0	0.0									
Nashville, TN										Pullman, WA										5542 DD									
SIF	0.1	0.2	0.3	0.4	3578 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	244.0	122.0	70.6	42.5	24.5	0.0	0.0	0.0	0.0	0.0	LCR (DG)	194.0	89.3	45.8	18.2	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	384.1	172.4	104.2	72.3	53.2	40.2	29.5	20.4	11.9	0.0	LCR (DQNT)	316.3	143.3	86.3	57.1	39.5	27.4	18.5	10.9	0.0									
Oak Ridge TN										Richland, WA										5941 DD									
SIF	0.1	0.2	0.3	0.4	3817 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	221.8	110.9	63.6	37.5	20.4	0.0	0.0	0.0	0.0	0.0	LCR (DG)	195.0	87.2	42.9	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	351.8	159.8	97.4	67.5	49.9	37.6	27.5	18.9	10.8	0.0	LCR (DQNT)	320.5	143.5	85.3	55.3	37.5	25.6	17.0	9.6	0.0									
Brownsville, TX										Seattle, WA (Univ. of Wash.)										4424 DD									
SIF	0.1	0.2	0.3	0.4	600 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	1308.7	740.8	492.6	350.8	258.3	192.4	142.2	101.4	65.0	0.0	LCR (DG)	243.7	109.0	57.4	28.1	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	1607.2	801.6	533.0	390.2	299.8	234.6	183.2	137.7	94.7	0.0	LCR (DQNT)	380.2	167.0	98.8	64.9	44.3	30.4	20.4	12.0	0.0									
El Paso TX										Spokane, WA										6655 DD									
SIF	0.1	0.2	0.3	0.4	2700 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	508.2	278.1	177.4	120.9	84.9	59.7	41.0	25.9	0.0	0.0	LCR (DG)	156.6	67.2	27.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	668.3	331.4	209.3	149.9	113.7	88.0	67.6	49.8	33.0	0.0	LCR (DQNT)	276.5	123.0	72.6	47.0	31.7	21.3	13.6	6.8	0.0									
Fort Worth, TX										Madison, WI										7863 DD									
SIF	0.1	0.2	0.3	0.4	2405 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	474.1	230.6	145.7	98.4	68.2	47.2	31.4	18.5	0.0	0.0	LCR (DG)	104.5	40.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	590.3	279.9	177.0	127.1	96.1	74.6	57.1	41.8	27.4	0.0	LCR (DQNT)	212.2	93.3	55.3	37.1	26.2	18.4	12.0	6.4	0.0									
Midland, TX (Sloan Field)										Lander, WY										7870 DD									
SIF	0.1	0.2	0.3	0.4	2591 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	449.4	246.2	156.3	105.9	73.8	51.3	34.6	21.1	0.0	0.0	LCR (DG)	182.8	92.8	53.1	30.2	13.3	0.0	0.0	0.0	0.0									
LCR (DQNT)	616.0	297.5	187.6	134.4	101.8	79.1	60.6	44.5	29.4	0.0	LCR (DQNT)	289.5	137.8	87.0	61.2	45.3	33.9	24.6	16.6	9.1									
San Antonio, TX										Laramie, WY (State Univ.)										7381 DD									
SIF	0.1	0.2	0.3	0.4	1546 DD	0.5	0.6	0.7	0.8	0.9	SIF	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9									
LCR (DG)	644.3	350.8	224.4	154.5	110.2	79.3	56.2	37.6	21.3	0.0	LCR (DG)	171.9	86.1	48.8	27.4	0.0	0.0	0.0	0.0	0.0									
LCR (DQNT)	872.9	405.5	255.7	184.4	140.1	109.5	84.7	63.1	42.6	0.0	LCR (DQNT)	277.7	130.1	81.8	57.9	43.6	32.9	24.1	16.5	9.3									

- (6) Wray, William O. and Balcomb, J. D., "Trombe Wall vs Direct Gain: A Comparative Analysis of Passive Solar Heating Systems," presented at 3rd National Passive Solar Conference, San Jose, CA, Jan. 11-13, 1979.

