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EGYPTIAN RENEWABLE ENERGY FIELD TESTING PROJECT

Volume I of III Volumes

Active/Passive Technology
Reference Notebook

R628/8.de

RENEWABLE ENERGY RESOURCES FIELD TESTING

VOLUME I of III VOLUMES

ACTIVE/PASSIVE TECHNOLOGY REFERENCE NOTEBOOK

Prepared for:

New and Renewable Energy Authority
Cairo, Egypt

Submitted to:

LOUIS BERGER INTERNATIONAL, INC.
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Preface

The exploitation of solar-derived energy is as old as life on this planet. Animals and vegetation adapt their lives, forms and movement to the sun. Animals lie in the sun, shade, or hide in sheltered spots.

Plants turn toward or away from direct sunlight. Flowers adjust their petals so as to focus sunlight to their interior surfaces where pollen is. The warmth generated there then attracts insects necessary for pollination.

The efforts of humans to produce an interaction between buildings and local conditions for space comfort are not new. At least three thousand years ago, mankind constructed shelters so as to collect, store, transmit, divert, or isolate solar energy with respect to his habitat.

Passive designs and materials create comfortable buildings where physical or mechanical effort is minimized.

The use of modern mechanical/electrical components in solar energy systems is referred to as "active" exploitation of solar energy.

The sun's energy has been harnessed not only for space conditioning but also for power production or useful work. An American engineer, F. Shuman, developed solar-driven hydraulic pumps, jointly with C.V. Boys in 1913. This development resulted in the construction of a 50 hp solar engine for pumping irrigation water from the Nile River near Cairo.

The Government of Egypt, with the assistance of the United States Agency for International Development (USAID Mission, Cairo, Egypt), is undertaking a program to adjust internal energy prices to levels more in line with free market values, decrease the use of fossil fuels as an energy source, and minimize environmental impact due to energy consumption.

This document is intended as an "easy to read" notebook of solar energy use in space conditioning and domestic hot water heating.

The electrical, mechanical, structural and thermodynamic principles of solar energy engineering are well understood. Their translation into practice can be realized more easily today than few years ago because of the accelerated development of materials and fabrication processes.

This notebook is intended to serve as a broad background resource, and the reader is referred to the extensive index for additional information.

The following have been involved in the preparation of the technical content of this manuscript: Samer Faraj, Carole Read, William Jones, Joseph Kohler, Vic Reno, and Dan Lewis. Margaret Reiser and Marigrace Richard were responsible for production.

James H. Porter
President, Energy and Environmental Engineering, Inc.
Cambridge, Massachusetts, USA, 1986

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APPENDIX - VOLUME I

1. INTRODUCTION

This Active and Passive Solar Technology Reference Notebook is intended to give an overview of the development of building active and passive heating and cooling technologies. The following major application areas have been developed in this notebook; active heating, active cooling, passive heating, passive cooling, and domestic hot water heating.

The main theme in the notebook is the detailed description of the various options available for building climatization. It is intended to be a source of technical as well as practical information for users with mixed technical background.

There are no prerequisities for using this notebook, as it is written in a nontechnical style. However, users with technical backgrounds will find in the text and in the appendices a wealth of useful technical information.

The climatic conditions in Egypt have had an important impact on the subject treatment presented. The sections dealing with active and passive cooling have recieved particular attention to ensure they will meet the needs of the Egyptian reader.

The development of sections dealing with cooling applications has been limited by the comparatively small amount of technical information available in the U.S. The passive solar field is much more developed in terms of heating applications rather than cooling. Nevertheless, the reader will find a fairly strong and integrated treatment of building climatization.

This notebook has nine separate sections and seven appendices. The first technical section (Section 2) presents an overview of the theory and fundamentals governing solar applications. Section 3 focuses on

passive climatization systems and is followed by sections on active heating systems and active cooling systems. Section 6 discusses the usage of solar domestic hot water systems. Section 7 identifies design considerations for active systems. Section 8 summarizes the research and development status of all the technologies and assesses their future prospects. Section 9 discusses the special conditions in Egypt. The appendices include a detailed solar visit book, conversion factors and properties of materials. Also included in appendices are sunpath diagrams, a discussion of space conditioning and human comfort, a list of U.S. equipment manufacturers, and identification of system implementation and operation issues.

2. SYSTEM FUNDAMENTALS AND DEFINITIONS

2.1 Solar Radiation Fundamentals

2.1.1 Availability

The source of solar energy is the sun, a gaseous star composed of approximately 80% hydrogen and 18% helium on a mass basis. The sun is a 13.9 $x10^5$ km diameter sphere which is composed of layers of progressively hotter gases. The outermost layer, from which energy is radiated, has an equivalent black body temperature of 5760°K. The rate of energy emission from the sun is $3.8x10^{23}$ kW, resulting from the conversion of $4.3x10^9$ kg/s of mass to energy. Of this total, only $1.7x10^{14}$ kW is intercepted by the earth which is located 150 million km away.

2.1.1.1 Solar Constant

The average amount of solar radiation released into space, near the earth, is 1,353 kW/m^2. Since the sun-earth orbit is elliptical, the sun earth distance varies by $\pm$1.7 percent during the year. As a result the extraterrestrial incident radiation also varies slightly by a similar amount throughout the year. For engineering purposes, the extraterrestrial flux is taken to be constant and is called the solar constant. Exhibits 2-1a and 2-1b illustrates the monthly variation of extraterrestrial radiation.

Date	Radius vector[a]	Ratio of flux to solar constant	Solar radiation (kW/m^2)
Jan. 1	0.9832	1.034	1.399
Feb. 1	0.9853	1.030	1.394
Mar. 1	0.9908	1.019	1.379
Apr. 1	0.9993	1.001	1.354
May 1	1.0076	0.985	1.333
June 1	1.0141	0.972	1.312
July 1	1.0167	0.967	1.308
Aug. 1	1.0149	0.971	1.312
Sep. 1	1.0092	0.982	1.329
Oct. 1	1.0011	0.998	1.350
Nov. 1	0.9925	1.015	1.373
Dec. 1	0.9860	1.029	1.392

[a]Ratio of sun-earth distance to mean sun-earth distance.

EXHIBIT 2-1a Annual Variation of Solar Incident Extraterrestrial Radiation From Orbital Eccentricity (KRE-1)

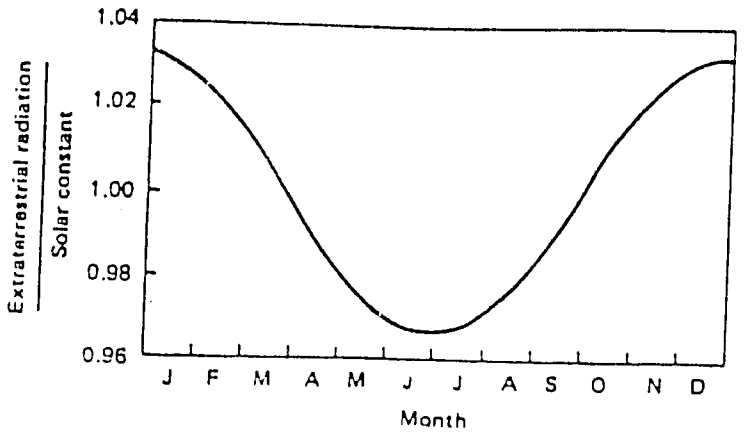


EXHIBIT 2-1b Effect of Time of Year on Ratio of Incident Extraterrestrial Radiation to Nominal Solar Constant (KRE-1)

2.1.1.2 Spectral Distribution

The solar constant represents the total energy emitted by the sun over the entire spectrum of wavelengths. Most of the extraterrestrial solar radiation is distributed on wavelengths between 0.2 and 2.6 microns (One micron equals 10^{-6} meters). "Light" or "visible radiation" is the band represented by wavelengths between 0.35 and 0.75 microns. Infrared occupies a band between 0.75 and 100 microns, while ultraviolet occupies the band below 0.35 microns. Although solar radiation covers a fairly wide band of wavelengths, (as seen in Exhibit 2-2), the peak intensity occurs in the band of visible light.

2.1.2 Extraterrestrial Radiation and Atmospheric Effects

Solar radiation is considerably altered in its passage through the earth's atmosphere. The two principal mechanisms for this alteration are absorption and scattering. Exhibit 2-3 illustrates the atmosphere's effect on extraterrestrial radiation transmittance. As a result of atmospheric effects, radiation striking the earth's surface is either beam (or direct) or diffuse. Beam or direct radiation is the components which strikes the surface as parallel rays. Beam or direct radiation is not scattered, absorbed, or reflected as it travels through the earth's atmosphere. Diffuse radiation arrives at the surface from a number of different directions. By measuring the amount of atmospheric scattering and absorption, one can estimate the intensity and arrival angle of the beam component of extraterrestrial radiation incident at a location.

2.1.2.1 Absorption by the Atmosphere

There are several atmospheric constituents that absorb a fraction of the incoming solar radiation. One primary absorber is ozone, which absorbs nearly all the ultraviolet portion of the spectrum. The other primary absorber is water vapor, which absorbs radiation in specific wavelength bands in the infrared region. In addition to the two primary absorbers, carbon dioxide, oxygen, other gases and particulates, absorb smaller amounts of incoming solar radiation.

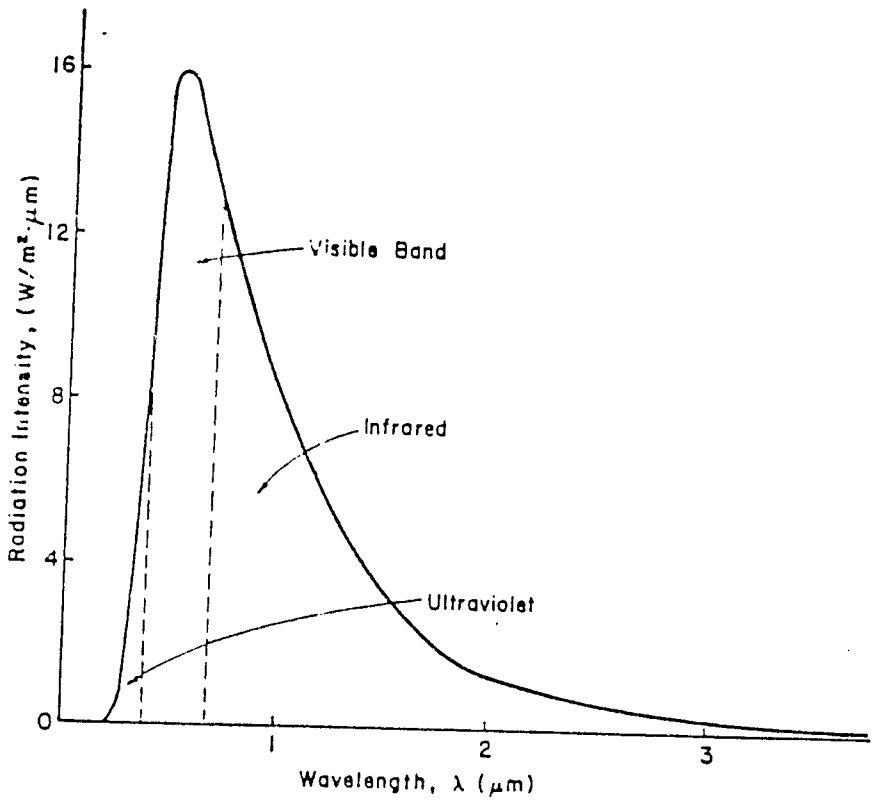


EXHIBIT 2-2 Approximate Representation of the Useful Spectrum of Solar Energy (SOL-1)

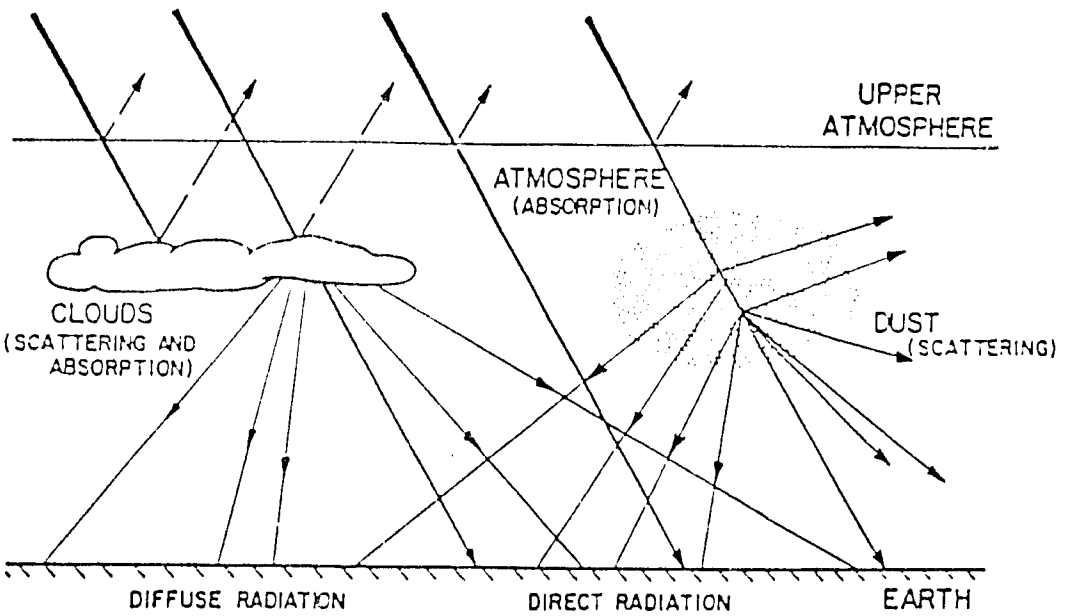


EXHIBIT 2-3 Atmospheric Effects on Solar Radiation Reaching Earth (SOL-1)

2.1.2.2 Reflection and Scattering

When solar radiation strikes the earth's atmosphere, a portion is immediately reflected back into space. The atmospheric constituents primarily responsible are gas molecules, particulates, and water droplets. The scattering is mostly uniform in direction; however, it is strongly wavelength dependent and primarily affects short wavelengths.

2.1.3 Solar Radiation Geometry

Most solar collectors are fixed or move with only limited freedom. Thus they do not face the sun directly at all times. As a result, calculation of the beam component of incident extraterrestrial radiation is insufficient; more information is needed to estimate the fraction of energy intercepted by the collector.

For the purpose of understanding the relationship of the sun's energy incident on the collector to that incident on the earth, the analysis of the sun's motion can be simplified if the Ptolemaic view of the earth as the center of the universe is employed. (KRE-1) Based on this view, the earth is fixed in space and the sun's virtual motion is assumed to take place in a coordinate system based on the earth as its origin.

2.1.3.1 Altitude, Zenith, and Azimuth Angles

In the Ptolemaic view, the sun can move with two degrees of freedom with respect to the earth. Thus the position of the sun by an earth-based observer can be described by two parameters: the altitude angle and the azimuth angle. As illustrated in Exhibit 2-4, the altitude angle is measured between a line colinear with the sun's rays and the horizontal plane. The point directly overhead of an observer is called the zenith. The angle between the zenith and the line of sight to the sun is called the zenith angle. This angle is the complement of the altitude angle.

The azimuth angle is measured in the horizontal plane between a line drawn due south and the projection of the site-to-sun line on the horizontal plane. The sign convention used is positive east of south and negative west of south. The altitude angle and azimuth angle depend on the latitude, declination, and hour angles which are described in the following section.

2.1.3.2 Latitude

The latitude is the angular distance separating a site from the equator.

The latitude is considered positive, north of the equator and negative, south of it. Latitude as an angular distance is illustrated in Exhibit 2-5.

2.1.3.3 Declination

The solar declination is the angular position of the sun at solar noon with respect to the plane of the equator. In other words, the declination has the same value as the latitude at which the sun is directly overhead at noon on a given day. Declinations north of the equator are positive; declinations south of the equator are negative. (This is illustrated in Exhibit 2-5.)

2.1.3.4 Hour Angle

The hour angle is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis. Morning hours are negative; afternoon hours are positive. (This is illustrated in Exhibit 2-5.)

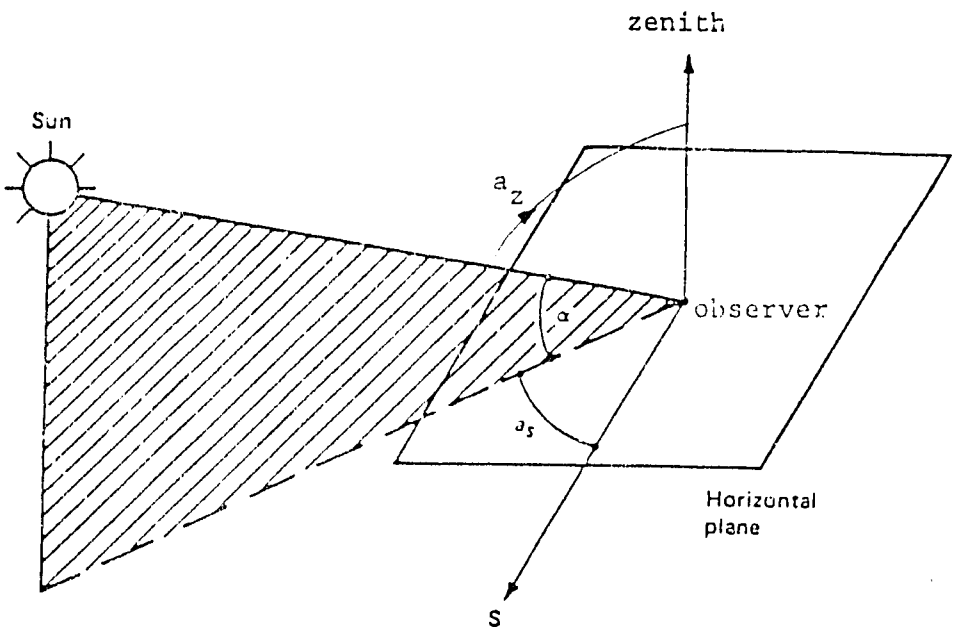


EXHIBIT 2-4 Diagram showing Solar Altitude angle, α; Solar Azimuth angle, a_s; and Zenith angle, a_z (KRE-1)

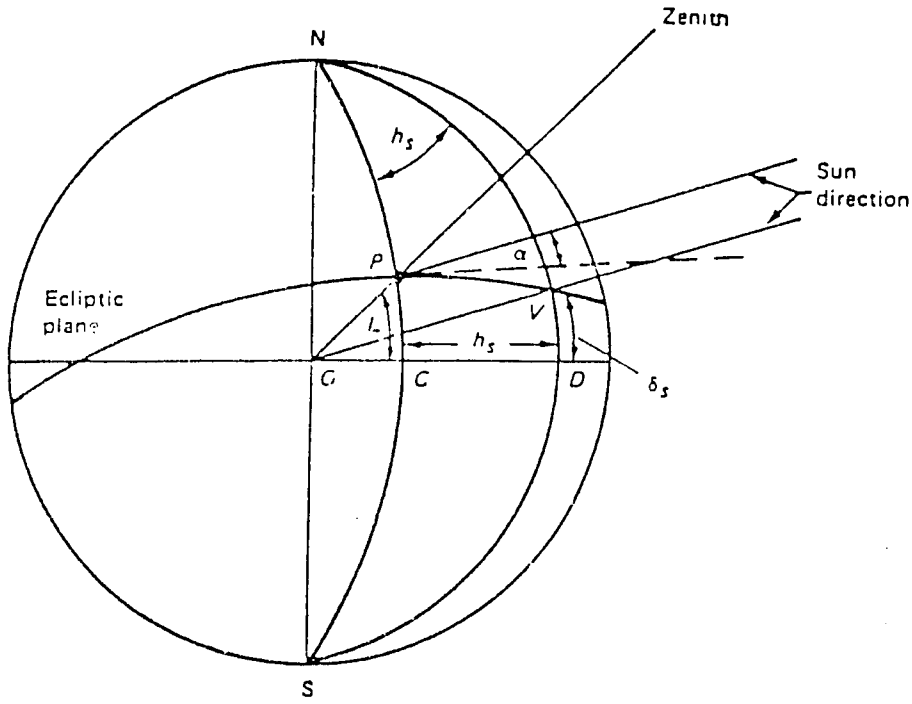


EXHIBIT 2-5 Definition of hour angle, h_s, CND, Solar Declination (VOD), Latitude (POC); P, Site of Observer; Equator (OCD) (KRE-1)

2.2 Passive Technology Fundamentals

2.2.1 Introduction

In contrast to a typical active solar system which is identified by solar collectors, piping, pumps, and heat exchangers, passive solar systems are not so easily characterized. The term "passive" is used to describe an alternative approach of building design which emphasizes simple technology and the use of on-site energy available from the surrounding environment. In the the recent past, buildings have been designed with no regard for the effect of the local climate; massive central space conditioning systems would regulate the interior environment of the building, consuming large amounts of conventional energy in the process.

Passive solar designs utilize architectural components in combination with on-site energy to produce a comfortable living environment, whether in the winter or summer. The building materials serve dual purposes. A wall serves as structural support as well as a thermal storage device. A window collects solar energy as well as provides lighting. Every structure collects some portion of the sunlight striking it; building materials, colors, the building's orientation to the sun and floor plan further influence a building's capability to capture incident energy. A properly designed structure will take full advantage of this collection process and supplement it with heat storage, natural ventilation, and summer cooling capabilities.

2.2.2 Passive Design Classification

The terms direct, indirect, and isolated are often used to describe approaches to designing and building passive structures. Depending on the building's location, climate, and comfort needs, more than one approach may be combined for maximum efficiency and aesthetics. Another classification scheme defines passive designs according to physcial configuration. These categories are direct gain, indirect gain, and isolated gain.

2.2.3 Basic Passive Designs

2.2.3.1 Direct Gain

In a direct heating design, the simplest of all solar heating systems, solar radiation is admitted directly into a living space, via windows, where it is absorbed and converted to heat in floors or walls which serve as thermal mass. At night, stored heat is transferred from the warm mass surface to the cooler living space. During the summer, shading devices are utilized to reduce unwanted solar heat gain. Night ventilation and other natural ventilation techniques are employed to maintain building comfort. Exhibit 2-6 illustrates a simplified direct gain building.

2.2.3.2 Indirect Gain

With the indirect gain approach, sunlight strikes a surface before it enters the interior living space. Heat is first absorbed by the surface (usually concrete, masonry, or water) which is positioned directly behind south-facing glass. Later in the day, energy is then released to the room by radiation, convection, and conduction. Moveable insulation between the mass and the double-panel glazing may be used to reduce nighttime heat loss through the glass.

In the cooling season, the thermal mass provides a thermal lag effect. Summer solar gain does not affect the building's interior climate until later in the day when it might be needed. As in direct gain systems, natural ventilation is important in order to provide additional cooling. Exhibit 2-7 is an illustration of a thermal wall design, a typical indirect gain design.

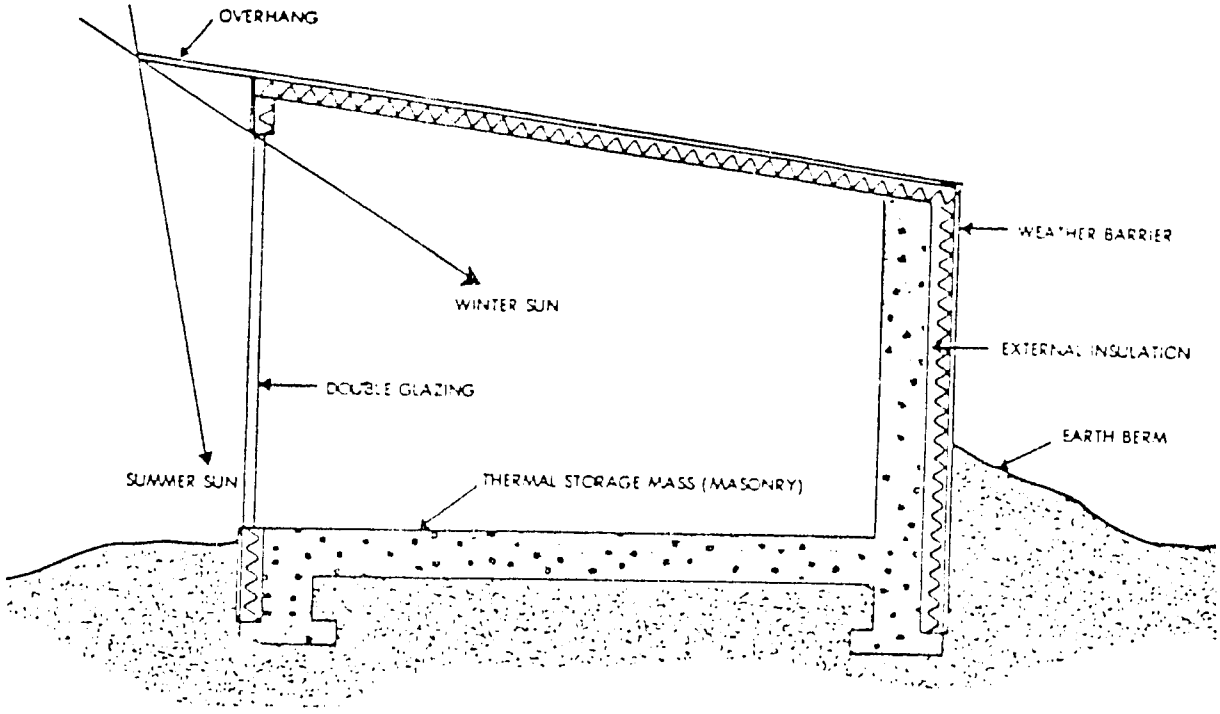


EXHIBIT 2-6 Simplified Direct-Gain Passive Design (PAS-2)

2.2.3.3 Isolated Gain

In an isolated heating system, solar heat is collected and stored in an area set apart from the living space. This collection space is thermally isolated from the rest of the building. Its temperature is allowed to swing from as low as 40°F to 100°F (4.4°C to 37.8°C). Therefore, this area is not considered "conditioned" space; it is not heated with a conventional furnace or cooled with a conventional air conditioner. Because the main living area is not directly exposed to the sun, the amount of heat it receives can be more closely controlled with this type of system than with other system approaches. Exhibit 2-8 illustrates a sunspace, a typical isolated gain design.

2.2.4 Passive System Components

Basic passive systems are comprised of five mutually dependent basic components: collector, absorber, storage, distribution and control.

2.2.4.1 Solar Collector

A passive solar collector is usually a transparent or translucent glazing sealed in a frame and located on the south side of the building (Northern Hemisphere). The collector glazing surface can be positioned vertically, as in windows, or sloped, if installed on the roof.

2.2.4.2 Absorber

The absorber is a solid surface, usually dark colored, that is exposed to direct and diffuse solar radiation entering through the collector glazing. The absorber "converts" the incident solar radiation into heat which is either delivered directly into the living space for immmediate use or stored in a "storage" component.

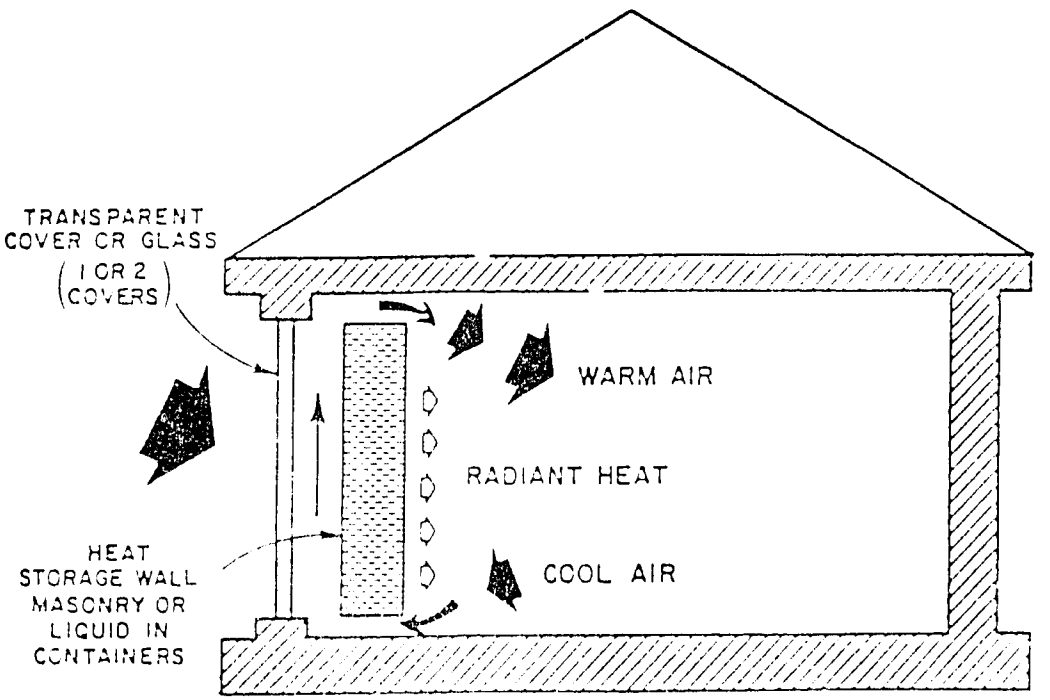
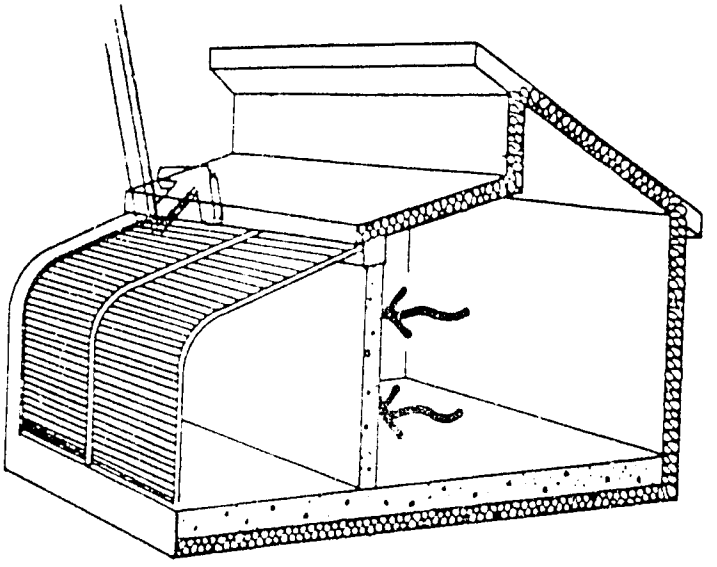


EXHIBIT 2-7 Simplified Thermal Wall Passive Design (Indirect Gain) (SOL-1)



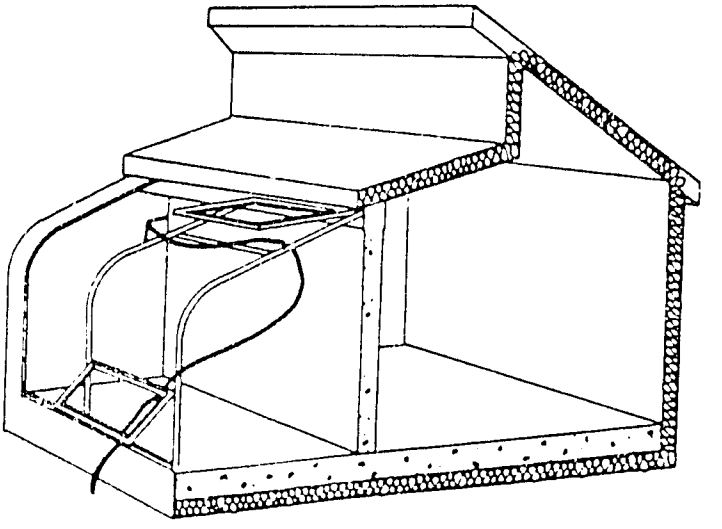


EXHIBIT 2-8 Diagram of Isolated Gain Sunspace (PAS)

2.2.4.3 Storage Component

Thermal storage is typically composed of one or more materials which have the capacity to retain energy for a period of hours. The density, heat capacity, and thickness or surface area are all important measures of its capacity to store heat. The slow rate of energy discharge from the storage materials helps maintain a steady, comfortable temperature within the space. In some cases, the storage materials can be used to cool the living space by absorbing heat from the room and effectively cooling it, or by providing a thermal lag effect. The absorber and storage component are often one and the same, as in a masonry floor or wall.

2.2.4.4 Distribution

The distribution system delivers the collected and/or stored heat or cooled air into the conditioned space. Distribution can be by natural means, such as the radiation of heat from a wall or the movement of air by natural convection or can be assisted by small pumps or fans which blow heat away from the absorber to the living spaces or to remote storage. Mechanical equipment such as pumps of fans may be used for more efficient operation in passive systems.

2.2.4.5 Control Components

Control components regulate the heat loss/gain into and out of the passive system. Examples of control devices are as follows:

(1) Shading devices: They reduce the amount of solar radiation allowed to enter into the conditioned space.

(2) Reflectors: The increase the amount of solar radiation incident on the collector glazing.

(3) Moveable insulation: It reduces the heat loss/gain through the collector glazing.

(4) Louvers, doors or duct vanes: They alter the amount and direction of air movement into and out of the building and distribution systems.

2.2.5 Human Comfort

The question of comfort depends primarily on the maintenance of a thermal environment in which the body can lose heat at a rate equal to its heat production without the need to perspire or provide heat such that the body does not have to shiver to keep warm (MAZ). The human body uses three basic mechanisms to maintain comfort: convection, evaporation/respiration, and radiation. Factors affecting comfort are air temperature, humidity, air speed, and mean radiant temperature. (PAS-4)

Mean radiant temperature (MRT) is the temperature that the surfaces of an imaginary black enclosure (equal in size and shape to the actual room involved) would be required to have if the surfaces were to exchange with a person an amount of heat (by radiation) equal to the amount of energy that the person is actually exchanging with all of the surfaces of the room he or she is in. It is, in effect, the average temperature of all the surrounding surfaces (walls, ceiling, floor). Different combinations of MRT and air temperature can produce the same comfort sensation. A 1°F change in MRT is normally assumed to have a 40% greater effect on body heat loss than 1°F change in air temperature. Or, for the same feeling of comfort at 70°F (21.1°C), the air temperature can be reduced 1.4°F for each 1°F increase in MRT. The following pairs of combined numbers (in degrees C) produce the equivalent sensation of 21.1°C (70°F): (PAS-4).

Air temperature	9.4	13	17	21	25	29	33
MRT	29	27	24	21	18	16	13

For example, the last pair of numbers indicates that if the air temperature is 33°C and the MRT of the surrounding surfaces is 13°C, the comfort sensation or feeling experienced by most lightly-clad occupants will be similar to the sensation they would experience in a room with an air and wall surface temperature of 21°C.

This can have important design implications. For example, the better a wall is insulated, the higher its interior surface temperature will be during cold weather. This warmer surface temperature allows interior air temperatures to remain lower and still provide sufficient comfort; in turn, heat loss to the outside is reduced because of the smaller difference between indoor and outdoor air temperatures. Lower heat loss reduces the size of the conventional heating system required.

Exhibit 2-9 is a chart showing temperature and humidity ranges for comfort. For additional information on determining criteria for conditions for human comfort, consult (ASH-1), "Psychological Principles, Comfort and Health".

The effect of MRT is crucial for providing comfort in passive solar design because may passive systems relay on warm (or cool) surfaces to exchange energy with the air.

2.3 Active Technology Fundamentals

2.3.1 Operating Principles

Passive designs permit or prohibit the entry of direct solar or solar derived energy into buildings by use of large windows, selective site orientation, stationary thick walls, etc. The flow of heat or the cooling process, as a result of careful building design, occurs spontaneously, either by conduction, convection, radiation or evaporation.

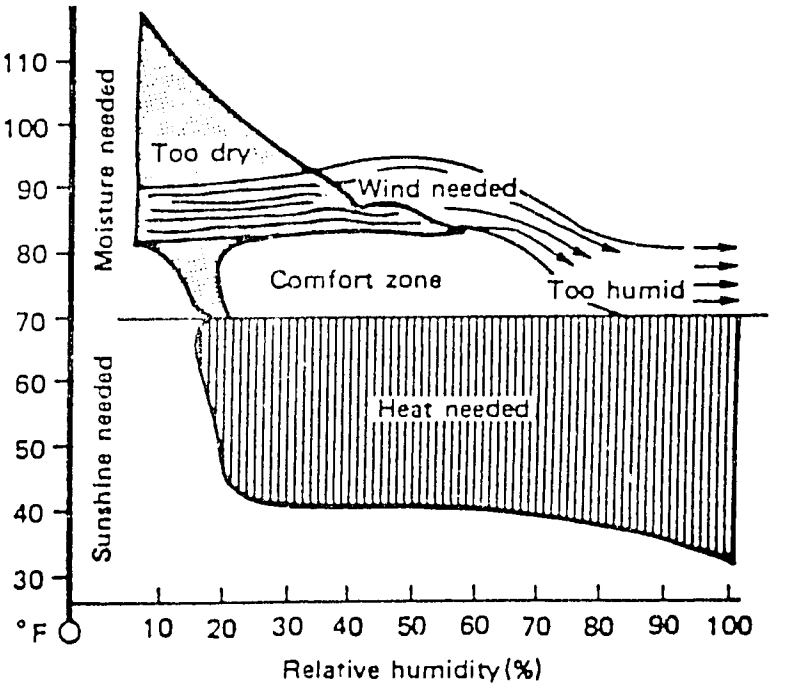


EXHIBIT 2-9 Bioclimatic Chart Showing Temperature and Humidity Regions for Comfort (KRE-1)

Active space conditioning and/or liquid heating systems require special equipment for collecting solar energy, processing it as heat or cold, storage, and distribution to the end use. The heat or cooling flow is entirely forced, by either fans or pumps.

The key components are a solar collector, a heat storage device, an auxiliary heat source, and facilities for the distribution of heat to the building, process, or domestic water system.

Active cooling systems require a heat-operated air conditioning (cooling) unit. The solar collector must be of different design because heat-operated cooling (chillers) requires higher temperatures than are available from flat plate solar collectors.

An auxiliary source of heat is required to supply backup heat when the solar collector/thermal storage subsystem is unable to meet heating demands. Although the solar collector and storage unit could be sized large enough to meet the full heat requirements throughout a year, the overall cost is generally prohibitive.

Simplified active solar systems are illustrated in Exhibit 2-10 A and B.

2.3.2 System Components

2.3.2.1 Solar Collectors

A solar collector is a device used to convert incident solar radiation to heat energy which is captured in either a gas or a liquid. There are two principal types of solar collectors: flat plate and concentrating (non-focusing and focusing). Each has its own advantages and disadvantages. Choice is based on application, complexity, overall benefit, and economics.

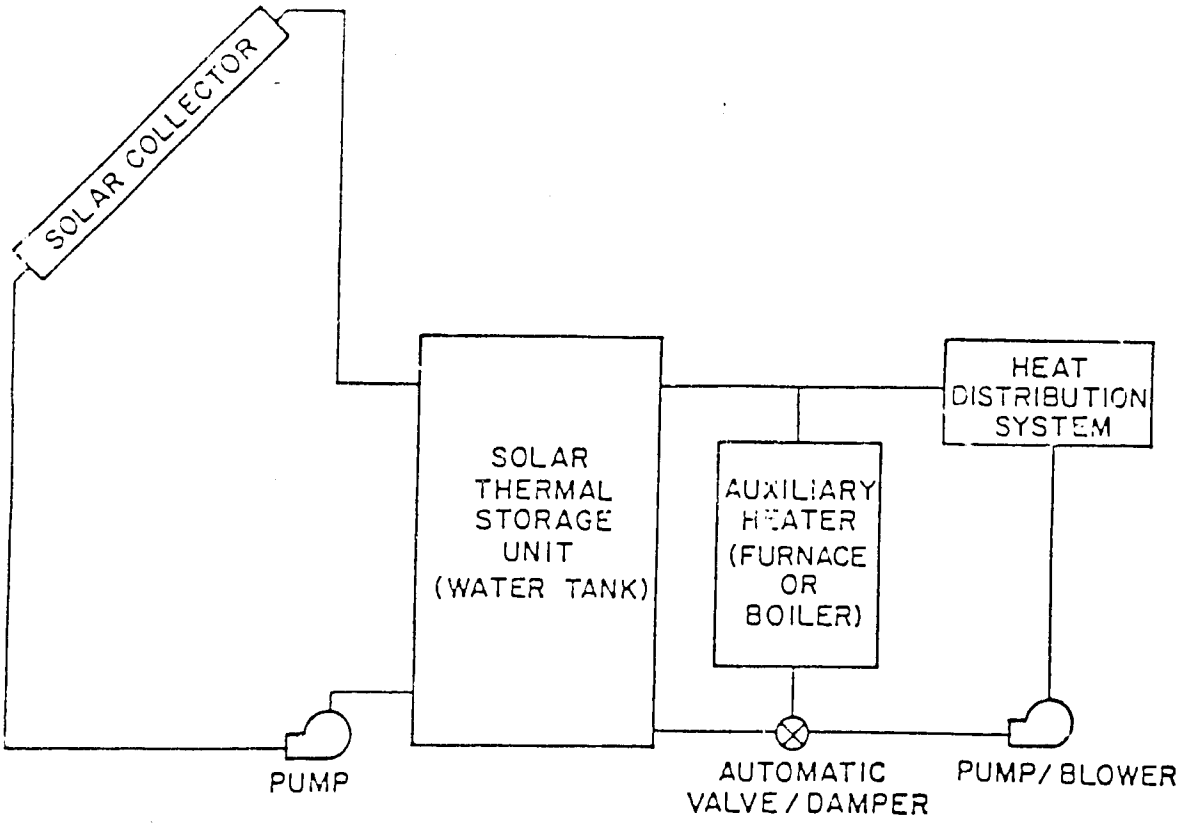


EXHIBIT 2-10A Simplified Liquid Solar Systems

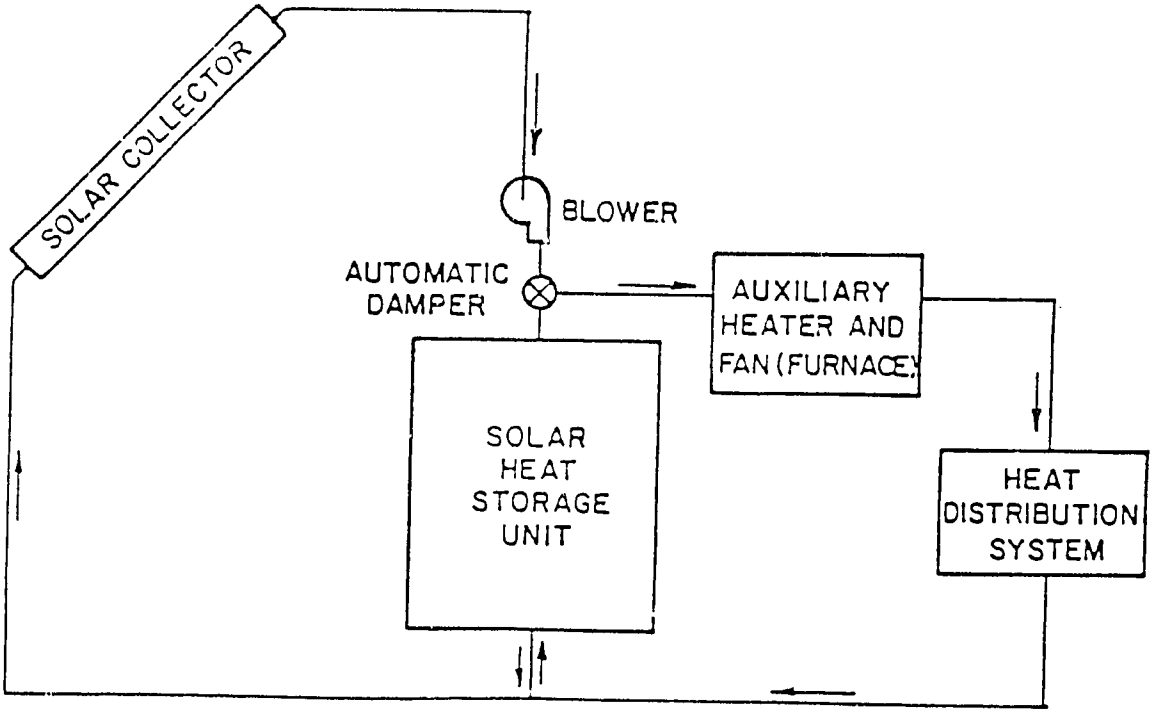


EXHIBIT 2-10B Simplified Air Solar Systems

2.3.2.2 Flat Plate Solar Collectors

Introduction:

A flat plate collector in its simplest form consists of a flat metallic absorption plate which is oriented in space so that the sun's rays impinge as perpendicularly as is feasible. The surface is either blackened or coated with a selectively absorbing surface in order to absorb (capture) the incident electromagnetic (sunlight) energy and to convert it to heat. (See Exhibits 2-11 and 2-12). In Exhibit 2-12, the absorption plate may be used as an air collector, with the air to be heated flowing over the top of the absorber plate. If intended for use in heating a liquid, the water may flow over the surface of the absorber plate or through tubes which are in immediate contact with the absorber plate as shown in Exhibits 2-11 through 2-14.

In a "liquid-tube" system, a fluid flows through pipes attached to the flat absorber. The heat energy in the absorber is transferred to the liquid which, in turn, is delivered to some other point in a system where the heat is extracted for intermediate storage for eventual end-use (space heating, domestic hot water, etc.). Heat-transport systems (from absorber plate to the liquid containing passages) are shown in Exhibits 2-13 and 2-14.

The liquid need not flow through metal tubes attached to the absorber plate. Cool water may be allowed to escape from a series of small holes in a pipe (header) at the top and trickle over the absorber surface, becoming warm on its way down, to a collecting trough or gutter, thence into a pipe. This concept is illustrated in Exhibit 2-15.

Gas (Air)

In a gas (air) collector, the air passes between a confined space over the absorber plate and underneath a glass or clear plastic cover. The air is heated as it flows from the bottom to the top as illustrated in Exhibit 2-16.

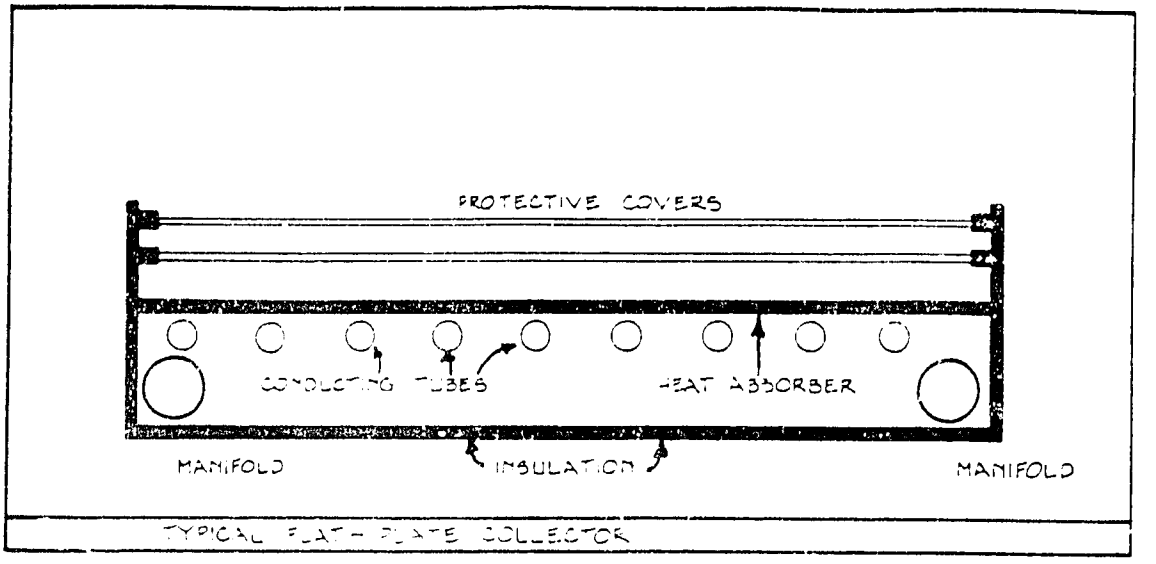


EXHIBIT 2-11 Cross section view of conducting tubes which are in direct contact with the absorber

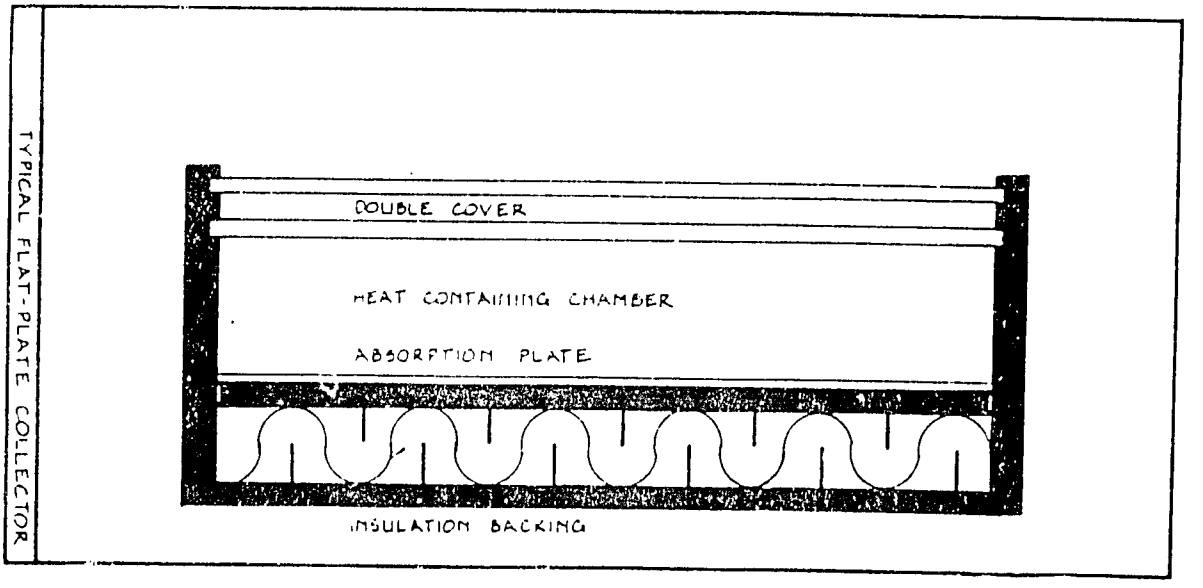


EXHIBIT 2-12 Cross section view of Flat Plate Collector for Air or Liquid Applications

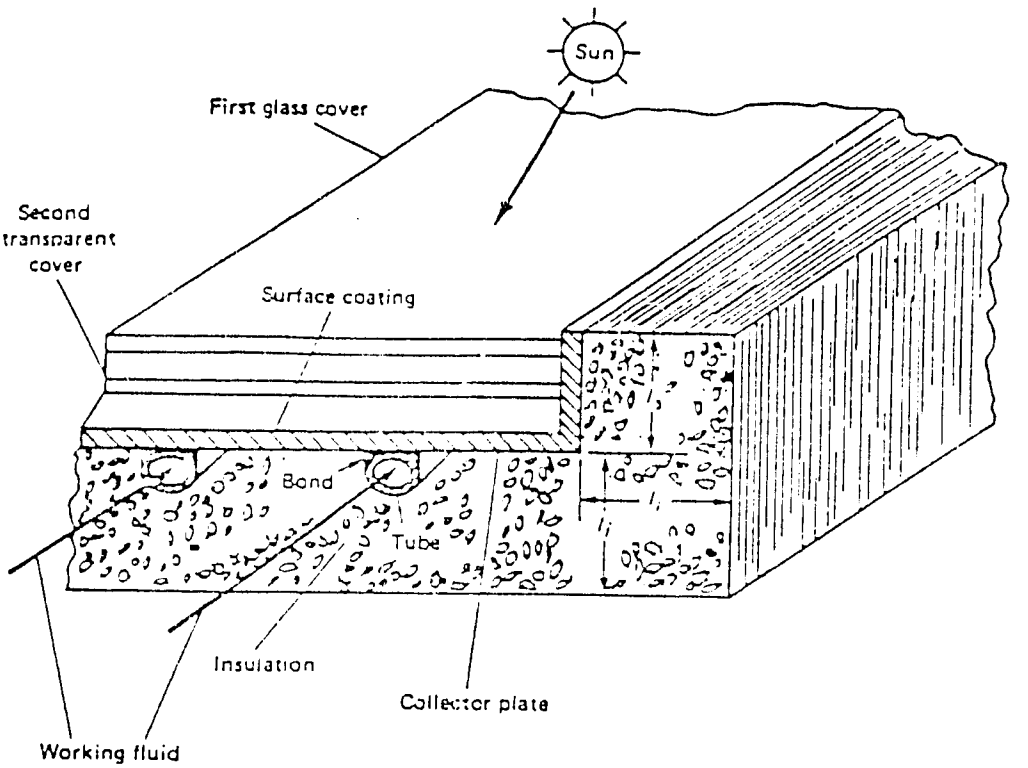


EXHIBIT 2-13 Solar Collector with Two Covers (KRE-1)

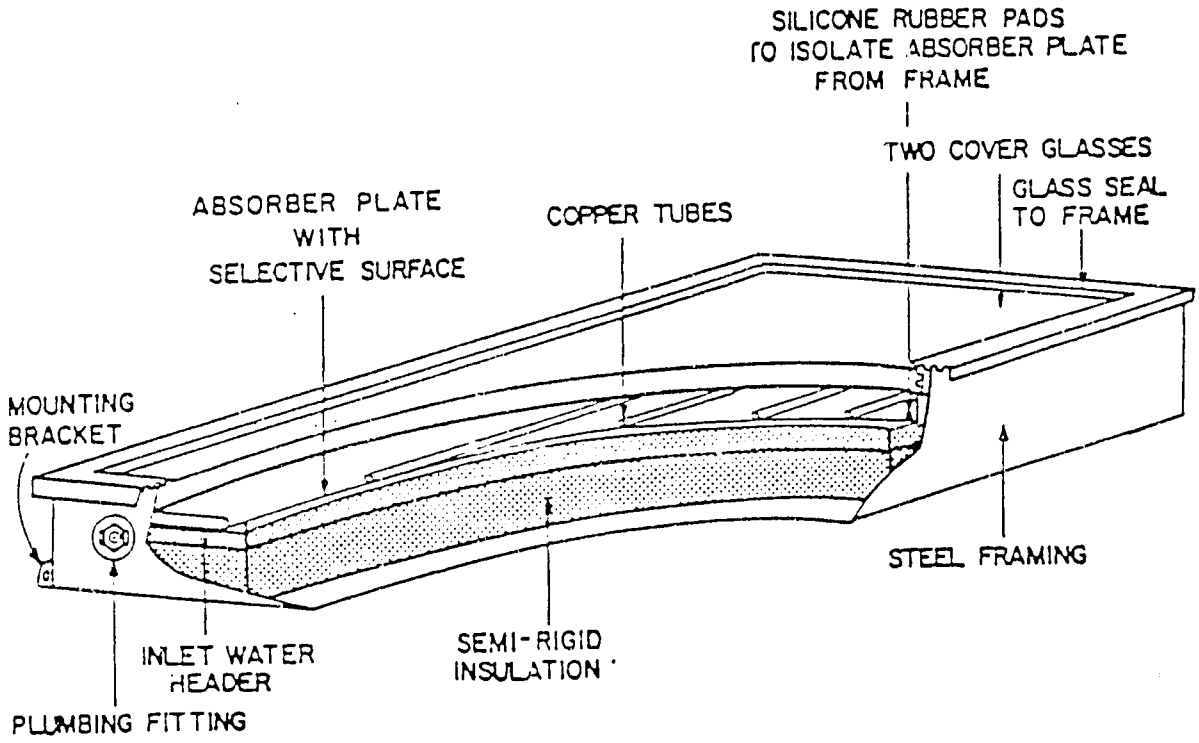
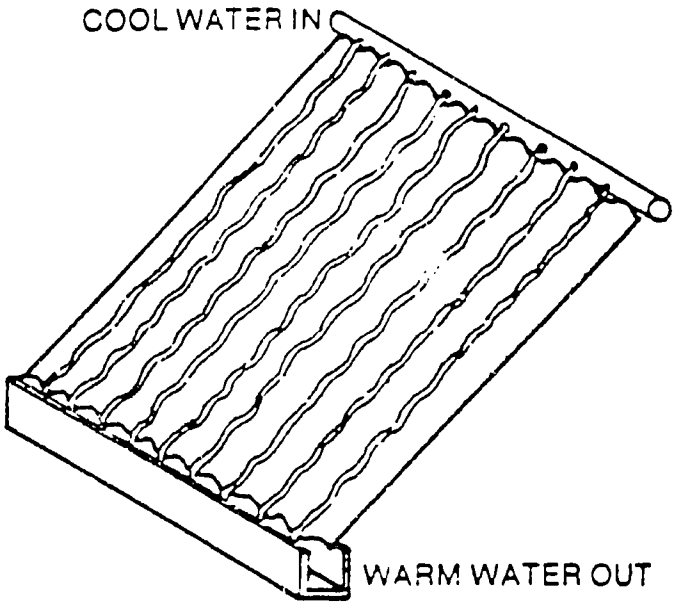


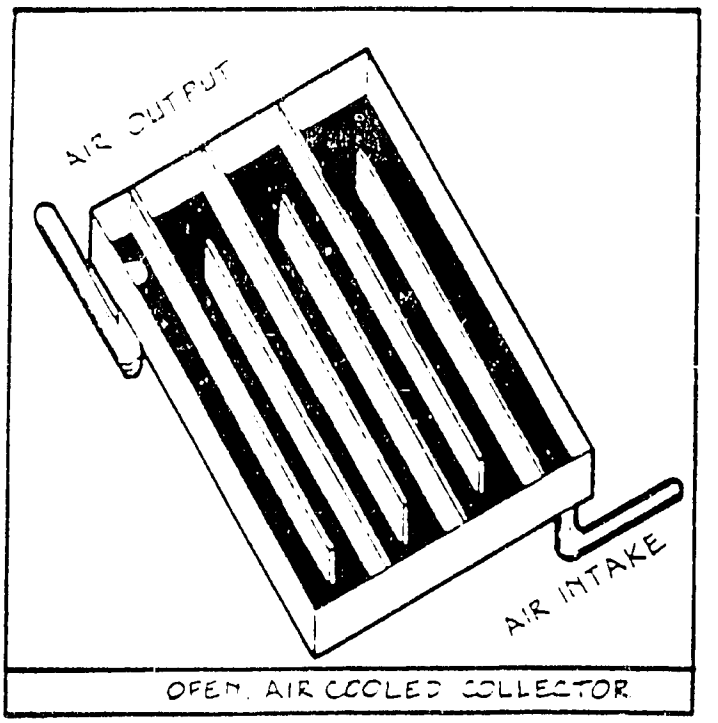
EXHIBIT 2-14 Solar Collector with Two Covers



TRICKLE

EXHIBIT 2-15 "Trickle Down" Liquid Collector

Warmed air output



cool air intake

EXHIBIT 2-16 Cut-away view (cover plate removed) of an air collector warming air.

Collector Design and Construction

A critical element in a solar heating and cooling system (SHAC) is the collector. The above comment is very general in nature; as one cannot distribute or use heat that has not been collected.

Collector Mounting

Installation of solar collectors on a building requires special mounting arrangements. Collectors are usually attached directly onto a sloped roof or on a separate structure onto a flat roof. In both cases, the attachments and mounting structures should be designed to carry the maximum dead load and any supporting structure. In addition, mounting devices have to support any live loads, including wind, rain, hail, and snow. These live loads are determined from historical climatic data of the region.

There are many methods that can be used to mount collectors on sloped and flat roofs. Exhibit 2-17 illustrates a method for installing free standing collectors onto a flat roof. This design uses "pitch pocket" penetration through the roof membrane and attachments to structural members beneath the roof. No more than one vertical support should be used per pocket. This design requires continuous maintenance and replenishment of pitch to preserve a leak-proof roof. Other methods for flat-roof mounting include curb mounting, in which the collectors are attached to concrete curbs that are integral parts of the roof.

On sloping roofs, solar collectors can be attached directly to the subroof and structural components beneath it. The collector can then be flashed onto the roof as an integral part of the roof. A disadvantage of this approach is, if collector replacement is ever required, significant extra costs for roof replacement will be incurred. An additonal method is to locate collectors above the roof surface on spacers; thus,

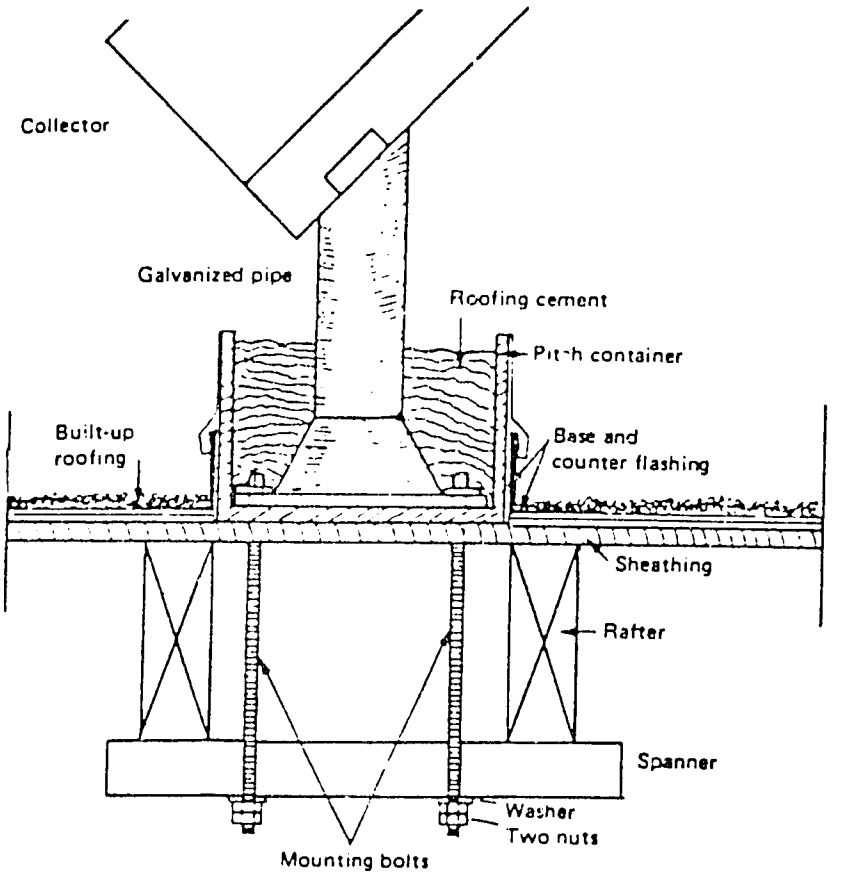


EXHIBIT 2-17 Example collector mounting detail in the pitch pocket approach for a flat, wooden residential roof. (KRE)

the collector is not part of the roof. This method permits rapid placement of collector; however, roof repair or replacement is difficult, sometimes requiring collector removal.

Heat Transfer

A solar heating and cooling system (SHAC) operates on the transport of heat from one place to another. If cooling is desired, heat must be transferred from the volume to be cooled. If heating is desired, heat must be transferred to the volume to be heated.

There are three mechanisms that are employed in transfer of heat. They are conduction, convection, and radiation.

Thermal Conductivity

The mechanism of thermal conduction in gases is explained qualitatively by kinetic energy. The physcial mechanisms of conduction in liquids is qualitatively similar even through the mechanism is more complex.

All molecules, whether in a gaseous, liquid, or solid state are in motion. Molecular velocities are a function of temperature. Their velocities will be a measure of the kinetic energy of the individual molecules. The average velocity, hence kinetic energy, of a group of molecules may be high or low.

Because molecular motions are random, collisions between the molecules will occur. As the molecules collide a transfer of kinetic energy from the one with higher kinetic energy to the one with the lower kinetic energy occurs.

Consider a mass of gas, say air, in a long horizontal pipe. At one end, the gas is first heated and the source of heat is removed. The kinetic energy of those molecules at that end is increased. The molecules at the high temperature end of the pipe have a high kinetic energy. These higher kinetic energy molecules will collide with adjacent molecules and

transfer some of their kinetic energy to the adjacent molecules with lower kinetic energy. The observed temperature of the second group of molecules (those with lower kinetic energy) will also rise. As the molecules of the second "group" move randomly, they will collide with molecules further down the pipe, transferring some of their kinetic energy to those molecules. Thus, the upstream molecules lose kinetic energy and the down stream molecules gain kinetic energy. This process continues along the length of the pipe with kinetic energy transferring from molecules of higher kinetic energy to those with less kinetic energy. Eventually, all of the gas molecules will have nearly the same velocity and temperatures will have essentially the same "average" value. This process represents the fundamental mechanism of conduction.

If heat is applied continuously to one end of the pipe, while heat is removed at the same rate at the other end, a continuous transfer of kinetic energy from one end of the pipe to the other end will occur. Heat energy introduced at one end of the pipe will be captured at the other. The molecules of gas do not, in the classic case, travel through the pipe. They more or less stay where they are transferring kinetic energy through the collision process. This energy transfer process is referred to as conduction.

If the pipe is placed in a vertical position and if the bottom end of the pipe is heated, the kinetic energy of gas molecules at the bottom will increase and will through the collision process, transfer some of their kinetic energy to those molecules immediately above which have lower kinetic energy. Again the molecular collision/kinetic energy process can continue up through the pipe until all gas molecules are at the same temperature.

Because the pipe is in a vertical position, another mechanism of heat movement takes place. The hotter group of molecules at the bottom of the pipe will tend to rise and displace or "push" against the molecules of gas above. The whole mass of molecules will eventually be set into motion. High kinetic energy (higher temperature) gas molecules will

rise and low kinetic energy (lower temperature) gas molecules at the very top of the pipe will move downward along the inside walls of the pipe. Eventually, when all of the molecules have approximately the same temperature, the movement will cease. This movement is referred to as convection. In the absence of a motivating device such as a fan (or a pump if the fluid is a liquid) this is called natural convection. If a pump or fan is used to increase the movement, this heat transfer process is referred to as "forced convection".

One must keep in mind that heat conduction through intermolecular collision still takes place. In a vertical pipe, heat transfer occurs by both conduction and convection.

Exhibits 2-18, 2-19, 2-20 and 2-21 illustrate the conduction characteristics of several gases, liquids and metals. It can be seen that thermal conductivities for copper and aluminum are high. The use of such materials for absorber plates may be expensive and if used together, may be subject to intense corrosion.

The flow rate of water or air through an energy collector affects its performance. Low flow rates allow the water or air to get very hot, but reduce the total energy collected. Because heat loss from the collector to the surrounding atmosphere is a function of relative temperatures, there will be an increase in heat loss.

Higher flow rates usually improve performance, but require larger pipes or ducts and more electrical power for pumps or fans. Optimum performance and optimum system cost usually coincide when about 1.2 to 2 gallons per square foot (50 - 83 liters/square meter) of collector medium circulates each hour. This results in a temperature rise through the collector of about 10°F (6°C) on a sunny day.

Material	Thermal conductivity at 300 K (W/m · K)
Copper	386
Aluminum	204
Carbon steel	54
Glass	0.75
Plastics	0.2–0.3
Water	0.6
Ethylene glycol	0.25
Engine oil	0.15
Freon (liquid)	0.07
Hydrogen	0.18
Air	0.026

EXHIBIT 2-18 Thermal Conductivities of Some Metals, Nonmetallic Solids Liquids, and Gases

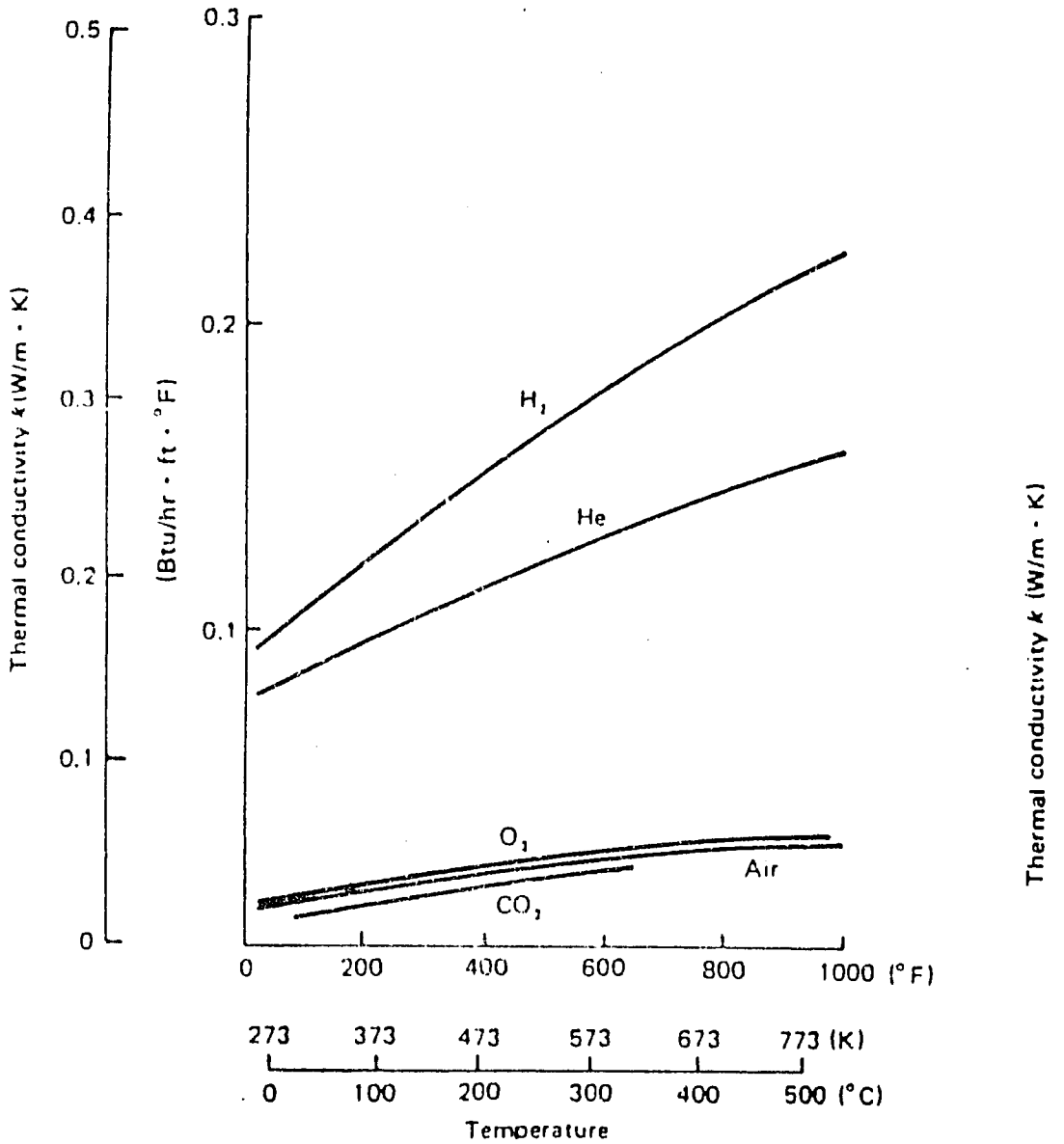


EXHIBIT 2-19 Thermal conductivities of some typical gases, 1 w/m - K = 0.5779 Btu/hr - ft - °F.

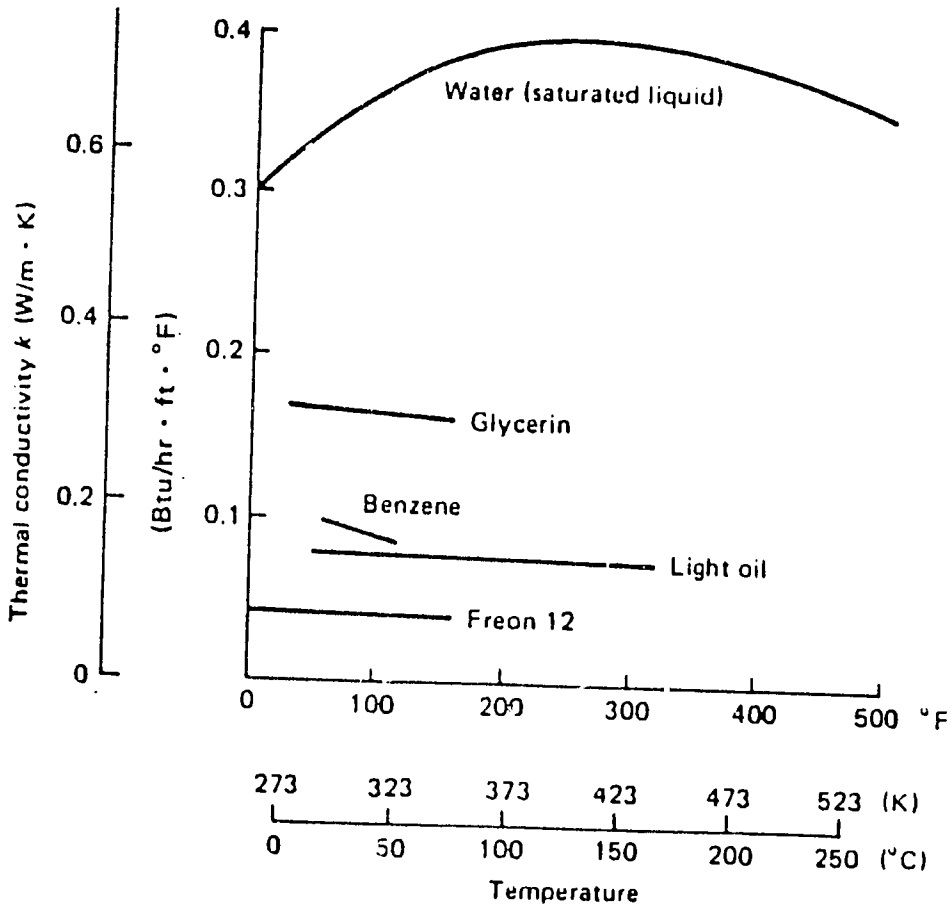


EXHIBIT 2-20 Thermal conductivities of some typical liquids.

