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Passive Solar Progress

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A Simplified Guide to the 3rd National Passive Solar Conference

Published October 1980

Prepared for:

U.S. Department of Energy
Assistant Secretary for Conservation and
Solar Energy
Office of Solar Applications for
Buildings
Washington, D.C. 20585

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Published October 1980

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PASSIVE SOLAR PROGRESS

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Preface

This book has been prepared to introduce some of the concepts and practices that have come to be known as "passive solar heating and cooling" and to present a current picture of the field. Much of the material found in this book is derived from papers presented at the 3rd National Passive Solar Conference held in San Jose, California in January 1979 and sponsored by the U.S. Department of Energy. Extracts and data from these papers have been integrated in the text with explanatory and descriptive material. In this way, we have attempted to present technical information in an introductory context.

An extensive list of references will lead the curious to further exploration of passive solar concepts. The primary reference for the book is *Proceedings of the 3rd National Passive Solar Conference*, edited by Harry Miller, David Richards, and Michael Riordan and published by the American Section of the International Solar Energy Society (AS/ISES). Copies can be obtained through AS/ISES, P.O. Box 1416, Killeen, Texas 76541.

Interest in the passive solar approach to the design of buildings and energy systems is burgeoning as its benefits and advantages become apparent. Practical experience plus analysis are bringing an understanding of how natural heating and cooling take place, and a supportive industry is emerging to supply the needed materials and products. This book provides a view of activities in passive solar applications today.

Introduction

A passive solar building is one that is designed to use its architectural and structural elements (floors, walls, windows, and roofs) to collect, store, and distribute some of the heat required by the building, and to discharge unwanted heat to the cooler parts of the environment. Many people assume that passive solar design is new. It is not.

Every time the drapes are opened to let in the sun on a winter day, a direct-gain system is being put into operation. And whenever windows are opened to catch a cool breeze, natural convective cooling is taking place. Thus it seems that some of our energy needs are already being provided by passive solar techniques.

How much passive solar energy is already being used? It is not possible to tell since energy use is recorded (by your utility meter) only when energy is sold as a commodity. Even if a large part of the public turns to passive solar design, it may not show up on any official records and thus may not be obvious to anyone except the building's occupants, whose high level of thermal comfort is costing them very little in fuel bills. Passive solar is not a fuel, it is a well-designed building.

There are many ways that buildings can be designed to make maximum use of their immediate environmental resources (their "on-site energies") and minimum use of conventional fuels. However, certain functional elements are found in most solar space-conditioning systems: *collection*, whereby solar radiation is trapped and converted to useful heat energy; *storage* of the collected heat in thermal mass—materials that are particularly well-suited to the task (most common are water, rocks, or concrete); a living *space* to be heated or cooled; and *distribution* controls (heat regulation devices), such as dampers and movable insulation, which direct the flow of heat among the other elements. Systems are generally classified according to the means by which energy is moved among

the elements. In a passive system, energy can flow by purely natural means from collection to storage *and* from storage to the living space. A hybrid system employs mechanical assistance (pump or fan) to move energy either from collection to storage *or* from storage to space, while the other heat transfer is by natural means. An active system uses mechanical means to transfer energy both from collection to storage *and* from storage to space. In this book, we are concerned primarily with passive systems, but several hybrid systems are also discussed. Hybrid systems are fairly common, as the small cost of electricity to operate a fan is, in some cases, substantially lower than the cost of installing the larger solar system that would be required if heat were to be transferred by purely natural means.

Fig. 1-1 (a) Direct gain through south windows and clerestories. (b) Direct cooling by natural ventilation or radiation to the night sky.

Types of passive systems are also distinguished by considering where the heat transfers take place, in other words, where the elements are located in relation to each other.

Direct gain systems contain all the system elements within the living space (Fig. 1-1). Direct heating occurs when sunlight is admitted directly into the interior space of a building. The solar energy is converted into heat as it is absorbed and released (by radiation and convection) by surfaces of people and objects within the space. Excess heat is stored by building components (floors and walls) that have good heat storage capacity; these components must be directly exposed to the incoming sunlight for the system to work well.

Direct gain systems, therefore, involve living directly with the collection, storage, and distribution of solar energy.

Indirect gain systems utilize solar collection at the building's weather skin. Indirect heating is accomplished when sunlight is absorbed and released (as before, via radiation and convection) by a surface at the weather skin, usually a glazed concrete wall or containers of water. Some of the absorbed heat is stored for later use. With an indirect gain system, one lives directly only with storage and distribution elements. (Fig. 1-2)

Isolated gain systems are those in which collection occurs at a location that is either thermally isolated (by insulation) or physically distant from the living space. The amount of heat that

enters the space can be closely regulated. One lives only with the control elements. (Fig. 1-3)

In general, direct gain systems offer greater efficiency but place more constraints on space planning than isolated gain systems. A direct gain configuration offers quicker response to solar gain, i.e. the space will warm up more quickly on cold winter mornings. An isolated gain system will allow collection and storage of heat at higher temperatures (at any time of day) than a direct gain building. Indirect gain systems lie somewhere between the other two in both efficiency and freedom of interior design.

These passive system types can be, and often are, combined for greater comfort

Fig. 1-2 (a) Indirect heating by means of a thermal mass wall or a roof pond. (b) Indirect cooling with a thermal mass wall or a roof pond, or by evaporation.

and efficiency. For example, a window for direct gain can be installed in a Trombe (indirect heating) wall; the window heats the space during the day and the Trombe wall takes over in the evening.

As we will see, cooling also can be accomplished by natural means, often using the same components as the heating system but operating in a reverse mode. Cooling is often the result of a combination of techniques that include simply preventing the sun from entering the living space, designing for good cross-ventilation, using the cool night sky as a heat sink, using the cooling effect of evaporating water, and others.

Use of the sun's radiant energy for heating and the night environment for cooling is

very ancient, spanning all human history. In fact, the intuitive wisdom that leads to passive solar design is evidenced by many forms of life, including ants, bees, and bears, as each attempts to build its own kind of protective shelter (Refs. 1-1, 1-2). Thus much of our current work in passive building design has a basis in nature itself.

In the polar bear's world, passive solar construction consists mainly of digging the den into a south-facing snowbank that will warm up quickly in the spring and give the new cubs a warm place to play and grow. In our human experience, passive solar design is the purposeful collection, storage, distribution, and rejection of environmental heat in our living space. It involves a lot of concern with thermal energy: someone is always predicting it,

measuring it, rejecting it, designing for its flow patterns, or just generally worrying about it so that the building's occupants can simply enjoy a comfortable thermal environment.

As time goes by, the potential of passive solar applications for being both reliable and cost-effective becomes more apparent. A lot is happening (Ref. 1-3):

- ◆ One can now find effective passive applications throughout the country, each different because of the local and regional sensitivity of passive design.
- ◆ For the first time, there is an identifiable group of people whose lives and livelihood are being strongly influenced by passive solar concerns.
- ◆ Materials and components are rapidly being developed. In particular, the rediscovery of windows as heat sources, as well as recognition of their potential for heat loss, have led to a large array of material and component choices.
- ◆ For the first time, there is a substantial data base derived from monitored passive buildings and test structures, which is providing engineers, designers, and occupants with valuable performance information. These data have led to one of the most significant advances of the past year—the ability to make computer models of some passive designs and to predict their performance.

Although indigenous and traditional architecture remains an important source of example and inspiration to designers, passive buildings are no longer inevitably imitative. Indeed, new regional styles are beginning to emerge, based on a broader perception of heat flow and thermal comfort and on new materials and products.

Fig. 1-3 (a) Isolated heating by means of a sunspace or a thermosiphoning air heater. (b) Isolated cooling by means of a cool tube or a cool pond.

Design Considerations

A passive solar building is carefully planned to function in harmony with local sun and weather patterns. The designer orients the building and its openings, arranges interior space, and selects construction materials to enable the structure to take full advantage of its environment—soaking up sun for nighttime heating, fending off winter winds, and cooling itself in the summer. Spaces and components are arranged so that heat transfer is primarily by natural convection and radiation; thus air flows are gentle and interior surfaces are near body temperature. The result is comfort as well as energy efficiency.

CLIMATOLOGY

The most important climatic factor in the design of a passive solar-conditioned building is the *amount of solar energy* the building site receives; the second is the character of the *regional and local weather*, which makes specific demands regarding the amount of heating and cooling that will be needed to keep the building comfortable. Detailed information on both of these factors, plus data on the construction techniques and materials of the building itself, are needed to obtain a building that responds appropriately and sensitively to its solar and weather environment.

Solar Energy Received

The intensity of solar energy reaching the ground (also called *insolation* or *global radiation*) has been measured at a number of locations; it usually is recorded as "total radiation on a horizontal surface," in a variety of different units. The amount received per square foot per day depends on the latitude of the site and the time of year, as well as on the amount of water vapor, dust, and absorbing molecules that are present in the air (Fig. 2-1). It should be noted that although the sun is above the horizon for the most hours at the summer solstice (June 21), the highest summer temperatures are reached some weeks later as we feel the effect of the heat that is gradually being stored in the earth and its atmosphere. Similarly, the coldest temperatures

Fig. 2-1 Incoming solar radiation is diminished by the earth's atmosphere.

of the year usually occur some weeks after the shortest day of the year (which is December 21) as the earth continues to lose more heat than it gains. As a result, our maximum heating and cooling needs tend to lag behind the seasons—making April cooler than August, for example, although both are two months from the solstice.

When a solar installation is being planned, it is desirable to have as good an estimate as possible of the insolation at the specific site and how it varies throughout the day and year. The best way to determine this is to take measurements for several years; next best is to use someone else's collection of solar data for a nearby (and similar!) location. One useful data source is the *Climatic Atlas of the United States* (Ref. 2-1). This volume gives the monthly averages of the mean solar radiation striking a horizontal surface on a clear day for many U.S. cities. Hourly values of solar and weather data are provided by the SOLMET computer-readable magnetic tapes, also obtainable from the National Climatic Center. Hourly solar radiation data can be found in *NBS Building Science Series 96* (Ref. 2-1). Because existing solar data are incomplete, and sometimes inaccurate, and because of the increased interest in solar energy applications, there are now many new government, university, and utility company programs to improve both the quantity and the quality of all types of solar-related measurements. Solar designers should make some effort to learn what sun-related data may be (newly) available in a particular region. Information may sometimes be obtained from local governments, colleges, airports, and weather stations. Work also is being done on devising mathematical models based on standard weather data which can be used to estimate the solar radiation at places where no solar data exist.

The total solar radiation at the ground consists of three components: direct beam, diffuse (scattered), and reflected (Fig. 2-2); each should be measured or estimated for accurate solar design. For example, the ratio of direct to diffuse is needed to find the radiation on vertical or sloping surfaces (i.e. walls and roofs) from the measured values of total radiation on a horizontal surface. In the absence of site-specific measurements, this ratio can be estimated from mathematical formulas (developed by Liu and Jordan and modified by others) and used to estimate the solar radiation falling on surfaces of any orientation. (Refs. 2-2 and 2-3).

Estimating Total Solar Radiation on a Shaded Surface

Typical passive solar designs usually include roof overhangs to shade south-facing walls and windows in the summer in order to reduce unwanted heat gain from direct-beam radiation (Fig. 2-3). However, the overhang also reduces the diffuse radiation in both summer and winter. Recently, a simple method has been developed at the University of Wisconsin (Ref. 2-4) for using the geometry of the shading situation plus the usual solar data to find the monthly average daily radiation on a shaded vertical surface. This average daily radiation is used as input to design methods for passive solar-heated buildings, such as the solar load ratio method (Ref. 2-5), which is described in Chapter 4.

Measurement of Infrared Sky Radiance

The infrared radiation that is continually being exchanged between the earth and molecules in the atmosphere is of particular importance to the design of cooling schemes for passive solar buildings. Very effective cooling can be accomplished by encouraging building heat to flow toward the cool night sky or toward cool spots in the daytime sky; however, the infrared radiation measurements of the sky that are needed to calculate the rate of heat transfer have never been routinely gathered. Such work is now under way at Lawrence Berkeley Laboratory in California, which has designed and constructed spectrometers for obtaining the infrared data (Ref. 2-6). Three of these instruments are currently in the field. Samples of the data have been compared with computer calculations for similar meteorological conditions. There is general agreement which indicates that both the computer and the instruments produce reliable information. In future work, the researchers will make a more detailed comparison between theory and experiment.

Regional and Local Weather

A well-designed passive solar building is adapted to its climate so that it tends to maintain a comfortable interior environment no matter what the weather does. Both the regional weather pattern and the variations specific to a particular site are important.

Regional climatic factors that affect the heating and cooling of a building are the ambient air temperature, the timing and heaviness of clouds and precipitation, the

Fig. 2-2 Components of solar radiation.

Fig. 2-3 Roof overhang blocks summer sun and admits winter sun.

Fig. 2-4 Solar window is scribed by the seasonal variations in the sun's path. Objects intruding into this window will shade the house during the useful solar collection hours of 9 AM to 3PM.

Fig. 2-5 Effects of planting on air flow. (a) Vegetation properly placed can deflect a flow of cold air. (b) Multilayer vegetation provides an even better barrier. (c) Clusters of trees decrease wind speed for 5 as their height windward and 25 times their height leeward.

wind speed and direction, and the humidity. The building should use these factors selectively when they contribute to building comfort, and screen them out when they do not. Data on regional climates can be obtained from weather stations and from the National Climatic Center.

A convenient measure of the demand for building heat made by the climate is the number of heating degree-days for a particular location. This number indicates how much of the time the outdoor temperature is below 65° F, and how far below. (By definition, one heating degree-day is equal to one day with the temperature one degree colder than 65° F.) The daily values are summed to obtain a monthly or yearly total for the number of heating degree-days, and the higher the number the more heat will be required by the building. Records of monthly heating degree-days for many locations are available from Ref. 2-1. Cooling degree-days are also given; this number indicates the extent to which summer heat will be a problem. (By definition, one cooling degree-day is equal to one day with the outdoor temperature one degree warmer than 65°F.)

After becoming familiar with the regional climate patterns, the passive solar designer should look at the weather peculiar to the site and its surroundings (the wind and sun microclimate). The microclimate will share many of the characteristics of the regional weather, but it also will have some peculiarities of its own due to site topography and landscaping, and to the proximity of surrounding buildings, hills, water, and open areas.

Information on the microclimate of the site—local winds, clouds, fogs, and temperature variations—can be found by talking to residents of the area, and by spending time at the site to make personal observations. Some of the questions to consider are: Will nearby hills, trees, and structures permit sunshine to reach the solar building (Fig. 2-4)? Will the building be in a depression where cold air collects? Will it be sheltered from winter winds and can summer breezes reach it (Fig. 2-5)? Is the night sky unobstructed, for radiative cooling? Are there large areas of water or asphalt nearby which will modify summer and winter temperatures? This type of detailed information about a site enables one to tailor a passive building to take best advantage of its environment. For example, if microclimate observations reveal that winter mornings at the site are usually misty, then the building might be warmer if oriented slightly southwest to receive more

Fig. 2-6 Heat transfer processes. (a) Heat is transferred from hot cup to hand by conduction, (b) from hot tea to air by convection, (c) from fire to person by radiation.

afternoon sun; or if too much heat in the late afternoon is a problem, or if one wants a building to warm up quickly in the morning, then the building should be oriented slightly southeast.

Descriptions of Climate Types

Some of the new climatological work that is being done is the preparation of practical descriptions of the many climate types found in California; these descriptions are being developed by the Climate Resource: Data Development and Mapping Project sponsored by the California Energy Commission (Ref. 2-7). A majority of the climate and topographic conditions found in the United States have been identified in California, according to this survey; thus its methods should find application in many other places. From various sources the project has compiled a master data table incorporating the following climate elements: uniform insolation, temperatures, humidities, degree-days, winds, and topography. Extreme weather events, such as prolonged hot or cold spells, were also taken into account; knowing how and when these events happen makes it possible to design to minimize the discomfort they cause. The first phase of the project, now completed, examined and adjusted for consistency and accuracy all the solar data records in California; results have been presented in the *California Solar Data Manual*, available from the California Energy Commission. In this model document, California's best solar data source, the solar resource is described by zones of uniform insolation. The master data table has been used to generate a "Building Climate Zone Map," with text describing each zone in detail, which will soon appear in a builder's design manual.

Tennessee Valley Design Guidelines

The Tennessee Valley Authority (TVA) is developing a series of manuals, *Design Guidelines*, to provide designers in the Tennessee Valley with data and methodologies for energy conservation and passive solar design (Ref. 2-8). Hopefully, promotion of these concepts will result in the construction of more energy-conserving structures. A major factor in TVA's involvement in this undertaking is the fact that self-sufficient buildings actually create a net savings for utilities when designed carefully for peak electric load management. The *Design Guidelines* series will be published in looseleaf format and distributed by TVA's Public Information Office. The first two volumes are: Volume 1: Regional Climatic and Solar Data Bases with Simplified Calculation Method, and Volume 2: Principles and Methods of Energy Conservation and Passive Solar Design.

HEAT FLOW

In passive solar houses, the practical matter of heating and cooling consists of using building design (occasionally assisted by fans or occupants) to control the flow of heat as it tries to move from hot places to colder ones. In winter and at night when the outdoor temperature is low, heat flows out of a building and must be replaced; when the weather is hot, heat flows in and must be removed. By controlling heat flow, one can prevent having extreme temperatures within a building. For example, adding insulation slows down the rate of heat flow, helping to keep heat inside in the winter and outside in the summer. Massive building materials soak up excess heat in the

Fig. 2-7 Convective air flow through the Karen Terry house.

daytime and release it later when the air temperature drops. Strategically placed vents encourage air to flow at night from a cool-warm building to the cooler outdoor environment.

Heat Transfer Processes

Since heat flow in a passive building relies primarily on the natural heat-transfer processes of radiation, conduction, and convection, the solar designer (and even the homeowner) should have a clear understanding of these processes (Fig. 2-6).

Part of the heat flowing outward from hot objects to colder ones is *radiation*. Radiant heat travels like light does, as a wave through space. This is how the earth receives heat from the sun and how one's hands are warmed by a fire; it is how one becomes chilled when sitting near a cold wall, toward which body heat automatically flows. In passive solar buildings, radiant light and heat from the sun are collected through south-facing glazings and used for heating. Cooling can be accomplished by heat radiating from the warm building to the cold night sky.

Heat flows by *conduction* directly through a substance from a hotter place to a cooler one, as one can feel by touching the back of a sunheated wall. Heat is conducted at different rates through different materials

—quickly through metal roofing (a conductor) and slowly through styrofoam (an insulator). Thus selection of materials is one way to control conductive heat flow in buildings. The rate of conductive heat flow depends on the thermal conductivity and thickness of the material, and the area through which the heat flows, and the temperature difference between the front and back surfaces of the material. For example, solar heat absorbed by a masonry wall placed directly inside a sunlit window will flow slowly by conduction through the entire wall, reaching the living area some hours later (see Trombe Walls in Chapter 3); by judicious choice of wall material and thickness, the delivery of the daytime heat can be delayed until late evening if desired.

When heat flows by means of currents of warm air (or water), it is called *convection*. Air touching sun-warmed window glass becomes more buoyant (less dense) than the cold air around it and rises; colder (and heavier) air moves down to replace it, setting up natural convective circulation which tends to mix the air. Convection is the process by which heat is carried away from a building by winter winds, or by summer breezes; it can be inhibited or encouraged, as desired, through landscaping and house design. Passive solar buildings often rely on natural air flow for cooling, although sometimes fans are used to increase the rate of flow; this requires

careful planning. Through choice of the number and types of openings (windows, vents, doors, and chimneys) and their size and location, one can pull in outside breezes and can increase the convective flow and exhaust of warm inside air.

Air Currents in Passive Buildings

Air currents have been observed and examined in two classic (and highly successful) passive solar homes by an unusual method: the release of incense smoke (Ref. 2-9). The flows were fascinating to watch, and somewhat surprising in their massiveness and their individuality. The indoor climates, although well protected, were highly energetic and distinctive. In one house, a natural pumping process pulled cold air uphill and warm air down, resulting in a temperature stratification that was much less than expected in a high room with lots of windows (Fig. 2-7). In the second house, the currents were involved in a figure-eight convection loop, beginning with heated air rising in uniform sheets along a massive sunlit wall and then making a smooth lateral slide through the tops of open doorways to replace the cooler air in other rooms, which formed pools one to three feet deep. The cooler air drained into a greenhouse where it supplied the downdraft for the windows before returning to rise along the thermal wall (Fig. 2-8).

Fig. 2-8 Convective air flow through the First Village Unit 1 house.

Heat Distribution by Natural Convection

Although computer-simulation methods can (in some cases) predict the effect of direct solar gain on temperatures throughout a building, they cannot assess the effect of natural convection on heat distribution. However, properly scaled architectural models can help in this analysis, according to work done at the Massachusetts Institute of Technology (Ref. 2-10). These physical models enable one to measure the effect of design changes on convective air currents. The modeling procedure comprises four steps: analyzing the thermal properties and performance of the proposed design; choosing a scale and departure factor for the model and constructing the model; balancing the model's heat losses through its various skin components; and measuring the convection in the model. This use of architectural models for simulating convection currents in direct-gain passive solar houses was validated experimentally in test cells by the MIT research group.

Natural Convection in a Trombe Wall

In a passive solar house with a Trombe thermal-storage wall, heat will flow to the living space by radiation and natural convection from the inside surface of the wall, and by the flow of warm air up the duct

between the wall and the glazing and through the vents into the room. (See Heating with Indirect Solar Gain in Chapter 3.) Experiments have shown that the contribution of heat from the duct flow to the building is much less than that provided by conduction through the concrete wall, unless the system is designed to maximize convective heating with forced-air circulation through the duct (Ref. 2-11).

Heat Flow Through Glass

When solar radiation falls on a transparent material such as glass (Ref. 2-12), three processes occur simultaneously (Fig. 2-9):

1. Some of the radiant energy is *transmitted* through the glass virtually unchanged.
2. Some of the energy is *reflected* from the front and rear surfaces of the glass.
3. Some of the energy is *absorbed* within the glazing itself. This absorbed energy raises glass temperature until the resulting heat can be dissipated to the outdoor and indoor air.

The part of the solar radiation that is transmitted flows into the living space where it is absorbed by interior surfaces and objects. About two-thirds of the heat flow at the inner surface of a sunlit window is due to radiation between the sun and the room, while the remaining one-third is due to natural convection between the warmed glass

and the indoor air. At the outer surface of a window, forced convection due to wind is an important mode of heat transfer although radiation also plays a role by carrying heat away in winter and moving heat to the glass in summer. The ability of glass to carry out these processes is determined by its optical properties — its transmittance, reflectance, and absorptance — which in turn are controlled by the thickness and composition of the glass and by the angle at which solar radiation strikes the collecting surface.

Building Heat Losses and Gains

Knowledge of the rates of heat loss and gain for a building are needed to determine heating and cooling requirements for various passive solar designs and to make reliable calculations concerning, for example, the area of sunlit glass needed for heat gain, or the amount of thermal mass needed for heat storage, or the minimum size backup system needed to keep the building comfortable throughout the year (Fig. 2-10).

In passive buildings, heat is lost in the following ways:

- ◆ Heat transfer through the building skin (its walls, windows, roofs, and floors) to the cold outdoor air. The transfer takes place by a multistep process involving conduction through the various layers of the building skin, plus convection and

Fig. 2-9 Transmission, absorption, and reflection of solar radiation by glass.

Fig. 2-10 Building heat losses and gains by radiation, conduction, and convection.

* 1/4 inch clear plate glass

radiation to and from the inner and outer surfaces of the skin and the air film lying next to them (Fig. 2-11).

- ◆ Infiltration of cold outdoor air into the building through cracks and crevices in the skin, and through open doors and windows.
- ◆ Heat flow into heat-storage components and systems.

Heat gain in passive buildings results from:

- ◆ Heat transfer through the building skin by conduction, radiation, and convection.
- ◆ Infiltration of warm outdoor air into the building.
- ◆ Solar radiation through windows and other transparent (or translucent) surfaces.
- ◆ Heat generation by occupants, lights, and appliances (Fig. 2-12).
- ◆ Heat flow from heat-storage components into the living space. There is a time lag between this part of the heat gain and its effect on indoor temperature which depends on the heat-storage capacity of the building components.

Building heat loss and gain are calculated using long-term weather data for the site and detailed information about the building structure, materials, and use-patterns. Discussions on how to make these calcula-

tions, plus convenient tabulated data, are available in many architectural, building, and solar books, including Ref. 2-13. For *accurate* predictions of building performance (i.e. how much auxiliary energy will be required to maintain a given temperature, or what will the temperature be if no auxiliary energy is used), the heat losses and gains should be calculated on an hourly basis if sufficient data are available. This is best done by a computer, and relevant computer programs are beginning to be available to help in the design of some types of passive buildings; much research activity is going on in this area.