GRAPHIC TOOLS

SOLAR CALCULATOR

(44° N. LATITUDE)

The primary intent of this simplified user's solar guide is to:

- 1) Provide users with a basic understanding of where and how the sun works in relation to a building and site.
- 2) Provide users with a simplified method of calculating sun angles and the available heat energy from the sun on vertical and horizontal surfaces.

contents:

TOOLS:

- A. How the Sun Works2
- B. The Sun Chart3
- C. The Solar Intensity Masks.....6

APPLICATION:

- D. Plotting the Skyline (obstructions)10
- E. Calculating Solar Energy for Heating11

This is the first working draft of a more comprehensive user solar guide being developed by Edward Mazria and David Winitzky (June 1976).

Portions of the text of this guide come from: 1) Solar Energy in Pacific Northwest Buildings, John Reynolds; 2) Solar Energy Workbook, Edward Mazria; and 3) The Impact of Solar Energy on Architecture, Robert Gray. The computer data used in developing the sun chart and solar intensity mask was supplied by Steven Baker.

A. How the Sun Works

earth's orbit

As every modern person knows, the sun is at the center of the solar system, the earth moves in a circular orbit around the sun in a years time, the earth is spherical in shape and rotates on its axis once a day, and this axis is tilted at twenty-two and one-half degrees away from vertical to the plane of the earth's orbit around the sun. This tilt, causes a given point on the earth's surface to receive different amounts of solar energy at different times of the year which causes the seasons and their changes in temperature.

winter

spring & fall

summer

B. The Sun Chart

In order to understand and be responsive to the effects of the sun on the location and design of places, it is necessary to know, at any given moment, the sun's position in the sky. This information is necessary in order to calculate solar heat gain, and in locating buildings, outdoor spaces, interior room arrangements, windows, shading devices, vegetation and solar collectors. The chart which is developed here provides a convenient way of locating the sun for 44° N. latitude at any time and date. The following is a sequential description of how the sun chart was developed. It is included here to provide basic solar background information.

Two coordinates are needed to locate the position of the sun in the sky. They are called the altitude and the azimuth (also called the bearing angle).

altitude

Solar altitude is the angle, above the horizon, of the position of the sun measured from the horizon. The horizontal lines on the chart represent altitude angles in 10° increments above the horizon.

azimuth

Solar azimuth is the angle, along the horizon, of the position of the sun measured to the east of west from true south. The declination map on page 4 provides the magnetic variations for true south for locations within the United States.

skydome

So, the grid on the chart represents vertical and horizontal angles of the whole skydome. It is as if there was a clear dome around the observer, and then the chart was peeled off of this dome and laid flat.

sun position

With the altitude and azimuth angles, the sun can be located at any point in the sky.

sun path

By connecting the points of the location of the sun throughout various times of the day, the sun's path for that day can be drawn.

seasonal paths

Thus, we can plot the sun's path for any day of the year. Those paths shown represent summer, fall/spring, and winter. The sun path is greatest during the summer when it reaches its highest altitude and rises and sets with the widest azimuth angle from true south. During winter, the sun is much lower in the sky and rises and sets with the narrowest azimuth angles from true south.

times of day

Finally, if we connect the hour lines on each path, we get the heavy dotted line which represents the hours of the day. This completes the sun chart.

NOTE: The times on the sun chart are for solar time. This may vary from standard time as much as an hour and fifteen minutes for different locations and different times of the year. This is alright for most practical uses of the sun chart. It is important to remember to at least use standard time when using the charts.

latitude & declination

These paths vary according to site locations on the earth's surface by latitude. I.e., a different sun chart is required for different latitudes. Only the sun chart for 44° N. latitude is included in the guide. The map to the left will assist users in understanding which areas within the United States will use the 44° N. latitude sun chart.