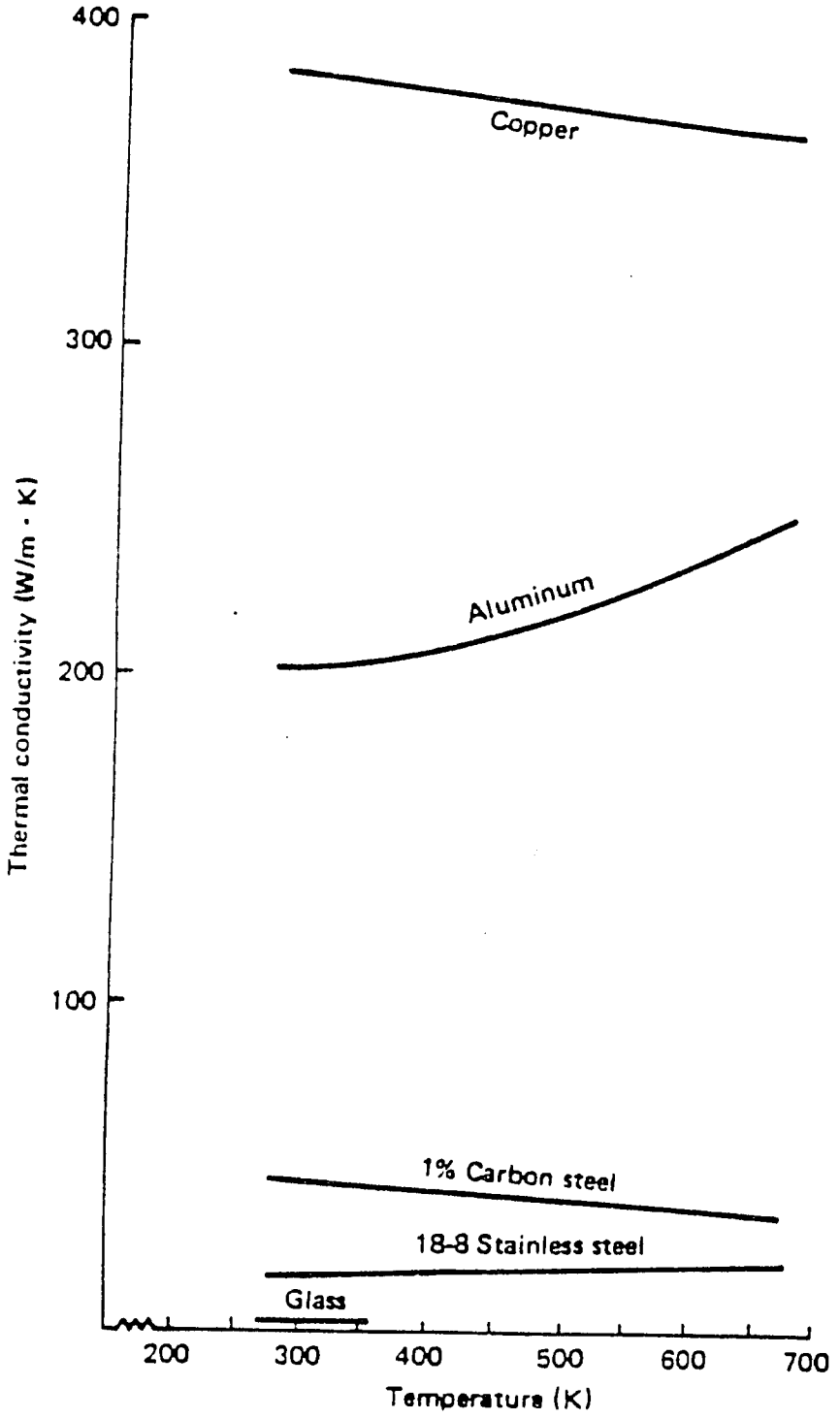


EXHIBIT 2-21 Thermal Conductivities of Some Typical Solids

Air systems usually operate with a larger temperature rise because it is expensive to move large volumes of air. Typical flow rates are 2 to 4 cubic feet per minute per square foot (0.62 - 1.22 cubic meters per minute per square meter), with a resulting temperature rise through the collector of 40°F to 80°F (4.5° to 27°C).

The actual efficiency of a collector (i.e., the proportion of solar energy absorbed as heat in the heat-transport medium) also depends on the design of the system and its components, but the following data provide a rough indication of what might be expected.

For a temperature rise of 108°F (60°C), say from 77 to 185°F (25 to 85°C), the overall efficiency could be expected to be close to 30 percent.

For an increase of only 54°F (30°C), however, from 77 to 131°F (25 to 55°C) the efficiency might increase to about 50 percent.

Average efficiencies of flat plate solar collectors have been found in practice to generally be between 35 to 40 percent.

A black collector plate can reradiate much of the solar energy that it absorbs. One method to reduce these reradiation energy losses is to isolate the absorber plate from the lower temperature environment. The absorber should be enclosed in a frame (metal or wood) that rests on insulation. Insulation should cover the sides and the top should be covered with sheets of glass or other transparent material.

Exhibit 2-22 illustrates how a flat plate collector efficiency varies as a function of incident solar radiation, the number of cover plates in the glazing, and the temperature of the fluid as it enters the collector.

Convection Heat Transfer

When a fluid (gas or liquid) comes in contact with a solid surface at a different temperature than the contacting fluid, the resulting thermal energy exchange process is called convection heat transfer.

There are two types of convection processes: free convection and forced convection. In the first type the density difference which results from fluid contact with a surface of a different temperature gives rise to bouyant forces and energy transfer. Typical examples are the heat transfer between the wall or roof of a house and the surrounding air on a cool day, the heat transferred to the fluid in a tank in which a heating coil is immersed, or the heat loss from the cover of a solar collector to the air above the collector when there is no wind blowing.

Forced convection occurs when an external force moves a fluid at a velocity greater than "free" velocity past a surface having a higher or lower temperature than the fluid. Under these conditions more heat can be transferred at a given temperature difference.

The increase in the rate of heat transfer is produced by additional work required to move the fluid past the surface.

In SHAC (Solar Heating and Cooling) systems, both free and forced conduction characteristics are exploited. The use of free or forced conduction is dictated by efficiency differences, cost, and necessity.

Convection losses from a solar collector through the cover plate can be minimized by using more than one cover. Two covers are considered the economic/efficiency optimum. See Exhibit 2-22.

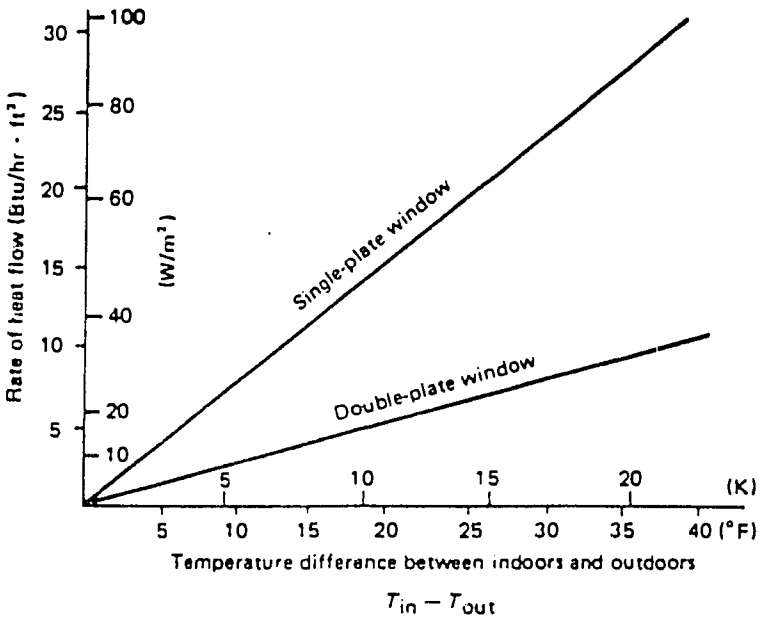


EXHIBIT 2-22 Effect of various temperature differences $T_{in} - T_{out}$ for single- and double-plate windows on heat flux (q/A).

Radiation Heat Transfer

Thermal radiation is one kind of electromagnetic energy. All bodies emit thermal radiation by virtue of their temperature. When an item or substance is heated, its atoms, molecules or electrons are raised to higher levels of activity, called excited states. However, they tend to return to lower energy states and, in this process, energy is emitted in the form of electromagnetic waves.

Electromagnetic waves can travel through a vacuum. They do not depend upon the presence of any medium such as air, metal, liquid, etc. A hot electric wire, inside of an evacuated glass bulb, emits visible and thermal radiation that travels through the vacuum space and impinges on the glass envelope.

Visible light passes through the glass. Some of the invisible thermal radiation (referred to as "infra-red") is absorbed by the glass and is converted to heat which can be felt by touching the glass. The warmed glass will radiate that heat as infra-red energy. A portion of the infra-red energy will pass through the holes between the molecules of glass and appear on the outside of the bulb and continue on its way along with that directly radiated by the glass.

When radiation, such as solar energy, strikes a body, glass cover plate, or a plain black absorber plate, a portion of the radiation is reflected, a portion is absorbed and, if the material is transparent, a portion is transmitted.

The fraction of the incident radiation reflected is defined as the "reflectance", ρ, the fraction absorbed as the "absorptance", α, and the fraction transmitted as the "transmittance", τ.

According to the first law of thermodynamics (energy is conserved, i.e., all must be accounted for) these three componnets must add up to unity, or:

$$p + \tau + \alpha = 1$$

Completely opaque bodies do not transmit any radiation, and therefore $\tau = 0$. In the case of a plain black absorber any and all radiation penetrating the glass or transparent covers of a collector falls onto the surface of absorber and is converted to heat energy.

In the absence of some means to remove this heat energy by conduction or convection (such as air flowing over the surface or water flowing in metal tubes in contact with the plate), the absorber must reradiate the heat energy and reach an equilibrium point where radiation outwards equals radiation energy into the absorber.

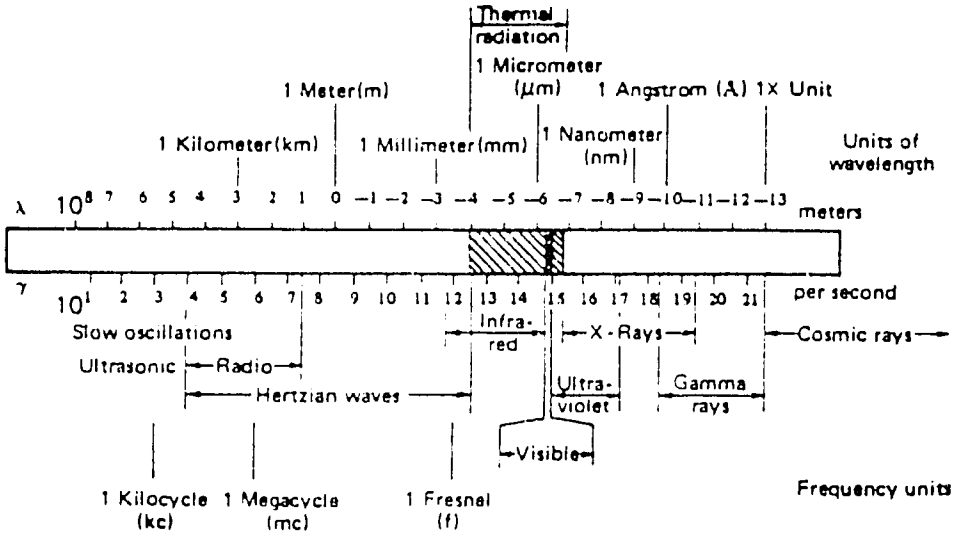
Exhibit 2-23 and shows a portion of the electromagnetic wave spectrum. The region of interest for solar energy applications extends between 1 x 10^{-8} to 1 x 10^{-4} meters (0.01 to 100 microns).

Thermal radiation is usually considered to fall within the band from 0.1 x 10^{-6} to 100 x 10^{-6} meters (0.1 to 100 microns).

Most solar radiation energy is in the range between 0.1 x 10^{-6} to 3 x 10^{-6} meters (0.1 - 3 microns). (See Exhibit 2-24)

The absorber surface should have a high absorptance index within the band of wavelengths contained in the sunlight (solar energy). The high absorptance index means high conversion of the solar energy to infrared electromagnetic (thermal) energy.

At the same time the absorber should have high reflection (low emittance) within the band of wavelengths in which infrared electromagnetic (thermal) energy exists.



Electromagnetic wave spectrum.

EXHIBIT 2-23 Electromagnetic Wave Spectrum (KRE)

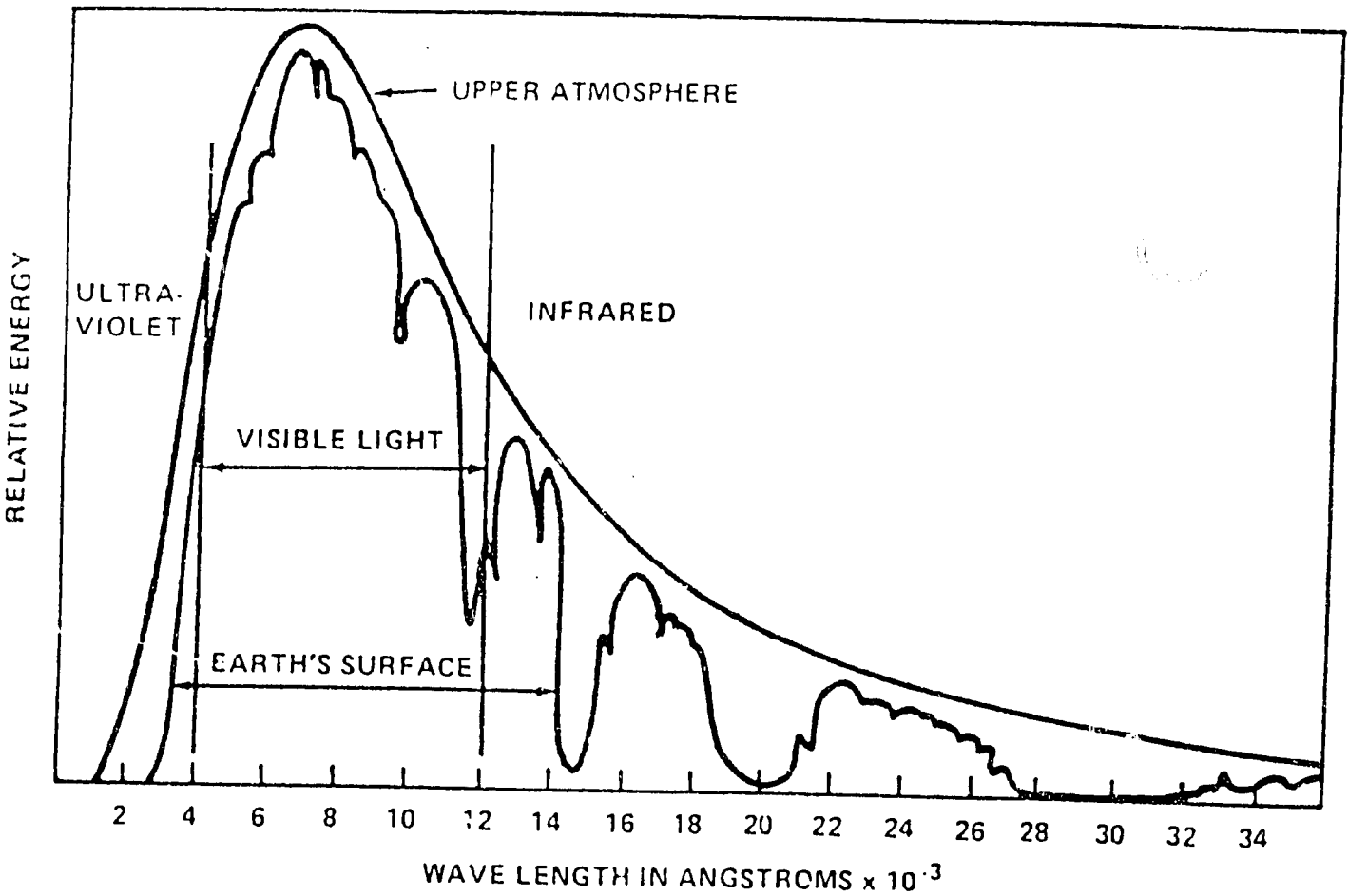


EXHIBIT 2-24 Solar Energy Spectrum Source: Eppley Laboratory, Inc., Newport, R.I.

The radiation of the thermal energy from the absorber is outward to the space above, so that the heat transfer medium (air or liquid) can accept the thermal energy by conduction for transmittal to storage or point of use.

Selective surfaces, produced by chemicals and/or special physcial surface treatment, combine a high absorptance for solar radiation with a low emittance for the temperature range in which the surface emits radiation.

This combination of surface characteristics is possible because 98 percent of the energy in incoming solar radiation is contained within wavelengths below 3 microns. Ninety-nine percent of the radiation emitted by a black surface at 127°C is at wavelengths longer than 3 micrometers. The ideal selective surface characteristic is illustrated in Exhibit 2-25.

Real surfaces do not approach this model of ideal performance. The monochromatic reflectances for two real selective surfaces, typical of those used on commercially available solar collectors, are illustrated in Exhibit 2-26.

Transparent Materials

As mentioned above, incident radiation associated with a given material, including a transparent material, must satsify the condition that the sum of the absorptance, reflectance and transmittance must equal unity. However, transmission of radiation through a transparent material, such as glass, is a rather complex process and depends on the wavelength of the radiation, the angle of incidence, the refractive index and the extinction coefficient (which determines the amount of light absorbed in a substance in a single pass of radiation).

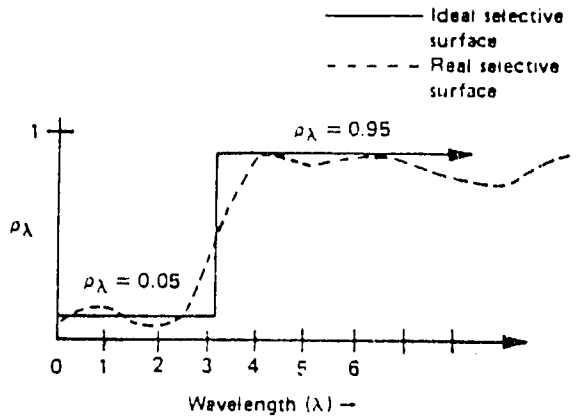


EXHIBIT 2-25 Ideal Selective Surface Characteristics (KRE)

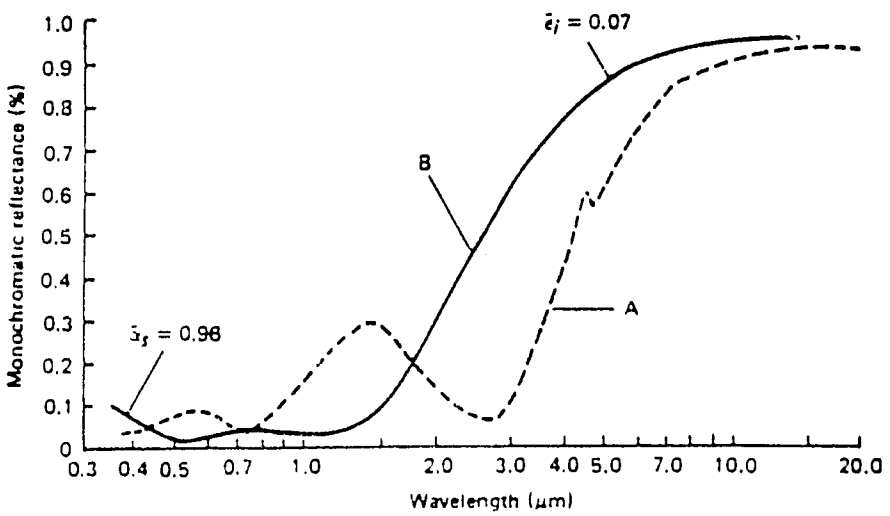


EXHIBIT 2-26 Special Reflectances of (A) Tabor Solar Collector Surface, Chemcial Treatment of Galvanized Iron and (B) a Two-layer Black Nickel on Nickel-coated Steel (KRE)

Transparent covers are used to reduce heat losses from the radiation - absorbing surfaces of solar collectors. Materials for this type of application should be able to transmit solar radiation at all angles of incidence, should have dimensional stability, and should have long-term durability under exposure to the sun and the weather.

Other desirable properties include low weight, low infrared transmittance, and low cost.

Exhibit 2-27 defines the angles used in analyzing reflection and transmission of light at the surface of a cover plate. The reflection represents a reduction (loss) of some of the solar energy that reaches the cover plate. The reflection is related to the refractive index of the material. Exhibit 2-28 lists refractive indices for various substances. The higher the index, the greater the reflection. Cost, stability under weather conditions, and sunlight conditions generally restrict cover plate material use to glass, "Mylar" and "Tedlar".

Etching

The reflectance may be reduced by a factor of four by a surface etching process. For example, if glass is immersed in a silica-supersaturated fluosilicic acid solution, the acid attacks the glass and leaves a silica surface layer. This layer has an index of refraction (hence reflection) intermediate between glass and air. By having a gradual change in index of refraction, reflectance losses are reduced significantly. Researches have devised processes for producing glass with reflectance of 1 percent per interface (2 percent per pane of glass). The effectiveness is illustrated by the graph in Exhibit 2-29.

Despite the obvious benefits of etching, the etched surfaces will capture dirt, dust and films that will reduce overall transmittance. For etched cover plates to be worthwhile they must be cleaned frequently.

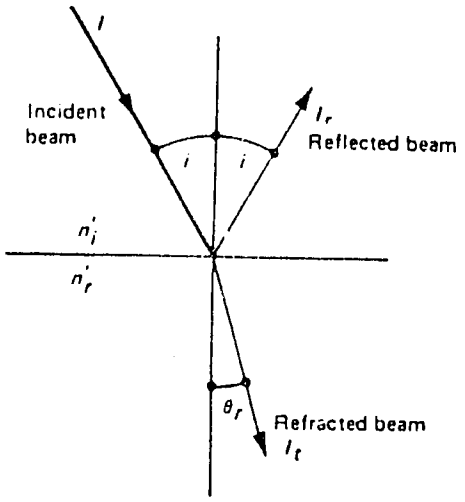


EXHIBIT 2-27 Diagram Showing Incident, Reflected, and Refracted Beams of Light and Incidence and Refraction Angles for a Transparent Medium

Material	Index of refraction
Air	1.000
Clean polycarbonate (PCO)	1.59
Diamond	2.42
Glass (solar collector type)	1.50-1.52
Plexiglass[a] (polymethyl methacrylate, PMMA)	1.49
Mylar[a] (polyethylene terephthalate, PET)	1.64
Quartz	1.54
Tedlar[a] (polyvinyl fluoride, PVF)	1.45
Teflon[a] (polyfluoroethylenepropylene, FEP)	1.34
Water–liquid	1.33
solid	1.31

[a]Trademark of the DuPont Company, Wilmington, Delaware.

EXHIBIT 2-28 Refractive Index for Various Substances in the Visible Range Based on Air

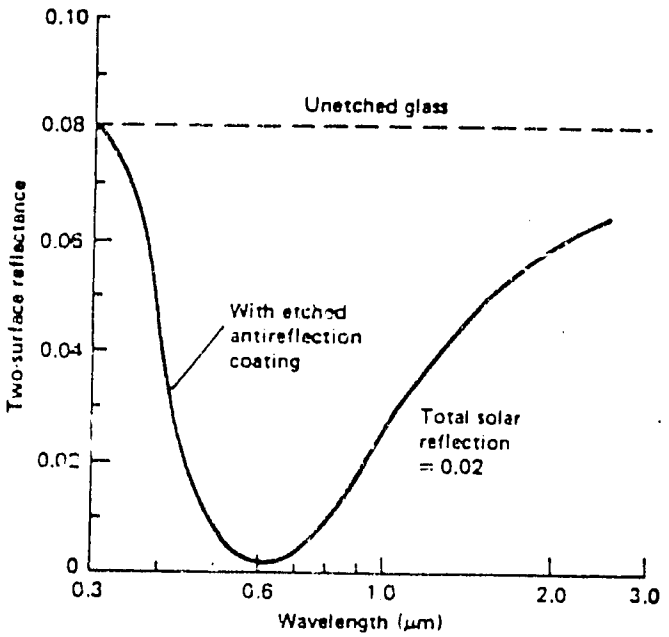


EXHIBIT 2-29 Reflection Spectra for a Sample of Glass Before and After Etching

The refractive index can be reduced by use of coatings similar to those used on camera lenses. The durability of such coatings on outdoor-mounted solar collector cover plates is not yet such that its use can be encouraged.

Exhibit 2-30 is diagrammatic representation of a flat plate collector with 2 cover plates. The relationship of incident radiation, reflected radiation, transmitted radiation, absorbed solar radiation, and captured heat energy for end use are shown. Exhibit 2-31 summarizes the transmittance figures for single and double glazing for various angle of incidences. Exhibit 2-32 summarizes vital characteristics of different glazing materials.

2.3.2.3 Concentrating (Focusing) Collectors

Introduction

For many applications (as listed in Exhibit 2-33) it is desirable to deliver energy at temperatures higher than those possible with the use of ordinary flat plate collectors. This can be accomplished in at least two ways:

a) Raising the level of incident energy on the energy-absorbing surface;

b) Decreasing the area of the absorber from which heat losses occur.

By interposing an optical device between the source of radiation (typically the sun) and the energy absorber surface both of the above are met. For solar energy applications the devices can be "nonimaging" concentrators or "imaging" concentrators. Many designs have been set forth for concentrating collectors.

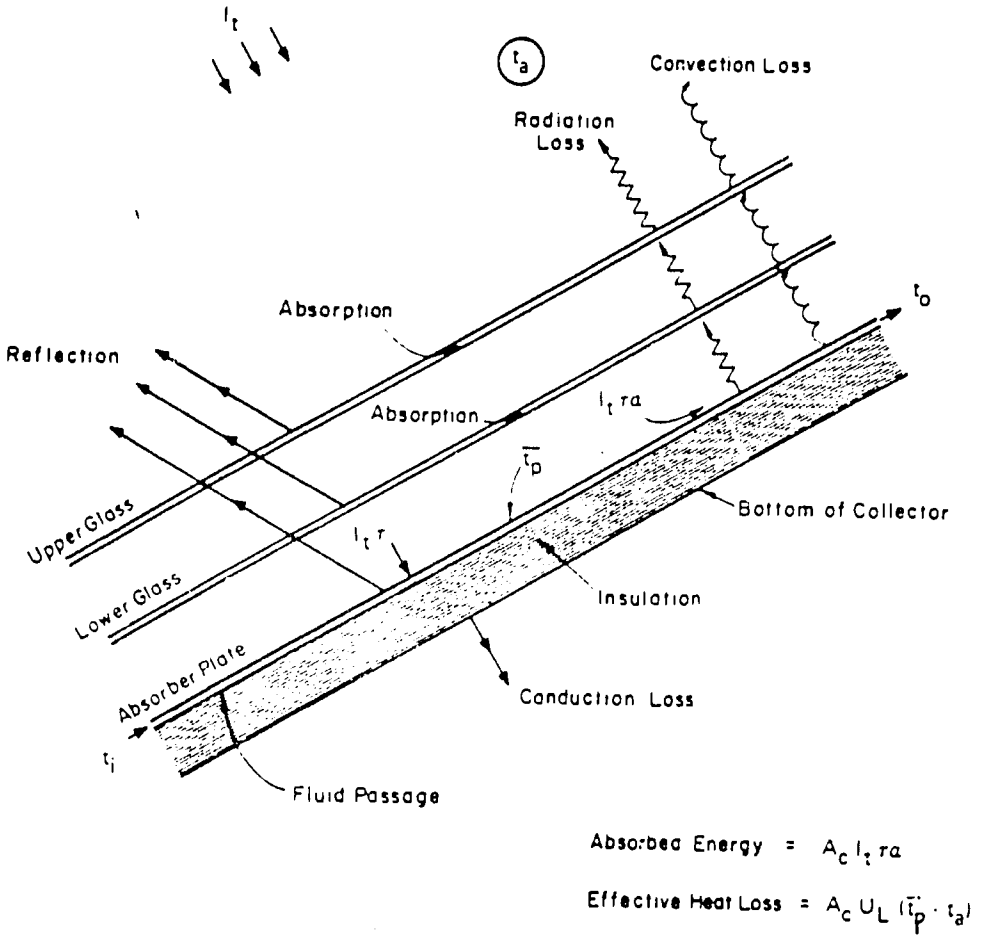


EXHIBIT 2-30 Flat Plate Collector with 2 Cover Plates Showing Relationships of Incident Radiation, Reflected Radiation, Transmitted Radiation, Absorbed Radiation and Capture Heat Energy

Angle of incidence (deg)	Transmittance		Absorbance: flat black absorber surface
	Single glazing	Double glazing	
0	0.87	0.77	0.96
10	0.87	0.77	0.96
20	0.87	0.77	0.96
30	0.87	0.76	0.95
40	0.86	0.75	0.94
50	0.84	0.73	0.92
60	0.79	0.67	0.88
70	0.68	0.53	0.82
80	0.42	0.25	0.67
90	0	0	0

EXHIBIT 2-31 Transmittance-Absorbance Values for Solar Collectors with Glass Glazing and Absorber Plates Painted Flat Black

Trade name	Manufacturer	Type	Light transmission	Light transmittance after aging 10 years	Longevity (years)	Maximum operating temp °C	Maximum operating temp °F
Teflon	Dupont	Fluorinated hydrocarbon film	Transparent	96% for 1-mil film	Very stable	204	400
Sun-Lite Premium	Kalwall Corp.	Fiberglass-reinforced polyester (FRP)	Translucent	80% after 2 years	Approx. 20	93	200
Sunwall and Sun-Lite Glazing Panel	Kalwall Corp.	Two layers of FRP, each 1 mm (0.040 in.) thick, separated 3.8 cm ($1\frac{1}{2}$ in.) by aluminum beams	Translucent	77%	Approx. 20	93	200
Flex yard	3M Company		Transparent		7 to 10	82 (unsupported) 121 (framed)	180 (unsupported) 250 (framed)
Tuffak (Sheet and TwinWal	ROHM and HAAS	Polycarbonate sheet, single or "twin wall"	Transparent	82 to 89% (depending on thickness)	5 to 7	121	250
Plexiglas G.	ROHM and HAAS	Acrylic sheet	Transparent (translucent also available	91%	10 to 20	82	180
Tedlar	Dupont	Polyvinylfluoride film	Transparent to translucent	92 to 94%	20		
Excelite	Graham Products Ltd.	Fiberglass-reinforced polyester	Translucent	83%			

EXHIBIT 2-32 Glazing Materials, Based on General Information

SOLAR COLLECTOR TECHNOLOGY

concentrating

non-concentrating

Temperature °F	APPLICATIONS
500 -	
	- Production of electrical power (fluids other than water)
400 -	Process steam
	- Evaporation in various processes
	- Digestion in paper pulp, kraft
	- Drying diatomaceous earth
	- Drying fishmeal, lumber
300 -	Alumina via Bayer's process
	- Drying farm products; canning of food
	- Evaporation in sugar refining
	- Fresh water by distillation
	- Drying of cement slabs
	- Most food drying
200 -	Space cooling by absorption refrigeration (lower limit)
	- Food drying (lower limit)
	- Space heating
	- Animal husbandry
	- Greenhouses (lower limit)
	- Mushroom growing
100 -	Hot baths
	- Swimming pools, biodegradation, fermentation
	- Fish hatching, fish farming

EXHIBIT 2-33 Required Temperature for Various Applications
Adapted from Koomanoof, 1976

In this context, the word "collector" will denote a system consisting of the "receiver" and "concentrator". The "receiver" is that element of the system ("collector") where solar radiation is absorbed and converted to heat energy. Components of the "receiver" includes an "absorber", associated covers, and insulation as required.

The "concentrator", or sunlight "optical system" is composed of all parts of the collector that direct intercepted solar radiation onto the "receiver".

Concentrators can be reflectors or refractors. They may be cylindrical or surfaces of revolution, continuous or segmented.

Receivers can be convex, flat, or concave and can be partially covered or uncovered.

"Concentrators" can have concentration ratios (the factors by which radiation flux on the energy absorbing surface - the "receiver" - is increased) from low values of 1.5 or 2 to higher values of 10,000 or more. Increasing ratios indicate increasing receiver temperatures or, in effect, temperatures at which energy can be delivered.

With respect to concentration ratio, the term that best applies to a solar energy system is the "area concentration ratio". It is the ratio of the area of aperture to the area of the receiver as illustrated in Exhibit 2-34.

The area concentration ratio, C, in equation form is:

$$C = \frac{A_a}{A_r}$$

where: A_a is the aperture area
A_r is the receiver area

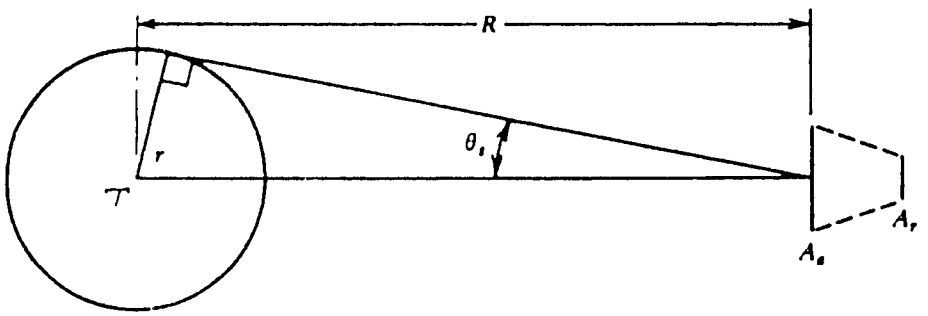


EXHIBIT 2-34 Schematic of Sun at T, at Distance R from a Concentrator with Aperture Area A_a and Receiver Area A_r. Adapted from Rabl, (1976). (BEC)

The total amount of solar energy insolation (diffuse and direct) at a given point on the earth's surface at a particular time and the amount seen by the aperture area for any collector, is the same. The portion of energy delivered to the absorber (receiver) of different types of collectors depends upon the optical path between the aperture and the receiver.

For a perfectly flat plate collector, there are no geometrical obstructions to any ray that arrives at the cover plate (aperture).

In a concentrating collector the area concentration ratio, C, has an upper limit that depends on:

a) Whether the concentration of optical paths is represented by a three dimensional (circular) concentrator such as a paraboloid or a two dimensional (linear) concentrator such as a cylindrical parabolic concentrator;

b) The angle of orientation of the plane of the aperture to a direct ray from the sun.

c) The proportion of direct incident solar radiation to the aperture plane as compared to the diffuse portion. This is diagrammed in Exhibit 2-35.

From Exhibit 2-35 it can be seen that a major disadvantage of a pure concentrating solar collector is that only direct solar radiation can be used as an energy source. Diffuse radiation usually makes up one half of the solar insolation at a point on the earth's surface. In fact, on a cloudy day, most of the radiation is diffuse.

Additionally, the optical system can be designed such that a limited degree of orientation is maintained.

Reflectors or focal point can be moved in order to maintain "track" conditions.

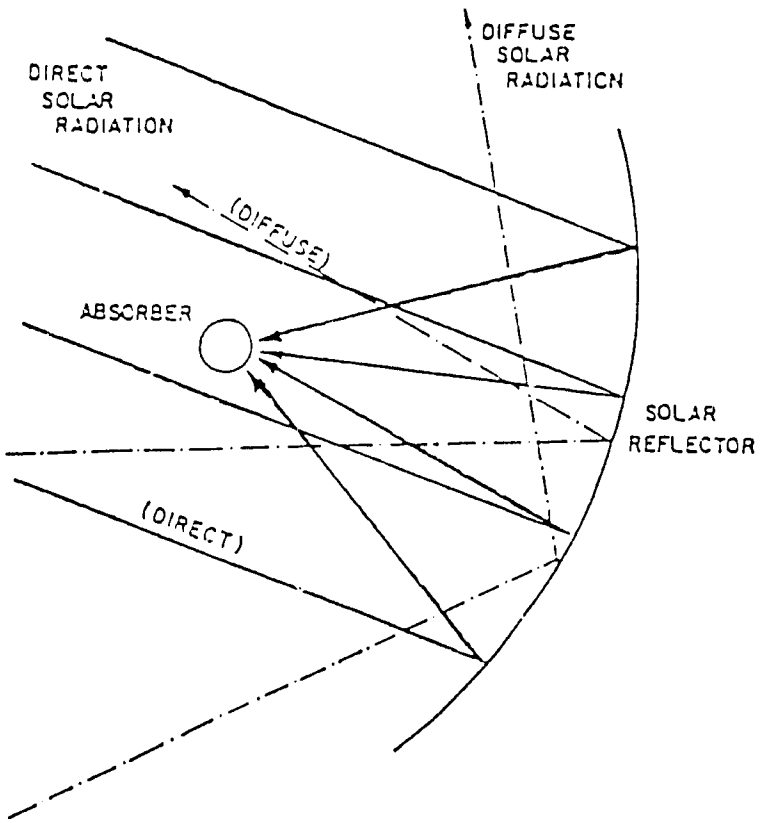


EXHIBIT 2-35 Direct and Diffuse Radiation on a Solar Concentrator (SOL-1)

As the area concentration ratio increases, the performance of the system becomes more dependent on the:

a) optical quality of materials utilized;

b) precision of construction;

c) precision of collector positioning with respect to the angular orientation of the sun's rays;

d) immunity to collector distortion and position changes caused by ambient temperature, wind, etc.;

e) "projected" optical area of the concentration,

f) heat handling characteristic of the absorber (receiver);

Therefore, the cost of delivered energy from a concentrating collector is a function of the temperature at which it is available. At the highest range of concentration concentrating collectors are termed solar furnaces. Solar furnaces are generally either laboratory tools for studying the properties of materials at extremely high temperatures or experimental high efficiency electric power generating plants.

Even at lower temperatures there are new maintenance requirements for concentrating collectors as compared to those for flat plate collectors. Additional measures are required to retain the quality of optical systems for long periods of time in the presence of dirt, weather and oxidizing or other corrosive atmospheric components.

The combination of initial cost for collectors, cost of special mounting facilities, and operating and maintenance costs restricts the utilization of concentrating collectors. New materials and more precise engineering of systems are needed in order for the use of collectors to become more widespread.

In addition to optical configuration of the concentrator there are other factors that influence the percentage of the energy (as seen by the area aperture) that reaches the absorber (receiver) for conversion to usable heat energy. Among the relevant factors are:

a) reflectivity of the surfaces in and along the optical path;

b) conversion efficiency of the absorber surface;

c) temperature of the absorber;

d) heat transfer efficiency of fluid/absorber interface;

e) magnitude of radiation losses from the absorber.

Exhibit 2-36 illustrates the relationships between concentration ratio and temperature of receiver operation for three categories of collector geometry: cylindrical, conical, paraboloid.

Optical Configuration

In Exhibit 2-37, four configurations are shown (with the absorber denoted by A_b).

A) represents a plane receiver with plane reflectors at the edges to reflect additional radiation onto the receiver. Area concentrations associated with these type systems are relatively low, with a maximum value of four or less. These collectors can be considered flat plate collectors with augmented radiation.

B) illustrates a reflector of conical section which could be a cylindrical surface (with a tubular receiver).

C) represents a parabolic concentrator which could be a surface of revolution (with a spherical or hemispherical receiver).

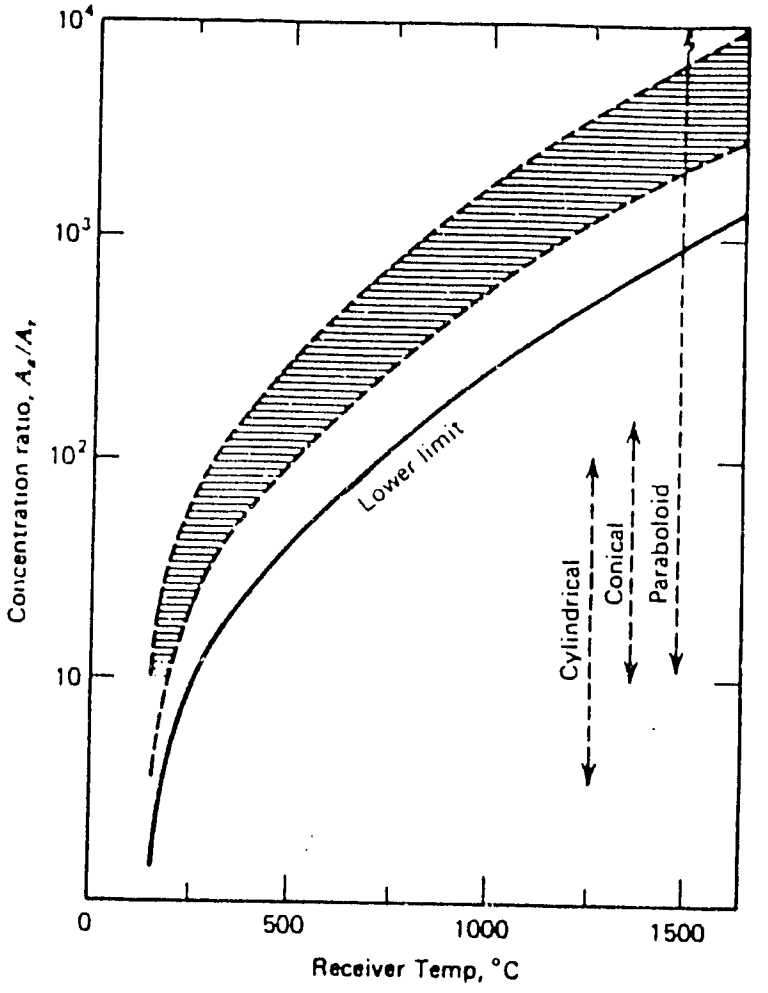


EXHIBIT 2-36 Relationships between concentration ratio and temperature of receiver operation, the "lower limit" curve represents concentration ratios at which the thermal losses will be equal to the absorbed energy; higher ratios will then results in useful heat gain. The shaded range corresponds to collection efficiencies of 40 percent to 60 percent, and represents the usual range of operation. Also shown are approximate ranges in which several types of reflectors might be used. (Note: This figure is not intended to be a basis for design.)

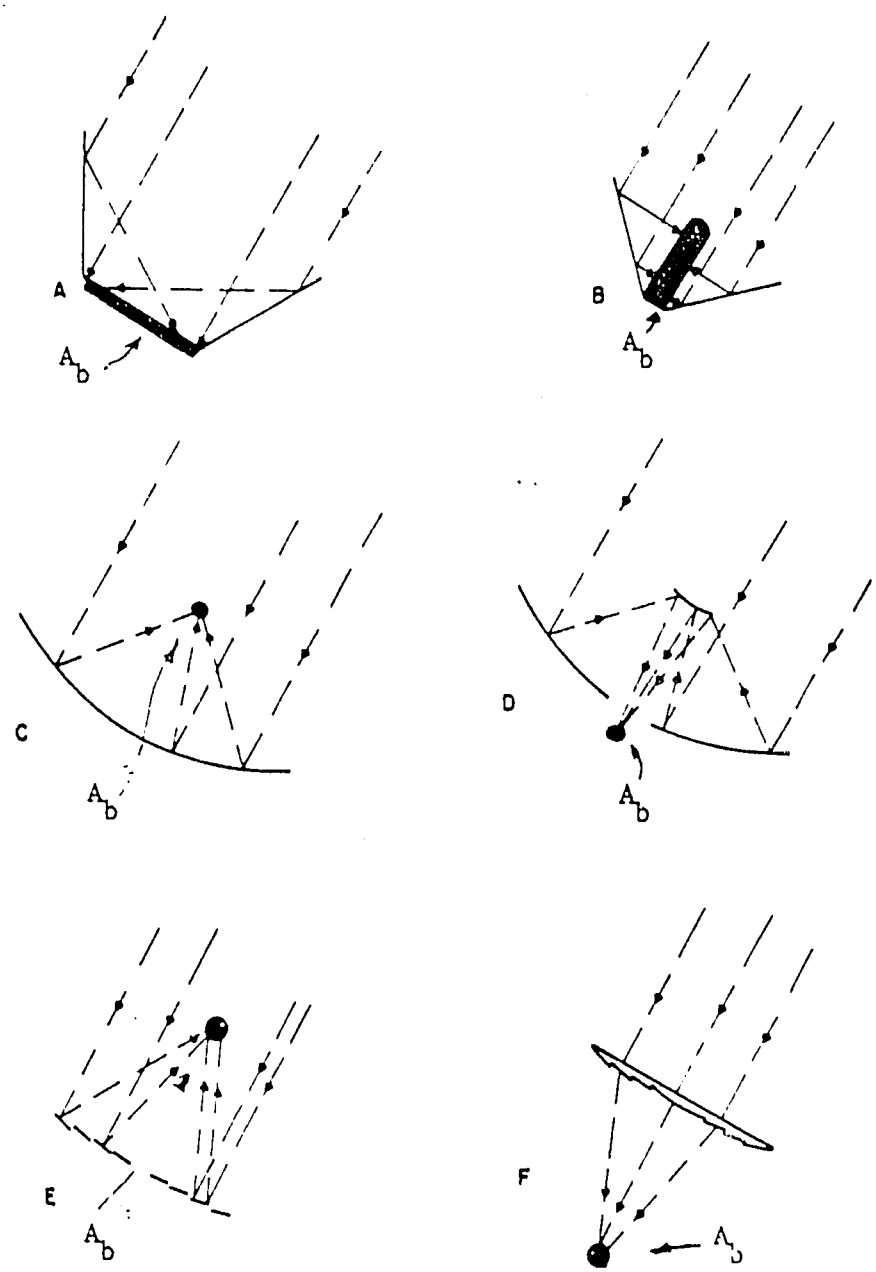


EXHIBIT 2-37 Some possible focusing system configurations: A) Plane receiver, Plane reflector; B) Conical reflector cylindrical receiver; C) Paraboloidal concentrator; D) Paraboloidal concentrator with secondary reflector; E) Fresnel reflector; and F) Fresnel refractor.

D) illustrates a parabolic reflector with a second reflector surface located at the normal focal point, which refocuses the radiation through a small hole in the primary reflector to a point behind the primary reflector. This arrangement permits utilization of the simplest and lightest weight structure in front of the primary reflector, minimizing shadows on the primary reflecting surface and reducing the inherent moment arm effect. The tubes, necessary to convey the heat transfer fluid to and from the receiver (absorber), are out of the way. A partial housing can also be built around the absorber to minimizes radiation and conduction losses from, and the effects of weather on it.

E) illustrates a Fresnel reflector or a series of flat reflectors on a moving array.

F) illustrates a Fresnel refractor.

Concentrators can be divided into two general categories: non imaging and imaging. Non imaging concentrators do not produce clearly defined solar images on the absorber; they distribute radiation from all parts of the solar disc onto all parts of the absorber. The associated concentration ratios are in the low range, generally below 10.

Imaging concentrators, in contrast, form images directly on the absorber. Concentration ratios for this type of concentrator can be much higher.

Tracking

Movement of the entire collector assembly provides potential for the greatest accuracy in sun tracking.

Reflectors that are formed by a surface of revolution (circular concentrators) generally must be oriented such that the focus, vertex and sun are in line, and therefore must be able to move about two axes. For example, these axes may be horizontal and vertical.

Orientation systems can provide continuous or nearly continouous adjustment, with collector movement adjustable to compensate for the changing hourly position of the sun. For some low-concentration linear collectors it is possible to adjust their position intermittently (daily, weekly, monthly or seasonal) depending upon the design.

The orientation may be manual, mechanized or a combination of the two. Even for relatively crude tracking, the mechanism required is costly. In an effort to minimize tracking expense several schemes have been devised. Exhibit 2-38 illustrates some of them.

In the linear parabolic unit in (a) of Exhibit 2-38, the reflector moves only in elevation. The absorber is in a fixed position. The reflector in (b) is a circular parabola which is rigidly fixed to the earth. As the sun moves the rays arrive at different angles and the focus point moves also. The absorber (receiver) moves simultaneously along the path taken by the changing focal point.

(c) and (d) are variations of a reflecting Fresnel mirror. The individual segments that make up a Fresnel configuration move individually so that the focal point (absorber) may remain fixed with respect to the overall geometry.

Figure (e) shows a refractive Fresnel lens where the lens is fixed. The absorber is a flat plate located a distance below the Fresnel lens. Increasing the distance will increase the concentration ratio. The focus of the Fresnel lens will move as the incoming rays from the sun move with respect to the lens. The focused rays, as they move, will always impinge on some portion of the flate plate absorber.

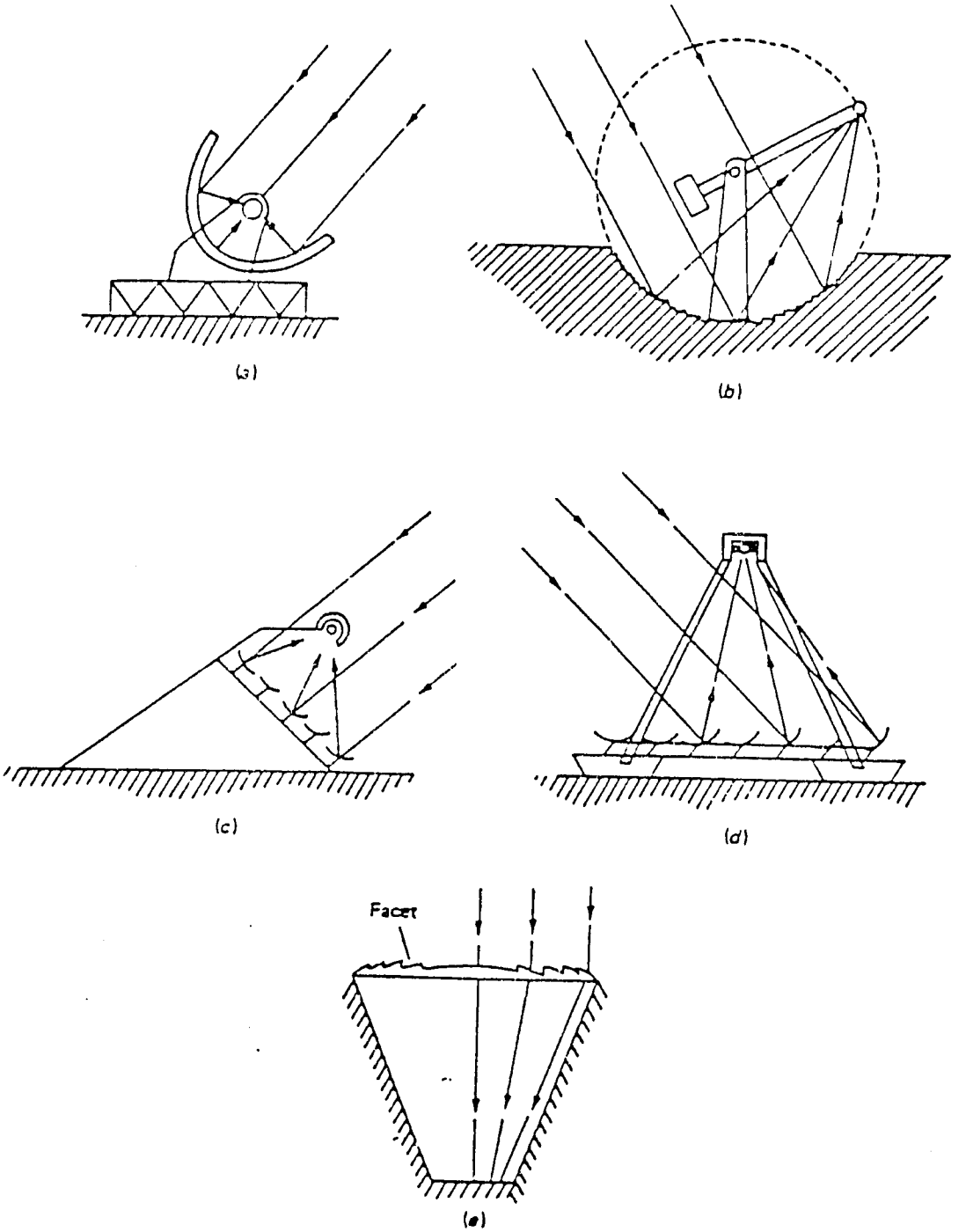


EXHIBIT 2-38 Single Curvature Concentrators: a) Parabolic trough; b) Fixed circular trough with tracking absorber; c) and d) Fresnel mirror designs; e) Fresnel lens. (KRE-1)

Non Imaging Concentrators

It is desirable to have concentrating collectors that can function daily and annually with minimum requirements for tracking and that can accept not only direct radiation but diffuse radiation also. The concentrator (optical system) should have the capability of reflecting to the receiver (absorber) all the incident radiation on the aperture over ranges of incidence angles within wide limits. The limits define the "acceptance angle" of the collector. Compound parabolic concentrators (CPC) most nearly meet these objectives as compared to other types of concentrators.

In Exhibit 2-39, the basic concept of the CPC is shown. The CPC is potentially most useful as a linear or "trough type" concentrator.

Each side of the CPC is a parabola, only the focus and axis of the right-hand parabola are indicated. Each parabola extends until its surface is parallel with the CPC axis. The angle between the axis of the CPC and the line connecting the focus of one of the parabolas with the opposite edge of the aperture is referred to as the "acceptance half-angle", θ_c. If the reflector is perfect, radiation entering the aperture at angles between $\pm\ \theta_c$ will be reflected to a receiver at the base of the concentrator by the parabolic reflectors at each side of the axis.

Concentrators of this type have area concentration ratios (denoted as "C_i") which are functions of the acceptance half angle θ_c. The relationship for such an ideal two-dimensional system is:

$$C_i = \frac{1}{\sin(\theta_c)}$$

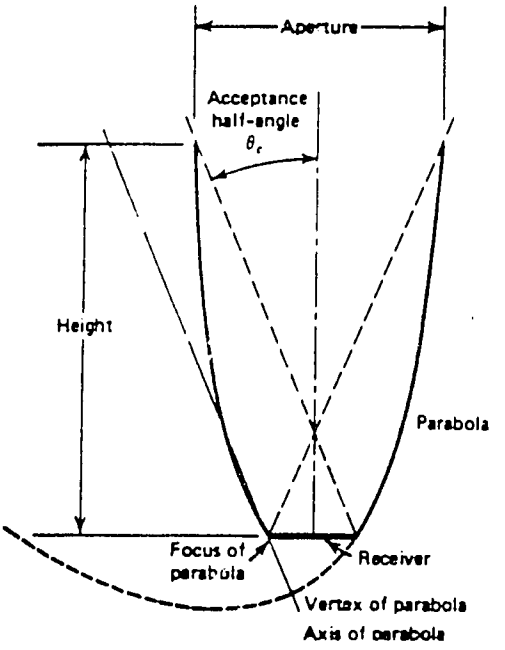


EXHIBIT 2-39 Cross Section of a Symmetrical Nontruncated CPC

The "sides" of the parabola need not be extended to the height at which they are exactly parallel to the axis. For practical reasons, the sides are shorter, but the concentration ratio C_i is reduced. The relationship between the amount of truncation (height/aperture ratio), acceptance angle, and concentration ratio is illustrated in Exhibits 2-40 and 2-41.

The heat transfer medium for concentrating collectors is typically liquid. Water is the most common liquid used. Other liquid mixtures may be employed if water cannot provide the particular physical characteristics that may be required.

Circular reflecting and refracting types of concentrators focus on what are essentially very small flat absorbers. Two dimensional reflecting concentrators (cylindrical) generally use long tubes aligned at the focus along the axis of the trough.

In Exhibit 2-42, a schematic section and longitudinal view of a typical cylindrical parabolic concentrator are shown. Note that insulation (to reduce radiation and conduction losses) covers that portion of the receiver away from energy that is reflected towards the absorber.

A more detailed view of absorber construction is illustrated in Exhibit 2-43. A concentration collector is subject to losses for several thermodynamic reasons and will have a conversion efficiency less than unity due to the relative geometry of the reflector/absorber.

The relationship and relative values for two concentrating collection systems with different aperture/receiver ratios are illustrated in Exhibits 2-44 and 2-45.

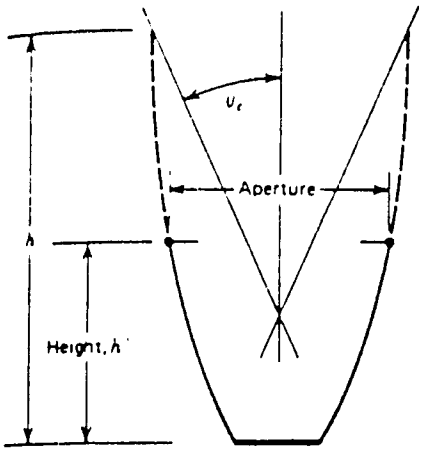


EXHIBIT 2-40 A CPC truncated so its height/aperture ratio is about half of the full CPC

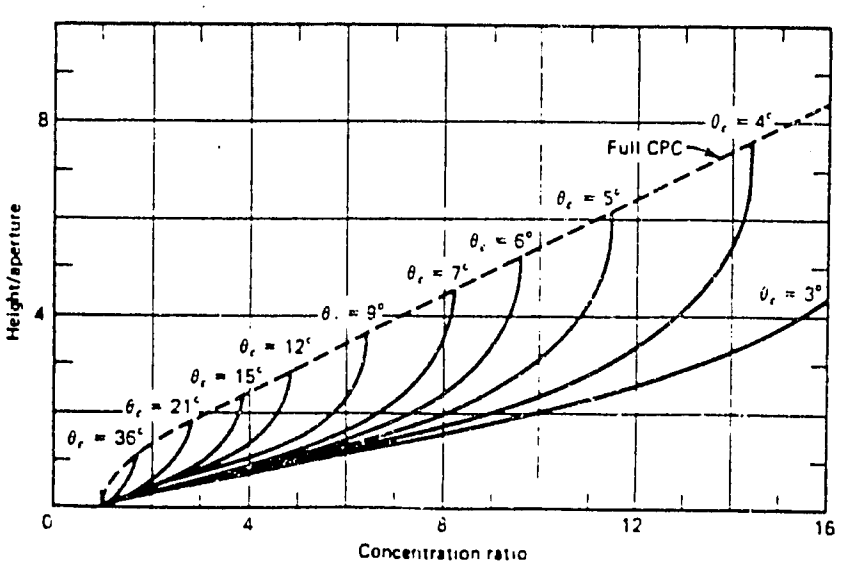


EXHIBIT 2-41 Ratio of height to aperture for full and truncated CPCs as a function of C and θ. Adpated from Rabl (1976b).

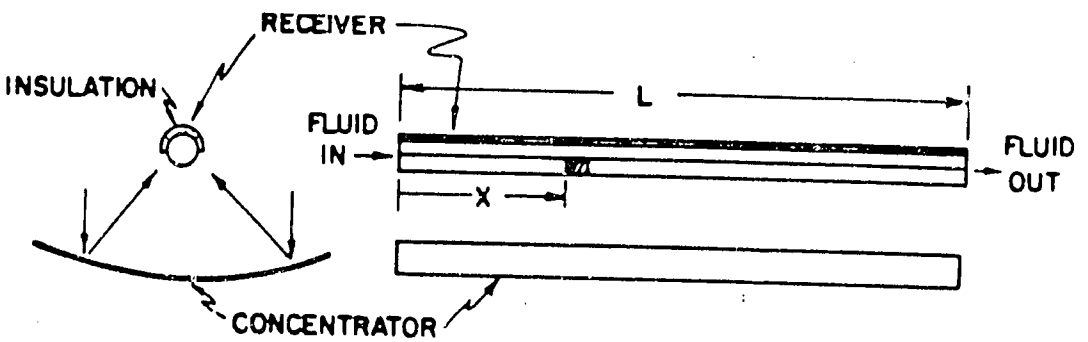


EXHIBIT 2-42 Schematic section and view of a cylindrical parabolic concentrator with cylindrical receiver shown insulated on top portion.

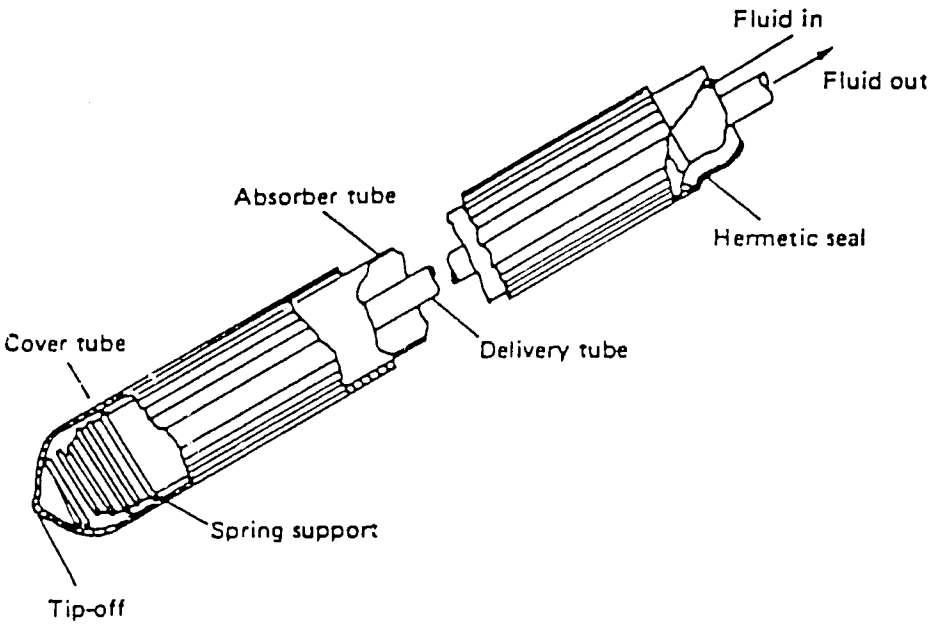


EXHIBIT 2-43 Cutaway view of an evacuated-tube absorber for a concentrating solar collector manufactured by Owens-Illinois, Inc. (KRE-1)

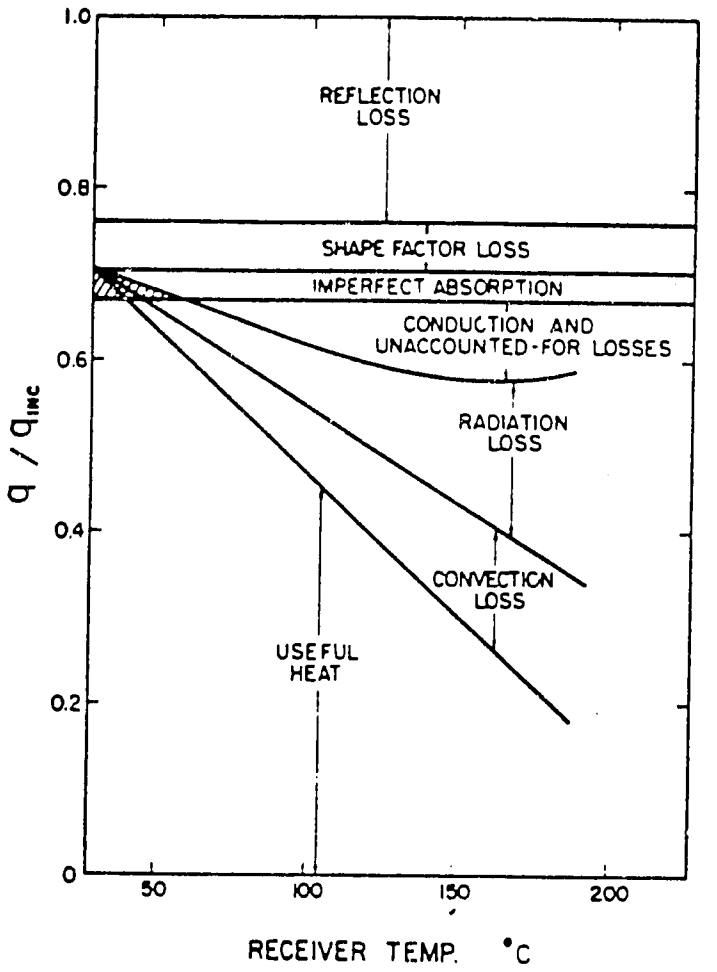


EXHIBIT 2-44 Distribution of incident energy for the 1.89 m reflector with 60 mm diameter receiver as a function of receiver temperature. From Lof et al. (1962).

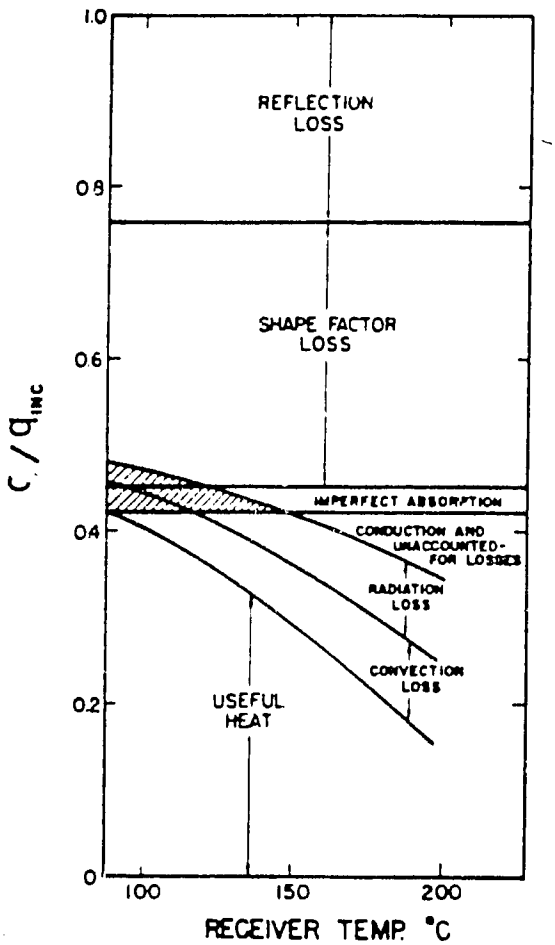


EXHIBIT 2-45 Distribution of incident energy for the 1.89 m reflecto with 27 mm diameter receiver. From Lof et. al. (1962).

2.3.2.4 Storage

Energy Demand/Available Sunshine

The day/night cyclic variation in sunlight can be derived from calculated solar position and the seasonally varying properties of a standard atmosphere. Economic analysis requires that performance prediction be based on historical variations of solar insolation for the actual site.

Data can give some insight into long-term (seasonal or yearly) average behavior of a solar energy system under local atmospheric conditions. Such data is useful but not sufficient. Short-term fluctuations of sunlight due to overcast conditions may last for days. Whereas broken cloud cover may block the sun for only a fraction of an hour.

An analysis of sunshine availability for the United States New England Region was conducted by Prof. A. Dietz of the Massachusetts Institute of Technology in connection with a series of experimental solar houses. The data collected for the experiments was used for space heating studies. The information was not taken for summer months. However, available data is pertinent and adequate for the analysis which follows.

The 57-year U.S. Weather Bureau monthly average figures, for percentage of sunshine in the Boston, Massachusetts area are plotted together with the corresponding observed numbers for 1949-50 in Exhibit 2-46. The seasonal variation of 1949-50 is quite marked as compared to the rather smooth 57-year average.

On the same figure, the percentage of time during the 1949-1950 period that the collectors on the MIT solar house were in operation as compared with the total potential sunshine hours (assuming no overcast during the entire season) is plotted. Although this curve in general follows the percentage sunshine curve for 1949-1950, there is a noticeable difference in February indicating that the percentage of available sunshine for that month was not a reliable guide to the amount of solar energy collected.

In the absence of a satisfactory explanation for the difference, one may speculate that the collector or recording systems were defective, that wind, snow, and/or temperature conditions impaired operation, or many other reasons. We will assume the "best case" and continue our discussion on the premise that available sunshine and collectable sunshine can have a constant relationship.

Exhibits 2-47a and 2-47b illustrate the distribution of days of various degrees of sunshine in January and April for the period 1940-1950. This weather information illustates that the chances of having very sunny or very overcast days are much better than the chance of having intermediate days.

Exhibit 2-48 presents another analysis of percentage sunshine figures.

It shows the probable sequence of days having high (75-100) percent sunshine, which can be expected to provide an excess of energy available to be stored for future use, and the probable sequence of days of low (0-25) percent sunshine, which can be expected to be of little or no use in providing solar-derived energy.

Additional information on the probable sequences of periods of no-collection of solar energy is provided in Exhibit 2-49. The collection and no-collection periods, as recorded at the solar houses, were analyzed and the periods in hours of "no collection" were plotted. No periods of less than 14 hours are found because the shortest sunset-to-sunrise time during the period was close to 14 hours.

Of the total no-collection periods, nearly 50 percent are represented by periods of less than 48 hours, and nearly 90 percent are represented by periods of less than 72 hours. Periods above 90 hours (roughly 4 days) are rare. Collection and storage for 6 sunless days would have been necessary in 1949-1950 to meet all the requirements of a base-load type of electric power plant.

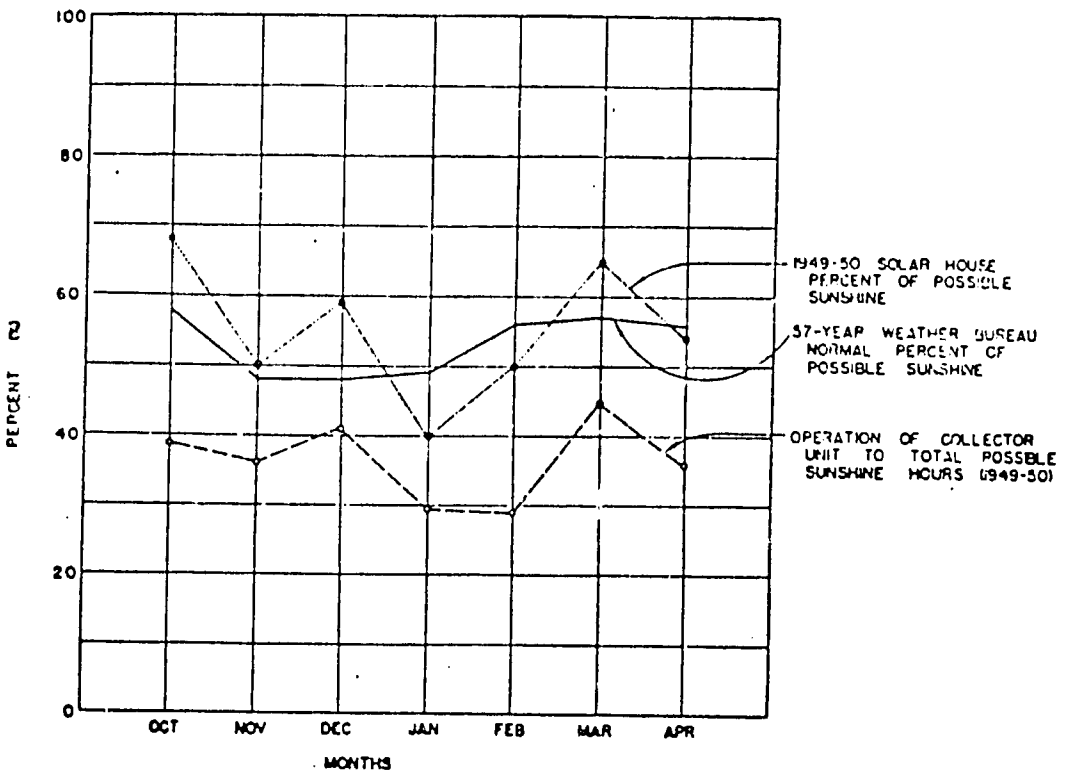


EXHIBIT 2-46 Percent Sunshine of Possible Sunshine and Time of Operation of Collector Unit (from Dietz, 1954)

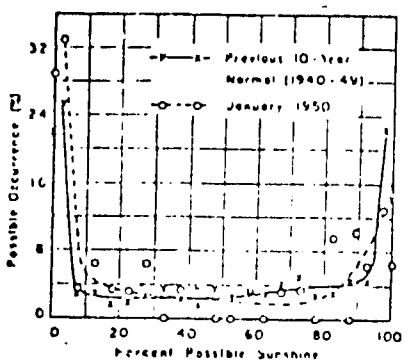


EXHIBIT 2-47a Probable Distribution of Possible Sunshine for the Month of January

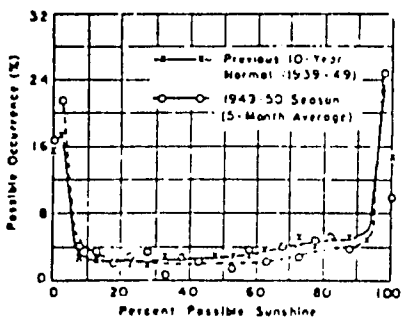


EXHIBIT 2-47b Probable Distribution of Possible Sunshine for the Period October through April

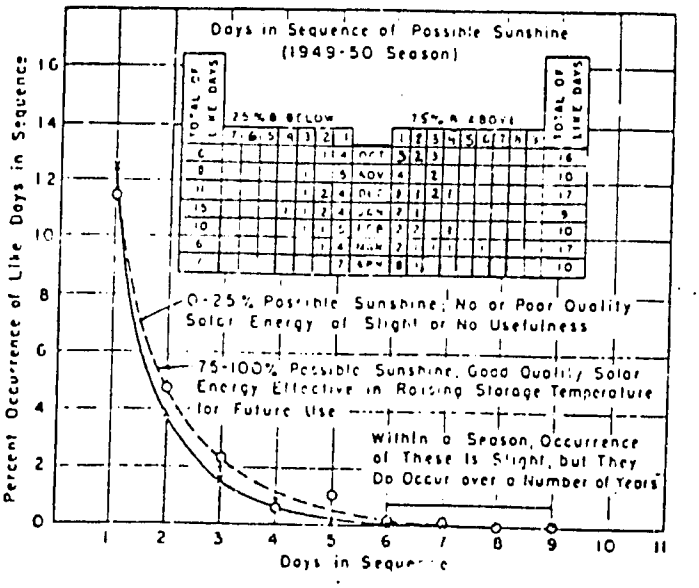


EXHIBIT 2-48 Probability of Sequences Occurring of Like Days for the Total Number of Days Considered (10-Year Average for October through April) (Source: Dietz, 1954)

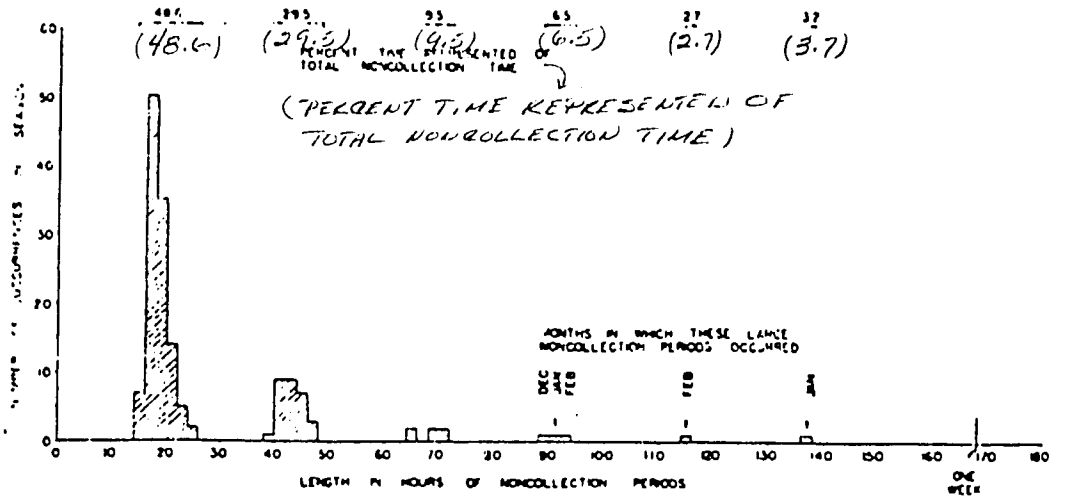


EXHIBIT 2-49 Distribution of Periods of No Collection of Solar Energy (1949-1950) (Source: Dietz, 1954)

The data and analysis cited above hold for the particular weather conditions around Boston, Massachusetts. The same analysis should be followed for the particular site in Egypt under consideration. There are significant differences in the availability of solar energy between coastal areas, riverside locations, and more desert-like sections.