Heat Flow and Building Response

Passive solar design is concerned with determining the rates at which heat flows in and out of a building and how these heat exchanges affect the interior temperature and the amount of backup fuel required to maintain comfort. The underlying physical principle is the *conservation of energy*: that is, over some interval of time, the heat that enters a building or is generated inside must either leave the building or be stored inside (in the air, the structure, or the furnishings). If there is a net heat gain, the

amount of stored heat will increase and the air temperature will tend to rise; if there is a net heat loss, the stored heat will decrease and the air temperature will tend to fall.

In a direct-gain solar building, for example, the average indoor air temperature during the day is determined by the amount of heat collected by the south glazing, by the insulating properties of the building, and by the outdoor weather. The daily fluctuations above and below this average indoor temperature are determined by the amount of heat the building can store in its thermal mass. The heat-storing ability of the thermal-mass components is related to their size, distribution, material, and (in some cases) their surface color. Generally, more indoor mass means less indoor temperature swing.

Existing passive solar buildings have a fairly wide range of response to their climate: some can maintain a rather even temperature and some cannot. But often, the thermal environment of a passive home is perceived by the occupants to be extremely comfortable, and the room temperature does not need to be so closely controlled as in a conventional house (Ref. 2-14).

Fig. 2-11 Heat transfer through a building wall by radiation, conduction, and convection.

Fig. 2-12 Internal heat gains.

HUMAN THERMAL COMFORT

The primary object of all buildings is to provide protection from the environment for its occupants. Generally, this includes having a thermally comfortable space in which to live and work. Human thermal comfort is determined by more than just the air temperature; also important are air movement, humidity, heat radiation, clothing, and activity levels (Refs. 2-14, 2-15).

The Body's Heat Loss

Human beings are constantly producing body heat and must continually transfer it to their environment in order to maintain a

constant body temperature (Fig. 2-13). Circulating blood carries internal heat to the skin where it is transferred to the air by convection, to surrounding surfaces by radiation, and to the environment by evaporation of perspiration and respired air. The flow of blood is increased in warm weather so the skin can reject heat more rapidly, and decreased in cold weather to conserve body heat. The body constantly strives to achieve a balance between its rate of heat loss to the environment and its rate of internal heat production. Thermal comfort is recognized when the body can maintain this heat balance without working at it very much.

Clothing slows the rate of heat transfer from the body. The unit of the insulating value of clothing is the "clo" (1 clo = a heavy busi-

ness suit; 0.3 to 0.4 clo = lightweight summer clothing). The amount of clothing the person is willing to wear (or not wear) can significantly broaden the acceptable temperature range in a building (Fig. 2-14).

Humidity usually does not have a major effect on thermal comfort unless it is extreme. If the humidity is high enough so that the skin remains damp because evaporation is slow, or is low enough to make the mouth and sinuses feel dry, then complaints may be heard (Fig. 2-15). Otherwise our sensitivity to humidity is low: a 30% rise in humidity will allow a drop of about 2°F in operative temperature to maintain the same level of comfort. (*Operative temperature* is the average of the ambient air temperature and the mean radiant temperature; *mean radiant temperature*, *MRT*, is

Fig. 2-13 Heat loss by the body.

Fig. 2-14 Insulative value of clothing.

Fig. 2-15 Excessive humidity impedes evaporative heat loss.

the mean temperature of the surrounding surfaces in a living space.)

Air movement can facilitate evaporative heat loss from the skin, thereby enhancing thermal comfort in warm weather, a principle utilized in many space-cooling systems. Air velocities in passive buildings may be relatively low, as they often are driven by natural convection.

Activity levels also significantly affect a person's thermal comfort. An operative temperature decrease of 10°F can be accommodated by doubling one's rate of metabolic activity, thereby achieving an equivalent sensation of comfort (Fig. 2-16).

Radiant Heat and the Thermal Environment

When the average temperature of the surfaces in a room (their mean radiant temperature) is different from the indoor air temperature, radiant heat exchange between these surfaces and the human body may be the most important factor in determining comfort (Fig. 2-17), a fact which often is either overlooked or not understood (Ref. 2-15). If the mean radiant temperature is considerably lower than body temperature, the body heat being lost to cold room surfaces may make a person feel cold even if the inside air temperature is relatively high. And whenever the mean radiant temperature exceeds the body temperature, the effect of heat being added to the body will be quite (uncom-

fortably) evident. A change in the mean radiant temperature will have about 40% more effect on comfort than an equivalent change in air temperature. In other words, it only takes a 1°F increase in mean radiant temperature to compensate for a 1.4° decrease in air temperature.

In many conventional buildings (those without large expanses of uninsulated glass), ambient air temperatures remain relatively constant, and the ambient air temperature and mean radiant temperature are usually about the same. That is, conventional buildings have *uniform thermal environments*. Passive solar buildings usually have *nonuniform thermal environments*; the indoor air temperature cycles (swings) during the day, and the air temperature and the mean radiant temper-

Fig. 2-16 Body heat production (Btu/hr.) for various activity levels.

Fig. 2-17 Radiant heat and comfort. The body loses less heat to warm surfaces (a) than to cold ones (b), and therefore will be more comfortable when surrounded by warm surfaces, even when the air temperature is lower.

ature are not necessarily the same. In a passive solar building, the large thermal storage mass, when charged with solar heat, produces a mean radiant temperature that is higher than the air temperature. When this radiant temperature is about the same as body temperature, the body finds it easy to maintain its heat balance and feels comfortable. Large glazing areas may result in higher mean radiant temperatures whenever the sun is shining on them. However, the mean radiant temperature is likely to be lower than air temperature when stored heat is exhausted, or when windows are not covered with movable insulation at night; then the body may lose heat rapidly and feel cold even when the air temperature is reasonably high.

Contrary to popular belief (and some conventional heating system designs), a constant thermal environment is not necessarily the most pleasant. In preliminary experiments at the Pierce Foundation Laboratories in New Haven, Connecticut, people do not notice operative temperature swings of about 1°F/hr and are actually pleased with temperature swings of about 7°F every 9 min. Thus the temperature swings that are typically found in passive solar buildings may be more than merely acceptable.

Researchers at the University of Washington (Ref. 2-16) have developed a computer routine called COMFORT which can be used to predict the degree of acceptability

of the thermal conditions that will occur in a given passive solar building. COMFORT is used in conjunction with the computer program UWENSOL which simulates the thermal performance of passive solar buildings.

3

Passive and Hybrid Systems and Applications

The passive solar components of a building are designed to serve various functions in the collection, storage, and dissipation of heat and the control of its flow. Among such components are glazed surfaces, Trombe walls, water walls, rockbeds, solar chimneys, and pools of water. When integrated into an operating passive solar system, a component often will have more than one function, and may even be a structural element of the building. Invention, development, and commercialization are underway on all types of components and configurations; as a result, passive solar products and possibilities are continually increasing, as are the number of successful applications of passive design, some of which are described in the following sections.

HEATING WITH DIRECT SOLAR GAIN

In the simplest type of passive system, a building is heated by solar energy shining directly through south-facing glazing into the rooms where it is absorbed and stored by the floors, walls, or ceilings; that is, solar heat is collected, stored, and distributed directly by the living space. The design of a direct-gain building must provide for sufficient south glazing to allow adequate solar gain to meet the building's heating requirements, and must locate the thermal storage mass so that the incoming sunlight can reach it.

Cottonwood Residence, Arizona

The Cottonwood residence (Ref. 3-1) is an example of a direct-gain house designed to appeal to the average homeowner in Arizona (Fig. 3-1). The passive system is expected to provide 80 to 90% of the heating required in the 3000°F degree-day climate and to reduce the cooling costs by 70 to 90%. The 1352-ft² house uses 160 ft² of south glazing which exposes to direct sunlight a rock-veneered thermal storage wall built of 8-in. concrete blocks, and a tile-covered 4¼-in. slab floor (6574 Btu/°F storage capacity in all). All windows are double-glazed; walls have a thermal resistance of R-25, ceilings R-36; and the north and west walls are earth-bermed. The south windows are protected by folding movable insulation panels consisting of

Fig. 3-1 The Cottonwood residence, Arizona: south and north facades.

1-in. thick polyurethane sandwiched between ash door skins.

South-Facing Glazing

The south-facing glazed areas of a building are the most important components for capturing solar energy for direct solar heating. These glazed areas usually are ordinary windows but may be clerestory windows or skylights; they readily transmit sunlight which, once absorbed by interior surfaces, is converted into heat. The heat accumulates inside the building because the glazing prevents its loss through convection, and in some cases because the glazing material is opaque to thermal radiation. This is commonly known as the "greenhouse effect." One familiar example of heat trapped by glass is shown in Fig. 3-2.

The solar heat gain through window glass receiving direct sun can be more than 40 times the gain through the same area of wall or roof. However, the amount of gain depends strongly on glazing orientation. South-facing surfaces receive by far the most winter sun, which is relatively low in the southern sky; so passive buildings are designed with enough south-facing windows to take advantage of this for winter heating. In the summer, windows facing south and west (and sometimes, east) will often collect too much heat and should have some kind of shading to keep out unwanted sun, which at mid-year shines more strongly from the top, east, and west than from the south. Many possibilities exist for shading, including overhangs, balconies, awnings, indentations, louvers, or landscaping on the outside, as well as special coated glass

or shades, drapes, or shutters on the inside.

Sunlight can be admitted into a room through clerestory windows and skylights to avoid direct sun and glare, or if there is a need for privacy, or to get daylight farther into the interior space (Fig. 3-3). Clerestory windows should be shaded and insulated like other south-facing glass. Skylights, which face upward, have especially severe problems with both heat gain in the daytime and heat loss at night. They should be carefully designed and constructed and provided with movable insulation.

Although a number of materials are being used for glazings, including glass and various plastics, these materials vary considerably in their ability to transmit sunlight and trap heat, as well as in their durability. Glass is still one of the best choices (see Ref. 3-2). It transmits a high percentage of the incident sunlight—85 to 91%, depending on the angle of incidence and on its thickness and iron content (if high in iron, which absorbs light, glass looks green on the edge). Glass also is opaque to thermal radiation. It does not deteriorate at high temperatures and is resistant to scratches and weather; although if winds are high, extra-thick sheets may be required for large areas. Tempered glass, used overhead and in patio doors for safety, is about four times as strong as ordinary glass and considerably more expensive. The disadvantages of glass are that it must be handled carefully and in small pieces and that it is comparatively heavy.

Plastics are less expensive than glass and come in large lightweight sheets. Their solar transmittance is usually high if the sheets are thin. However, all thin plastics are partially transparent to thermal radiation and so lose heat readily. They also soften and weaken at high temperatures and degrade quickly in sunlight unless treated with ultraviolet inhibitors. Thick plastics absorb almost all the thermal radiation, and are often less sensitive to ultraviolet degradation than thin plastics.

The solar energy that actually passes through a glazed area depends on the amount of sunshine striking it and on the transmittance of the glazing. Thermal losses depend on the glazing material, the windspeed, surrounding surface temperatures, and the indoor/outdoor temperature difference. Methods for making estimates of the solar heat gains and the heat losses through all kinds of

glazings in virtually any location can be found in the *ASHRAE Handbook of Fundamentals* (Ref. 2-13).

Preventing Heat Loss

In winter, a house with ill-fitting, non-weatherstripped, poorly-located single-glazed windows could easily be losing a third of its carefully acquired heat through these windows. Glass is a good heat conductor; thus in all but the mildest climates, windows (especially those that do not face south) should be insulated by adding extra panes of glass with air spaces between. This is accomplished either by building or buying multiple-glazed units or by using storm windows (or both) as shown in Fig. 3-4. Commercial insulated-glass units consist of two sheets of glass hermetically sealed around the edges to keep out dust and prevent water condensation between the sheets. Generally, double glazing cuts winter heat loss through the glass by about half compared with single glazing and triple glazing cuts it by two-thirds; however, extra glazings also decrease heat gain.

Triple glazing—three panes of glass with two air spaces—is often cost-effective in the U.S. snow belt. It is usually accomplished by adding a storm window to a double-glazed unit. (Only a few manufacturers are making a hermetically sealed triple-glazed unit in a single frame.) Storm windows today are vastly improved over those of the past with respect to both convenience and insulation. They may be either hinged or clipped in place, or they may slide on a track; they may be either inside or outside existing windows.

The type of window frame used also is a factor in heat loss. Wood is a good insulator, but metal is not. The better quality metal-framed windows and patio doors are now being made to reduce conductive heat loss by "thermal break" construction, which means separating the outside metal framing from the inside metal by an insulating gasket.

Movable Insulation

Windows, the most important building element for admitting solar light and heat, are also the factor most responsible for excessive heat loss in a well-insulated house. Whenever heat loss is a problem, some compromise must be found with respect to a window's ability to both gain and lose large amounts of heat. One solution to the problem is to install *movable*

insulation, which covers the windows whenever control of heat flow is needed but exposes them whenever more heat and light are desired. Types of movable insulation are as varied as window styles themselves; they can be designed into a new structure or retrofitted to existing buildings, often by the homeowner.

Basically, movable insulation is a panel or curtain made of some kind of insulating material such as fiberglass, polystyrene, or several layers of cloth, anything that can create a dead air space. When in place, either inside or outside the building, the panel or curtain fits flush against the window and tightly against the frame, leaving no cracks around its edges through which heat can be lost. Panels may be fastened to swing open like shutters, fold aside accordion-style, slide past

windows on tracks, or be completely removed when direct sun is desired. Curtains and shades may slide horizontally or roll up and down. Louvers may be horizontal or vertical, with slats fixed or variable in angle (Fig. 3-5).

Most insulating devices are designed to be operated manually. Though they tend to be fairly simple and cost nothing to operate, they do require the homeowner's time and presence to see that they are placed appropriately during the day. One of the simplest and least expensive methods is to add a layer of aluminized Mylar to existing unlined drapes; the Mylar is sewn to the drapes so that it lies flat when the drapes are closed. A more effective window insulation is the window quilt, a multilayered curtain which rolls up into a housing at the top of the window (after

Opposite page

Fig. 3-2 Solar radiation trapped by glass.

Fig. 3-3 Direct gain through a clerestory window.

This page

Fig. 3-4 Multiple-glazed window units.

Fig. 3-5 Some of the many types of movable insulation.

passing behind a roller that keeps the quilt at a specified distance from the window). A wood frame at the side and bottom edges of the window helps seal against air leaks. A commercial Window Quilt (Fig. 3-6) is manufactured by Appropriate Technology Corporation (Ref. 3-3). This is an ultrasonically welded sandwich of five layers: two layers of polyester batting separated by a vapor barrier of metallized polyester film and enclosed in a protective and decorative covering of polyester fabric.

Also on the market is the Self-Inflating Curtain (Fig. 3-7), an automatic but simple device developed by Thermal Technology Corporation, in which layers of thin, reflective film inflate by natural convective

updrafts whenever the curtain is warmed by the sun or the thermal mass (Ref. 3-4).

One extraordinary insulating device, the Beadwall (Fig. 3-8) invented by Zomeworks, is an integral part of the window itself (which consists of two widely spaced panes of glass). When insulation is desired, the space between the panes is filled (by means of a vacuum cleaner motor) with tiny styrofoam beads; to clear the window, the motor draws the beads back into storage drums until they are needed again (Ref. 3-5).

An increasing number of types of movable insulation are being designed to move themselves automatically. Some of these are mechanically operated and controlled

by thermostats; panels are opened when the thermostat senses a certain rise in temperature and closed when the temperature drops. Such panels involve operating costs as well as initial cost, but they save time and will operate in the owner's absence. Other automatic devices are temperature-activated using temperature-caused differences in liquid volume or vapor pressure as the driving force.

All types of movable insulation can be used to help maintain summer coolness as well as winter warmth; one simply reverses the schedule for managing the movable insulation, letting the panels cover windows exposed to solar heat in the daytime and removing the panels at night to allow heat to radiate from the rooms to the cool sky.

Solar Greenhouse with Accordion-Type Shutters

A 1025-ft² direct-gain solar greenhouse for a Massachusetts community was built by CETA workers with funds from the Community Services Administration's Community Food and Nutrition Program (Ref. 3-6). Construction was completed in April 1978. Of special interest are two structural innovations used in this greenhouse: electrical metal tubing (EMT) glazing supports and the accordion-type thermal shutters.

The 1000 ft² of south glazing is composed of Kalwall (fiberglass-reinforced plastic) mounted on 2 X 6 in. framing members that are spaced at 4-ft intervals. A dead-air space of 3 in. separates the Kalwall from the 12-mil polyvinyl storm windows used as an inner glazing layer. Corrosion-resistant and structurally sound 1-in. aluminum conduit (EMT) is used to support the glazing between the framing members. The Kalwall is not attached to the EMT, but can lean against it under any stress from snow or wind. The manufacturer recommends glazing support every 2 ft, but doubling the number of framing members would have caused significantly more shading.

Fig. 3-6 The Window Quilt.

Fig. 3-7 The Self-Inflating Curtain.

Fig. 3-8 The Beadwall.

The accordion thermal shutters are made of 1-in. insulation boards of foil-faced rigid polyurethane that slide in standard sliding-door tracks. The movable insulation forms a fake roof over the planting beds, reducing the interior volume by a third and preventing upward radiative and convective heat losses.

Heat gained through the 100 ft² of glazing is stored in 55-gal water drums that support the planting beds, in more drums stacked along the north wall, and in a centrally-located, below-grade rockbed containing approximately 450 ft³ of rocks. Ducts leading in and out of the rockbed are fitted with two-way dampers to allow vertical charging and discharging from the top or the bottom with air driven from the greenhouse peak by two ¾-hp fans. Backup heat can be provided by an airtight wood stove.

Direct-Gain Heat Storage

Some of the heat that is collected by a direct-gain building will be absorbed by the building structure itself—its walls, floors, ceiling, and interior partitions. Later when the room temperature falls, this absorbed heat will flow of its own accord back into the living space. To enhance this heat-storage effect, heavy dense building materials can be used, especially for the floor and walls (Fig. 3-9). It is important that sufficient heat-storage mass be provided to avoid overheating the interior space on a sunny day.

In a direct-gain house, the floor inside the south-facing windows is often made of several inches of concrete or tile,

preferably a dark color to absorb more solar radiation. To allow the floor to store heat, it must be well-exposed to the incoming sunlight, with no carpets and not too much furniture in the way; and it must be well-insulated around the perimeter to prevent heat leakage into the surrounding soil. Perimeter insulation is often a couple of inches of styrofoam board extending one or two feet into the ground.

A designer also may arrange to have heat stored in the wall opposite the south glazings. This wall will be made of concrete or masonry (or water in containers), and the glazings will be located so that winter sunlight will enter the building and strike the wall. Heavy exterior walls also can store heat—if they are insulated on the *outside*.

Fig. 3-9 Direct-gain heat stored in walls and floors.

The Hodges Residence

An earth-integrated direct-gain structure (Fig. 3-10) was designed by David Block with assistance from the owner, Laurent Hodges (Ref. 3-7). The large 2200-ft² two-level house is bermed on the north, east, and west sides. An expanse of 545 ft² of double-paned south glass will allow sunlight to strike the 2-in. aggregate topping over the 8-in. thick concrete cored-slab floor that separates the two levels (Fig. 3-11). This slab has cylindrical cores that run through its length. The small fan on the auxiliary gas furnace will be used to pull sun-warmed air from the south of the house through the cores to the north, thereby charging the slab with heat. The north, east, and west walls of the lower level are 8-in. thick poured concrete. The total

Fig. 3-11 Concrete cored-slab.

Fig. 3-10 The Hodges residence, Iowa.

mass of the house will be about 250,000 lbs. Therefore, the house's total heat capacity is about 50,000 Btu/°F (or 100 Btu/°F per ft² of south glass). Nighttime insulation of the south glass is accomplished by the use of 2-in. styrofoam panels covered by foil and fabric. The panels stack on a cart that is stored when they are not in use. The owner is comfortable with the 10 to 20 minutes per day commitment to installing and removing the panels. It is estimated that the passive system will provide 85% of the home's heating needs.

HEATING WITH INDIRECT SOLAR GAIN

In an indirect solar gain system, sunlight is trapped, absorbed, and converted to heat

by some part of the building skin—the walls, roof, or floor—and the contents of the living space are not exposed to the direct sun. The architectural goal is to arrange building components so that the sun's energy first strikes crucial storage masses, from which the heat then flows or is distributed to the living space. Many of the same design techniques are used as for a direct-gain system: the building is oriented with plenty of south-facing glazing, and materials with high heat capacity are used for construction.

Indirect-gain systems are of two basic types: *thermal storage walls* (Fig. 3-12), which are constructed of either masonry or water in containers, and *roof ponds* (Fig. 3-13), in which large bags of water on the roof of a building provide its primary

thermal storage mass. Masonry thermal storage walls placed directly in front of the south glazing are often called "Trombe walls" after the French inventor of this system, Felix Trombe. Water walls are formed from various types of containers; 55-gal steel drums, steel culvert pipes, custom-fabricated steel tanks, and translucent fiberglass tubes and tanks have all been used successfully.

Moderate Cost Mass Walls in Virginia

In Thomas Village, architects at TVA have designed three houses with concrete-block thermal storage walls for the moderately priced housing market in southwest Virginia (Ref. 3-8). Keeping the houses from using power during daytime

Fig. 3-12 Thermal storage walls. (a) Masonry. (b) Water.

Fig. 3-13 Roof Pond.

Fig. 3-14 Thomas Village Solar House 1, Virginia. (a) Floor plan. (b) Details of thermal-mass wall. (c) Perspective.

peak-demand periods was a stated design objective. Since days in Virginia are usually warm while the nights get quite cold, an unvented mass-wall design was used. This design cuts down on material cost by eliminating operable vents, and does not have to rely upon owners remembering to open or close the vents.

The floor plan of the 1000-ft² Solar House 1 (Fig. 3-14) is such that all sedentary living spaces are along the south mass-wall. Surface bonding cement was used to hold the concrete blocks together, in an attempt to avoid the cost of using a skilled mason; but the bonding cement proved too expensive and failed to provide an acceptable finish. So the concrete blocks of the 500-ft² mass wall were filled with 140 lb of concrete at a cost of \$1200. Sand and

stone mixture fills are being investigated in order to lower the materials cost on future projects.

Solar House 2 (Fig. 3-15), a 1500-ft², three-bedroom, two-story house, includes a double-glazed sunporch, with typical roof construction and standard floor trusses to support the weight of water storage. The carpenter-built sunporch proved more economical than the originally planned pre-fab greenhouse on a concrete slab with sunshading louvers.

Solar House 3 (Fig. 3-16) is a 1600-ft² three-bedroom house dug into a steep south-facing slope. Besides the mass wall, this house uses its earth integration, a solar atrium, and water storage tubes above a fireplace to store heat, either from the sun

or from the fire. High ceilings and strategically placed windows allow cross-ventilation for summer cooling.

Plans for Solar Houses 1 and 2 are being made available to the public by TVA.

Thermal Storage

On sunny days, a building with south-facing windows often receives more solar energy than it can use. In a passive solar building, this excess energy is stored as heat for later use at night and on cloudy days. If there is inadequate storage mass, the living space will overheat during the day and quickly become cold at night. As interior masses store and release heat, the inside temperature of the building will vary

Fig. 3-15 Thomas Village Solar House 2, Virginia. (a) Floor plan. (b) Perspective.

Fig. 3-16 Thomas Village Solar House 3, Virginia. (a) Floor plan. (b) Perspective.

around some average value. If these daily temperature variations are uncomfortably large, the amount of heat-storage mass should be increased.

By using dense materials such as concrete, adobe, brick, stone, and water (in containers or pools), one can greatly increase a building's ability to absorb and store heat—particularly if the dense material (the thermal mass) is located *inside* the building insulation and is exposed directly to the incoming sunlight (Fig. 3-17). Adding thermal mass to a building is usually desirable although it will probably increase the initial cost of construction. One way to include thermal mass is to place concrete or masonry walls, or containers of water, within the building, especially near a sunlit window.

Other possibilities are massive fireplaces; interior partitions of concrete, brick, or double layers of sheetrock; and floors topped with several inches of concrete, brick, or tile. There is increasing use of rockbeds in crawl spaces, through which overheated air is circulated to store heat in the rock.

Crucial to the success of a material as a heat-storage medium is its ability to absorb heat as its temperature increases and to lose heat as its temperature decreases (Fig. 3-18). One measure of this ability is the *specific heat* of the material, which is the Btu's needed to raise one pound of the material by one degree F. To compare different storage materials, the *volumetric heat capacity* (Btu/ft³°F) is more useful; it tells how much heat can be stored in a

given volume of material during a given temperature rise, and can be obtained by multiplying the density of a material by its specific heat.