The map also shows the magnetic compass variations (declinations) for your area. It is necessary to adjust your compass reading by a few degrees east or west to obtain true south. The heavy broken lines on this map connect points of equal magnetic variation, and present a generalized picture of the magnetic variations. Due to "local attraction," it may be quite different for your specific locality. This chart is accurate enough for most uses of the sun chart; for more exact information, consult a local surveyor.

44° N. SUN CHART

C. The Solar Intensity Masks

vertical and horizontal surfaces

60° inclined surfaces

30° inclined surfaces

P.T.U.^{1/2}/FT²/HR.
WINTER MONTHS

SOLAR INTENSITY MASK

60° Tilted Surfaces

60°

ALIGN POINTER TO DIRECTION TILTED SURFACE FACES

SOLAR RADIATION ON HORIZONTAL SURFACE

351
333
305
266
210
163
102
40

B.T.U.'s/FT²/HR.
WINTER MONTHS

SOLAR INTENSITY MASK

Vertical & Horizontal Surfaces

90°

ALIGN POINTER TO DIRECTION VERTICAL SURFACE FACES

B.T. L¹/₄ / P¹/₄ / HR.
WINTER MONTHS

SOLAR INTENSITY MASK
H: 30° Tilted Surfaces
30°

ALIGN POINTER TO DIRECTION TILTED SURFACE FACES

D. Plotting the Skyline

transit

OR

compass

&

hand level

To find the amount of direct sun that any point on your site receives, it is necessary to plot obstructions which block the sun as seen from that point. We call this plotting the "skyline" and it is done in a similar way in which we plotted the sun's path. If the skyline is low, that is with no tall trees, adjacent buildings, abruptly rising hills, or other obstructions, the following procedure is unnecessary as all the points on the site will receive sun.

You will need: 1) a transit or compass for the bearing readings and a hand level for altitude readings, and

2) a copy of the sun chart for your location.

Place yourself at the approximate location where you wish to know the solar radiation. This may require a ladder if the location is on the second floor or roof of a building-to-be.

site plan

Find the altitude of the skyline as follows:

-- Determine which direction (bearing) is true south. (Remember magnetic variation; true south will be about 21° east of magnetic south in Eugene, Oregon.)

-- Aiming your level true south, determine the altitude (angle above the horizon) of the skyline. Plot this point on your chart above 0° true south.

-- Similarly, find and record the altitudes of skyline for each 15° bearing, both east and west of south, to at least 120° . This is a total of 17 altitude readings. Plot these readings for the respective bearing angles on the sun chart and connect them.

-- For isolated tall objects that block the sun such as tall evergreen trees, find both the bearing angle and the altitude for each object and record them at the appropriate point on the chart.

-- Finally, plot the deciduous trees in the skyline with a dotted line. These are of a special nature because they will block the sun during spring through fall and let most of the sun pass through when their leaves are gone, fall through spring.

This completes the skyline. The open areas on your completed chart are those times when you will get sun at that spot.

completed skyline

E. Calculating Solar Energy

ALIGNMENT EXAMPLE:

Vertical Surface facing
45° west of south:

Set the pointer on the intensity mask to line up with 45° west on the base-line of the Sun Chart. Be sure that the base lines of both sheets are in line.

-- Mask and Sun Chart are now aligned to read solar intensity values.

S - SUMMER
W - WINTER

In the design of solar heating and cooling systems, it is important to know the amount of thermal radiation (sun's heat measured in BTU's) that strikes a surface at some particular time of the day, hour, or daily or monthly totals. This can all be determined by the use of the solar intensity masks which fit over and are used in conjunction with the Sun Chart. The mask marked "90°" is for vertical and horizontal surfaces, mask "60°" for inclined surfaces of 60°, and likewise, mask "30°" for inclined surfaces of 30° (as measured from the horizon).