It is clear that if one requires solar energy to match the performance of a fossil fuel fired system, enough energy must be collected and stored not only for night time, but also sufficient to provide energy during the periods of serveral sunless days in a row which do not occur frequently throughout the year.

Additionally, there is the requirement (as revealed by the statistical history Exhibit 2-4) that, once exhausted, the storage should be recharged within three days (20 to 33 collection hours, depending upon the season) in order for the facility to be functional during the next cloudy spell.

Economic considerations constitute the primary basis for a decision to employ a storage facility or an auxiliary source energized by externally derived fuels. Secondary considerations include: a) space for installation requirements for storage/auxiliary facilities; b) the skill level or training level of personnel required for operation; c) additional space required to capture the solar energy to be converted for storage purposes.

Usually, a combination of storage and auxiliary facilities is chosen. The combination of a solar system with some storage capabilities and of smaller capacity than that which would be required to supply the full heat load at all times with an auxiliary heat source sized to meet demands results in more effective use of the solar equipment throughout the heating season and a lower total annual cost.

Analysis by calculations permits selection of the most cost-effective sizes for the solar energy/auxiliary heat system. This calculation procedure will be discussed in a later section.

Storage Materials

There are two commmon ways to store heat. One way involves storing heat in a solid substance such as rock or concrete. A second method involves storage in a reservoir of water.

There is a third way of storing heat which is not common. It involves the exploitation of a phase-change characteristic. There are difficulties in obtaining reasonable life from such a design. It will be described because the current efforts to overcome its limitations may result in a satisfactory capability.

Rock storage can be achieved by blowing heated air from solar collectors through a bed of rock into which the heat is absorbed, and returning exhaust air to the collectors for reheating. This is illustrated in Exhibit 2-50. In a similar manner, pumped water can transport heat from the collectors to storage as illustrated in Exhibit 2-51. Heat storage by passive means is possible using either solid or liquid storage systems when no blowing or pumping is required.

Sensible Heat Storage

Sensible heat storage occurs when the storage medium experiences a rise in temperature following contact with the heated fluid from solar collectors. The rate of heat rise depends on the sizing of the system; stored heat must be retained in a well-insulated compartment to reduce heat losses.

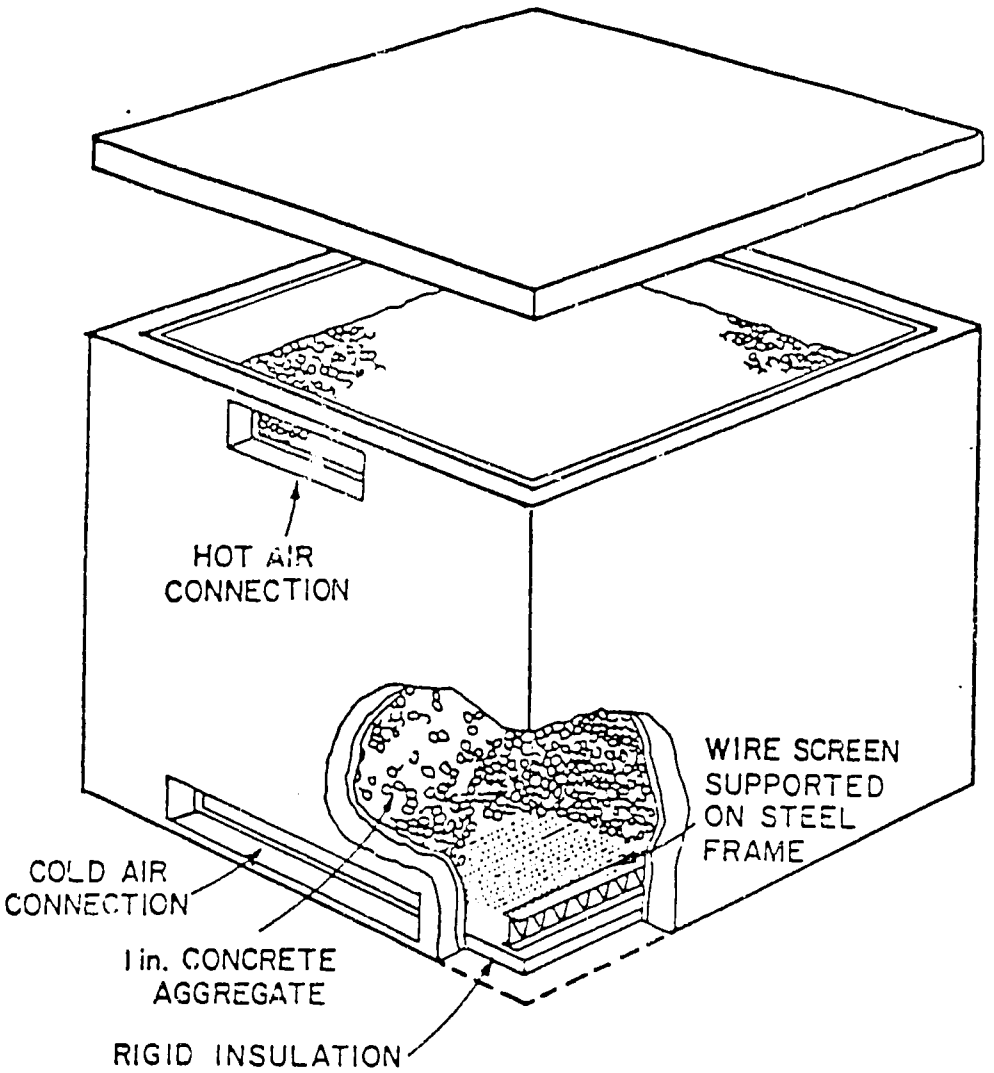
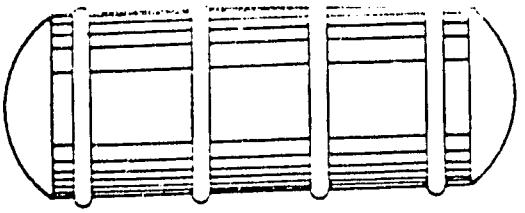
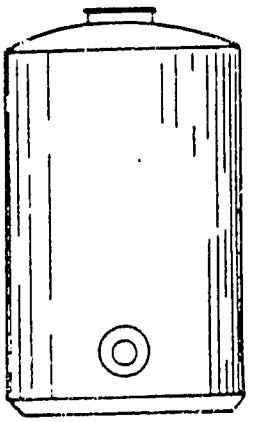


EXHIBIT 2-50 Diagram of Pebble-bed Heat Storage Unit (SOL-1)



UNDERGROUND STORAGE TANK



ABOVE-GROUND STORAGE TANK

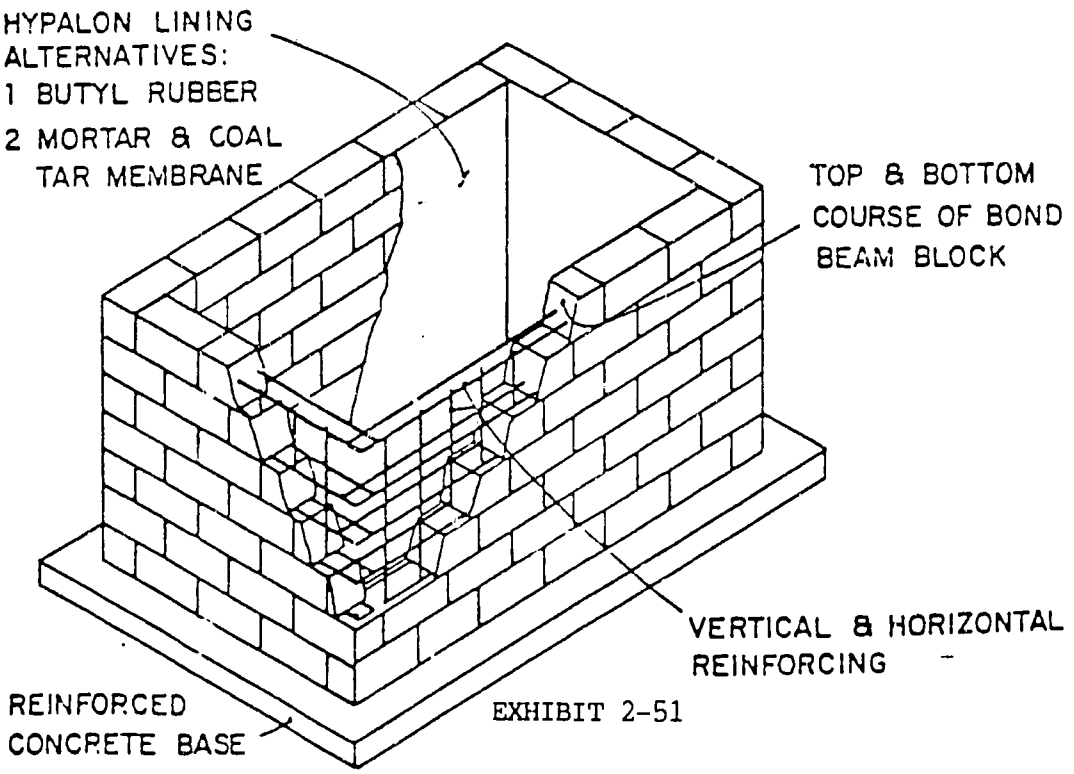


EXHIBIT 2-51

Air systems using rock storage are favorites of many builders, especially those with limited plumbing and sheet metal skills. The main critieria for constructing good air systems are proper sizing of the storage container and the collector, proper manifolding, adequate insulation, and airtightness of the system. Rocks do not corrode or leak water, and are relatively inexpensive materials that can be used to construct the storage system. Rocks must be selected and washed before installation. Another disadvantage is that rodents and other animals tend to take up residence in the warm rocks. Their presence, alive or dead, can be quite obnoxious. It is also possible for mildew and/or algae to thrive on the warm rocks when air moisture is also sufficient to support life. Well-constructed rock systems may last many years.

Rock systems are bulky requiring about three times the storage volume of a water system. Water systems must be constructed to minimize the dangers of corrosion or freezing. A well-constructed water system is likely to be more expensive, however it is generallly a more compact and appealing for professional buildings. Advantages and disadvantages are listed in Exhibit 2-52. With water systems, one can look to many years of trouble-free service for systems that use quality components and that are properly designed and installed.

The equation that expresses sensible heat storage is

$$Q = m \times s \times T$$

wher Q is the stored heat, m is the mass of the storage medium, s is the specific heat of the storage medium, and T is the useful temperature difference or rise.

Advantages	Disadvantages
Abundant	High vapor pressure
Low cost	Difficult to stratify[a]
Not toxic	Low surface tension—leaks easily
Not combustible	Corrosive medium
Excellent transport properties	Freezing and consequent destructive expansion
High specific heat	Nonisothermal energy delivery
High density	
Good combined storage medium and working fluid	
Well-known corrosion control methodology	

EXHIBIT 2-52 Advantages and Disadvantages of Water as a Thermal Storage Medium (KRE-1)

The specific heat of rock is 0.2 Btu/lb°F (0.84 J/g°C). The specific heat of water is 1 BTU/lb°F (4.19 J/g°C). Therefore water can store heat five times better than rock. As an example the following equivalent masses represent a system having the same heat storage capability and temperature rise:

25,000 lb water (11,340 kg)
125,000 lb rock (56,699 kg)

This represents a volume of 400 ft^3 for water and 1,042 ft^3 for rock. For water, this represents a cube about 7.4 ft (2.3 m) wide on a side or 3,000 gal. (11,355 liters). For rock, this represents a cube 10.1 ft (3.1 m) wide on a side or 7,800 U.S. gal (29,500 liters).

Various solid materials have been tested for storing heat: iron, iron ore pellets, slag, broken tile, concrete, bricks, and aluminum. According to the data provided in Exhibit 2-53, rock is the optimum choice for a cheap material. Iron is a good choice but it is fairly expensive and must be protected from rust. Iron ore pellets are subject to powdering and are therefore not recommended. Aluminum is not much better than rock, and concrete and brick are slightly inferior to rock.

Rock for a solar storage system must be properly selected. Rounded chunks of granite and metamorphic stones make the best choice because they are hard and resistant to powdering. Air flows smoothly past their rounded contours to give a lower pressure drop across the storage bed.

Crushed stone should be avoided as there is a tendency for powdering and the angular edges impede air flow. A good source of rock is glacial till, which contains a large amount of rounded chunks of granite and hard metamorphic rocks. Optimum rock sizes range from pebbles that are about 2 cm (0.8 in.) across to fist-sized rocks.

Material	Specific heat [Btu/(lb · F°)]	Density (lb/ft³) no voids	Heat capacity [Btu/(ft³ · F°)]	
			No voids	30 percent voids
Water	1.0	62.4	62	—
Scrap iron	0.12	490	59	41
Scrap aluminum	0.23	170	39	27
Rock	0.21	170	39	25
Concrete	0.23	140	32	22
Brick	0.20	140	28	20

EXHIBIT 2-53 Materials for Storing Sensible Heat (British Expressions)

Water Tanks

There are several different types of water tanks used in solar heat storage. Steel and fiberglass-reinforced plastic (FRP) are commonly used. Steel tanks are more appropriate for the higher water temperatures usually encountered with concentrating type solar collectors. Another type of tank is made of concrete or masonry blocks and is lined with impervious waterproof material. Exhibit 2-51 illustrates different types of water storage tanks.

Water tanks may be located below or above ground level, inside or outside a building. It is recommended that storage tanks be placed within the building enclosure. An indoor location protects the vessel from weather. Also, heat losses from the tank can help satisfy part of the heating load of the building space in which it is located.

Latent Storage

Another way in which the advantages of latent heat can be illustrated is to describe the physcial barrier of water. Let us consider a block of ice which has been cooled to -30°C. We will now add heat energy and measure the temperature of the ice. We will have to add one calorie per gram of ice in order to raise the temperature of each gram of ice one degree Celsius. The temperature of the ice increases linearly with the addition of heat until the ice reaches 0°C. The heat added along this path is called sensible heat.

At 0°C we find that as we add heat the temperature of the ice does not increase, unless we add 80 calories for each gram of ice. At this point, the ice changes to water. The difference in temperature versus energy input is called the "heat of fusion" or the "latent heat" which is added with no temperature change but a change in physical state from a solid to a liquid.

As we continue to add heat at the rate of one calorie per gram, the temperature of the water increases one degree Celsius until we reach 100°C. There we find that we must add 540 calories of heat per gram before the temperature begins to increase. Simultaneously we find that the physical state of the water changed to a gas or steam.

As we continue to add heat the temperature of the steam rises in accordance with the previous "sensible" heat performance of one degree Celsius, per gram of steam per calories added. This latent heat is commonly referred to as the heat of vaporization.

The process is completely reversible. As we extract heat we note two points on the temperature scale, 100°C and 0°C, where heat is removed <u>without</u> a change in temperature.

Various materials have different temperatures at which the phase state changes occur and the values of the latent heat for vaporization or fusion are different. Exhibit 2-54 lists relevant properties of materials of interest in solar energy applications.

We must use materials for which the "heat of fusion" falls within the range of solar energy temperature. There are two principle advantages to latent heat/phase change phenomena. First, during phase change, we can extract or add heat at a constant temperature. This is unlike rock storage where the storage source temperature changes continuously as we extract heat.

Secondly, the volume of latent storage material required to store heat is considerably reduced. One cubic meter of latent storage medium will store as much heat as 14.5 cubic meters of rock or 5.6 cubic meters of water.

Name	Chemical formula	Transition temperature °C	Transition temperature °F	Heat of fusion kJ/kg	Heat of fusion Btu/lb	Density kg/m³	Density lb/ft³	Cost (dollars) per 220 kg or 1000 lb)
Inorganic hydrates								
Calcium chloride hexahydrate	$CaCl_2 \cdot 6H_2O$	29-39	84-102	174	75	1634	102	15
Sodium carbonate decahydrate	$Na_2CO_3 \cdot 10H_2O$	32-36	90-97	247	106	1442	90	20
Disodium phosphate dodecahydrate	$Na_2HPO_4 \cdot 12H_2O$	36	97	265	114	1552	95	45
Sodium sulfate decahydrate	$Na_2SO_4 \cdot 10H_2O$	31-32	88-90	251	108	1458	91	10
Sodium thiosulfate pentahydrate	$Na_2S_2O_3 \cdot 5H_2O$	48-49	118-120	209	90	1666	104	72
Sodium sulfate decahydrate	97.5% $Na_2SO_4 \cdot 10H_2O$							
Plus borax	+2.5% $Na_2B_4O_7 \cdot 10H_2O$	32	90					
Organic compounds								
Naphthalene	$C_{10}H_8$	80	176					
Propionamide	$C_2H_5CONH_2$	79	174					
Stearic acid	$CH_3(CH_2)_{16}COOH$	72	162					
Palmitic acid	$CH_3(CH_2)_{14}COOH$	63	145					
Lauric acid	$CH_3(CH_2)_{10}COOH$	44	111					
Paraffin wax		38-66	100-150	242	104	865	54	150
Dow polyglycols			vary					
Mixtures (wt percent)								
51.8 percent benzamide 48.2 percent benzoic acid		79	174					
25.1 percent propionamide 74.9 percent palmitic acid		50	122					
33.4 percent ammonium bromide 66.6 percent urea		76	169					

EXHIBIT 2-54 Latent Storage Materials

There are serious limitations as to the number of cycles during which heat addition/extraction can take place before the chemical mixtures separate or break down and become unuseable.

Because of the great advantages of the latent heat characteristic there is considerable research and development activity dedicated to practical solution of this limitation.

Storage Tank Insulation and Installation Guidelines

Because of the intermittent nature of solar energy, storage is needed in active systems to provide energy for times when the sun is not directly available, i.e, during nightime and during cloudy periods. The volume and type of storage medium used is dependent on collector area, type of system, and economic considerations. Usually the storage medium is large enough for all-day solar heat collection without decreasing collector efficiency and small enough to raise the temperature in storage to a degree sufficient to meet heating load requirements.

There are several types of storage containers for possible use in solar applications. Steel tanks are most appropriate for storage of high temperature fluids; fiberglass-reinforced plastic (FRP) is also applicable but controls are needed to limit the temperature in the tank so that it does not exceed a critical temperature. Concrete or masonry tanks with an appropriate liner can also be utilized. For concrete or masonry units, the foundation must be carefully considered because settlement can cause cracks and the liner can be damaged if the cracks are large. Prefabricated preinsulated modular tanks are particularly applicable to retrofit situations as pieces can be easily carried through doorways. A waterproof liner is also required in this type unit.

The exterior portions of any storage tank should be well-insulated to prevent any heat loss to the surroundings. Even if the storage tank is placed inside the main building, the structure must be insulated because

losses from storage to building are not controllable and may occur when no heat load is present.

Insulation that is used should have a resistance value of at least R-30, English units. Several types of insulation can be used, such as:

- o Foam installed at factory:
- o Batts installed on site;
- o Separate insulated housing for tank itself.

The amount of insulation used is an economic tradeoff between cost of the added insulation, and the benefit of greater retention of solar energy. The following equation from (KRE-3) can be used to calculate the optimum thickness of insulation on the storage tank.

$$T_{opt} = \frac{C_f \; T \; t \; k - R_o k}{CRF \; (i,N) b}$$

T_{opt}	optimum thickness, feet.
C_f	levelized cost of fuel.
T	average temperature difference across insulation, deg. F.
t	number of hours per year during which heat loss occurs.
k	insulation thermal conductivity in English units.
CRF	Capital Recovery Factory
b	cost of insulation ($/ft thickness*ft^2 area)
R_o	thermal resistance for heat loss in absence of insulation

It was previously mentioned that it is important to insulate all exposed surfaces of the storage medium. For cylindrical tanks the bottom and saddle or leg supports are the most difficult to insulate. If a flat bottom tank is used, rigid insulation may be used below it. Insulation should be supported above the floor in all cases so that it will not become wet.

When the storage tanks are placed underground, the insulation around the tank must be a type that does not absorb moisture. An example of this would be neoprene foam. In addition, the tank should be placed below the frost line unless a concrete-lined pit is provided. It is important to remember that water and other liquids will expand and contract with temperature differences, so open vents should be provided to prevent tanks from becoming pressurized.

Pebbles or crushed rock are commonly used in air-based sytsems to store energy. In such systems, hot air from the collectors flows through the bed of crushed rock where heat from the hot air is rapidly transferred to the rocks. Pebble bed containers can be constructed of wood, concrete, or steel enclosures. All containers must be designed so that they are structurally adequate to prevent cracking due to weight of pebbles or by settlement of the container foundation. To prevent heat losses, all walls should be reinforced, insulated and the interior surfaces sealed. Insulating to a degree of R-10 to R-13 (English units), is usually sufficient.

2.3.2.5 Circulation System

In practice, for space heating the source of heat energy (coal, oil, natural gas, or solar energy) has little effect on the design of the appropriate circulation system.

Because water or air temperatures are often lower than that obtainable with fossil fuels the size and extent of the circulation system may be larger with solar energy sources.

Conventional baseboard strip heater installations are designed to operate with hot water at temperatures of 71°C to 82°C. Temperatures in solar-heated storage tanks seldom exceed 66°C. As a result either additional baseboard strip heating surface area is needed or solar derived energy must be supplemented by an auxiliary source.

In ducted warm air heating systems, the warm air from an air heater collector is used directly or if a water or liquid collector is used, the hot water is supplied from heat storage to a finned coil heat exchanger in the main air duct and returned by pump to a tank. Air is circulated through the exchanger by a conventional fan or blower.

Galvanic Corrosion

Galvanic corrosion occurs when a combination of dissimilar metals and a conductive fluid is used. Pitting and corrosion occur on the more chemically active metal.

Corrosion can be avoided by:

1) Using a nonconductive heat transfer fluid such as silicone or hydrocarbon oil.

2) Using one type of metal for all metal parts throughout the system.

3) Using an air-to-water system with no dissimilar metals on the water side.

Most commercially available heat transfer fluids are sold with chemical inhibitors already added. Most of the common inhibitors used are sacrificial; the inhibitor is attacked rather than the plumbing. Therefore, a regular maintenance schedule to replace the heat transfer fluid or to replenish the inhibitor as it is consumed is required.

Freezing

Preliminary design should take climate into account. For regions that experience freezing temperatures in winter, a closed system that uses heat exchangers to transfer energy from collectors to storage tank should be utilized. If conditions are severe, antifreeze treatment of the collector fluid circuit, insulating and heat tracing the system, and/or "drain down" provisions should be provided.

Maintenance Required

1) Periodically check antifreeze solution (if used), for chemical breakdown and replace if necessary.

2) Check and lubricate pumps.

3) Periodically change air filter on fan coil unit.

4) Check liquid system filters and replace if clogged.

5) Check fluid levels in system.

2.3.2.6 Auxiliary Heaters

There are several methods utilized to supply auxiliary heat in a liquid solar system. In the majority of cases, auxiliary heat is supplied to the fluid stream by which heat is distributed to the occupied spaces. With hydronic distribution heating system (i.e., baseboard strips, individual fan coils, imbedded tubing and cast radiators), a fuel-fired or electrically heated hot water boiler is used. If a central heat exchanger and ducted warm air are used, auxiliary heat is best supplied by a furnace or electric heater through which the solar-heated air passes to the rooms.

In hydronic distribution systems, the auxiliary source is placed in parallel with the solar supply from storage. Only one source is used at a time. The series design is not used because some of the heat supplied to the water passing through the auxiliary boiler would flow through the primary exchangers and would be accumulated in the solar storage tank. The resulting temperature rise in the solar storage container would reduce collector efficiency and heat storage capacity.

If heat is distributed in warm air by exchange with solar-heated water, auxiliary heat is usually supplied to the air by a warm air furnace in series with the solar supply. In this design, there is not a possibility that auxiliary heat can affect solar storage. As a result, use of stored liquids at low temperatures of 27°C to 32°C is made possible.

2.3.2.7 Heat Exchangers

Simple Shell and Tube Counterflow Heat Exchangers

The addition of a heat exchanger into an active solar system imposes a penalty on performance, since there must be a temperature drop through the device in order to transfer heat.

Optimum heat transfer would theoretically occur when the temperature of the exiting tube fluid equals the temperature of the incoming shell fluid. However, this can never be achieved in reality. The difference in temperature between the entering shell fluid (T_3) and the exiting fluid (T_2) temperature is called the approach temperature ($T_3 - T_2$). Most heat exchangers in solar system applications are designed with an approach temperature of 10°F (5.6°C). Larger approach differences result in smaller, less costly heat exchangers. However, in solar applications, larger approach temperatures and a smaller heat exchanger tends to increase the operating temperature of the solar collector panel, thus decreasing its performance.

Most manufacturers of heat exchange units use computer routines to select a proper unit based on the flow and temperature conditions specified. To select a particular heat exchanger, the designer needs to provide the following information:

1. Approach temperature, usually 10°F (5.6°C).
2. Collector loop flow rate, usually 0.02 gpm per square foot collector area, or 0.014 $l/s*m^2$.
3. Q, collector energy output at specified design condition, kJ/s or Btu/hr.
4. Minimum storage temperature or the flow rate from storage through the heat exchanger.

Exhibit 2-55 includes schematic diagrams of several types of dual-liquid heat exchangers.

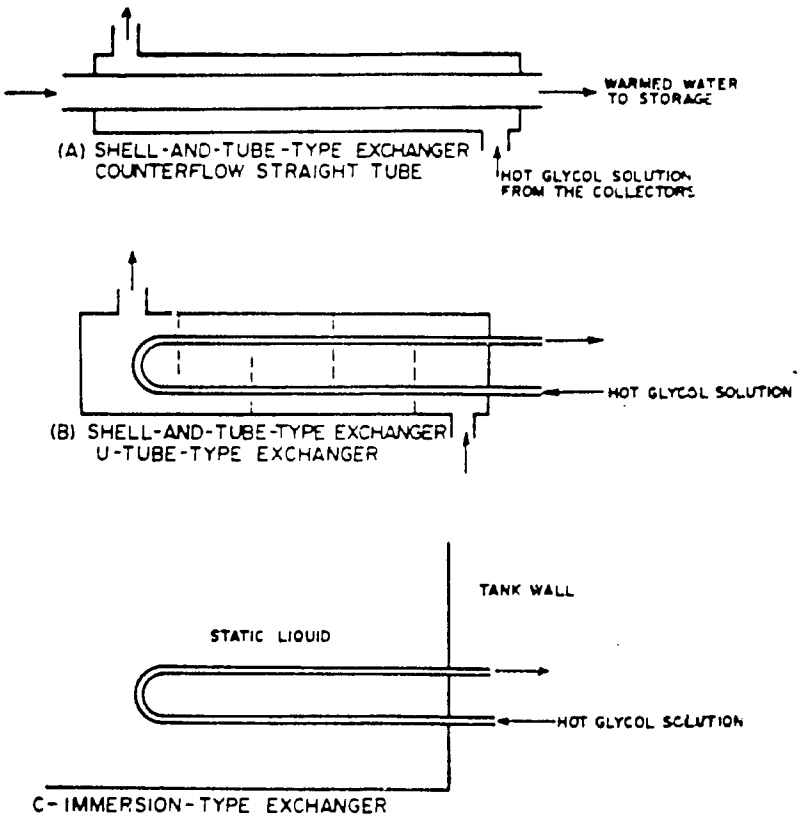


EXHIBIT 2-55 Basic kinds of heat exchangers for dual-liquid systems

2.3.2.8 Environmental Concerns

Materials for Heat Transfer

Many of the materials used for heat transfer and thermal storage in solar heating and cooling (SHAC) technology are toxic or yield toxic fumes during combustion or pyrolysis.

Freeze protection, corrosion inhibition and biocide type chemicals need to be replaced periodically. In addition, chemicals used in cleaning and flushing the liquid-carrying components must be considered with respect to handling and disposal requirements. Many of these chemicals are toxic and need to be properly treated before they are disposed of.

System leaks, overheating, fire, accidental spills, or improper disposal could present hazards to the users, chemical manufacturers, maintenance workers, and terrestrial or aquatic ecosystems. To a lesser extent, the same consideration must be given to insulation, collector materials, glazing, and sealants.

Exhibit 2-56 summarizes current information on the toxicity and flammability of many heat transfer fluids, heat storage materials, and absorption refrigeration fluids used in SHAC systems.

Toxic Effects of Leakage or Improper Disposal

The most common heat-transfer fluid is water. Common rust inhibitors and anti-freeze additives are ethylene glycol/corrosion inhibitor mixtures, such as used in automobile radiators. They are moderately toxic.

Chemical Substance	Toxicity	Flammability
Heat transfer fluids		
Dimethyl siloxane polymers (Dow Corning 200)	Low toxicity, although temporary irritation caused by direct contact with the eyes.	Low hazard; flash points range from 30 to 575°F, depending on viscosity.
Aromatic hydrocarbons (Monsanto therminol fluids, e.g., therminol 55, therminol 60, therminol 66)	Moderate; comparable in toxicity to light mineral oil; toxic if ingested; mildly irritating if contacts eyes; vapors mildly irritating with prolonged exposure.	Low hazard; flash points above 300°F.
Diethyl benzene (Dowtherm J)	Moderate; comparable in toxicity to kerosene; toxicity comparable to therminol fluids.	Moderate hazard if in contact with a source of ignition; flash point: 145°F; fire point: 155°F.
Paraffinic oil mixtures (Dowtherm HP)	Low toxicity; a laxative; may cause aspiration pneumonia	Low hazard; flash point greater than 440°F.
Ethylene glycol	Toxic if ingested; low toxicity otherwise.	Slight hazard if in contact with a source of ignition; flash point: 232°F.
Fluorocarbons (e.g., Dupont freons, such as freon 113)	Toxicity unknown but believed to be moderate.	Very slight when exposed to heat or flame.
Solar system heat storage materials		
Salt hydrates (e.g., sodium sulfate decahydrate)	Materials that have been tested were chosen for low toxicity.	Materials are nonflammable and noncombustible.
Diphenyl	Moderate to high with respect to inhalation and ingestion.	Slight hazard.
Diphenyl oxide	Moderate.	Moderate hazard when exposed to heat or flame.
Absorption refrigeration fluids		
Ammonia	Moderate toxicity with respect to irritation and inhalation; severe toxicity with respect to ingestion; vapor can cause skin burns.	Slight hazard; when heated emits toxic fumes.
Lithium hydroxide	Moderate toxicity with respect to ingestion and inhalation; see sodium hydroxide, below.	No flammability hazard.
2-ethylhexanol	Slight toxicity.	Moderate hazard when exposed to heat or flame.
Sodium chromate	High toxicity with respect to irritation, ingestion, inhalation.	Low flammability.
Sodium hydroxide	Moderate-high toxicity corrosive action on tissue causes burns; vapor can damage eyes; inhalation can damage upper respiratory tract.	Low flammability hazard.

EXHIBIT 2-56 Properties of Solar Heating and Cooling Working Fluids and Heat-Storage Media[10]

Lithium bromide	No toxicity problem reported; toxicity low in small quantities.	No flammability hazard.

One situation in which their toxicity could become significant is that glycol mixtures on one side of a heat exchanger and domestic hot (potable) water on the other side. Obviously, leaks could contaminate the potable water. This problem is discussed further under "domestic hot water" systems.

Given a large number of SHAC systems, periodic replacement and the ultimate disposal of large quantities of ethylene glycol solutions into municipal sewage systems would impose a large organic or biological oxygen demand on the local water treatment plant. Unsupervised disposal of such materials on land or in the water may contaminate potable groundwater or affect aquatic ecosystems, and contaminate soil.

2.3.2.9 CONTROL SYSTEMS FOR ACTIVE SOLAR SYSTEMS

Introduction

Controls in active solar systems have two main purposes:

1. To effectively regulate the collection and distribution of solar energy.
2. To effectively operate conventional auxiliary heating system in conjunction with the solar system.

A properly designed, properly installed, and properly calibrated control system will ensure that the maximum amount of solar energy will be collected and that the heating or cooling load of the building will be satisfied as needed. Control systems regulate collecting and storing solar energy devices, such as pumps, blowers, valves, and dampers.

The design of control systems is very complicated and beyond the scope of this reference notebook. However, it is important to basically understand how control systems operate. The basic components of a typical control system are:

Sensor ⟶ Comparator ⟶ Output Device

The comparator receives information, typically temperatures and pressure differential data, from the sensor(s). Based on that information, the comparator "decides" what action is needed and then acts upon the appropriate output device, i.e. a pump or valve.

Control Arrangements

Designers of control systems take one of two basic approaches.

A. For each control operation, sensors, (including thermostats and pressure devices) and operating relays are used to engage or disable pumps, fans and valves, etc. The thermostat or pressure detector acts as the sensor and the comparator. Typically, separate sensors control different operations of the solar system. However several sensors and comparators can be pre-set or interconnected, so as to perform multiple operations in a system.

B. A microcomputer is used to control the operation of the solar system. The computer receives information from sensors located at critical points in the system. Based on sensor information, the computer decides which action is necessary and controls the appropriate output device. The microcomputer can vary in complexity depending upon the number of sensors, number and type of actuating devices, and the desired inter-relationships of the components. Simple designs can result in a microcomputer "board" 20 cm x 30 cm x 40 cm in size, to a unit 1 meter x 20 cm x 10 cm in size with illuminated indicators that display valve status (percent open or closed), temperatures at critical points, etc.

The advantages of a computer system include:

1. The use of a computer as a comparator permits a more sophisticated analysis of the data available and a greater degree of automation. It is possible to make more intelligent decisions in operating such a system and therefore the efficiency is maximized.

2. On/off set point ranges and other control parameters can be changed from the computer control rather than adjusting each individual thermostat.

3. In addition, self-diagnostic routines allow the computer to sound an alarm in the event of component or system failure. The computer can also compile and analyze performance data.

Solar heating or cooling systems must compete with long established conventional technologies which meet the same purposes with fossil fuels and electricity, which also are generally less costly in capital investment requirements.

The state of the art for these existing and widespread conventional systems is such that very little knowledge of the theory their operation is required by the owner/user.

In areas where solar energy has made significant market penetration trends have favored the simplest, most automatic solar installations.

Sophisticated systems that use microcomputers are employed primarily where operational data are required.

Description of Typical System Components

1. Thermostat

a)	Indoor space:	Control of the area temperature within the living space for heating and cooling operations.
b)	Two-stage space:	One stage involves the choice of heat from the collectors or from thermal storage. The second stage takes over when the solar system is unable to provide for the load demand; the auxiliary system is then enabled. Thus, the auxiliary unit is used only if the solar energy system is incapable of supplying demand.

c) Outdoor: Measures outdoor temperatures and determines certain logic sequences. For example, this type of thermostat may prevent the auxilary unit from working until a certain outdoor temperature is reached. This is called a "wait let us see" circuit. "Let us make sure it will be cold enough to need auxiliary heat in an hour or so."

d) Differential Temperature Controller: Measures the difference between two temperatures. This temperature difference, delta T, determines whether action is taken by some output device. For example, some blowing or pumping sequences are started or stopped depending on the value of delta T or temperature difference.

e) Temperature Controller: This thermostat initiates an action whenever the temperature at a specified location crosses a predetermined set point. Examples include freeze protection, overheating protection, etc.

2. Timer: Determines minimum cycle time that might occur during system start-up or shut-down.

3. Control Valves: Required in a liquid-based system. Controls the movement of liquid about the various loops. It is operated with settings dictated by the thermostat.

4. Dampers: Required in an air-based system. Diverts or restricts air flow to provide the various modes of operation.

5. Economizers: Determines when the outside temperature can be used for cooling.

6. Relays: Converts on/off signals from the comparator device to a sufficient energy level to turn on/off blowers and pumps or open/close dampers.

7. Sensors: Devices to measure temperature and occasionally pressure or flow. Temperature sensor types typically include:
   a) thermocouple
   b) thermistor
   c) silicon transistor
   d) bimetallic element
   e) liquid or vapor expansion unit.

8. Transformers: Convert line voltage (120 or 240V) to lower voltage.

Control Systems

Solar energy control systems design is dependent upon existing facilities (if any) that will be included in the final configuration, the nature of the solar components, the insolation data for the site, etc.

In a notebook such as this, a definitive discussion on this topic is not feasible. There are a number of books, referenced in the index, which should be used by a reader who is interested in more information.

We have found that Marian Jacobs Fisk and H. C. William Anderson, in Introduction to Solar Technology, present a particularly concise and clear discussion. Attached to this volume, as an appendix, is an excerpt from the book which illustrates why we have arrived at this opinion.

APPENDIX

VOLUME I

TAKEN FROM:

Introduction to Solar Technology

Marian Jacobs Fisk, Solar Research & Engineering Corp.

H. C. William Anderson, Solar Research & Engineering Corp.

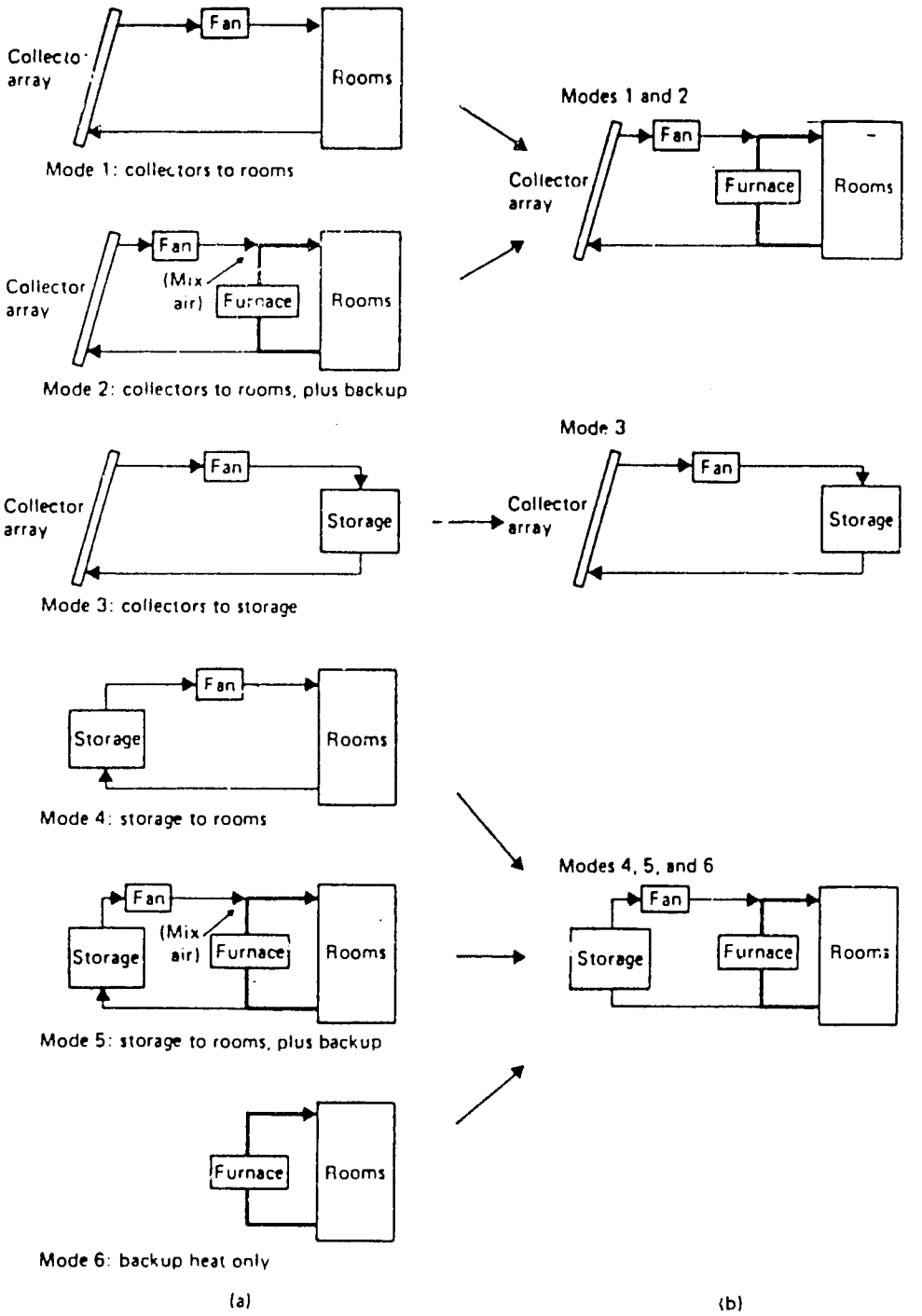


Fig. 5.9 Consolidation of similar modes: (a) desired modes for system, (b) similar modes consolidated.

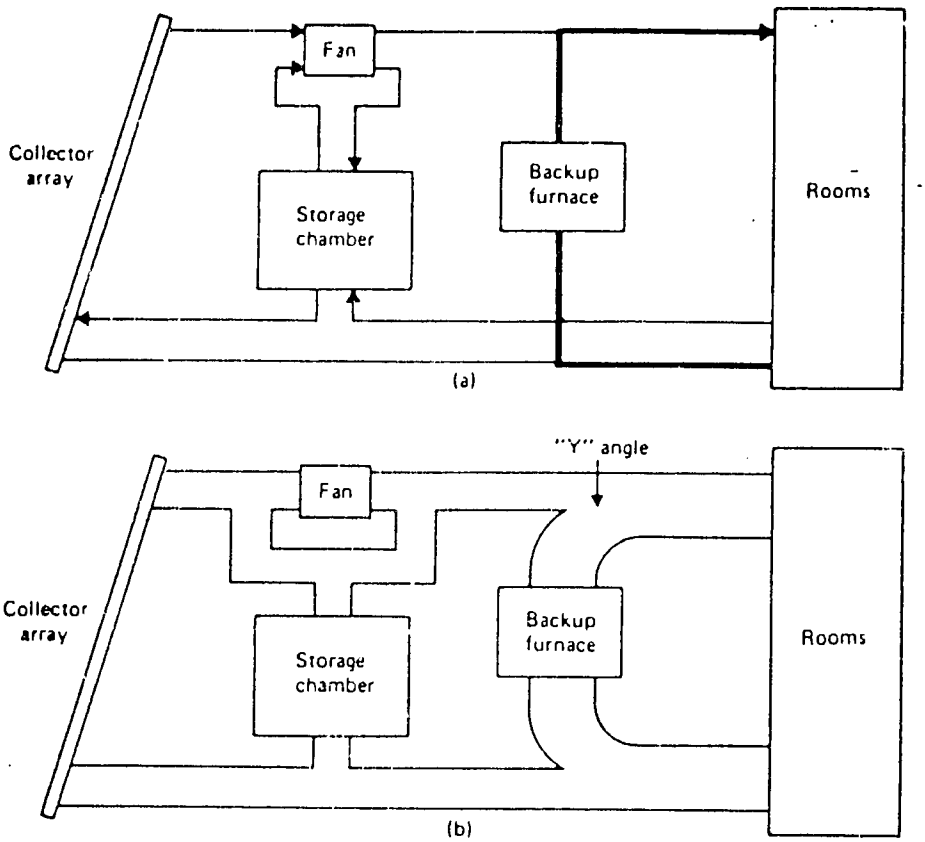


Fig. 5.10 Duct system laid out using a system-flow map: (a) system-flow map, (b) one possible duct layout.

Now we have drawn a duct layout, but the system will not function as drawn. In each mode the air must take a different path through the system. We need to put dampers in strategic places to direct and switch the airflow. We need dampers so that we can switch the system from one mode to another. (Valves perform this function for liquid systems.)

There are three basic classes of dampers. A backdraft damper is chosen whenever possible. A backdraft damper is like a one-way air valve. Air can flow through it in one direction, but not in the reverse direction. These dampers are preferred because they are simple, inexpensive, and do not have to be operated by hand or by a motor. A motorized damper must be used where air must be prevented from flowing in both directions. Sometimes a backdraft damper is not enough or does not allow enough control of the airflow. Motorized dampers are expensive and must be controlled by electric signals, like fans. Sometimes a duct will have to be opened or closed so seldom that it may be acceptable to do the job by hand. Then a manual damper may be used if it is not too

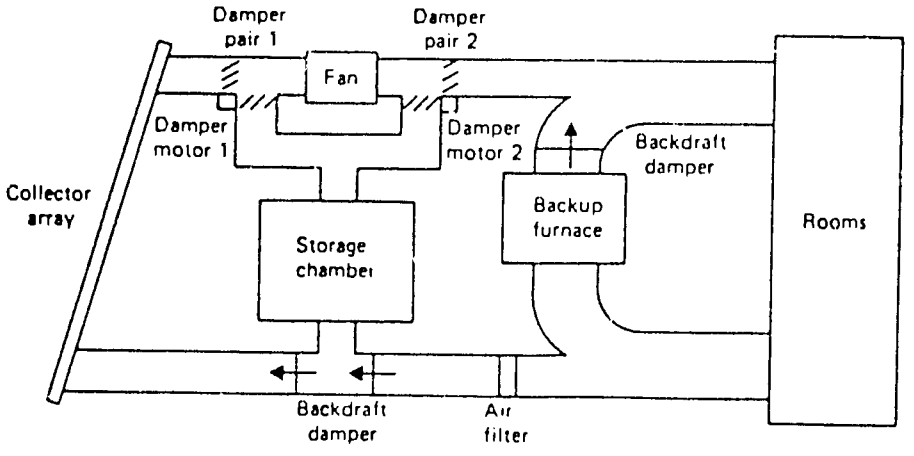
inconvenient. In small systems and in areas where essentially no heating is needed in the summer, a system may be designed to be manually set for summer operation. Manual dampers can eliminate the expense of several motorized dampers, relays, and associated equipment.

For example, perhaps some late spring day an alarm will sound, indicating that the building is warm, that the storage medium is full of heat, and that the temperature of the collectors is rising toward the overheating point. As the alarm sounds, the system might also send newly collected heat into the building—for safety and as an additional hint to set the system for summer operation. This is done by opening and closing some manual dampers and flipping some switches.

Deciding on the type and placement of dampers is largely a matter of trial and error. Each mode must be traced through the system so we can determine which ducts need to be shut off during that mode. As one mode is traced, it might be decided that a backdraft damper is needed in one duct. Later, as another mode is traced, it might be found that the backdraft damper is not sufficient and that a motorized damper is needed for more control. If two motorized dampers are required at the same intersection, sometimes a double motorized damper with a single motor can be used instead (Fig. 5.11). This drawing shows two motorized, two-way dampers and three backdraft dampers (perhaps the cloth type). If the system pictured here looks familiar, it is because it is very similar to the basic air-type system shown in Fig. 5.4.

It should always be verified that the system layout will work, even if a published system layout is chosen. A separate sketch of the system should be made for each mode, indicating where air (or liquid) flows, which dampers are open, and which equipment is on. The sketches in Fig. 5.12(a–f) verify that our example system will function.

Fig. 5.11 Example of a completed layout for an air-type system.



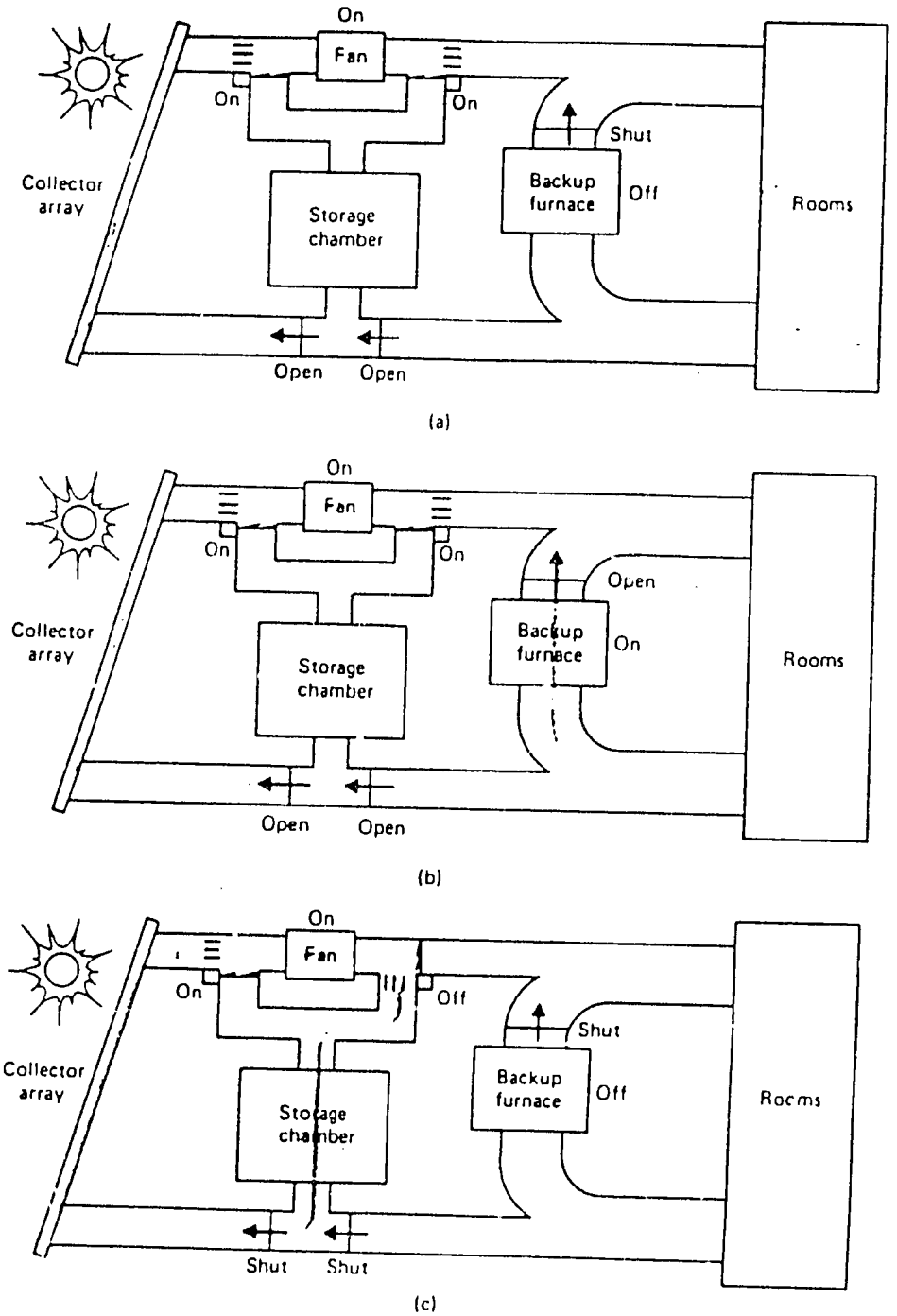


Fig. 5.12 Verification that the system works in each mode. (a) mode 1, collectors to rooms; (b) mode 2, collectors to rooms (with backup heat); (c) mode 3, collectors to storage; (continued)

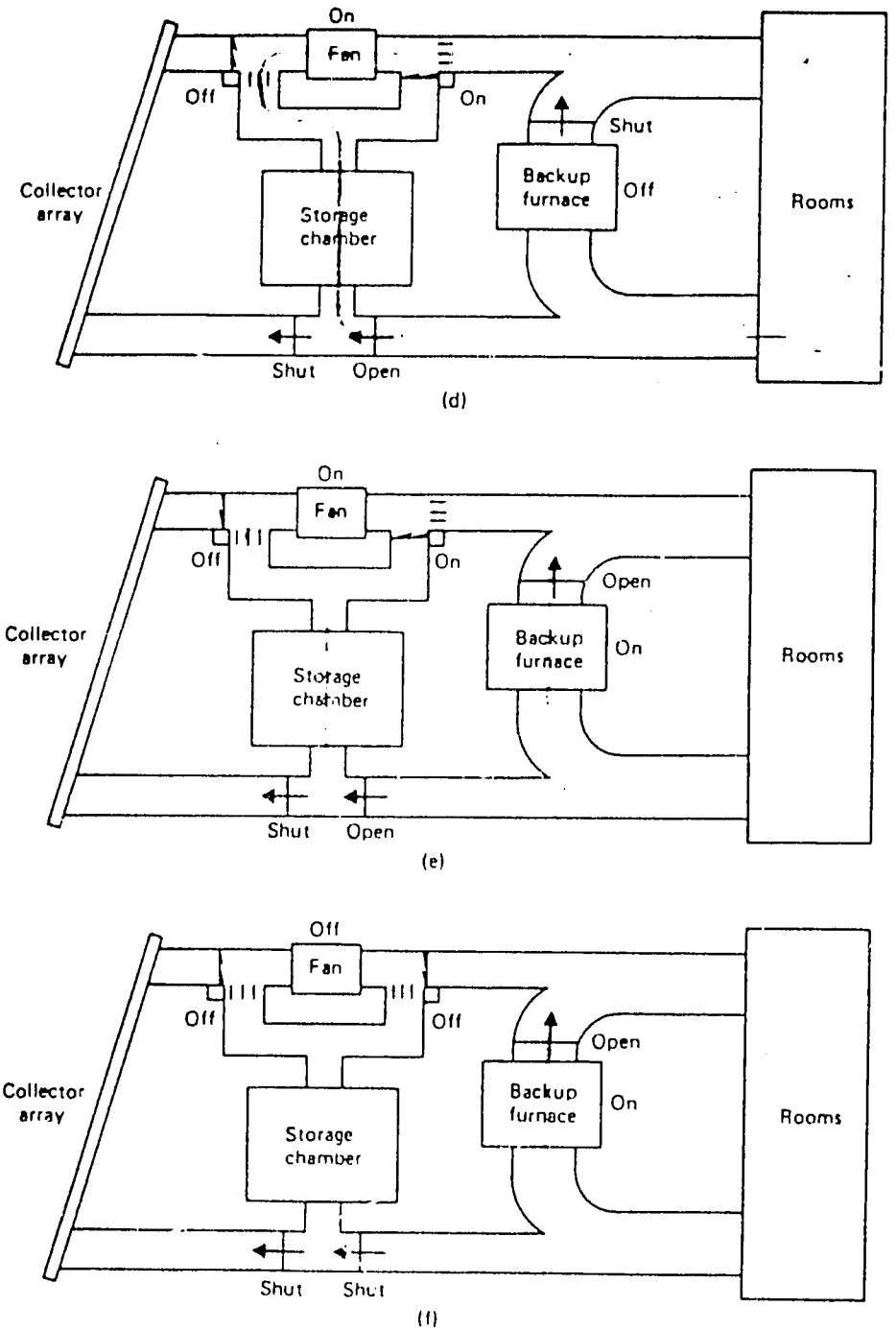


Fig. 5.12 (continued) (d) mode 4, storage to rooms; (e) mode 5, storage to rooms (with backup heat); (f) mode 6, backup heat only.

5.3.3 Controls Design

Once the equipment needs are known and a system diagram exists, it is possible to specify an electronic control system that will automatically adjust the system to meet changing conditions. The control system "decides" which mode the system should be in at any given time, and then switches on the appropriate equipment. As shown in Fig. 5.13, a basic control system has three parts: sensors, a control circuit, and electronic switches. The sensors (such as thermostats) detect the various temperatures and other conditions. The control circuit, or logic circuit, "makes the decisions" and turns on the appropriate equipment, making use of electronic switches (such as relays). To specify a control system means to:

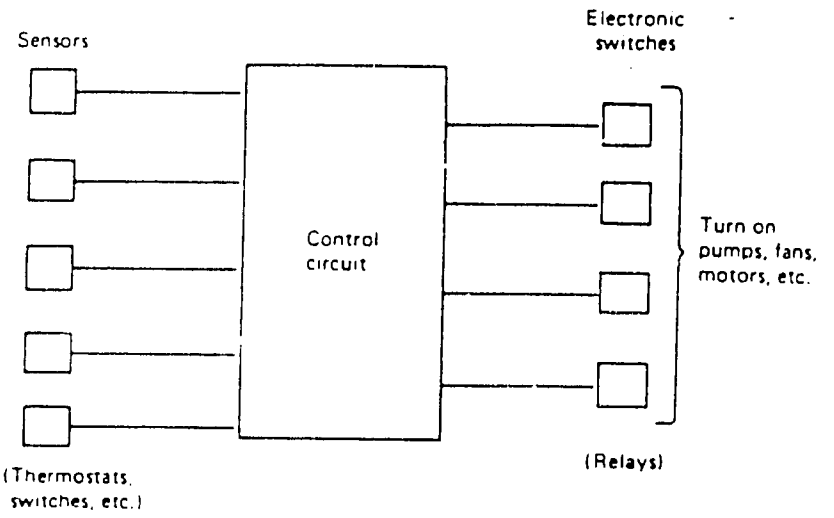
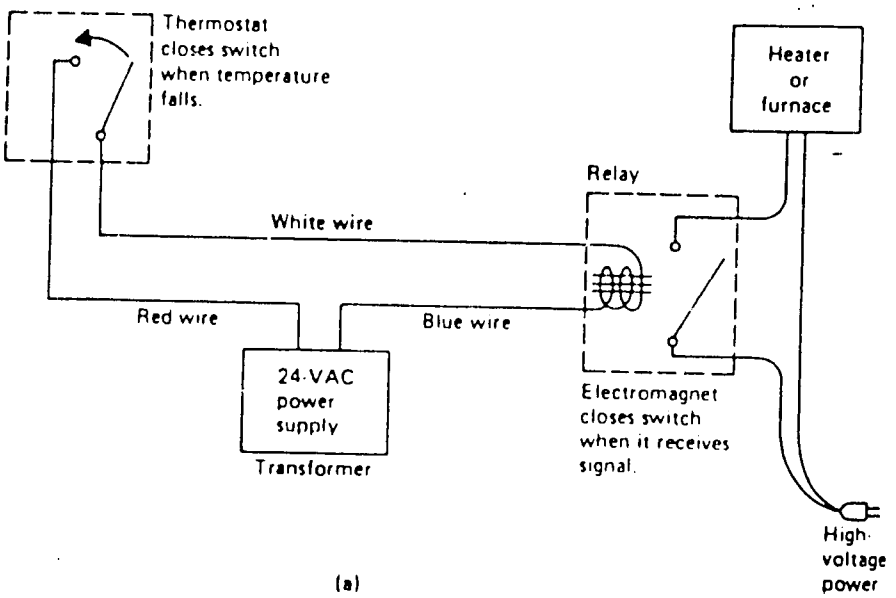


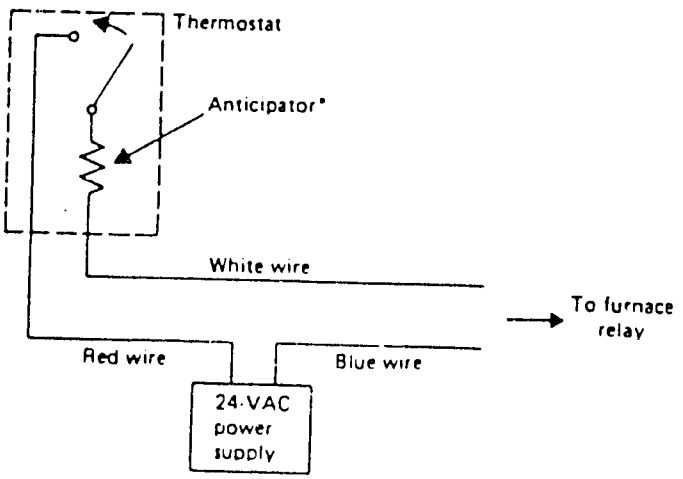
Fig. 5.13 The three basic parts of a control system.

perature in the building drops below the set point, the thermostat switches on, which sends off a 24-VAC signal to a relay, which turns the furnace on (Fig. 5.14).

Fig. 5.14 Conventional-heating-system thermostat: (a) basic operation; (b) heat anticipator, a common feature.



(a)



(b)

*The anticipator is a tiny heater that heats up the thermostat to speed up the heating cycle. Heat from the furnace takes time to arrive at the thermostat. The anticipator helps the thermostat "anticipate" heat's arrival.

Table 5.2 **The Status of Each Piece of Equipment During Each Mode**

	Motor 1	Motor 2	Fan	Furnace
Mode 1	On	On	On	Off
Mode 2	On	On	On	On
Mode 3	On	Off	On	Off
Mode 4	Off	On	On	Off
Mode 5	Off	On	On	On
Mode 6	Off	Off	Off	On
Mode 7	Off	Off	Off	Off

The second step in specifying a control system is to list precisely which pieces of equipment should be activated during each system mode. Usually, for simplicity, systems are designed so that the equipment is either on or off. The fan is either running or it is not. A damper is either powered (in the open position) or it is off (a spring returns it to the closed position). One exception to this is *proportional control*, in which the speed of a fan or pump is varied to match the amount of sunlight available. We can specify what equipment is activated for each mode by making a table (Table 5.2).

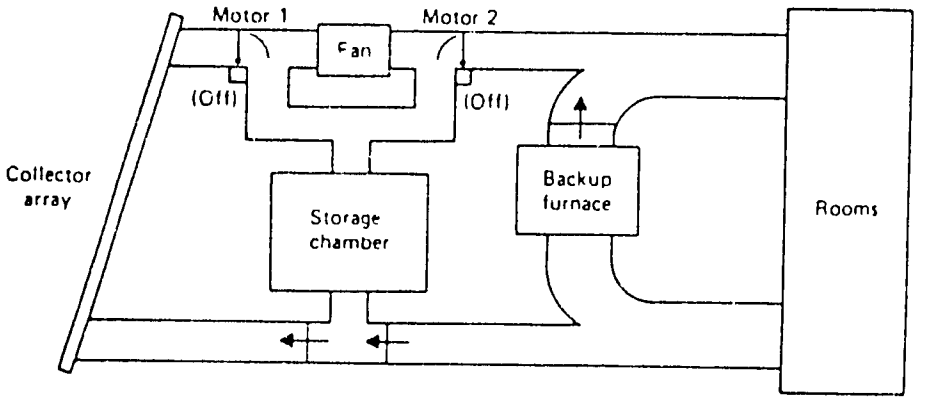
Example For the following air system, specify what equipment is on and what is off for each mode (Fig. 5.16):

Mode 1: collectors to rooms

Mode 2: collectors to rooms, with backup

Mode 3: collectors to storage

Fig. 5.16 A complete basic air-type system.



Mode 4: storage to rooms

Mode 5: storage to rooms, with backup

Mode 6: backup heat only

Mode 7: standby

Solution Let us define the "up" position for each damper, shown in Fig. 5.16 to be the "off" position. When all power is off, the storage chamber is closed off and no hot air can leak out. We can make a table that shows the status of each device during each mode (Table 5.2).

The final step in specifying a control system is to put all the information that has been developed into one table that can be referred to easily. Table 5.3 is a table for the system shown in Fig. 5.16. First, the modes were listed. Second, sensors were decided upon for recognizing each mode. Third, it was decided which equipment must be on for each mode. Fourth, all of the information was tabulated. With this table, a competent electrical engineer should readily be able to design a control logic circuit that will meet these specifications.

Table 5.3 appears to be complete and it nearly is, but an electrical engineer is likely to find some information missing or not quite accurate. The first time a control circuit is specified, it is very difficult to imagine

Table 5.3 Basic Control-Circuit Specification* for System in Fig. 5.16

	Sensors Needed	State of Sensors	Equipment States			
			Motor 1	*Motor 2*	*Fan*	*Furnace*
Mode 1	W_1, T_c, W_2	W_1 on, T_c on, W_2 off	On	On	On	Off
Mode 2	W_2, T_c	W_2 on, T_c on	On	On	On	On
Mode 3	W_1, T_d	W_1 off, T_d on	On	Off	On	Off
Mode 4	W_1, T_c, T_s, W_2	W_1 on, T_c off, T_s on, W_2 off	Off	On	On	Off
Mode 5	W_2, T_c, T_s	W_2 on, T_c on, T_s on	Off	On	On	On
Mode 6	W_2, T_c, T_s, T_d	W_2 on, T_c off, T_s off, T_d off	Off	Off	Off	On
Mode 7	W_1, T_d	W_1 off, T_d off	Off	Off	Off	Off

Definition

W_1 = first-stage heating thermostat; on when solar heat required

W_2 = second-stage heating thermostat; on when backup heat required

T_c = collector thermostat; on when collector temperature > 75°F (57° C)

T_s = storage thermostat; on when storage temperature > 75°F (57° C)

T_d = differential thermostat; on when collector temperature > storage temperature + 5°F, off when collector temperature < storage temperature + 1°F

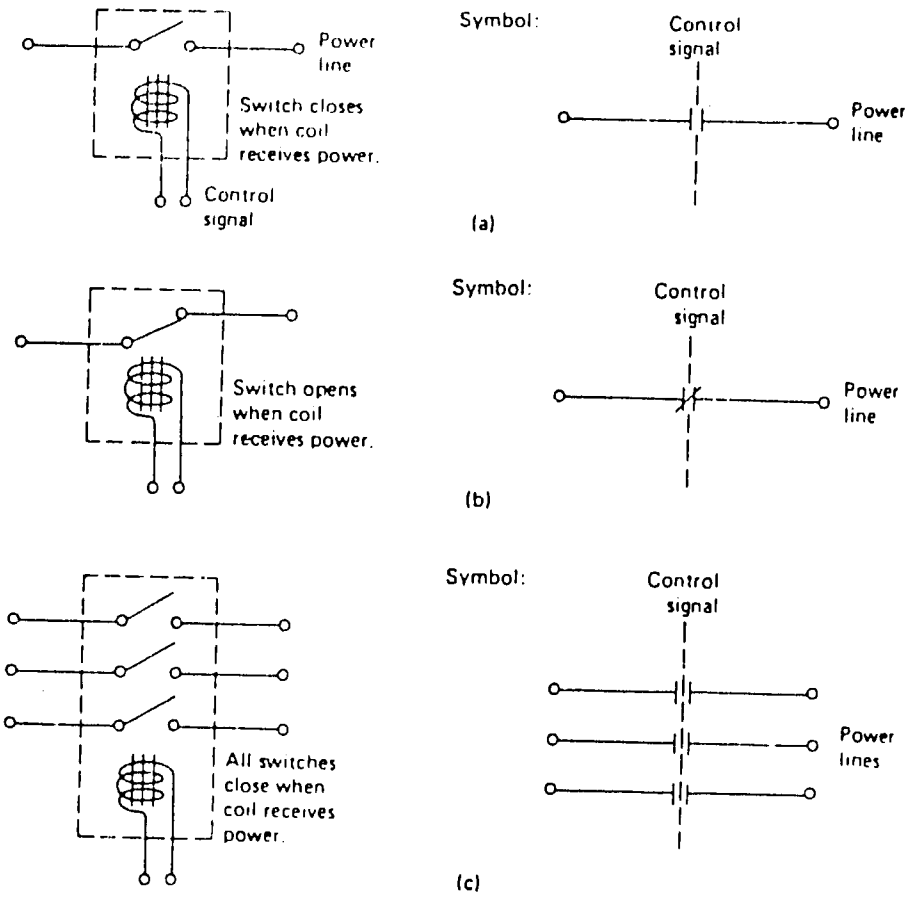
*Not a complete specification, but a good starting point for the circuit designer

every possible combination of sensor states that can occur. But the engineer will find and consider every possible state while designing the circuit. Any errors are likely to be caught in this phase of design. Errors are not always caught, however, and it is important to remember that a system having poor controls or bad logic wastes solar energy that it could otherwise be using.

The control circuit, or logic circuit, is the "brain" of any system. Most active control systems are simple enough so that the control circuit can be built from a few relays. Larger systems may require microprocessors or other solid-state circuitry, but basic systems often do not benefit from the use of solid-state electronics.

A relay is an electrically powered switch. If the coil is supplied with current, the switch will close (Fig. 5.17[a]). Most relays are *double-throw*

Fig. 5.17 Various types of relays: **(a)** a normally open switch, **(b)** a normally closed switch, **(c)** a three-switch (three-pole) relay.

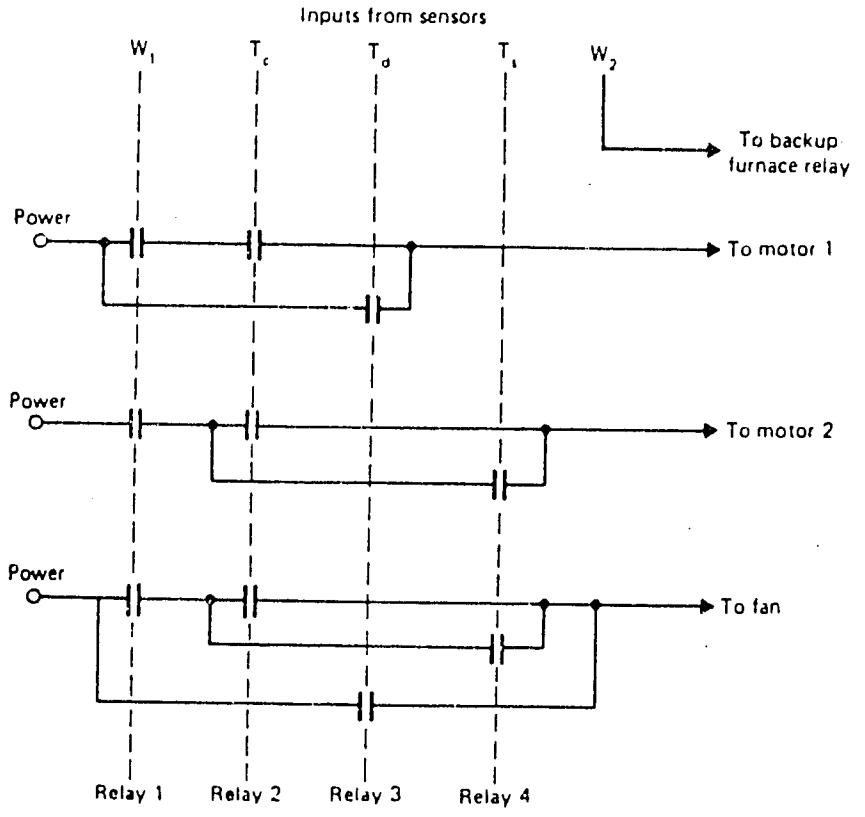


types, meaning that they can also be wired so that the switch opens when the coil is supplied with current (Fig. 5.17[b]). Logic circuits often have relays with more than one switch or *pole* (Fig. 5.17[c]).

A simple relay control circuit is shown in Fig. 5.18. This circuit could be used to control the basic air-type system shown in Fig. 5.16. It matches the control circuit that was specified in Table 5.3. This relay control circuit consists of only four relays. It is best understood if we observe that:

1. Each piece of equipment can receive power only if the right combination of switches is closed.
2. The sensors close the switches (i.e., the sensors provide the control signals that energize the relay coils).

Fig. 5.18 A simple relay-type control system.



W_1 = first-stage (solar) heating
W_2 = second-stage (backup) heating
T_c = collector thermostat
T_s = storage thermostat
T_d = differential thermostat

Therefore, it takes the proper combination of sensor inputs to turn on any piece of equipment. For example, during the collectors-to-rooms mode we want motor 1 to be on so that the collector damper is open. When W_1 is closed (building needs heat) and T_c is closed (collectors are warm), the system should be in the collectors-to-rooms mode. Figure 5.18 shows that when these two switches are closed motor 1 does receive power.

The relay-type control circuit in Fig. 5.18 was designed using the principles of *logic design*. This is the field of the electrical engineer, and is beyond the scope of this book. For more information, refer to the Bibliography at the end of the chapter.

Once a solar heating system has been fully specified and laid out, and once the control circuitry has been thought out, it is time to begin the final phase of design. Collector arrays, fans, pumps, ducts, pipes, and heat-storage units must all be sized to fit the building, and detailed system plans must be drawn to scale. Once this phase is complete, the system design is complete.

5.4 A WORD ABOUT OBSOLESCENCE

In a field such as solar heating, where new advances are a daily occurrence, how is it possible to know that a system installed today will not be obsolete in 10 years, 5 years, or even 2 years? It is not possible. Many areas are under study and we cannot guarantee that there will be no major breakthroughs. Many important discoveries are likely to be made within 10–20 years. Today's exotic materials and methods will be made practical.