From the above values one can calculate that a given volume of water is able to store more than twice as much heat as the same volume of solid concrete:

Volumetric
Heat Capacity
(Water)

Volumetric
Heat Capacity
(Solid Concrete)

=

=

62

23

=

2.7

The heat stored in these common materials is called *sensible heat* (because it can be felt or sensed); another type of heat, *latent heat*, can also be stored, as discussed later in the section on phase-change materials.

Masonry and Adobe Walls

Masonry blocks have been used for many thermal storage walls, as well as for entire buildings (Fig. 3-43). They are easy to handle and have a fairly high heat capacity, especially when the voids are filled with heat-absorbing materials such as concrete or water (in containers).

Thick walls of adobe—as thermal walls or for the entire house—provide excellent heat storage. The material has proved itself over the centuries to be long-lived and effective in making buildings thermally comfortable. Heat moves slowly through adobe, allowing buildings to stay warm in winter and cool in summer. It is fireproof and termite proof, readily available, and inexpensive. There is now extensive literature on soil selection and stabilization, on labor and time-saving techniques, and on structural design and earthquake reinforcement. Workshops are being presented in various cities to teach people how to use this re-discovered building material.

Heat-Storage Properties of Materials			
MATERIAL	DENSITY (lb/ft ³)	SPECIFIC HEAT (Btu/lb°F)	VOLUMETRIC HEAT CAPACITY (Btu/ft ³ °F)
Solid Concrete†	144	0.16	23
Adobe	123	0.20	25
Brick	106	0.24	25
Water	62	1.00	62
Rocks† (30% voids)††	165	0.21	24
Scrap Concrete† (30% voids)††	144	0.16	7
† Values may vary considerably with type.			
†† Experiments with loose materials such as rocks or scrap have shown that they usually pack with a void fraction of 30 to 40% if the pieces are all about the same size, regardless of what the size may be; the heat capacity of the assemblage is then reduced by the amount of the void fraction.			

Fig. 3-17 Thermal storage materials.

Fig. 3-18 Heat-storage properties of materials.

Trombe Walls

A Trombe wall is a masonry wall placed only a few inches inside a south-facing glazing where it is fully exposed to the sun; its south side is usually blackened to increase absorption of solar energy. The delay in delivery of heat to the interior of the building is on the order of 5 to 8 hours (for 8 to 12 in. thick walls); thus maximum heating can occur in the evening hours (Fig. 3-19). This time delay is quite evident in all the thermal walls that have been instrumented and monitored. Vents are often placed in the top and bottom of Trombe walls so that heat will also flow into the living space by natural convection during the day and early evening. This thermocirculation is sometimes aided by a small fan. Windows can be placed in the wall if a view to the south is desired.

The interior finish of a concrete thermal wall must not stop the heat from radiating into the room. An exposed aggregate surface may be used, or the concrete may be sandblasted or brushed, or sealed and painted; but sheet materials such as gypsum-board or wood will interfere with the wall's function.

Inclined Trombe Wall in Truckee

In the summer and fall of 1978, architect Dick Munday built a 1780-ft² single-family home with an inclined Trombe wall at a site in Truckee, California near Lake Tahoe—5900 ft elevation and 8200 heating degree-days (Ref. 3-10). The inclined Trombe wall design (Fig. 3-20) was chosen because construction immediately to the south made it undesirable to open the liv-

ing space in this direction (as would be necessary with a direct-gain system or a greenhouse system). A relatively long heating season (10 months of the year) led the designer to slope the Trombe wall 45 degrees for maximum annual efficiency. The Trombe wall forms the south wall/roof of the living room, and a wood-burning stove with 30 ft. of exposed single-wall flue is located next to the wall. The 10 X 14 ft. wall is 8-in. thick poured-in-place reinforced concrete and has a mass of approximately 15 tons. Insulating panels (3 in. of rigid styrofoam sandwiched between ¼-in. plywood skins) slide on garage door tracks between the wall and the glazing; 4-in. diameter PVC pipes placed in the form before the concrete was poured serve as the bottom inlet ports in the wall. The outlet ports are the space between the roof beams as they

pass the top of the wall. A 4000-cfm ceiling fan is installed at the top of the house (above the stairwell near the clerestories) to decrease heat stratification.

The owner estimates that the passive systems added six weeks to the construction schedule and \$20,000 to the construction cost (including both labor and materials). A significant portion of the extra time was attributable to the insulating panels: construction of the roof above the wall required more precision than normal to allow for the operation of the panels. The panels are manually operated by ½-in. nylon rope that passes through a pulley at the top of the house and is fastened to standard brass sailing cleats at the bottom, allowing the owner to "sail" his house.

Fig. 3-19 Thermal time lag for various types of walls.

Fig. 3-20 House with inclined Trombe wall, Nevada.

Trombe Wall in the Northwest

During the first eight months of 1978, Terry Haroldsen of Haroldsen Construction built a 1650-ft² house heated with a Trombe wall (Fig. 3-21) for the medium-price market in the Tri-Cities area in southeastern Washington state (Ref. 3-11). The low cost of locally available hydroelectric energy (1.2 cents/kWh in 1979) made cost-competitiveness with conventional housing especially important. Masonry is not a common building material in this geographic area and therefore is expensive. The design solution was to keep the masonry Trombe wall but use a "space-efficient" floor plan, reducing the gross floor area. Thus the house has an open plan on three floors with a minimum of hallways and unusable space. The living room is the only

room that is not adjacent to the Trombe wall; it uses a backup wood stove when required.

The Trombe wall consists of 12-in. thick concrete blocks with filled cores. It is two stories high and is supported by a 4-ft wide poured concrete footing. Both the wall and footing use steel reinforcing bars in accordance with local building codes. The interior and exterior wall surfaces are fibrous stucco. Glazing is an inner layer of 3-mil Tedlar film with an outer layer of corrugated, UV-stabilized fiberglass held $\frac{3}{8}$ -in. from the Tedlar. Manually operated dampers, used on the upper vents of the wall, are opened when immediate daytime heating is required. At other times, they are kept closed so the heat will be stored in the wall. Plastic-film backdraft dampers on the lower vents prevent nighttime reverse thermosiphoning. Auxiliary heating ducts are arranged so that warmer air near the ceiling can be circulated throughout the house to maintain a uniform temperature and prevent possible stratification problems. To prevent summer overheating, the Trombe wall will be vented and shaded by a fixed overhang and (until a deciduous vine gets thick enough) an inexpensive bamboo shade. The Trombe wall has 805 ft² of net glazing area (equivalent to about 50% of the floor area) and is sized to provide about 60% of the annual space heating needs.

None of the local banks were willing to finance the construction of the house if it was to be built for speculation; so a buyer was found (Laird Parry) and the house was financed as a custom home. After the house was built, Haroldsen was able to secure financing on other speculative passive homes.

No major construction problems were encountered on this home although minor troubles caused delay and increased costs. The most significant problem was the inadequate quality of the subcontractors' work. Although the design was simple, the subcontractors viewed the project as an unknown and risky venture and put it low on their priority list.

The Trombe wall cost about \$10,000 to build (just under 25% of the total construction cost) and approximately a third of that went for the foundation necessary to support a two-story wall.

The owner is enjoying the house's comfort and low utility bills, the builder is satisfied and is building other passive homes, and visitors have been favorably impressed.

Water Walls

Passive solar systems using water walls for thermal storage are among the most effective and economical installations for natural heating and cooling (Fig. 3-22). Water can store more than twice as much heat as the same volume of concrete; thus it can provide the same amount of heat storage as concrete in considerably less space. The water may be contained in metal tanks, drums, culvert sections, fiberglass tubes or tanks, or tanks of masonry, concrete, or wood lined with plastic. These containers are placed inside the house where they catch sunlight entering south windows. Usually, the side of the water wall facing south is a dark color to absorb more radiation.

Steel tanks are versatile, easy to fabricate, and lightweight. They come in many sizes

and shapes and can be assembled in various arrangements. They can be textured and painted to match the room, or wallpapered. They can — and should — serve other purposes besides storage, such as kitchen counters, window seats, plant shelves, or room dividers.

Continuously-welded steel culvert pipe has been very successfully used for heat storage in a number of homes (Fig. 3-23). The material is attractive to many people, is durable, and takes little space since the pipes can be tall. The two most common methods of installation have been to weld a plate to the bottom of the culvert pipe and bolt the plate to the concrete slab floor, or to fasten the pipe to the concrete with an epoxy filler and a concrete plug. Both work well. Because of the height of the culvert

sections used, temperature stratification of the water is pronounced (water in the top is considerably warmer than that in the bottom); this is a disadvantage for heating. But it is probably outweighed by the large surface area of the culverts, which is an advantage for cooling.

One of the first types of water wall used in passive solar homes—stacks of 30- or 50-gal oil drums—is continuing to be used (Fig. 3-24). The drums are less expensive than steel tanks; but they are also less esthetic, harder to clean, and take more time to install.

Modular fiberglass tanks and tubes have been used successfully, and are currently being made by at least two manufacturers. They are relatively inexpensive near the

place of manufacture, and their appearance is pleasing. However, some of them are vulnerable to puncture with sharp instruments and require careful bracing for seismic activity.

Relatively new are several types of visually transparent modular water walls made of fiberglass, or glass and metal, which can be stacked to form a wall of any size (Refs. 3-12, 3-13). Although these walls are somewhat transparent, there is strong light attenuation; so there is no glare or deterioration of fabrics and furniture. The water contains an additive to inhibit the growth of algae.

Suncatcher with a Water Wall

The Bruce Maeda/Lynn Nittler House (Fig. 3-25), in the Village Homes subdivision in Davis, California uses the "Suncatcher" design developed by Living Systems in Winters, California (Ref. 3-14). The seasonally-adjustable Suncatcher reflectors (made of aluminum) concentrate sunlight through clerestory windows onto dark blue water-filled steel culverts. The bedroom uses direct gain through south windows with heat storage in the parquet-covered slab floor and in water drums. Hot water is provided by a four-tank breadbox solar water heater. Double-pane glass, R-30 ceilings, R-19 walls, insulated shutters and drapes, and careful caulking have resulted in a thermally tight house. Cooling is by nighttime ventilation, solar rejection, and use of the water mass for heat storage.

The house has been the subject of extensive performance monitoring. Solar is providing over 75% of the space-heating needs, especially since shutters, drapes, and a commercial cat door have been

Opposite page

Fig. 3-21 The Parry/Haroldsen Trombe wall house, Washington.

Fig. 3-22 Water walls.

Fig. 3-23 Water-filled culverts for heat storage.

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Fig. 3-24 Water-filled drums for heat storage.

Fig. 3-25 A California Suncatcher house with a water wall. (a) Perspective. (b) Floor plan. (c) Suncatcher ray paths.

added. Cooling is entirely by natural means, although temperatures did rise to 84°F on three afternoons during an exceptionally hot period of the summer. House fans provide some relief; but supplementary cooling equipment could not be cost-justified for the short period it would be used. The shutter system has proved to be critical in preventing overheating as the Suncatcher reflectors double the diffuse sunlight through the windows during the summer.

The primary heat storage is in the seven water-filled culverts which store and release approximately 47,250 Btu during a daily cycle on sunny winter days. The upper portion of the tubes goes through a daily temperature swing of about 8°F, while the lower portion swings only 1°F. The tem-

perature of the 55-gallon water barrels in the bedrooms and the study seems to vary by 9 to 10°F each day, storing and releasing 2405 Btu each. The owner plans to increase the water mass in the study and bedrooms because the house reaches 80°F on sunny winter days, which is somewhat warmer than desired.

Bainbridge House, with a Metal Water Wall

In 1978, Virginia Thigpen (Ref. 3-15) designed and built a home using a rectangular metal-tank water wall for David Bainbridge in Village Homes (Fig. 3-26). The house is carefully weatherstripped and insulated, with R-19 walls and R-30 roof. Insulating glass is used throughout, and all windows and skylights have insulated shut-

ters or drapes. Primary heat storage is in the slab floor, made of 35,000 lbs of exposed concrete painted dark brown. Some heat is stored in a water-filled rectangular metal tank that is 4-ft high, 12-ft long, and 2-ft deep. Additional heat storage is in 24 water-filled 5-gal tin cans.

A small fan and duct recirculate heat from the top of the house to the north bedroom. Backup heat is provided by an airtight wood stove. Hot water is provided by an owner-built breadbox solar water heater situated on the carport roof. Nighttime ventilation and south overhangs keep the house cool in summer. The owner finds the house very comfortable, the thermal mass is not obtrusive, and the windows provide light and ventilation as well as solar heat.

Fig. 3-26 The Bainbridge house, California. (a) Floor plan. (b) Section. (c) Steel water-storage tanks.

Roof Ponds

Another way to use water for thermal storage for passive heating and cooling is to place it on top of the house in plastic bags. The bags should be in good thermal contact with a sturdy flat roof and ceiling made of metal (for its high conductivity). Movable insulating panels are used to control heat gain and loss. In winter (Fig. 3-27), the roof pond is uncovered during sunny days to absorb solar heat; at night, it is covered to retain the heat and to warm the space below. In summer (Fig. 3-28) the pond is uncovered at night so the water can lose heat to the cool night environment; during the day, it is covered and absorbs heat from the living space.

Small Southern California Home with a Roof Pond

A small 400-ft² home in the San Gabriel mountains near Los Angeles (Fig. 3-29) is heated and cooled by a 100-ft² roof pond that was handcrafted from galvanized steel water trays located between the roof joists (Ref. 3-16). The trays are covered with a fiberglass-reinforced plastic glazing. The insulated cover/reflector is operated by a hand crank. The north side of the house is dug into the hillside, and solar heat entering through the south windows is stored in the adobe floor tiles. A thermosiphoning solar water heater and the electricity provided by 90 watts of silicon solar cells, allow this family to enjoy a truly energy-conserving lifestyle.

Phase-Change Materials

In some experimental buildings, *phase-change materials* are being used for heat storage. These materials, usually hydrated salts or hydrocarbons, absorb a large amount of heat when they melt (which cools their environment) and release a large amount of heat when they solidify (which heats their environment); the amount of heat absorbed or released (without temperature change) is known as the *latent heat* of the material. The latent heat stored by these materials is locked up in their molecular structure and does not make them feel warm to the touch.

Because phase-change materials have much higher heat capacities than water or masonry, much less weight or volume of

Fig. 3-27 Roof-pond operation, winter.

Fig. 3-28 Roof-pond operation, summer.

Fig. 3-29 The Baker roof-pond house, California.

storage material is required. In addition, air temperature fluctuations are reduced because the energy exchange in phase-change materials takes place at nearly constant temperature.

For a number of years, research has been underway to find substances that change phase at temperatures useful for space heating and cooling; it would be desirable if the substance also were nontoxic, non-corrosive, noncombustible, durable, easily available, and low in cost. No such perfect material has yet been found, but the two most promising are hydrated salts (especially sodium sulfate decahydrate) and hydrocarbons (especially paraffin).

To compare the heat-storage ability of water (which stores sensible heat) with that

of sodium sulfate decahydrate (which stores latent heat), one needs to specify the temperature rise of the water during heat storage in the system. If this rise is from 90 to 122°F, then the water will absorb:

$$1.00 \text{ Btu/lb}^\circ\text{F} \times (122-90)^\circ\text{F} \times 62 \text{ lb/ft}^3 = 1984 \text{ Btu/ft}^3$$

Sodium sulfate decahydrate, which melts at 90°F and has a heat of fusion of 108 Btu/lb and a density of 91 lb/ft³ can absorb:

$$108 \text{ Btu/lb} \times 91 \text{ lb/ft}^3 = 9828 \text{ Btu/ft}^3$$

The ratio of the two quantities is $(9828/1984) = 4.95$. Thus a given volume of this salt can store about 5 times as much heat as the same volume of water undergoing a 32° temperature rise.

Hydrated salts, although they have a high latent heat content and are inexpensive, have had a history of unreliability in this application—supercooling, separation, and package corrosion being the most serious problems. Seed materials (e.g. borax) have been added to aid crystallization, a clay stabilizer has been included to prevent separation, and plastic containers are now being used; but long-term performance has not yet been demonstrated. Research continues and phase-change systems are being tested in several experimental buildings.

One current research project is exploring the use of phase-change materials in portable heat-storage trays (Fig. 3-30). The trays are mounted on a frame that allows them to be fully exposed to a south window during the day, and then to be folded up and wheeled to a north room to provide heat at night (Ref. 3-17).

Another research effort is evaluating the effectiveness and reliability of phase-change materials in metal cans placed in the voids of concrete blocks (Ref. 3-18). The concrete blocks are then built into thermal storage walls.

HEATING WITH ISOLATED SOLAR GAIN

When passive solar buildings are heated by isolated solar gain, sunlight is converted to heat by absorption on a surface separate from the living space; the heat is then delivered as desired, either directly to the living space or to a heat-storage system (usually water or rock) from which it is extracted as needed. Heat delivery is by natural convection, radiation, or conduction, or it may be forced with blowers and fans. Thus the air temperature in the building can be regulated independently from that of the collecting and storage areas. The advantages are significant. Even if the isolated-gain system is completely passive, the heating of the living space can be fully regulated—and can even be turned off and on as desired. Energy collection can be optimized since temperatures in the collecting area may be allowed to fluctuate over a wide daily range, which can greatly reduce heat losses at night and on cloudy days. In less sunny and colder climates, isolated-gain systems may be less efficient than direct-gain or indirect-gain systems because of increased distribution losses. Examples of isolated-gain systems are:

Roofs or walls, insulated from the living space, which collect and store solar heat; heat is then transferred to the living space by convection through vents in the ceiling or wall.

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Fig. 3-30 Heat-storage trays.

Opposite page

Fig. 3-31 Solar greenhouse operation. (a) Heating. (b) Cooling.

Fig. 3-32 Water barrels used for heat storage also support planting beds.

Remote glazings which collect solar heat; the heat flows by natural convection to storage under an insulated floor, and then to the living space through floor vents.

An outdoor solar pond for heat collection and storage; the heated water flows through pipes in the floor, heating living space by radiation.

Sunspaces or solar greenhouses, attached to the house or integrated into the floorplan, where heat is collected through large expanses of south glazing; collected heat is stored in a thermal wall between the sunspace and the living space, or in free-standing heat-storage masses. Heat is transferred to living areas by radiation through the thermal wall, by convection through

vents, or by direct flow through open doors and windows.

Solar Greenhouses and Sunspaces

The solar greenhouse or sunspace is a direct-gain space with extensive glazing which may be attached to the south side of a building, or may be an integral but separate part of the interior space; there should be considerable thermal mass in or adjacent to the greenhouse. One approach is to separate the greenhouse from the living space by a thermal-storage wall. Thus the greenhouse or sunspace acts as a buffer, reducing heat loss in the winter, reducing heat gain in the summer, and damping the daily air-temperature fluctuations within the building (Fig. 3-31). The heated air is deliv-

ered directly to the building through doors, windows, vents, and also is stored in the thermal wall from which it radiates into the house. Such a design usually produces all the heat needed by the greenhouse or sunspace itself plus a substantial amount of heat for the building. The advantages of a solar greenhouse (compared with a sunspace) are that it can produce fresh food and also can add oxygen and moisture to the air in the living area.

Attached Solar Greenhouse in Northwest Arkansas

A 100-ft² greenhouse was built onto the Trahan's 1800-ft² house in Madison County, Arkansas to provide food, a sunny space, and some heat for the house (Ref. 3-19). Reflective insulating shutters along the south knee-wall increase the radiation striking the heat-storing water barrels (Fig. 3-32) by about 30%. The front water barrels exhibited 10°F daily temperature swings. The barrels also support the planting boxes, which benefit from the warmth. Rigid insulating panels reduce heat loss from the upper windows at night. All greenhouse windows use clear vinyl as the inner glazing and tempered glass as the outer glazing. The knee-wall shutters and glazings are removed for the summer and replaced by screens. Air circulation is induced when vents in the upper east and west walls are opened. A small thermostatically controlled fan delivers excess greenhouse heat to the house in winter, providing 10 to 15% of the house's heating requirements.

The foundation footings were made from 8 X 8 in. oak railroad ties secured to the

ground by 2-ft long, 1/2-in. diameter reinforcing bars driven through holes in the wood at 4-ft intervals. Two-inch rigid insulation boards reduce heat loss around the footings. A galvanized gutter below the tilted south glass collects rain water for use in the greenhouse and protects the knee-wall footing from soaking.

The occupants have welcomed the sunny space, lowered heating bills, and year-round food supply. The plants endured a record-breaking ice storm with negligible damage in the 100% solar-heated greenhouse.

Two other Arkansas greenhouses were built to be integral with the living space, with no dividing wall (Fig. 3-33). These greenhouses actually act as direct-gain

systems, and the owners report there is no problem in getting increased heat delivery to the living spaces. The only improvements suggested were to use an interior winch to control the shutters, and insulating curtains instead of the rigid boards that now cover the tilted glazing.

Convective Loops

Another type of isolated gain system uses the natural convection of air heated in a flat-plate collector as the primary energy distribution force (Fig. 3-34). Although the residential systems described here include rockbed heat storage to provide heat in the nighttime whenever it is needed, many buildings with daytime-only use patterns often do not require storage.

The collector's absorber plate is usually made of expanded metal lath painted black. Sometimes multiple layers of lath are used (Fig. 3-35). Because the sunlight filters through the upper layers, and both sides of the lath transfer heat to the air, multiple layers can result in a large ratio of heat-transfer area to glazing area. A sheet of corrugated metal could be used instead of the metal lath, but some early experiments found the lath to be more efficient (more heat is transferred to the air in the collector and less is lost to the glazing).

As the air is heated in the collector, it becomes less dense and rises to the storage bin where it transfers its heat to the rocks. Cool (return) air from the bottom of the storage bin or from the house enters the collector at the bottom (inlet) and replaces the

heated air. The storage bin should be located as high above the collector as possible. A properly designed collector should have an inlet-outlet temperature difference of 30 to 50°F on a sunny day.

Convective Loop in Southeastern Arizona

An owner-built retirement house in the Arizona mountains (Fig. 3-36), at an elevation of 4800 ft and with 5000 degree-days, was designed by Jeffrey Cook in 1975 with consultant Herb Wade. The house was completed in August 1978 (Refs. 3-20, 3-21). The air collector uses a 4-layer diagonal metal mesh which lies on the insulated back of the collector under the glazing, so that the upward-flowing air must contact the mesh. When the air-flow

rate is reasonably high, the air is not heated until it contacts the mesh, which keeps the air adjacent to the glazing relatively cool, minimizing heat loss. The top half of the collector is double-glazed. The collector efficiency (ratio of energy delivered to storage to solar energy striking the collector) generally runs from 40% in midwinter to 50% under milder conditions. The maximum air-flow rate is about 4 to 5 ft³ per minute around noon on sunny days; the collector outlet-inlet temperature difference is about 50°F during this time. The temperature stratification in the rockbin storage is very good (i.e. the upper rocks are hottest, so the air going to the house passes the hottest point just before leaving the rockbin.) Natural convection from rockbin storage to the house (discharging mode) is more than sufficient when all the

vents to the house are opened.

The system's performance could be improved if the collector depth were reduced from its current 8 in. (1/12 of the collector length) to 5 in. (1/20 of collector length). The smaller depth would increase the air velocity and eliminate the hot spots at the top of the collector between the mesh and the glazing.

Thermosiphoning Air System

Mark Jones and Bruce Hunn of Los Alamos Scientific Laboratory have designed a thermosiphoning air system for Jones' house in Santa Fe, New Mexico (Ref. 3-22). The 2650-ft² house uses a site-built collector with 532 ft² of absorber area (Fig. 3-37). The blackened absorbers are 3-in. deep

Opposite page

Fig. 3-33 Interior view of the Trahan integral solar greenhouse.

Fig. 3-34 Convective-loop heating systems.

Fig. 3-35 Two air collectors: corrugated steel (left), and expanded metal lath (right).

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Fig. 3-36 A convective-loop house, Arizona. (a) Perspective. (b) Air collector and rock storage.

Fig. 3-37 The Jones house, New Mexico.

galvanized sheet-metal pans with 3 layers of $\frac{3}{8}$ -in. mesh wire lath set at the top of the pans. The collector glazing is a single layer of fiberglass-reinforced plastic. The collector is over 8-ft long and is 10-in. deep. It faces due south and is tilted at 45 degrees.

In this design, some sections of the absorber and plywood backing have been replaced with fiberglass glazing to form skylights that illuminate the large triangular greenhouse under the collectors. The rock storage bin is approximately 500 ft³ and contains 30 tons of washed 1.5- to 3-in. river rock. This is about 100 lbs of rock per ft² of collector. The storage is charged purely by natural convection; around noon on sunny days the inlet-outlet temperature difference is around 100°F. A 1000-cfm fan sends heat from storage to the house. The system has performed well, maintaining a comfortable temperature range of 65 to 70°F without the use of auxiliary heat.