The solar intensity masks have a center axis and base line which are used for alignment with the Sun Chart. To align the mask for a particular surface, determine the direction the surface is facing and set the center axis of the mask on the bearing angle (the direction the surface is facing) of the Sun Chart. Keep the base line directly over the base line of the Sun Chart. You are now ready to determine the solar intensity values for that surface.

hourly totals

To determine the clear day hourly totals of heat energy striking a surface:

- 1)-- Select the proper mask based on the surface slope.
- 2)-- Align the mask on the Sun Chart based on the orientation of the surface to the east or west of south.
- 3)-- Select the month when you want the reading and use that sun path to read the values.
- 4)-- Select the hour and month in which you want the reading; the intersection of the hour line and the sun path will locate the position of the sun. Read the number of BTU's for that sun's position from the radiation mask - if the point where you want the reading falls between radiation lines, interpolate to find the value.

NOTE: This clear day number needs to be adjusted depending on your location in the U.S. Find the line which is closest to your area on the map below. S is for summer adjustment numbers, and W is for winter adjustment numbers. Multiply the clear day totals from the mask by these adjustment numbers.

daily totals

To determine the total daily amount of heat energy striking a surface:

- Simply follow the procedure for the hourly totals for each hour of the day and total these to get the daily total. If the hourly totals have not been adjusted for your area, then adjust the daily total by multiplying it by appropriate adjustment factor from the map.

Thresheld and Jordan, Transactions of the American Society of Heating and Air Conditioning Engineers, 1968, v.64.

SUN CHARTS
for
28°NL, 32°NL, 36°NL, 40°NL and 48°NL

A
SUPPLEMENT
to the
SOLAR GUIDE AND CALCULATOR

Edward Mazria
Eugene, Oregon

DAILY ETU NET GAIN (OR LOSS)
THROUGH SOUTH-FACING GLASS

SEATTLE AVERAGE INSOLATION

(SEATTLE AIRPORT)

BTU/SQ. FT./DAY INCIDENT
ON SOUTH-FACING SURFACES

2000
1500
1000
500
0

NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP

HORIZONTAL

R 50

R 60

VERTICAL

INFORMATION SOURCES

SOLAR INFORMATION SOURCES - HIGHLIGHTS

General Information Book

Anderson, Bruce, The Solar Home Book. Cheshire Books, Harrisville, NH 03450 - 1976.

More Technical Books with Emphasis on Active Systems

Kreider and Kreith, Solar Heating and Cooling - Engineering, Practical Design, and Economics. McGraw Hill Book Co. 1976.

Passive Solar Heating and Cooling Books

Wright, David, Natural Solar Architecture. Van Nostrand, 1977. Good and easy to read.

Mazria, Edward, Passive Solar Energy. Rodale Press, Emmaus, Pennsylvania, 1979. Just published. Appears to be the reference on the subject.

Solar Radiation Data

Baker, M. S., Insolation on Tilted Surfaces for Pacific Northwest Locations. Center for Environmental Research, University of Oregon, Eugene, OR 97403 - 1975. \$2.50.

Environmental Data Service, National Climatic Center, Federal Building, Asheville, NC 28801.

Periodicals - To Keep Up to Date

"Solar Age," Solar Vision Inc. Church Hill, Harrisville, NH 03450 \$20/year or free for ISES Members.

"Solar Engineering Magazine," 8435 N. Stemmons Freeway, Suite 880, Dallas, TX 75247. \$15/year. The official publication of the Solar Energy Industries Associations.

Solar Societies

International Solar Energy Society, American Section, American Technological University, P. O. Box 1416, Killeen, TX 76541. Membership includes a subscription to Solar Age, conferences, reduced prices for publications, etc. Vital if you want to keep informed.

Pacific Northwest Solar Energy Society, 2332 East Madison, Seattle, WA 98112. \$15/year (\$10/year for AS/ISES Members). Good for keeping abreast of developments in the Pacific Northwest. Subchapters in Western Washington (Western