The system or component that becomes obsolete does not necessarily lose its original value, however. An automobile may become "obsolete" within five years, yet it will certainly remain in running order if well maintained. A computer may have lost 95% of its resale value in seven years, yet if it can still perform the job it was originally set up to do and if the owner bought a large enough system to begin with, it should retain its original value for that owner. The important point is not whether a thing will become outdated and outmoded, but whether it was properly chosen to begin with and continues to fulfill its original purpose.

Consider heat-storage technology. Today, the two most economical solar-heat storage units are (1) a tank of water and (2) a bin of rocks. Both units are fairly large and heavy, yet both work well and will continue to work well for many years. It is likely that methods for storing solar heat in reversible chemical reactions will soon be discovered, which will dramatically reduce the size and cost of heat-storage units and possibly even reduce the complexity of solar-heating systems. Does this mean that buildings that now have rock or water storage will be forced to scrap

Volume II of III Volumes

Active/Passive Technology
Reference Notebook

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FIELD TESTING

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3. PASSIVE SOLAR BUILDING CLIMATIZATION

3.1 Overview of the History of Passive Solar Design

3.1.1 Definiiton of Passive Solar Design

Passive solar systems are currently defined as follows:

> Passive solar energy systems are methods for heating or cooling buildings in which thermal energy from the sun flows by natural means.

A more meaningful definition might be the following:

> Passive solar systems are an alternative approach to building design. The structure and surrounding climate are treated as one system. Passive solar buildings are designed to utilize on-site energy flows (wind, solar insolation, vegetation) to generate conditions of comfort.

Passive solar systems are incorporated into the building's architecture. Architectural components serve multiple purposes; for example, a wall provides structural support as well as a thermal storage medium and energy absorber. In contrast to active solar systems, passive systems are not easily added to existing structures. Passive designs take advantage of the physical and and thermal properties of building materials (absorption, heat capacity, density, conductance, reflectance) to collect, store, and transmit heat and to provide adequate ventilation.

A properly designed passive structure permits thermal energy transfer into and out of the building envelope, into and out of thermal energy storage, and around and through a conditioned space without the use of mechanical power. A fan or other motivating means may be added to a passive system to improve the energy transfer or to provide an addition-

al level of control over the amount and time of such transfer. Systems of this type are sometimes referred to as "hybrid". It is important to emphasize that a building need not be exclusively passive or exclusively active in design. Combinations of the two designs often produce structures which are ultimately more efficient in providing year round interior comfort conditions.

3.1.2 Passive Solar Versus Building Practices in the Recent Past

Passive solar technology does not represent a new concept. Only in the 20th century, with the invention of modern central space conditioning, fluorescent lighting, and complex fluid distribution systems, have architects effectively designed buildings in which areas with different functions are not thermally and visually undifferentiated. These buildings, with sealed interior environments, require large quantities of conventional energy to maintain constant temperature and lighting levels. High energy prices make such design methods economically undesirable.

The passive design process manipulates building form, orientation, and building materials to offset conventional energy needs. The design process requires trade-offs and compromise. Application of passive solar technology is not limited to residential single-family structures, but may be adapted to fulfill the needs of multi-family and commercial office buildings. Design priorities for these three types of occupancies differ. Single family residential structures are often termed "skin dominated". The chief concern for single-family dwellings is to use on-site energy to overcome heat loss/gain through the building envelope. Commercial office buildings are "internal load dominated". Here, emphasis is placed on removing heat that is generated by lighting, building occupants, and equipment. Multi-family structures have characteristics in the middle of the spectrum. Because of shared interior walls, individual units have less exposed surface than single-family structures, and consequently have lower heat loss rates. However,

shared walls result in poor natural lighting and inadequate cross ventilation. Passive solar design must ultimately be tailored to the needs of the individual building.

3.1.3 Brief History of Passive Architecture

Before the advent of modern central space conditioning systems, building design interfaced more easily with the outside environment. The only way to create an acceptable indoor environment was to adapt a building to its climate. Variations in weather conditions and building materials resulted in such diverse solutions as Arab sunscreens and ventilating towers, native American adobe dwellings, and ancient Greek and Roman cities. Indeed, passive solar design has a long and rich history. Local influences and cultures produced varied forms dependent on different building materials. Exhibit 3-1 illustrates an example of "passive" design incorporating evaporative cooling.

One such example of a building design which responds to local climate is the Eskimo igloo (NEW). Local building materials are blocks of ice which are used as masonry units. The form of the building is a hemisphere which minimizes the exposed surface area. Insulation is provided by snow piled up high against the structure. Infiltration losses are reduced because cracks between ice blocks are sealed due to melting from the interior heat. Building location is considered also; a single sheltered entrance is oriented opposite from the prevailing wind. Thus this local "passive" design combines compact volume, insulation, and orientation to maintain interior comfort.

Underground structures in southern Turkey and Iraq utilize the available resources of earth to provide effective insulation for heating and cooling. The high heat capacity of earth retention is especially important in arid climates where significant diurnal temperature swings exist. Adobe and mudbrick buildings in the southwestern region of the United States also utilize the thermal properties of earth to keep the interior of a building cool by day and warm at night.

Another local response to climate and material availability is represented by the Trulli houses in southern Italy (NEW). In these structures thermal mass and compact volume are combined to generate comfort conditions. The available material is stone. The buildings are conical in form which is effective in reducing exterior surface area. Built without the use of mortar, each structure consists of progressively smaller stone rings. The heavy mass generated by this technique has high heat absorption and storage capabilities. Exhibit 3-2 is a photograph of a Trulli house.

The final examples of existing "passive" forms are the wind tower and wind scoop present in Arab and Indian architecture (NEW). Wind scoops are incorporated in these tall thin buildings which face prevailing winds and deflect air into a channel within the walls of the building. Conduits are located within the interior wall and therefore are protected from solar radiation. As the conduits pass through rooms and eventually into the courtyard, warm air is pushed forward and upward. Wind towers are slightly different in that they face all four directions. Individual funnels are provided to intake and exhaust air. The windward face catches and directs air inward and downward; consequently, suction is created at the leeward side which draws warm air out from the interior, effectively cooling the building. Exhibit 3-3 is a photograph of a wind tower.

From the preceding illustrations, we can easily conclude that what we call passive solar design is not new. Rather, it is a return to more appropriate building design. Exhibit 3-4 illustrates a modern office building that is "passively" designed. Note the shade control devices and the fact that all of the building's faces are <u>not</u> identical.

3.1.4 Energy Conservation Versus Passive Solar

3.1.4.1 Difference Between Approaches

Today's building designers are creating structures which use less conventional energy. Probably the most successful method to reduce energy

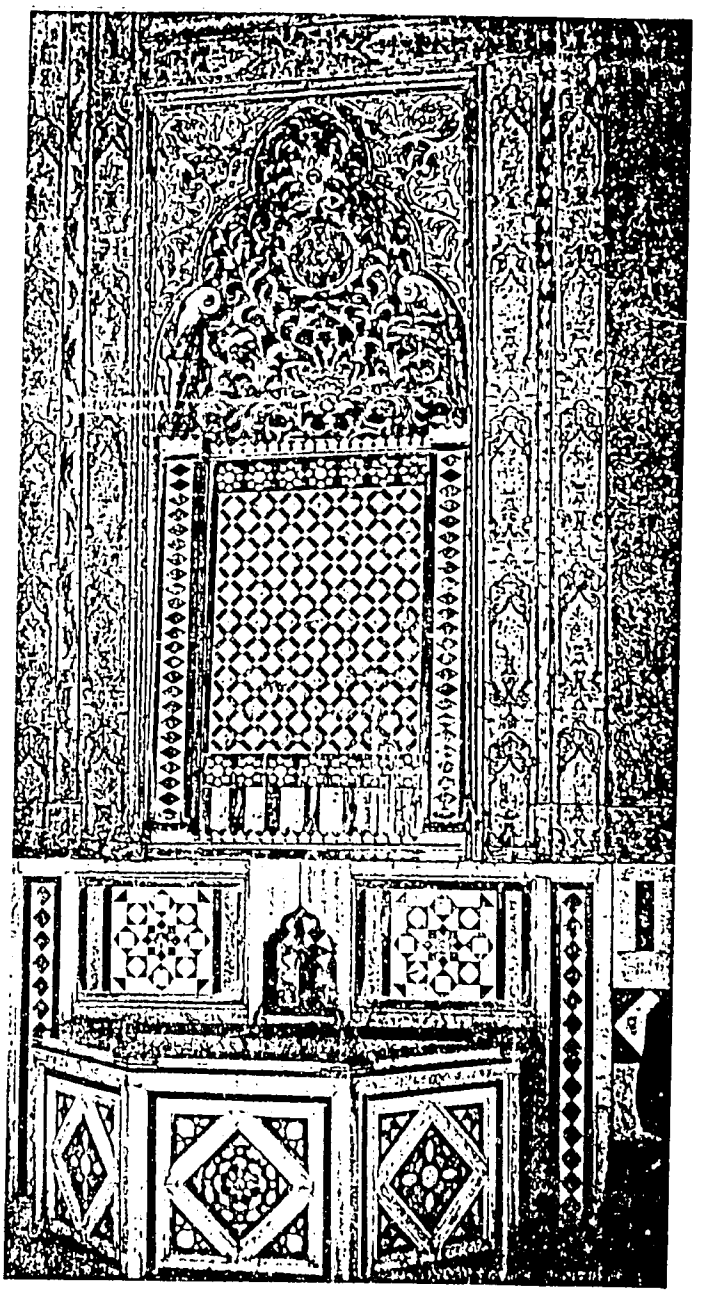
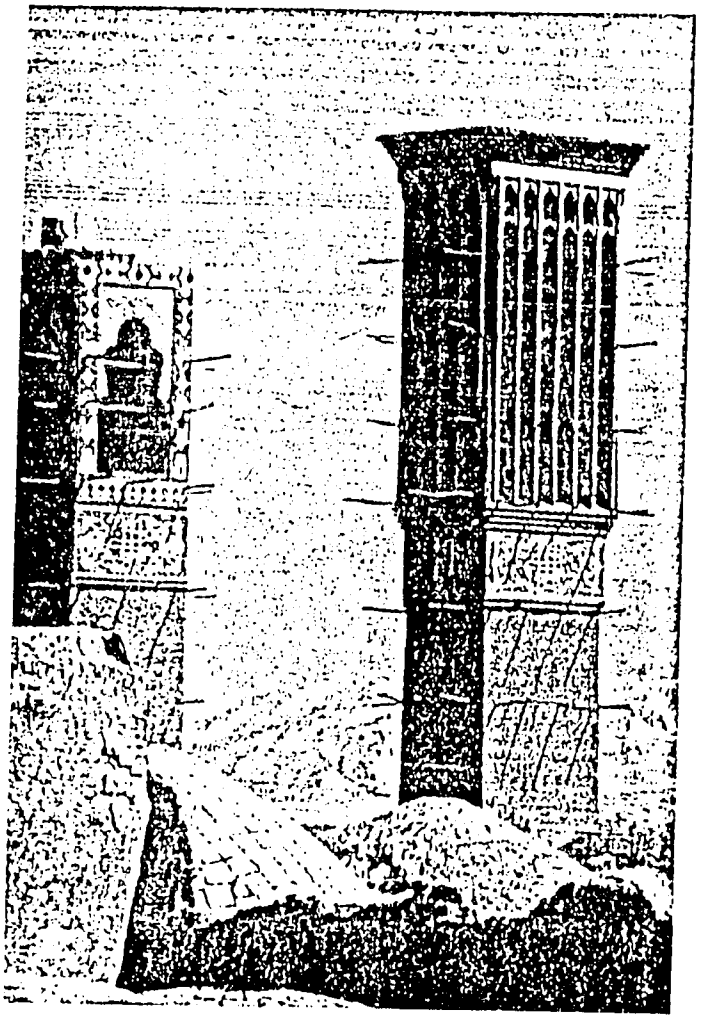


EXHIBIT 3-1. An interior fountain at Beited-Dir, Lebanon provides an example of comfort control that is practical, energy-efficent, and beautiful. As water runs across the mosaic tile, it evaporates to humidify, and thereby cool, an otherwise dry climate. (NEW)

EXHIBIT 3-2. An example of a Trulli house found in Southern Italy.(NEW)



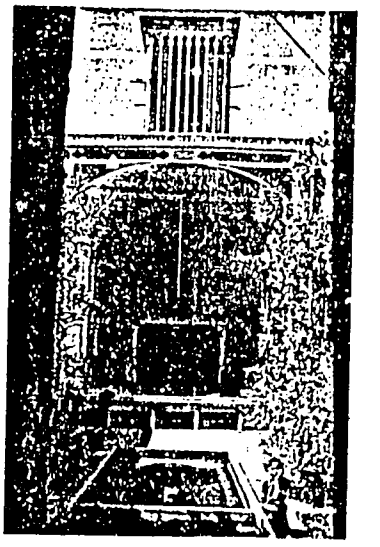
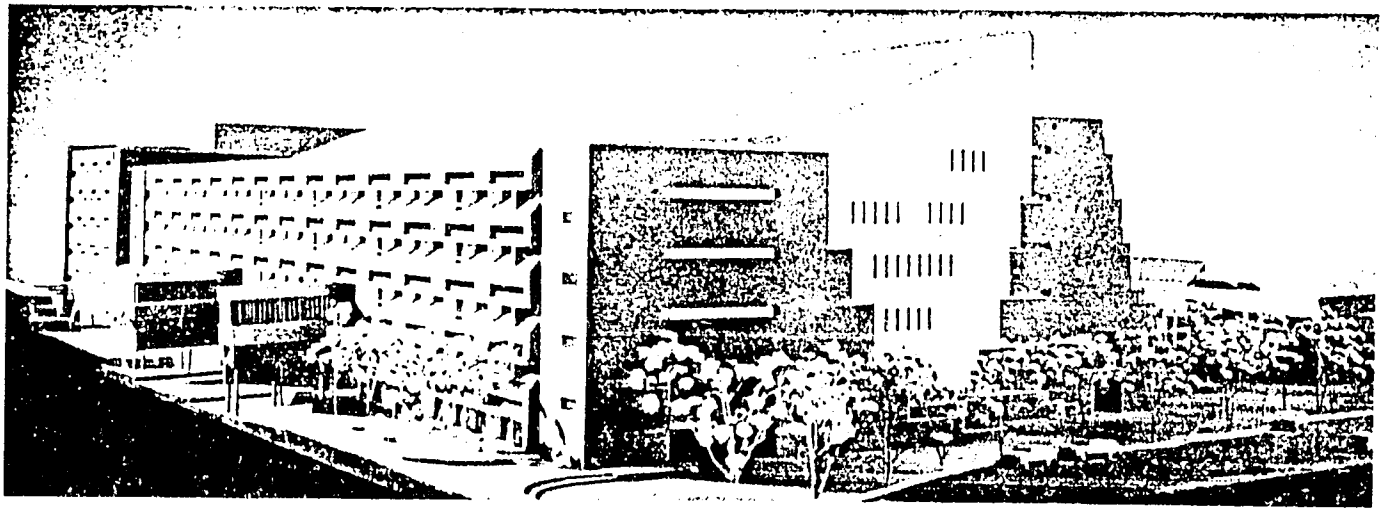


EXHIBIT 3-3. Examples of Wind Towers (NEW)



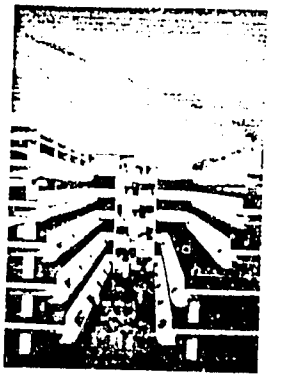


EXHIBIT 3-4. The TVA Office Complex in Chattanooga, Tennessee, USA. (NEW)

consumption is by applying energy conservation techniques such as insulation, weatherstripping, and application of vapor barriers. However, problems arise if energy conservation is the sole concern. One of the references (ROU) has noted that designing buildings with energy conservation as the chief and only concern is like designing a good thermos bottle. In that instance, the goal is to thermally isolate the interior from the outside environment. Thankfully, buildings are not thermos bottles; the function of a building is to provide an acceptable living and working environment for people, not solely to retain heat.

If focusing on energy conservation alone is not the answer, how does passive solar design fit into the overall building design equation? As mentioned previously, energy conservation designers often view a building as the sum of its energy saving components. Frequently, the effect of solar energy absorbed by the building envelope is forgotten or ignored. As a result, many of these buildings experience problems of glare and overheating.

Passive solar designers view buildings not as the sum of energy saving devices but as a system which "taps" into and takes advantage of natural energy flows. Building siting, orientation, landscaping, building form, glass placement, material selection, and color selection are all important variables in a passive design. Rather than ignoring the surrounding climate, passive designers try to incorporate the building and surroundings into a unique system to achieve acceptable thermal and visual comfort. Exhibit 3-5 illustrates how microclimate and internal loads can provide a portion of the energy needs of the building.

Occasionally, the term "passive" may overlap with some energy conservation definitions. Energy conservation in buildings reduces energy consumption, whether the conserved energy is renewable (e.g.,solar) or nonrenewable (e.g., fossil fuel). Although solar energy systems can reduce consumption of fossil fuels, they are not generally regarded as energy conservation systems since they do not necessarily reduce the building's total energy use. Nevertheless, energy conservation practices and measures are important components of all efficient passive buildings.

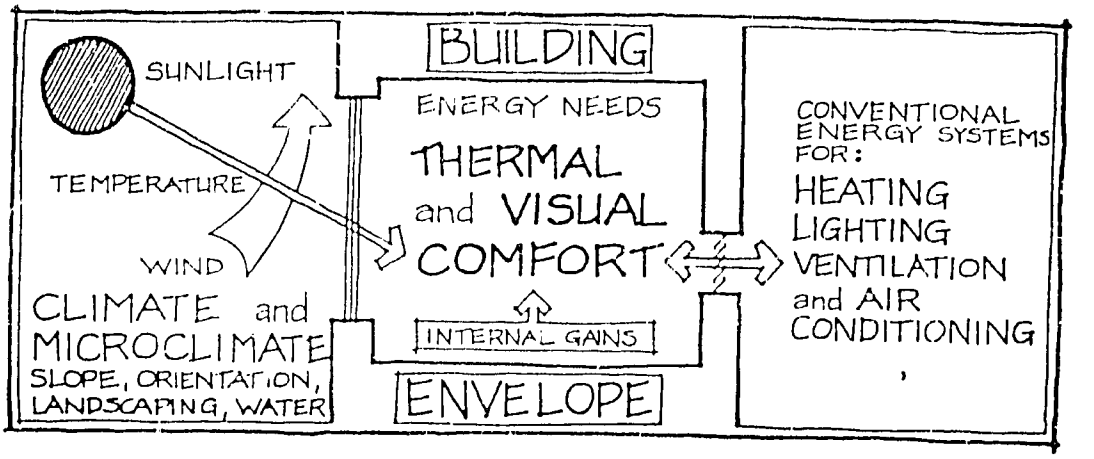


EXHIBIT 3-5. Example of How Microclimate and Internal Loads Can Provide a Portion of the Energy Needs of the Building. (ROU)

3.1.4.2 Energy Conservation in Passive Buildings

Passive solar heating and cooling methods extend our understanding of energy conservation and of designing with nature instead of against nature. Countless pages have been written on both the philosophy and the applications of energy conservation and of climate-responsive and site-sensitive design. Although this subject is not discussed in detail here, a few observations on the relationship between passive design and energy conservation are in order.

Energy conservation is the best first stop in thermal design of buildings. This makes sense from both an economic standpoint and a practical engineering standpoint. The procedure for determining the optimum amount of energy conservation is no different for a passive or active solar house than for any other building. Insulation is added until a point of diminishing returns is reached or until the cost of additional insulation begins to exceed the life-cycle cost of the fuel that the added insulation will save. The same procedure is used for determining the optimum size of the required solar energy system. Its size is increased until the cost of additional collection area, cost of storage, and all of the associated system costs begin to exceed the life-cycle cost of the fuel to be saved from increasing the system size.

By reducing energy demands through energy conservation, conventional and solar powered energy systems can be reduced in size and complexity. In some instances, the traditional elaborate heat distribution system may be eliminated. In its place, a central source of space heat (through--the-wall type or beneath-the-floor type) can heat a full-sized house.

3.1.4.3 Important Conservation Measures for Passive Solar Buildings

Conservation measures primarily reduce the energy flows that occur between the building interior and the ambient exterior environment. These energy flows are typically in the form of heated interior air escaping to the cold exterior and hot ambient air seeping into a cooled interior. Thus, energy conservation measures that reduce heat loss in the cold

weather will also be effective in reducing unwanted solar gain in the hot weather. Typical conservation measures include:

1. Insulation
2. Double and triple glazing of windows
3. Caulking
4. Weatherstripping
5. Installation of vapor barriers
6. Radiant barriers

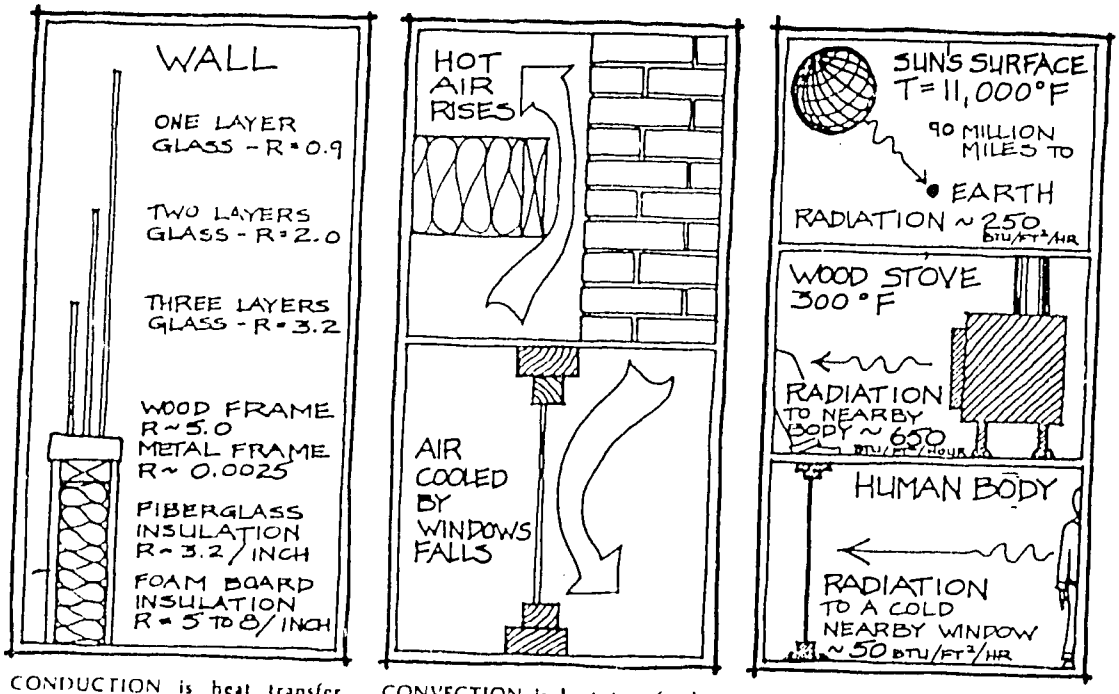
Heat loss/gain through a building envelope occurs via three heat transfer mechanisms - radiation, convection, and conduction. All three mechanisms transfer energy from a warmer region to a cooler one. Conduction heat loss results from molecular motion within the material. Convection losses occur primarily when a fluid flows past a solid surface and when there is a difference in temperature. While convection and conduction need a medium to pass through, radiation passes through a void. Radiation needs only two surfaces of different temperatures that "see" each other. Exhibit 3-6 illustrates the definitions of the three modes of heat transfer.

Conduction losses/gains are reduced by insulating the floor perimeter, walls, ceiling, and roof. Convection losses can be reduced by ventilating attics to remove heat in the summer, caulking and weatherstripping to reduce leakage, and providing vapor barriers in walls and attic. Radiant barriers such as aluminum foil installed in walls and roofs greatly reduce radiation heat transfer.

3.1.5 Advantages and Disadvantages of Passive Designs

3.1.5.1 Advantages

When compared with active systems, passive solar systems have both advantages and disadvantages. Most advantages stem from their inherent simplicity which results in greater reliability, lower installation costs, and longer life. Exhibit 3-7 is a photograph of a passively



CONDUCTION is heat transfer between molecules. It occurs in all substances, solid, liquid, or gaseous. A material's resistance to conduction is its R-Value.

CONVECTION is heat transfer by fluid movement. Whereas conduction consists of heat movement through a material, convection is movement of the material itself.

RADIATION is energy in the form of electromagnetic waves. The hotter an object, the more energy it radiates.

EXHIBIT 3-6. Examples of Conduction, Convection and Radiation (ROU)

heated building. Notice the simplicity of its design and the difference between the north and south views. Most of the disadvantages are related to "marked acceptability" by home buyers and the building industry, and lower "efficiency" of operation.

Reliability

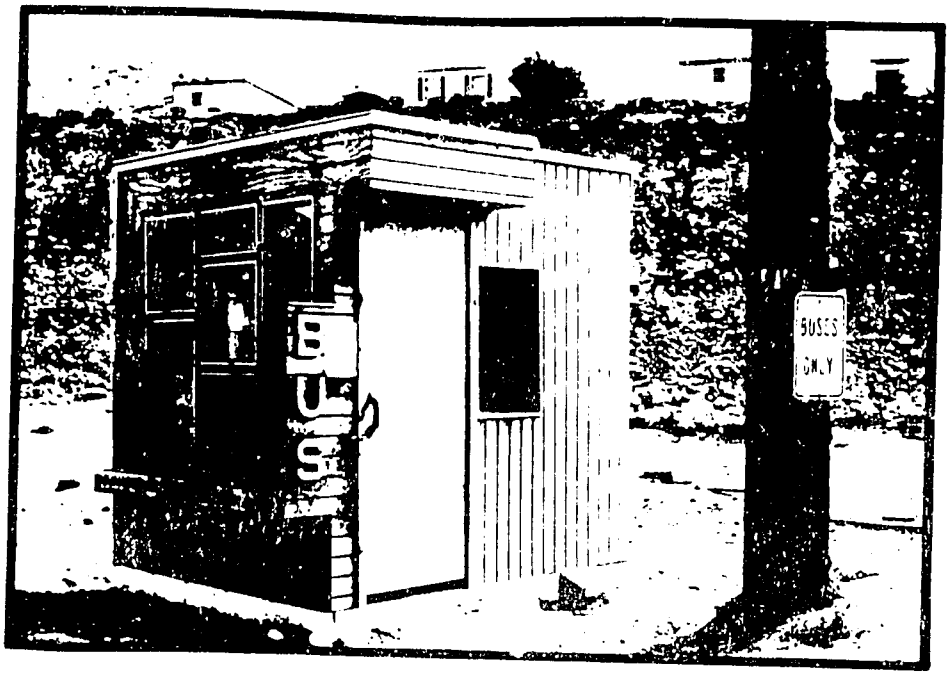
Since passive systems usually employ conventional building materials, and have few or no moving parts (no motorized dampers, automatic valves, sophisticated controls), their performance is as reliable as the quality of the materials employed. Using conventional building materials such as glass, concrete, and brick involves well-known construction techniques, and materials such as those mentioned here are long-lasting. Passive solar systems perform their task effortlessly and quietly without mechanical or electrical commands or requirements. Generally, there are few maintenance requirements. If any control is required (e.g. shutter movement), it is usually a simple task performed by the building occupant.

Cost-Effectiveness

Simplicity, low initial costs of conventional materials, low maintenance costs, and long life all contribute to the cost-effectiveness of well-designed passive solar systems. But perhaps the most significant reason for cost-effectivenss is long life. For the life of the building, a passive system should maintain, if not improve, its value in at least equal proportion to the rest of the building. It should require no more maintenance than any other wall or roof. This is particularly true when the passive system fulfills the dual role of admitting solar energy and forming an integral part of the building's surface and structure.

Saving on Fossil Fuels

Passive solar systems offer many benefits to society. The most obvious benefit is a savings of fossil fuels, which helps the economy and preserves these resources for other more appropriate applications. The



Bus shelter--simplicity of design, operation and maintennace; north and south views.

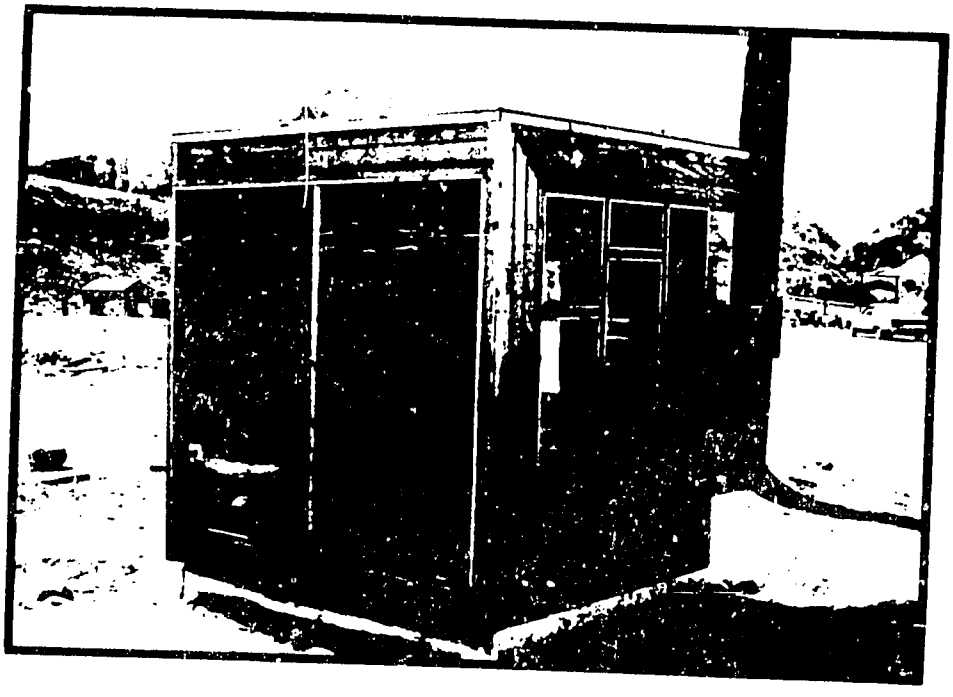


EXHIBIT 3-7. Example of Passive Design's Simplicity (MAZ)

economy profits both by reducing the balance of payments deficit if fuels are imported or if domestic fuels can be exported. The cost savings for fossil fuel then can be used for other areas. The decrease in fossil fuel usage also decreases the impact on the environment. After installation, a typical solar heating and cooling system requires few, if any, transmission lines, or pipe lines; it produces no dangerous radioactive wastes and does not pollute the air or the water. Indeed, solar systems have few negative effects on society.

Radiant vs. Conventional Heating

Many feel that radiant heating from large surfaces, characteristic of most passive systems, is more comfortable than conventional heating methods, which usually heat the air first. The concept of mean radiant temperature (MRT), discussed previously, has important design implications in passively conditioned buildings. Different combinations of MRT and air temperature can generate the same comfort sensation. The effect of MRT is crucial in passive designs which rely on warm or cool surfaces to exchange energy (predominantly by radiation) with the air. For heating, passive designs which generate high MRTs provide comfort at relatively low air temperatures. On the other hand, a frequent characterization of some passive designs is wide temperature swings; in well-designed systems these swings are small, generally in the order of 3°C. In any case, some people prefer warmer room temperatures during the heating season that can be generated by a simple passive system.

3.1.5.2 Disadvantages

It is often difficult to incorporate passive solar design without significantly affecting the appearance of a traditionally designed building. This may affect the willingness of builders to construct it or the willingness of buyers to purchase it.

It is important to stress that passive solar designs "work" all the time; they cannot be "turned off". As a result, preliminary system design should stress year round building climatization rather than, for

example, the reduction of a January heating bill. Properly designed, with solar control, natural ventilation, and properly placed thermal mass, passive designs do indeed work constantly providing building comfort.

The primary disadvantage of passive design is that in most cases it increases construction cost. To achieve a large solar fraction (i.e., a large decrease in conventional fuel bills), the cost can approach that of active systems. However, the financial outlay can be limited by building only a small system. Because the chances of failure in a properly designed system are so small, the decision to use passive designs is relatively risk-free.

3.1.6 Design Priorities of Passive Solar Design

The Massachusetts Multi-Family Passive Solar Program of the Executive Office of Energy Resources (ROU) made the following conclusions on the design priorities of passive solar design. The program stressed that it is important to consider energy savings in the context of other critical design issues including the following:

1. Residential buildings are not built to save energy, but for people to live in. Energy conservation and solar energy should be treated as integral parts of the design process.

2. Passive solar design involves more than a system for space heat; natural ventilation, cooling, and lighting are all important concerns.

3. Comfort is an essential part of performance. Schemes to save energy should not be developed at the expense of visual and thermal comfort.

4. High quality illumination and excellent thermal conditions are more important than constant lighting levels and constant indoor temperatures.

5. The percentage of solar contribution is less important than the total reduction in energy use achieved through passive and conservation methods. Beware of estimated solar saving fractions.

6. There exists no clear mix of conservation and passive features. Cost and performance, even for similar systems, are too variable to permit easy generalizations.

7. Passive solar amenities are valuable. Good passive designs enhance natural light, thermal comfort, and visual appeal.

It must be emphasized that passive solar design for single-family, multi-family, or even commercial office buildings is not a simple three-step process. Numerous variables are involved, including climate, site orientation, landscaping, window placement, and material selection.

3.2 Design Methods Which Emphasize Cooling

3.2.1 Introduction and Overview

In almost every climate, buildings can be designed and constructed to remain cool during hot weather. It may require extraordinary measures, but, in most cases, it is also possible to eliminate the need for mechanical cooling by utilizing passive methods. Many passive solar cooling techniques are not strictly "solar"; some are indirectly driven by the sun, while others represent cooling methods requiring little or no mechanical power.

As was previously discussed, passive solar designs utilize on-site energy sources to provide acceptable levels of comfort. In many areas that emphasize a predominant need for cooling, heating may also be required at night due to large diurnal temperature swings. Since passive systems should be designed to provide year-round climatization, a carefully planned solar building will include provisions for such phenomena.

Note: Design information in this reference notebook is based generally on the northern hemisphere. Northern/southern relationships are reversed when the site is located in the southern hemisphere.

The principal sinks that can be used to provide cooling are:

Cooling Sinks

1. Sky and space -- Radiative cooling
2. Outside air
   $T_{amb} \leq 23.9^{\circ}C$ -- Convective cooling
3. Wet surfaces -- Evaporative cooling

Passive solar cooling designs consist of one or more of the following methods:

1. Solar control
2. Convective cooling
3. Evaporative cooling
4. Radiative cooling
5. Ground cooling

Even though passive cooling systems were used to manfuacture ice as early as 300 B.C. and passive cooling designs were included in buildings in the Middle East since antiquity, the state-of-the-art for passive cooling lags far behind that for solar heating. The climatic information necessary to make wise decisions is sparse. Analytical codes are nearly nonexistent. Little hardware is available. The reader is advised to complement the modern techniques described in this section with a study of ancient architecture.

3.2.2 Solar Control

3.2.2.1 Introduction and Overview

Solar control implies shading the building's windows, walls, and roof. It is the first and most important step to take in keeping the sun's energy from hitting or entering the building. The most effective shading arrangements prevent the incoming solar radiation from striking the building envelope. In fact, where monthly mean temperatures average less than 21°C, control of solar heat gain can virtually eliminate the need for other forms of cooling.

The first step to take in solar control is to shade walls and windows on the south, east, and west sides of the structure. The second measure is to slow the rate of energy passage through the walls and roof with heavier insulation along with glazing systems which reduce heat gain. As was mentioned, insulation retards the flow of energy into and out of the building envelope, reducing both heating and cooling loads. Shading of walls and roofs is critical in hot climates. Heavily insulated walls and roofs need less shading than poorly insulated ones.

Multi-layered glazing reduces heat flow into the building during hot weather. Weatherstripping restricts uncontrolled infiltration into the building. Entrances on exterior walls that face hot dry winds should be equipped with "airlocks." Proper orientation of windows, especially minimization of east and west glazing in favor of heat-gaining south glass (when desired), is most important in reducing summer solar heat gain. Where east or west glazing is used, it is especially important to shade it, a difficult job because of the low and variable sun angles. Vertical, moveable devices may provide the best solution.

Light-colored surfaces can also be used to reduce heat gain. A dark sunlit roof can be 15°C hotter than a light colored roof. The thicker the insulation in the roof or wall, the smaller the effect a lighter color surface will have. Lighter colored walls not only lessen heat gain, they also show less dust. If the building isn't white-washed fre-

quently, the buildup of darker dust will absorb more radiation, increasing relative cooling loads.

3.2.2.2 Shading

Shading devices are most effective when they intercept incoming solar radiation before it enters the building interior. It is expected, therefore, that exterior devices will be more efficient than interior shading devices. This is the case mainly because interior devices intercept radiation after it has penetrated the interior. Part of the incoming radiation has already been absorbed by the glazing, contributing to unwanted solar gain. Since shading must be calculated with respect to latitude as well as climate, there are no generalized shading solutions. Information on controlling solar heat gain is abundant. The most significant sources include the 1982 ASHRAE Handbook of Fundamentals; Solar Control and Shading Devices by Aladar and Victor Olgyay; Architectural Graphic Standards by C.G. Ramwy and B.R. Sleeper; The Passive Solar Energy Book, by Edward Mazria; and Sun Angle Calculator, published by Libbey-Owens-Ford Co., Toledo, Ohio (ASH-1) (OLG-2) (RAM) (MAZ).

3.2.2.2.1 Window Orientation

Window orientation means positioning fenestration (building, doors, and windows) in relation to the north, south, east and west. In hot climates, solar orientation of windows is critical, especially to minimize summer heat gain. The following paragraphs summarize the effect of glazing at various directional orientations.

North: The north side of a building rarely receives direct radiation (in the northern hemisphere). Consequently, there is always a net thermal loss in the heating season. Windows oriented north can also add to the cooling load due to the diffuse radiation and late afternoon direct sun. As a result, window area on the north wall should be minimized except to provide for cross ventilation and views. Shading devices are not effective for shading diffuse radiation incident on north windows.

South: Windows on the south side of a building always receive a net solar heat gain in the winter, and often during cloudy periods. All direct radiation can be shaded with a properly designed exterior overhang to reduce unwanted solar gain.

East: East windows may be desirable to admit early morning sunlight to warm a cool space. However, east glazing tends to produce overheating in the fall, spring, and summer. Due to the year-round low sun angle, entering light can be glaring and difficult to control. Horizontal overhangs are ineffective in blocking incident solar radiation. For control purposes, east windows should be narrow with a deep inlet. Vertical louvers, slats, or wing walls can be used to provide shading.

West: Although west windows are desirable for aesthetic purposes, i.e., view of sunsets, west light produces severe glare and overheating problems. The same control procedure used for east glazing should be employed. West glazing should be avoided if possible, espeically in very hot climates.

Exhibit 3-8 summarizes typical shading strategies and materials for all four orientations.

3.2.2.2.2 Shading South Glazing

A fixed overhang on a south wall can be designed to allow sun to enter the building in the winter while completely blocking the direct summer sun. Unfortunately, the amount of shading that fixed overhangs provide coincides with the seasons. The middle of the sun's summer is June 21, the solstice, but the hottest weather occurs from the end of July to the end of August when the sun is lower in the sky. A fixed overhang designed for optimal shading on August 10 causes the same shadow on May 10. The overhang designed for optimal shading on September 21, when the weather is still somewhat warm and solar heat gain is unwelcome, causes the same shading on March 21 when the weather is cooler and the solar heat gain is welcome. One practical solution is use of adjustable shades.

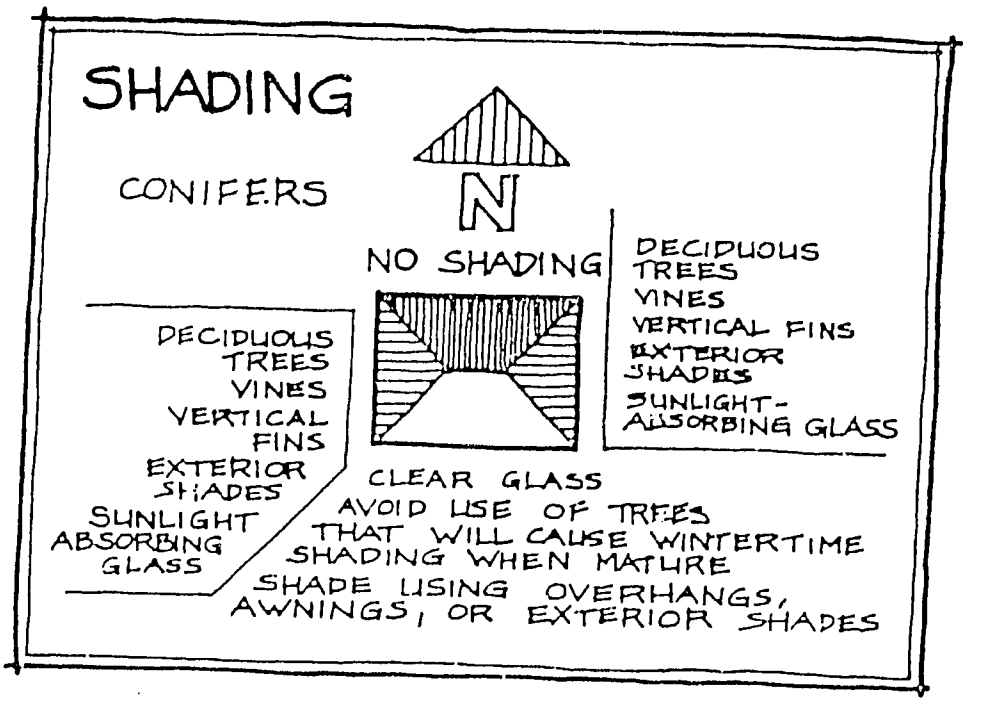


EXHIBIT 3-8. Shading Strategies and Materials for North, South, East and West (Northern Hemisphere). (ROU)

3.2.2.2.3 Sizing the Overhang

As mentioned in the previous paragraph, a compromise is needed to determine what time of year optimal shading is needed. This will then affect the performance of the overhang in the heating months.

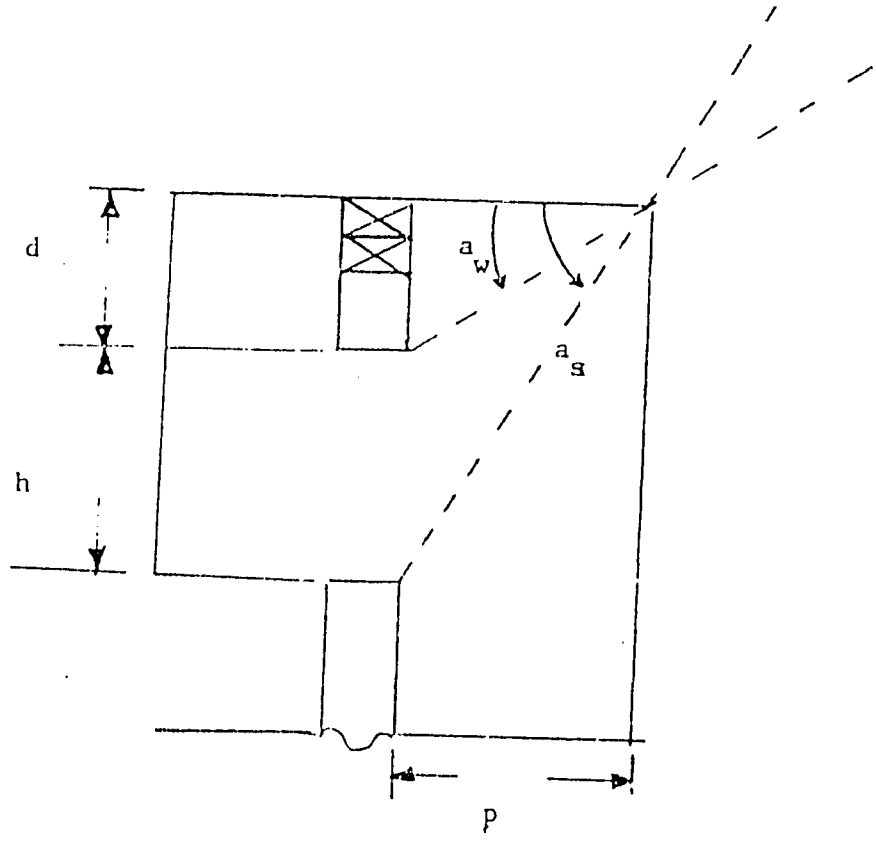
For the typical fixed horizontal overhang, the following sizing procedure as illustrated in Exhibit 3-9 is recommended in the California Energy Commission's Energy Conservation Manual for New Residential Buildings (CEC-6).

Sloping south overhangs are treated in the same manner. Whether the sloping is upward or downward the sizing method is the same:

1. Use local climate data; determine periods when south glazing should be lit and periods when it should be shaded.
2. For these times determine a_s and a_w (summer and winter profile angle at noon) using standard sun charts.
3. From the above equations, calculate the length of overhang (the overhang projection) and the vertical distance from glazing to overhang for a window of specified height.

An overhang is designed according to the data or sensors chosen to be lit or shaded. Before the date that the solar altitude angle exceeds a_w, the winter profile angle, the glazing will be fully illuminated. After that date the solar altitude angle exceeds that of the glazing; as a result the glazing will be shaded. The California Energy Commission's Passive Solar Handbook suggests the following guidelines when designing fixed overhangs for south glazings. (CEC-3).

1. If June 21 sun angle was chosen for a_s, the summer profile angle, poor shading would result during the late summer and fall. A good rule of thumb is to let a_s = 102 - latitude. This gives 70% shading until August 20.
2. Flexibility is required to finely tune south overhangs to account for spring and fall climatic variations.



Where:

d: distance above window
h: height of windows
P: overhang projection
a_w winter profile angle
a_s summer profile angle

Overhang Projection =

$$\frac{\text{Window height}}{\text{Tangent (summer profile angle) - Tangent (winter profile angle)}}$$

Distance above window =

Tangent (winter profile angle) * overhang projection

EXHIBIT 3-9. California Energy Commission's Procedure for Sizing Overhangs (CEC-3)

3. Adjustable louvers placed between open rafters can be designed to provide more shading in the fall and less shading in the spring.

4. Seasonal Inserts: Longer rafters than the overhang are fixed to receive a louvered frame. The frame is then stored elsewhere in the winter and spring.

5. Trellis with Deciduous Vines: A light trellis with deciduous vegetation at the end of the overhang can provide the desired flexibility if the proper species of vine is chosen.

Sun angles are the same in the fall and spring; however, climatic seasons are not. An overhang designed to block the sun until September 30 will block desired heat gain in March when ambient temperatures are still relatively low. As a result, sun control is very difficult to control at these times. Flexible south overhangs are one effective response to this situation, allowing more sun in the cooler spring, yet still providing more shade in the hotter autumn. The illustration in Exhibit 3-10 defines the parameters used in the design of these devices.

It has been suggested (CEC-3) that an a_w of 70° minus the latitude will ensure that the glazing be fully illuminated until January 21. An a_s of 86° minus the latitude provides noontime shading until October 1.

Flexible overhangs can be one or more of the following designs:

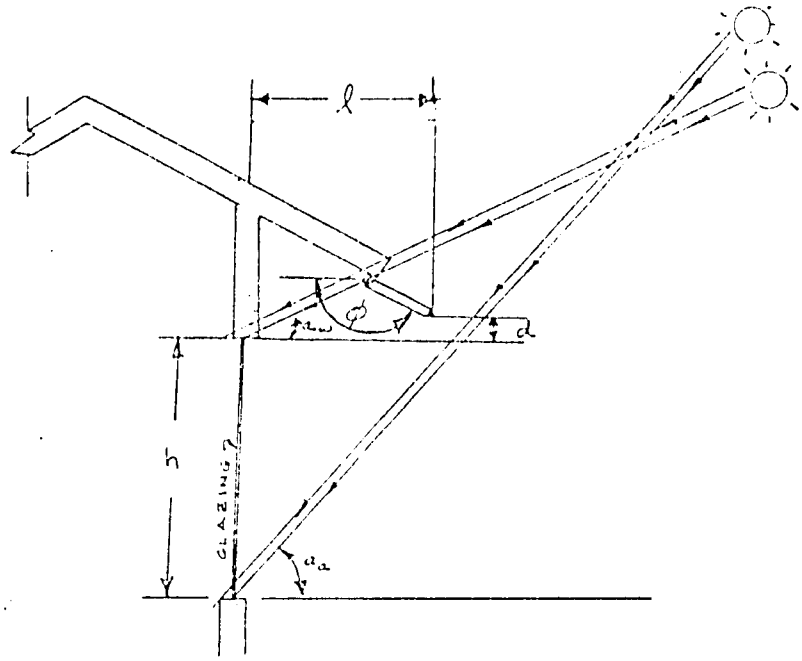
1. Hinged end -- an overhang is hinged and fixed with a locking mechanism, which allows the angle to be adjusted.

2. Flap -- a hinged flap may be lowered to extend the overhang.

3. Sliding extension -- tight shades on tracks are extended to lengthen the overhang.

3.2.2.2.4 Shading East and West Glazing

Shading east and west facing glass is difficult because when the sun is in the eastern and western skies, it is at a low altitude year round. Overhangs on the east and west cannot prevent penetration of sun during



Where:

L:	overhang projection
d:	distance above windows
a_w:	chosen winter noon sun angle
a_s:	chosen summer noon sun angle
a_a:	noon sun altitude when overhang is extended
h:	window height

1. Use local climatic data to determine at what time of the year shading is desired.

2. For these selected times, use standard suncharts to determine the summer profile angle, a_s, and the winter profile angle, a_w.

3. Calculate a_a, noon sun altitude when overhang is extended.

$$a_a = \frac{(90^\circ) + a_s)}{2}$$

4. Calculate length of overhang, L, and the vertical distance from window to overhang, d_s, for a specified glazing height, h.

$$L = \frac{h}{[\text{tangent } (a_a) - \text{tangent } (a_w)]}$$

$$d = L * [\text{tangent } (a_w)]$$

5. The maximum value of $\emptyset$ is $90^\circ + a_s$.

EXHIBIT 3-10. Designing Overhangs (CEC-3)

the summer any more than they can during the winter. Vertical louvers, trellises, trellised vegetation, shutters, screens, exterior roll binds, or other vertical extensions of the building itself are probably best for alleviating this problem.

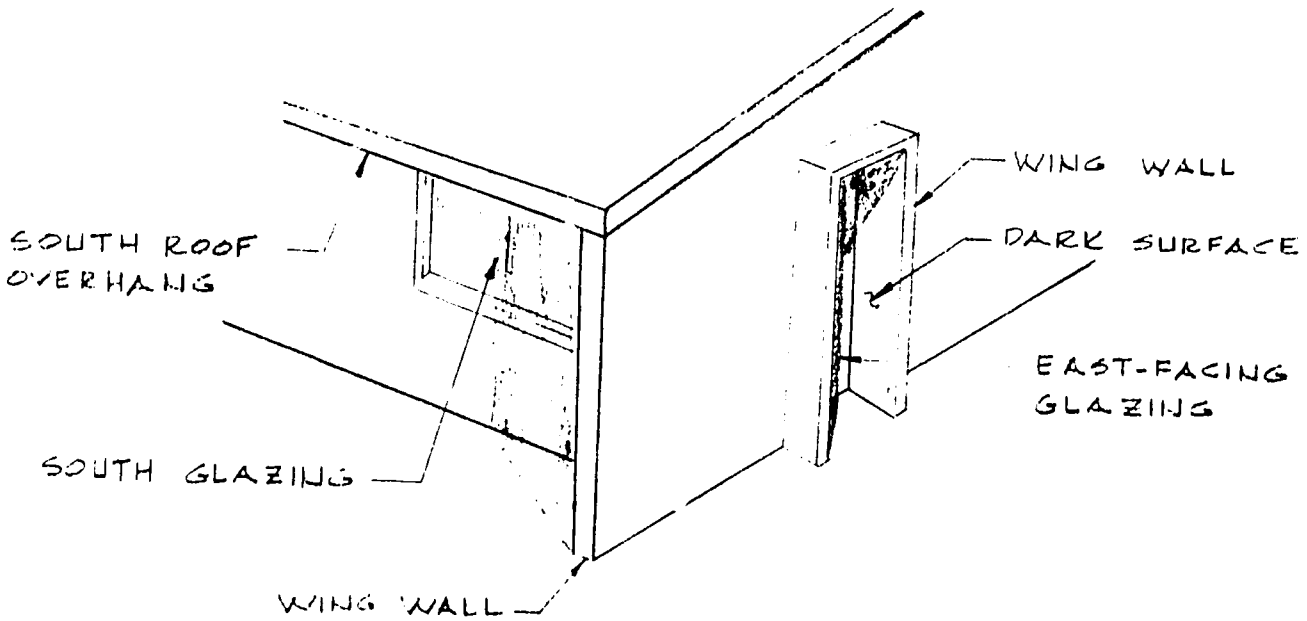
Where view and light are important on east and west buildings, sides or facades, window areas can be minimized by using eye-level, shallow horizontal windows under deep overhangs. The time during which the sun penetrates the windows is short, and the resultant solar impact is minimized.

Many exterior and interior shading devices are effective on east and west oriented glazing. The disadvantage is that the majority of these devices, (roll blinds, shades, sun screens, etc.) will not allow unobstructed views.

As was discussed in the preceding section, horizontal devices such as overhangs and awnings are very effective in shading south glazing. In contrast, vertical devices are very effective in providing shading for east and west glazing. Wing walls are very effective on narrow east facing or west facing glazing. In this design the interior surfaces of the wing wall (facing the window) are usually dark in color to prevent reflection into the window. This is illustrated in Exhibit 3-11.

This concept is also effective for controlling the low angle sunlight at the edge of the south-facing overhang.

Another effective control device is a system of vertical louvers as illustrated in Exhibits 3-12 a. and 3-12 b. These devices can be designed so that they can control diffuse as well as direct incident solar radiation. Properly designed, louvers can be tilted to prevent low angle summer sun from entering while still allowing access to the winter sun.



EHXIBIT 3-11. Examples of Wing Walls for Providing Shading of South Glazing and East-Facing or West-Facing Glazing (CEC-3)

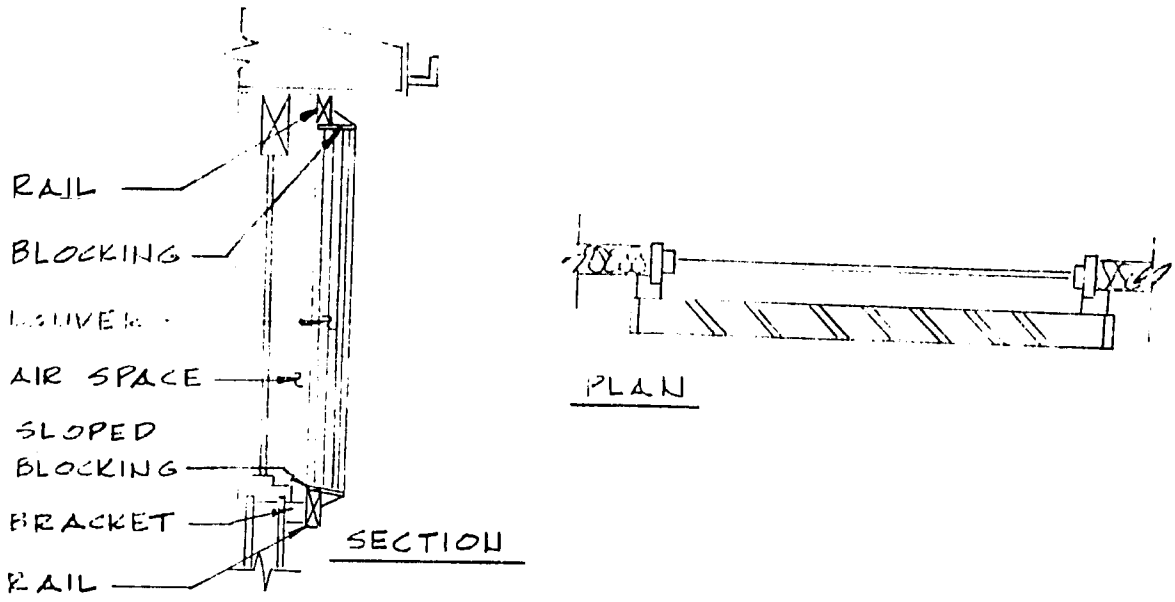
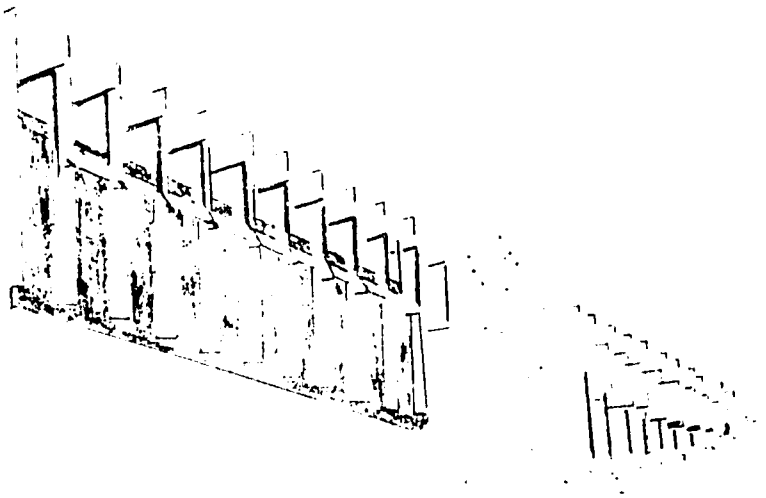


EXHIBIT 3-12a. Example of Vertical Louvers and Angle Louvers for Controlling Sunlight on East/West Windows (CEC-3)



For conditions where buildings rely mainly on night cooling, louvers of thin lightweight materials can be effectively used as in this primary school building.

EXHIBIT 3-12b. Example of Shading on West-Facing Glazing (BAL)

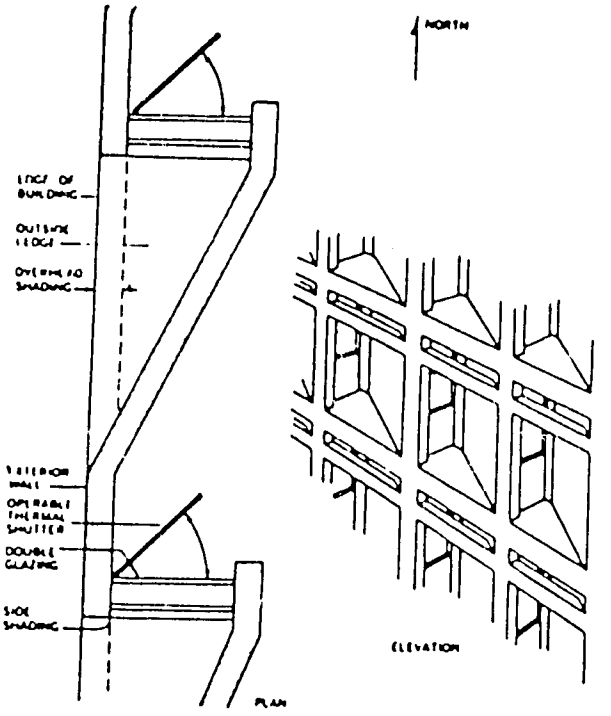


EXHIBIT 3-13. Sawtooth Arrangement for Windows on the West Facade of a Building Allowing Solar Heat Gain During the Winter but Excluding It During the Summer (AND-2).

Vertical louvers are used to control the sun on east and west windows. Angle louvers to prevent low summer sun from entering while still allowing access to the low winter sun.

Another example of shading west-facing glazing is illustrated in Exhibit 3-13.

3.2.2.2.5 Miscellaneous Shading Devices

Deciduous Vegetation

Shading from properly selected deciduous vegetation more closely follows the climatic seasons and, therefore, the energy needs of buildings that need both heating and cooling. On March 21, for example, most trees are bare and will therefore allow relatively unobstructed passage of sunlight. On September 21, however, trees are still full and provide necessary shading. Deciduous trees in front of south-facing windows can provide shade from the intense midday summer sun. An overhang trellis with a climbing vine that sheds its leaves in the winter is an excellent alternative. However, a deciduous tree completely bare of leaves still blocks 20 to 40 percent of the sun's direct radiation, proportionately reducing solar gain in winter.

In cool climates, shading with evergreen trees and shrubs can be successful. Shading east and west walls and windows, which receive 50 percent more radiation than north and south walls during the cooling season, will significantly reduce cooling loads. The resulting 3°C to 5°C lower temperatures in shaded areas next to the wall reduce heat transfer by conduction. Shading the air conditioner will increase its effectiveness.

Designing and installing a trellis is a relatively easy operation. As was just mentioned, besides being an attractive method of sun control, deciduous vegetation on trellises will automatically adjust to cool springs or hot falls. It is very important for the plant to be carefully selected.

Some design guidelines as recommended by the California Energy Commission in their Passive Solar Handbook (CEC-3) are the following:

a) Trellis over south glazing: Design considerations should make sure that the structure itself does not cause too much shade in the heating season.

b) Tension Trellis: This option provides minimum structural shading of the south glazing.

c) Trellis/Balcony: This combination provides adequate shading for a second story (or multi-story) facing east or west.

Exhibit 3-14 provides detailed design suggestions for the trellis designs mentioned above.

Operable Shading Devices

Operable shading devices such as awnings are even more versatile and adaptable to human comfort. Yet such devices attached to the outside of buildings are difficult to maintain, and most designs deteriorate rapidly. Efforts to make awnings more durable are usually unsuccessful. However, with rising fuel prices and greater emphasis on shading, increased efforts have been made to produce better operable shading devices. Awnings are perhaps the simplest and most reliable operable device, but their aesthetic appeal is limited.

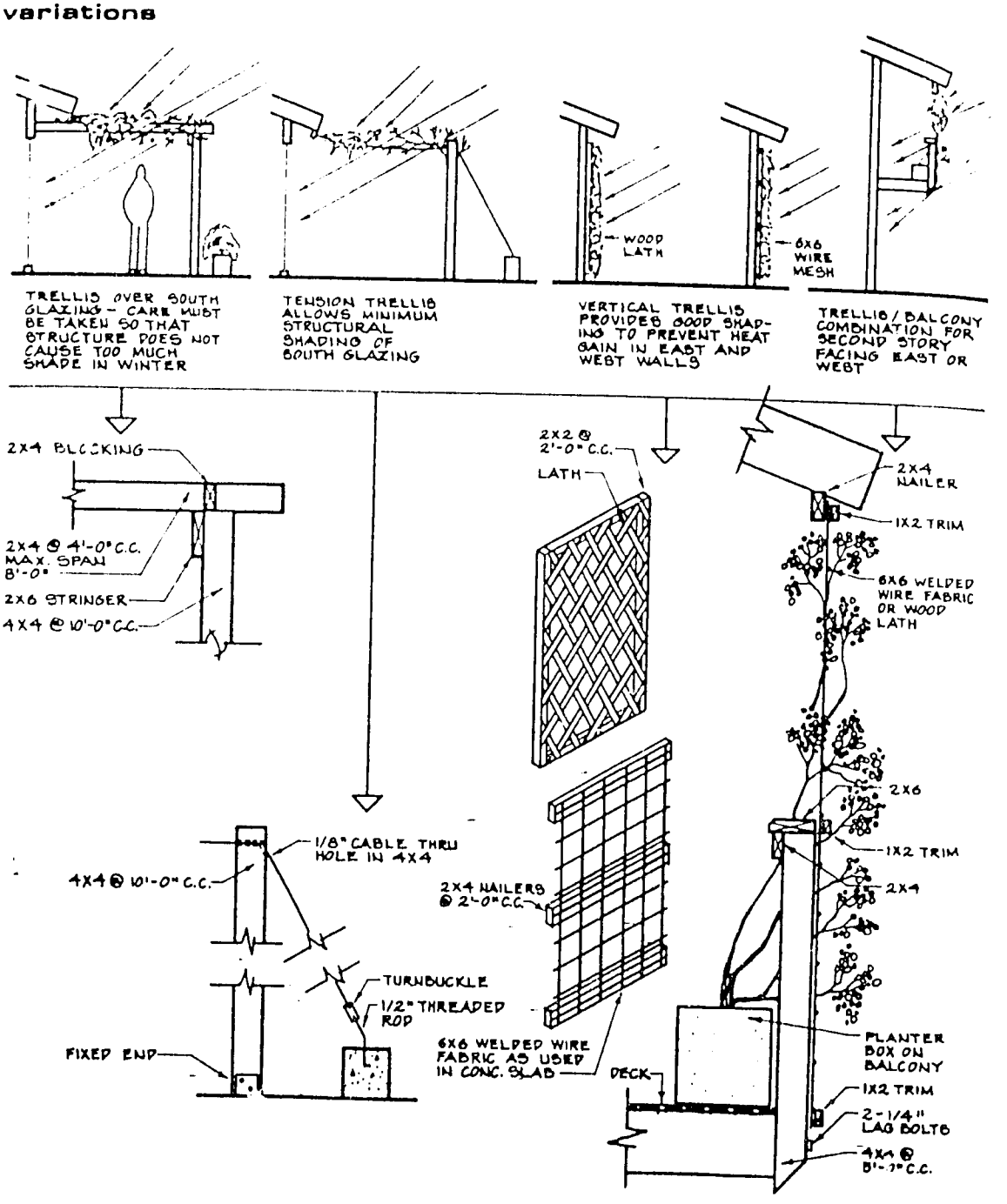


EXHIBIT 3-14. Design Suggestions for Trellis Designs (CEC-3)

Advantages of Moveable versus Fixed Shading

Both fixed and moveable shading devices have advantages and disadvantages. The ultimate choice is based on various criteria including cost, weather conditions, and occupant participation. Fixed shading is advantageous because once the design is complete and the device is installed, it becomes a permanent part of the building. Usually, minimal maintenance is required; the device typically performs for the life of the building without any further user intervention. The primary disadvantage of fixed shading devices is that climatic seasons do not coincide with sun angle seasons. Fixed overhangs designed to provide optimum shading at the solstices cannot respond precisely to the shading and exposure needs of summer and winter. An advantage of moveable devices is that they allow the building and weather to be tuned to each other on a daily basis. The disadvantage is that these devices require the participation and sensitivity of the occupant. In addition, moveable elements of the device occasionally break.

Surrounding Buildings

Designers should also consider the shading effects of buildings on one another and on the surrounding environment (i.e., whether the shading occurs on buildings that directly or indirectly use the sun's heat or light, or on wild vegetation, or gardens that need sun in order to grow). On the positive side, buildings can be clustered, with narrow streets between them to shade each other, or can be oriented to direct or block the wind (depending on the climate). Common walls help reduce heat gain. Narrow streets reduce dust problems. Windowless walls facing the street block the entry of dust into the buildings while light and air can enter through openings onto the traditional courtyard.

An important part of building design involves site planning which considers the effect of surrounding buildings and property. It is beyond the scope of this notebook to go into detail about this subject.

Some references for further information are the following:

a) Consultant Report: Planning Solar Neighborhoods, Living Systems, Jonathan Hamond, Principle; for the California Energy Commission, 1980, report # P500-81-018.

b) Energy Principles in Architectural Design, Edward Dean, Shelley Dean and Fuller Architects for the California Energy Commission, 1981, report # P400-81-004.

c) Solar for your Present Home, Charles S. Barnaby, Philip Caesar and Bruce Wilcox, Berkeley Solar Group and Lynn Nelson, Environ/Mental, for the California Energy Commission, 1978.

Exhibit 3-15 summarizes the basic concepts for solar control of glazing: horizontal shading for south-facing orientation and vertical shading for east/west orientation.

3.2.3 Glazing

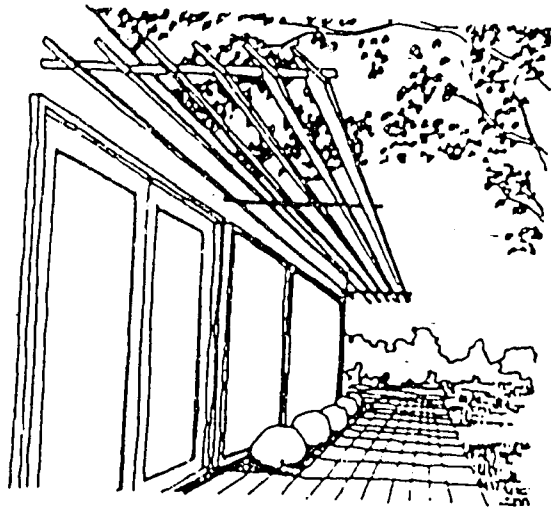
One method of reducing heat gain through glazing on walls is to orient the glass to the north or south. By facing the glass north (for Northern Hemisphere), only indirect irradiation will be admitted, a favorable lighting effect for many tasks. However, by facing the glass south, solar heat is admitted during the winter season.

It is important to remember that windows or glazing influence the heating or cooling of the building interior in two ways:

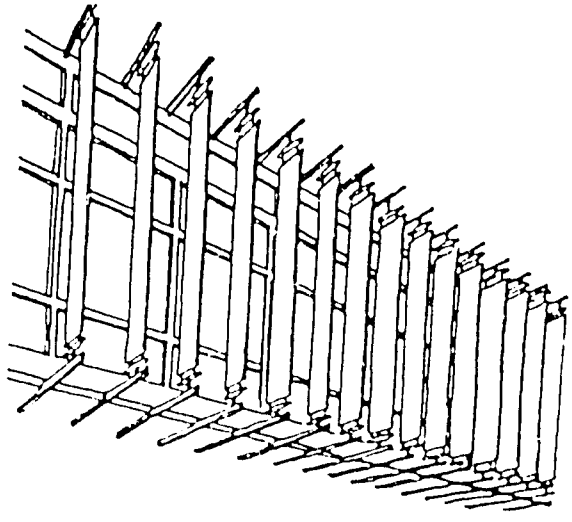
a) Conduction of energy - whenever there is a difference between the inside temperature and outside or ambient temperature.

b) Radiation of solar energy - both visible and invisible, through the transparent glazing.

The best control for conduction is the use of multiple glazings; the best solution for radiation is controllable shading or special glazing materials.



Horizontal Shading for South Orientation



Vertical Shading for East or West Orientations

EXHIBIT 3-15. Concepts for Solar Control of Glazing (CEC-5)

In a desert climate, it is important that all rooms have openable windows or operable vents, as there are days during a year when outside air is desired. Cross ventilation is an important source of comfort during the day in winter and at night during the beginning and and end of the summer. Operable windows can also be used to exhaust spent air from evaporative coolers. In most locations, especially in desert areas, double glazing not only significantly reduces heat flow, but also provides improved comfort with no operating expense.

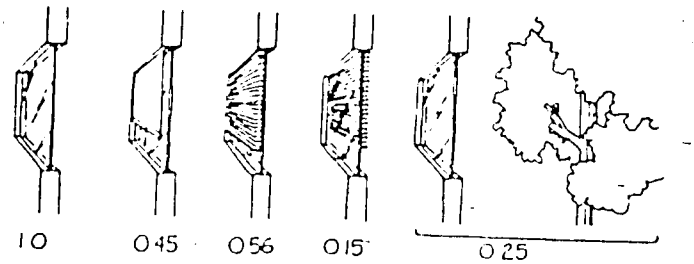
3.2.3.1 Shading Coefficient

The notion of shading coefficient is important in comparing the relative effectiveness of various shading devices. By definition, a single layer of clear, double-strength glass has a shading coefficient of 1.00. The shading coefficient for any other glazing system in combination with shading devices is the ratio of the solar heat gain through that system to the solar heat gain through the double-strength glass under identical solar conditions. Thus, solar gain through a glazing system is the product of its shading coefficient times the solar gain for clear, double-strength glass. Exhibit 3-16 lists some typical shading coefficients for various shading systems and conditions.

In locations with a severe or extreme cooling season, shading control is especially important. In most cases, more than one shading control device will be used on a particular window. Methods have been developed to estimate the overall shading coefficient of a system made up of several of these control devices. One much method obtained from the California Energy Commision's Energy Conservation Manual for New Residential Buildings (CEC-6) consists of the following procedure:

1. Determine the shading coefficient (SC) of one of the devices with the applicable glazing type (usually manufacturer's information).

2. Determine the SC of the other device in conjunction with single clear glazing (no mullions or framing). Be careful not to use the actual glazing used because this would result in double counting. (Note: A mullion is a slender vertical member placed between windows or doors.)



Shading Coefficients of Some Typical Window Systems

Window System	Shading Coefficient
1/8" DS Clear Unshaded Glass	1.00
w Inside dark roller shade completely drawn	0.80
w Inside dark venetian blind fully drawn	0.75
w Inside medium venetian blind fully drawn	0.65
w Dark-colored drapes fully drawn	0.58
w Average tree casting shade	0.60–0.50
w Inside white venetian blind fully drawn	0.56
w Inside white roller shade fully drawn	0.41
w Light-colored drapes fully drawn	0.40
w Outside vertical fixed fins on east/west sides	0.31
w Outside canvas awning	0.25
w Overhang, continuous on south side	0.25
w Dense tree casting shade	0.25–0.20
w Outside venetian blind	0.15
w Outside moveable horizontal or vertical louvers	0.15–0.10
Unshaded 1/4" Heat-Absorbing Glass (gray or other tints)	0.70–0.50
Unshaded 1/4" Reflective Glass	0.60–0.40
Unshaded Clear Glass Block	0.65

EXHIBIT 3-16. Shading Coefficients of Some Typical Window Systems

3. Calculate Combined SC

$(SC)_{comb}$ = $[0.25 * (SC)_{max}] + [0.75 * (SC)_{min}]$

$(SC)_{comb}$ = Calculated SC for combination of two shading devices in conjunction with the applicable glazing type.

$(SC)_{max}$ = Larger of the two SC's.

4. If there are more than two devices in use, repeat above steps using the combined SC determined in previous application of step 3 as result of step 1.