Rules-of-Thumb for Air Systems

Some basic guidelines for building thermosiphoning air systems have been developed from the experience in the above (and other) houses with collective loops (Refs. 3-20, 3-23):

- ◆ Collector depth should be about 1/15 of collector length (1/20 for diagonal mesh absorber).
- ◆ Rock storage should be 100 to 200 lbs/ft² of collector, and should be placed as high as possible above the collector.
- ◆ All ducts and plenums should be at least as large in diameter as the collector outlet to reduce air restrictions in the system.
- ◆ Larger rocks should be used for deeper bins.
- ◆ Collector tilt should be more than 45 degrees.
- ◆ An adequately sized vent should be placed high on the collector to allow summer venting; otherwise, the collector should be covered in summer.

Radiant Discharge Systems

Scott Morris of Santa Fe, New Mexico (Ref. 3-20) is experimenting with thermosiphoning designs that allow rock storage masses under slab floors to be heated by natural convection, thus providing radiant heat to the living space (Fig. 3-38). He is also trying a scheme using a rock storage wall that could be placed anywhere in the house (an advantage compared with the restrictions on locating direct- or indirect-gain mass walls).

NATURAL COOLING TECHNIQUES

The provision of passive cooling for a building should be considered along with arrangements for passive solar heating since integration of the two will result in a more efficient and cost-effective design. Although the principles of natural cooling have been utilized for centuries, they have been ignored of late and currently are not as well understood as those of natural heating. However, both rely on the same basic fact: heat flows of its own accord from a warm place to a cooler one. Any or all of the following processes can be used to cool a building: solar control, natural and induced ventilation, evaporation, and radiation.

Solar Control

The most cost-effective method of natural cooling is solar control: stopping the sun before it enters the space. After application of insulation and weatherstripping, it will always be the first step in reducing unwanted heat gain. Both interior and exterior solar control devices are now receiving attention from manufacturers, designers, and researchers.

An important factor in solar control is window location. To make control easy, most windows should be located on the broad south side of the building where they can be shaded with a roof overhang sized to admit the low winter sun and block the higher summer sun. In summer, east- and west-facing windows present difficult shading problems since the sun is low in the east in the morning and in the west in the afternoon; exterior shades and

Fig. 3-38 Convective charge/radiant discharge systems. (a) Center-glazed collector for heating masonry floor. (b) Standard U-tube collector for heating masonry floor. (c) Convection-charged mass storage wall.

screens, as well as landscaping, are particularly effective in controlling sun on these areas (Fig. 3-39). North windows, which can provide glare-free natural light in winter, may receive direct sun for a short while around midsummer. They can be similarly shaded if the summers are hot enough to warrant it.

Summer heating also can be reduced by making the roofs as light in color as possible (dark roofs can be 60 to 80° hotter than light ones). Shading the roofs and walls may also be desirable, and can be achieved with proper design and landscaping.

Most interior solar control measures are lower in cost, and also lower in performance, than exterior measures; but in mild climates they still may perform well enough to eliminate the need for an air conditioner. In other cases, it will take a combination of interior and exterior measures to eliminate air conditioning. But even if the cooling load is merely reduced, the savings on air conditioning equipment and on power will often more than pay for the solar control equipment.

Ventilation

After solar control, one of the most common and economical methods of cooling a building is simply good ventilation. The easiest way to provide it is to have operable windows and vents on more than one side of each room for flow-through ventilation; an "open" floor plan with few partitions will increase the effectiveness of this type of cooling. Windows and vents can be located and sized to take advantage of prevailing summer breezes, and even to increase the flow of air through the building.

Ceilings that slope upward to high vents will help exhaust hot air that rises by convection, especially if air is entering at the same time through low vents on the cool side of the building (Fig. 3-41). The convective exhaust of hot air can be further enhanced by placing ventilation chimneys near the roof peak. And if natural ventilation is not sufficient to provide a comfortable flow of air, fans and ventilators can be added.

Convective exhaust of heated air works best in hot-dry climates where hot summer days are followed by comfortably cool nights. Then the large nighttime temperature difference between the indoor and outdoor air is effective in driving the natural convective flow. A site's potential for convective cooling can be estimated from information on the daily temperature, humidity, and wind patterns.

In hot-humid climates, where night temperatures are nearly as high as day temperatures, ventilation is effective only if enough air moves past the body fast enough to ensure rapid evaporation of perspiration. However, fast-moving air itself can be uncomfortable. Thus it may be necessary to dehumidify the ventilation air to achieve thermal comfort.

Natural Ventilation on Ossabaw Island

Residences for the staff at a wildlife management preserve on Ossabaw Island off the coast of Savannah, Georgia, have been sited to make effective use of land and sea breezes for cooling (Ref. 3-24). The climate of the area is very humid with 1952 heating degree-days and 2383 cooling degree-days. To accomplish the design objectives for these buildings—maximum solar gain

Fig. 3-39 Movable shading devices: awnings, overhangs, blinds, deciduous vines or trees.

Fig. 3-40 Natural convective cooling.

in winter with minimum heat loss, and maximum summer cooling—the architects developed a summer-type house that can easily be winterized (Fig. 3-41).

Major living areas of the 1248-ft² houses are on the south side to take advantage of direct-gain solar heating in the winter; and a 320-ft² south-facing sunroom supplements this heat. In the summer, the entire sunroom is covered with panels of foil-faced rigid insulation. These panels are removed one-by-one as the fall and winter seasons advance and heat is needed.

To provide summer cooling, air flows through the house were calculated for optimum natural ventilation making the house virtually transparent to the breezes. The 8-ft ceiling slopes upward in the center to 10 ft,

but interior partitions are only 8-ft high; as a result, air circulation is excellent. A stack effect is created by the ceiling vents at the highest part of the ceiling and roof, through which heated air flows to the outside. The raised floor, required for buildings on the coast, provides increased air movement in and around the house which has eliminated all moisture in the crawl space.

The sloping ceilings, ceiling vents, and strategic placement of windows to capture breezes completely eliminate the need for air conditioning and thus reduce the total electric generation capacity required to operate the preserve.

These minimum energy-use dwellings were built at a cost comparable to that of conventional buildings. They meet main-

land and coastal building codes and are designed to be factory built.

Ventilation Cooling for Stables

To make cattle comfortable and increase milk production, a natural ventilation system for a stable is being constructed this year in Veracruz, Mexico, which has a hot-humid climate (Ref. 3-25). Sky conditions at the site are frequently cloudy with much relatively intense diffuse radiation.

Designed by the Universidad Nacional Autonoma de Mexico, this cattle building takes advantage of the trade winds which blow all year from the northeast at speeds of 5 to 14 mph (Fig. 3-42). Building orientation and movable louvers ensure excellent

Fig. 3-41 Typical Ossabaw Island house, Georgia. (a) Perspective. (b) Floor plan and air flow. (c) Methods of cooling used.

cross ventilation. A solar air heater, incorporated into the roof, helps exhaust hot interior air by convection in the middle of the day when winds are weakest. At night and when it is cloudy, rooftop wind turbines augment the ventilation.

Radiative Cooling

Heat that accumulates during the day in the mass of a building or in a special heat-storage system will radiate away from the building at night if the warm surfaces can be directly exposed to the sky. The sky at night, especially straight overhead, is often quite cool and can provide a good heat sink. A well-known example of this radiative cooling is the Skytherm type of building whose roof is covered with a pond of water

(in large plastic bags); on summer nights, the roof pond's insulating panels are rolled back to expose the water bags to the sky and allow the water to cool (Fig. 3-43).

The daytime sky also has a cool spot which can be used as a heat sink; this is in the north sky at a right angle to the sun. (Averaged over the day, the coolest exposure is due north at a height above the horizon equal to 90 degrees minus the height of the sun at noon). Water in a shaded pond that is cooled by being open to the north sky can be used to cool a house, either by circulating the water through the pipes in the floor or by letting the water thermosiphon (circulate by natural convection) between interior tanks and a raised exterior pond.

Evaluation of Roof-Pond Cooling

The effectiveness of roof-pond radiative cooling has been evaluated for eleven different areas in the United States by a group at Trinity University in San Antonio, Texas (Ref. 3-26). They find that the method can meet the cooling load of a well-designed residence almost everywhere—if dehumidification or good ventilation are also provided. In many cities, there is cooling capacity far beyond the residential requirements, which suggests that roof-pond systems could find use in commercial buildings as well. Several alternative methods of decreasing humidity were compared:

Small electric dehumidifiers have a low first cost and can meet the latent heat load when air infiltration is low, but electricity consumption may be high.

Chemical desiccant devices are high in first cost and in operating cost, although use of solar heat to regenerate the chemical could lower operating cost.

Ventilation when ambient temperatures are not too high can provide comfort at low cost in all but the most humid weather.

In this work, the group found that accurate calculation of the amount of heat a roof-pond building can dissipate at night requires certain meteorological data that are not readily available (Ref. 3-27). The parameters needed are the nighttime temperature, dewpoint temperature, atmospheric pressure, windspeed, and opaque sky cover. Although hourly values are available in the SOLMET format, most people cannot use these tapes. Instead, tables of the monthly average data are used. The researchers find that as an aid to assessing nocturnal cooling, these monthly average data have some drawbacks for the designer which lead to poor estimates of cooling rates. They strongly recommend that nighttime averages be included in the tabulated data in the future.

Fig. 3-42 Naturally cooled stables, Mexico.

Fig. 3-43 Skytherm house, California.

Nocturnal Cooling with Collectors

Flat-plate collectors and their water storage tank, used for winter solar heating, are being used for summer cooling as well in several houses built by Tandem Construction, Inc. in Davis, California (Ref. 3-28). The 1150-ft² three-bedroom homes are heavily insulated and well-caulked and weatherstripped; they are variously glazed and carpeted for this test situation.

The basic solar heating (and nocturnal cooling) system being used consists of eight water-cooled, flat-plate solar collectors (each 4 X 8 ft); two small water storage tanks; and a radiant floor slab with polybutylene tubing 9 in. on center. In winter, the system performs like other active solar energy systems; heated water from the collectors is pumped to the two tanks, one tank for heating domestic water and the other for floor heating.

In summer, heat is delivered each day from the collectors to the domestic water as usual; but at night, water from the floor-circulation tank is pumped through the collectors, where it loses its heat to the night sky and air. The next day, the cooled water circulates through the floor to cool the

house. For summer cooling, the collector glazings are removed and stored.

Throughout a very hot summer, these houses have not used any form of backup cooling, although sometimes a room fan to increase air movement would have been desirable. With no collector glazings, the domestic water did not get hot enough when the weather was windy; but replacing two of the eight glazings solved the problem. Overall, this experimental use of collectors for both heating and cooling is a success; and Tandem will continue to use it in future home construction.

Evaporative Cooling

Evaporation of water, which uses up almost 1000 Btu for every pound that is vaporized, is a powerful cooling method. In dry climates, one can take advantage of the effect very simply just by letting the incoming air blow through or past a moistened pad; or a hot roof can be sprayed or flooded with water (Fig. 3-44). But in humid climates, evaporative cooling is not so effective. For one thing, the air may already be nearly saturated with water vapor. For another, adding more water vapor through evaporation may only increase people's discom-

fort; and condensation of water onto surfaces may become a problem. Thus if temperatures are very high, removing some of the water vapor from the building air becomes an essential part in providing thermal comfort.

The protection of natural wind flow, and its enhancement, are important when evaporative cooling is used because the windspeed across a surface is a major factor in the rate of evaporation (and thus of cooling). Care must be taken with the design of the evaporating surface since poorly designed edges or lips may deflect the wind from the surface, lowering the evaporation rate. A major deterrent to widespread use of evaporative cooling is that many of the hot and dry areas where it would work best lack water.

Evaporative Cooling in the Mojave Desert

With summer temperatures as high as 115°F, an evaporative cooling system installed by Raintree Construction in a home in California's Mojave Desert is delivering a continual flow of air at 73°F (Ref. 3-29). Insulation is heavy in this 1500 ft² house, with walls at R-24 and the ceiling at R-27. Dry hot air is precooled as it is drawn through a decorative fountain into 200 ft of unglazed clay pipe that is kept moist by a slow but continuous flow of water. The clay pipe is chimney flue liner joined by 4-in. strips of plastic and buried 3-ft deep in a trench under the shade of the eaves. The resulting 73°F air flows via natural convection to a 35-ton insulated rockbin (which also serves to store heat from the solar collectors in the winter). From the rockbin, the air is blown by solar-cell powered fans to a subfloor plenum for delivery to the building. The fans can also run on regular AC current.

The Cool Pool

The Cool Pool, a passive cooling system invented by Jonathan Hammond of Living Systems in Winters, California (Ref. 3-30), is an evaporative, shaded roof-pond which thermosiphons cool water into water-filled columns within a building (Fig. 3-45). The roof pond requires no movable insulation.

Fig. 3-44 Evaporative cooling methods. (a) Wind. (b) Interior pool. (c) Passive evaporator.

Fig. 3-45 The Cool Pool.

Although evaporation is the most important method of heat rejection, the Cool Pool does not introduce any additional water vapor into the interior space.

Experiments to date have proven the Cool Pool to be a powerful passive cooling system, capable of providing 100% of the cooling needs for a building in many areas of the country. It requires no daily tending and functions without any supplementary power. The thermosiphoning Cool Pool allows the pool to be thermally isolated from the interior space, thereby increasing design freedom compared with other evaporative roof ponds. The water-filled columns can be used as thermal mass for a solar heating system during the winter.

The Cool Pool was tested in a small (144-ft²) heavily insulated experimental building near Winters. The roof pond consists of a 60-ft² X 1-ft deep galvanized steel pan, located on the northern portion of the roof of the test building. The pond is covered by a plywood shade that prevents direct radiation from striking the water. The bottom of the pond is insulated from the test building interior by R-19 fiberglass batts. The pool is connected to four steel culvert pipes (8 ft high, 18 in. diameter) located in the test building. A 5-ft plastic pipe brings water from the bottom of the pool to the bottom of the cylinders. A riser carries warmer less dense water from the top of the cylinder to the top of the pool. Both the pool area and the number of columns could be reduced, since this experimental system is oversized for the cooling load of the test building. Work underway will verify performance of the Cool Pool and make possible accurate sizing for different cooling loads and climates.

Simulations of Rockbin Cooling

The feasibility of using rock bins for comfort cooling in a small energy-efficient residence has been examined by computer simulation at Trinity University in San Antonio, Texas for the following cities: Albuquerque, Atlanta, Bakersfield, Baltimore, Dodge City, El Paso, Nashville, San Antonio, Shreveport, and St. Louis (Ref. 3-31). The 1224-ft² house used as a base in this assessment has good energy-conserving properties. The house is assumed to have cathedral ceilings (no attic) and to be slab-on-grade construction. It faces south, with the carport and the utility room on the west.

The rockbed is assumed to have a volume of 512 ft³ and an air-flow rate of 1200 ft³

per minute; selection of these values was based on thermal storage requirements and pressure loss considerations.

Operation of the rockbed is as follows:

- ◆ At night, if the ambient dry-bulb temperature is lower than the average rockbed temperature, air is drawn through an evaporative cooler, through the rockbed, and vented outside.
- ◆ During the day, rockbed air is circulated through the house if the house temperature is above 74°F and the rockbed temperature is below 78°F and lower than the house temperature. Otherwise, the air conditioner is used.

A comparison of the electrical consumption, for each of the ten cities, of a house conventionally cooled and a house with this rockbed system showed (as expected) that the most significant savings were in hot dry climates; hot humid climates showed marginal savings; and moderate-temperature high-humidity climates showed little or no savings. The critical factor in the application of rockbeds for comfort cooling seems to be the nighttime ambient wet-bulb temperature, since the rocks cannot be cooled below this.

COMBINATIONS

Many successful passive solar homes combine various passive features. For example, the south-facing side of a building may consist of alternate direct-gain and Trombe-wall sections: the direct gain to provide quick warm-up in the morning and the Trombe wall to store heat for the evening. Thus by combining passive system types, one can take advantage of the best features of each type to obtain a system that is more flexible and versatile than a single-system type would be.

MILD CLIMATE RESIDENCES

Vertical Solar Louvers for the Bier House

Jim Bier (Ref. 3-32) has designed and built a two-story passive solar house in Ferrum, Virginia using *vertical solar louvers* which are rectangular masonry columns set at an angle immediately behind the 330 ft² of south-facing glass (Fig. 3-46). The 1300-ft² home uses an inverted two-story plan with the main entrance, kitchen, and living room

Fig. 3-46 The Bier house, Virginia, with vertical solar louvers. (a) South side showing louvers. (b) Floor plan. (c) Operation of louvers.

on the second level and the bedrooms on the first floor. The louvers extend the full height of the house and are oriented 45 degrees from the south (along the SE-NW axis) to admit morning sun directly and absorb afternoon sun for use in the evenings. The louvers are made from concrete blocks filled with sand as are the exterior and first floor partitions.

A long clerestory provides direct solar gain to the north side of the second level. Measurements taken before storm windows and insulating shades were installed found the indoor average temperature to be 67°F upstairs (20°F swing) and 62°F downstairs (10°F swing) during a four-day cold spell with 32°F outdoor temperature. The outer face of the wall experienced temperatures from 70 to 140°F, while the inner face varied

from 70° to 80°F. The owner recommends that others use gravel-and-sand aggregate block instead of the light-weight concrete block that he used. The heavier, more conductive aggregate could probably cut the temperature swing in half.

Hybrid ClearView Collectors in Tucson

Five ClearView collectors (Fig. 3-47) using heat-absorbing glass and a small fan are keeping a 1500-ft² house in Tucson, Arizona warm during sunny periods of winter (Ref. 3-33). The collector is a transparent site-built unit that uses off-the-shelf components: heat absorbing "solar bronze" glass, tempered double patio-door glass, and masonry block walls. The outer glazing covers the exterior masonry wall, which

has ClearView absorbing glass in it. The fan circulates the collected solar heat throughout the house. The ClearView panels are esthetically pleasing and allow light to enter the room without obstructing the view.

The Geisel Residence in New Jersey

Harrison Fraker and Lawrence Lindsey of the Princeton Energy Group (Ref. 3-34) have designed the Geisel Residence in Princeton to incorporate a combination of focusing roof aperture, water walls, and direct-gain heating systems (Fig. 3-48). The large 2880-ft² two-story house in the moderately cold New Jersey climate (4512 heating degree days) is also designed to allow the owner to take advantage of time-

This page

Fig. 3-47 ClearView collector using heat absorbing glass.

Fig. 3-48 The Geisel residence, New Jersey. (a) Section. (b) South facade, showing water walls and direct gain windows.

Opposite page

Fig. 3-49 Direct gain into living and dining areas.

Fig. 3-50 The focusing roof aperture for the Geisel house. (a) Exterior. (b) Shutter and reflector. (c) Hallway. (d) Entry.

of-day utility rates: the thermal storage is charged with heat from the electric backup system during the off-peak period (9 PM to 5 AM). Electricity used at night costs less than half of that used during the day.

Water walls made from Kalwall fiberglass-reinforced plastic tubes are located on the south side of the lower level. Insulating shutters lower by a bottom hinge and expose their inner mirrored surface (LUMAR reflective plastic film) to reflect additional sunlight onto the water walls. At night, the R-9 shutters are closed by means of a simple winched pulley to keep the stored heat in the house. A small space between the bottom of the shutter and the bottom of the glazing allows snow or rain to run off the shutter as it is closed. Crushable weath-erstripping around the edges of the glazing

insures an airtight fit for the shutter.

Because there is a sheetrock wall between the water-filled tubes and the living space, the heat distribution is primarily convective. Natural thermosiphon loops take heat from the tubes upward through the southern upstairs rooms and then down to the north side of the lower level. The designer recommends that the sheetrock wall be omitted so that heat from the water wall can be transferred by radiation, which is significantly more comfortable when the exterior insulation is in place. The southern upstairs rooms also benefit from direct solar gain, with water-barrel storage (Fig. 3-49). Detachable rigid insulation boards prevent nighttime heat loss from the upstairs windows.

The focusing roof-aperture arrangement (Fig. 3-50) keeps the north side of the upper level warm. The arrangement consists of a vertical layer of acrylic glazing which resembles a clerestory window but which admits sunlight into the triangular attic space; from there it is reflected (by the mirrored side of an adjustable rigid insulation board) through a horizontal layer of acrylic glazing which resembles a skylight. Directly below the horizontal glazing a series of water-filled barrels stores the solar heat. The adjustable insulation boards are closed over the horizontal glazing to keep the heat in the house at night. One feature of this arrangement is that the overhang, which permits solar gain in winter, virtually shuts off the roof-aperture heating system in summer. The tops of the barrels under the roof aperture generally

get extremely hot, and temperature stratification problems have been experienced. The owners are trying transparent barrel covers and are attaching conductive materials from the steel drum covers into the water. Preliminary performance evaluations indicate that the house will exceed its predicted 70% solar contribution.

COLD CLIMATE RESIDENCES

Two Passive Solar Homes in Colorado

Architect Peter Dobrovoly and consultant Ron Shore have designed two homes that take advantage of site conditions in the mountains of Colorado (Ref. 3-35).

The 1850-ft² Kairath residence in El Tebel, Colorado (7100 ft. elevation, 7500 heating degree-days) is constructed partially below grade and has sod roofs (Fig. 3-51). The exterior walls are masonry covered with urethane insulation on the outside. Above grade, plywood and cedar strips cover the insulation. Solar heating is provided by a combination of direct gain (165 ft² of glass facing the south and east views), a 300-ft² 12-in. thick dark blue Trombe wall (in 3 sections), and a greenhouse that has 155 ft² of glazing. The Trombe wall uses insulating curtains composed of several layers of thin, flexible material which are inflated (creating airspaces) by warm air updrafts, either from the Trombe wall on winter nights or from the heated window glass on summer days. The living-room Trombe wall uses

conventional design, but the main-level south-bedroom Trombe wall is slightly unusual: the top vents of the wall open into the framing space where heat is directed to the hollow brick wall between the north and south bedrooms. Heat stored in that wall and direct solar gain from the clerestory windows keep the north bedroom warm.

Excess heat from the greenhouse is stored when air from the top of the greenhouse is blown into gravel between two masonry walls on the north side. Heat radiates from the gravel to the room on the north. The house has performed quite well, requiring electric backup heat for only a few days during cold cloudy spells.

The Fox Residence located in Snowmass, Colorado (elevation 7200 ft, 8500 heating

Fig. 3-51 The Kairath residence, Colorado. (a) Perspective. (b) Section. (c) Floor plan.

degree-days) was integrated into a steep hillside (Fig. 3-52). The partially subterranean building has sod roofs that have been seeded with native grasses and wild flowers. The client, an active outdoorswoman, requested a cold sleeping place under the stars; to meet this requirement, the high sleeping loft has a large amount of glazing and no thermal mass. Only 590 ft² of the house's total 1146 ft² is heated space. Greenhouse, sleeping loft, utility room, storage space, stair, and hallway areas all act as buffer zones between the outdoor environment and the warm living area.

Hours of available sunshine at the site are short, so a direct-gain approach was used to take advantage of them; and glazed areas are insulated by shutters and curtains when the sun goes down. Solar heat is

stored in the thick foundation walls required for subterranean construction and in a central gravel-filled masonry wall through which warm air from the greenhouse is forced. The greenhouse itself uses water cans containing 265 gallons and a solid north masonry wall to store heat and maintain a warm growing space. The vertical form of the house will aid natural summer ventilation.

The house performs well to the owner's specifications: inside air temperature ranges from 50 to 80° and the sleeping loft experiences a 35 to 75° range. The electric backup is rarely used, but the efficient woodstove helps on some colder nights. The owner enjoys a varied thermal environment and, by design, has extended the range of comfortable temperatures

within her home in keeping with her lifestyle.

The Tymura Residence in Canada

The Tymura residence, Thunder Bay, Ontario (Ref. 3-36) is partially earth-bermed and uses passive and active space-heating systems to cope with a 10,500 heating degree-day climate (Fig. 3-54). Extensive south glazing, augmented by a reflective canopy, admits direct solar gain during the day. Insulating shutters prevent heat loss at night. An overhang and deciduous trees protect the house from overheating in the summer. The active space-heating system employs flat-plate liquid collectors that heat water for the large storage tanks located in the house next to the

Fig. 3-52 The Fox residence, Colorado. (a) Perspective. (b) Floor plan. (c and d) Sections.

north wall. These tanks radiate directly into the open areas of the house. A heat exchanger in the tank provides approximately 80% of the heat received for the domestic hot water.

COMMERCIAL AND LARGE RESIDENTIAL BUILDINGS

Nature Center in Indiana

A 3200-ft² public building (Fig. 3-54) uses direct and reflected solar gain, plus heat storage in quarry floor tiles and two rows of water-filled fiberglass tubes, to maintain a comfortable space for visitors in Patoka Reservoir Indiana State Park (Ref. 3-37). The 1530-ft² south roof (at a 60-degree tilt) is a Beadwall; this device consists of two

layers of tempered glass forming a space that is filled with insulating polystyrene beads when the sun goes down. When sun is admitted through the south glazing, it strikes either the row of water-filled tubes on the north or the north ceiling which is covered with acoustical tiles coated with mirror-finish aluminized polyester film. Sunlight striking these tiles is reflected down to the south row of water tubes or to the thermal storage in the floor (wire mesh lecture seats allow the reflected sunlight to pass through them). A small north clerestory panel that provides natural illumination also uses a Beadwall. Operation of the south Beadwall can be reversed in the summer to provide shading during the day (panels can be partially filled) and to expose the space to the night sky for nocturnal radiative cooling.

Solar Housing Project in Kentucky

Lakeland Wesley Village (Fig. 3-55), a 96-unit housing development for the elderly in Kentucky, was redesigned by the TVA for energy conservation just prior to construction (Ref. 3-38). The redesign included direct-gain and Trombe-wall passive systems, an atrium that provides a buffer zone and a social space, solar domestic water heating, and backup heating by a solar-assisted water-to-air heat pump. The site plan was changed to use east-west oriented linear rows of connected apartment buildings, providing more southern exposure in a more compact form than clustered apartments, with less chance of self-shading.

The architectural components of the build-

Fig. 3-53 The Tymura house, Ontario. (a) View from the south. (b) View from the northwest.

Fig. 3-54 The Patoka Nature Center, Indiana. (a) Winter operation. (b) Summer operation. (c) North roof Beadwall system.

ing were chosen to increase the thermal mass. Polystyrene-filled concrete block exterior and party walls were used. Polystyrene insulation boards were placed on the outside of the exterior walls. All windows were double glazed to reduce heat loss and operable to allow natural ventilation.

The passive systems in the project include an unvented Trombe wall made from concrete-filled concrete block to heat each apartment and direct gain through window openings in the Trombe walls and through the clerestory windows in the atrium. Overhangs protect the solar apertures from the summer sun. The Trombe walls in the southern row of apartments are double glazed; those in the northern units that face the atrium use single glazing. The passive

systems are expected to provide about 70% of the annual heating requirements. It was estimated that the redesign would save \$2,000,000 in energy over a 30-year period (assuming fuel costs escalate at 8% per year) when compared with the original design.

RETROFIT PROJECTS

Designing a passive solar system to fit an existing house is often more difficult than designing a system for a new house because the designer has less control over the orientation, shading, and space planning. However, a few passive systems, especially solar greenhouses (also called sunspaces) and Trombe walls, have been notably successful in retrofit applications.

Smaller devices such as convective window boxes and panels are also being used in retrofitting.

The Telluride School

One of the largest solar retrofits is the Telluride School in Colorado (Ref. 3-39). After the building's roof and perimeter insulation were added, the most significant energy-loss problem was the numerous leaky single-glazed windows and doors. The design solution was to enclose parts of the building in glazed "solar envelopes," collecting heat in the southwest envelope, and storing it below the northeast envelope (Figs. 3-56, 3-57). Some heat is also stored in the masonry wall of the southwest envelope. The envelopes add 4600 ft² of usable space that can include a

Fig. 3-55 The Lakeland Wesley Village, Kentucky. (a) Floor plan. (b) Site plan. (c) Section.

greenhouse, play space, and individual study areas. Heating of the classrooms is provided by open doors and windows (in what used to be the exterior wall). In addition, the southwest wall of the gymnasium wing was converted to a 2000-ft² Trombe wall, collecting and storing solar heat (Fig. 3-58). Ceiling fans in the gym help circulate the warm air throughout the space.

Test Studio in Wisconsin

In 1977, Don Schramm designed and built a sunspace onto the south face of an existing farm building (Fig. 3-59) so that the building could be used as a studio and office space in the severe winters experienced near Madison, Wisconsin (Ref. 3-40). The 350-ft² building, originally built

in 1920, already had good southern exposure with a roof overhang to block the summer sun. The retrofit consisted of extending the 45-degree roof line with glazing (4 panels of 0.040-in. Kalwall fiberglass-reinforced plastic and 4 panels of 1/4-in. Plexiglass) to an insulated wood base on the ground. The Plexiglas at a total material cost of \$4.90/ft² was about twice as expensive as the Kalwall. Heat is stored in the 12-in. deep gravel bed and in the 12-in. thick, 3-ft high concrete south wall of the existing building. Vents at each end of the sunspace exhaust summer heat. An operable skylight performs that function in the building itself. The existing windows in the south wall now act as dampers to control the flow of air from the greenhouse. A wood stove provides backup heat.

An inexpensive monitoring program, using simple thermometers and manual recording of readings taken twice daily, indicate that thermal performance is better than estimated. The calculations indicated that about 55% of the season's heating load would be met by the passive system, but the solar fraction actually turned out to be 70%.

A 1910 California Bungalow

Kenneth Haggard and Polly Cooper have rehabilitated a California bungalow in San Luis Obispo (Ref. 3-41). The bungalow-style house typically includes large overhangs for shade and large vented attics for natural cooling (Fig. 3-60); but the light frame construction contains very little

Fig. 3-56 The Telluride school storage envelope section.

Fig. 3-57 Collection envelope section.

Fig. 3-58 Trombe wall for the Telluride gymnasium.

Fig. 3-59 Sunspace test studio, Wisconsin. (a) Floor plan showing thermometer locations. (b) Section.

thermal mass, and virtually no insulation. San Luis Obispo is surrounded by steep hills that limit the town's growth, so new home construction is almost impossible and renovation is a much more attractive solution. Aside from the energy savings from the solar retrofit, the high-quality materials and mature vegetation that "come with the house" are valued benefits.

The retrofit consisted of three systems:

Direct-Gain Dormer. The attic was transformed into a direct-gain solar dormer using water tubes for thermal storage. To accomplish this, the south side of the existing roof was replaced with 80 ft² of vertical double glazing. The rafters were reinforced to form a high open space with glazing on the south and containing horizontal water tubes (12-gauge steel

tubing painted inside with asphalt emulsion). The tubes hold 4000 lbs of water and store 50 Btu/°F per ft² of glazing (Fig. 3-61).

Solarium. The solarium is formed by a large double-glazed bay window with a carefully designed overhang. Heat is stored in the floor, which is composed of 1-5/8-in. thick concrete block wall caps over plywood over R-13 polyurethane foam insulation. The block wall capping is about one-tenth the price of conventional tiles and much better for thermal storage. The winter sun penetrates most of the block floor area, but the mass/aperture ratio is low: 6 Btu/°F per ft² of glazing. The excess heat will rise to the attic and be transferred by convection to the water storage tubes (Fig. 3-62).

Sunspace/bath. The bath on the lower level creates a sunspace made of glass block with a wireglass ceiling. The separate water closet has a lowered ceiling, allowing a duct to the north study to set up a thermosiphoning loop with the only room that has no southern exposure (Fig. 3-64).

Beadwall Retrofit in Kansas City

Eric Kjelskus has installed a Beadwall system in his 35-year-old two-story frame house as part of the remodeling of the second floor (Ref. 3-42). The modification added 550 ft² to the living area, which is now 1724 ft². The weatherization part of the retrofit included caulking around the foundation and windows, blown-in R-16 cellulose wall insulation, storm windows, and

Fig. 3-60 California bungalow retrofit. (a) Before and after floor plans. (b) Before and after sections.

Fig. 3-61 Direct gain attic space with horizontal water tubes.

Fig. 3-62 Solarium collects sunshine through large bay windows.

Fig. 3-63 New sunspace/bath heats a north study.

attic ridge and gable vents (0.5% of floor area). The principal element, however, was the Beadwall that heats the room on the south end of the second floor (Fig. 3-65). The walls of the room were built with R-19 insulation and the ceiling R-40.

The Beadwall is slightly unusual in its pentagonal shape; 11 ft 9 in. wide at the base, it has vertical sides of 5 ft 6 in. and 6 ft 9 in. and is peaked at its 10 ft 5 in. height. Approximately 20 ft² were added by not squaring the Beadwall at a 7-ft height. Framing obstructs only 6% of the surface. The Beadwall glazing is 3/16-in. acrylic sheets (Plexiglas).

The main construction problems involved the use of Plexiglas for glazing. The backing paper did not peel off easily (it took 20

hours) and the static electricity problems of the Beadwall (the styrofoam beads tend to stick to the sides) were increased with Plexiglas. The Beadwall room usually stays at about 60 to 70°F and rises to 80°F even when the outside temperature drops to 10°F. In summer, the Beadwall room does not require any mechanical cooling, though the rest of the house may need air conditioning 4 or 5 days a year.

In strict economic terms, the \$2000 investment in materials may not pay back for 20 years. However, the owner feels the house has greatly increased in value by the addition of 550 ft² of quality living space with no added heating or cooling.

Three Passive Devices for Low-Cost Retrofits

The Bergen County Community Action Program (BCCAP) in New Jersey has developed three passive retrofit devices to supplement their federal weatherization program for low-income families (Ref. 3-43). Since the program is carried out by federally subsidized employment (CETA) trainees, the design of the devices had to be kept simple enough to allow on-the-job learning. Window-box air heaters, thermosiphoning air panels, and direct-gain glazing with storage were the three designs chosen.

The window box (Fig. 3-66), a detachable device used with double-hung windows, depends on natural convection to provide daytime heating. Because no storage is included, and because the expense of insulating and sealing the back and sides increases the initial costs (around \$130 in 1978), the Bergen County program found this device to be only marginally cost-effective for use on residences.

The thermosiphoning air panel (Fig. 3-67) consists of a metal plate in a glazed box that is built into the wall of the house. Air flows behind the blackened metal collector plate. Heat losses from the side and back are reduced because the back of the panel is the interior wall of the house. Storage is generally omitted with this device as well; however, the lower cost (\$115) and higher efficiency make the panels preferable to the window boxes for daytime solar heating.

Glazing and storage form a direct-gain system when part of the south wall of a house is replaced by two layers of fiberglass-reinforced plastic glazing, and water-filled storage tubes (made of the same material) are installed across the room from the new glazing. Thermal curtains cover the glazing at night. The 1978 cost for materials averaged \$219 for this application. When site conditions are appropriate, the BCCAP favors this system for solar heating, if a significant change in the living space is acceptable.

Fig. 3-64 Beadwall retrofit for the Kjels house, Missouri. (a) Second-floor plan. (b) Perspective of Beadwall.

Fig. 3-63 Window-box retrofit, New Jersey.

Fig. 3-66 Thermosiphoning air panel retrofit, New Jersey.

Sizing Methods and Performance Prediction

Passive solar design is a relatively new field; and the mathematical techniques most appropriate to efficient and accurate analysis are still being developed, tried out, and modified as learning continues.

At the present time, analysis techniques can be found at all levels of sophistication from simple rules-of-thumb for deciding on the size of passive solar components to powerful and sometimes complex computer methods that can mathematically simulate the hour-by-hour thermal performance of an entire building.

In the design of passive solar buildings, *sizing* refers to finding the dimensions of the functional elements of a design; the term also is used loosely to include determination of the shape, mass, location, orientation, and so on, of those elements. It is especially important that approximately correct sizing and placement of large passive components (such as Trombe walls, direct-gain south windows, and clerestories) be done as early in the design phase as possible; otherwise, entire portions of the design may have to be redone, and much of the work done up to that point may be wasted.

Performance prediction is the estimation, usually before a structure is built, of quantities such as temperature distribution, internal air temperature, mean radiant

temperature, comfort, total energy use, backup energy use, operating costs, and economic performance. Most of these eventually relate in some way to user satisfaction or dissatisfaction with the building.

There are two major ways in which performance may be predicted: theoretically and experimentally. In the theoretical approach, the laws of physics are used to mathematically predict what will happen to a structure, given details about the structure and some appropriate input conditions (climate and resident lifestyle, for instance). This assumes that all the necessary equations can be written and solved. Experimentally, a building can be constructed and its performance measured over some period of time. If another similar building is constructed later, its perform-

COMPUTER TYPES AND PROGRAMMING LANGUAGES

Programmable Calculators can handle only simplified passive design calculations since they are limited by their slow speed (on the order of 100 instructions per second) and their relatively small memories (usually less than 2000 instructions). Instructions are fed into the calculator via special keys. Most calculators for scientific and engineering work are made by two companies: Texas Instruments (TI), whose calculators use algebraic notation in which equations are entered in a form similar to their written form; and Hewlett-Packard (HP), whose calculators use "reverse Polish notation" in which numbers are stacked in successive memory positions and the operation is entered after them. These two languages are not compatible; a program written for a TI calculator will not run on an HP, and vice versa.

Microcomputers, which are desk-top size, operate at several thousand instructions per second, although their effective speed depends somewhat on the programming language used. Most have 16,000 to 64,000 8-bit words of memory, and power requirements are from tens of watts to a few hundred watts. They are usually used by one person although timesharing systems for more than one user are available for many microcomputers.

Minicomputers, which vary from desk-top size to refrigerator size, operate slightly faster than microcomputers and have a memory of 16,000 to 256,000 16-bit words. Power use is from a few hundred watts to a few kilowatts.

Large-Scale Computers, sometimes called **Maxicomputers**, are normally used by several people simultaneously. Computers such as the CDC-7600, for example, perform several million operations per second and may use tens of kilowatts of power. Memory for the 7600 is 572,000 64-bit words.

The **Computer Programming Languages** most likely to be encountered in analysis of passive solar systems are FORTRAN, BASIC, and PASCAL. These languages simplify program writing since one word or character may stand for a whole sequence of machine operations.

BASIC (Beginners' All-purpose Symbolic Instruction Code), introduced in 1965, has become widely used on microcomputers since it does not require a large memory to run. There are many versions, each designed for a specific machine or family of machines; it may be difficult to modify a program to run on a different machine.

FORTRAN (FORMula TRANslator), in use since 1957, is the most widely used computer language for scientific and engineering problems; and most passive solar programs written for large computers are in FORTRAN. Several similar versions are in use, and FORTRAN programs written for one computer may not run on a different computer without modification.

PASCAL, named for a 17th-century mathematician, was developed in 1971 to teach structured programming concepts. Its popularity has been rising rapidly, especially with microcomputer users. Efforts are underway to internationally standardize this language and make it easy to transfer programs from one type of computer to another.

ance will be expected to be similar to that of the previous building.

In fact, both of these approaches are used. Theory provides the basic framework and is augmented by data obtained from experience. Equations contain constants and coefficients whose values depend on the materials used and on the building design—numbers that usually can be obtained only from experience. In some cases, theoretical calculations would be very time-consuming or expensive, and experimental data can be substituted. Performance prediction is desirable because it is much cheaper and faster to calculate what is likely to happen to a building than it is to construct the building and find out by testing.

HAND-CALCULATION METHODS FOR SIZING AND PERFORMANCE PREDICTIONS

When energy was cheap, it appeared to be sufficient for designers to do only a "worst case" analysis of the heat loss or heat gain of a building. The temperature inside the building was assumed to be a known constant, the worst likely outside temperature (the design temperature) could be estimated from past meteorological records, and the overall thermal resistance of the building was calculated from the design. Knowing these, one could calculate the maximum rate of energy loss and size the heating system accordingly. The same principles were applied to calculation of cooling loads. Solar gain was not usually included directly in the calculations. For most buildings, this is still the only type of thermal analysis done.

Although the above calculations are not trivial, they are not enough for passive solar buildings. In designing passive buildings, it is important to know the amount of heat gained and lost by the building on some particular day of the year, or monthly, or as an average for the year; however, the daily performance of the building should also be calculated so the designer can make a judgment about whether the building is likely to be comfortable. The designer also should know something about the distribution of heat within the building, especially if air movement from one part of the building to another depends on natural convection.

Many of the first passive solar buildings were constructed without undergoing a "complete" thermal analysis; this is still true of many now being designed and built. In some cases, there is not yet enough expe-

rience from similar buildings on which to base a numerical calculation; the best that can be done is to make use of approximations and qualitative information from previous structures. For designs which differ substantially from any existing building, data are not available on which to predict performance. In some cases, designers are not aware of techniques that could be used. For other designs, adequate calculation techniques simply do not yet exist.

The primary reasons that available sizing and performance prediction techniques are not used more widely (aside from their cost which is sometimes prohibitive) is probably that architects and designers are not familiar with them, or do not understand them completely, or have not yet seen enough proof that they work well. Many architects, even those who know something about passive buildings, are hesitant about getting involved in passive solar design because of the additional calculations needed.

These extra calculations for passive solar buildings, beyond those normally needed for conventional buildings, have been the subject of many papers presented at recent conferences. Some possible approaches are shown below:

Rules-of-Thumb

At the present time, performing an exhaustive thermal analysis of a building during the early stages of design is impractical, time-consuming, expensive, and probably unnecessary. For many designs, early use of simple rules-of-thumb will help to insure that sizing of passive components is reasonable. These rules-of-thumb have come from experience gained from monitored buildings, from patterns observed in computer simulations of specific designs, from geometrical considerations, and from simplifications of heat transfer theory.

Many methods of sizing and performance prediction, especially hand methods, rely on breaking up the problem into smaller, more manageable pieces by making simplifying assumptions. As an example, it is possible to calculate separately the average temperature and the temperature swings and then to combine them to obtain an estimate of the temperature profile during the day.

Buildings with small amounts of mass will have about the same average temperature as buildings with large mass, but their daily temperature swings will be larger. Thus it is the amount of mass (the "effective mass," really) that determines the maximum deviation of the indoor temperature from the average temperature.

Fig. 4-1 Ratio of south-glazing area to floor area.

Note: These ratios apply to a well-insulated space with a heat loss of 8 Btu/day-°F per ft² of floor. If the heat loss is more or less than this value, adjust the ratios accordingly.

Source: Refs. 4-1 and 4-2.

Ratio of South-Glazing Area to Floor Area				
Outdoor Temperature ¹	36°N	40°N	44°N	48°N
Cold Climates				
20°F	0.24	0.25	0.29	0.31
25°F	0.22	0.23	0.25	0.28
30°F	0.19	0.20	0.20	0.24
Temperate Climates				
35°F	0.16	0.17	0.19	0.21
40°F	0.13	0.14	0.16	0.17
45°F	0.10	0.11	0.12	0.13

¹ Average clear-day temperatures for December and January, usually the coldest months.

A building that has no heat-trapping capabilities will have the same average temperature as exists outside. A building that traps heat in the winter has a higher average temperature than outside, the actual temperature being determined by the balance between solar gain and thermal losses.

If the amount of sunlight and the outside temperature were constant (conditions which do not exist), the internal temperature of a building would gradually reach a "steady-state" value where the heat losses just balance the solar heat gain. Under the somewhat more realistic assumption that solar radiation and outside temperature vary daily in a periodic manner, then the inside temperature will fluctuate each day above and below the average steady-state temperature.

To facilitate preliminary sizing, Mazria (Ref. 4-1) has provided the following table (Fig. 4-1) of the ratios of south-glazing area to floor area that are needed to maintain an average interior temperature of 68°F for a space having an average heat loss of 8 Btu/day-°F per ft² of floor space, for several combinations of latitude and average winter temperature. The ratios must be adjusted for other heat loss rates.

Although the above table is derived from a combination of computer simulations and

actual experience, its usefulness is limited. For one thing, when the building heat loss is estimated initially, a certain area of south glazing must be assumed. Now if the table shows that a different south-glazing area should be used, the heat loss of the building may be substantially changed. Going through the procedure one more time with the new heat loss rate would give a better estimate. In addition, Mazria's table (Ref. 4-1) assumes clear-day insolation. If your design is for an area which is cloudy much of the winter, it might be better to increase the south glazing, while also increasing thermal mass to reduce the likelihood of overheating on clear days. The point is, the designer needs to understand the assumptions made and the limitations of rules-of-thumb to be able to use them properly.

Similar tables for thermal storage design (Trombe walls or water walls), also from Mazria (Refs. 4-1, 4-2), are presented in Figs. 4-2 and 4-3.

The best thickness and surface area for the thermal mass depend on material used, type of system, surface color, and so on; computer simulations are probably the best source to date for this design information.

Several general rules-of-thumb for sizing south glazing in the northeastern United States are listed by Kohler et al. (Ref. 4-3).

One rule is to provide minimum south-aperture areas of at least 1 ft² for every 40 to 60 Btu/°F-day of heating load, and to provide additional south-aperture area up to 10.8 ft² for every 10 Btu/°F-day of load (or to architectural limits) but only if rules-of-thumb for sizing thermal mass are met.

Rules-of-thumb are very useful for sizing components in the initial stages of some of the "traditional" passive designs to get things approximately right; but they have not been in existence very long, and the accuracy of rule-of-thumb methods alone has not been verified by extensive experience. Additional analysis should be done later in the design process to insure that components are sized correctly.

Solar Load Ratio Method

One step up in complexity from rules-of-thumb are the graphical and tabular methods, such as the *solar load ratio* (SLR) method, for predicting the performance of passive designs.

The solar load ratio method was originally developed as a design tool for active solar systems (Ref. 4-4). It was later adapted for Trombe-wall and water-wall designs (Ref. 4-5) and now has been extended to include direct-gain systems

Fig. 4-2 Ratio of masonry wall area to space floor area.

Note: Ratios apply to a well-insulated space with a heat loss of 8 Btu/day-°F per ft² of floor. If the space heat loss is more or less than this value, adjust the ratios accordingly.¹

Source: Refs. 4-1 and 4-2.

Ratio of Masonry Wall Area to Space Floor Area				
Outdoor Temperature ²	36°N	40°N	44°N	48°N
Cold Climates				
20°F	0.71	0.75	0.85	0.95
25°F	0.59	0.83	0.75	0.84
30°F	0.50	0.53	0.60	0.70
Temperate Climates				
35°F	0.40	0.43	0.50	0.55
40°F	0.32	0.35	0.40	0.44
45°F	0.25	0.26	0.30	0.33

¹ For thermal walls with a horizontal specular reflector equal to the height of the wall in length, use 67% of the recommended ratio. For thermal walls with night insulation (R-8), use 85% of the recommended ratio. With both night insulation and reflectors, use 57% of the recommended ratio.

² Average clear-day temperatures for December and January.

Fig. 4-3 Ratio of water wall area to space floor area.

Note: Ratios given apply to a well-insulated space with a heat loss of 8 Btu/day-°F of floor. If the space heat loss is more or less than this value, adjust the ratios accordingly.¹

Source: Refs. 4-1 and 4-2.

Ratio of Water Wall Area to Space Floor Area				
Outdoor Temperature ²	36°N	40°N	44°N	48°N
Cold Climates				
20°F	0.52	0.55	0.65	0.80
25°F	0.45	0.47	0.55	0.64
30°F	0.36	0.39	0.45	0.55
Temperate Climates				
35°F	0.28	0.31	0.35	0.40
40°F	0.23	0.25	0.29	0.32
45°F	0.17	0.18	0.20	0.24

¹ For thermal walls with a horizontal specular reflector equal to the height of the wall in length, use 67% of the recommended ratio. For thermal walls with night insulation (R-8), use 85% of the recommended ratio. With both night insulation and reflectors, use 57% of the recommended ratio.

² Average clear-day temperatures for December and January.

(Ref. 4-6). The monthly solar load ratio is defined as the ratio of the solar energy transmitted through the glazing of the solar aperture during a one-month period to the total building heating load in the same one-month period. It is based on results from the PASOLE/SUNSPOT computer program, which will be discussed later.

If the performance of a particular building in a particular location is known, can the performance of a similar building in another location be predicted? The answer is "Yes" if a computer simulation is used to predict the building's performance. In addition, after several simulations have been run for different locations, the building's performance can be characterized well enough that simple formulas, graphs, and tables can now relate its performance in those locations to its performance in other locations. This is essentially what the solar load ratio method does.

The method relies on first calculating the amount of solar energy available; then calculating the building heat loss rate (from the thermal characteristics of the building); and finally using the ratio of these two for a particular location to estimate the approximate monthly solar heating fraction (the portion of the monthly energy needs that will be supplied by solar heating). The annual solar heating fraction can be determined from the monthly solar heating fractions.

The solar load ratio method has the advantage of being quite easy to use; the equations or graphs are few and relatively simple, and the process can be carried out in a very short time. In addition, tables in Ref. 4-6 for 84 cities in the United States and Canada allow the user to look up the monthly solar heating fraction with even fewer calculations.

The method has the disadvantage that, to date, information has been presented for only a few passive designs. And since the method is not exact in the first place, extrapolating to a different design is likely to produce results that are even more inaccurate. The method cannot predict hour-by-hour performance; and it contains some assumptions that may not always be valid, such as that the air temperature in the building is allowed to vary only from 65 to 75°F (backup heating or cooling would be used outside this range). Shading can have a significant effect on the performance of a passive solar building, but it is not included in the method.