3.2.3.2 Special Glazings

Using different types of glass for different orientations is one acceptable method of solar control. Where reduction of heat gain is critical, heat-absorbing and heat-reflecting glass can help, especially on east and west facades. A reflective window film is more effective than an absorptive film, and the new low-e (low-emissivity) films are better than either type. A low-e coating transmits visible and near-infrared light energy, but reflects long wave energy. This means it will reflect heat from the outside in summer to lower cooling costs, and reflect heat back to the inside in winter, lowering heating costs.

Low-e coatings can be placed on film or glass. Vacuum sputtered low-e coatings, called soft-coats, must be protected from moisture and handling, so they must be installed in insulation units. The hard-coats are low-e coatings sprayed on molten glass as it comes off the float line. These are more durable than soft-coats and are unaffected by moisture and handling. In buildings where the cooling mode is dominant, the inner pane of glass is an insulated unit. Low-e glazings can save over 25 percent more in cooling costs than double-glazed reflective glass, even when placed on north facing windows.

Exhibits 3-17 and 3-18 illustrate and summarize the effect of special glazing used in various orientations on fenestration heat gain.

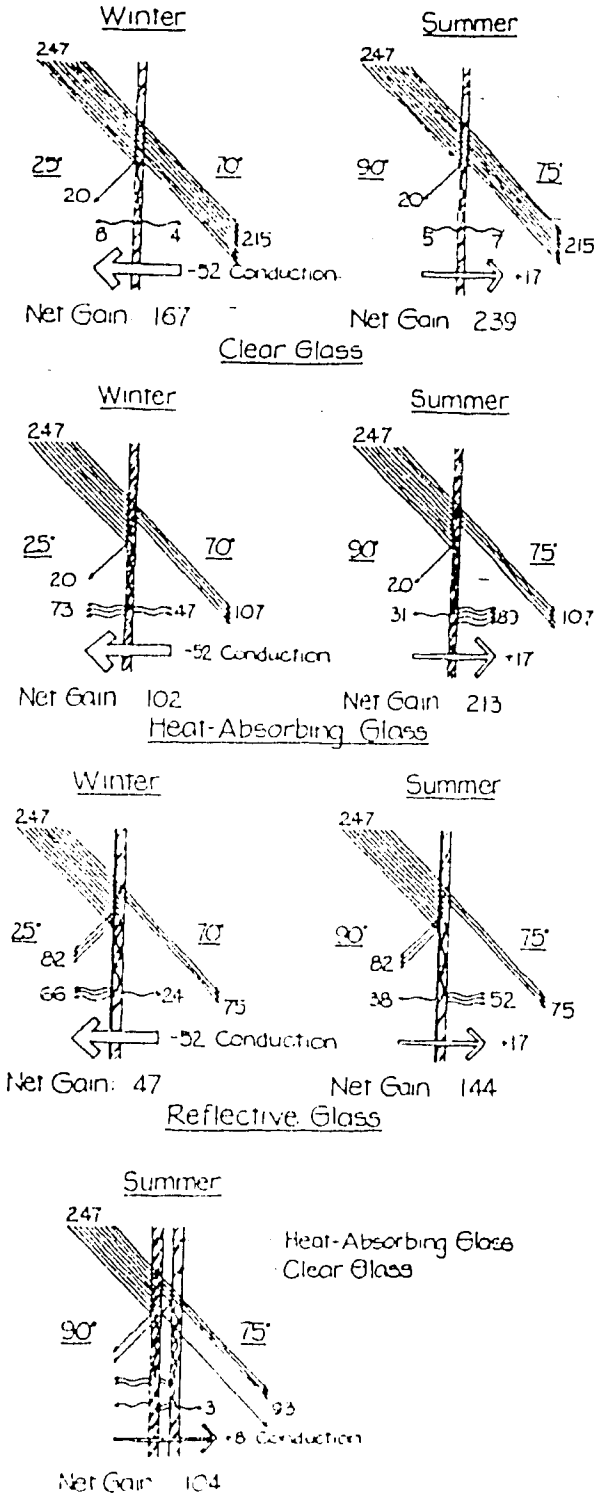


EXHIBIT 3-17. Summary of the Effects of Using Different Special Glazings and the Net/Heat Gain (CEC-5)

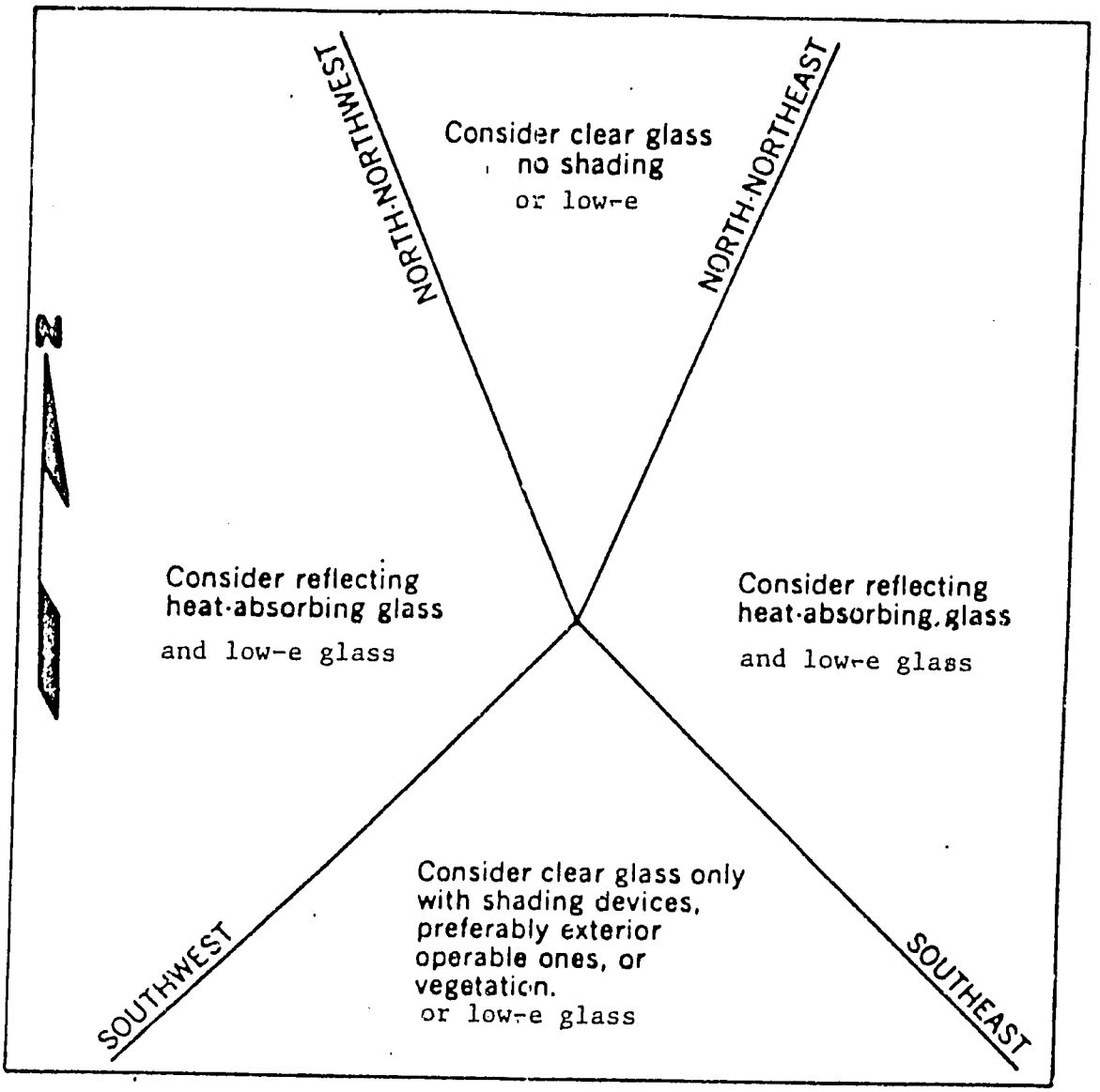


EXHIBIT 3-18. Considerations for Glass Types for Various Orientations of Windows (Approximations for Continental United States) (AND-2).

3.2.3.3 Factors to Consider

The important factors to consider in the use of special glazings include the following:

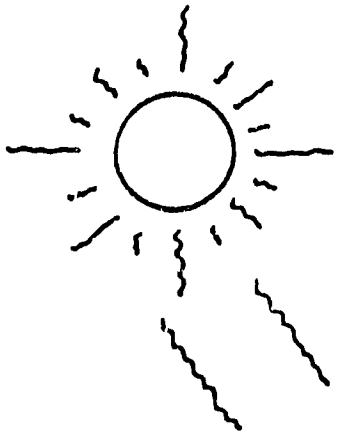
- Special glazing reduces solar heat gain. Although this can be an advantage in the summer, it can also be a disadvantage in the winter.

- Heat-absorbing and reflecting glass can be used for glare control on north, north-northeast, and north-northwest orientations. Little solar heat will be gained on south facades, except in latitudes south of 30°N.

- Heat-absorbing and reflecting glass usually should not be considered for south-facing windows except as a means of controlling glare or excluding winter solar heat (e.g., in large office buildings). The heat gain through south-facing glass can be relatively small in summer (as illustrated in Exhibit 3-18).

- Vegetation and operable shading devices are more practial and sensible solutions than heat-absorbing or reflecting glass for south, southeast, and southwest orientations. Shading devices are most effective on the exterior of the building; those between two layers of glass (such as mini-blinds) are the next most effective; and interior devices such as blinds, shades and draperies are least effective as they stop the sun's rays after they have penetrated the building (as illustrated in Exhibit 3-19). Even so, highly reflective devices are only slightly less effective on the inside than between the two layers of glass. That is, as a highly reflective device is effective anywhere it is placed, its location is not as important as the location of shading devices that are not reflective.

- Some advertisements for heat-absorbing and reflecting glass suggest that such products will reduce both the initial cost of air conditioning equipment and cost of equipment operation, especially as such costs affect energy consumption. However, the savings are usually obtained by comparing costs with those for all-glass buildings rather than with those for buildings already designed to conserve energy. Rarely is it mentioned that substantial savings could be achieved by switching to opaque, well-insulated walls with reduced glass areas areas on the east and west walls and to a design that allows the sun to penetrate through the south glass during the winter (if desired) with shading during the summer.



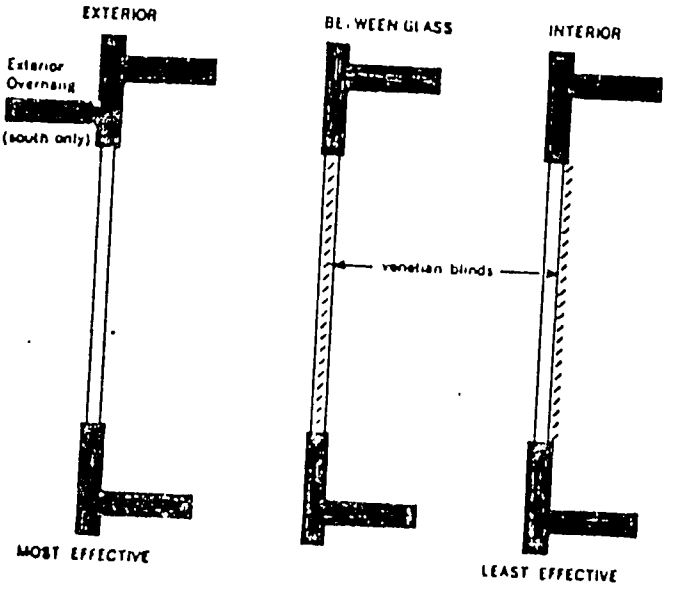


EXHIBIT 3-19. Possible Locations for Shading Devices (AND-2).

All building facades should not be identical in appearance. This is particularly true of buildings that use large areas of glass. Although there may economic, social and aesthetic reasons for building glass boxes, glass clearly has been misused as a design element.

3.2.3.4 Commercial Buildings

Large buildings which have small exterior wall and roof areas compared to a large amount of interior floor area often require air conditioning year round. This is because a tremendous amount of internal heat is generated from lights, applicances, equipment, and the activities of people. The use of glass that is shaded 12 months a year instead of only during the summer will be the most successful solution in such buildings. Every effort should be made to reduce the amount of heat that is produced by lights and machines and vent it before it flows to other rooms in the building. The most energy conscious designs for such buildings employ waste heat recovery systems that remove heat from overheated areas and deliver it to those spaces that need heat. Heat not immediately required may be stored for later retrieval. The dependance on artificial lighting can be reduced by using daylighting, by lowering lighting levels, or by placing light fixtures directly where light is needed (this is referred to as task lighting).

3.2.3.5 Radiant Barriers

Radiant barriers are becoming more popular in hot climates. They reduce radiant heat transfer by restricting the passage of the longest wave infrared (far-infrared) radiation for one surface to another. Radiant barriers composed of materials with low emissivities that are highly reflective, need an air space directly adjacent to them in order to be effective. Aluminum foil is the cheapest most effective barrier. It reflects 95 percent of the long wave energy that strikes it. Radiant barriers reduce the flow of heat into the building by lowering the temperature of the wall or ceiling outside the insulation or high mass material, before the heat can be conducted into interior spaces.

Radiant barriers are very effective on east and west walls. South facing walls benefit more from shading than radiant barriers in climates that also need winter heating, as the foil will reduce solar gains through the south wall in the winter. Radiant barriers in attics (above the insulation and below a vented air space created with furring strips) are very effective in hot climates.

Diminishing returns prohibit using more than one radiant barrier at a time. The first layer will block 95 percent of the radiant transfer, but the second layer will block only 95 percent of the 5 percent that wasn't reflected from the first layer.

Many products are available today that incorporate a layer of foil as a radiant barrier. Builder's foil is available in a wide range of strengths and costs. Cheaper foils can cost more in the end as they are more difficult to install. Fiberglass batt and rigid foams are available with foil faces. Structural sheating, composed of laminated cardboard layers, has foil on both sides. Exhibit 3-20 lists energy characteristics of some common building materials.

3.2.4 Convective Cooling

3.2.4.1 Overview

At temperatures below 33°C, the movement of air across the skin cools by drawing heat from the skin by means of convection and the evaporation of perspiration. Air movement up to 0.25 meters per second goes unnoticed. Over 1.0 meters per second, it becomes annoying. Movement above 1.2 meters per second adversely affects health and reduces indoor work efficiency (OLG-1).

The most straightforward method of convective cooling is not an innovation. It simply involves the admission of cool nighttime breezes into the house to drive out the warm air inside. A simple design is exemplified by the following:

Energy Characteristics of the Surfaces of Common Building Materials

	Solar Energy		Radiant Heat	
	Absorptance	Reflectance	Emittance (& Absorptance)	Reflectance
White-painted Walls	0.15	0.85	0.90	0.10
Green-painted Walls	0.50	0.50	0.90	0.10
Black-painted Walls	0.90	0.10	0.90	0.10
Green Roll Roofing	0.90	0.10	0.90	0.10
Red Brick	0.55	0.45	0.90	0.10
Concrete (fresh)	0.60	0.40	0.90	0.10
Asbestos Cement Board	0.60	0.40	0.95	0.05
Sheet Metal (Shiny)	0.20	0.80	0.20	0.80
Polished Aluminum	0.10	0.90	0.10	0.90

EXHIBIT 3-20. Energy Characteristics of the Surfaces of Common Building Materials (CEC-5)

- A high vent or open window on the leeward side of the building will let the hottest air near the ceiling escape away from the prevailing breezes.

- Cooler night air sweeping in through open vents on the windward side will replace this hot air and generate comfort.

The use and control of air movement to condition building interiors involves three processes--site selection, wind protection, and natural ventilation. Careful consideration of air movement will:

a) Determine the most suitable microclimate on the site for building location. (Most important areas with large topographical variations.)

b) Reduce heating loads by providing wind protection. (Reduces infiltration losses).

c) Allow cooling during periods of hot weather by the use of natural ventilation.

In many areas, natural ventilation has the potential of providing a large fraction of the cooling load. This is especially true in areas with large diurnal temperature swings; even if the days are very hot, comfort can be achieved through the use of ventilation cooling at night.

There are several parameters that are used to design a building that can utilize convective cooling with maximum efficiency. Relevant factors include building orientation and form, landscape elements, room and window orientation, and location and size of inlet and outlet vents.

A rectangular building with its long side facing the prevailing summer winds make it easier to naturaly ventilate all rooms. In addition, breaks in the roof level or a dropped plenum over halls will allow natural ventilation of rooms served by hallways. A simplified diagram of this design is provided as Exhibit 3-21.

Natural ventilation through buildings is also influenced by land planning. Cooling night breezes should not be blocked from entering buildings. Building shape, proper clustering of buildings, and other landscaping features such as vegetation and fences can enhance natural wind flow patterns (GUY). Unfortunately, vegetation or neighboring buildings can also block night-sky radiational cooling.

Room and window orientation are also very important factors. In order to provide overall room coverage, the following rules-of-thumb should be followed: (CEC-3)

1. If windows are on opposite sides, the room should be oriented askew to the prevailing wind direction.
2. If windows are on adjacent walls, the room should be oriented to face directly into the prevailing wind.

Air patterns within a room are largely determined by air inlet location and its relationship to the exterior surfaces of the building. Three examples of this are illustrated in Exhibit 3-22.

In Figure I of Exhibit 3-22, greater air pressure is created on the right side of the inlet and consequently directs air patterns to the left side of the room. Barriers such as a wing wall (figure II of Exhibit 3-22) negate the effect of air pressure on the right side of the inlet. As seen in Figure III of Exhibit 3-22, a 4" (10.2 cm) slot between the barrier and wall negates the effect of a barrier on the interior air pattern.

The velocity of the interior ventilation air is dependent upon the outlet size in relation to the inlet size. Examples of this are illustrated in Exhibit 3-23.

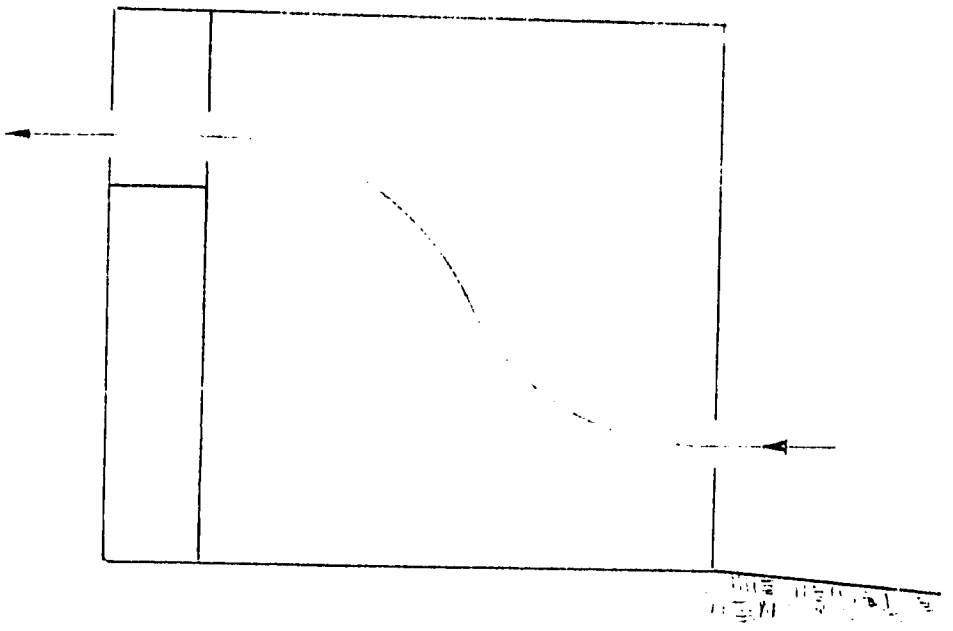


EXHIBIT 3-21. Simplified Diagram of Dropped Plenum Over a Hallway Used for Ventilation

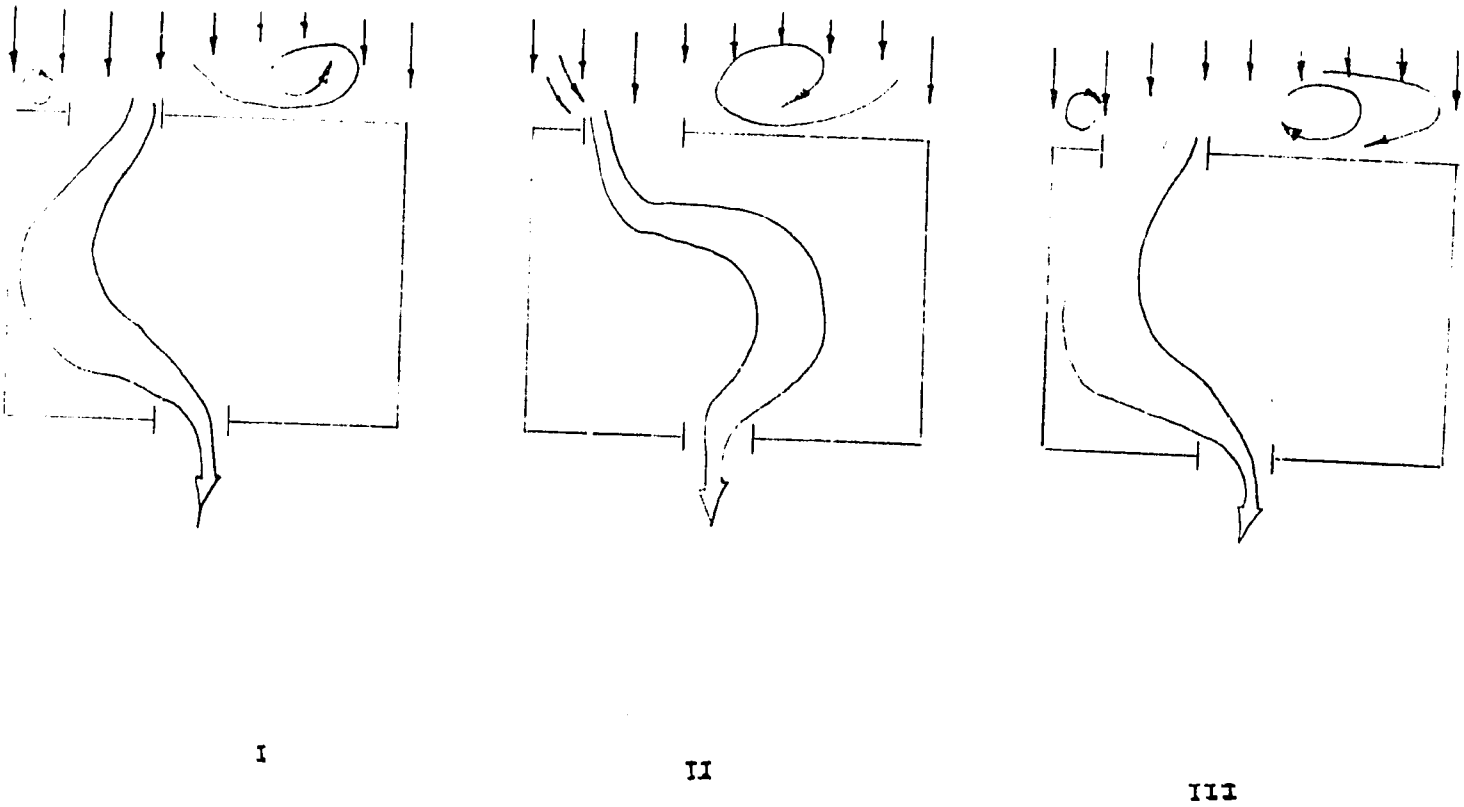
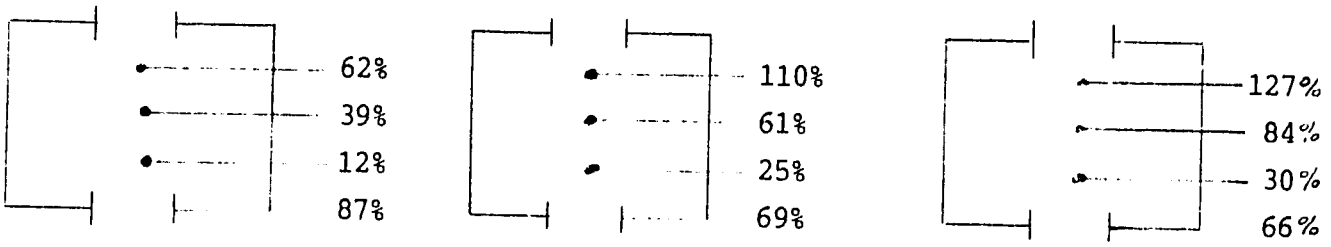


EXHIBIT 3-22. Three Examples of Air Flow Through a Room with Windows or Opposite Sides With and Without Wing Walls. (CEC-3)



2′ inlet 2′ outlet (.61 m)	2′ inlet 4′ outlet (.61m, 1.2m)	2′ inlet 6′ outlet (.61m, 1.8m)

EXHIBIT 3-23. Interior Air Speed as Percentage of Outdoor Air Speed.

3.2.4.2 Cross-Ventilation

The most common way to create air movement without using mechanical power is to open windows and allow natural breezes to blow into a building. This simple concept is often forgotten. Although an open window can admit dust, and in many cases, warm air, the cooling effect of merely opening a window should not be underestimated if done at the appropriate time of day or year. Proper window location can aid natural ventilation. Even if there are only light breezes at the site, natural convection can still be used to cool. As the coolest air outside a house is usually found on the north side (especially if this area is shaded by trees and/or shrubs), intake vents are best located as low as possible on the north wall. Air inlet locations also governs the airflow pattern in the building. An inlet window high in the wall will create an airflow above the living area. Lower openings will direct the air into and through the occupied area. The outlet location has almost no effect, but the cross-sectional area of the outlet should be as large as possible for maximum air speed--at least equal to the inlet area. This is because interior wind speed is largely determined by the relative size of the inlet opening(s). Ventilation is further enhanced if the outlet is located higher than the inlet. Window shape may be more important than position. Horizontal windows permit more airflow than square or vertical windows--especially if the wind strikes the opening at different angles. The ventilating efficiency of any opening is cut drastically by use of shades, horizontal louvers, and vertical louvers. "Deep" floor plans or room arrangements (e.g., two to three rooms stacked "in series", and very large, deep offices) are extremely difficult to ventilate with windows only.

3.2.4.3 Wing Walls

Cross-ventilation is not always possible. When openings can only be placed in one all of a room, wing walls can increase ventilation. A wing wall is a tall fin built perpendicularly to the exterior of the

building to one side of a window. When two windows are side by side, two wing walls are installed between the windows (as diagrammed in Exhibit 3-24). A positive pressure is created at one window and a negative pressure is created at the adjacent window.

3.2.4.4 Methods to Enhance Convective Cooling

There are two basic methods to make convective cooling designs more efficient: increase the air flow rate escaping the building or bring cooler air into the building. The cooling rate obtained by convective designs can be approximated by the following equation: (in English units) (CEC-2)

$$\text{Cooling Rate} = 1.08 * V * \triangle T$$

Where:

Cooling Rate	[=]	BTU/hour
V	[=]	Volume of air escaping, ft^3/min
$\triangle T$	[=]	Indoor/Outdoor temperaure difference, $^\circ F$

The table in Exhibit 3-25 gives sample values of cooling rates obtained for various air flow rates and indoor/outdoor temperature differences.

The addition of a turbine vent at the roof peak has been found to enhance air flow and improve the cooling rate. This is illustrated in Exhibit 3-26. Breezes flowing up and over the roof peak create an upward suction that draws out the interior air.

3.2.4.5 Stack Effect

The "stack" effect in buildings can induce ventilation even when there is no breeze. This effect occurs when warm air rises to the top of a tall space. A opening at the top natually exhausts the warm air while openings at floor level admit outdoor air to replace it. Natural ventilation can be further inducted by using belvederes, wind vanes, and wind scoops.

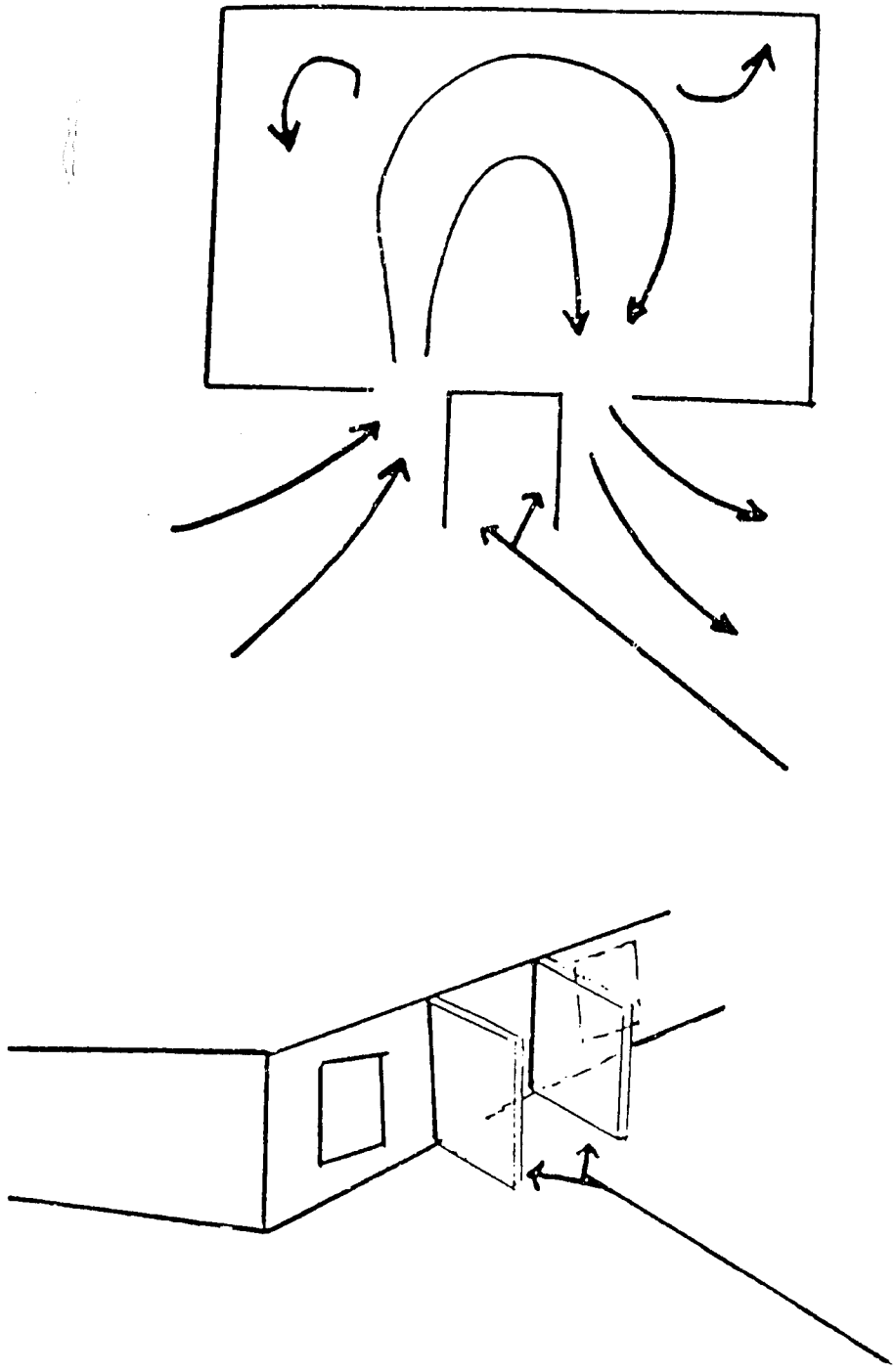
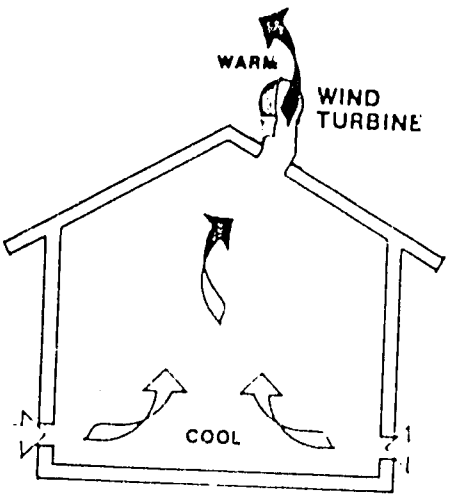


EXHIBIT 3-24. Wing Walls Increase Ventilation in Rooms That Can Have Openings Along One Wall Only.

(0.2928 BTU/hr = 1 W)

Air Flow, V	Temperature Difference, T			
	5°F	10°F	15°F	20°F
100 cfm	0.5	1.1	1.6	2.2
500 cfm	2.7	5.4	8.1	10.8
1000 cfm	5.4	10.8	16.2	21.6
2000 cfm	10.8	21.6	32.4	43.2

EXHIBIT 3-25. Convective Cooling Rates, (CEC-2) (Thousands of BTU's per hour)



Wind turbines can be used to increase the ventilation rate of rooms.

EXHIBIT 3-26. Illustration of Wind Turbine Increasing the Room Ventilation Rate (CEC-2)

3.2.4.5.1 Solar Chimney

As illustrated in Exhibit 3-27, a solar collector exhausts hot air to the outdoors and pulls house air through its plenum, creating natural ventilation. Many variations of this "solar chimney" have been used widely in the past and are being developed again today. In thermosiphoning wall collector designs, the collectors are vented to the outside during the hot summer weather and pull building air through to induce ventilation. This same technique can be integrated into the skin of a building by incorporating an air space just inside the outer surface of the wall. A reflective radiant barrier, such as building foil, is placed on the innermost surface of the air space, which is vented at the top and bottom. As the exterior wall is heated up by the sun, the foil reflects the heat. The air space acts like a thermosiphoning panel bringing its cool air at the bottom of the wall and exhausting it at the top. This eliminates the effect of the "sol-air" temperature, which is a combination of solar radiation and outside air temperature. This venting technique is most effective on west walls and sloping roofs, where the late afternoon sun contributes heavily to the cooling load.

3.2.4.5.2 Design for Stack-Effect

In designing for stack-effect ventilation, the greatest airflow is achieved by maximizing both the height of the stack and the temperature of air in the stack. The volumetric airflow is proportional to the inlet area and to the square root of the product of height times the average temperature difference as in the followng equation:

$$Q = 9.4 * A * [h (t_u - t_d)]^{1/2}$$

Where:

Q is cubic feet per minute of airflow

A is the area of the inlet(s) in square feet

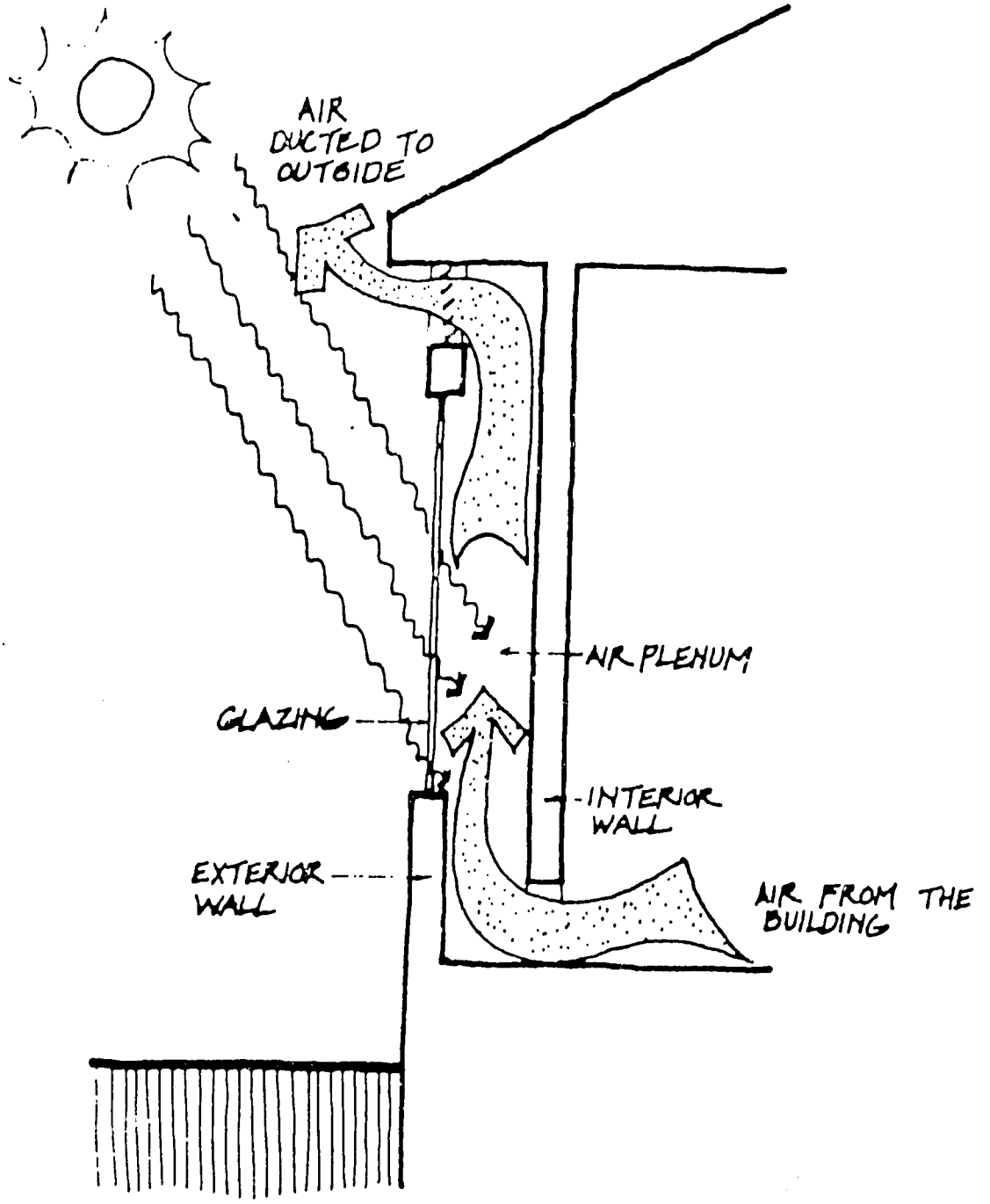


EXHIBIT 3-27. Solar Collector Wall Design Used to Induce Ventilation Through a Building (CRO) (PUT).

h is the height in feet between inlets and outlets

t_u is the average temperature of the air in the "chimney", in °F

t_d is the average temperature of the return air (normally just the ambient outside temperature, in °F)

(Conversion factor to convert ft^3/min to m^3/sec is $4.719*10^{-4}$)

Thus, it is better to add heat (presumably using a passive air-heating collector) at the bottom of the chimney or stack than at the middle. In this method the entire column of air in the chimney is hot, creating the buoyancy required to cause the air to flow.

3.2.4.5.3 Wind Tower

A common architectural feature in the Middle East is the wind tower (or wind catcher) that harnesses the prevailing summer winds to cool the building by first cooling the air and then circulating it through the building. Wind towers resemble chimneys with one end in the basement and the other end rising high above the roof.

When air in and around the wind tower changes temperature, its density also changes. The difference in density creates a draft that pulls air either up or down through the tower, depending upon the time of day and associated weather conditions. Doors open into the basement at the lower part of the tower and into a central hall on the main floor. By opening and closing these and other doors, airflow through different parts of the building is controlled.

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During the day the walls of the wind tower absorb solar heat. The thick walls of the tower provide sufficient heat storage and heat transfer to warm the air at the top of the tower. The warmer air is less dense; air pressure at the top of the tower is reduced, and an upward draft is created. Air in the building is drawn up through the tower, and cool outdoor air is pulled into the building through doors and windows on the north side. Stack ventilation may be improved by as much as 90 percent by adding an air-foil, delta-wing, or air shield cap. Tests have indicated that the addition of a turbine cap does little to improve air flow.

During calm days (with little or no wind), wind tower operation is the reverse of the chimney. In the morning the walls at the upper part of the tower are cooled from the previous night. The hot outside air cools and becomes denser when it comes in contact with the cool walls, and the cool air sinks down into the wind tower, creating a downdraft. The cool air enters the building at the bottom of the tower and room air exits through doors and window. When there is wind during the day, the rate of downdraft increases.

The cooling effect will increase if the operation of a wind tower is combined with evaporation of water from pools and fountains (see section 3.2.5, **Evaporative Cooling**).

Where hot dusty winds blow from one direction, and cooler winds blow from another, the openings in the wind tower are placed towards the cooler winds. In winter, if airflow through the tower is undesirable, the openings can be blocked or closed.

Wind towers are not perfect designs. Dust, insects, and birds can come into the tower from the top and enter the building through the openings at the bottom. Screens can block insects and birds, but the smaller the mesh, the more it will impede air flow in and through the tower. Dust pockets or shelves at the bottom of the tower do little to reduce the entry of dust. Taller towers draw less dust into their depths, and provide cooler air at higher velocities, but are more expensive to build and maintain.

Exhibits 3-28 and 3-29 illustrate examples of some wind towers in use in traditional Middle Eastern architecture.

3.2.4.6 Roof Shape

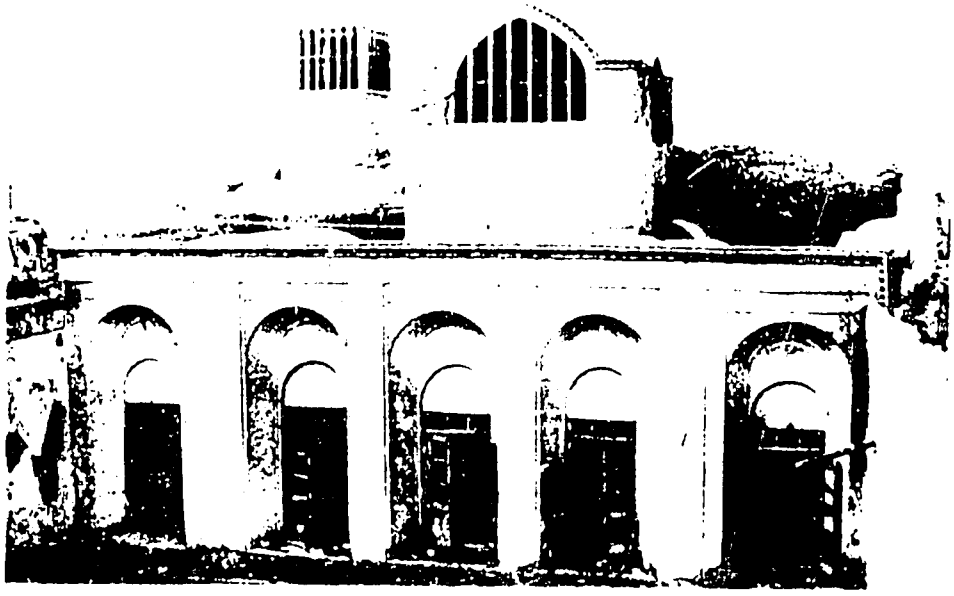
Cylindrical and dome roofs are popular in hot arid climates. Air velocity increases and air pressure decreases as air moves over a cylinder or sphere. Passing air carries away more heat from a dome than from a flat roof, but their effective areas -- that intercept solar radiation -- are about equal. Therefore, typical heat gain through a dome is less than that through a flat roof. An added bonus is that hot air inside the space stratifies in the dome, reducing the temperature difference between inside temperature and outside temperature, reducing heat gain further. One last bonus is that a hole through the apex of the dome, when the pressure is lowest, will allow hot air under the roof to vent. This hole should be blocked in climates where winter heat retention is desired.

The shape of a surface can also affect heat gain. Much of the heat that escapes from a hot surface is caused by the flow of air across it. Many surfaces can induce their own natural convection currents due to their shape. Exposure to breezes helps considerably to enhance this action.

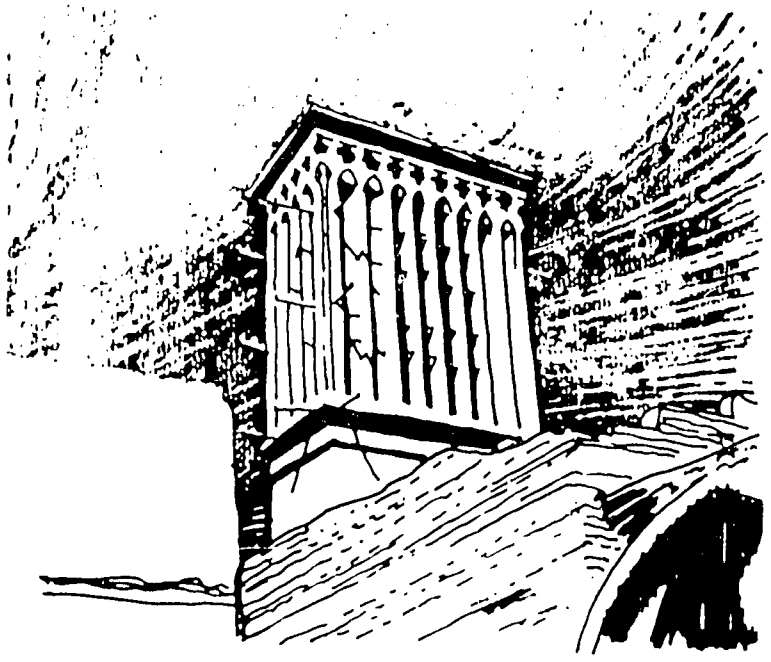
3.2.5 Evaporative Cooling

3.2.5.1 Overview

Evaporation of water can provide comfort conditions in buildings. When water evaporates it absorbs a large amount of heat from the surroundings, approximately 1000 BTU/lb (2323.7 kJ/kg) water evaporated. When the dry bulb temperature of air is higher than the wet bulb temperature, humidification will cool the air. The most familiar example of evaporative cooling is the cooling effect obtained when perspiration evaporates on the human skin. The cooling effect of moving air is enhanced if it contacts water prior to contacting with people.

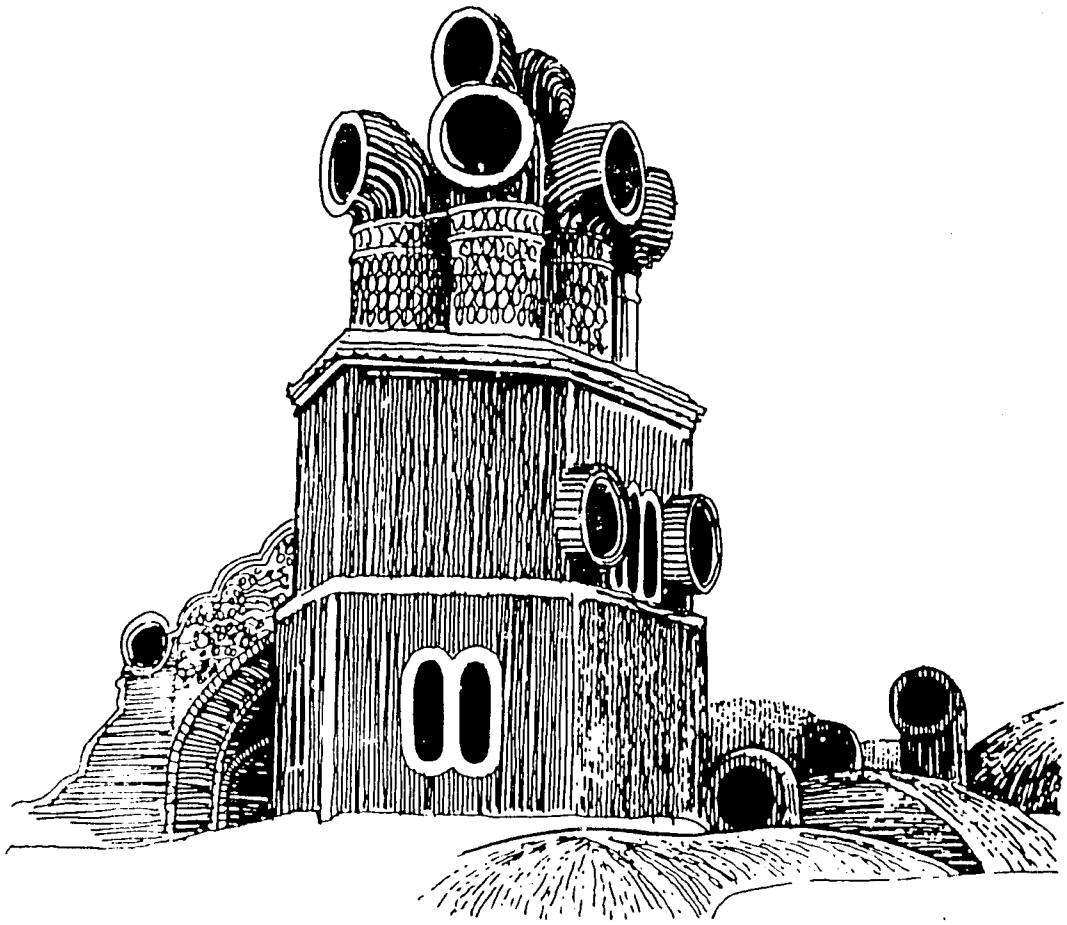


Wind tower and living quarters, second floor of aristocratic house, Sirjan, Iran.



Wind tower, Nain

EXHIBIT 3-28. Illustration of Middle Eastern Wind Tower (GOL)



Famous wind tower which catches wind from all directions. Sirjan.

EXHIBIT 3-29. Illustration of Middle Eastern Wind Tower

Although evaporating water into the air occurs in many ways, the most important methods are to ensure large water-to-air surface contact areas and to increase the turbulence or movement of water in contact with the air. For example, large shallow ponds increase surface contact. Moving streams and sprays from water fountains increase turbulence and surfce area. Air blowing across the surface of the water can do both.

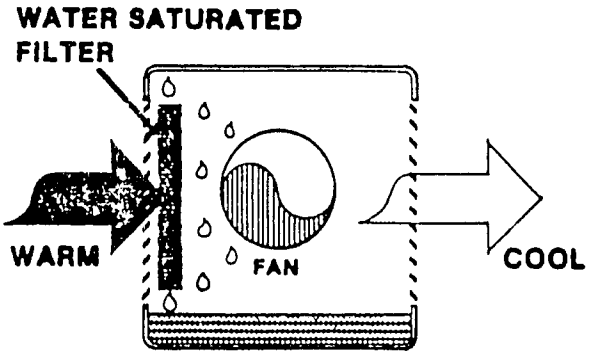
One method of cooling and humidifying air is to bring the warm outside air into the house through a moist filter or pad. (This is illustrated in Exhibit 3-30). If underground intake pipes are made from a porous material, the ground above them should be well-watered. Some evaporation will then occur at the inner surface of the pipe.

Mechanical evaporative coolers can increase the evaporative cooling effect, usually with an associated energy requirement substantially below conventional compression and absorption air conditioning.

Another evaporative cooling concept is the Cool Pool™ (CEC-2). An open pool of water is located above the living spaces on the north side of a building. This pool is shaded from the summer sun but exposed to the cool north sky day and night. It has been observed that the evaporation from the pool surfaces keeps the water in the pool 30°F (16.7°C) below ambient without the use of insulating panels. Natural convection currents bring the cool water into the house, producing a cooling effect. Exhibit 3-31 is a diagram of the Cool Pool™ design.

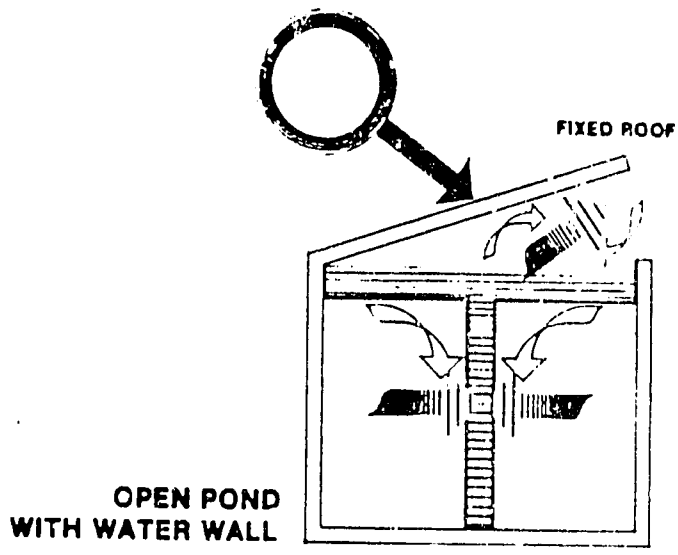
3.2.5.2 Roof Spray

Evaporative cooling can also keep roofs cool. Evaporative roof spray cooling has been used successfully in severe cooling climates. Flooded roofs, although inexpensive, are somewhat inefficient in hot dry climates. Shaded roof ponds can be very efficient at cooling the living space below if the ponds are open to night evaporation, even though the shading element virtually eliminates the radiational cooling. Exhibit 3-32 provides a schematic diagram of an operational roof spray.



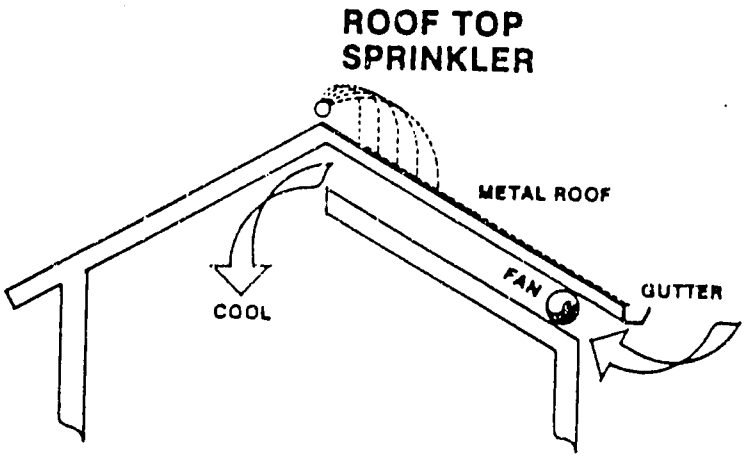
SWAMP COOLER

EXHIBIT 3-30. Evaporative Cooling Where Drier Outside Air is Drawn Through a Moist Pad. As Moisture is Picked Up by the Air, Heat is Absorbed by the Water. The Result is Cooler Air. (CEC-2)



Combined systems can be devised, as in this concept, to provide direct cooling for all interior spaces.

EXHIBIT 3-31. Illustration of Evaporative Cooling Concept Called "Cool Pool" Using a Water Wall and Pool of Water Above the Ceiling and Below the Roof (CEC-2)



Combined radiative and evaporative cooling can be integrated to increase the rate of cooling.

EXHIBIT 3-32. Illustration of Using Combined Radiative and Evaporative Cooling (CEC-2)

The sprayed water performs two functions: it protects the roof materials from ultraviolet damage, and it cools the roof by evaporation of water. The most important effect is the evaporation of water. For an evaporation rate of 0.254 to 0.381 meters per month, a cooling rate averaging between 1.3 to 2 MJ/m^2 per day can be obtained(SEL).

Wind is a primary factor in evaporation rate. Wind flows across roof ponds should, if possible, be enhanced. Only crude calculations of evaporative cooling potential are possible because of limited data on wind speed. However, where wind velocity is known, rough approximations of evaporative cooling effects are possible.

Some problems associated with evaporative cooling include insect and plant growth and a buildup of mineral compounds, such as lime, on evaporative surfaces.

Water sprays can be effective in preventing temperature buildup on rooftops during hot summer days (YEL-2). For example, under intense sunshine, spraying horizontal roofs approximately 40 seconds out of each minute maintains roof surface temperature within 15°C of the ambient dry bulb temperature. During early morning and afternoon hours, spraying reduces roof temperatures well below the ambient dry bulb temperature to within a few degrees of the wet bulb temperature. Approximately 1.46 kilograms of water per square meter of roof surface area is needed to accomplish this. Assuming that the power required to pump the spray must be charged against the cooling process and that a water pressure of 0.7 Kg/cm^2 is needed to enable the sprays to function properly, approximately 7.46 watts of power will be required per 93 square meters of roof area. The resultant cooling effect is approximately 88,000 watts (YEL-2).

With all evaporative cooling methods, the following guidelines must be kept in mind:

1. Encourage maximum air flow past exposed water.

2. Fresh air must be continually available to replace the humid air being built up near or over the water. If this is not done, air will quickly become saturated with moisture, and evaporation rates and cooling rates will decline rapidly.

3. Edges, lips, and other portions of buildings that obstruct prevailing winds away from the water surface should be avoided.

3.2.6 Radiative Cooling

3.2.6.1 Overview

A constant exchange of energy in the form of thermal radition occurs between objects that can "see" each other. Terrestrial surfaces having a given temperature radiate energy to anything that is colder. A net energy transfer occurs from the warmer object to the cooler object. The earth, for example, radiates heat to clear night skies that are very cold even during hot weather. The northern sky can also be quite cool during the day. This radiation to the sky primarily has wavelengths between 6 and 16 microns (BUD). Radiant energy will travel until it strikes a nontransparent barrier that absorbs thermal radiation. In sky or atmosphere, the main absorbent barrier is water vapor.

One of the best sources of engineering data and analyses of radiative cooling is "Atmospheric Radiation Near the Surface of the Ground: A Summary for Engineers" (BLI). Exhibit 3-33 illustrates the net radiative exchange factor (R), the net radiative loss rate, from an exposed, thermally black, horizontal surface at air temperature. It provides estimates of heat (radiation) loss rates from a horizontal surface to the sky. To use the graph, determine any two of three primary parameters: air temperature, humidity level, and dewpoint. Note that, from the graph, the heat loss rate (cooling effect) is usually from 47 to 95 W/m^2.

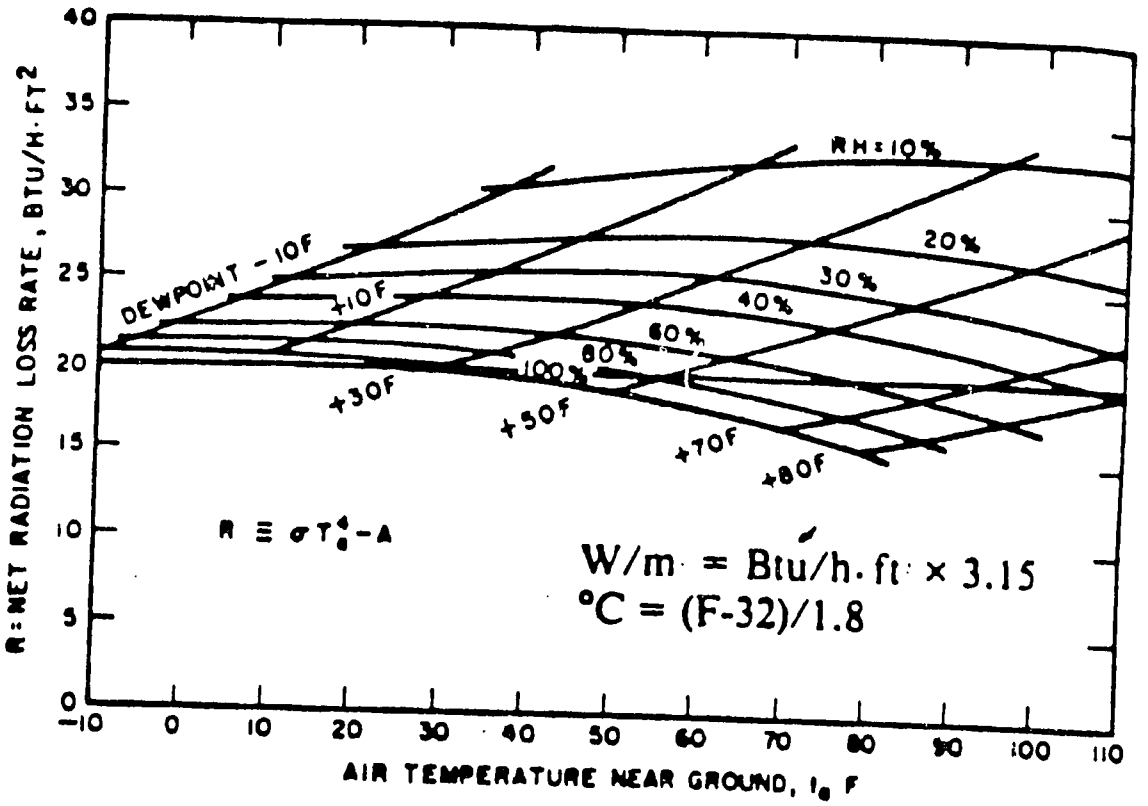


EXHIBIT 3-33. Typical Values of Radiation Loss From Horizontal Surfaces to the Sky at Sea Level (BLI).

3.2.6.2 Night Sky

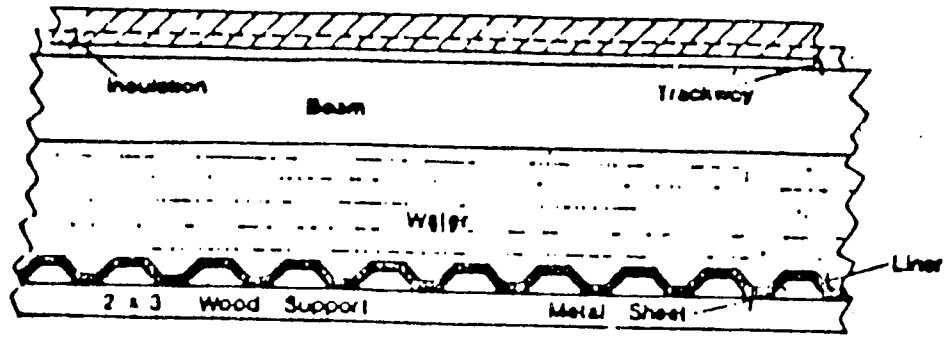
Most radiation to the sky occurs at night. The average temperature of the night sky typically ranges from 10°F to 50°F (5.6° to 27.8°) lower than air temperature near the ground; heat is always radiated from the building to the sky. The amount of radiation varies from 100 percent possible directly overhead at the zenith to virtually none at the horizon. The most effective radiant cooling surface is horizontal. Obstructions such as trees, walls, and adjacent buildings replace night sky cooling because they block radiation to the night sky (BAI).

An unobstructed vertical surface yields about 40 percent of the radiant cooling effect of a horizontal surface. For additional infomration on radiative cooling see the following references: (ABR), (BAI, (BAR), (BRO), (DUB), (GEI), (KEL), (KNO), (NEW), (PIT), (PLE), (REI), (SEL).

During a 10-hour night, the total cooling effect is between 1,700 and 3,400 KJ/M^2. This range holds true in many climates, making night radiant cooling widely applicable. However, it is far less effective in humid climates where the dewpoint temperature is relatively high. Cloud cover seriously interferes with effective cooling performance by absorbing thermal radiation. Radiative cooling effects in such climates have yet to be substantiated. To be effective, the radiating surface must be carefully protected from the warming effects of breezes. Lower effective sky temperature and greater heat sink effect will be direct results of low relative humidity in the night air.

3.2.6.3 Roof Ponds

The most common acknowledged radiative cooling concept was first developd by John Yellott and Harold Hay in the United States. Hay continued the development of roof ponds with water contained in black plastic bags. (See further discussions of the heating side of these concepts in Section 3.3.3.) The water is cooled by nocturnal radiation. During the day, the ponds are shaded by sliding panels above them. (This is illustrated in Exhibit 3-34).



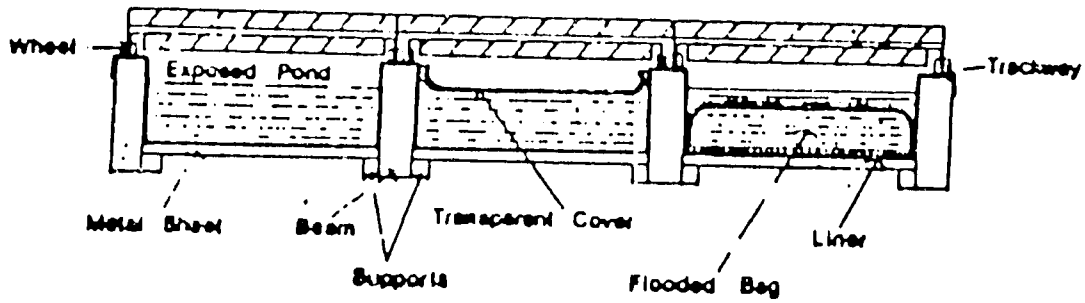


EXHIBIT 3-34. Cross-section of Different Types of Ceiling Ponds

Water in the pond cools the house by absorbing interior heat through the metal ceiling from the living space. The bags can be flooded with water to provide substantial additional cooling by evaporation. With only slight inputs of mechanical power, 6.8 MJ/m^2 to 14.8 MJ/m^2 can be dissipated skyward during a summer night through a combination of radiation and evaporation (ROB).

This system has successfully and comfortably provided 100 percent cooling for a 102 square meter house in the southwestern United States. Annual temperature profiles, inside and outside, are provided in Exhibit 3-35 for an earlier prototype having similar preformance characteristics.

Exhibits 3-36 through 3-38 illustrate three examples of design concepts using radiative cooling. Exhibit 3-36 provides a relevant description of a house in the southwestern United States having a radiant cooling system that is a form of a roof pond system. The percentage of roof covered by the system is smaller, and the sliding insulation panels are replaced by a hydraulicaly powered hinged panel. Even during hottest weather, the air temperature in this house has not exceeded 78°F (25.6°C).

The "Cool Pool" concept, as shown in Exhibit 3-37, was developed and tested by Living Systems in California, USA. The roof pond radiates its heat to the sky. The coolest water settles down into the radiant wall panel, cooling the interior of the house.

3.2.6.4 Multi-Story

Another U.S. designer used a thermosiphoning cool slab concept (as indicated in Exhibit 3-38). Locating the tank on the ground level facilitates maintenance. A modification of this concept is a nocturnal air cooling system being developed for integration into the structure of a building. The heat dissipator in this system is an oversized sill inclined 45° to the sky with a ducted metal plate and a selective cold-body surface coating (as illustrated in Exhibit 3-39). The warm

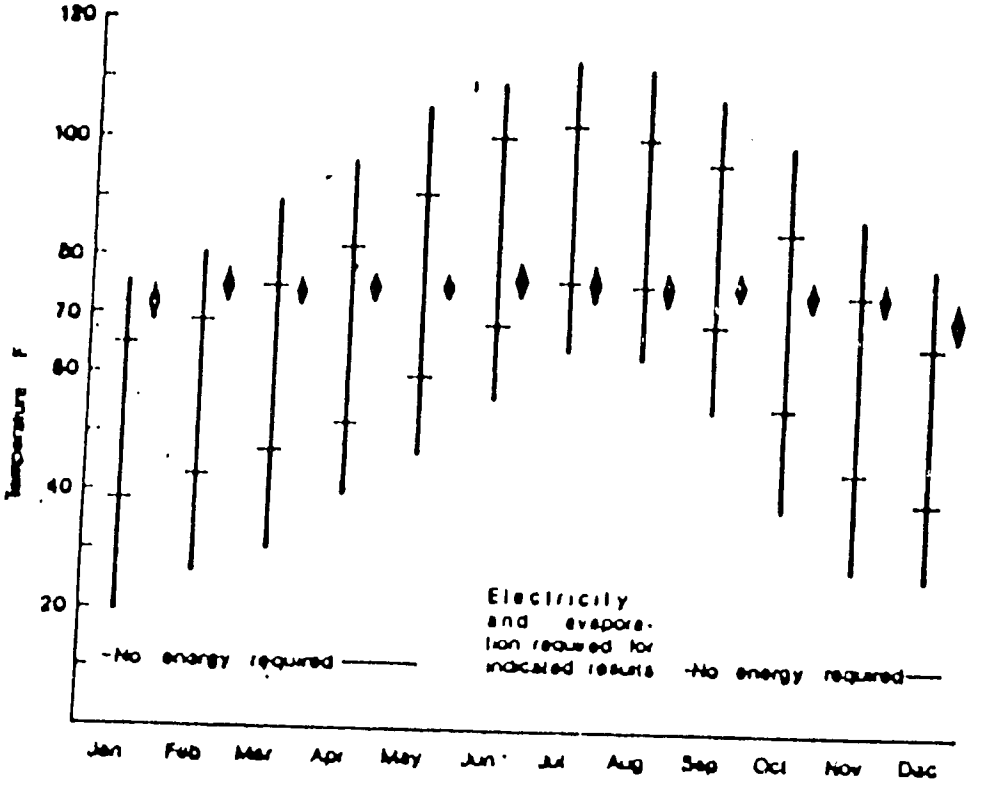
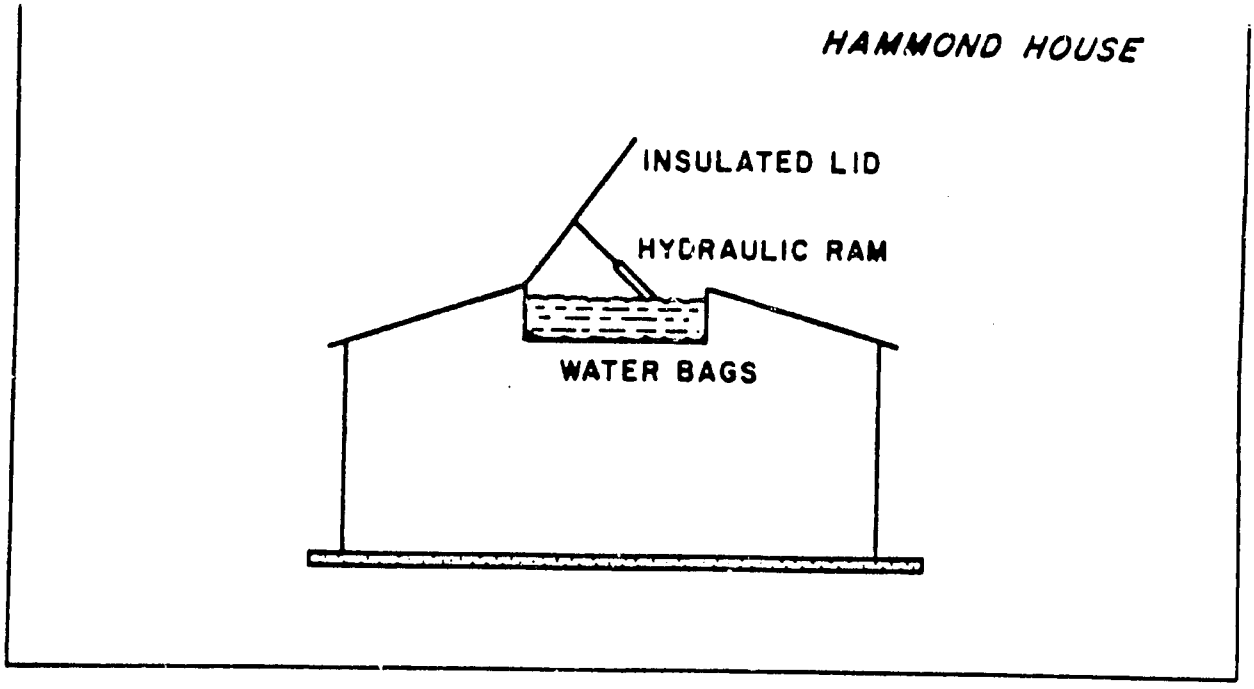


EXHIBIT 3-35. Profile of Inside and Outside Air Temperature of Southwestern United States Home Using Roof Ponds (YEL-3).