The solar load ratio method has been adapted by several organizations for use on programmable calculators; some of these programs, which are commercially available, are mentioned below (Ref. 4-7):

- ◆ PSLR, from Fuller Moore of Miami University (Ref. 4-8), a program for the TI-59 calculator, uses the solar load ratio method for Trombe and water walls.
- ◆ PASCALC, from Total Environmental Action (Ref. 4-9), analyzes combinations of Trombe wall, water wall, and direct gain, with and without night insulation, by the solar load ratio method.
- ◆ SEEC VI, available from Solar Environmental Engineering (Ref. 4-10) for TI-59, HP-67, and HP-97 calculators, uses the solar load ratio method for Trombe and water walls and includes an economic program.

LASL6

LASL6, a microcomputer program written in BASIC, developed by Davis Alternative Technology Associates (Ref. 4-11) is also based on the solar load ratio method. In addition, this program includes calculations such as building heat loss, monthly solar radiation, etc., which generate data needed for the solar load ratio calculations. The program produces an output summary of auxiliary energy used and percent solar (month by month); it also estimates energy cost due to operation of auxiliary heaters. The program was designed for use in analysis of passive solar water-wall and masonry-wall systems.

SOLAR-5

Architects are trained to deal with graphic information; so it is no surprise that this computer program, developed in the Department of Architecture at UCLA, depends heavily on graphic presentation of information. SOLAR-5 (Ref. 4-12) is an interactive program (information exchanged back and forth between computer and user). It runs on a large computer and uses standard ASHRAE algorithms to compute quantities such as incident solar radiation, heat loss, and heat gain on an hour-by-hour basis.

The SOLAR-5 computer program plots a contoured surface on a video terminal. Up to 15 different quantities relating to thermal gain or loss can be displayed for a particular building design. For instance (Fig. 4-4), the program can show energy balance as the vertical dimension of a contoured surface, with the months of the year along one horizontal axis and time of day as the other horizontal dimension. The resulting surface appears to be a flat sheet that has been deformed; high spots represent heat gain and low spots show heat loss.

From the shape of the surface, the architect can easily see for what time of day and during what months heat is gained and lost. The best building design will have the flattest surface when overall heat gain and loss are displayed. It takes less than a minute to input design changes, compute a year's worth of data, and plot out a new set of curves. The architect gets immediate feedback on the consequences of a design change.

Fig. 4-4 SOLAR-5 graphic output.

BUILDING RESPONSE METHODS

The walls of buildings respond to sunlight and ambient temperature in a manner which depends on their heat-transfer and heat-storage properties. The way the surface temperature of a wall will vary with time can be predicted if the characteristics of the wall are known and if the variation with time of the driving forces (solar radiation and ambient temperature) are also known. Building response methods lead to much simpler and faster calculations than do the hour-by-hour simulation methods that use nodal networks (which will be described later); this technique is thus more amenable to the smaller and slower programmable calculator.

A performance prediction method devised by Goldstein (Ref. 4-13) generates building response functions that are used to write equations that will predict room temperatures during a day. The method is simple enough that it can be programmed on a calculator and takes about 30 minutes to run. Goldstein's model includes the effects of unequal absorption of sunlight by various interior surfaces, rather than assuming that absorption is the same everywhere, as some models do; but it assumes the fraction absorbed on each surface is known in advance by measurement or calculation. The diffusion equation (the differential equation that describes heat conduction within a material) is solved to obtain wall surface temperatures in terms of response

functions of the materials and of building.

Response functions show the relative surface temperature changes in materials as a result of changes in solar radiation and ambient temperature. Example response functions indicate, as expected, that concrete has less response than wood when external conditions vary rapidly.

The room temperature is derived from the wall surface temperatures. The model can be used to predict room temperatures for direct-gain, Trombe-wall, and water-wall systems. The method applies to buildings whose temperature is free-floating (uncontrolled), but approximations can be made to model managed buildings. Comparison with test data indicates good agreement for all hours of the day.

MODAL EXPANSIONS

Another calculation method for predicting the performance of direct-gain, Trombe-wall, and water-wall systems has been described by Carter (Ref. 4-14). Because Fourier-series solutions to the diffusion equation do not work well for situations where conditions change suddenly, such as when insulation is placed over a window or drapes are opened and closed, Carter uses *modal expansions*; these are solutions of the heat conduction equation in the form of an infinite series of exponentially decaying terms.

Fig. 4-5 Sample nodal network for a conventional house (nodes 1-6) plus water storage (node 7).

The contribution of the first few terms of the series is the greatest. Other terms are important when conditions change rapidly, but those terms decrease quickly and can usually be ignored with little sacrifice in accuracy. A three-mode solution satisfies the boundary conditions for a Trombe wall and accurately describes the wall's thermal performance.

Carter also describes two single-mode models. The principal (first) mode is the more important. If all other terms are ignored, additional simplifications can allow a programmable calculator to solve the equations. Single-mode models cannot predict the time-varying details of performance, but they can predict overall thermal performance.

NODAL NETWORK MODELS

In most standard heat-gain and heat-loss calculations for a building, heat conduction is assumed to be one-dimensional (i.e., heat is assumed to flow in only one direction within a building component); in the analysis of heat conduction through a wall, for instance, it is assumed that heat flows only perpendicular to the surface of the wall. In traditional heat-gain and heat-loss calculations, it also is usually assumed that heat conduction is steady-state; in other words, temperatures do not vary with time. These assumptions lead to equations which are easily solved. In passive solar energy calculations, however, where temperatures are known to fluctuate, conduction must be assumed to vary with time; but it still can usually be assumed to be one-dimensional. The differential equations which describe time-varying heat conduction can be solved exactly only for simple problems, but these equations can be replaced by finite-difference equations (which are approximations of the differential equations). Finite-difference equations can be solved by numerical methods with calculators or computers.

To set up the finite-difference equations a mathematical model of the passive system must be constructed. The model consists of a *nodal network*, in which the building and its components are subdivided into smaller masses (nodes). Temperature is assumed to be uniform for each node (see Fig. 4-5). One node might be assigned to a water wall, for instance, on the assumption that the water in the wall is all at the same temperature. A large, massive element might be

modeled by several nodes; for example, a masonry wall is modeled as several layers, one node per layer, each at a uniform temperature. Heat flow occurs only between nodes. The thermal resistance to heat flow between nodes is shown schematically as an electrical resistance symbol. If the temperature at each node in the model is known at some instant of time, and if the time-variation of external conditions (outside temperature, sunlight, etc.) is known, the future temperature at the nodes at some later time can be predicted, using the finite-difference equations.

The set of finite-difference equations (one equation for each node) is most conveniently solved by matrix methods, in which all the equations are solved simultaneously for the unknown values (the temperature at each node).

Twenty-two definitions of "simulation" are given in an article in the publication *Simulation* (Ref. 4-15). And Webster (Ref. 4-16) defines the term as "the imitative representation of the functioning of one system or process by means of the functioning of another, as in a computer simulation of an industrial process." As used here, "simulation" refers to the process of applying time-varying input conditions, such as sunlight and temperature, to the nodal-network model of a building to predict the thermal performance of the building in response to those varying conditions.

Many computer simulations are done on an hour-by-hour basis. That is, the temperatures within the building are predicted at a certain time, based on the conditions that existed one hour before and on the assumed values for sunlight, outside temperature, etc. during the past hour. These new temperatures then become the basis for calculations for the next hour. The maximum size of the time interval (or step) which can be used depends on the mathematical way in which the building is modeled. Some sets of equations require time intervals shorter than one hour.

Weather data, from a SOLMET weather tape or from some other source, may be used as climate input to a nodal network model which has been constructed from the known characteristics of the building. The response of the building to that input is then calculated over some period of time (usually a year for large computers and shorter times for smaller machines). At the end of the calculations, one can go back and see what the highest tempera-

tures were, what the temperature distributions were, and how much energy was used.

It is possible to use programmable calculators to do hour-by-hour simulations using nodal networks. These simulations do not model an entire year because this would take too long, and a very large amount of climate data would have to be put in by hand; but calculations can be done easily for a period of two or three days. An additional difficulty is that the programmable calculator does not have enough memory to do a detailed hour-by-hour simulation for a system as large as those that have been simulated with large computers; so calculator programs do the same types of calculations, but for smaller systems.

PEGFIX and PEGFLOAT

The Princeton Energy Group (Ref. 4-17) has developed two hand-held calculator programs for the design of direct-gain and attached-sunspace buildings. PEGFLOAT simulates a space to which no auxiliary heat is added and from which no excess heat is removed; the air temperature is allowed to float in response to exterior conditions. PEGFIX allows the user to specify maximum and minimum temperature limits and calculates the amount of energy added or removed to maintain those limits.

Both programs use a two-node network where only the average indoor air temperature and the average storage surface temperature are represented. These pro-

grams assume that air has no heat capacity, that masonry can be represented by a single value of effective heat capacity, and that all heat loss from storage is to room air.

TEANET

TEANET, available from Total Environmental Action (Refs. 4-3, 4-18, 4-19), is a general-purpose nodal-simulation program designed for the Texas Instruments TI-59 calculator with printer.

The TEANET calculator program is capable of simulating the operation of a model having up to 7 nodes, a limit which prevents use of the program to analyze designs for buildings with complex geometries. It will simulate the performance of direct-gain systems, Trombe and water walls, greenhouses, roof ponds, heavy mass buildings, rockbeds, or combinations of these systems.

TEANET calculates the temperature at each node on an hourly basis for 24 hours. Radiant and ambient temperatures are generated or can be entered manually. Upper and lower limits for thermostats can be set, and internal gains can be simulated.

TEANET consists of two programs: one stores and preprocesses data, and the second processes the data. Approximately 30 minutes are required to complete a 24-hour 7-node solution. Figure 4-6 illustrates the kind of nodal network that might be analyzed with the program.

Fig. 4-6 TEANET nodal network. The example house has a sunspace and a blower-assisted rockbed. Nodes are designated as T 's; capacitances (C 's) depend on the effective thermal mass; and heat transfer by convection or conduction is denoted by G 's.

CALOR

CALOR (Refs. 4-20, 4-21) is a microcomputer thermal simulation program for small buildings; it is written in BASIC. At present, CALOR models each element of the design as one node; this is appropriate for lightweight buildings but may not be accurate for buildings containing massive elements such as Trombe walls.

To simplify data input, typical daily temperature and insolation curves are reconstructed from historical average monthly data. Other inputs include building geometry, glazing areas, shadow factors, infiltration rate, occupant schedules, and material properties. Outputs include hourly nodal temperatures and heat flows, hourly loads, monthly loads, and fuel requirements.

The time it takes the program to run depends on the number of months for which the simulation is carried out and on the time step used. About 2 hours are required to simulate 12 months, using one-hour time steps.

PASOLE

PASOLE (PASSive SOLar Energy) (Ref. 4-22), a FORTRAN program developed by researchers at Los Alamos Scientific Laboratory (LASL) with funding from the Department of Energy, is probably the oldest and best known of the large passive simulation programs. It requires the use of a large computer, such as the CDC-6600 for which it was first written.

The program contains several predefined models—one for a Trombe wall, for instance, and a separate model for a water wall. The water wall is represented by a single node; the Trombe wall contains several nodes. The user can make changes in a model within the constraints that have been set up but should not use the model for a system for which it was not designed. In other words, there is a certain amount of inflexibility within individual models. The number of nodes is limited to 50. Auxiliary heat can be modeled as entering the system under the control of a thermostat, in this case modeled by a control node temperature.

An hour-by-hour calculation for an entire year for a 10-node model requires about 5 minutes of computer time on the CDC-6600. A model with 30 nodes takes about 40 minutes. Using a linearized calculation

procedure described in the PASOLE manual, the calculation time might be reduced by a factor of three.

PASOLE is not a user-oriented program; it was designed to be a research tool. The user is expected to have some knowledge of heat transfer principles and FORTRAN programming. It has been used extensively in validation studies at LASL to determine the accuracy of modeling methods. Passive test cells were constructed, data taken, and the results compared with computer simulations using the program. Several types of passive designs have been analyzed with PASOLE, and hundreds of computer runs have been made (Refs. 4-23 and 4-24). Recently, it was used to develop the solar load ratio method discussed earlier.

DEROB

DEROB (Dynamic Energy Response Of Buildings), another large simulation program, has been under development since 1972 by Dr. Francisco Arumi-Noe at the University of Texas at Austin (Refs. 4-25 and 4-26). DEROB is intended to be an architect's design tool, and it is capable of handling complex architectural shapes. The user specifies building geometry as part of the program input, and the program is then capable of displaying the structure of the building in perspective. For example, the user can view the building from the direction of the sun for various times of the day for several months of the year to see whether architectural shading devices appear to be effective. Thermal calculations at the outer surfaces of the building take into account direct and diffuse solar radiation and convective heat transfer but do not make allowance for moving shadows from external solar obstacles. Shading calculations in the program include effects from obstructing surfaces of the building itself as well as effects due to specular reflections but ignore diffuse radiation and diffuse reflection. DEROB also can handle thermally coupled volumes (heat exchange between rooms).

In February of 1978, weather data taken at the Balcomb house in Santa Fe, New Mexico, were used as input for a DEROB simulation of the house (Ref. 4-26). Temperatures predicted by DEROB were compared with temperatures measured in the Balcomb house for the same period of time. Agreement was close enough to continue validation studies of DEROB and to offer the program as a design aid tool.

DEROB handles building geometry well; but its solutions, based on a thermodynamic model, have not been extensively validated although the thermal network solutions of PASOLE have an extensive history of validation. The two programs were combined in 1978, creating a new program, DEROB/PASOLE (Ref. 4-25), which should be in the public domain and available for distribution when its validation has been completed. Long-range plans call for forming a design package that will be used by a larger number of people and will probably be compatible with use on microcomputers.

Los Alamos Scientific Laboratory has twelve test rooms, each with a different passive solar system, which have been instrumented and monitored. In the first phase of the validation of the DEROB/PASOLE program, six of these test rooms were simulated by students at the University of Texas at Austin (Ref. 4-25). Two water walls, one Trombe wall, one convective loop, one direct gain, one bead wall, and one concrete storage wall were selected. The DEROB/PASOLE system has the same inherent limitations as PASOLE in the number of nodes that can be run economically. For the purpose of this test, this limit was set at 39 nodes. Agreement between measured and simulated values fell consistently within 5%.

Initial validation results have been encouraging. The next phase in the development of the program is expected to consist of integrating the staggered nature of the thermodynamic model of the original DEROB into the bookkeeping logic of DEROB/PASOLE. Dr. Arumi-Noe estimates, based on past experience with the original DEROB, that this approach can result in increasing the number of nodes up to 200 or more while reducing the execution time by a factor of 10.

INTERFACING PASSIVE DESIGN PROGRAMS WITH BUILDING LOAD ANALYSIS PROGRAMS

Architects and engineers often use computer programs for building energy-load analysis on larger projects (Refs. 4-27 to 4-30). Passive design capabilities are being added to several of these, most notably DOE-2 (formerly DOE-1) as indicated in Refs. 4-30, 4-31, 4-32.

DOE-2 is an energy-analysis tool that simulates the hourly heating and cooling loads for each space in the building; the operation of the HVAC (heating, ventilating, and air-conditioning) distribution systems; and the operation of the building's primary heating, cooling, and electrical plant. It then calculates the hourly, monthly, and yearly energy requirements for the building and the building's life-cycle cost. It will also execute a cost-benefit analysis, allowing the user to rank various design options on the basis of cost and energy use.

The addition of passive capabilities to DOE-2 requires the generation of "weighting factors" suitable for the materials used in typical passive systems. Weighting factors are used in the load-determining part of the program to account for the time delay between an instantaneous heat gain (i.e. a pulse of solar energy entering a zone) and its effect on the heating or cooling load. This work has been successful in a test version of DOE-2, where a simulation of the direct-gain test cell at the Los Alamos Scientific Laboratory has predicted cell temperatures that agree well with measured data. Future work will be directed at accommodating other passive designs.

Efforts are also being made to add the HVAC-systems capability of the BLAST loads analysis program (Ref. 4-30) to the DEROB passive design program discussed above.

DAYLIGHTING DESIGN

As passive solar design is applied to larger structures, such as commercial buildings, interest in the use of daylighting techniques (Ref. 4-33) has begun to grow rapidly because daylighting can save a significant portion of a commercial building's lighting energy. Only about 10% of a residential building's energy budget goes for lighting (and most of this is used when daylight is not available) whereas up to 50% of an office building's energy is used to provide light during the day.

Commercial buildings are well suited to saving energy by daylighting because they are used mostly in the daytime and because they have relatively high levels of artificial lighting (expressed as installed watts/ft²). Shutting off artificial lights can also reduce the cooling load in such a building, since 75 to 90% of the energy used by a lamp is given off as heat. In the interest of energy conservation, natural lighting techniques should be combined with more efficient lighting systems and components, less wasteful design practices, and better system operation and maintenance.

Buildings that use daylighting have a further advantage in that they are much less sensitive to power interruptions than artificially lighted buildings. Life (and

work!) can go on even if the lights go off. The economics of commercial buildings are such that if daylighting can allow productive work during a power failure, as much money can be saved in one hour as would be saved by reducing the lighting energy demand for an entire year.

Energy Savings and Peak Power

The actual amount of lighting energy that can be saved in a building will vary from about 10 to 75% according to several factors: the availability of daylight, the age and efficiency of lighting equipment, control system design, and use patterns. However, in addition to charges for energy consumed, commercial buildings often pay a "peak power demand" charge, which can be a large portion of their energy bill. If the utility company has a summer peaking profile, the building's lighting demand will coincide with the utility system's peak—a most expensive situation for the building operator. Daylighting can save 10 to 20% of peak power demand, if both lighting and reduced cooling loads are considered, in a building that has about one-third of its floor space in the perimeter zone. (A "perimeter zone" usually extends about 15 ft from the window toward the building's interior.)

Thermal vs. Illumination Benefits

Although passive solar design and daylighting have the common goal of saving energy, the features used for one may con-

Fig. 4-7 Perimeter vs. area for a compact and an extended building form.

flict with the other. For example, heat loss from windows used for illumination (especially high windows or skylights on the north side of the building) may increase the heating needed, thus offsetting the savings in lighting energy. Solar heat gain may be undesirable where illumination is needed, especially on the south and west. Unlike solar heat which is collected primarily from the south, daylight is available from all building orientations; and it is easiest to design without direct sunlight. The form of a building designed for thermal efficiency will most likely be compact, to reduce conductive heat transfer through the building "skin" (walls, roof, and windows). Daylighting design, on the other hand, would dictate an extended building form to provide greater access to daylight and natural ventilation for more of the occupants. In other words, a daylit building should have a greater portion of its floor area in the perimeter zone. (A building can, for example, be designed to have twice as much perimeter zone area as another building that has the same amount of gross floor area, as shown in Fig. 4-7.)

The energy-saving capability of daylighting is now being considered in analyzing and predicting thermal performance of buildings, especially when some of the large computer programs are used. In most cases, daylighting benefits justify larger windows than would be considered optimum by thermal analysis alone.

Illumination Data

When daylighting designers are considering a specific building or site, they need to know whether the local sky is generally classified as clear (less than 30% cloud cover), partly cloudy (30 to 70% cloud cover), or cloudy (more than 70% cloud cover), because the brightness characteristics of each differ substantially. They also need to know whether certain acceptable conditions of outdoor brightness will be met, and for what portion of the time the building is in use these conditions will be met. Currently, this information is not readily available for most U.S. cities; so designers must rely on graphical approximations of available illumination levels.

Researchers at Lawrence Berkeley Laboratory (see Ref. 4-33) are attempting to find a computational procedure that will convert solar radiation data (which are reasonably reliable) to usable illumination data. At a site in San Francisco, radiation data and illumination levels are being recorded simultaneously to enable validation of such a computer program.

Design Methods

Several methods exist by which the levels of interior daylight illumination on a given horizontal plane (see Fig. 4-8) can be predicted and designed (Refs. 4-34, 4-35). There are graphs and tables, nomographs, protractors, and diagrams that can serve

as daylighting design tools; and actual scale models can be very successfully used outdoors or under artificial skies. Computer programs can indicate interior daylight illumination (in footcandles or equivalent-sphere illumination levels), although they cannot adequately model the effects of room details such as furniture.

There are currently two prominent methods of calculating available daylight:

- ◆ The *lumen method*, popular in the U.S., can handle either clear or overcast skies; but only a limited number of window configurations and relatively few calculation points within the room can be used.
- ◆ The *daylight factor method* can consider a wide variety of window configurations but until recently could handle only overcast skies; it now has been expanded at the University of California at Berkeley to accommodate clear skies (Ref. 4-36).

For design, it is important to remember that when the sky is overcast, the part of the sky overhead is three times as bright as the part at the horizon. And when the sky is clear, the section along the horizon is the brightest.

The daylight factor is the ratio of the daylight illumination at a given interior design point to the illumination available from an unobstructed sky on a horizontal plane outside. The idea is that once you find a daylight factor you multiply it by the available daylight to determine the interior illumination (in footcandles). The daylight factor accounts for light that reaches the design point by three paths (Ref. 4-37): the *sky component* which comes directly from the sky, the *externally reflected component* which reaches the interior point after being reflected by external surfaces, and the *internally reflected component* which has been reflected by the internal surfaces of the room (Fig. 4-9).

Fig. 4-8 Illumination and brightness: (1) light from source (in lumens); (2) light striking surface, or illumination (in foot candles); (3) light reflected or reflectance (in % of light from source); (4) light from surface, or brightness (in foot-lamberts).

Fig. 4-9 The three components of the daylight factor: sky component (SC), externally reflected component (ERC), and internally reflected component (IRC).

Researchers at the University of Washington (Ref. 4-38) have developed a simplified procedure for daylighting design that is based on calculations done using the computer program UWLIGHT (which is, in turn, based on the daylight factor method). The procedure is presented as a catalog of "daylighting fixtures," meaning windows and skylights. Each "fixture" has a corre-

sponding pattern of light distribution called a "footprint" which depends on the shape and location of the window or skylight. These footprints can be sketched onto a building plan in the design phase to show the combined effects of windows and skylights and their relative sizes and placement (Fig. 4-10).

Fig. 4-10 Footprints technique for predicting daylight distribution patterns. (a) Room perspective. (b) Footprints for the three windows. (c) Footprints for the clerestories. (d) Combined daylight distribution pattern.

Implementation Issues

The degree to which passive solar technology will be utilized on a wide scale will be determined by several nontechnical factors. First, the investment in a passive solar building must make good economic sense; that is, the benefits must equal or exceed the costs. Second, builders must be able to identify the increased profitability of passive projects, or (at least) the ways in which the passive elements can increase a project's chance of success. Third, the public must be educated about the benefits of passive buildings. And last—but not at all least—the federal, state, and local governments must provide support for innovation and research as well as incentives for builders and buyers.

ECONOMICS OF PASSIVE SOLAR BUILDINGS

For the designer, builder, or homeowner who is considering passive solar construction, questions concerning economics inevitably come to mind:

- ◆ How much will passive solar features increase the initial cost of a home? What effect will they have on resale?
- ◆ What size and configuration of glazing and heat storage will provide the most comfort at the least cost?
- ◆ What energy savings can be expected?
- ◆ How long will it take for the solar investment to pay for itself?

Obviously, some understanding of the economics of passive solar systems and the factors that influence system performance is needed for deciding whether or not to buy or build a solar home, and what solar design should be considered.

Measures of Economic Efficiency

Even though solar buyers may be well educated, environmentally aware, and interested in good quality construction and design, they often act as if the *time to simple payback* (the incremental cost of the passive features divided by the annual fuel savings) were the only economic factor that determines the feasibility of a solar design. But in reality, the economics of solar heating and cooling is strongly affected by a number of factors including building costs, current fuel prices and future increases, property and income taxes, insurance, and maintenance costs. The comfort and convenience afforded by particular passive solar features will also enter into the design decisions, as will esthetics and energy-conservation construction techniques.

A more realistic approach to the economics of passive solar buildings than calculation of the time to simple payback is the *life-cycle cost method* which takes all present and future expenses into account. The basic principle is to reduce all costs, present and future, to the common basis of present worth (called discounting). In a life-cycle analysis, the cash required for house heating (for example) is calculated for each year; these yearly amounts are discounted to their present value and then summed over the expected life of the system, which results in the "life-cycle cost" of the heating system. This procedure is followed for each of the solar and nonsolar systems under consideration to find which one has the lowest life-cycle cost.

A variant of life-cycle cost analysis is *ownership-cycle cost analysis*. The average holding or ownership period of homes in the United States is 5 to 7 years, which is substantially less than the expected system life of most passive designs. Year-by-year cash flows can be calculated over the ownership period, and the resale value of the solar elements can be included in the final year of analysis. As in life-cycle cost analysis, the yearly dollar heating costs of both the solar and non solar home can be discounted to their present value, summed over the ownership period, and compared.

The size of the passive solar components with respect to the heating and cooling load of the building is critical to the economics of a passive solar design. The solar design is optimally sized if, under specified cost and financial conditions, no other size will produce a larger sum of discounted net benefits over the appropriate analysis period. Determining the system size that maximizes the net present value of a series of alternate design sizes is identical to determining the system size that minimizes the cost of delivered heat. The *cost of delivered heat* is a more revealing measure of the economic feasibility (cost effectiveness) than either system cost or system performance.

SERI Simulations and Cost Studies

Because of the growing interest in passive solar design, there is a need for continuing evaluation of the economic performance of passive solar buildings and components as new and updated cost and thermal performance data become available.

The Solar Energy Research Institute (SERI), as part of its solar commercial-readiness activity, has performed computer simulation and cost studies for a variety of passive systems, and has compiled data on the economics and performance of several types of existing passive structures (Ref. 5-1). The economic information has proven hard to obtain and the data sample is small (50 passive systems from 33 sources); thus the results (Fig. 5-1) should be considered tentative. No attempt has been made to control for differences in design and climate, the costs have not been adjusted for location and year, and the separation of passive solar costs from other costs is not easy. For the various types of passive design considered in the study, the range of cost of energy delivered is given in Fig. 5-1, in dollars/MMBtu-year. This is simply the add-on solar construction cost (\$) divided by the annual energy savings (MMBtu/yr). This measure is not an indicator of cost

over the ownership or life cycle, but it does provide a common basis for comparison.

The values in the above table were obtained from actual cost and performance data from operating buildings, and from selected performance simulation and cost estimate studies. It should be noted that the ranges of delivered energy cost for direct- and indirect-gain systems are quite large because the solar contribution to the annual heating load varied in the simulations from 5 to 95%; furthermore, the range is based upon simulations for a large number of cities throughout the U.S., so climate variations also contribute.

In summary, the SERI studies indicate that:

- ◆ Cost and performance for the passive systems vary widely because of difference in design configuration, collector sizing and building thermal characteristics, and climate.
- ◆ The performance of most actual systems either matches or exceeds that of simulated systems; also, the cost of delivered energy for the real systems is less than for the simulations.
- ◆ In a few cases, monitoring of a system shows that the actual system is performing better than had been predicted.

Economics of Trombe Walls vs. Direct Gain

Comparisons of the economic performance of two types of passive solar heating design, Trombe walls and direct gain, have been made for many cities in the United States by the Los Alamos Scientific Laboratory and the University of New Mexico (Ref. 5-2). To facilitate regional comparisons, both passive designs were integrated into the same kind of building, a ranch-style tract house of 1500 ft². The extra costs for the solar components were established for each design according to regional differences in prices for materials and labor. Passive system sizes were optimized against both natural-gas and electric-resistance alternatives after current prices and future price escalation were established for each region.

The computer program used in this comparison study is a variant of the life-cycle cost analysis in which a series of home-heating systems having solar fractions of 5 to 95% were evaluated to find the economically optimal mix of solar and backup heating systems; the optimal mix occurs when the net present worth of the solar features over the system lifetime is maximized. The net present worth is the discounted present worth of energy savings plus tax benefits (e.g. mortgage interest deductions) minus solar system costs. Again, this is equivalent to minimizing the cost of delivered heat to the home over a specific lifetime.

Preliminary results of this economic performance study are given in terms of the solar fraction for Trombe walls with night insulation and for direct-gain systems with night insulation, with natural gas as the alternate fuel and with electricity. When solar systems are compared with natural gas, the geographic pattern of solar economic feasibility is generally equivalent for the Trombe-wall and direct-gain designs as costs are varied. Even when the cost of passive is relatively high (\$24 per ft² of glazing), solar is competitive with natural gas in the New England, Eastern Seaboard, and Pacific Northwest regions. When costs are somewhat lower, solar is economic in the West, North, Midwest, and South, as well. And when the cost of solar drops to \$12 to \$14/ft² of glazing, then solar becomes economic in the mid American states.

The importance of night insulation for the Trombe-wall design is apparent throughout the nation; for most states, the increase in building performance outweighs the

Range of Cost of Energy Delivered	
Direct gain	\$(/MMBtu yr)
Simulated	32 to 538
Actual (monitored)	30 to 139
Actual (unmonitored)	33 to 127
Indirect Gain	
Thermal storage wall	
Simulated	85 to 887
Actual (monitored)	36 to 244
Actual (unmonitored)	89 to 156
Thermal storage roof	
Simulated	179 to 1092
Actual (monitored)	83
Isolated Gain	
Attached sunspace	
Simulated	33 to 58
Actual (unmonitored)	12 to 120
Convective Loop	
Simulated	64 to 147
Hybrid	
Actual (monitored)	
Residential	26 to 168
Commercial	278
Actual (unmonitored)	
Residential	120
Institutional	308

Fig. 5-1 Range of cost of energy delivered for various passive solar energy systems, as determined in studies by SERI. (Ref. 5-1).

increase in cost of night insulation. For direct-gain designs, adding night insulation improves economic performance in the North but not in the South. In fact, in the South, direct gain without night insulation outperforms the Trombe wall with insulation. Thus it appears that the Trombe wall with night insulation is the best choice for the North and direct gain without night insulation is the choice for the South.

Both designs compete much more favorably when the escalation rate for natural gas is increased from 4% to 5.5%.

When electric-resistance heating systems are compared with Trombe-wall and direct-gain designs, solar add-on costs are not nearly so critical. Both designs are competitive at the highest cost considered except for states in the lower Mississippi Valley, the Ohio River Valley, and the Pacific Northwest regions. Optimal solar fractions are higher for the direct-gain than for the Trombe-wall design at the two higher cost levels, except in the most northern states. At lower costs, the solar fractions are usually equivalent. Both types of passive design do better with night insulation than without it at the optimal system size, when solar is compared with electric-resistance heating.

These economic comparisons are based upon historical average costs for conventional fuel. Since replacement cost of electricity and natural gas is much higher than historical average costs, passive solar will be an even stronger competitor if the basis of comparison is changed. For example, electricity costs in the Pacific Northwest are extremely low because of the large and historically cheap hydroelectric energy base. If passive solar design can be used to reduce the requirement for new nuclear or gas-fired electric generating capacity, these higher cost energy sources should be the basis for comparison, rather than historical average costs, which are dominated by a hydroelectric base that has little potential for expansion.

Economics and Marketability

In a study made by the Mitre Corporation (Ref. 5-3), regions in the United States are pointed out where direct-gain and Trombe-wall passive space heating systems can be most easily marketed at the present time on the basis of their economic competitiveness. This analysis assumes that the mood and tastes of home buyers do not change; that is, the buyers will continue to demand the same kind of effort-

less, constant temperature, and spacious environment that they have preferred in the past. If buyers could come to accept larger daily temperature swings in their homes and more responsibility for system control, all solar energy systems would become more economically attractive.

The basic building in the Mitre study is an 1800-ft² two-story home with frame construction and a basement. The direct-gain building is double-glazed and has a roof overhang and a 4-in. slab concrete floor. The Trombe wall is 12-in. thick concrete painted black, with circulation vents, double glazing, and a roof overhang. Neither system includes night insulation. The performance and cost of the auxiliary energy system is important in determining overall feasibility of the solar energy systems, so the economics of these systems must be evaluated on a regional basis. Electric-resistance space heating and electric heat-pump systems were the auxiliary system considered.

Based on an analysis of performance, cost, and economic criteria, the following conclusions have been drawn by Mitre:

- ◆ On the basis of life-cycle cost, large passive solar systems are economically feasible now throughout the Northeast and Midwest, while smaller systems are feasible in Southern California.
- ◆ On the basis of the time to simple payback, no large passive solar systems are feasible at the present time without substantial tax credits (30 to 50%); smaller passive systems are now feasible in Southern California with existing tax credits.
- ◆ The economic attractiveness of passive solar energy systems is very sensitive to property taxes and would be much more feasible if the value they add to the building were not taxed.
- ◆ Passive systems (like active systems) are most attractive where fuel prices are highest and initial costs are lowest.
- ◆ The greatest annual fuel savings are realized with passive solar systems in northern climates, even though the solar heating fractions are smaller.
- ◆ Trombe walls have a better economic performance than direct-gain designs in the colder climates, while direct-gain designs are the more economic in warm climates.
- ◆ Electric heat-pump auxiliary systems for passive solar homes are most attractive in places having cold climates

with mild summers. It is not clear that electric heat pumps are ever more economically attractive than electric-resistance auxiliary heating.

Cost-Benefit Studies of Passive Features

The State of Wisconsin, Division of Housing, is currently involved in the development of a number of passive home designs for low- to moderate-income persons (Ref. 5-4). These designs, which will be made available to the public, are intended for use within the home loan program of the Farmer's Home Administration (FmHA). Five prototype homes designed specifically for the Wisconsin climate will be constructed in the spring of 1980.

In connection with this design and building project, the Division of Housing is preparing cost-benefit analyses to demonstrate the usefulness of various passive solar features that are now termed luxury items by the FmHA, which finances most of the low- to moderate-cost homes built in the state. Among the "luxury" items that cannot now be financed are sliding glass doors, greenhouses, tile floors, and outdoor decks. The FmHA also has strong opinions about the type of house that can easily be resold: namely, 3-bedroom ranch-style, split-level, and Cape-Cod houses with garages. The goal of the state program is to demonstrate that passive components can be installed at reasonable cost and are useful marketable commodities, not luxuries.

Fuel Comparisons

In all current evaluations of the cost-effectiveness of solar energy designs, the cost of the solar features is expected to compete with systems based on oil and natural gas. But in fact, oil and natural gas are not the competitors of solar energy. Solar energy really will be replacing synthetic fuel from coal, our long-term resource, which even now costs around \$40 a barrel. With such sources, solar systems are very competitive. And they are marginally competitive even with Alaskan natural gas and with nuclear-generated electricity.

BUILDER INCENTIVES

The production home builders' job is not an easy one. These people are involved in using borrowed money to buy land on which they hope to be allowed to manufacture a very expensive product. They must satisfy planning officials, building officials, and lenders. They must deal with, schedule, and supervise a large number of independent contractors. And they must sell the home to a consumer who probably has never before made such a large money investment. As a result of all these pressures, builders often do not have the frontier spirit; they feel they already have enough troubles. The solar energy community, however, would like builders to have enough confidence in solar designs and components and in the salability of solar homes to at least give the technology a try. (See Ref. 5-5.)

Builders are becoming aware that there may indeed be an energy problem and that state and federal policies are increasingly supportive of the solar energy solution to the problem. Tax incentives do provide strong motivation. In California and elsewhere, builders can take advantage of solar tax credits and can also receive free administrative and technical assistance from state agencies for real estate developments incorporating solar features. Further motivation will come from increased consumer interest in solar homes.

One further step toward increasing builder confidence and motivation has been taken by the California Energy Commission which sponsored a number of solar seminars for builders. The goal of each set of seminars was to motivate builders to take an interest in solar energy, rather than to teach them everything they need to know. The first topic was solar domestic water heating because builders were already somewhat acquainted with the concept of active solar systems and because a solar water heater is a simple device, much like any other new appliance to a builder. Pas-

sive solar concepts were explained as extensions of current building practices. Two worries became very apparent during the seminars: the lack of specific design data for passive systems and the lack of information about how passive systems perform. As a result of the seminars, a few production builders have now begun to include passive design in their new developments. A large subdivision in Northern California has worked out a site plan that incorporates proper solar orientation, and the homes are designed to take thermal advantage of their orientation. A very large land development in Southern California is also currently including solar features in its development plan.

SOLAR COMMUNITIES

Besides the many individual solar homes that are now being built, there is a growing emphasis on using solar energy in subdivisions and developments; most often, this involves passive solar design for the building itself and solar collectors for swimming pools and domestic water. In California alone, there are now over 64 major subdivisions that have solar water heating.

All-Solar Subdivisions

The first clusters of solar homes were initiated and planned, and often built, by solar energy advocates. Experience with these homes has proven that solar communities are not only feasible but are very marketable. In fact, designers and builders have found that selling a solar home is easiest if it is in an all-solar community or subdivision. Since a passive solar home is a new product in a conservative industry, it seems to be most acceptable when in a complete and complementary setting. We are social creatures; and the home buyer, including the solar home buyer, is attracted to a community of like-minded people.

Another advantage of an all solar development is that it concentrates public interest in solar, with an increase in visibility for the project and the builder. Although solar cannot make a poorly conceived real estate venture successful, it can give a well-done project a small but important advantage in a local market.

First Village, New Mexico

One of the pioneering solar communities is First Village near Santa Fe, New Mexico

This page

Fig. 5-2 First Village Unit #1, New Mexico. (a) Floor plan. (b) Perspective.

Opposite Page

Fig. 5-3 First Village Unit #3, New Mexico. (a) Perspective. (b) Floor plan.

Fig. 5-4 First Village Unit #4, New Mexico. (a) Perspective (b) Floor plan.

(Refs. 5-6, 5-7). From 1975 to 1978, Wayne and Susan Nichols built 8 custom solar homes in their own subdivision; they had no trouble finding buyers. The buildings are of various types, each on 5 acres of land; five were built for sale and three for owners. Prices ranged from \$95,000 to \$170,000. Water conservation and open spaces were designed into the plan to save the existing topography and landscape.

The builders observed that people who buy solar homes, at least in New Mexico, are generally well educated, have small families, and tend to be professionals or self-employed. They are environmentally aware and interested in quality construction and design. They see the builder of passive solar homes as "more responsible" than other builders. Design, site planning, construction practices, and finished detailing must all fit together to give a consistent picture of responsible development, construction, and marketing.

The design process for First Village consisted of three elements: site planning, designing each home, and designing the solar energy system for each home. Site planning was determined by the existing rural zoning of one dwelling per 5 acres. Once the site was purchased, the builders

were locked into the market segment, which limited the design options. For a solar community, the development process often works backwards—from site selection, site planning, and financing to final house and solar design. In First Village, the solar system often determined the house design.

Construction began in 1975 with Unit #1 (Fig. 5-2), a hybrid building having both active and passive solar features, and Unit #2, an active air-collector system with rockbed heat storage. Both buildings were two-story adobe structures with a solar greenhouse. Unit #3 (Fig. 5-3) was the first attempt to build a tract-style home, and the Nichols' believe this house to be close to a design and performance optimum. Its passive solar features are clerestory windows in the northwest corner bedrooms, an atrium and greenhouse with thermal mass along the rear (north) wall, and a south-facing side consisting of alternating direct-gain windows and 16-in. concrete Trombe walls. The 1800-ft² home is set 3 to 4 ft into the ground. After being on the market for six months, it sold immediately as soon as the weather turned cold, which indicates that passive solar is experiential and sells best when people can sense directly what they are getting for the extra

expense. The solar fraction is 80 to 90%.

Unit #4 (Fig. 5-4), which received a demonstration grant from the U.S. Department of Housing and Urban Development, was designed to test the concept of vertical cast concrete Trombe walls filled with water. This frame and adobe house is built into a hill on the north and has minimum windows on east and west. The two identical bedroom wings are closed to the south by a solid water wall but open onto a central courtyard. The rest of the house is heated by direct gain from the south windows of the living room, plus a large clerestory through which the sun shines directly onto a 10-in. cast concrete interior north wall. The heating performance is acceptable in the water-wall rooms but is slightly low in the direct-gain parts of the building. The solar fraction is about 70%.

The last four homes in First Village are a refinement of the principles and components used in Unit #3: alternating Trombe-wall and windowed sections, using clerestories, and sinking the homes a few feet into the ground. The final unit is a split-level style with a greenhouse. An adobe mass wall acts as a buffer between the greenhouse and the living spaces; a rockbed under the living room stores excess

heat collected by the greenhouse.

The construction of a passive solar home is obviously more than just the addition of some glass on the south wall. In the Nichols' experience, passive solar homes always cost more. Everything from the slab floors to the roof is built differently from tract construction, and any deviation from the tried and true in the building business costs money. The builders found much community interest in their solar homes and construction methods; they have given hundreds of tours, held open houses, and had some of the homes monitored by the Los Alamos Scientific Laboratory and the Public Service Company of New Mexico. The public interest and their community educational efforts played an important role in the success of First Village.

Thomas Village, Virginia

Thomas Village, a passive solar community, was established by the Tennessee Valley Authority (TVA) to provide homes for flood victims in Southwest Virginia (Ref. 5-8), a project in keeping with its obligations to provide water management, flood control, and economic development in the 7-state region of the Tennessee Valley. TVA's interest in solar energy stems from its interest in electrical power management; solar homes not only reduce the total energy load in the region but also make their demand for power at off-peak times, which is of advantage to a power supplier. Details of these prototype buildings can be found in Chapter 3.

TVA's new policies have led to an expanded solar housing program that will include 11 new designs, which are to be built and tested throughout the Tennessee Valley during the coming year. The three award winning prototypes already developed are now being built by private developers and individuals in the Valley. The goal is to familiarize the public and the construction industry with this new technology and remove some of the mystery surrounding solar energy use.

Community Planning

With only a few exceptions, solar development to date has assumed the continuing expansion of suburbia. It is certainly true that solar buildings use less conventional energy for heating and cooling than other homes. But buildings are not built in a vacuum; they are surrounded by other buildings and are a part of a neighborhood and community. Thus they are tied to energy

use not only by their own heating and cooling systems but also by their need for services and transportation.

A solar house 20 miles away from its neighbor is only a partial cure for energy-intensive living. A great deal more energy can be saved if communities are designed as a whole rather than unit-by-unit. Planning for mixed land uses has the potential for creating coherent and vital urban villages, with lowered total energy consumption and on a more human scale. Thus planning good solar neighborhoods involves more than insuring sunlight to solar collectors. Its broadest goal is to create exciting, livable environments within an integrated energy-conserving framework. Patterns of circulation, land use, landscaping, food production, recreation, employ-

ment, shopping, and education all have important energy-use implications. An energy-conserving neighborhood would incorporate cottage industries, corner groceries, neighborhood child-care centers, and jointly developed open spaces and gardens.

Village Homes, California

According to Michael and Judy Corbett who designed and built the very successful Village Homes development in Davis, California (Fig. 5-5), the basic principles for planning a passive solar community (Refs. 5-9, 5-10) include the following:

(1) The neighborhood should be designed to accommodate the passive solar home:

Fig. 5-5 Site plan for Village Homes, California.

- ◆ Homes on the north side of the street must be set back on the lot and have a fence between the house and the street to give privacy to residents living with large expanses of south glass.

- ◆ Streets must be narrow and tree-shaded to reduce summer heating. In Davis, an expanse of unshaded asphalt can raise the local air temperature by 10°F in the summer, increasing the need for air conditioning.

- ◆ Lots on the north side of the street must accommodate side or rear entrances so that south-facing glass can be maximized.

- ◆ Tree plantings must be chosen to be compatible with the passive design.

(2) The subdivision should be designed to reduce energy consumed during the building process:

- ◆ Pave less land, which leaves more land available for collecting sunlight through photosynthesis; it also reduces materials and labor. In Village Homes, this is accomplished by having narrow streets, long cul-de-sacs, and two-story houses.

- ◆ Use fewer materials. If fewer materials are consumed, less energy is required for manufacture and transportation. Some built-in appliances can be eliminated.

- ◆ Use local materials if possible. This results in less energy used for transportation.

- ◆ Use materials that require less energy in the manufacturing processes.

- ◆ Hire local residents, which also will reduce energy spent on transportation.

- ◆ Use longer lasting materials to reduce energy consumed in manufacture of components and replacements. Tile roofs, and concrete bike paths and parking bays, are two examples from Village Homes.

(3) Features should be provided that will enable the residents to minimize their energy consumption:

- ◆ Provide for waste disposal within the neighborhood. A natural drainage system for run-off water is installed in the common areas located behind Village Home houses. Grey water drains are provided, recycling is accommodated, and composting areas are scattered throughout the development.

- ◆ Incorporate bicycle paths and arrange traffic patterns so that it is more convenient to travel within the neighborhood by bike or foot than by car.

- ◆ Set aside areas for neighborhood food production.

- ◆ Provide neighborhood recreational facilities to reduce automobile use. Possibilities are swimming pools, meeting rooms, craft centers, ball courts, playgrounds, and tot lots.

- ◆ Develop work opportunities for neighborhood residents. A small commercial center is being set up in Village Homes which will include a restaurant, medical offices, light manufacturing, and a cooperative store. Some community residents are already employed in construction and agriculture.

(4) Plan for features that will permit and encourage the development of a cohesive and self-reliant community, since such a community is likely to consume far less energy than today's typical neighborhood or town. The designers feel that a self-sufficient development requires a sense of community among the residents and that the following elements will promote that sense:

- ◆ Keep the scale appropriate, somewhere between 50 and 300 living units.

- ◆ Provide defined boundaries to the community.

- ◆ Set aside a substantial amount of land to be held in common so the

community can expand and change its activities in the future.

- ◆ Develop means for obtaining community income. In Village Homes, the homeowner's association owns income property including apartment houses and the commercial center, both located within the neighborhood. Financial returns from community-owned property provide for the economic and social welfare of the community.

In designing Village Homes, the developers have concentrated on small low-cost homes because there is a need for small homes of high quality and low energy consumption. The results are customized, 75% passively heated solar houses with solar water heating and 100% natural cooling at a construction cost equal to that for standard, non-solar semi-custom houses. The passive components vary from house to house but include containers of water for thermal mass (the more the better), open floor plans for good air circulation and to gain an illusion of larger size, south glazing with overhangs, double or triple pane windows, slab perimeter insulation, R-19 wall and R-30 ceiling insulation, rigid hot-water pipe insulation, weatherstripping and caulking, and a minimum number of exterior doors.

Plans for some of the Village Homes houses have been published (Ref. 5-10).

Dinuba Solar Neighborhood, California

The solar neighborhood being developed in Dinuba, California, by Robert Burkart and designed by Jon Hammond of Living Systems uses as organizing concepts the desired circulation flow for people and vehicles and the anticipated shadow patterns of the planned buildings (Ref. 5-11). The highest density, tallest housing has been located to the north of the site to minimize shading conflicts and to provide access to the commercial center and major streets, thus reducing car use within the site. The Master Plan (Fig. 5-6) shows the finished design of the Dinuba community. Its streets, lots, buildings, and trees are planned to allow the various kinds of solar collecting surfaces to function effectively.

La Vereda, New Mexico

Another integrated solar community is being designed by Wayne and Susan Nichols who originated the First Village development in Santa Fe, New Mexico (Ref. 5-6). This second development, La Vereda (Fig. 5-7), will be a market test of passive solar buildings as a viable product for the builder/developer of medium to small size homes. The project consists of 19 passive solar homes ranging from 1100 to 1800 ft²

on 10 acres in Santa Fe, New Mexico. The homes are clustered into three villages on 4 acres with open space between the villages; 5 acres are open with one acre taken for roads. The streets and utilities are private, owned and maintained by the Homeowner's Association. The passive solar homes, which will be standardized to keep costs as low as possible, will utilize concrete Trombe walls, mass-backed greenhouses, and clerestories.

The developers are assuming that their market is the same as for First Village, merely less affluent. They expect their site planning approach of clustered homes on small individual lots plus common ownership of substantial open space to impart a sense of community to the residents.

The location of the development property and the type of neighbors determined the specific planning approach. To get planned-unit zoning, which would give the flexibility to site homes for solar orientation, required neighborhood approval. To obtain this approval, it was agreed that open space would be left as a buffer on the north portion of the property. During the planning phase, the developers walked each site and located each house to fit the existing topography. Some preliminary house designs were discarded as inappropriate and

other plans developed that would better fit the demands of the lot. All homes will be sunk 3 to 5 ft into the ground, which should give the whole project a unique esthetic when complete. Water conservation will be used in each home, and the Homeowner's Association will have the ability to install other resource-saving technology in the community if the residents so desire. Construction cost strategy will lie somewhere between that of a production builder using all subcontractors and an all-custom approach.

Planning Guidebook

A guidebook on planning solar neighborhoods, *Site Planning for Solar Access: A Guidebook for Residential Site Planners and Developers*, has been prepared for HUD by Living Systems, Inc., in Winters, California, in conjunction with the American Planning Association (Ref. 5-11). In this volume, four procedural steps are described for the process of comprehensive solar planning; these steps are to be carried out in conjunction with conventional development practices:

- (1) *Regional climate consideration.* Analyze residential heating and cooling needs as they are influenced by the regional climate. Understand how major

Fig. 5-6 Site plan for the Dinuba Solar Neighborhood, California.

topographic features, bodies of water, and wind and weather patterns combine to give the region its characteristic climate.

(2) *Site selection and analysis.* Examine the site's microclimate influences and determine the extent to which obstructions may shade potential solar collecting surfaces. The influences of most concern are those that were found to be critical in the regional climate analysis.

(3) *Preliminary planning.* Allocate major uses of the land according to the microclimate determined in Step (2). High-density housing should get the sites with the best solar access and the most favorable microclimate. Sites with poor solar access can be used for circulation, parking, open space, wildlife areas, etc. Community gardens need sun only during the growing

season while playgrounds should receive sun for most of the year.