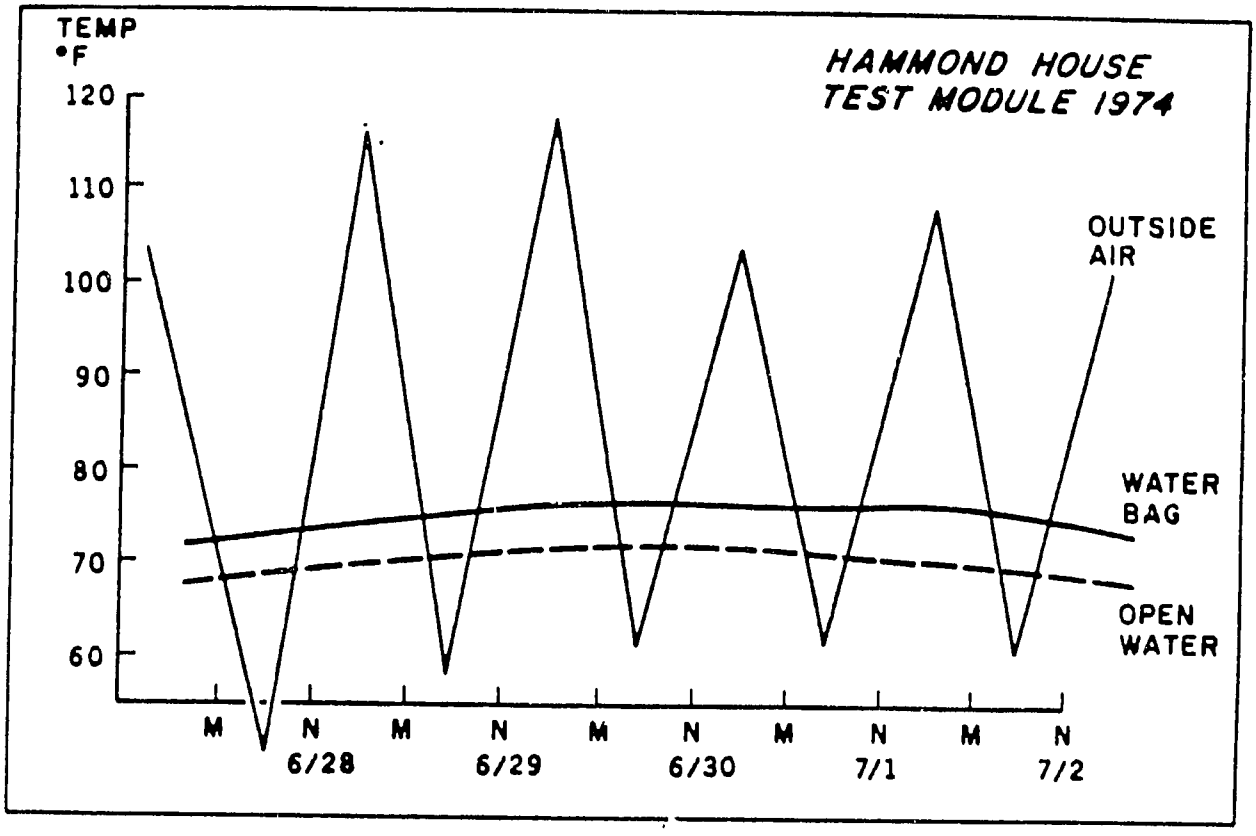
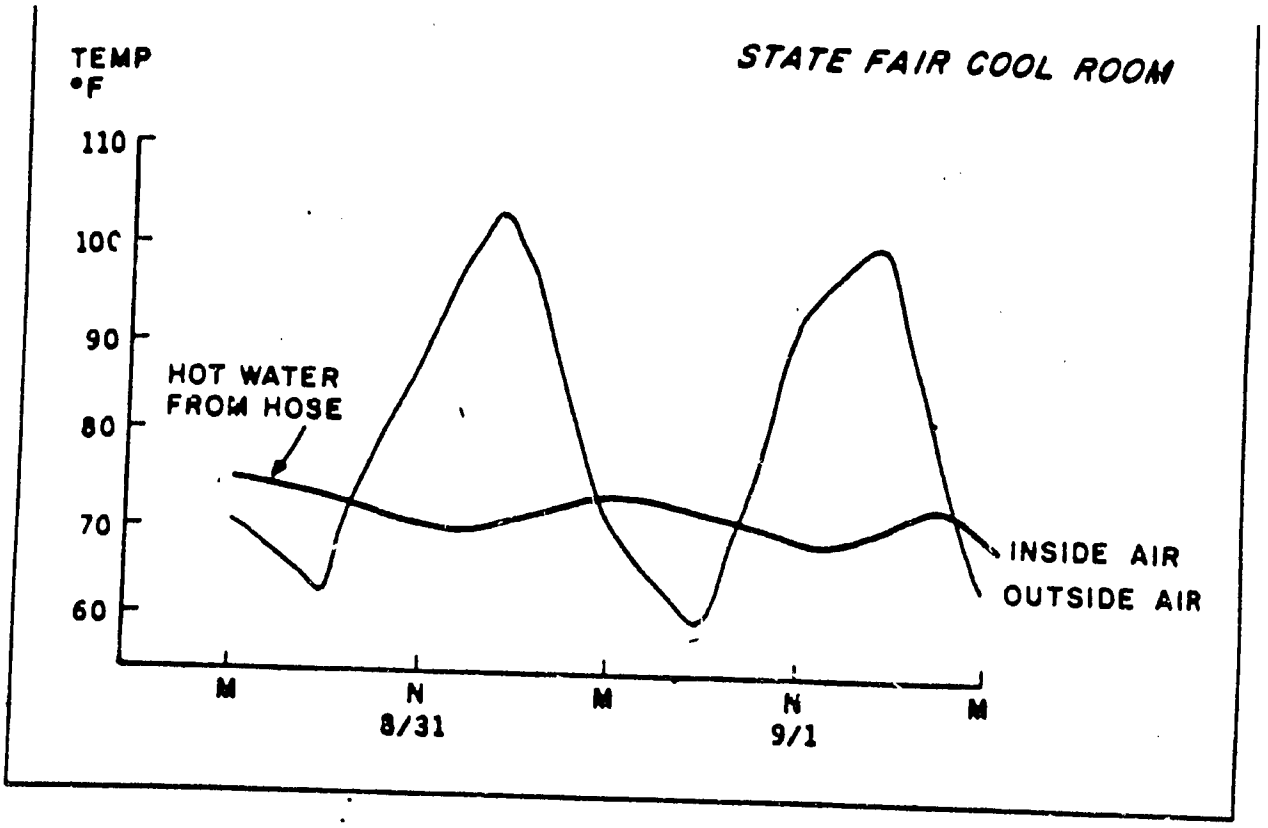


EXHIBIT 3-36. Hinged Roof Pond on Hammond House, California, U.S.A. and Its Performance in Maintaining Indoor Temperature



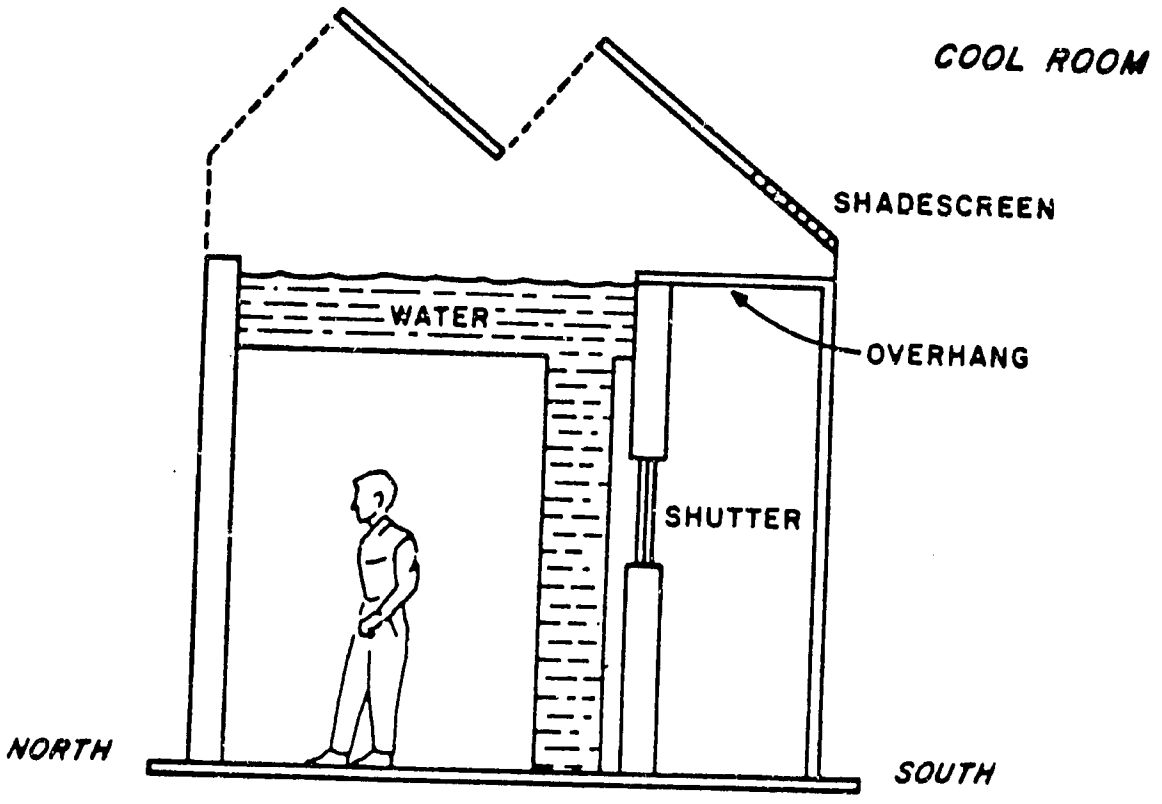


EXHIBIT 3-37. The Cool Pool Concept by Living Systems

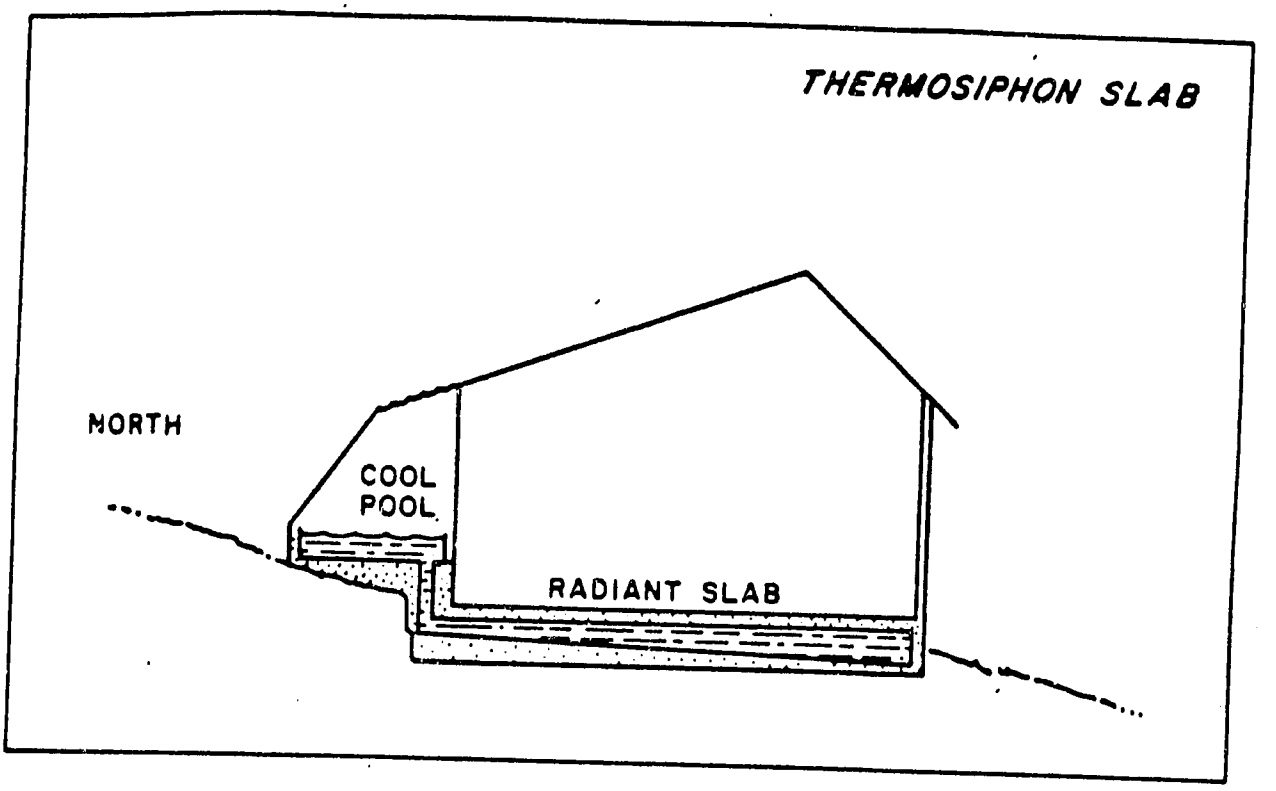


EXHIBIT 3-38. Thermosiphoning Cool Slab Concept

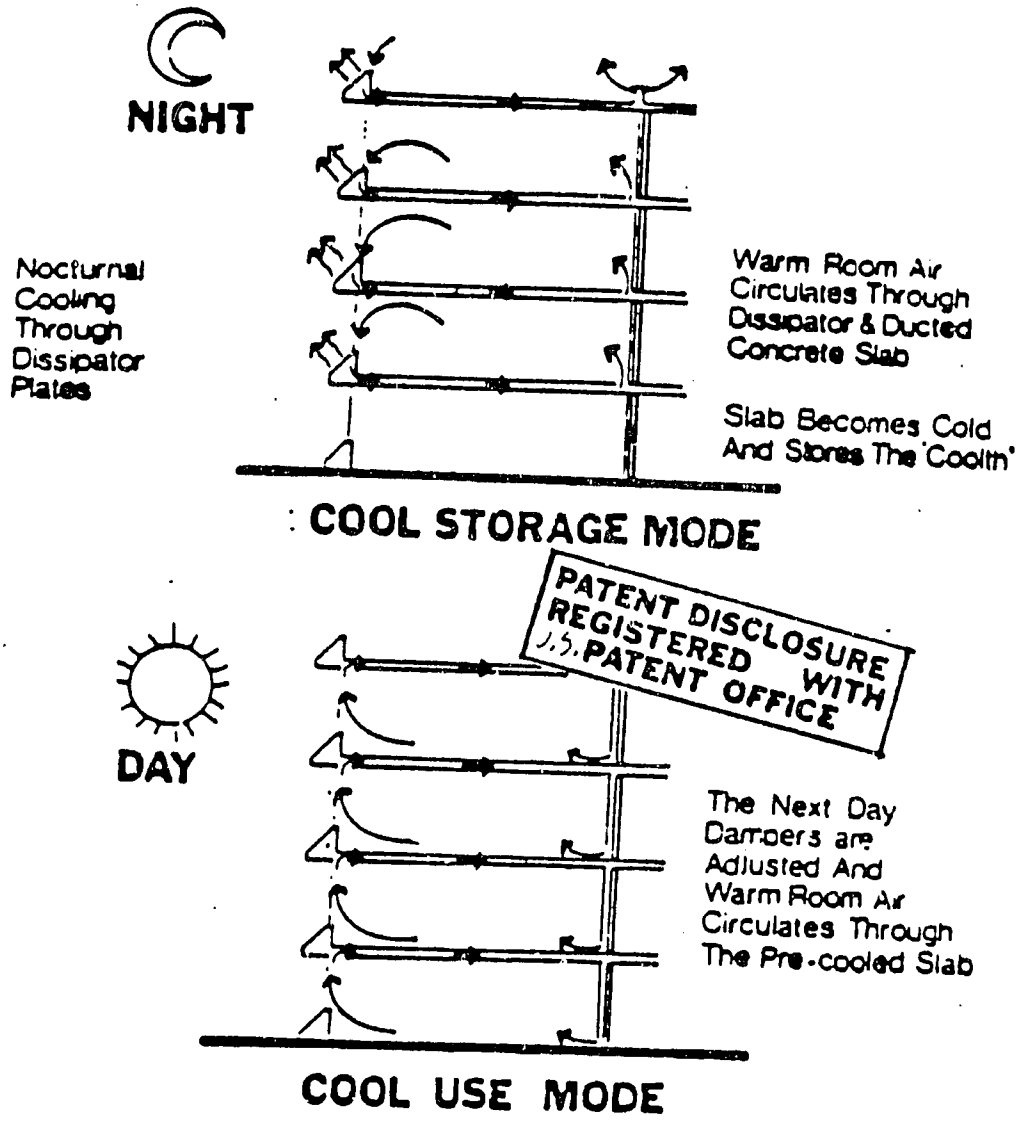


EXHIBIT 3-39. A Nocturnal Air Cooling System for Multi-story Buildings (PIN).

roof air is ducted through the heat dissipator when it is cooled. From there, it passes through ducts in a concrete floor slab that "stores" the coolness. Airflow can be enhanced by adding fans. This system can be easily integrated into multi-story construction. With modifications, solar heating could also be included.

3.2.7 Ground Cooling

As the ground is nearly always cooler than the air during the cooling season, the more a building is in contact with the ground, the cooler the building will be. Situating a building below grade or into the side of a hill is the easiest way to obtain more ground contact.

3.2.7.1 Berming

Berming is a term for filling earth as high as possible or covering buildings with earth or sod. High levels of comfort and serene quiet usually accompany well-designed bermed housing. Reducing the temperature of the ground in direct contact with the building will increase the cooling effect. One method to reduce ground temperature is to provide shading from direct sunlight which will then reduce surface soil temperatures. Horizontal insulation below the soil's surface will also reduce ground temperatures.

Undergrounding housing in cold climates requires well-insulated walls in contact with the ground. Insulation and special weatherproofing techniques keep the interior surfaces of the walls warm and dry. In hot climates, the walls in contact with the earth should remain uninsulated. The cool interior surface will tend to be damp from condensation, especially in humid climates. Particular care must be taken to waterproof the surface of the wall which is in contact with the soil. A 40 percent cooling load reduction is possible with ground "coupling" in desert climates because of the lower infiltration rate and slower conductive loss through the walls and floor.

3.2.7.2 Earth Tubes

Earth tubes are not well suited to hot climates because the soil temperatures are too warm and moisture content of the soil is too low. The length of tube required to conduct heat from the outside air to the soil, and the required depth to which the tubes would be buried to find cool soil, are prohibitive. Even in more moderate climates, earth tubes are seldom used because they can be difficult to design and install because they can be expensive.

3.2.8 Thermal Mass

3.2.8.1 Overview

Thermal mass in buildings can be advantageous in locations where nighttime temperatures drop below comfort levels. Such temperatures below the comfort range are often called "temperatures of opportunity". The cool air of late night and early morning air can be circulated by mechanical means or via natural convection through a building. The coolness is "stored" in thermal mass for use during the day. Mechanical systems that use outdoor air for comfort purposes are often termed "economizer cycles".

In arid regions, courtyards that shade residents are common. The thick masonry walls of such courtyards help dampen diurnal temperature swings, reducing their impact on interior spaces. The courtyard is open to the sky, surrounded by tall high-mass walls. Most of the rooms open onto the courtyard, where vegetation and fountains or pools evaporatively cool the shaded space. Spaces for use during summer are oriented to the north so they are always shaded. Water sprinkled onto the floor of the courtyard adds to the evaporative cooling of the pool and helps keep down dust.

An alternative to utilization of a thermal mass inside a building is mechanical cooling of a rock storage bed by a fan circulating night air through the rock bed. During the day, room air is circulated through the cooled rock bed and provides a cooling effect for the building.

3.2.8.2 Convective Coupling

In a medium-to-high mass building, the building can be "closed" during the day, allowing the thermal mass to absorb heat from incident solar radiation. At night, when the outside air temperature drops below the inside air temperature, the building can be "opened" to ventilation, using natural or forced convection to flush out the warm interior air and also to cool the mass for the next day's cycle. To increase night cooling, the building designer should try to maximize the surface area of the interior mass, increase the surface heat transfer coefficient, and increase the conductivity of the mass and consequently its heat capacity.

Where mean daily temperatures drop to within a range from 16°C to 18°C, nighttime ventilation combined with a maintained integral thermal mass should be seriously considered for implementation.

3.2.8.3 Peak Load Reduction

Natural cooling and natural energy storage in the mass of a given building can significantly reduce peak cooling loads and therefore lower the need for new power plants. Thermal mass can absorb heat during the day, producing a thermal lag and delaying the need for cooling until after the peak demand period in the afternoon. During later hours, required cooling could be delivered at lower usage or consumption rates, reducing required equipment size.

Other methods of reducing cooling loads can also reduce peak loads. Natural cooling systems that incorporate thermal mass, such as roof pond concepts, can be integrated with offpeak cooling systems. In general, if the required mechanical equipment is operated at night to "store" cooling for use during the day, the cooling equipment operates more efficiently and consumes minimal or no electrical wattage during peak hours.

3.2.8.4 Large Buildings

A, with passive solar heating, passive cooling need not be limited to residential structures. The first step toward facilitating the compatibility of large buildings with passive cooling is to decrease the cooling load of the building. In many cases, major savings can be realized with natural lighting and natural ventilation by increasing the exterior surface area of the building. Proper design of the increased external wall area with regard to thermal considerations (by using high levels of insulation and thermally efficient glazing systems) can compensate for any unfavorable gain or loss of heat. The potential annual energy savings that can be realized from the integration of natural lighting with winter solar heat gain and summer natural ventilaton should not be underestimated.

Passive cooling methods present several challenges when applied to large buildings. For example, it is difficult to provide sufficient amounts of airlfow through the building during nighttime ventilation. In addition, large commercial office buildings are often referred to as "load dominated" as opposed to "skin dominated". Most of the energy consumption of large buildings is used to remove heat generated inside the building by lighting, people, and equipment. Because these buildings share common walls, the reduced outside exposure results in poorer natural lighting from daylight and natural ventilation.

The larger the building, the more likely it is that fans will be required to circulate cool night air. The electrical consumption of these relatively large fans must not exceed that of conventional mechanical cooling systems. Analytical methods to determine the net cooling effect of night air ventilation on a seasonal basis still need to be developed. However, estimates can be made.

As a general guideline for building design in hot dry climates, an air circulation rate of 0.0051 m^3 per square meter of floor area can provide about 0.397 MJ of cooling per day per square meter of floor area. Building mass should be about 195.3 kg per square meter of floor area, with an exposed surface area of about 1.75 m^2 per square meter of floor area. Larger airflows are desirable. Airflows of 0.015 to 0.02 m^3/s per square meter or larger, in combination with interior building mass of 366 to 732 kg per square meter of floor area, can provide about 1.14 MJ of cooling per day per square meter of floor area. Similar cooling effects of the building mass in other areas of the country will occur where the minimum daily temperature is 15.5°C to 18.3°C or below during most of the cooling season. For this same temperature range, the building mass will be cooled to between 18.3°C and 21.1°C (ROB).

3.2.9 New Technologies

Heat exchangers with heat pipes, desiccant cooling, phase-change heat storage, and lightweight radiators are just a few of the many techniques being investigated for passive and hybrid cooling. As electrical costs rise and the study of passive cooling becomes more important, both new and traditional cooling methods (abandoned with the advent of cheap energy) will become a part of the total design process.

Traditional methods are being rejudged. The formation of ice during the winter, stored underground for use as a source for summer cooling, was once popular in hot arid climates. Long shallow trenches oriented east-west were protected from the sun with high adobe walls to the south, east, and west. Severe heat loss to the night sky in winter would allow the water in the trenches to freeze. The ice was then moved inside for summer use. This method, and the storage of cold water underground in deep cisterns, had been abandoned in the Middle East for health reasons. But both methods are being reactivated for utilizing the ice and cold water for cooling only, and not also for human consumption.

3.3 Design Methods Which Emphasize Heating

The principal on-site energy sources that can be used to heat buildings are the following:

1. Solar Radiation, both direct and diffuse.
2. Outside Air, usually when the ambient temperature is greater than 23.9°C.
3. Internal Metabolism (from people, appliances, and electric lighting).

A properly designed passive structure will use these heat sources plus the heat sinks discussed previously to condition the building interior year round. Passive designs which emphasize heating are often classified as either direct gain, indirect gain, or isolated gain, depending on the means by which the solar energy is collected and distributed.

The terms direct, indirect, and isolated gain were defined in section 2.2, Passive Technology Fundamentals. For the sake of clarity, condensed definitions follow.

Direct gain:	Thermal transfer between heat source and heat sinks occurs inside the interior of the building.
Indirect gain:	Thermal transfer occurs at the building envelope. The building envelope serves as a thermal barrier between the exterior heat sources and heat sinks and the building interior.
Isolated gain:	Thermal transfer occurs outside of the building envelope, separate from the interior conditioned space of the building.

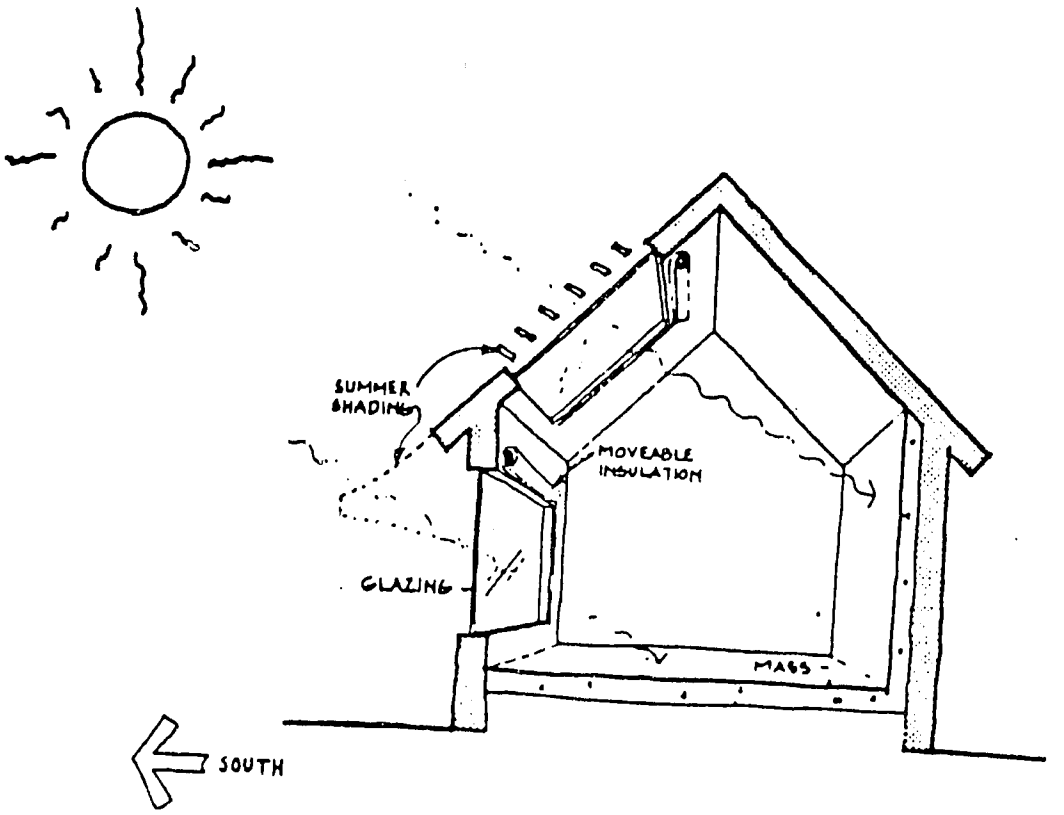
3.3.1 Direct Gain

3.3.1.1 Definition

In direct gain systems, sunlight is admitted through south-facing glazing (windows) into living space inside the house. Exhibits 3-40, 3-41, and 3-42 illustrate examples of direct gain passive designs. Thermal mass usually prevents overheating and excessive temperture swings by utilizing thermal storage characteristics of the mass (i.e., high heat capacity, density, thermal conductivity). This mass may be in the form of masonry materials, containers of water, or other massive building materials. For modest direct gain apertures, the mass of the existing construction materials in the building and its contents may be sufficient.

3.3.1.2 Glazing

Standard manufactured windows and skylights or any translucent or transparent glazing systems incorporated into the south wall or roof of a building may be used as the solar collector in direct gain systems. To prevent heat loss associated with windows (such as conduction or infiltration), glazing areas associated with direct gain systems must 1) be fitted with moveable insulation for use at night and during cloudy periods, 2) be double glazed, or 3) use one of the new low-emissivity glazings. Moveable insulation may be in the form of a shutter, curtain, or shade, which are operated automatically or manually from the inside of the house (as illustrated in Exhibit 3-43). The material of the moveable insulation should have an R-value of at least 4 (English units), and the bottom and sides of the installed insulation must have an airtight seal to prevent air leakage. New "high performance" glazing with low emittance metal oxide coatings offer performance equal to triple glazing at a lower cost. Exhibit 3-44 summarizes typical advantages and disadvantages of various glazing materials.



DIRECT GAIN

EXHIBIT 3-40. Example of Direct Gain Passive Design

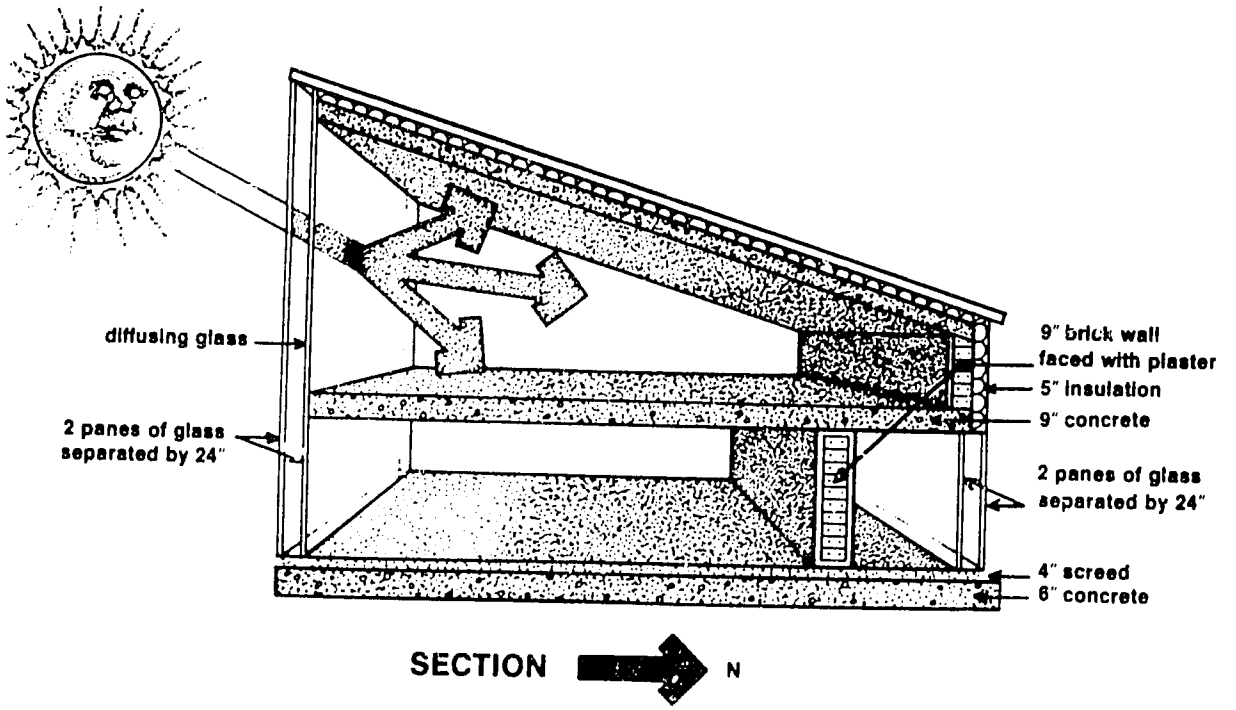


EXHIBIT 3-41. Schematic Diagram of a Direct Gain Passive Design in which Sunlight is Diffused Over a Large Surface Area of Masonry. (MAZ)

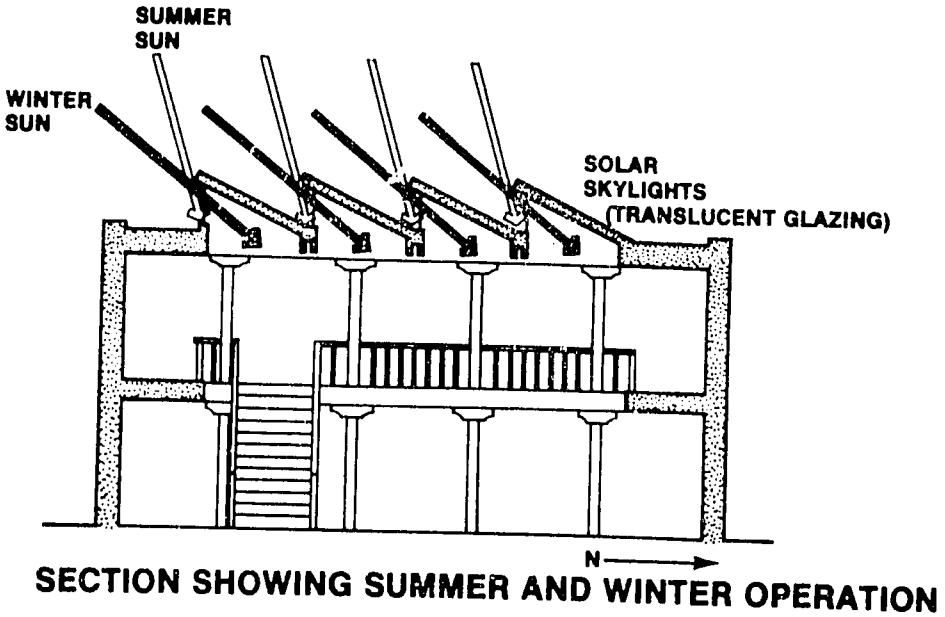
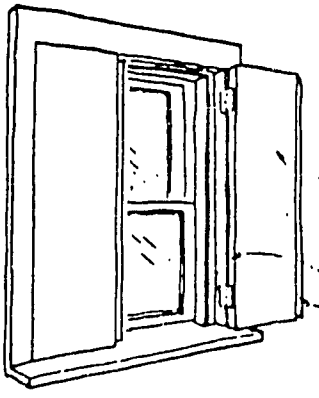
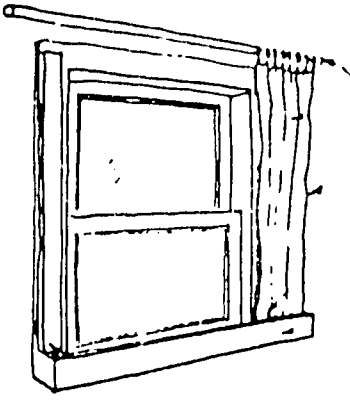


EXHIBIT 3-42. Schematic Diagram of a Direct Gain Passive Design Using Sawtooth Clerestories. (MAZ).





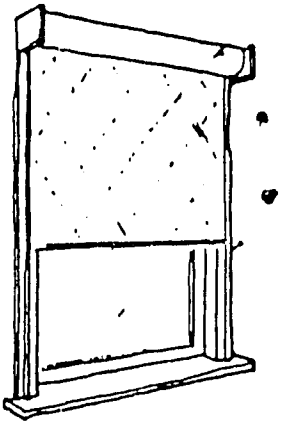


EXHIBIT 3-43. Examples of Movable Insulation

Glazing: Advantages and Disadvantages

	ADVANTAGES	DISADVANTAGES
GLASS	o excellent selective transmission o transparent o good weatherability o heat, air-pollution and u-v resistant o low thermal expansion o easily obtained	o expensive o breaks easily o heavy o often difficult to install in large sheets
ACRYLIC	o high optical clarity, strength and weatherability o lightweight and easy to handle o impact resistant o insulation and transmission similar to glass	o expensive o prone to surface abrasion o buckles and cracks if not properly installed o significant expansion and contraction characteristics o will sag at high temperatures
POLYCARBONATE	o very high impact strength o similar to acrylics, but less solar transmission	o scratches easily o not rigid o becomes brittle and changes color after prolonged exposure to the sun
FIBERGLASS REINFORCED POLYESTER	o low cost, easy to handle o high strength and durability with coatings such as Tedlar o available flat or with corrugations	o solar transmittance reduced when u-v coatings are added o will yellow and 'blossom' without coatings o medium lifespan
POLYESTER FILM	o low cost o high surface hardness	o medium lifespan o u-v degradation if not coated o relatively high longwave transmittance
POLYETHYLENE FILM	o very inexpensive o light, flexible, easy to install o good inner glazing properties	o short lifespan (less than one year) o poor resistance to long-wave radiation o wind and temperature can cause sag
POLYVINYL FLUORIDE FILM	o excellent weatherability and strength o high solar transmittance o can be bonded to fiberglass as a u-v resistant screen	o expensive o available only in thin films o relatively high longwave transmittance

EXHIBIT 3-44. Glazing: Advantages and Disadvantages (PAS)

3.3.1.3 Thermal Mass

3.3.1.3.1 Overheating

For comfort reasons, direct gain systems must not be overheated. If the south-facing glazing area in a well-insulated house is greater than 5 to 10% of the floor area and no thermal mass is provided, the living space may overheat on sunny days (both in winter and summer). Overheating not only causes discomfort to the building's occupants, but also indicates passive design inefficiency. Unlike insulated or noninsulated walls, glazing areas offer little resistance to conductive heat loss/gain. For example the overall heat transfer coefficients, U, of a single pane window and masonry wall typically are as follows: (SOL-1)

Item	U, BTUh/ft^2/°F	U, W/m^2/°C
Single Glass Metal Sash (Winter)	1.13	6.41
Masonry Wall (face brick, 4" [10.2 cm], 1/2" [1.27 cm] cement mortar, 8" [20.3 cm] cinder block, 3/4" [1.9 cm] air space and 1/2" [1.27 cm] gypsum board)	0.21	1.19

From the above tabulation, it can be seen that the potential heat loss through a window is several times greater than the potential losses through a wall.

Care must be taken to properly size south glazing collection area. The excess glass area (which contributes to overheating during sunny winter days) increases the heating load at night and during cloudy periods. It is also responsible for additional cooling loads in the summer (increased area for summer solar gain).

The size of direct gain systems (i.e., glazing area) may be increased in buildings having interiors constructed of massive materials. Mass heats up and cools off slowly (providing a thermal lag effect); this effect can prevent sunny day overheating and help offset nighttime heating loads. Thermal mass is most effective when placed in direct sunlight. Exhibit 3-45 illustrates the effect of massive building materials on interior daily temperature swings.

3.3.1.3.2 Suitable Materials

Exhibits 3-46a and 3-46b are schematic diagrams of typical masonry and interior water wall storage systems in direct gain systems.

The following physical properties are used to characterize a material's potential for use as a thermal storage medium:

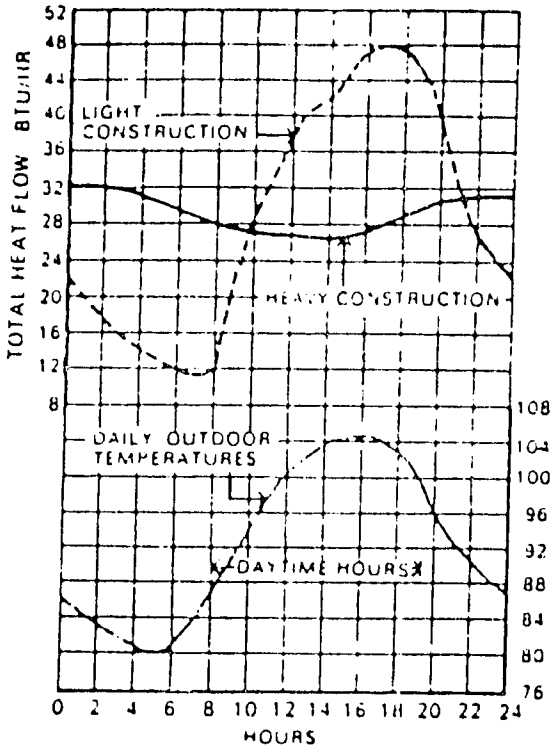
1. Heat capacity, KJ/Kg°C, represents the amount of energy required to increase the temperature of a unit mass of material. For example, if 1 kg of water were heated from 15°C to 30°C, it stores:

   (1Kg) (15°C) (4.19 KJ/Kg°C) = 62.8 KJ of energy.

2. Thermal conductivity, W-M/m²°C, is a measure of a given material's resistance to energy flow within the material. A high thermal conductivity value means the material will easily conduct heat through the material; it is a "good conductor". A low value denotes resistance to heat flow; the material is a "good insulator".

K, maple or oak	0.17 W/m°C
K, glass wool	0.038 W/m°C

3. Density, kg/m³



Thermal behaviour comparison of heavy and light construction in Iraq during July.

EXHIBIT 3-45. Illustration of the Effect of Heavy and Light Weight Building Materials on Interior Daily Temperature Swings (BAL)

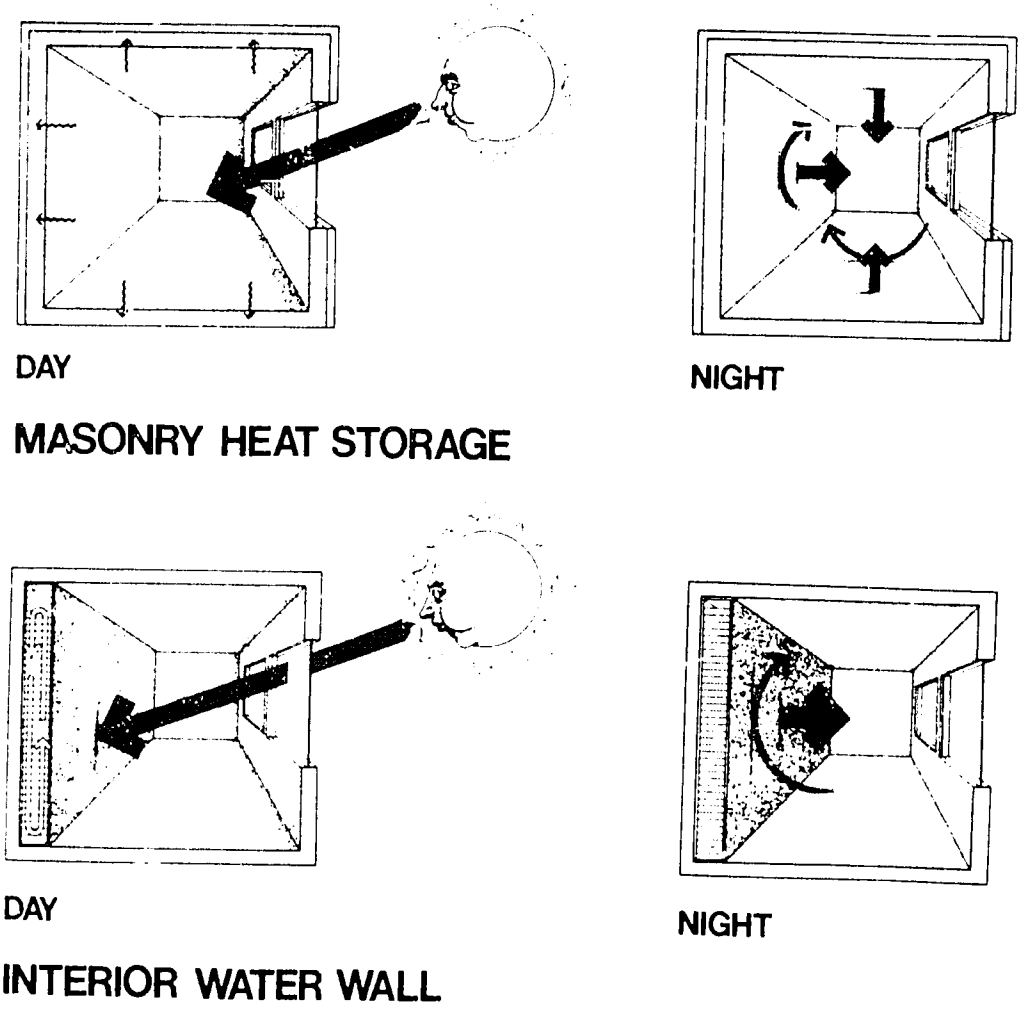


EXHIBIT 3-46a. Example of Masonry and Interior Water Wall Storage in a Passive Direct Gain System. (MAZ)

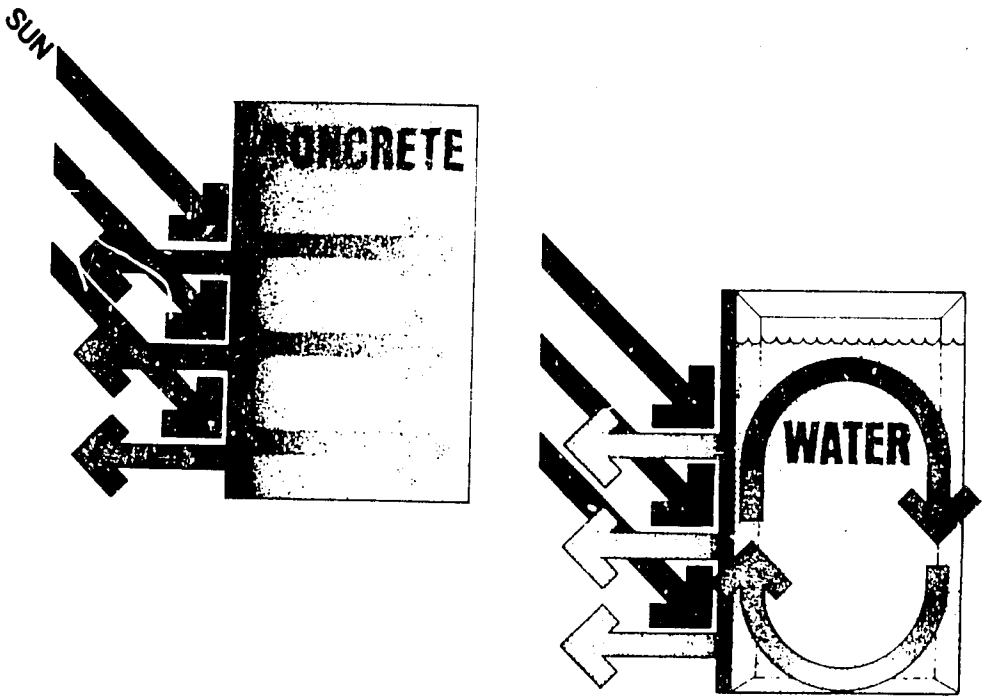


EXHIBIT 3-46b. Illustration of Heat Transfer in Concrete and Water Storage Mass Systems. (MAZ)

4. Absorptance, the fraction of incoming solar radiation that is absorbed by a material.

5. Emissivity, the measure of a material's ability to radiate thermal (long-wave) radiation.

Building materials suitable for use as direct gain heat storage are as follows:

For Floors: Concrete, either poured-in-place or precast panel systems, and either on-grade or on upper floors, are suitable. Concrete made with lightweight aggregates such as perlite and vermiculite are not suitable, because of their low specific heat (storage) characteristics. Concrete should be at least 4 inches (10.2 cm) thick and insulated at the building perimeter. The concrete must be left exposed, painted, or tiled with ceramic (not vinyl or resilient tile). Carpeting is not acceptable because it acts as an insulator. Concrete poured on-grade must always be poured atop a vapor barrier to minimize moisture absorbance and increase in conductive heat loss. The amount of floor mass depends on the amount of glazing, the space available, and the location of the mass.

For Walls: Poured concrete, concrete block, or brick work well. The interior surface of the storage walls are generally left exposed, painted, or plastered on the interior so that the plaster is in direct contact with the masonry. If wall finishes are attached to the wall with any framing system that leaves an air space, the wall will not be effective (stagnant air acts as an insulator). The exterior surface of the walls must be insulated to prevent heat loss to the outside. Poured, lightweight aggregate or lightweight blocks are not desirable.

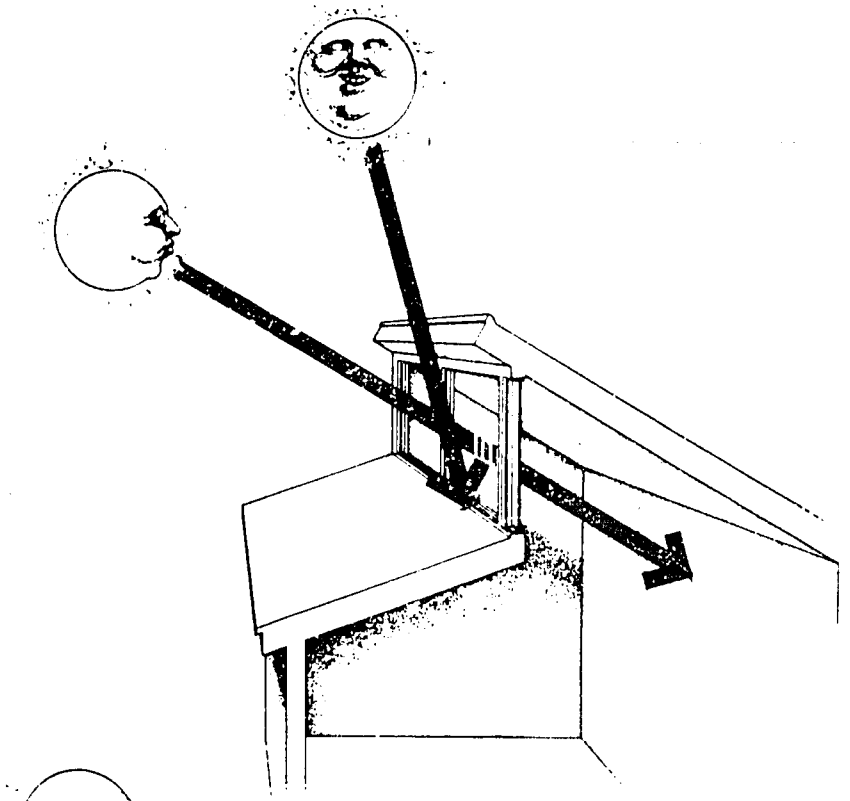
Water: Containers of water placed in direct sunlight--culvert pipes, 55-gallon (208.2 l) drums and fiberglass-reinforced plastic tubes--are among those currently being used. Metal containers should be rustproofed. Water should be sealed off from air so it will not evaporate. It should be chlorinated so that it is unable to support plant life.

Eutectic Salts: Although eutectic (phase change) salts have a large heat storaage capacity per unit volume, they may not always be suitable for heat storage in passive systems unless sufficient surface area is maintained. Eutectic salt storage should not be sized based on heat storage capacity alone, but on surface area exposed to direct or indirect solar radiation and living space air (which effects heat transfer rates from storage to the living space). Containers one inch to two inches (2.5 cm to 5.1 cm) thick are desirable. The phase change temperature must be near the normal comfort range (70°C–75°F, 21.1°–23.9°C). The cyclic storage and removal of heat (or cold) from two-phase materials such as eutectic salts are beset with problems associated with the physical compounds. There have been a number of changes in volume and shape of containers that result in an increase in the number of satisfactory cycles that can be experienced before the mixture becomes ineffective or inoperative. However, the life time is, as of this writing, far from satisfactory. As advances are constantly being made, an investigation of the state-of-the-art at the time of consideration is advisable. If the problems can be solved, the advantages of eutectic salt storage are highly superior to those of other storage mediums.

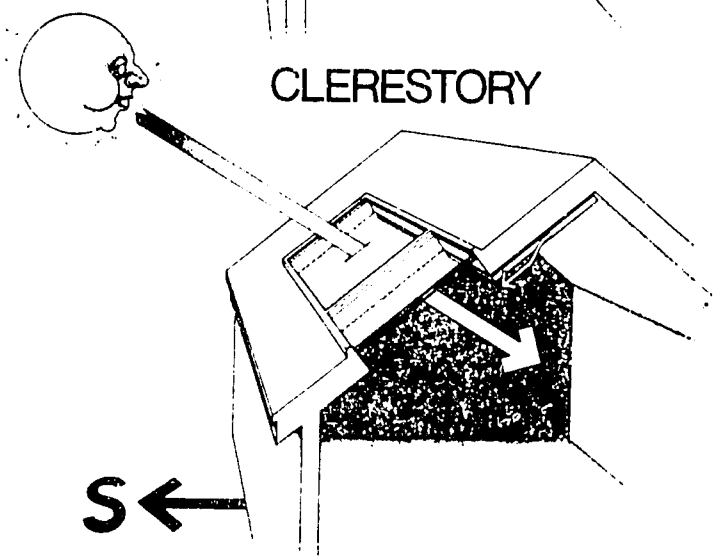
3.3.1.4 Shading

Effective direct gain systems must not increase summer cooling loads. For vertical windows, moveable shading that totally shades the window during the cooling season is required. Clerestories with vertical glazing must also be shaded. (Examples are illustrated in Exhibit 3-47) (See Section 3.43, **Shading Passive Apertures** and Section 3.2.2, **Solar Control**).

Skylights are more likely to cause summer overheating than south-facing windows because they face the high summer sun more directly. Skylights are also more difficult to shade on the outside. A reflective shade or shutter, closed directly inside the glass, will be almost as effective



CLERESTORY



SKYLIGHT

EXHIBIT 3-47. Examples of Shading of Direct Gain Systems (MAZ)

as outside shading. The reflective surface may be any shiny metal or aluminized film that acts like a mirror, reflecting the light out of the building. It must be designed and constructed so that it will not deteriorate in heat and sunlight. A reflective surface on the back of a thermal curtain or shutter will make it useful both in summer and winter, because the desired heat gain to or heat loss from the occupied space can be attained by presenting the proper side to the sun.

3.3.1.5 Advantages and Disadvantage of Direct Gain Designs

3.3.1.5.1 Advantages

- Glazing is a relatively inexpensive form of solar collector and is widely available and thoroughly tested.

- The complete system can be one of the least expensive means of solar heating.

- Direct gain is the simplest solar energy system to conceptualize and can potentially be the easiest to build. In many instances it is achieved by simply relocating windows to proper orientations (i.e., true south).

- Glazing serves multiple functions. It allows solar radiation to enter the building for conversion to heat, it admits natural daylight, it provides visual access to the outside, and it minimizes heat loss to the outside.

- To provide only a fraction of the heating needs of a building, direct gain systems do not necessarily require a means of thermal storage.

3.3.1.5.2 Disadvantages

- Large expanses of glass area can result in too much glare during the day and undesirable loss of privacy at night.

- Ultraviolet radiation in sunlight will fade fabrics, photographs, paintings, etc.

- If the design is to achieve large energy savings, then relatively large glazing areas and large amounts of thermal mass are required to reduce wide temperature swings.

- Internal diurnal temperature swings of 15°F to 20°F (8.3°C to 11.1°C) are common.

- Providing for reduced heat loss at night through the glazing can be expensive and awkward.

3.3.2 Indirect Gain (Mass Walls)

3.3.2.1 Definition

In mass wall systems, sunlight shines through vertical south-facing glazing directly onto a heat storage mass but not directly into the living space. The heat storage mass is thermally connected to the living space either by radiation, by a one-way convective loop, or by a combination of radiation and a convective loop (this concept is illustrated in Exhibit 4-48). The primary material of the heat storage mass may be masonry, stone, brick, or water. Systems employing masonry materials are often referred to as Trombe walls. In Trombe walls, conduction through the wall introduces a thermal time lag between the time at which the solar energy is collected and the time at which it is

delivered to the house. Typically, heat is not conducted through the wall until early evening. Vents are sometimes added to minimize or eliminate this time delay and facilitate provision of daytime heating.

The components of a mass wall are: glazing, mass, venting (optional), and summer shading.

3.3.2.2 Glazing

Glazing may be any transparent or translucent glass or heat resistant plastic, made as airtight and watertight as other residential window systems. Although double glazing is common, triple glazing or night insulation provides notable increases in performance. Extra attention should be given to minimizing air infiltration by use of caulking or other airtight sealant in all cracks and joints around the frame. Caulking compounds should be able to resist temperatures up to 180°F (82.2°C).

In vented systems where house air circulates behind the glass, provisions should be made for cleaning the inside of the glass. The glazing panels should be made removable or the space between the glass and the mass should at be at least 16 inches (40.6 cm) wide with an integral access door.

3.3.2.3 Mass

Materials for indirect gain mass may be masonry (stone, brick, concrete) or contained water. (Examples are provided in Exhibit 3-49.)

3.3.2.3.1 Masonry

Masonry may be poured concrete, stone, or concrete masonry units not made with lightweight aggregate. Cores of hollow bricks and blocks should be filled with mortar or sand, as air spaces decrease thermal performance. Reinforcing bars, when needed for structural reasons, will

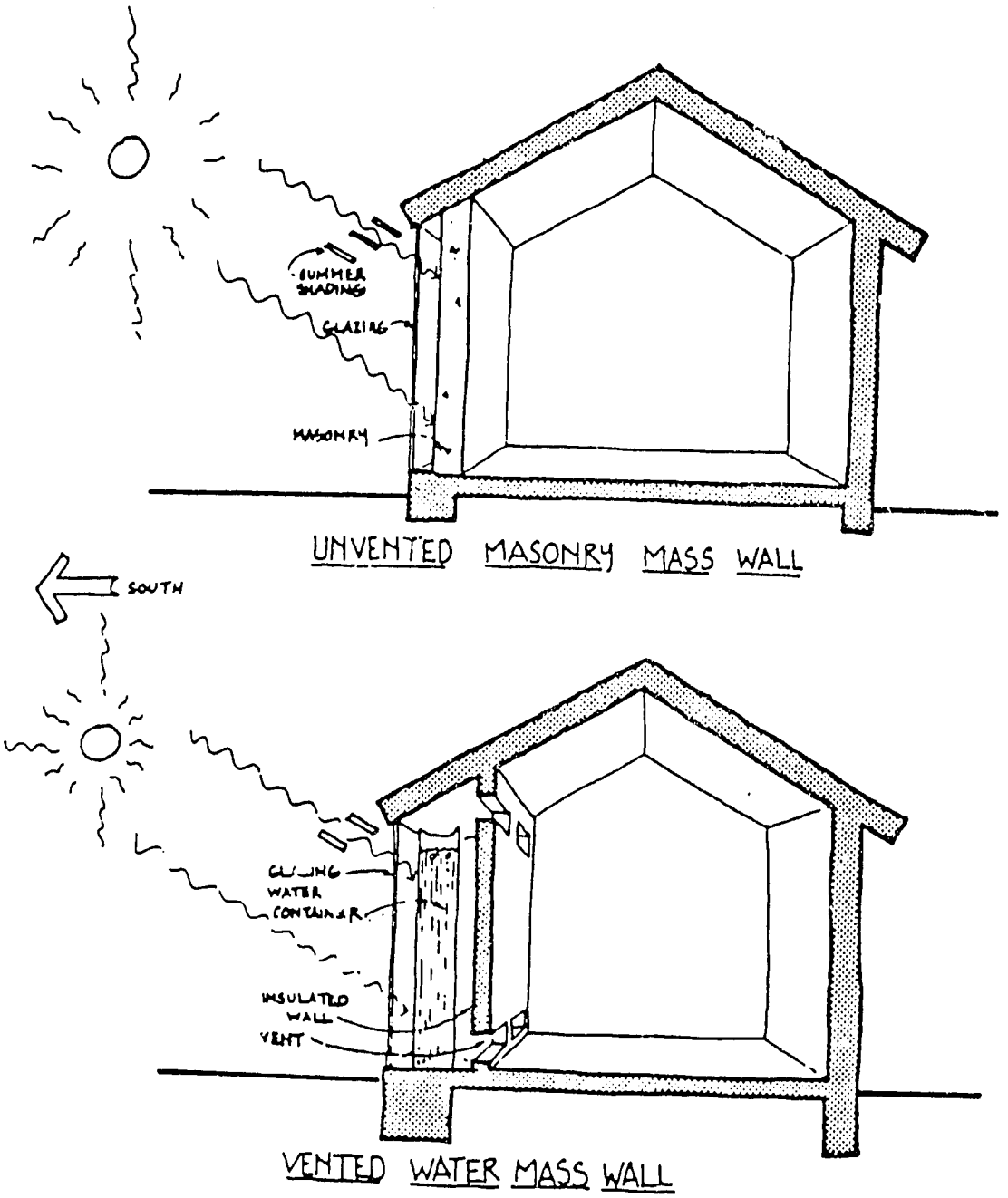
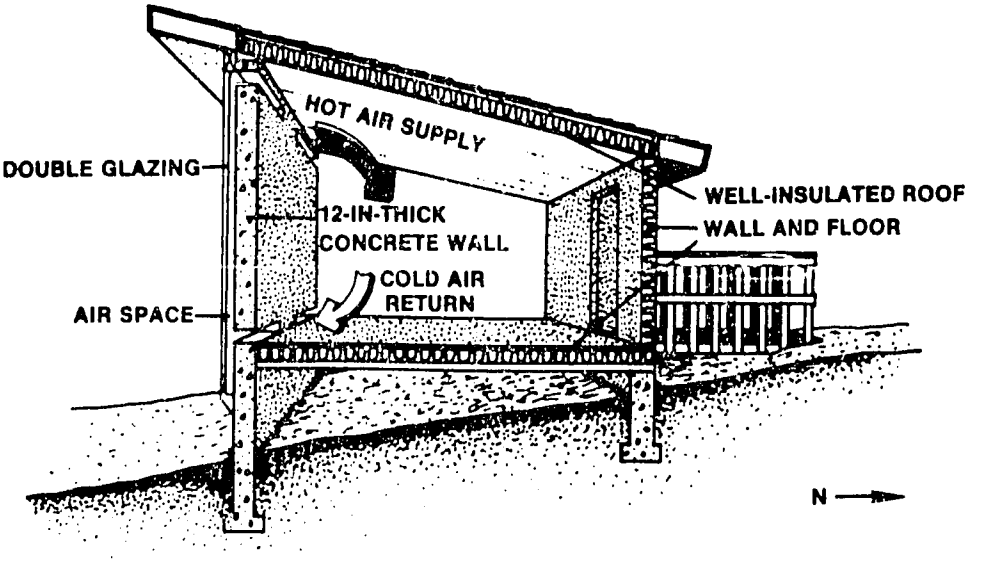


EXHIBIT 3-48. Examples of Mass Wall Passive Systems

Steve Baer house.



Section, Trombe house, Odeillo, France.

EXHIBIT 3-49. Examples of Indirect Gain Mass Systems

not degrade performance. The wall should have a thickness of at least 8 inches but not more than 18 inches (20.3 cm to 45.7 cm). The side of the wall presented to the outside should be a dark color, preferably black. Paint, if used should withstand temperatures of up to 180°F (82.2°C). Walls facing the building interior should be either left unfinished, painted, or plastered directly over the masonry without using any furring or framing system that leaves an air space. Perimeter insulation is necessary to prevent excessive heat loss to the ground or walls at the ends of the glazing. Large wall units may need extra floor support due to increased loads.

3.3.2.3.2 Water

Containers of water, as described in the Section 3.3.1, **Direct Gain**, may be used to constitute the mass of a wall system. In this application, the containers are built into a space separate from the occupied space, and the two are connected by vents. Systems where water containers are not in a space separate from the living space are direct gain systems. The weight of the water must be accounted for when the building floor loads are calculated and the structure designed. Exhibit 3-50 lists the thermal lag effect obtained from the use of various materials. Exhibit 3-51 illustrates the effect of mass thickness on interior temperature swings.

3.3.2.4 Venting

A mass wall can be vented to the interior at the top and bottom to provide a thermosiphon loop. Venting keeps the wall's surface (exterior face) cooler, allowing for more efficient energy collection. Potential problems occurs at night when unwanted cooling of the room occurs as the air in contact with the exterior face of the wall cools, drops, and flows back into the interior. Prevention of such an action is accomplished by installing self-closing dampers for the vents. Exhibit 3-52 provides a schematic diagram of a vented Trombe wall.

Experimental values of time-lag in transmission of solar heat through walls[1]

Construction	Time-lag (hr)
Wood siding, 1-in (2.54 cm) sheathing, studding, lath and plaster	2
Wood siding, 1-in (2.54 cm) sheathing, stud space filled with insulation, lath and plaster	5
4-in (10.2 cm) brick, 1-in (2.54 cm) sheathing, studding, lath and plaster	7
4-in (10.2 cm) brick, 8-in (20.3 cm) tile and plaster	$10\frac{1}{2}$
9-in (23 cm) brick, plastered	$5\frac{1}{2}$
13-in (33 cm) brick, plastered	12

EXHIBIT 3-50. List of Thermal Lag Effects (BAL)

Effect of Wall Thickness on Space Air Temperature Fluctuations

Material	Thermal Conductivity (Btu/hr-ft-°F)	Recommended Thickness (in.)	Approximate Indoor Temperature (°F) Fluctuation as a Function of Wall Thickness[1]					
			4 in.	8 in.	12 in.	16 in.	20 in.	24 in.
Adobe	0.30	8-12	...	18°	7°	7°	8°	
Brick (common)	0.42	10-14	...	24°	11°	7°	...	
Concrete (dense)	1.00	12-18	...	28°	16°	10°	6°	5°
Brick (magnesium additive)[2]	2.20	16-24	...	35°	24°	17°	12°	9°
Water[3]	...	6 or more	31°	18°	13°	11°	10°	9°

[1] Assume: a double-glazed thermal wall. If additional mass is located in the space, such as masonry walls and/or floor, then temperature fluctuations will be less than those listed. Values given are for winter-clear days.

[2] Magnesium is commonly used as an additive to brick to darken its color. It also greatly increases the thermal conductivity of the material.

[3] When using water in tubes, cylinders or other types of circular containers, use at least a 9½-inch diameter container of ½ cubic foot (31.2 lb or 3.74 gal) of water for each one square foot of glazing.

EXHIBIT 3-51. Illustration of the Effect of Wall Thickness on Space Temperature Fluctuations (CEC-2)

During the cooling season, vents to the interior remain closed during the day. The exterior surface of the wall can be vented to the outside. Cooling of the interior space is accomplished by using outside vents to enhance natural ventilation.

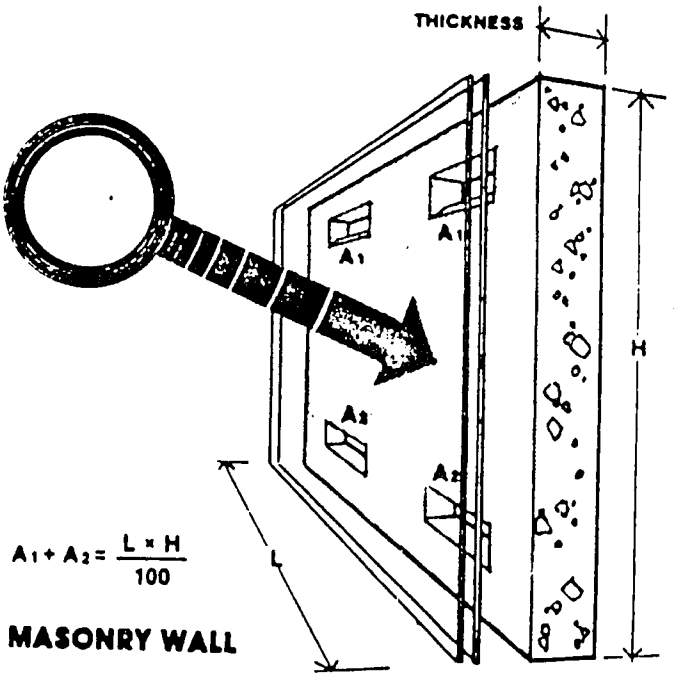
The usefulness of vents in mass walls is greater in colder climates where maximum daytime heating is desirable and required. Heat delivered by thermosiphon vents increases daytime heating but does not raise minimum nighttime temperatures. It has been suggested that in locations with average January temperatures greater than 50°F (10°C) and good insolation, vents are not needed for efficient design performance.

3.3.2.4.1 Direct Gain Systems

Unvented masonry walls are less expensive to construct than vented walls. The time delay due to the presence of an unvented mass is such that heat is not delivered to the house until early evening. Therefore, unvented walls are best used in conjunction with direct gain windows. The windows provide daytime heating, and the unvented wall helps provide heat as required.

3.3.2.4.2 Mass Walls Without Direct Gain Glazing

If mass walls are used without direct gain means, and the associated space is used during the day, venting should be included to facilitate daytime heating. As the air is heated, its density decreases and it flows upward in the space between the glazing and the mass. Vents are located near the bottom and the top of the mass wall. In a masonry wall, the vent openings are in the wall itself. In a water wall, the vents are in the partition between the water containers and the living space. When air in the system is warm, it will exit the living space through the upper vents and be replaced by cooler air entering the lower vent.



Vent placement and sizing in mass wall should be as shown in the illustration.

EXHIBIT 3-52. Diagram of a Vented Trombe Wall (CEC-2)

Air cooled at night will tend to drop or flow down the glazing and out of the bottom vent. This outgoing cool air will be replaced at the top of the glazing by warm house air. To prevent this reverse flow, an adjustable vent should be installed in each lower vent opening.

3.3.2.5 Shading

Mass walls should be shaded during the summer to prevent overheating. Fixed shades with awnings, night insulation or vegetation are possible solutions (see Section 3.4.3, **Shading Passive Apertures**).

3.3.2.6 Advantages and Disadvantages of Mass Wall Systems

3.3.2.6.1 Advantages

- Glare, loss of privacy, and degradation of room contents by ultraviolet exposure are not problems.
- Temperature swings in the living space are lower than with direct gain or thermosiphoning systems.
- The time delay between the absorption of radiant energy by the surface and the delivery of the resulting heat to the space provides warmth in the evening when most houses need it.

3.3.2.6.2 Disadvantages

- Two south walls, a glazed wall and a mass wall, are needed.
- Massive walls tend to be costly and are not generally used in modern residential construction (although thermal storage walls may be the least expensive way to achieve the required thermal storage as they are compactly located behind the glass).
- The mass wall occupies valuable space within the building.
- In cold climates considerale heat is lost to the outside from the warm wall through the glazing unless the glazing is insulated at night; moveable insulation tends to be expensive and awkward.

3.3.3 Isolated Gain (Thermal Storage Roofs)

3.3.3.1 Definition

In roof pond systems, the thermal storage means is located on the roof (as illustrated in Exhibit 3-53). One typical roof pond system utilizes water stored in large, clear vinyl bags that are supported on a black, waterproof liner on the roof. Solar radiation is absorbed both by the water and the black liners. This heat is then conducted and radiated through the ceiling, which is in contact with the bags, to the space below. Insulating panels cover the roof ponds at night to minimize heat loss.

This type of system can be used for cooling during the summer. The water absorbs heat from the space below during the daytime and radiates heat to the cold night sky. Evaporative cooling can be used effectively by flooding bags with water. The insulating panels then cover and shade the roof ponds during the day to minimize solar heat gain. They are removed at night to permit heat loss and therefore facilitate cooling.

3.3.3.2 Typical System Configuration

Exhibit 3-54 illustrates a cross-sectional view of a "Skytherm" roof pond and moveable insulation system used on a house in California, U.S.A. (NIL). The house was designed in accordance with applicable earthquake codes for the region. The living space has an area of approximately 1098 square feet (102 square meters). Above this ceiling is a layer of water 7.8 inches (20 cm) thick. The water is sealed in clear ultraviolet inhibited, 2 inches (50 mm) thick polyvinyl chloride bags, as shown. Underneath this 53,572 pounds (24,300 kilograms) of water is a thin layer of black polyethylene to help absorb irradiation at the bottom of the bags. Additionally, an air cell of inflated clear plastic sheet above the water bags enhances the greenhouse effect during the heating season. This air cell is deflated in the summer months to enhance radiative cooling. A 0.1 cm thick steel deck supports the water bags and provides good heat transfer to and from the living space.

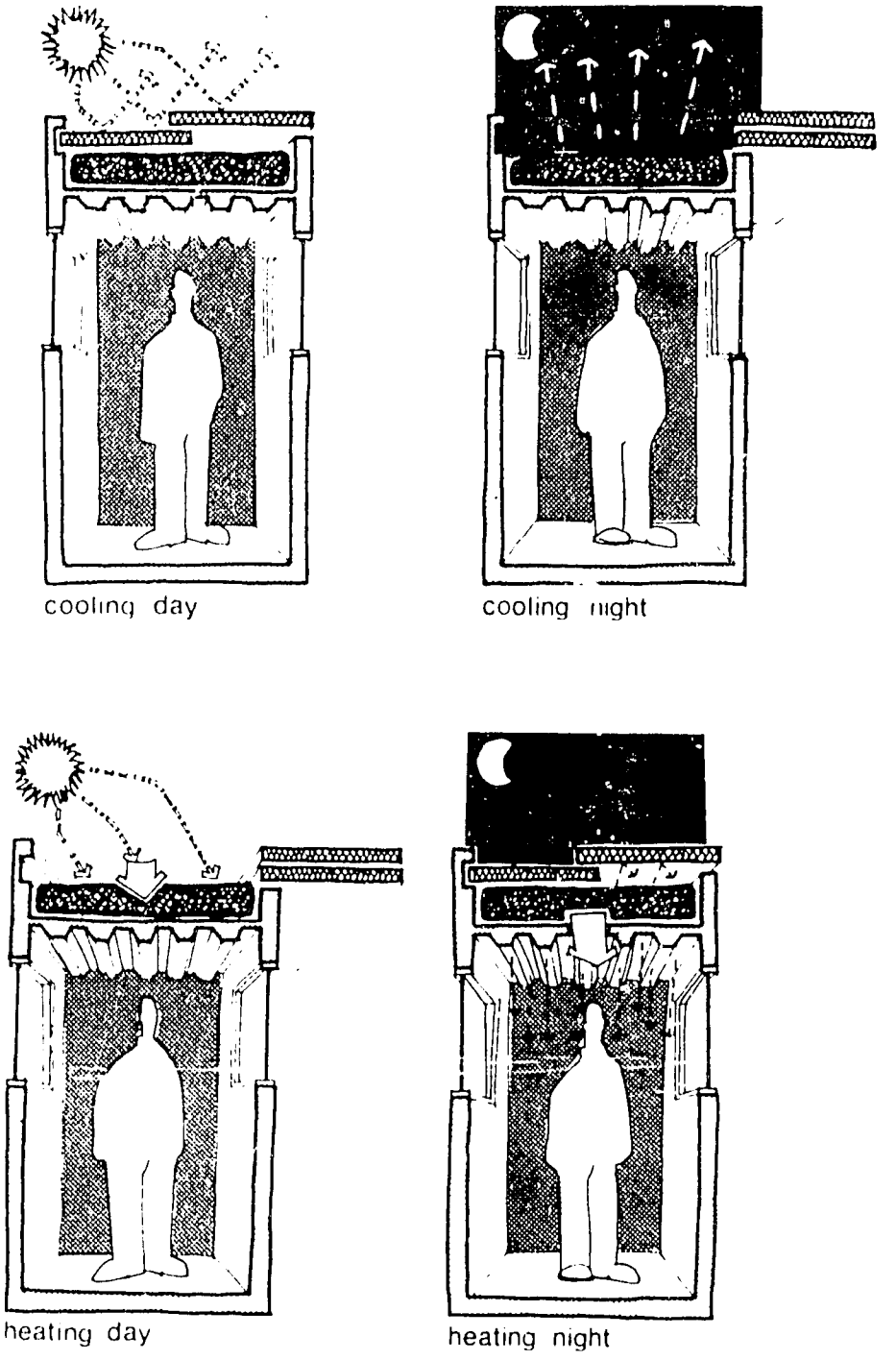


EXHIBIT 3-53. "Skytherm"[R] Thermal Storage Roofs: Summer and Winter Operation. (HON)

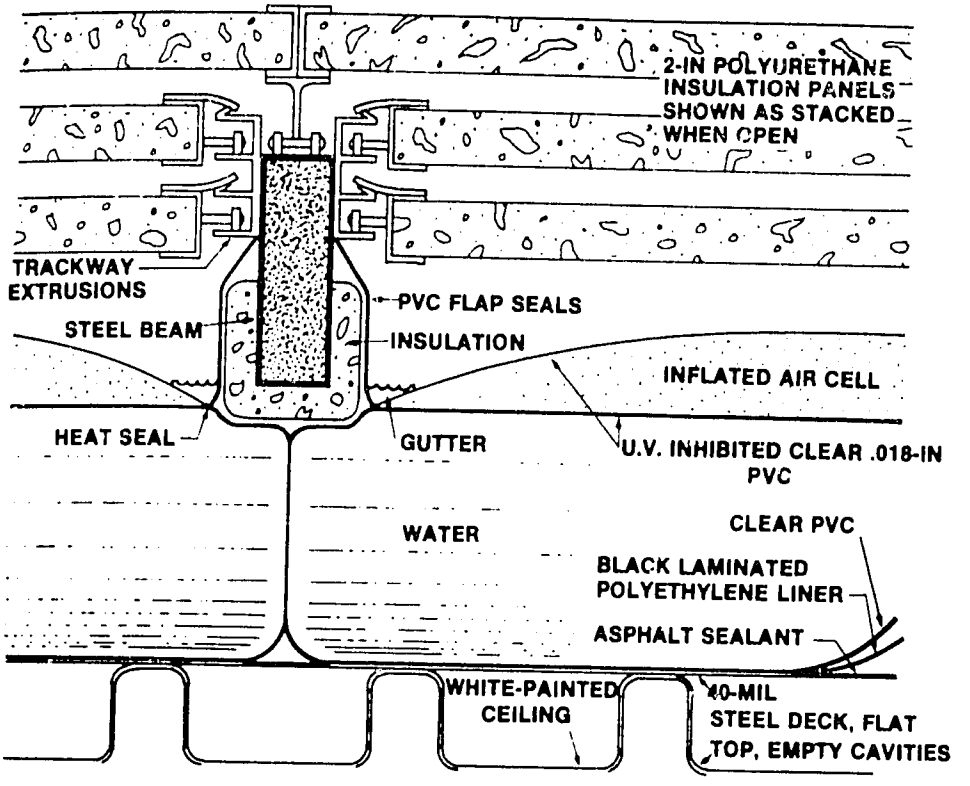


EXHIBIT 3-54. Cross Section of Water Bag and Panel System (MAZ)

Above the roof ponds, a system of moveable insulating panels is mounted on horizontal steel tracks. The insulation is rigid polyurethane 2 inches (5.1 cm) thick faced on both sides with aluminum foil. Movement of the panels is accomplished by means of a 1/6 hp motor operating about 10 minutes per day.