(4) *Detailed site planning.* The goal of site planning is to provide solar access to all collectors while achieving the overall functional and esthetic program for the neighborhood. There are three key elements: layout of streets and lots, choice and siting of houses and other buildings, and selection and location of trees. The guidelines presented below will work well in most U.S. climates:

- ◆ The principal goal is to allow sunlight to the collectors.
- ◆ Orient collectors, and buildings generally, to the south.
- ◆ Orient lots north/south and streets east/west.

- ◆ Site buildings and trees by considering the shadows they cast.
- ◆ Use trees to shade architectural glass during the hot season.

Fig. 5-7 Site plan for La Vereda development, New Mexico.

PUBLIC EDUCATION

Although many organizations of various sizes, from the federal government to one-man shows, have become involved in educating the public about the use of solar energy principles and systems, one of the most effective approaches seems to be direct, hands-on teaching in small groups.

Solar Sustenance Workshops, New Mexico

The Solar Sustenance Team in New Mexico, initiated and led by Bill Yanda, was one of the first to organize hands-on workshops in passive solar projects (Ref. 5-12). They began by building attached solar greenhouses (Fig. 5-8) but soon found that workshops are the most direct route for teaching people to install other solar and energy-saving equipment as well, including Trombe walls, solar water heaters, solar crop dryers, south-wall air collectors, and caulking and insulation. One of the primary appeals of the workshop is that one can learn and then build a solar application for much less than its commercial price.

Many elements are needed for a successful workshop, according to Yanda, with the most critical elements being a well-organized and technically qualified training team, a reasonable building site and project, and 5 to 20 participants to build the solar device. The general procedure is that the workshop organizers observe a need, query the community to determine the interest, and if the response is positive, set up the workshop.

Thus a workshop organized at the local level can deal with a specific local problem or characteristic. For instance, the organizers might notice that a nearby subdivision has many houses with low-pitched south-facing roofs suitable for solar water heaters. With very little effort they can make a survey to see if people are interested in learning to build the water heaters. Workshops, which deal most often with retrofit situations, could be very helpful to the 50 million or so families in the United States who now have energy-inefficient homes.

Financial support of a construction workshop can be obtained in several ways:

(1) *Through a federal or private sponsoring agency.* The National Center for Appropri-

ate Technology, the Department of Agriculture, and the Department of Energy, as well as several state energy offices all have funded such programs. However, as the demand for more workshops increases, it becomes increasingly difficult for small groups to obtain money from agencies.

(2) *Through state educational programs.* The community college systems or the vocational/technical schools are perfect vehicles for the solar workshop concept. They usually have a mandate to serve the educational needs of their region and are staffed to do so.

(3) *Through participant's fees.* A homeowner who wishes to have a solar greenhouse, for example, pays a workshop organizer for materials, design, and incidentals such as insurance, but not for labor. The organizers get a participant-crew together which pays the organizers a fee and with whom they work to construct the greenhouse. This type of solar hands-on education can continue to grow at the grassroots level regardless of the availability of state and national funding.

Whenever a solar construction workshop takes place, other solar projects are built as a consequence. This multiplier effect is very noticeable although hard to measure. In every community where experienced workshop leaders have been working for some time, there are a tremendous number of owner-built solar energy systems; examples are the San Luis/Alamosa regions of Southern Colorado, Northern California (San Francisco Bay Area), and almost anywhere in New Mexico.

A program run by the Solar Sustenance Team and funded by the DOE is seeking to extend the workshop concept nationally. Twenty teams from twenty states have been trained to organize and manage solar greenhouse construction workshops. These teams have all responded with one compulsory workshop, plus plans for many future projects. The main goal of this training project is to put the technical and management skills where they belong: at the local level.

Fig. 5-8 Greenhouse workshop, New Mexico.

Habitat Center, California

The Habitat Center is a nonprofit educational institute in the San Francisco area that is conducting a public program in the skills for designing and constructing low-cost passive solar buildings (Ref. 5-13). The primary activities of the Center have been hands-on workshops, in which the workshop participants receive instruction in passive solar design basics and then participate in building an actual passive solar structure. Most of the projects involve retrofitting existing homes with passive solar greenhouses, making adobe, and designing and constructing passive solar adobe homes.

The purpose of the workshops is to transfer to owner-builders and community groups the understanding and skills needed to design and construct low-cost thermally effective and esthetically pleasing passive solar homes (new and retrofit) in a primarily urban area.

The multiplier effect is high. For every workshop that the Habitat Center conducts, another two or three passive solar structures are built by workshop participants. Four other groups have now begun to conduct workshops on their own as a result of their participation in Habitat Center workshops.

Experience with the workshops indicates that the format works well for owner/builders and community groups as well as for professionals in the building industry. There have been two important results with respect to design:

- ◆ Thermally effective passive solar greenhouses can be retrofitted harmoniously to almost any architectural style in the San Francisco Bay Area, at very modest cost.
- ◆ Building-code restrictions that inhibit the construction of passive solar retrofits in urban areas can be overcome. One obstacle to getting solar greenhouse retrofits approved in California, or the West, is the requirement of the Uniform Building Code that all rooms in all homes must have access to outdoor light and air through operable windows and doors, which means it is a code violation to place a solar greenhouse over the only operable window in a room. The Habitat Center has found several ways around this restriction, one of which is to find an understanding building official who will overrule it. Local setback restrictions in urban and suburban areas are a greater problem.

They can be waived for "extenuating circumstances"; but so far, solar greenhouses do not qualify as such.

Recently, the educational program of the Habitat Center has been expanded to include extended-session classes in solar home and retrofit design and extended workshops in building new passive homes and rehabilitating existing homes. The Center facilitates construction of passive solar homes by owner/builders by providing assistance in dealing with the building departments and lending institutions, both of which are inclined to be conservative toward solar structures.

Grass Roots Technology Transfer, New Mexico

For six years, the New Mexico Solar Energy Association has been experimenting with a decentralized, community-based system for solar information transfer which has proven to be extremely effective (Ref. 5-14). In fact, there is a rapidly growing national network of grass roots groups providing citizens with information on all alternative technologies. The three characteristics that are crucial to successful programs are that the information must be accurate, the service must be responsive, and the directors must be committed to education. The New Mexico Solar Energy Association, as one of these many groups, has developed five programs to encourage individuals to explore technological innovations on their own:

The *Workshop Program*, which helps community groups organize weekend workshops to build inexpensive passive solar retrofits.

The *Publications Program*, which publishes the Southwest Bulletin—a compendium of articles, research reports, news, and construction information.

The *Technical Assistance Program*, which maintains a notable collection of classic and current papers and books, and which answers all requests for design help and technical information.

The *Education Program*, which works through the state and local educational system to inform the public about solar energy and related arts, especially by means of teacher-training workshops and courses.

The *Affiliate Program*, which works with solar energy associations throughout the state of New Mexico to select and adapt solar technology to the culture, economics, and environment of particular communities.

TVA Solar Program

The Tennessee Valley Authority (TVA) is in a unique position to foster action on solar energy. It has a history of demonstrating new energy technologies, but it is not just an energy producer. TVA's mission is to improve the economic and social well-being of the people in the Tennessee Valley region. The goal of its solar program is to develop an equitable, economically sound solar industry and a national position of leadership in the commercialization of solar energy in this region (Ref. 5-15).

The first major solar project, undertaken by TVA's Office of Power, was to prove that solar water heating is feasible and marketable in the Memphis, Tennessee area. This program began with building and installing ten solar systems and is now involved with 1000 units. Next will be an extension of this activity to the rest of the Valley. TVA is providing interest-free loans, training people in solar jobs, and selling the solar water heaters for the same cost as electric water heaters.

The second part of the solar program, being carried out by the Office of Engineering Design and Construction, is to look at all present and future TVA buildings with an eye to incorporating solar design and technology. This is a monumental task since TVA has over 300 major buildings and a one billion dollar construction budget. To accomplish this, well known solar specialists have been employed as consultants to educate TVA and help it inform area architects, engineers, builders, and developers of the TVA solar energy goals. To encourage the use of solar in all buildings in the Valley, the TVA Outreach Program provides information on climatology, solar angles, materials properties, calculation methods, and solar designs that work best in the region.

The solar program has generated a tremendous amount of enthusiasm within TVA. At present, the Authority is restructuring its organization in order to put even more emphasis on solar design and is working on more and larger solar-oriented projects.

GOVERNMENT INCENTIVES

The federal and some state governments are realizing their roles in the timely implementation of passive solar energy, and in the transition from fossil fuels to renewable energy sources. With financial and

technical support incentives from various levels of government, efficient and attractive passive solar buildings are becoming more numerous and widespread. Research and development efforts are resulting in more effective and regionally appropriate structures; design competitions are continuing to demonstrate that successful passive buildings can be cost-competitive and attractive; and solar tax credits are encouraging the adoption of passive solar elements and systems. The effect of these programs is to make passive buildings increasingly desirable and marketable.

Tax Credits

Although the Internal Revenue Service rulings severely limit the passive solar applications that are currently eligible for the federal solar tax credit, several states do offer a credit for passive systems. A tax credit is subtracted directly from one's income tax bill. (Some states offer tax deductions, which reduce the amount of income against which the tax is levied.) Most of these states require that systems meet some criteria to avoid fraudulent claims or ineffective systems. Your state tax office can provide detailed information about these requirements, and the local office of the U.S. Internal Revenue Service can provide the latest federal tax credit guidelines.

In Oregon, the criteria for the state solar tax credit (25% to a maximum credit of \$1000) also include a provision that the solar system meet at least 10% of the energy requirements for the dwelling (Ref. 5-16). The provision seems to have caused little or no problem for the 42 passive systems (out of 180 solar energy systems) that qualified for the Oregon credit by January 1979. Data compiled from those certified systems resulted in the following generalized guidelines for cost and performance in Oregon:

SYSTEM TYPE	SOLAR HEATING FRACTION	COST/ MBTU
Direct Gain	0.6	\$132
Trombe Wall	0.5	167
Sunspace (Owner Built)	0.35	90
Sunspace (Contractor Built)	0.42	130
Combination	0.55	145

Design Competitions

In 1978, the U.S. Department of Housing and Urban Development (HUD) conducted a Passive Solar Residential Design Competition and Demonstration (Ref. 5-17). HUD's two primary goals were to demonstrate the potential of passive solar heating and to make working drawings of regionally appropriate designs widely available. There were 557 applications received. Awards totalling \$1,396,000 were made for the design and construction of 242 passive solar homes (145 new homes and 97 retrofits); 80 of the 145 new-home awards went to speculative builders. Along with a large number of successful designs, the competition also identified some potential problems and three general areas (listed below) where educational efforts are needed to clear up misunderstandings:

Sizing. Collection and storage masses must be adequately sized in order to meet a significant portion of a building's heating requirements. Too small a collection area will simply not let in enough solar heat. An adequate collection area with too small a storage mass will very likely result in an overheated space. Storage mass must be sized by considering the material's ability to absorb, conduct, store, and emit heat.

Thermal coupling. Solar storage in a passive system must be located next to the collection aperture and to the space to be heated, or be directly coupled convectively to both elements. Radiant energy distribution requires that the storage mass be located next to the living space to be effective. Natural convective energy flow is driven by warm (less dense) air rising and flowing along the path of least resistance to the coldest part of the space. A convective distribution system must be designed so that the temperature differences between storage and living space (or else an adequately sized fan) are able to drive the heat flow.

User controls. The simple, but direct, methods of regulating heat flow in a building—movable insulation, dampers, registers, awnings, shades, exhaust vents—must be carefully located and sized.

The winning projects in the Design Competition are compiled and summarized in a HUD report *The First Passive Solar Home Awards* (Ref. 5-18).

In the Spring of 1979, California held its own Passive Solar Design Competition

(Ref. 5-19, 5-20), sponsored by the California Energy Commission (CEC) and the Governor's Office of Appropriate Technology (OAT). Thirteen winners were chosen from 75 applicants who submitted approximately 82 designs. In the course of the technical review of these buildings, computer simulations indicated that:

- ◆ Passive buildings used 90% less energy than a "conventional" reference house at the same location.
- ◆ For cooling, the more mass the better.
- ◆ The generic system types can be ranked in order of decreasing cost effectiveness as follows: direct gain with night insulation of glazing, direct gain without night insulation of glazing, Trombe wall, and convective loop.

DOE's National Passive Solar Program

The U.S. Department of Energy, specifically the Passive Systems Development Branch in the Office of Conservation and Solar Energy, has a comprehensive program that is designed to facilitate the widespread use of passive solar designs (Refs. 5-21, 5-22, 5-23). The program's many activities are performed, for the most part, at the regional or local level and managed from the Washington D.C. headquarters. This is important because passive solar design will be used by the design and construction industries, which are more regionally defined than most consumer hardware industries. Program activities are divided into two broad categories: *Technology Development* (research, product development, testing, technology assessment) and *Technology Utilization* (market assessment and development, technology transfer).

Technology Development Activities.

The physical and environmental phenomena that affect passive systems must be understood if designs are to be successful. To this end, DOE is conducting studies in the following areas:

Solar radiation data are being analyzed as to the type and quality of data required for passive design.

Sky radiation properties in various geographic locations are being studied to determine where radiative cooling will work and how well.

Atmospheric factors, such as *wind velocity, relative humidity, ambient dry-bulb temperature, and dewpoint*, are being measured and the data assembled. Computer simulations are being

used to determine the effects of these factors on the performance of various passive systems.

The *temperature and conductivity* of various soil types and conditions are being measured and compiled.

The factors of *terrain and surrounding structures* at the building site are under study to determine suitable site conditions for various passive systems.

Heat transfer processes as they are used in passive solar heating and cooling systems are being examined.

DOE also is supporting and encouraging the development of a full range of marketable products that can easily be integrated into a conventional building. These products will include new, more efficient materials as well as new assemblies of traditional materials. The following types of products have been identified for development under this part of the program:

Glazings having selective properties. These include highly transmissive materials (those that pass a larger than normal portion of the incident solar radiation), and materials that reflect heat while allowing light to pass. Glazing assemblies will be classified according to their optical and thermal transmission and reflection.

Absorption and emission characteristics of various materials. Better, more selective absorbers and emitters will make the thermal coupling among the elements of a passive system more efficient.

Reflectors, both for heat rejection and for increasing ground reflection. Some of these will be used in conjunction with movable insulation systems.

Insulation materials. Their properties are being reviewed with an eye to passive solar applications. Innovative movable insulation systems are being developed, including those that incorporate glazing, reflector, or storage components.

Storage materials that are lightweight and have high heat capacity. These include structural systems made of high thermal mass concrete, water containers, and containers for phase-change materials.

Assemblies that use any combination of glazing, reflectors, absorbers, emitters, insulation, or storage which could simplify passive system construction.

Fluids for heat transfer and improved sealants for the edges of dampers and movable insulation, to increase overall system efficiency.

Controls, sensors, and actuators (motors), which are being evaluated for cost, performance, and reliability.

Fans, pumps, and valves, which are being evaluated for their applicability to passive solar systems.

Heat exchangers, including innovative components such as for earth-air heat transfer.

The program for development of passive systems, as described and supported by DOE, involves work in nine basic areas:

Concept assessment, which is concerned with preliminary evaluations of cost and performance as well as physical descriptions of a system, its thermal processes, and its modes of operation.

System specification, including materials and fabrication, procedures controls, and operating strategies.

Systems analysis, which requires modeling and evaluation of the thermal and economic performance of passive systems; of their technical feasibility and environmental impact, and of their effect on human comfort.

Data and instrumentation, which specifies requirements for the accurate monitoring of a full-scale building using a particular passive solar system.

Performance data acquisition, including data from controlled experiments in test rooms and from instrumented buildings; these data will be used to validate the models developed in the systems analysis phase.

System studies, which determine how the system can be optimized, based on performance or economics.

Performance criteria (or expectations), which will be developed from the tests and studies.

Design tools, including handbooks, rules of thumb, and hand-held calculator programs.

Marketability testing, which determines the compatibility of the system and its components with the building market.

Technology Utilization Activities.

Technology utilization, also called *commercialization*, is the process of moving a technology from the research and development stage to widespread acceptance by the buying public. The activities by which DOE plans to accomplish solar commercialization fall into four classes:

1. *Commercialization readiness assessment*. For each solar technology (passive heating, passive cooling, domestic hot water, and agricultural and industrial applications), DOE will study the readiness of the technology to enter the marketplace. "Readiness" is evaluated by technical, economic, environmental, and institutional criteria. This assessment has been done for passive heating and will be done for the other technologies in the near future.
2. *Technology transfer*. To develop the building industry's ability to design, build, and market passive solar buildings, information about passive systems will be exchanged in three basic activities: *data management*, in which relevant information about performance, economics, design tools, and marketing will be assembled into a data base; *education and training* of architects, engineers, builders, tradespeople, planners, lenders, government officials, and realtors; and *information dissemination* to end-use consumers.
3. *Stimulation of technology delivery capability*. This means removing some of the potential barriers to using passive solar systems. Assuring solar access, accommodating passive systems in building codes and standards, and devising easily understood performance criteria are examples of activities.
4. *Stimulation of market demand*. To overcome initial prejudices or traditional attitudes, several strategies are planned to increase the demand for passive systems; these include: passive solar government buildings (federal, state and local), utility programs, design competitions, and financial incentives.

Glossary

Absorptance Ability of a surface to absorb solar radiation. Expressed as the ratio of solar energy absorbed to total incident radiation.

Absolute Temperature Temperature measured on the "absolute scale," either in degrees Kelvin or degrees Rankine (Kelvin temperature = Celsius temperature + 273.15°C; Rankine temperature = Fahrenheit temperature + 460°F).

Albedo Fraction of incident light that is reflected by a surface, such as the ground or a field of snow.

Altitude Angular distance between the sun and the horizon directly below it.

Angle of Incidence Angle between a ray striking a surface and a line perpendicular to that surface at the point of impact; perpendicular rays have a zero angle of incidence.

Aperture Glazed opening in a building or solar collector through which solar radiation is admitted.

ASHRAE Acronym for the American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Azimuth Angle formed between true south and the point on the horizon directly below the sun.

Beadwall Insulating double-glazed walls in which styrofoam beads are pumped into the air space between the glazings; the beads are pumped out to allow heat flow through the glazing (either solar radiation in, or space heat out).

Berm Mound of earth positioned against a house wall either to stabilize the house's inside temperature or to deflect the wind from the house.

BIT (Computer) The smallest unit of memory storage, capable of storing one piece of on/off information (one binary digit).

British Thermal Unit (Btu) Amount of energy required to heat one pound of water one degree Fahrenheit.

BYTE (Computer) 8 bits of computer memory, the number required to store one digit or alphabetic character.

Clear Sky Sky that has less than 30% cloud cover.

Clerestory An outside wall of a room or building that rises above an adjoining roof and contains windows.

Coefficient of Heat Transfer (U-Value) Rate of heat loss (Btu/hr-ft²-°F) through a building surface.

Conduction Transfer of heat through matter by communication of kinetic energy from particle to particle.

Conductivity (Thermal) Measure of the rate (Btu/hr-ft²-°F) at which heat will flow through a material.

Convection Transfer of heat by movement of fluid (liquid or gas).

Convection (Natural) Circulation of gas or liquid (usually air or water) due to density differences caused by heating or cooling the gas or liquid.

Degree-Day (Heating) One day with the mean of the daily minimum and maximum outdoor temperatures one degree colder than 65°F.

Delta-T (Temperature Differential, ΔT) Difference in temperature between two substances or surfaces. Controls the rate of heat flow.

Design Heat Load Total heat loss from a building (which must be compensated by heat gain from a heating system).

Design Temperature (Indoor) Temperature at which the interior space must be maintained in order to achieve thermal comfort.

Design Temperature (Outdoor, Winter) Temperature near the minimum temperature that is likely to occur at a given location. Design temperatures are established by ASHRAE.

Diffuse Radiation Solar radiation that has been scattered by clouds, air molecules, dust, etc. before it reaches the earth's surface, or that has been scattered before it reaches a building's interior.

Direct Radiation Radiation that emanates from the sun and reaches the earth unscattered by the atmosphere. Direct radiation is capable of casting a discrete shadow.

Discounting Converting costs and benefits occurring at different times to a common basis for comparison.

Dry-Bulb Temperature Temperature of a substance as indicated by an ordinary thermometer.

Emissivity Ratio of the rate of loss of radiant energy from a surface to the rate of loss from a perfect radiator (black body) at

the same temperature.

Equivalent Sphere Illumination Level of illumination required from a uniformly luminous sphere around the task to achieve the same task visibility as the actual situation.

Eutectic Salts See **Phase-Change Salts**

Evaporation Change of state from liquid to vapor.

Fenestration Arrangements, proportions, and design of windows in a building.

First Law of Thermodynamics Law of conservation of energy: the total energy of a closed system is constant (energy can be transferred but not created or destroyed).

Glauber's Salt (Sodium Sulfate Decahydrate) A salt used for phase-change thermal storage (melting point is 90°F; it absorbs 104 Btu/lb as it melts).

Glazing Windows, or collector coverplates.

Gravity Convection See **Convection (Natural)**

Heat The form of energy that is transferred by virtue of a temperature difference.

Heat Capacity See **Thermal Capacity**

Heat Sink Medium or container to which heat flows.

Heat Source Medium or container from which heat flows.

Illumination Light falling on a surface.

Infiltration Movement of air from outside into the heated space of a building through joints and cracks between building components (doors, windows, walls, roofs, floors) and through openings.

Infrared Radiation Thermal radiation with wavelengths longer than visible light.

Insolation Total amount of solar radiation incident upon a surface exposed to the sky; measured in Btu/hr-ft², in langley, or in w/m².

Insulation (Thermal) Material having a relatively high resistance to heat flow, used principally to retard the flow of heat.

Integrated System (Hybrid) Solar heating and/or cooling system which uses both active and passive components.

Kilowatt One thousand watts of power; equal to about 1-1/3 horsepower.

Latent Heat Heat energy stored or released when a substance changes phase, such as when a vapor condenses to a liquid or a liquid becomes a solid.

Latitude Angular distance north (+) or south (–) of the equator, measured in degrees of arc.

Life Cycle Cost Analysis Economic evaluation that considers all costs (including acquisition, maintenance, repair, replacement, and operating expenses) and all savings that occur over the useful economic life of a project.

Luminance Measurable brightness emanating from an object.

Mean Radiant Temperature Average temperature of the surfaces of a room.

Megawatt One million watts, or one thousand kilowatts, about 1300 horsepower.

Nocturnal Cooling Cooling of an object or building by nighttime radiation of heat to the cool sky.

Normal In geometry, a word meaning perpendicular.

Overcast Sky Sky that is completely covered with clouds, with no sun visible.

Passive System Solar heating and/or cooling system which does not rely on mechanical energy to transfer thermal energy.

Payback Period (Simple) Time required for the annual net benefits derived from an investment to pay back the investment.

Phase-Change Salts A group of chemical substances used for thermal storage; these substances give off heat when they solidify and absorb heat when they melt.

Photosynthesis Synthesis of chemical compounds with the aid of light, sometimes including the near infrared or near ultraviolet; the conversion of solar energy to chemical energy by the action of chlorophyll in algae and plants.

Present Value (Present Worth) Expression of costs and savings incurred at different times as if they were all to be incurred NOW.

Radiation Transmission of energy by means of electromagnetic waves.

Reflected Radiation Solar radiation that is reflected from the surrounding terrain or buildings onto a receiving surface.

Relative Humidity Measure of the degree of saturation of the air with water vapor at any dry-bulb temperature.

Resistance, Thermal (R-Value) Measure of the tendency of a material to retard heat flow.

Retrofitting Installation of a solar energy system on an existing building.

Rock Storage A bin, pit, or other container filled with rock which acts as a heat reservoir for an air-type solar system.

Shading Coefficient Ratio of the solar radiation passing through any glazing assembly to the solar radiation passing through a single layer of double-strength glass.

Solar Constant Intensity of solar radiation on a surface perpendicular to the sun's rays located outside the earth's atmosphere at the average earth-sun distance; its value is about 434 Btu/hr-ft², or 1367 W/m².

Specific Heat Thermal capacity of a substance per unit of mass. Specific heat of water is 1 Btu/lb-°F.

Thermal Capacity The ratio of the change in heat content of an object to its corresponding change in room temperature, usually measured in Btu/°F.

Thermal Mass (Thermal Inertia) Heat storage capacity of a building. A building with a large mass of materials with high specific heats has a large thermal inertia, and will usually change temperature more slowly than a building with low thermal mass.

Thermosiphoning See **Convection (Natural)**

Timesharing A mode of computer operation in which the computer performs tasks for a number of simultaneous users.

Ultraviolet Radiation Electromagnetic radiation having wavelengths shorter than visible light but longer than x-rays.

Wet-Bulb Temperature Lowest temperature recorded by an ordinary thermometer when its bulb is wrapped in a wet wick and the thermometer is placed in a moving current of air.

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