3.3.3.3 Thermal Characteristics

Water can store more energy per unit weight than other common building materials (sensible heat gain), and roof ponds typically have water depths of 7.9 to 11.8 inches (20 to 30 cm). Because of the inherent free convection of water within a water bag, the bags operate isothermally, quickly transferring any temperature gain or loss into the building space. This is quite different from concrete thermal storage walls that exhibit a time lag effect from the time the outer surfaces change temperatures to the time when the temperatures of inner surfaces change.

Initially, it may seem that a lack of time-delay would be a serious disadvantage of roof ponds as it would eliminate natural diurnal cycling. However, the moveable insulation largely controls the temperature of the roof pond. The temperature drops as low as 18°C (64°F) in summer and is permitted to climb as high as 29°C (84°F) in the winter. Typical day-long heat collection efficiency is 45 percent (YEL-3). Less than half of the available heat is transferred downward into the house; the remainder is lost through and around the closed insulation panels.

Exhibit 3-55 illustrates the overall thermal performance over a 9-month period for a selected dwelling built with thermal storage roof and movable insulation panels. As the figure indicates, only small variations occurred in indoor temperature. During the winter and summer, interior temperatures typically fluctuated beteen 19°C (66°F) and 23°C (73°F) while the outdoor average daily temperature fluctuated

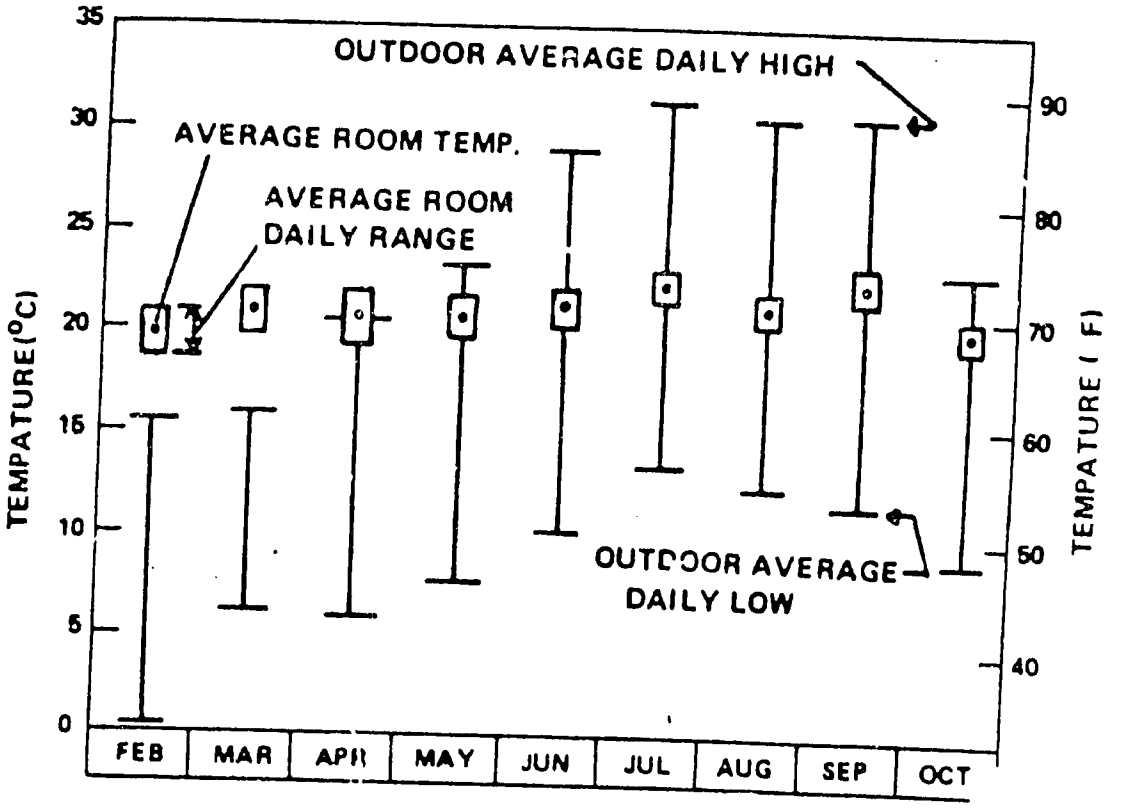


EXHIBIT 3-55. Monthly Average Temperature of the Atascadero House (NIL)

between 8°C (46°F) and 28°C (82°F) throughout the entire year. This house is 100 percent solar heated and cooled and has no backup system. Occupants of this particular dwelling have found the heating and cooling to be "superior" to conventional systems previously experienced (NIL).

3.3.3.4 Advantages and Disadvantages

3.3.3.4.1 Advantages

- Both heating and cooling can be provided.
- Compared with many passive systems, the heating and cooling effects are more uniformly distributed throughout the building.
- Temperature swings in the building may be small.
- Glare and ultraviolet degradation are not problems.

3.3.3.4.2 Disadvantages

- The heavy weight of the thermal mass above the ceiling might be psychologically unacceptable (especially in an earthquake-prone area).
- The thermal storage roof area must be at least 50 percent of the structure's total floor area to produce a significant fraction of the thermal energy needs of the building.
- Structural support for the heavy mass can be costly.

3.3.4 Isolated Gain (Sunspaces)

3.3.4.1 Definition

In sunspace systems as illustrated in Exhibits 3-56a and 3-56b), sunlight is admitted through south-facing glazing into a space that is large enough to use as living space, but which is thermally closed off by the building occupants from the rest of the building. (It is not heated or cooled by a conventional furnace or air conditioner.) Sunspaces are characterized by larger glass areas and larger temperature swings than would be acceptable in a direct gain space. These large swings are permitted because the sun space is not a conditioned living area. Typically, occupants will open windows and doors connecting the house and sunspace during sunny days, but close them during the night and during cold, cloudy periods.

A sunspace can be made suitable for plant growth by adding mass to dampen temperature swings and moveable insulation to retain heat at night. Sunspaces used as greenhouses will be humid, and interior finishes should be moisture-resistant using materials that are typical of the building exterior, or moisture-resistant paints and finishes as used in bathrooms and kitchens.

Because of their large glass areas, sunspaces are likely to cause summer overheating unless they are properly shaded and ventilated. Proper design and location of shading devices, vent openings, and limited sloped glazing will prevent summer overheating. The components of a sunspace are south-facing glazing, east and west walls, a boundary wall between the sunspace and house, operable openings in this wall, thermal mass, and summer shading/ventilation. Moveable insulation is an optional component that will improve the performance of a sunspace.

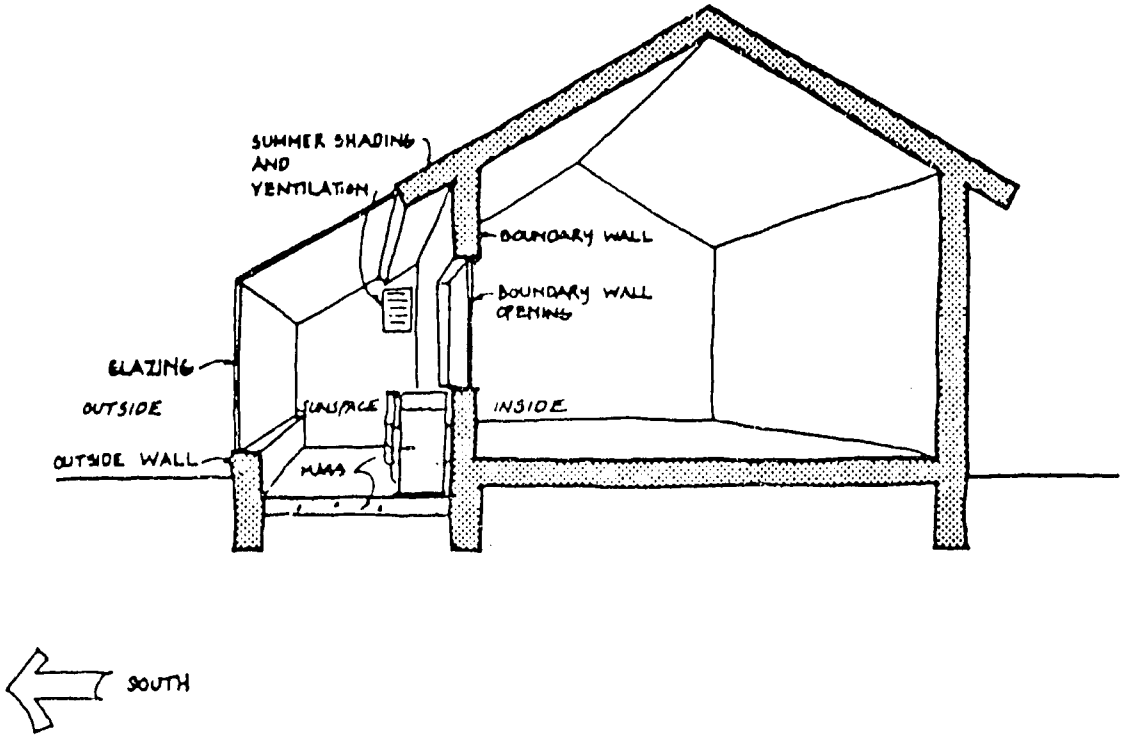
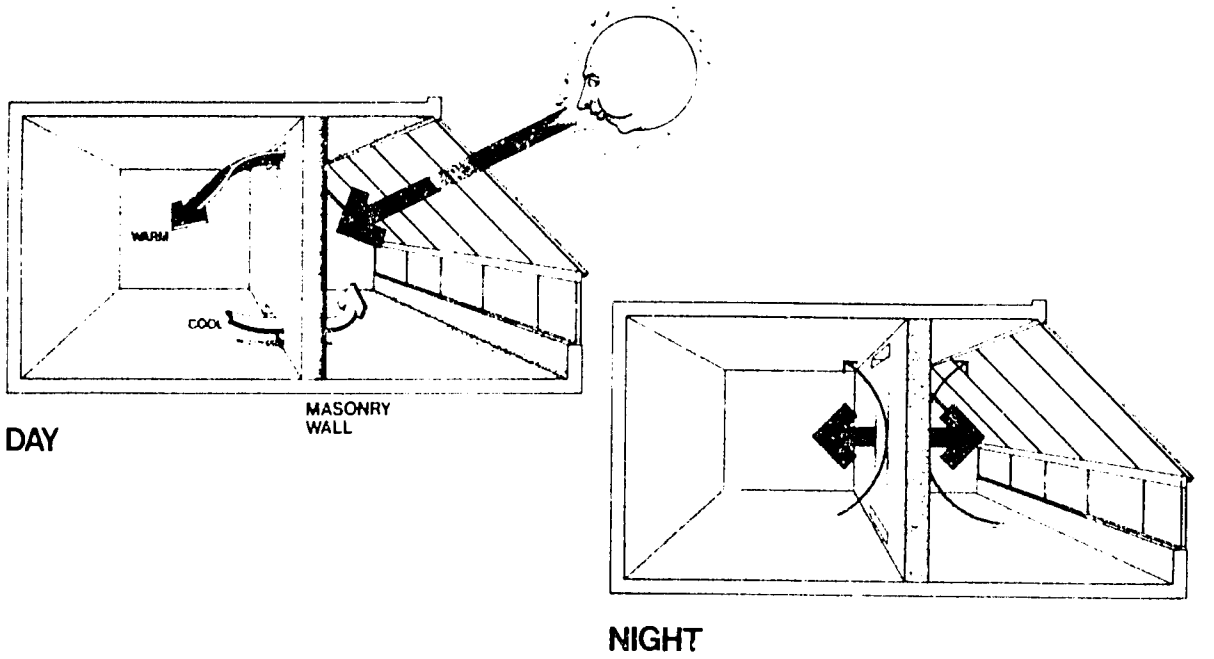


EXHIBIT 3-56a. Sunspace Passive System



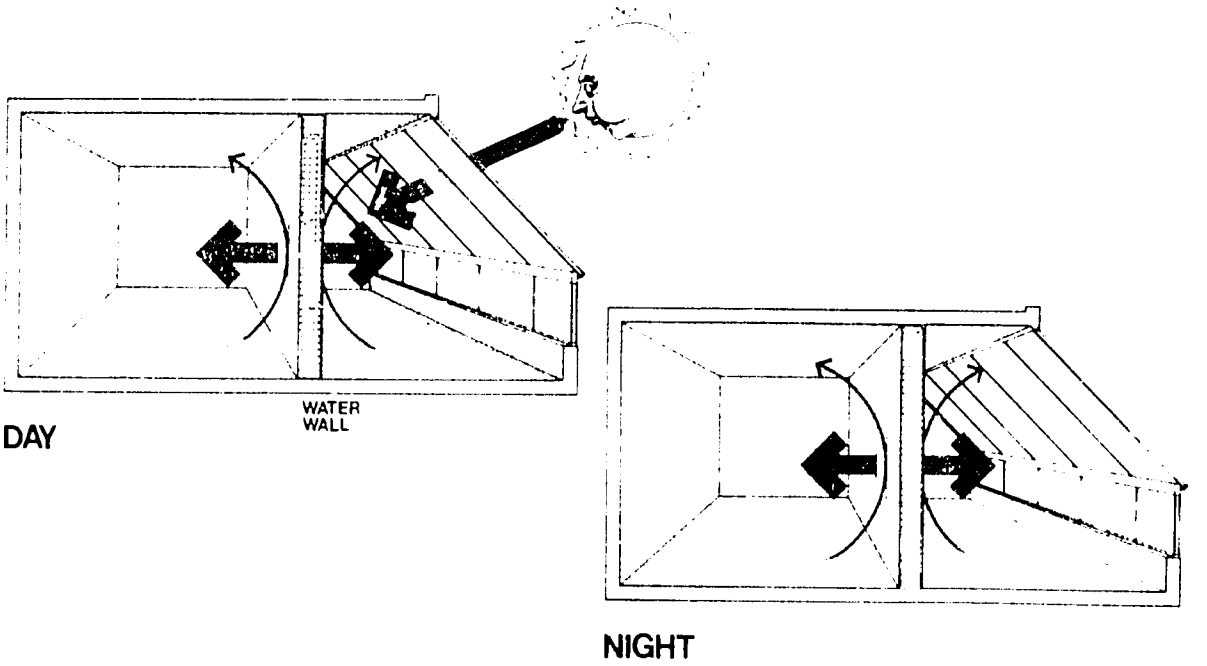


EXHIBIT 3-56b. Isolated Gain--Attached Greenhouse (MAZ)

3.3.4.2 Glazing

Glazing may be any transparent or translucent glass or plastic, either vertical or sloping, either manufactured or site-built. All glazing must be at least double-glazed, and metal frames should have a thermal break. Insulation should be installed between the outer and inner metal faces so as to inhibit direct thermal conduction. Glazing in sunspaces must be as airtight and watertight as any other residential window system. Special care must be taken to design watertight joints on sloped glazing. Since condensation is likely to form on the inner glazing, interior sills should be water resistant and should slope away from the glazing.

3.3.4.3 Exterior Walls

Walls and roofs between the sunspace and outdoor environment are to be built with the same amount of insulation and care against air infiltration as any exterior wall. They may be either insulated wood frame or insulated masonry. The perimeter of the sunspace at grade must be insulated, either at the edge of the floor slab or on the exterior of the foundation wall.

3.3.4.4 Boundary Walls

These walls must be either insulated walls or masonry heat storage mass walls. An insulated wall has as much insulation and is as resistant to infiltration as the exterior house walls.

3.3.4.5 Openings Into House

Openings may be standard windows and doors, or vents with operable grilles installed with the same precautions as taken against air infiltration through exterior doors and windows. Other operable openings, such as shutter or overhead garage doors, may be used provided they seal tightly when closed.

3.3.4.6 Mass

Mass must be provided for heat storage if the space is not closed off at night. Heat storage mass is commonly either masonry or water.

Masonry: A masonry building, a masonry exterior wall insulated on the outside, or a masonry floor insulated at the outside edge are all useful as heat storage mass. In addition, sunspaces may have gravel floors or pavers set in sand.

Water: Water in containers, as described in Section 3.3.1, **Direct Gain** section, will be useful as heat storage mass. Hot tubs or fish ponds placed in a sunspace are not useful as heat storage if their temperature is artificially maintained.

3.3.4.7 Shading and Ventilation

Because of large glass areas, sunspaces are likely to overheat in summer. Overheating must be controlled by adequate shading and/or ventilation that is either natural or forced.

3.3.4.8 Advantages and Disadvantages

3.3.4.8.1 Advantages

- Temperature swings in adjacent living spaces are small.
- Sunspaces provide space for growing plants.
- Heat loss from buildings is reduced since sunspaces act as buffer zones.
- Sunspaces are readily adaptale to existing buildings.
- Since the sunspace serves more than one function, it is a natural and integrated part of the building design.

3.3.4.8.2 Disadvantages

- Thermal performance from one design to another, which makes performance of sunspace designs difficult to predict.
- Sunspaces are a relatively expensive means of solar heating.

3.4 Passive Design Considerations

This portion of the notebook has tried to stress the fact that passive solar design is very site specific. Climate determines the needs of the building, whether heating or cooling are required. Therefore, unlike active solar systems, there are not set passive designs which are applicable in a variety of situations. The following references may be helpful for the process of preliminary passive solar design:

1. Mazria, Edward, Passive Solar Energy Book: Expanded Professional Edition, Rodale Press, Emmaus, PA, 1979.

2. Niles, Philip and Haggard, Kenneth L., Passive Solar Handbook, California Energy Commission, Sacramento, CA, 1980.

3. Balcomb, J. D., et. al., Passive Solar Handbook--Passive Solar Design Analysis, vol. 2, U.S. Department of Energy, 1980.

4. Total Environmental Action, Inc., The Thermal Mass Pattern Book, Harrisville, NH, 1980.

3.4.1 Solar Collection Surfaces

Perhaps the most difficult aspect of passive solar design is sizing the passive aperture (collector area). As the size of the aperture is increased, the heating energy requirements of the building generally decreases. It is essential to recognize diminishing returns which result form the inability of the passive system to use all the energy that it collects. The energy collected by the first square meter of glazing added is used throughout most of the heating season. However, energy collected by the four hundredth square meter (for example), is only useful during the coldest time of the year, as a smaller aperture would meet the heating load in the spring and fall seasons. Therefore, the average "productivity" decreases as the aperture size increases.

A second consideration in selecting the aperture size is the dynamic thermal performance, which affects the occupant's comfort. Passive systems usually collect more energy in the spring and the fall then can be used (or desired, as in the fall). This energy must be kept out of the building by use of shading or venting. Handling large, unwanted temperature swings should be considered when determining the aperture size.

Most homes contain enough mass in the normal building materials and have enough daytime heat loss to support a reasonable passive aperture without adding additional thermal mass.

A third factor that must be considered in sizing the passive aperture is the effect on the cooling load. Cooling loads increase directly as aperture area is added, and at some point will cancel out the heating savings. This point is the upper limit for the aperture size, and the optimum size is obviously smaller.

Sophisticated computer analysis, combined with accurate cost information, is required to determine the optimum passive aperture size. However, the following rules of thumb are useful for preliminary design:

- Incorporate sufficient passive aperture area to bring the house to the overheating point. This is typically 5 to 10 percent of the floor area, depending on the type of constrcution, insulation levels, and the climate.
- Locate passive collection surfaces within 30° of true south (not magnetic south).
- The collection surface should receive direct sunlight betwen 9 a.m. and 3 p.m. local standard time during the heating season.
- The collection surfaces should be completely shaded during the peak cooling season. Trellises, moveable louvers, awnings, roof overhangs, decks, lofts, or other external and internal shading devices can be used.

- Passive aperture areas can collect diffuse solar radiation; to take advantage of this, locate a fraction of the collection area on south-sloping roof areas.

- Allow sunlight to strike thermal storage mass (or any absorber surface).

- Glare can be reduced by collecting sunlight from windows facing north, east, and west. It is recommended that their combined area should be at least ten percent of the south glazing area.

- As a general rule of thumb (STR) south-facing glazing in rooms you want to heat by direct gain should total 13 percent of the floor area in these buildings. In extremely cold climates, (over 7500 degree-days/yr [°F]) south-facing glazing should be 15 percent of floor area; in warmer climates (less than 4500 degree-days [°F]) south glazing should total 10 percent of floor area.

- Use standard-size windows, sliding glass doors and skylights for direct gain apertures. Standard sizes are less expensive. Readily available sizes include: 71.1 x 193 cm, 86.4 x 193 cm, 124.4 x 193 cm, constructed of double insulated tempered glass.

- Use acrylic or fiberglass glazing materials in standard sizes of 4 x 8, 4 x 10, 4 x 12 feet (1.22 x 2.44, 1.22 x 3.05, 1.22 x 3.66 meters) for greenhouses or other applications where clear glass is unnecessary.

- Increase size of collection areas to compensate for shading of the collector area by trees or other obstructions; also increase aperture area to account for an orientation more than 20° from true south.

- If feasible, tilt collector surface at an angle perpendicular to the altitude of the sun at noon on December 21.

- Greenhouse or sunspace glazing should be tilted at an angle at 25° plus latitude.

- In areas with a short heating season and a long cooling season, use only vertical apertures. (Vertical surfaces are easier to shade than tilted surfaces.)

- Use translucent materials in the roof, house, or sunspace to reduce glare and to scatter light and energy. If feasible, use a reflective surface to direct sunlight into the collector areas and/or thermal mass.

- Consider triple-glazed window or door units on north-facing, east-facing, and west-facing openings.

Sizing Solar Windows for Different Climatic Conditions[1]

Average Winter Outdoor Temperature (°F) (degree-days/mo.)[2]	Square Feet of Window[3] Needed for Each One Square Foot of Floor Area
Cold Climates	
15° (1,500)	0.27-0.42 (w/night insulation over glass)
20° (1,350)	0.24-0.38 (w/night insulation over glass)
25° (1,200	0.21-0.33
30° (1,050)	0.19-0.29
Temperature Climates	
35° (900)	0.16-0.25
40° (750)	0.13-0.21
45° (600)	0.11-0.17

[1] These ratios apply to a residence with a space heat loss of 8 to 10 Btu/day-sq. ft-°F. If space heat loss is less, lower values can be used. These ratios can also be used for other building types having similar heating requirements. Adjustments should be made for additional heat gains from lights, people and appliances.

[2] Temperatures and degree-days are listed for December and January, usually the coldest months.

[3] Within each range, choose a ratio according to your latitude. For southern latitudes, i.e., 35°NL use the lower window-to-floor area ratios; for nothern latitudes, i.e., 48°NL use the higher ratios.

EXHIBIT 3-57. Direct-Gain Glazing, (CEC-2)

Sizing the Attached Greenhouse for Different Climatic Conditions

Average Winter Outdoor Temperature (°F) (degree-days/mo.)[1]	Square Feet of Greenhouse Glass[2] Needed for Each One Square Foot of Floor Area	
	Masonry Wall	Water Wall
Cold Climates		
20° (1,350)	0.9-1.5	0.68-1.27
25° (1,200)	0.78-1.3	0.57-1.05
30° (1,050)	0.65-1.17	0.47-0.82
Temperate Climates		
35° (900)	0.53-0.90	0.38-0.65
40° (750)	0.24-0.36	0.30-0.51
45° (600)	0.33-0.53	0.24-0.36

[1] Temperatures and degree days are listed for December and January, usually the coldest months

[2] Within each range choose a ratio according to your latitude. For southern latitudes, i.e. 35°NL, use the lower glass-to-floor-area ratios; for northern latitudes, i.e. 48°NL use the higher ratios. For a poorly insulated greenhouse or building, always use slightly more glass

EXHIBIT 3--58. Isolated Gain, Sunspace, (CEC-2)

Exhibits 3-59a and 3-59b provide tables of shading coefficients for various interior and exterior shade control devices used with various types of glazing.

3.4.2 Thermal Storage Mass

When well-insulated houses incorporate more than approximately 5-10 percent of the heated floor area in south-facing window area, there is potential for overheating the living space on sunny winter days. Such overheating can be limited by venting excess heat on sunny winter days. However, the energy that is wasted in this manner is unavailable later during the evening hours when it could help meet the heating load.

To help limit overheating during sunny winter days, different forms of thermal mass are often included in passive solar homes. Thermal mass includes heavy masonry materials such as concrete, brick, rock, tile, etc., and also water and various phase-change materials. All of these materials are characterized by large thermal capacities, or, the ability to store a large amount of energy per degree temperature rise either when the sun shines directly or diffusely on the thermal mass surface, or when the air in contact with the thermal mass surface becomes warmer than that surface so that heat flows into the thermal mass. When the room air in contact with the thermal mass drops below the thermal mass temperature, then heat is released to help warm the room.

The amount of thermal mass required to reduce overheating depends on the passive aperture and the location of the mass. Thermal mass located in the path of direct sunlight is charged by direct radiation and is most effective; remotely located thermal mass is charged by convection and is least effective. As the effectiveness of thermal mass decreases, it is necessary to increase surface area in contact with air.

Glazing Type	glass only S.C.	drapery[1] nonwhite[3] (see note 7)	drapery[1] white[4] offwhite	opaque[2] flat shading device dark[5]	opaque[2] flat shading device med.to[6] light	opaque[2] flat shading device white[7] offwhite
Solar reflectivity	-	0.21/0.15	0.42/0.30	0.10	0.30	0.70
1) Single Pane Clear Glass	(.88) 1.00 [.76]	(.80) 0.91 [.69]	(.55) 0.62 [.47]	(.81) 0.92 [.70]	(.64) 0.73 [.55]	(.30)[8] 0.34 [.26][9]
2) Double Pane Clear Glass	(.77) 0.88 [.67]	(.66) 0.75 [.57]	(.48) 0.55 [.42]	(.69) 0.78 [.59]	(.56) 0.64 [.49]	(.29) 0.33 [.25]
3) Triple Pane Clear Glass	(.73) 0.83 [.63]	(.56) 0.64 [.49]	(.45) 0.51 [.39]	(.62) 0.70 [.53]	(.52) 0.59 [.45]	(.27) 0.31 [.24]
4) Single Pane Heat Absorbing Glass	(.59) 0.67 [.51]	(.54) 0.61 [.46]	(.48) 0.54 [.41]	(.55) 0.63 [.48]	(.48) 0.54 [.41]	(.32) 0.36 [.27]
5) Double Pane Outer Pane:Heat Absorbing Glass, Inner Pane: Clear Glass	(.48) 0.55 [.92]	(.48) 0.54 [.41]	(.43) 0.49 [.37]	(.49) 0.56 [.58]	(.43) 0.49 [.37]	(.31) 0.35 [.27]
6) Single Pane Reflective Glass (S.C. = 0.40)	(.35) 0.40 [.30]	(.25) 0.28 [.21]	(.24) 0.27 [.21]	(.26) 0.29 [.22]	(.24) 0.27 [.21]	(.19) 0.22 [.14]
7) Single Pane Reflective Glass (S.C. = 0.30)	(.26) 0.30 [.23]	(.19) 0.22 [.17]	(.18) 0.21 [.16]	(.19) 0.22 [.17]	(.18) 0.21 [.16]	(.16) 0.18 [.14]

1. A drapery is a loose fabric hanging just inside and capable of covering a window. A drapery typically has folds, convolutions or loose pleats.
2. Flat shading devices are devices that can have their side facing the window made essentially flat such as mini-blinds, roller shades, venetian blinds and vertical blinds. Fabric may also be made essentially flat by hanging without folds or by stretching flat & tight.
3. All but white and offwhite colors. ALSO see note[4].
4. Whites and offwhites include whites with very light pastel tints e.g. cream colored, eggshell white, etc. They also include mirror-like metallic coatings that reflect images. Mirror-like means the ability to reflect images; however, the images may be distorted. For example, a polished metal surface as opposed to a burnished one.
5. Dark colors, e.g., blacks, browns, dark greens, dark blues, dark greys, purples.
6. Medium to light colors: all but 4 & 5 above. For example, bright reds, yellows, pinks, light greens, pastels, skyblue, metallic coatings that do not reflect images, or diffusely reflecting metallic colors.
7. The values in parentheses ( ) represent shading coefficients adjusted for a metal frame window without mullions.
8. The values in brackets [ ] represent shading coefficients adjusted for a wood frame window without mullions.
9. If there is disagreement or uncertainty regarding the color, transparency, "flatness," or other qualities of shading devices, the judgement resulting in the larger shading coefficient shall be used for compliance.

EXHIBIT 3-59a. Shading Coefficients for Interior Shading Devices with Various Types of Glazing With and Without the Effects of Metal and Wood Framing (CEC-6).

Window Framing/Mullion Factors

Frame Type	FMF w/o Mullions	FMF w/ Mullions
No Frame or Wood Doors	1.00	0.92
Metal Frame Windows	0.88	0.81
Wood Frame Windows	0.76	0.70

Shading Coefficients for Exterior Shading Devices with Single and Double Pane Clear Glazing

Shading Device	w/Single Pane Clear DSS Glass	w/Dual Pane Clear DSS Glass
1) Exterior Sunscreens with weave 53x16/inch	0.34	0.33
2) Louvered Sunscreens w/louvers as wide as openings	0.31	0.30
3) Low Sun Angle Louvered Sunscreens (e.g. LSA Koolshade)	0.15	0.15
4) Ordinary Bug Screens	0.67	0.65
5) Flat Roll Down Canvas Awning	0.15	0.15
6) Outside Venetian Blinds & Rolldown Slats	0.15	0.15

Exterior operable awnings (canvas, plastic, or metal), except those that roll vertically down and cover the entire window, should be treated as overhangs for purposes of compliance with the standards. For east-and west-facing glazing, operable (including movable or readily removable) awnings that shade all parts of a window from the sun when it is directly in front of the window at altitudes ranging from 30°-90° may be considered to provide shading comparable to adjacent structures or physical terrain.

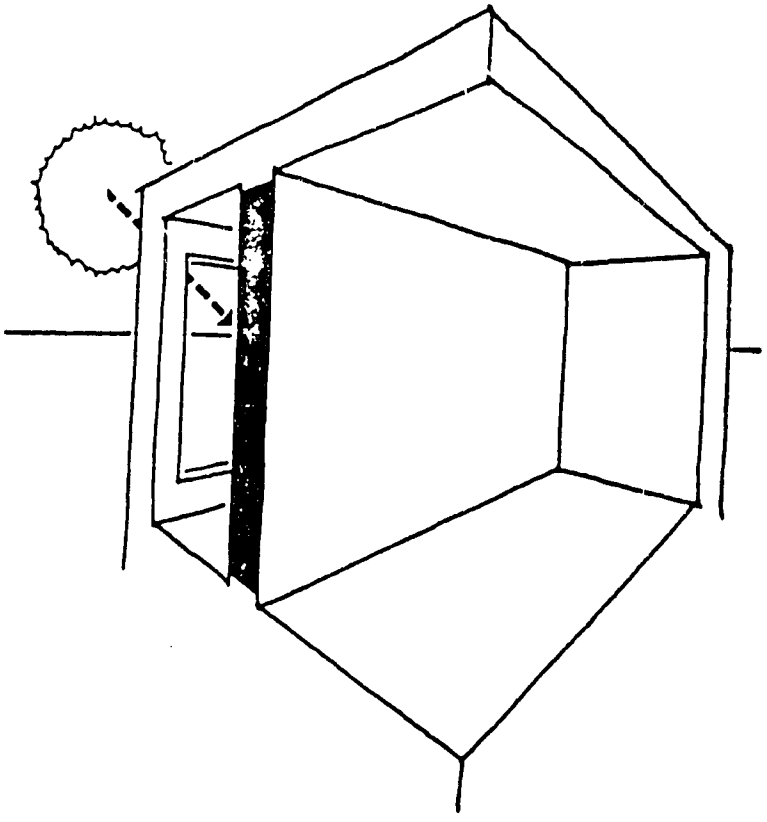
EXHIBIT 3-59b. Various Shading Coefficients (CEC-6)

One method of determining if there is sufficient mass involves assessing how much of the passive system can be "carried" by each type of mass in a building. Exhibits 3-60a to 3-60g indicate the mass patterns common to most passive buidings. Listed with each pattern is the mass surface area need to "carry" a square meter of glass. Note that, in patterns where the mass is located in direct sun, more glass can be carried by a square foot of mass, and the mass is effective at greater thicknesses.

To estimate the amount of thermal mass required to temper overheating, first subtract 5-10 percent of the heated floor area from the total south-facing aperture area. (As mentioned above, this is the south-facing aperture area that can usually be installed on a well insulated house without excessive overheating.) The remaining aperture area will contribute to excessive overheating unless extra thermal mass in some form is provided. Next, determine the appropraite thermal mass pattern from Exhibit 3-60a, 3-60b, 3-60c, 3-60d, 3-60e, 3-60f, or 3-60g. Listed in the Mass Sizing Table are the appropriate surface area and thickness of mass required to temper the overheating effect from one square meter of south-facing aperture. Dividing the total remaining aperture area by the listed mass surface area will yield the total mass surface area that must be provided. Conversely, a given total mass surface area can be divided by the listed mass surface area required per square meter of south-facing aperture area than can be "carried" by the thermal mass. The "carried" aperture area can then be subtracted from the remaining aperture area and the process can be repeated over and over with mass patterns until all the glass area has been accounted for. Unless sufficient thermal mass is provided, excessive overheating will occur (especially in the cooling season), and the passive home heating savings will drop significantly.

The following guidelines should be used for the preliminary design of thermal storage mediums. (STR), (CEC-2), (CEC-3), (MAZ)

- Locate thermal mass where it will intercept direct (or reflected) radiation for a major portion of the day (9 a.m. to 3 p.m.) during the heating season.

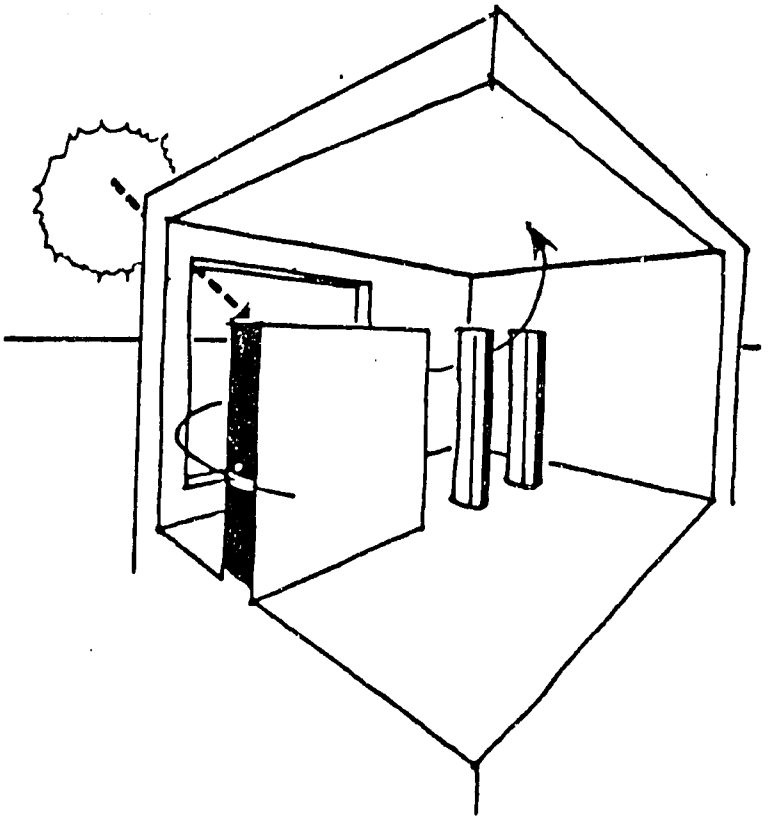


Directly sunlit wall of masonry or water; exposed to living spaces on back side only. Note that sunlit side is isolated from living spaces.

MASS SIZING TABLE

Irradiated mass surface area to passive aperture area ratio.	Masonry thickness (inches)	Water Wall thickness (inches)
1	8" - 18"	6" - 12"

EXHIBIT 3-60a. Thermal Storage Pattern A



(In English Units)

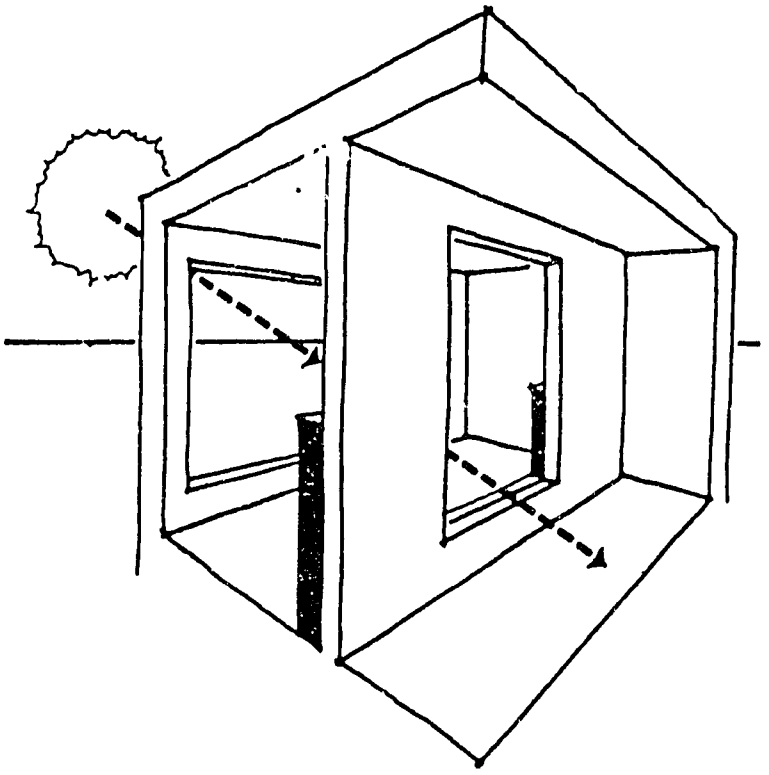
Directly sunlit wall of masonry or water containers; fully exposed on both front and back surfaces to living spaces. Note free air circulation around storage.

MASS SIZING TABLE

Masonry thickness (inches)	Irradiated mass surface area to passive aperture area ratio.
6	2
8	2
12	2

Watertubes or Drums: Use at least 7 gallons of water per square foot of passive aperture.

EXHIBIT 3-60b. Thermal Storage Pattern B



Sunlit mass surfaces in sunspaces are isolated from living spaces. Some mass in living spaces may be directly or indirectly exposed to the sun through connecting aperture.

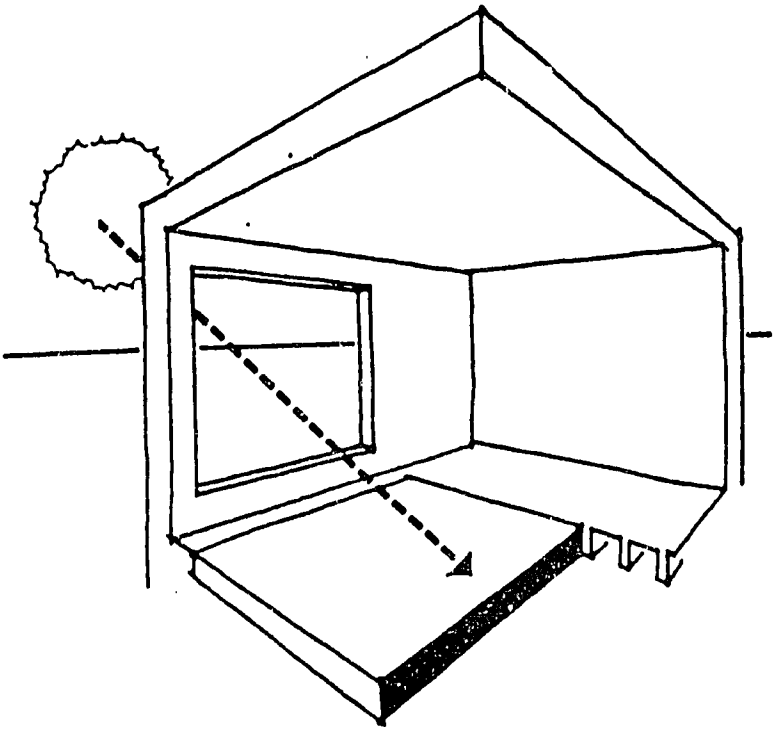
MASS SIZING TABLE

1. Count mass in sunspace as pattern A type.

2. Count mass in living spaces as patte D, E, or F as appropriate.

3. Passive aperture area is defined as sunspace aperture area.

EXHIBIT 3-60c. Thermal Storage Pattern C

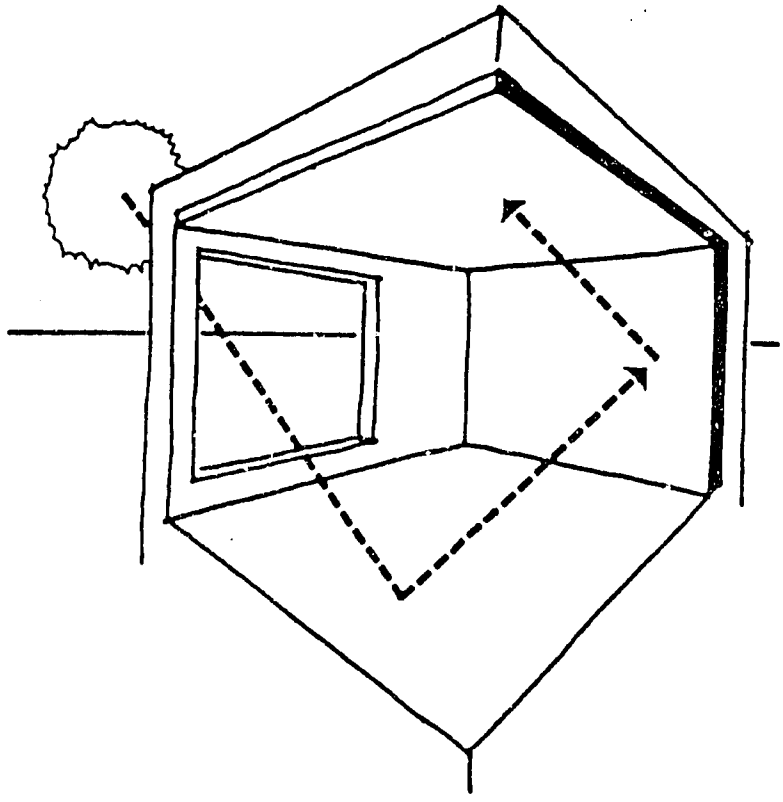


Directly sunlit floor or wall; exposed to living spaces on sunlit face, insulated on other face.

MASS SIZING TABLE

Masonry thickness (inches)	Irradiated mass surface area to passive aperture area ratio.
1	14
2	7
3	5
4	4
6	3
8	3

EXHIBIT 3-60d. Thermal Storage Pattern D



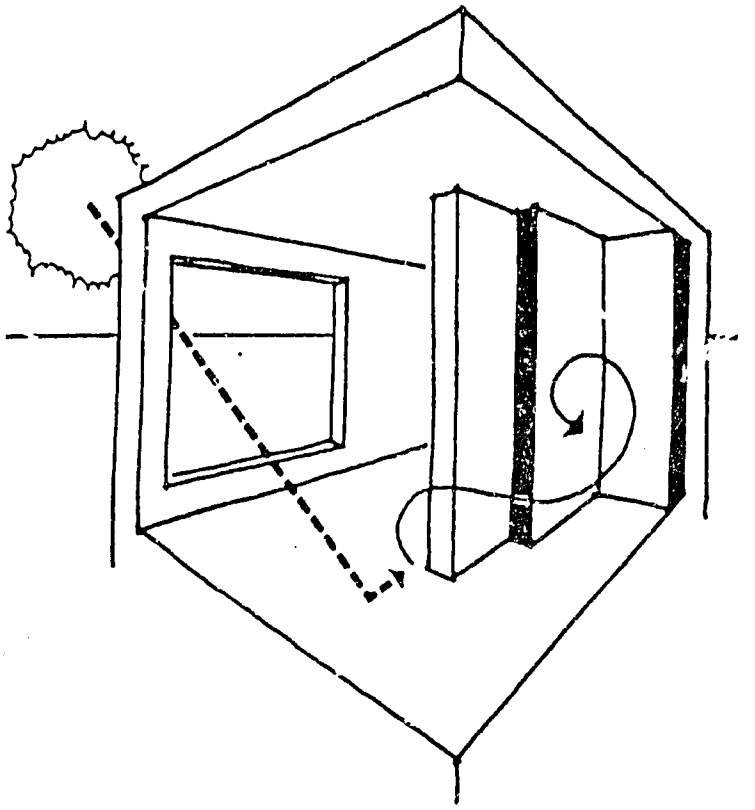
(In English Units)

Indirectly sunlit wall, floor or ceiling mass.

MASS SIZING TABLE

Masonry thickness (inches)	Indirectly irradiated mass surface area to passive aperture area ratio.
1	29
2	14
3	10
4	8
6	6
8	6

EXHIBIT 3-60e. Thermal Storage Pattern E

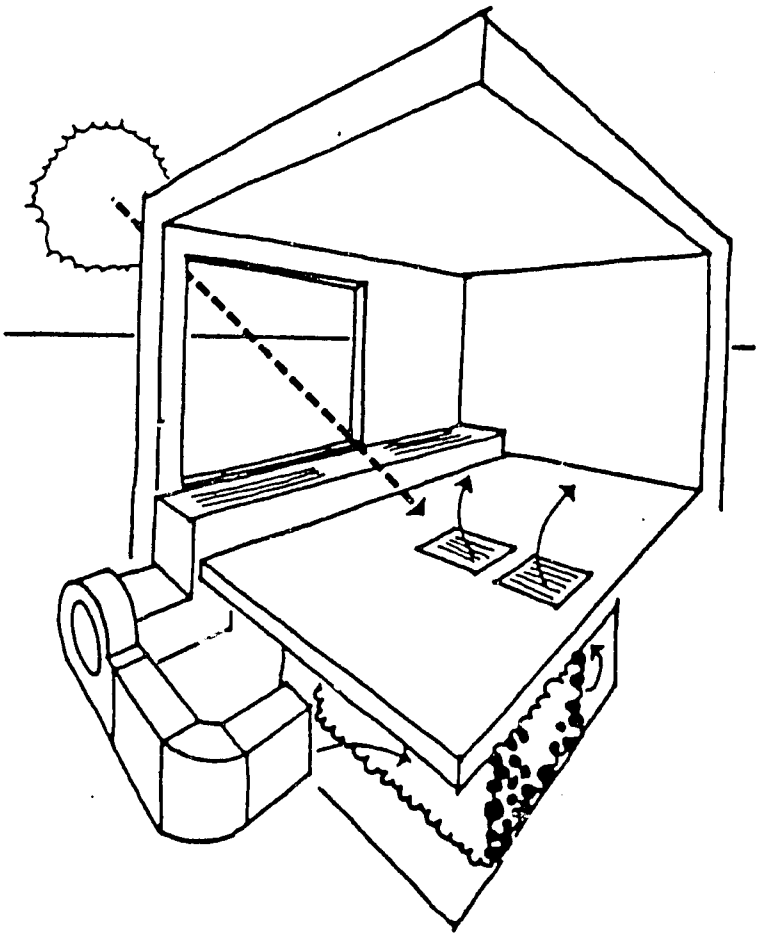


Remotely located wall, floor or ceiling mass; exposed only to heated air from sunlit spaces. No direct solar radiation.

MASS SIZING TABLE

Masonry thickness (inches)	Total mass surface area to passive aperture area ratio.
1	31
2	20
3	17
4	16
5	16
6	16

EXHIBIT 3-60f. Thermal Storage Pattern F



Remotely located, contained mass, operated in combination with fan-forced air circulation to moderate temperature swings in sunlit living spaces.

MASS SIZING TABLE

Rock volume to passive aperture area ratio. (cf/sf)	Air flow rate to passive aperture area ratio. (cfm/sf)
1½ - 2	6 - 9

EXHIBIT 3-60g. Thermal Storage Pattern G

- Locate thermal mass where it can conduct and radiate its stored energy to living spaces and be cooled by night breezes in the summer.

- The thermal mass should be in thermal contact with the ground; in addition, vapor barrier and perimeter insulation are needed down to the frost line (if applicable).

- Masonry: Use ratio of 2:1 between the area of an interior 8-inch (20.3 cm) thick solid masonry materials in direct sunlight and the area of south-facing glazing.

  Use ratio of 4:1 between the area of an interior 4-inch (10.2 cm) thick solid masonry material in direct sunlight and the area of south-facing glazing.

  Use ratio of 8:1 between the area of an interior 4-inch (10.2 cm) thick solid masonry in indirect or diffuse sunlight and the area of south-facing glazing.

- Water: Use 6 to 9 gallons (244.4 to 366.7 l/m^2) of water in dark-colored containers placed in direct sunlight for each square foot (square meter) of south aperture.

- PCM: Use 1 to 1-1/2 gallons (40.7 to 61.1 l/m^2) of phase change material (PCM) in containers placed in direct sunlight for each square foot (square meter) south aperture.

- Rock Bed: Use 1 cubic foot (0.152 m^3/m^2) of crushed rock, rounded 1 inch to 2 inches (2.5 cm to 5.1 cm) in diameter, for each two square feet (one square meter) of solar collector surface that supplies energy to the rock bed.

- Use corrugated face or rough textured concrete block for building new thermal storage walls. (These materials have more surface area than smooth materials for more efficient heat transfer).

- Fill existing hollow-core concrete bocks with poured concrete or with polyvinyl chloride containers filled with water to increase the thermal storage capacity of the existing wall. (Do not fill cores with sand or gravel because there is a large portion of dead air space between granules.)

Sizing a Thermal Storage Wall for Different Climatic Conditions

Average Winter Outdoor Temperature (°F) (degree-days/mos.)[1]	Square Feet of Wall[2] Needed for Each One Square Foot of Floor Area	
	Masonry Wall	Water Wall
Cold Climates		
15° (1,500)	0.72-1.0	0.55-1.0
20° (1,350)	0.60-1.0	0.45-0.85
25° (1,200)	0.51-0.93	0.38-0.70
30° (1,050)	0.43-0.78	0.31-0.55
Temperate Climates		
35° (900)	0.35-0.60	0.25-0.43
40° (750)	0.28-0.46	0.20-0.34
45° (600)	0.22-0.35	0.16-0.25

[1] Temperatures and degree-days are listed for December and January, usually the coldest months.

[2] Within each range choose a ratio according to your latitude. For southern latitudes (to 35°NL), use the lower wall-to-floor-area ratios, for northern latitudes (to 48°NL), use the higher ratios. For a poorly insulated building always use a higher value. For thermal walls with a horizontal specular reflector equal to the height of the wall in length, use 67% of recommended ratios. For thermal walls with night insulation (R-8), use 85% of recommended ratios. For thermal walls with both reflectors and night insulation, use 57% of recommended ratios.

EXHIBIT 3-61. Thermal Storage Wall (CEC-2)

Material	Recommended Thickness (in.)
Adobe	8-12
Brick (common)	10-14
Concrete (dense)	12-18
Water	6 or more

EXHIBIT 3-62. Recommended Mass Thickness (CEC-2)

- Remove interior insulation from existing south masonry walls used for Trombe walls.

- Remove carpeting or tapestries from portions of thermal mass (walls, floor slabs) which are struck by direct sunlight.

3.4.3 Shading Passive Apertures

It is necessary to provide nearly complete shading of the south, east, and west faces of a passive building during the cooling season to prevent increasing cooling requirements for the living space. It is essential that these shading devices have a minimal shading effect on the south face of the building during periods of needed solar gain.

The types of shading devices suitable for the south wall are considerably different than those most suitable for east or west oriented faces. Fixed shading devices cannot satisfy this shading requirement without being supplemented by other non-fixed (moveable) systems, trees, or vegetation.

As the seasonal heating calendar does not correspond to the solar calendar, fixed shading devices cannot provide full shading during the entire cooling season and at the same time provide no shading during the heating season. For example, if a fixed overhang over the south windows is designed to give no shading from October 21st to March 21st, it will also provide no shading on September 21st when shading would be desirable. Vice versa, if the shading requirement is satisfied for the cooling season, undesirable shading will occur during the winter. A fixed overhang designed for full summer shading will shade nearly half of the south windows in December. A fixed overhang designed for not shading during the heating season allows over half of the south windows to be irradiated during the peak cooling month of July.

Moveable or adjustable shading provides more optimal shading. There are a number of possible choices: moveable louvers, awnings, shutters, exterior hanging shades, or an open-frame trellis with seasonal foliage.

3.4.4 Sample Passive Designs

This section will present four preliminary designs commonly used: distributed/direct gain, thermal storage wall, attached sunspace, and thermal storage roof.

3.4.4.1 Direct Gain, Distributed Mass System

In a direct gain system, experience has shown that, when used, distributed thermal mass performs more effectively than mass concentrated in one particular location. It has been observed that mass that has been "spread around" or distributed stores energy more effectively and also provides better thermal comfort. In addition, distributed mass provides more surface area for contact with cool ventilation air in cooling applications.

The optimum construction configuration for this system type is a highly insulated, lightweight exterior shell with heavy interior structures. This configuration is a reverse of conventional designs in which the building has heavy exterior walls and lightweight partition walls.

The following table gives a range of relative values for the design of this system type. These values are intended to be used for schematic design purposes only.

Exhibit 3-63 illustrates a schematic diagram of a direct gain, distributed mass passive design.

DIRECT GAIN/DISTRIBUTED MASS PASSIVE SYSTEM

(CEC-3)

<u>Area of South Glazing</u>

Ratio of south glazing surface area to floor area being served = 0 to 0.33

Area of Distributed Mass

Heating emphasis: Ratio of distributed mass area to south glazing area: 1 to 8

Cooling emphasis: Ratio of distributed mass area to floor area being served: 1.0 to 3.5

Thickness of Distributed Mass

Floors: 2 inches to 6 inches, generally 4 inches (5.1 to 15.2 cm, usually 10.2 cm)
Walls: 2 inches to 4 inches (5.1 to 10.2 cm)

Openings for Night Ventilation

Area of A + B = 0 to 30 ft^2, (0 to 2.79 m^2)

Vertical Distance H Between Vents

H equals 8 feet to 16 feet (2.44 to 4.88 meters)

Flow Rate for Night Ventilation

Forced ventilation: 2000 cfm, (0.944 m^3/sec)
Natural ventilation: 1000 to 4000 cfm (0.472 to 1.888 m^3/sec)

3.4.4.2 Thermal Storage Wall System

Thermal storage wall systems come in many forms. Tube walls, unvented Trombe, vented Trombe, and water wall are just a few of the examples of an indirect passive systems or thermal wall system.

Numerous variations are available for this system. Thermosiphon loops are more effective in colder climates than in milder ones. It has been recommended that if the average January temperture is greater than 50°F (10°C) and good insolation occurs, vents can be discarded without loss of performance. The use of night insulation between the glazing and wall enhances the wall's efficiency. This can be accomplished by the use of a thermal shade between the glazing and wall, the use of a Beadwall^R, or the use of an exterior shutter. Water walls can be used instead of masonry or concrete. The behavior of a water wall is different due to internal convection currents which result in less thermal lag times. The greater thermal capacity of water permits thinner walls.

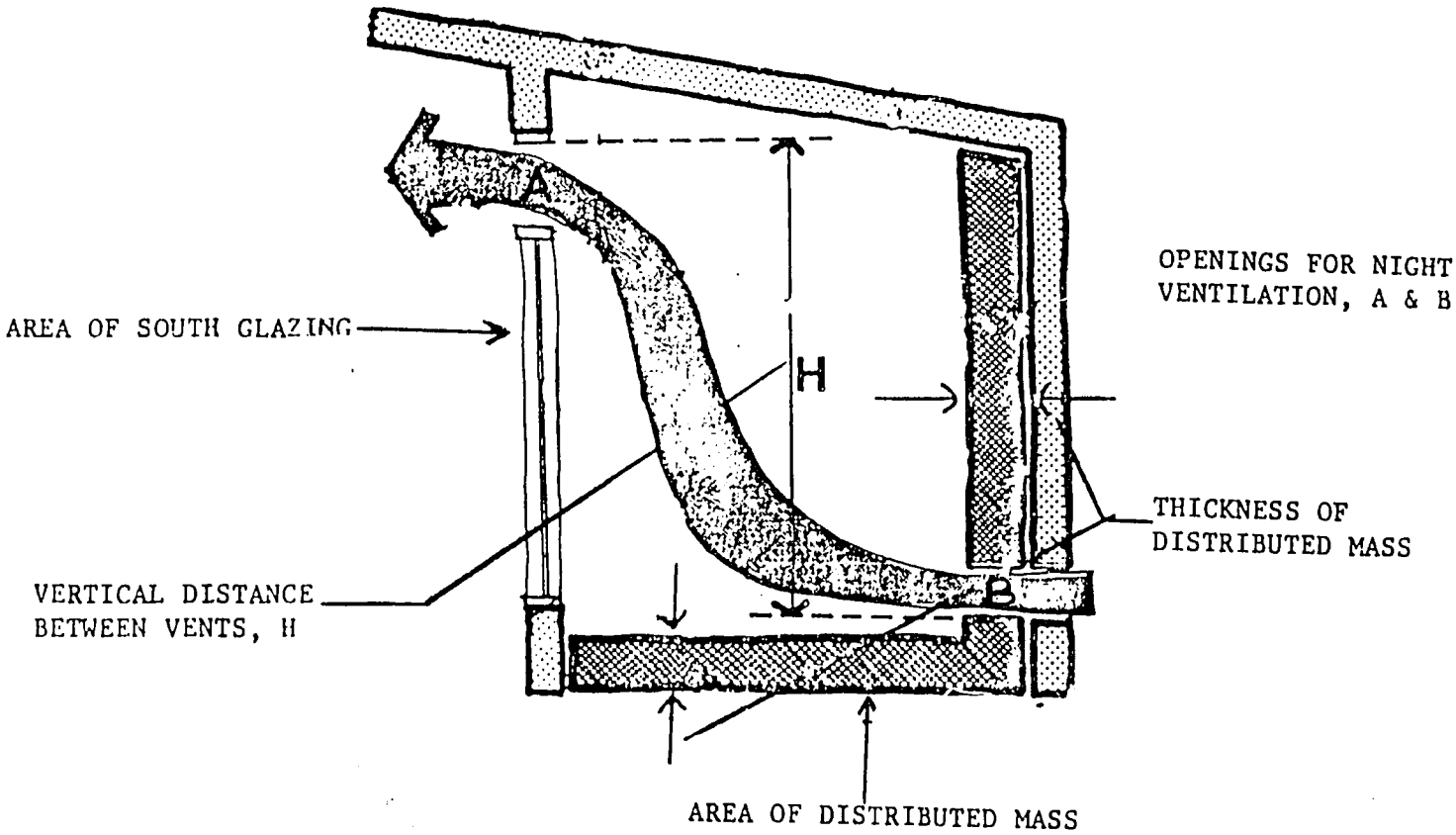


EXHIBIT 3-63. Direct Gain/Distributed Mass (CEC-3)

Exhibit 3-64 illustrates a schematic diagram of a thermal storage wall passive system.

The following table lists relative ranges of design variables for this system.

THERMAL STORAGE WALL SYSTEM

(CEC-3)

Area of Thermal Wall

Ratio: wall area to floor are served: .33 to .75

Storage Capacity of Wall

28 to 50 BTU/°F (572 to 1021 kJ/°C/m^2) heat storage for each sq. ft. of collecting surface. This amounts to 1.0 to 1.78 ft^3 (0.305 to 0.542 m^3/m^2) of concrete/ft^2 collector, or 140 to 240 pounds (63.5 to 108.9 kg) of concrete.

Thickness of Masonry Wall

4 to 18 inches--generally 8 to 12 inches (10.2 to 45.7 cm, generally 20.3 to 30.5 cm)

Width of Air Space Between Wall and Glazing

2 to 5 inches--generally 3 inches (5.1 to 12.7 cm)

Size of Thermosiphon Vents

(WHEN USED): Ratio of area of a set of upper & lower vents to the area of wall = 0.01

Temperature Range of Outer Wall Surface

55°F (12.8°C) at night to 155°F (68.3°C) during a sunny day

Temperature Range of Inner Wall Surfaces

Wall Surface: 65°F to 90°F (18.3 to 32.2°C)
Lag Time: Generally 6 to 8 hours

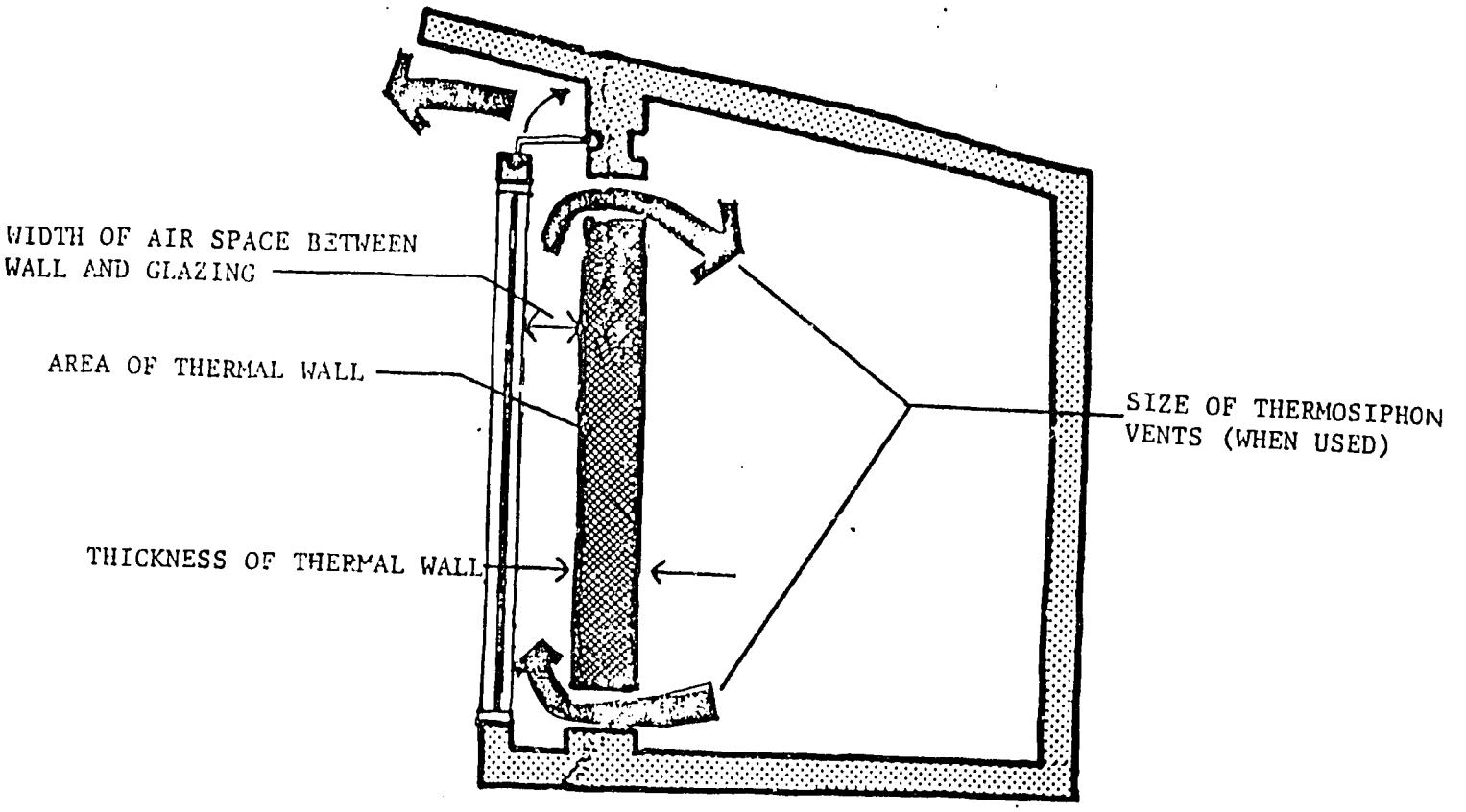


EXHIBIT 3-64. Thermal Storage Walls (CEC-3)

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3.4.4.3 Sunspace, Isolated Gain

The sunspace, greenhouse, or solarium is an intermediate environment between the interior and the exterior of the building. Because it is a thermally isolated space, large temperature swings can be accommodated.

Exhibit 3-65 provides a schematic diagram of a passive sunspace.

The following are preliminary design guidelines:

ISOLATED GAIN, SUNSPACE DESIGN

(CEC-3)

Area of Sunroom

Ratio of glazed area of sunspace to floor area of building being served = 0.1 to 0.5

Area of South Glazing

Ratio of floor area of sunroom to area of south glazing of sunroom = 0.6 to 1.6

Amount of Thermal Storage

Ratio BTU/°F of storage per square foot of sunroom floor area = 15 to 40, generally, 20 BTU/°F (306.3 to 816.8 kJ/°C/m^2, generally, 408.4 kJ/°C)

Area of Internal Vents

Area of A + B = approximately 1/6 of floor area of sunroom upper vent 1/3 larger than lower vent

Vertical Distance Between Vents, H

At least 6 feet, 1.83 meters

Area of Exterior Vents

Area of C + D = approximately 1/16 of floor area of sunroom.

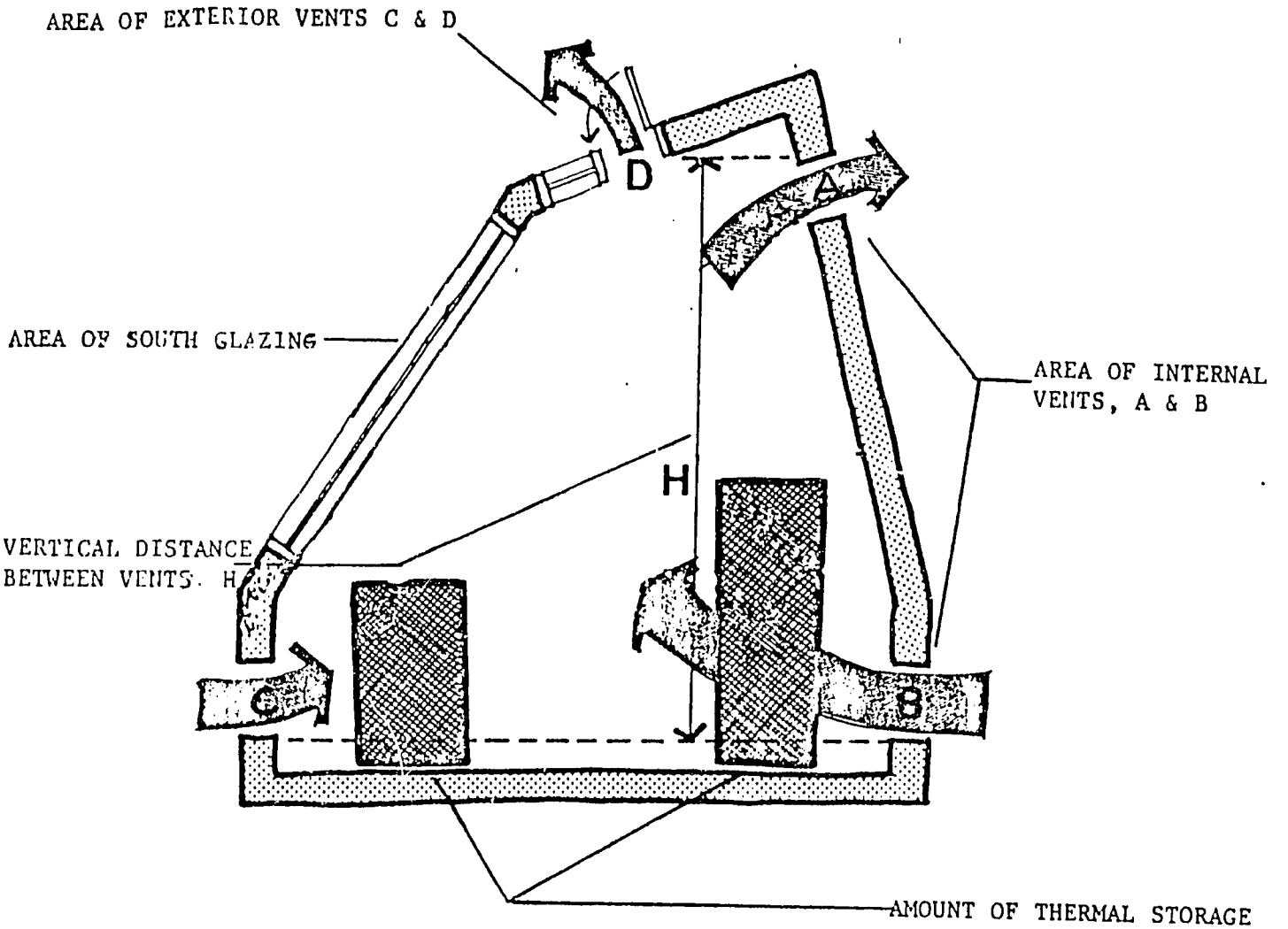


EXHIBIT 3-65. Passive Isolated-Gain, Sunspace (CEC-3)

3.4.4.4 Roof Pond, Isolated Gain

In this system, roof and ceiling are replaced with elements which serve as solar collector, energy dissipator, thermal storage, and solar control, as well as providing structure and protection.

As was mentioned, roof ponds exemplify of passive systems which emphasize, equally, solar heating and night sky cooling. Correctly designed, roof ponds are free from the rigorous orientation contraints of most other passive designs.

Exhibit 3-66 provides a schematic diagram of a roof pond system.

The following values provide information for the preliminary design of passive solar thermal storage roofs.

ROOF POND DESIGN

(CEC-3)

Area of Roof Pond

Roof of roof pond area to floor are being served: 0.3 to 1.0

Storage Capacity of Roof Pond

Heat capacity per square foot of pond: 20 BTU/°F to 65 BTU/°F (408.4 to 1327.4 kJ/°C/m^2

Dead Load on Roof

20 to 65 pounds per square foot (97.6 to 317.4 kg/m^2)

Thickness of Pond

4 inches to 12 inches (10.2 to 30.5 cm)

Thickness of Moveable Insulation

1.5 to 3 inches of expanded foam generally 2 inches, (3.8 to 7.6 cm)

Insulation Module Width

8 to 12 feet (2.43 feet to 3.66 meters)

Temperature of Pond

Heating: 70° to 90°F (21.1° to 32.2°C) to keep interior temperature at 67° to 72°F (19.4° to 22.2°C).
Cooling: 64° to 74°F (17.8° to 23.3°C) to keep interior temperature at 68° to 74°F (20° to 23.3°C).

Average Daily Interior Temperature Swing

Summer and Winter: 5° to 8°F (2.8 to 4.4°C)
Spring and Fall: 3° to 6°F (1.7 to 3.3°C)

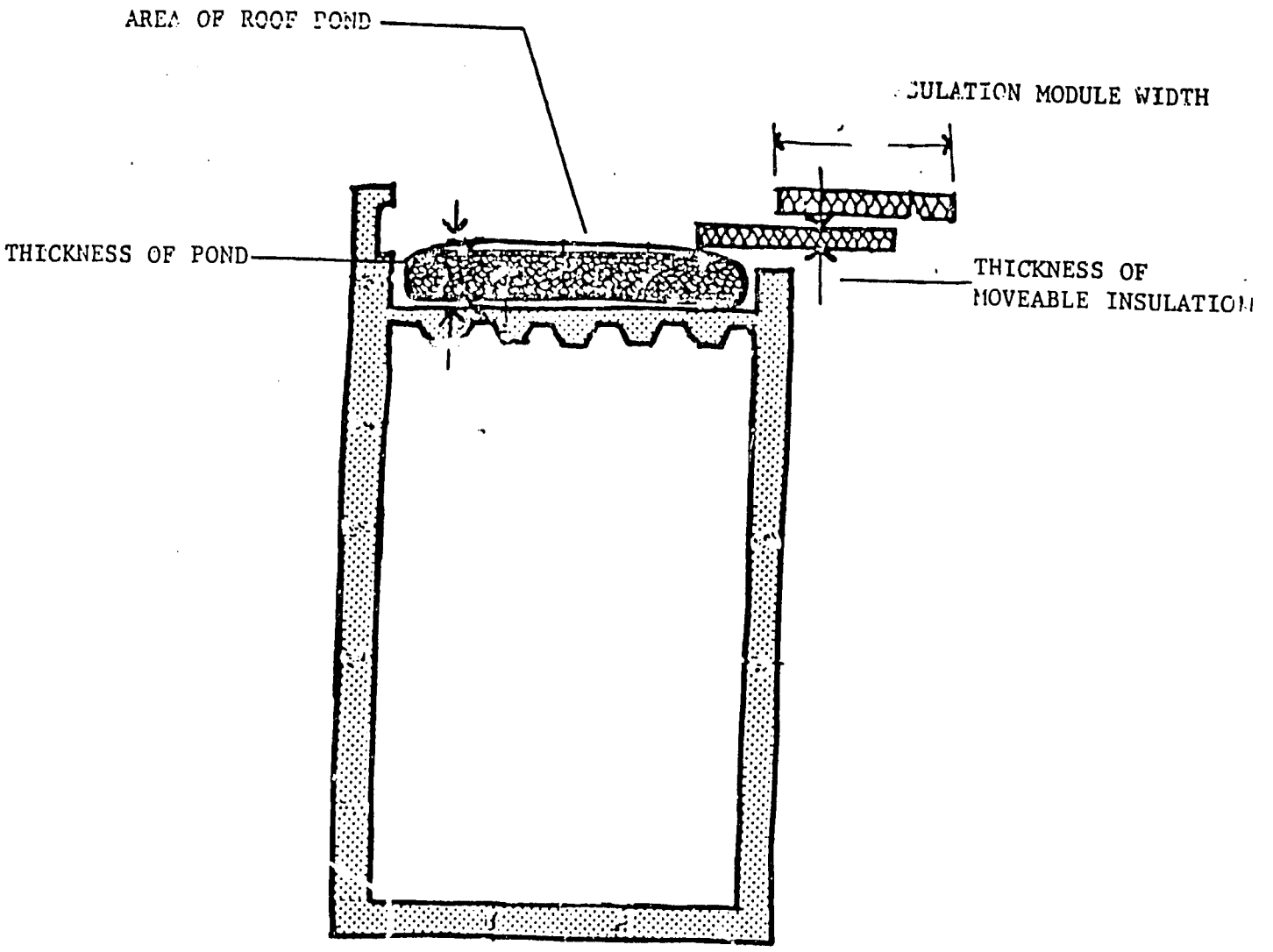


EXHIBIT 3-66. Thermal Storage Roof (CEC-3)

4. ACTIVE HEATING SYSTEMS

4.1 Introduction

"Active" solar heating systems are distinguished from "Passive" systems, comprising mainly static components, by the use of equipment especially dedicated to the collection, storage, and distribution of solar energy in a controlled manner. This technology employs dynamic means to augment energy conservation and management methods inherent in competent architectural practice, which optimizes utilization of solar energy resources by selective arrangement and orientation of structural features. As with any rational design resolution, the energy-saving contribution of passive solar methods must be integrated with active system components to maximize the overall efficiency of the functional composite system.

The essential elements of an active solar heating system are:

1. Solar Collector
2. Storage Facilities
3. Distribution System-Piping, Ductwork, Fluid Movers
4. Control System - Sensors, Switching Elements, Fluid Flow Modulators

Two general types of solar heating systems are well-developed conceptually and have been demonstrated extensively in performance evaluations. The two systems are functionally similar, differing basically in the types of energy collection and transport media employed. In one instance, the operating fluid is water, or a freeze-resistant aqueous solution (such as a glycol-water mixture). The second type uses a gas-phase transport medium, most commonly air. Aside from necessary differences in the collector and load interfaces due to fluid properites, the two types have similar configurations.

4.2 Liquid Space Heating Systems

Exhibit 4-1 illustrates a rather sophisticated active liquid heating systems which includes domestic hot water capability. Each of the components has been discussed in Section 2. The following discussion will address the operation of the system of connected components.

Solar energy contacts the collector as radiant heat. Water, circulated through the collectors by Pump No. 1., forces the heated water through the heat exchanger. This is referred to as the primary loop.

In the heat exchanger the thermal energy is transferred to the secondary loop of water which is pumped through the solar storage tank by Pump No. 2.

As long as the S1 (sensor or thermostat) senses hot water at or above the set point of sensor S1, Pump No. 1 operates. At night or during cloudy days, the collector will not heat water; as a result, sensor S2 senses cold water and acts to shut down Pump No. 1 and Pump No. 2.

There is a sensor, S3, in the building which is set so as to maintain a given constant temperature within the building. When that sensor detects that some heat must be introduced into the building, Pump No. 3 is activated and warm water is pumped out of the solar storage tank through Valve #1 which is open; Valve #2 is closed so the water must flow through the load heat exchanger inside the building. When sensor S3 is satisfied, Pump No. 3 is turned off. If sensor S3 calls for heat and the temperature of the solar storage tank water, as seen by sensor S2, is too low to deliver any heat to the load heat exchanger, Valve #1 is closed; Valve #2 is opened, and Pump No. 3 forces water through the auxiliary boiler which is heated by electricity, oil, coal or gas. The source of heat for the auxiliary boiler is not shown, and is normally selected to be the most favorable economic option.

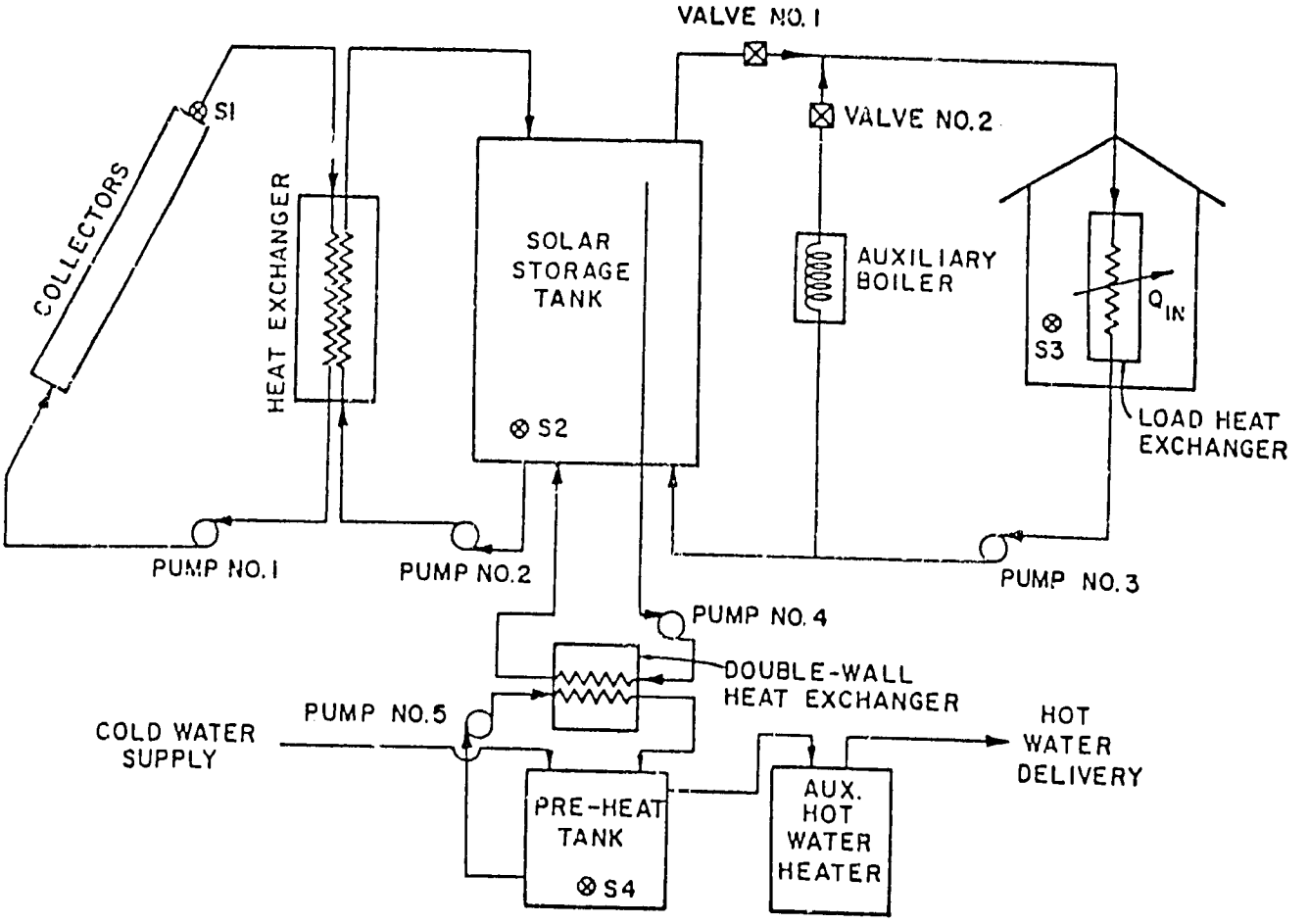


EXHIBIT 4-1. Sensor Locations in a Typical Liquid-Heating System (SOL-1)

Heat demand for the building is furnished from the auxiliary boiler until such time as sensor S2, "indicates" the solar storage tank water is at a useful temperature.

The desired domestic hot water temperature is generally higher than that which can be supplied by an optimum design solar space/water heating system. Solar-derived energy is employed to "pre-heat" (raise the temperature of) the incoming supply water to the limit that it can. The additional heat required to raise the water to the desired tempeature is furnished by an auxiliary heater.

In the system shown in Exhibit 4-1, the cold water supply flows through a pre-heat tank which is, in effect, a storage tank. Whenever sensor S4 detects that the temperature of the "holding" storage tank decreases, it turns on Pump #5 and forces some of the water through the double-wall heat exchanger. This heat exchanger transfers heat from the solar storage tank water that is forced through it by Pump No. 4. Should sensor S4 call for heat and sensor S2 indicate that none is available from solar storage, Pump #4 and Pump #5 are shut down.

Th auxiliary hot water heater has its own sensor set at the desired temperature for delivery to the hot water end-use. The auxiliary heater raises the temperature of inlet water from any received value to the desired delivery temperature.

The hot water must be potable. A double-wall heat exchanger should be used in order to insure that solar storage tank water does not leak into the hot water.

4.3 Air Heating Systems

4.3.1 Overview

Solar air-heating systems have four basic modes of operation:

1. Space heating directly from the solar collector.
2. Heat storage.
3. Space heating from storage.
4. Space heating using an auxiliary heating source.

Heat transfer between an absorber and air is less efficient than that between an absorber and a liquid. Therefore, certain steps are taken to increase the effectiveness of heat transfer. These are increased surface area (for heat transfer), relatively high air flow rate and increased turbulence.

The principal difference between liquid and air collector designs is the size and configuration of fluid conduits. The air passages are wide, permitting air flow to contact nearly the entire absorber surface. The channels are small in height so that air velocity will be sufficiencly high. Too high an air velocity can generate noise in the ducts and heated space.

Because air is not a corrosive fluid, cheaper metals such as aluminium or carbon steel can be used in the absorber plate or frame without danger of corrosion from the heat transfer fluid.

4.3.2 Air Heating Operation Description

The components for an air-based system are similar to that in the liquid-based systems. Exceptions are that blowers or fans replace pumps and dampers replace valves. In this example a pebble-bed is used for thermal storage as illustrated in Exhibit 4-2.

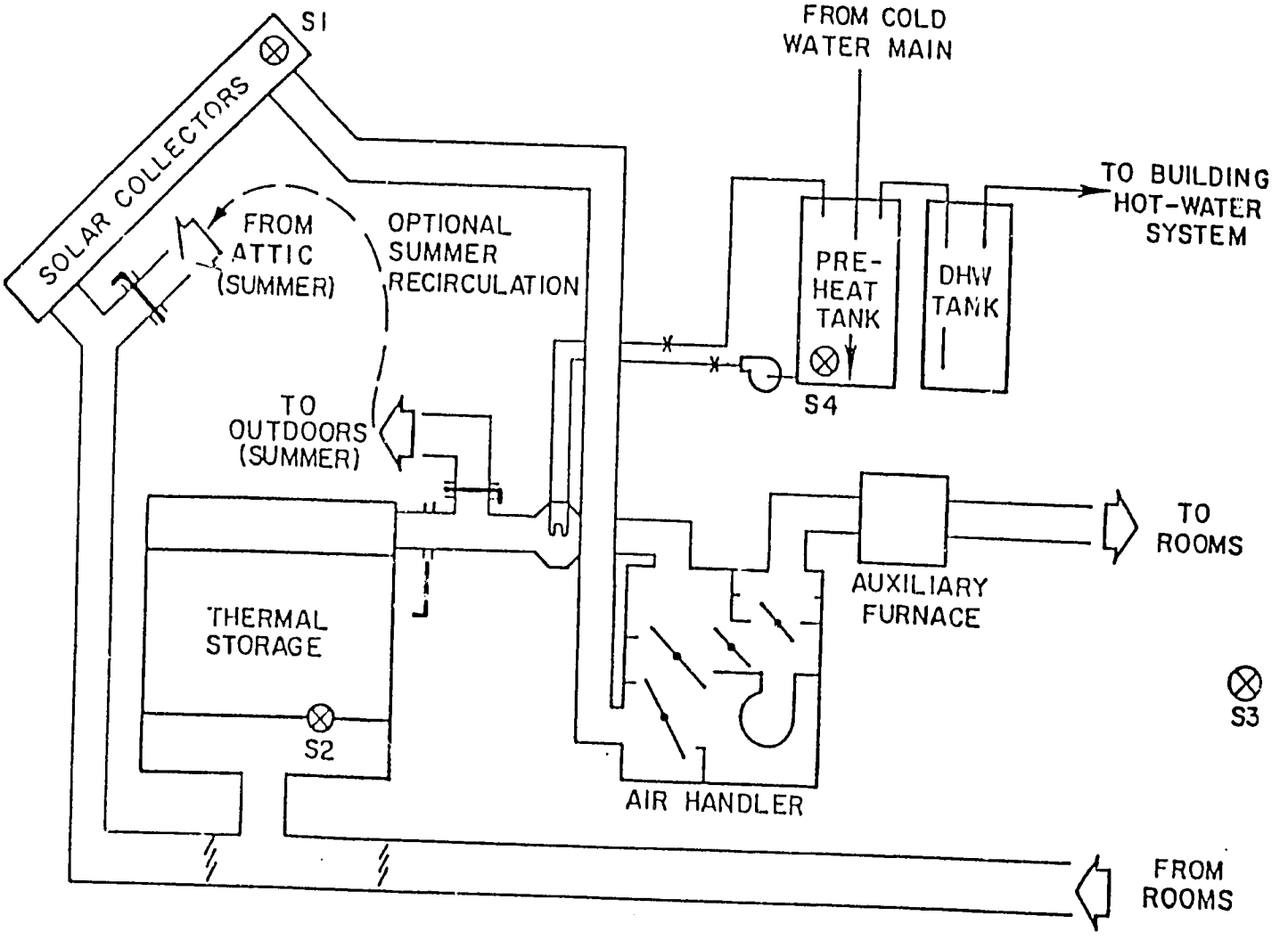


EXHIBIT 4-2. Sensor Location in a Typical Air-Heating System (SOL-1)

As in the liquid-based example, sensors are located near the top of the solar collector (S1) at the bottom of storage or in the air duct supplying the collector (S2), and in the living space (S3). Sensor S1 is located in the air stream near the top of the collector or attached to the back side of the absorber plate.

Collection in an air-based system is initiated whenever the temperature difference between the readings of sensors S1 and S2 is greater than a preset amount. When this occurs, the blower in the air handler is activated and heat is delivered from the collectors. A major difference between air-based systems and liquid-based systems is that the air system can be controlled to deliver heat directly to the rooms as well as to storage.

4.3.2.1 Delivering Collected Solar Energy to Storage

When the blower is activated, the dampers in the air handler are simultaneously positioned so that air is circulated through the blower and into the top of the storage bin. Since the pressure at the back air damper (at the bottom of the storage bin) is greater than atmospheric, the damper closes and air is directed to the collectors. The bed is designed so that the pebbles at the bottom of the bed remain close to room temperature throughout the operational day. As the day progresses, a temperature stratification develops in the pebble bed.

A series of cycles occurs during the early morning hours and during the late afternoon. These cycles are the same as those described in Section 4.2. The blower is activated when the temperature difference between sensor S1 and sensor S2 is a preset amount (typically 15°F, 8.3°C). As soon as the blower is activated, cooler air is blown into the collector which cools the collector. The temperature difference between S1 and S2 decreases until another setpoint is reached. The blower is then deactivated. The cycle begins once more when the stagnant air in the collector warms and the upper setpoint temperature difference is reached; the blower is activated again at that time.

4.3.2.2 Delivering Collected Solar Energy to Rooms

When sensor (or thermostat) S3 senses that room heating is required, dampers in the air handler are positioned so that air is directed to the rooms. The pressure in the duct leading to the collectors is now subatmospheric so that the air flows through the backdraft damper. If the temperature of the air stream is insufficient to satisfy the demand, the second stage of the thermostat is contacted. The auxiliary furnace is now enabled.

4.3.2.3 Heating From Storage

Sensor S3 controls room heating from storage. Usually a two-stage sensor is utilized. The first stage enables stored solar heat to be used to fulfill the heating demand. When the stored solar energy is inadequate to meet the need, the second stage of the sensor activates the auxiliary energy source. Room air is always circulated through the storage bed; thus, all stored energy, regardless of temperature, is utilized for space heating.

5. ACTIVE SPACE COOLING

5.1 Introduction

Space cooling or space conditioning results when heat is removed from air a room which results in a lowered temperature. In certain types of systems, the lowering of temperature can be accompanied by a reduction in humidity. The resulting effect on a human being can be an increased sense of comfort. Space cooling systems are classified as either refrigeration, desiccant or evaporative cooling. Solar energy may be used either directly or indirectly as the primary energy source.

5.2 Refrigeration Systems

5.2.1 Cycle Description

In a refrigeration cycle cooling is achieved by removing heat from air or water as it comes in contact with a cold surface. Exhibit 5-1 provides a schematic of a solar-powered vapor-compression air conditioner. The cooled surface is maintained at a lower temperature by evaporating a liquid at a lower temperature from the opposite side. This effect occurs in the evaporator shown in Exhibit 5-1. Heat absorbed by the evaporating refrigerant is supplied by the air or water being cooled. The most common way of providing the energy necessary to supply the refrigerant is by a electrically powered compressor which raises the pressure of the refrigerant vapor so that it can be condensed at a lower temperature and pressure.

Another process for supplying refrigerant to cool air or water involves the heating of a mixture of refrigerant and absorber liquid. The refrigerant is condensed and evaporated as in a vapor-compression cycle, then reabsorbed and returned to the generator where it is reheated.

At the present time, of the two principal types of commercially available refrigeration units, only the absorption type is driven by solar energy.

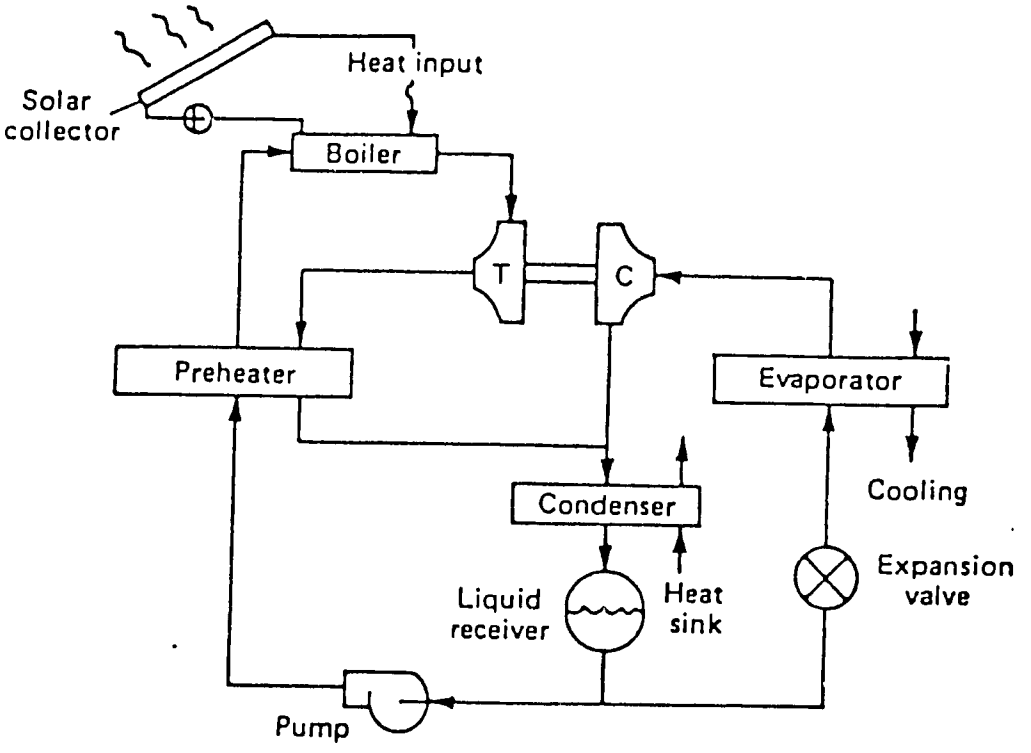


EXHIBIT 5-1. Schematic Drawing of a Single Fluid, Solar Powered Vapor Compression Air Conditioner. (KRE-1)

5.2.2 Absorption Refrigeration

The two basic absorption systems are the lithium bromide-water and the ammonia-water systems. Solar-heated hot water from solar collectors can be used to supply the necessary energy for the process. Presently, the lithium bromide-water system exhibits the most promise for solar applications because it will operate at lower temperatures than the ammonia-water systems. Exhibit 5-2 provides a schematic diagram of a solar-powered absorption refrigeration system.

5.2.2.1 LiBr-H_2O System Operation

Water acts as the refrigerant and lithium bromide as the absorber. The cycle begins when the lithium bromide-water solution at 28°C (82°F) in the generator.

(see Exhibit 5-2, position A), is heated by utilizing 71°C (160°F) to 99°C (210°F) hot water from the solar collector. At the low pressure in the generator, a portion of the water in the lithium bromide-water solution is converted to vapor. This water vapor is directed into the condenser, (position B), where it is cooled about 40°C (104°F) by a heat exchanger located inside the condenser. Upon being cooled, the water vapor condenses. This liquid passes through an expansion valve where part of the water is vaporized and then the vapor-liquid mixture passes through the evaporator coils, (position C), at 4°C (39°F). When warm air from the building passes between the evaporator coils, both heat and moisture are removed from the room air. This results in lowering both the temperature and humidity of the air in the building.

The warmed refrigerant flowing through the evaporator coils is then transported back to the absorber (position D), where the refrigerant (water) mixed with the concentrated lithium bromide solution from the generator at a temperature of 38°C (100°F). While the refrigerant from the evaporator is being mixed in the absorber, heat is released and removed by cooling tower water. The cooled absorber liquid is then

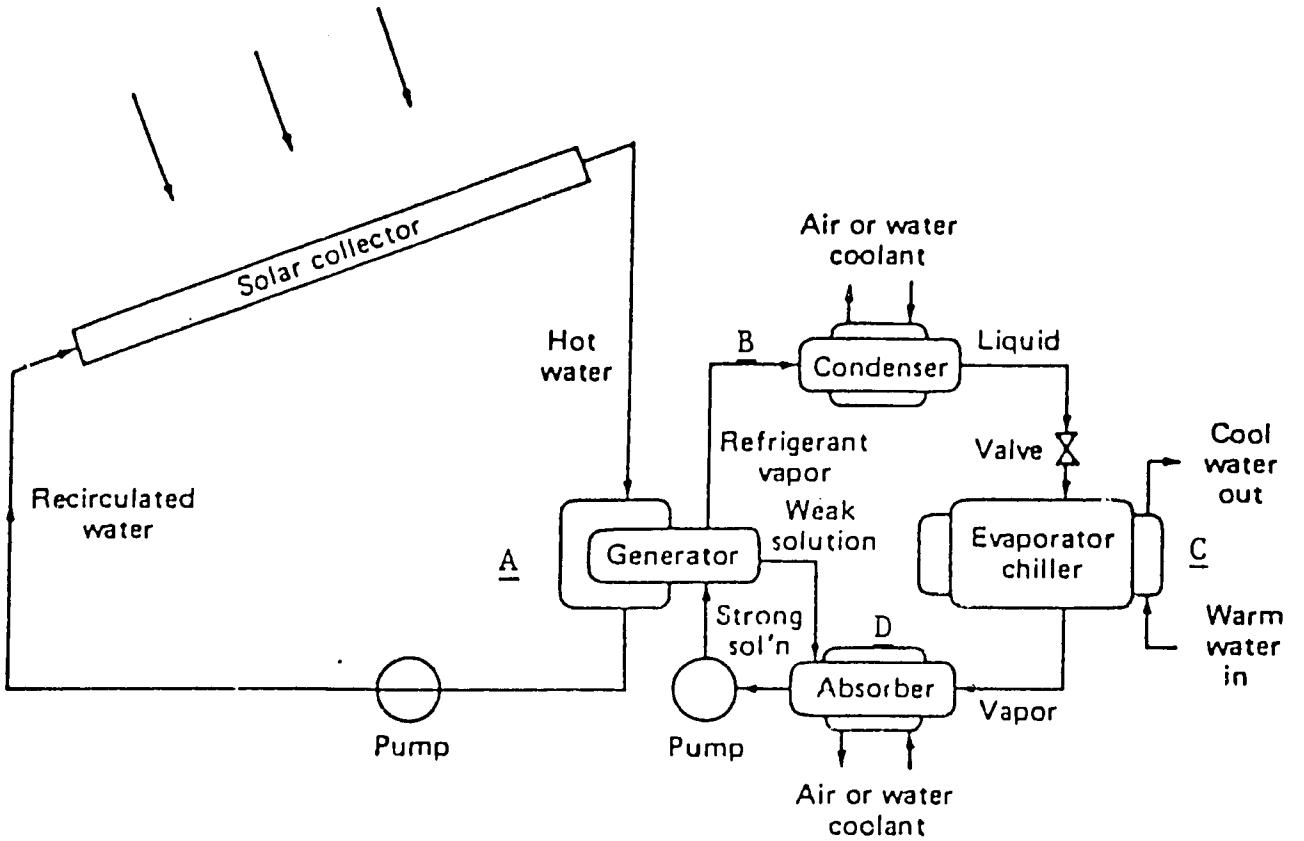


EXHIBIT 5-2. Schematic Diagram of a Solar Powered Absorption Refrigeration System (KRE-1)

pumped back to the generator to repeat the absorption cycle. Heat is transferred from the liquid solution flowing from the generator into the absorber to the cooler dilute soltuion flowing from the absorber into the generator. This preheating increases the efficiency of the absorption system.

5.2.2.2 LiBr-H_2O Temperature Restrictions

The temperature of the hot water supplied by the solar collectors to the generator is usually between 71°C (160°F) to 99°C (210°F). The heat input to the generator must be sufficient to boil the refrigerant (in this case water), from the solution. If the water temperature is below 71°C (160°F), the heat transfer rate may be too low for effective operation. Low temperatures in the recuperator can result in crystallization of lithium bromide in the outlet tube leading from the recuperator to the absorber.

Cooling water temperature is dependent upon atmospheric temperature and humidity. Design cooling water temperature is normally 27°C (81°F), but variation is common.

5.2.2.3 Types of LiBr-H_2O Absorption Systems

There are two types of lithium bromide-water absorption systems. The first type is a direct expansion tube. In this system air is circulated from the building to the evaporator coil where cooling and dehumidification take place. In the second type, water is cooled by circulation through the coil. Chilled water is then pumped through a separate fan-coil unit through which room air is circulated.

5.2.2.4 Design Rating

Refrigeration performance is indicated by two terms, "tons of refrigeration" and "coefficient of performance (COP)". "Tons of refrigeration" refers to the cooling capacity of the machine. One ton

of refrigeration is equiavalent to a heat removal rate of 12,000 BTU/hr or 3514.5 W. The COP indicates the efficiency of the refrigeration system.

$$COP = \frac{\text{Thermal energy removed}}{\text{Energy supplied from external sources}}$$

The COP is determined by dividing the design delivered capacity by the design input hot water requirements.

At the present time, most lithium bromide-water absorption machines operate with COPs ranging from 0.60 to 0.80. A COP less than one means that more energy is supplied to the refrigeration machine than is removed by the machine.

Commercial units are available in capacities ranging from 250 to 4200 thermal kW, driven by hot water at temperatures below 125°C (257°F). For commercial building applications, absorption equipment provides chilled water temperatures from 5°C (41°F) to 12°C (54°F).

5.2.2.5 Integration with Existing Solar Equipment

A number of components in a solar absorption air conditioning system may be shared with the solar space heating and/or solar domestic hot water system. Integration of these systems is generally done for economic reasons. In many installations, shared components include:

1) Solar collectors.
2) Backup boiler (auxiliary energy source)
3) Fan-coil unit
4) Storage tank
5) System control device
6) Piping and duct lines

In addition to the absorption unit and the previously mentioned components, a cooling tower is necessary for the absorption unit to operate properly.

The cooling water is sized to match the heat rejection requirements of the air conditioning unit. Thus, the higher the cooling capacity, the larger the cooling tower will have to be. For example, Yazaki cooling towers range from 0.67 m (2.2 ft) in diameter and 1.6 m (5.25 ft) tall for the 1.3-ton Yazaki residential unit to 5.7 m (18.7 ft) long, 2.0 m (6.57 ft) wide, and 2.7 m (8.86 ft) tall for their commercial size units.

5.2.2.6 Solar Absorption Systems Maintenance

Water mixed with antifreeze is generally used in the chilled water section of a solar absorption unit and needs to be periodically checked. The antifreeze solution prevents water in the evaporator coils from freezing. Another problem involves condensing water and the cooling tower. In most installations, the water running through the piping between the absorption unit and the cooling tower is tap water. When water evaporates in the cooling tower it leaves behind scale and solid particles. As water evaporates in the cooling tower, the concentration of particles present in the condenser increases, leading to scaling and corrosion in the condenser. This can be alleviated by allowing some of the water to bleed off. As this bleed-off water is drained from the cooling tower, fresh makeup water is introduced, compensating for water loss due to blow-down and evaporation.

Usually manufacturers supply suggested bleed-off rates. An approximation is provided by the following relations: (In English Units)

$$B = [M_H/(S_H - M_H)]E$$

B = bleed-off rate in gpm

M_H = makeup water hardness (ppm)

S_H = sump water hardness (ppm)

E = rate of evaporation (gpm)

and

$$E = C_R * R_F * 24/H_E$$

C_R = capacity of refrigeration (tons)

R_F = refrigeration machine heat rejection factor

H_E = heat of vaporaization for condenser water (1050 BTU/lb)

5.2.3 Solar-Assisted Heat Pump

A heat pump is basically a reversible refrigeration machine. In the heating mode, heat is produced as the compressor compresses the refrigerant. The heated refrigerant vapor is then transferred through the vapor line into the room to be heated. As the warm refrigerant vapor liberates heat to the room interior, the refrigerant condenses to form a cooler liquid. The liquid refrigerant then passes through an expansion valve to the exterior of the building where the cool liquid vaporizes. In this cold gaseous state, the refrigerant absorbs heat energy from the outside air and is transported back to the compressor where the cycle is repeated. In the cooling mode, the cycle is reversed. Heat is absorbed inside the building by the refrigerant and is rejected outdoors.

The heat pump, because of its ability to transfer energy efficiently from one point to another, has a high coefficient of performance (often as high as 4). However, as the outside air temperature drops, the heat pump's COP also drops.

The heating capacity of the heat pump can decrease to a point where it cannot supply the needed heat load. By using a solar collector to supply heat to the heat pump during cold outdoor temperatures, the efficiency of the heat pump is greatly increased. If a storage tank is also incorporated into the solar-assisted heat pump system, the heat pump will be able to function efficiently at night using stored solar-heated water.

5.2.4 Solar Rankine-Cycle Engine

In air conditioning applications, the solar Rankine engine replaces the electric motor used in operating the compressor in a vapor-compression refrigeration machine. Exhibit 5-3 provides a schematic drawing of a solar-Rankine vapor-compression system. In the cycle, a fluid, (usually a fluorocarbon), is heated in the boiler by solar-heated water. The liquid is vaporized and passed through a turbine. Work extracted from the turbine powers the air conditioning compressor. The gas leaving the turbine is cooled in a regenerator and is further cooled by cooling tower water circulating through the condenser. As the gas cools, it liquifies in the condenser, flows into a receiver, and is then pumped to the regenerator and back into the boiler.

In the air conditioning section, the cycle begins by the solar Rankine powered compressor compressing low pressure refrigerant gas for the vapor compression cycle.

This Rankine cycle engine is still in the testing and research stage and is not available for purchase as of this writing.

Exhibit 5-4 summarizes the advantges and disadvantages of the feasible active cooling technologies discussed.

5.2.5 Desiccant Cooling (Dehumidification) Systems

Cooling is accomplished in the desiccant cooling system by using solid or liquid sorbents to remove most of the water vapor from the air. Solar heat can then be used to regenerate the sorbent materials by driving off the collected moisture.

Solid materials such as silica gel or molecular sieves have the ability to adsorb water vapor because of their structure and makeup. These materials consist of billions of tiny pores.

Liquid sorbents function by presenting a lower vapor pressure than water at a given temperature, thereby reducing the equilibrium dew point.

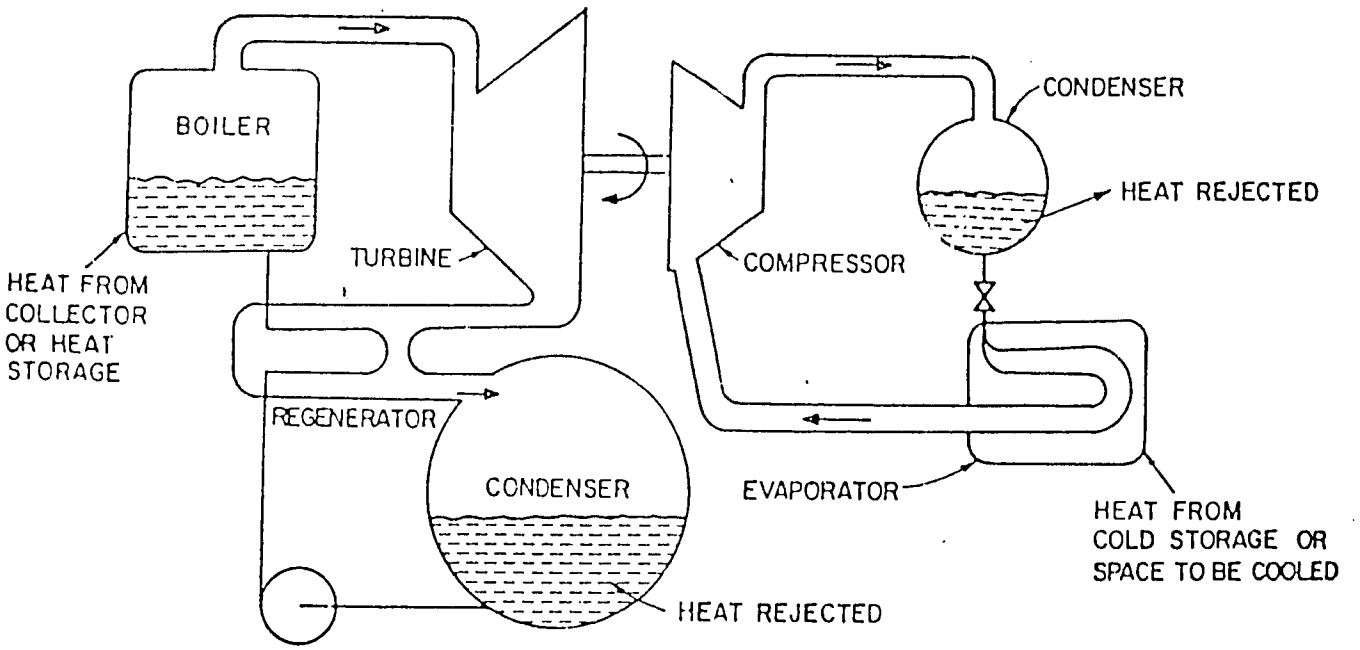


EXHIBIT 5-3. Rankine Cycle Vapor-Compression System (SOL-2)

Cooling Process	Advantages	Disadvantages	Overall COP Attainable	Status & Potential for Solar Cooling
Solar Rankine Vapour Compression	Wide range of operating temperatures. System may be designed to eliminate most pumping operations. May be used in heat pump mode and for electricity production during periods when cooling not required.	Noisy operation. Control problems during variable insolation.	0.32 Assumes COP Rankine cycle/ VC unit = 1.05. Collector efficiency = 30%	A number of systems are currently being tested. More research and development required to improve performance and reliability.
Photovoltaic Vapour Compression	No auxiliary pumps required. May be used in heat pump mode and electrical energy may be used for other applications during non-cooling periods. Silent operation.	Current high cost of photovoltaic panels. Necessity to convert DC to AC supply. High cost of electrical storage.	0.25 to 0.38 Assumes cell efficiency = 10%. COP VC unit = 4	Technically feasible. High cost of photovoltaics and balance of system presents major barrier.
Absorption Closed Cycle	Quiet operation. Can be operated by heat energy.	Auxiliary power needed to drive pumps and fans. Economics poor where heating not required.	0.18 Assumes collector efficiency = 30%	Commercial systems currently available. Further development required to improve reliability and performance.
Adsorption Closed Cycle	Simplicity. Quiet operation.	Disadvantages expected to be as those for closed absorption systems.	0.2 Estimate	No known solar applications but appears to have a potential equal to that of absorption closed cycle.

ADAPTED FROM LEIGH (1980)

EXHIBIT 5-4. Summary of Feasible Active Solar Cooling Methods and Their Applicability as Practical Alternatives to Conventional Systems (SAU)

5.2.5.1 Solid Desiccant Systems

These systems are still in the research and development phase and are not widely available commmercially, if at all. Prototype systems currently perform at coefficients of performance (COP) of 0.5 to 0.6.

Exhibit 5-5 provides schematic diagram of a solid-phase solar-powered adsorption systems. Outside air is dehumidifed by passing it through a matrix of desiccant material (such as silica gel). The air is simultaneously heated (by release of the heat of adsorption) and cooled (by a rotary heat exchanger). Afterward the air is passed through an evaporative cooler where the warm dry air is cooled by evaporation of water.

In the reverse cycle, air is returned to the system from the building and passed through the evaporative cooler to provide a "cold sink" temperature. After the cool air picks up heat in the exchanger, it is heated by fluid from a solar collector to a temperature high enough to "regenerate" (i.e. remove water from) the desiccant bed. The air is then exhausted outside the building. An open cycle solid desiccant cooling system is shown in Exhibit 5-6.

This system can also operate in a recirculation mode. Air from the building is circulated through the cooling section and outside air is used for the regeneration section. This method of operation is preferable when the humidity of the outside air is high and the ventilation mode cannot operate properly.

5.2.5.2 Liquid Desiccant Systems

Both organic and inorganic solutions have hygroscopic properties that permit some of them to be used in solar-energized cooling.

Exhibit 5-7 provides a diagram of a liquid desiccant system. In this type of system, the air to be conditioned is blown through a spray chamber and coil over which concentrated solution is applied. The coil

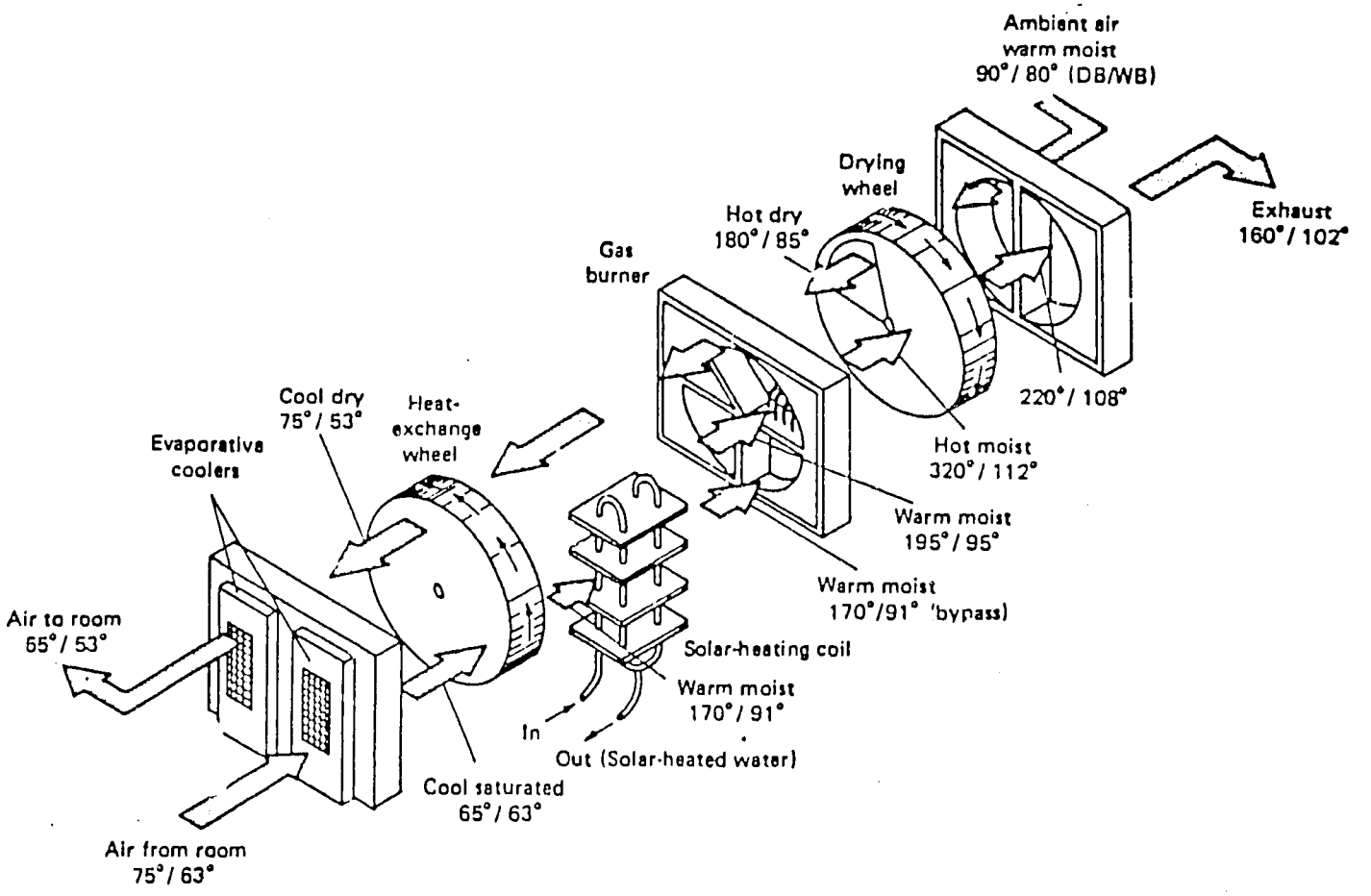
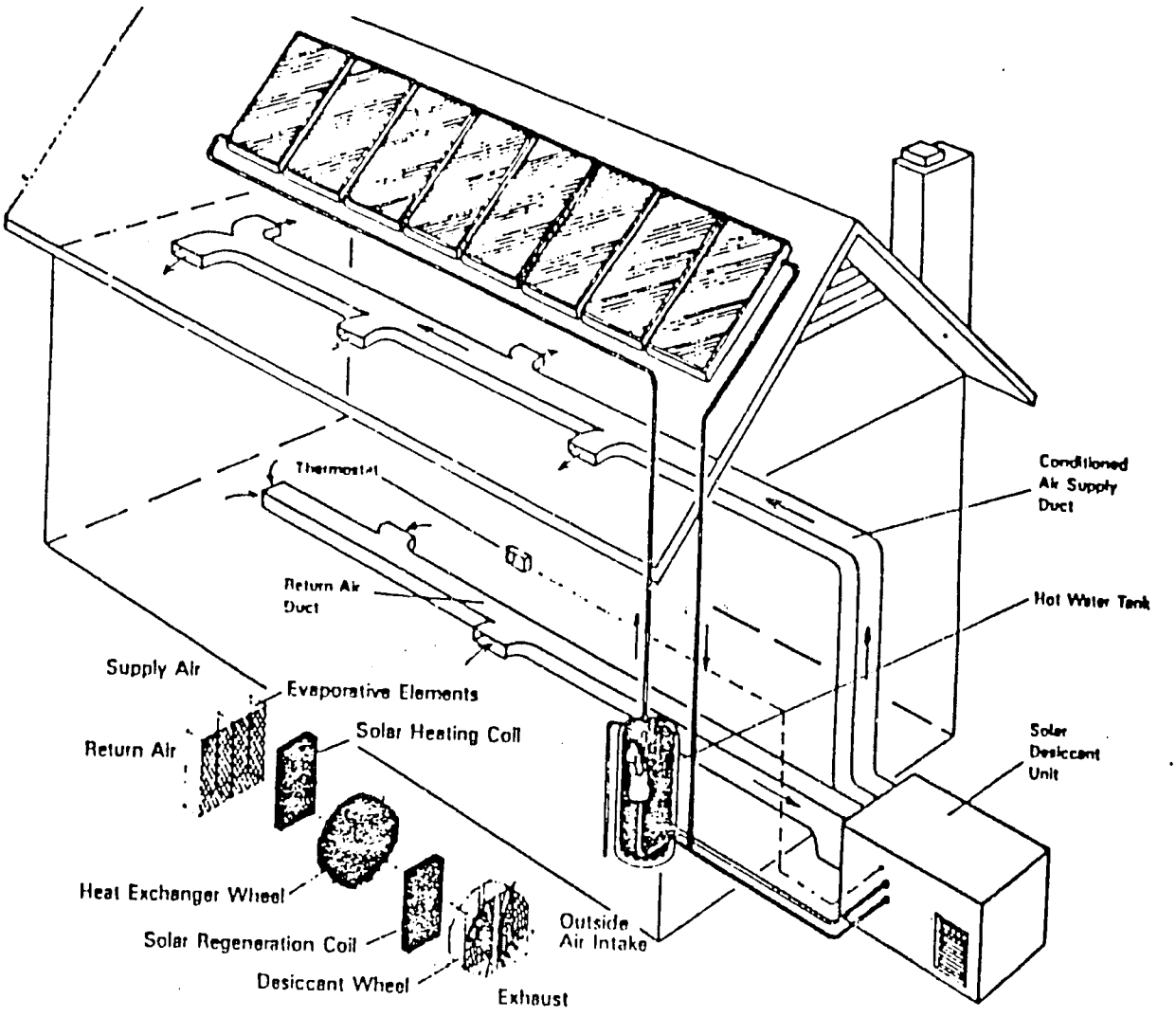


EXHIBIT 5-5. Schematic Diagram of a Solid-Phase Solar-Fired Adsorption-Dehumidification System That Uses a Molecular Sieve, (Munter's Environmental Control System). An Evaporative Cooling Stage is Also Shown. (In English Units), (KRE-1)

is cooled by a cooling tower to keep the air and solution at a low enough temperature for dehumidification to occur. The weakened solution drops into one section of the sump from which it is pumped through a heat exchanger to a second spray chamber through which scavenging air is passed to reconcentrate the solution.

The reconcentrated solution passes back through the heat exchanger to a separate section of the sump from which it is pumped back into the first chamber for dehumidifying more of the conditioned air stream.



Open Cycle Solid Desiccant Cooling System

EXHIBIT 5-6. Source: U. S. Department of Energy Solar Buildings Program (DOE-3)

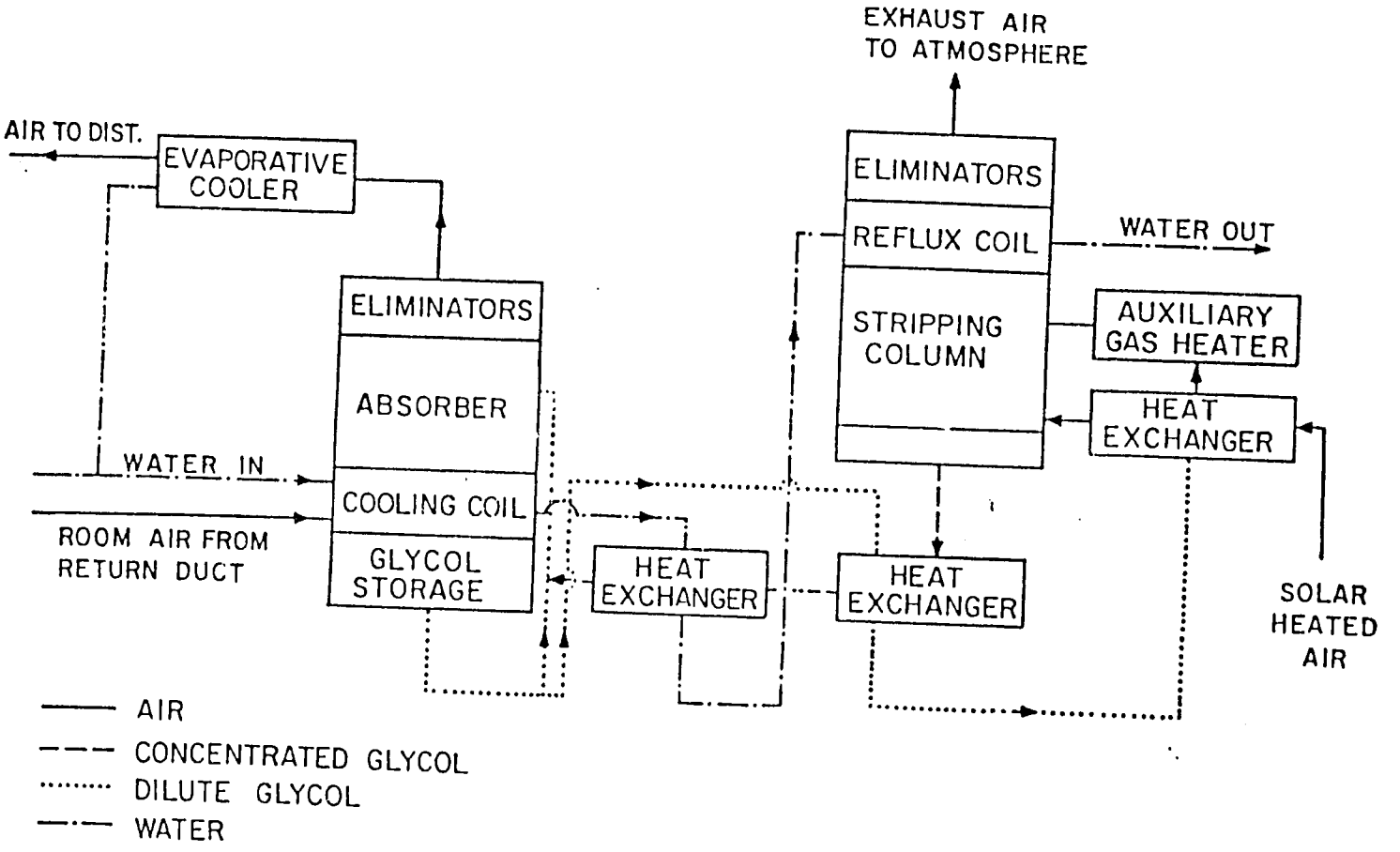


EXHIBIT 5-7. Schematic of Liquid Desiccant, (Triethylene Glycol), Open-Cycle Air Conditioning System. (SOL-2)

6. SOLAR DOMESTIC HOT WATER SYSTEMS

6.1 Introduction

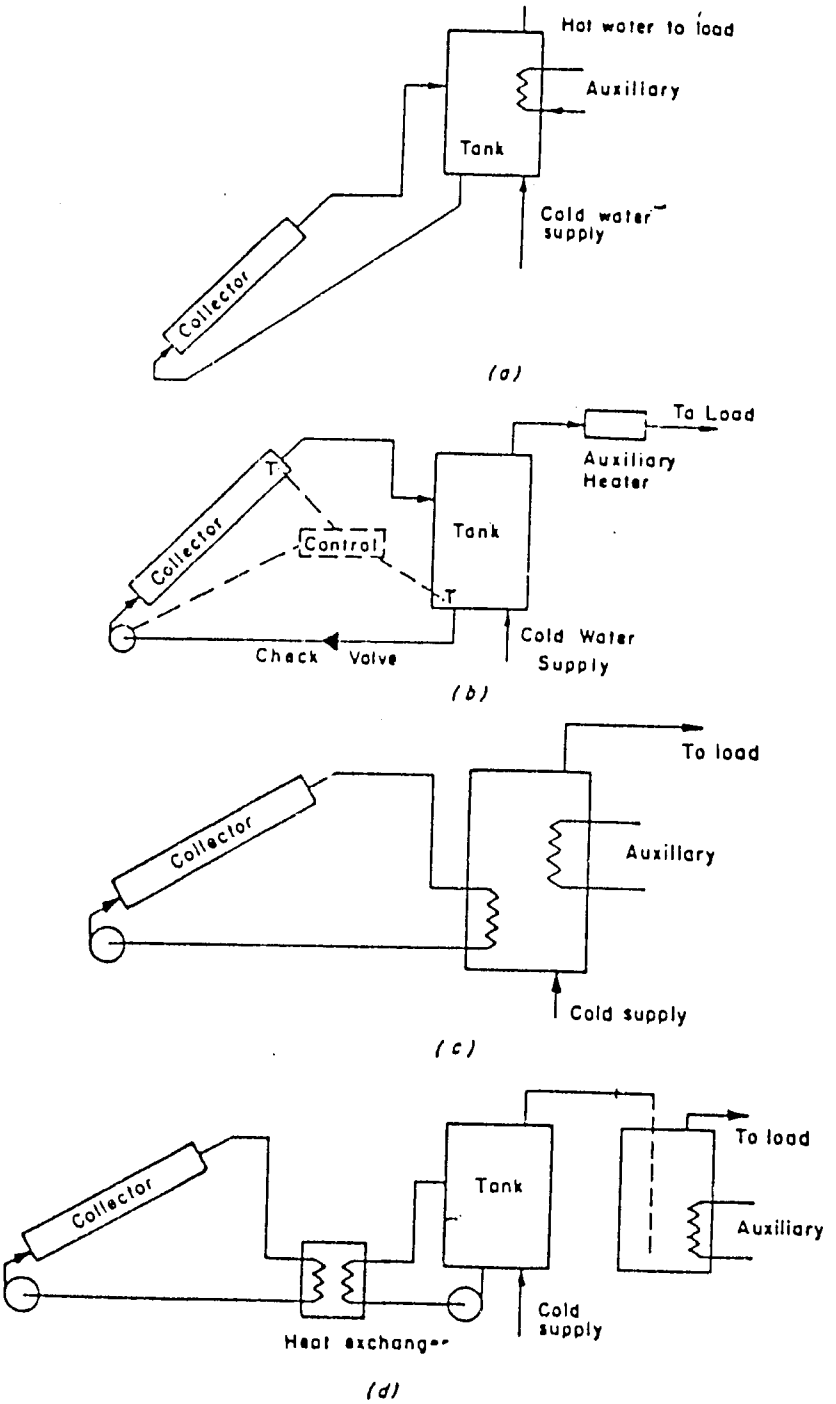
Solar heated domestic water (DHW) is one of the oldest, simplest, and cheapest applications of solar energy (as compared to solar space heating or cooling). Solar water heaters in the United States date back to the 1920's when they were abundant in California and Southern Florida.

Most of the commercially available solar domestic hot water systems have been classified as either active or passive. Active systems involve collecting heat in a fluid which is mechanically forced through a collector. This heat, in the form of hot water, is transferred to storage in a separate tank.

Passive domestic hot water systems are those systems that utilize no mechanical or electrical energy to collect and store solar energy for heating water. Although several types of passive DHW systems completely fill this definition, many are only truly passive in the collection mode, not the storage mode. The passive category can be divided further into integral collector storage (ICS), and phase-change systems.

Active systems are further classifed as either direct heating or indirect heating. In direct heating systems, potable water is heated directly in the collector; whereas, in indirect systems, a heat transfer fluid is used in the collector and transfers its heat to a storage tank of potable water.

Exhibit 6-1 illustrates basic passive and active DHW systems. Included in this illustration are: Thermosiphon, direct active heating, and indirect active heating systems.



Schematic Configurations of Water Heaters. (a) Thermosiphon; (b) One-tank active direct-heating; (c) One-tank active indirect heating with internal heat exchanger; (d) One-tank active indirect heating with external heat exchanger. (BEC)

EXHIBIT 6-1

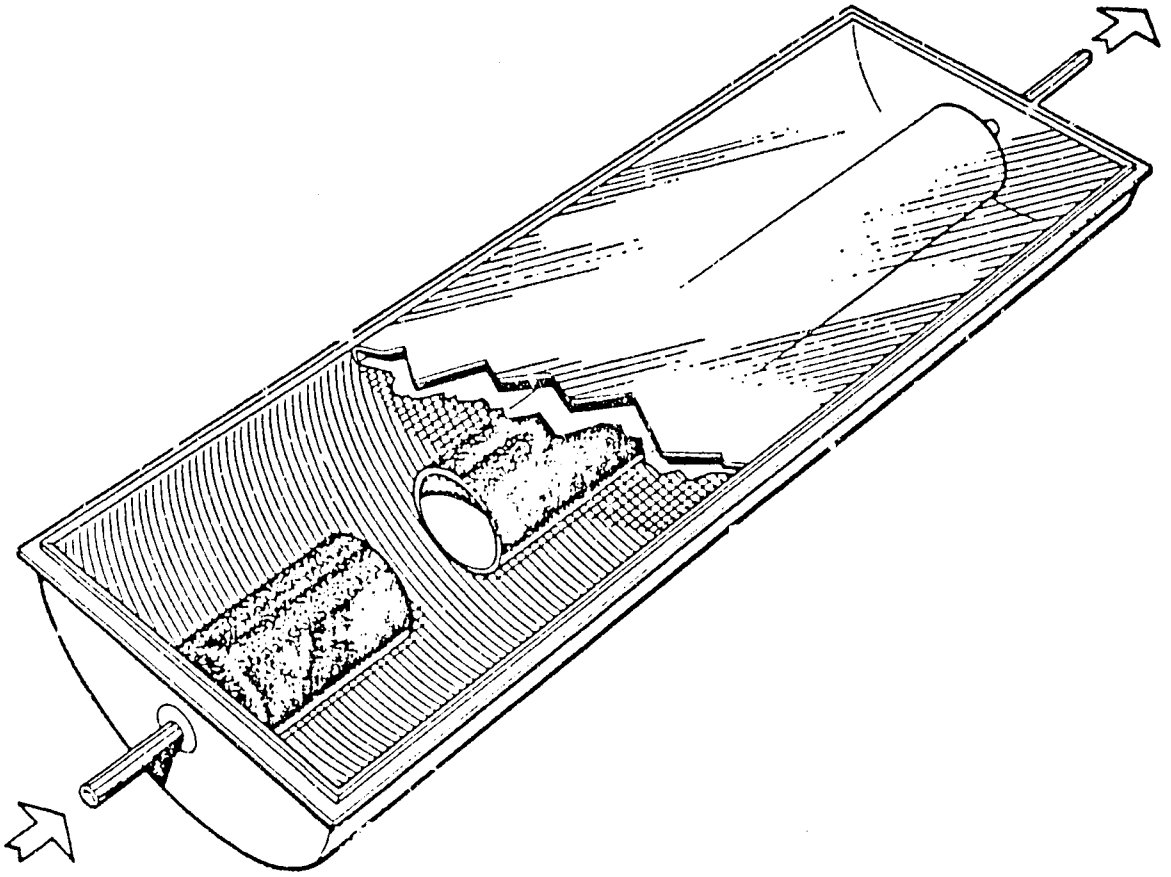
6.2 Passive DHW Systems

6.2.1 Integral Collector Storage

When these systems were first introduced to the market in the early 1970's they were referred to as "batch heaters". The early models were no more than recycled hot water tanks, painted black, built into an insulated wood box, and glazed with a single sheet of plastic. An insulated door on the south side of the box was used to minimize night heat losses. The units were placed in the sun and plumbed in series between the cold water supply and the domestic hot water tank. The whole tank heated in the sun, hence the name "batch". As water was drawn off the conventional domestic hot water tank, it was replaced by water from the batch heater, which in turn was refilled by the pressure from the cold water supply. Exhibits 6-2 and 6-3 provide diagrams of two "batch" heaters commercially available.

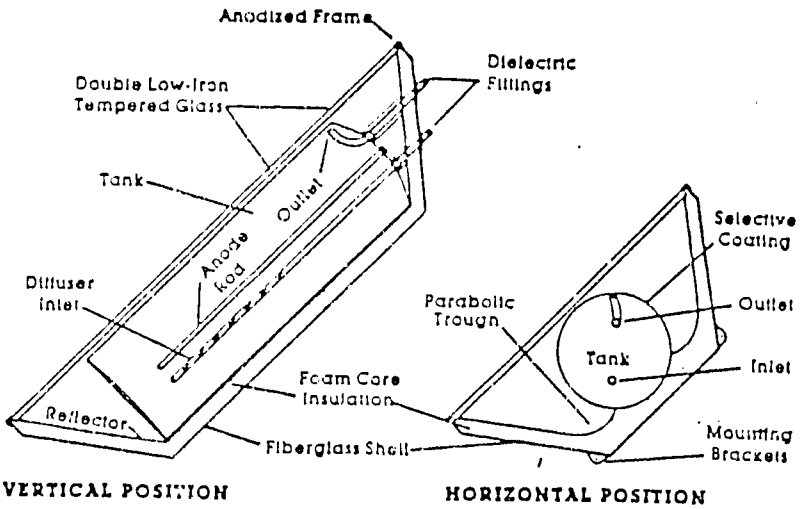
Batch heaters were not protected against freezing, except by the insulation around the box and the single layer of glazing. They were provided with a drain port to empty the tank during freezing periods and a bypass valve to route cold water directly to the domestic hot water tank. The tanks were also equipped with a temperature/pressure relief valve that directed steam in a safe direction outside the box in case water was not drawn over a period of several days (e.g., when homeowners were gone) and the water in the tank reached a certain temperature (this is illustrated in Exhibit 6-4).

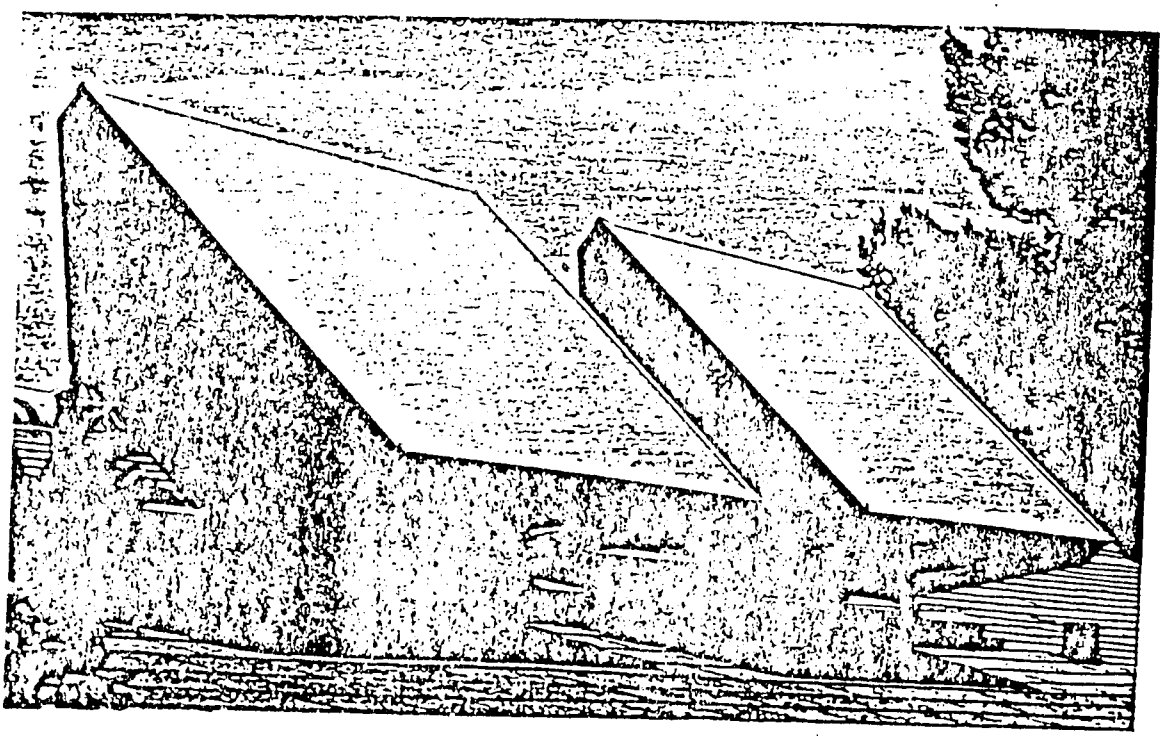
In time designs progressed; more insulation was added, reflective cusps were added under the tank to reflect more sunlight onto the tank, and a selective surface was painted on the tank to increase absorption. Double and triple glazed units were built, and some had an insulated front cover that could be closed at night to reduce heat loss. The cover often had a reflective inner face so that when it was open in front of the unit, it reflected even more light onto the tank.



"Batch" Water Heater. Solway Energy Corporation, Vancouver, British Columbia, Canada.

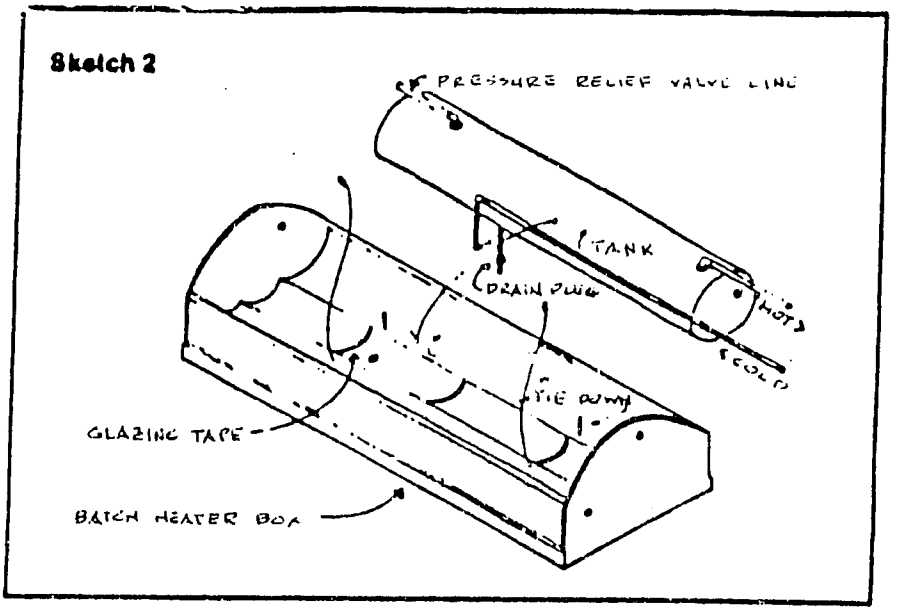
EXHIBIT 6-2





"Batch" Water Heater. Cornell Energy Incoproated., Tucson, Arizona.

EXHIBIT 6-3


Sketch 2
PRESSURE RELIEF VALVE LINE
TANK
DRAIN PLUG
HOT
COLD
TIE DOWN
GLAZING TAPE
BATCH HEATER BOX

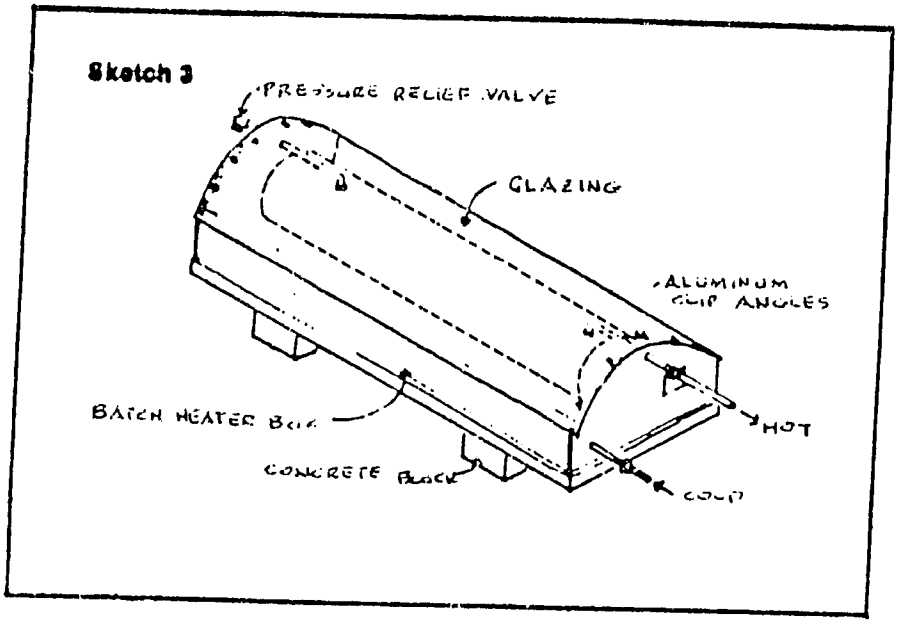

Sketch 3
PRESSURE RELIEF VALVE
GLAZING
ALUMINUM
CLIP ANGLES
BATCH HEATER BOX
HOT
CONCRETE BLOCK
COLD

EXHIBIT 6-4

By the late 1970's, "batch" units were being manufactured and sold on a larger scale. Their name was changed to integral collector storage (ICS) to overcome the do-it-yourself term "batch heater". The units became better insulated and constructed. Presently the most common type is comprised of a set of four to eight black plastic tubes, each about 15 cm in diameter, placed side to side encased in a box covered by glazing. This system is usually mounted in a tilted position. If polybutylene pipe is used, such systems have been able to withstand multiple freezes. Many manufacturers have attempted to give the units a lower profile so that they can be mounted on roofs, but concentrated roof loads can still be a problem.

The "batch" heaters and ICS units are DHW "preheaters", as they preheat the water for the conventional heater and rarely provide high enough temperatures to meet heating and end use requirements. However, if the water usage within a given structure is concentrated into the early evening hours when the water is its hottest, the greatest efficiency of the units can be relized. If all the hot water from the tank is used in the early evening, the high nighttime heat losses associated with these units can be eliminated.

6.2.2 Thermosiphoning Systems

6.2.2.1 System Description

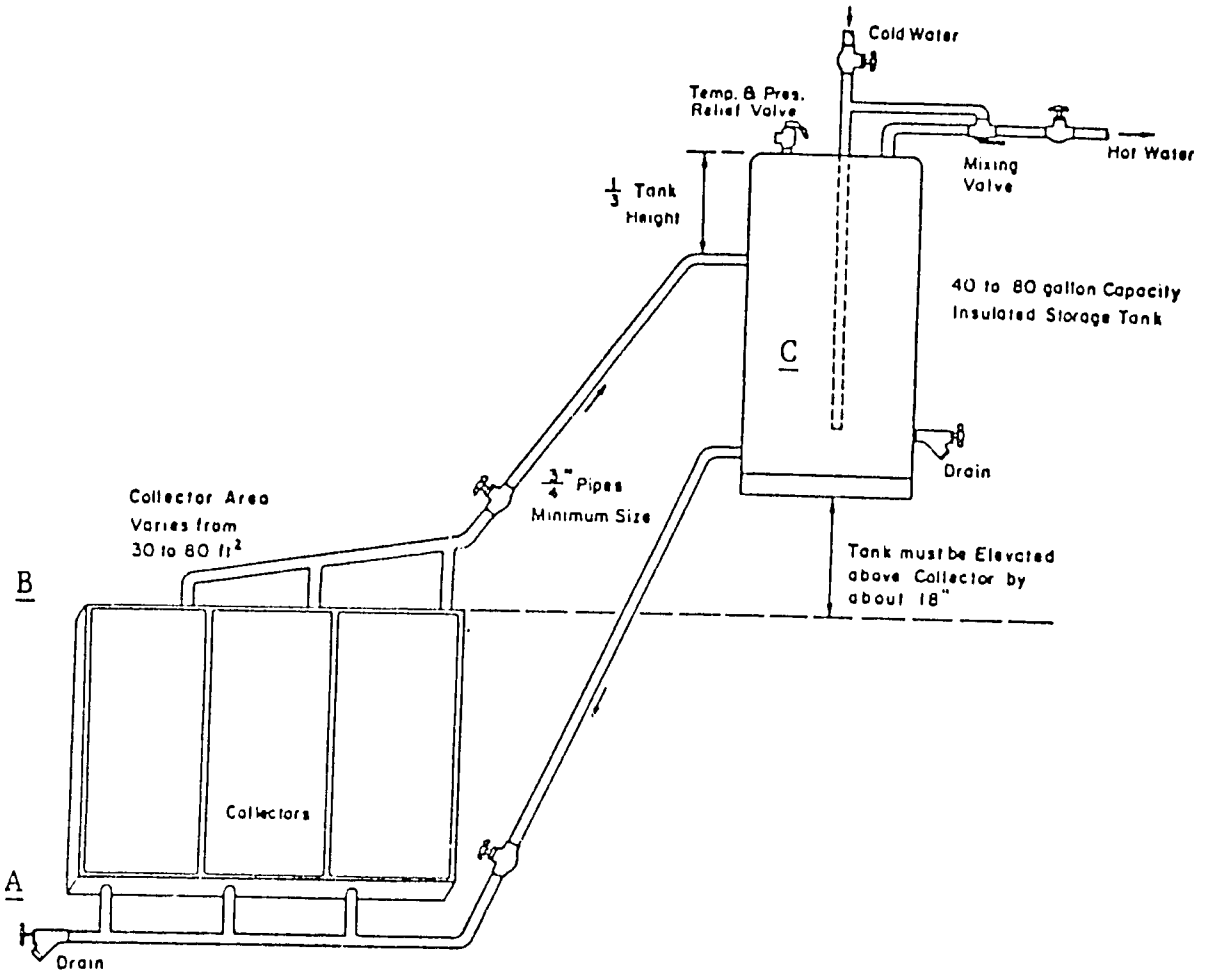
Thermosiphoning systems use natural convection to circulate the heat transfer fluid to a heat exchanger or storage tank. Exhibit 6-5 illustrates a schematic diagram of a thermosiphon DHW system. As the fluid in the collectors is warmed by radiant energy from the sun, its density decreases and it rises above the cold fluid to the top of the collectors from position A to B in Exhibit 6-5. A heat exchanger or storage tank is located above the collectors (position C in Exhibit 6-5). In one case, the warmed fluid gives up its heat to the fluid in the heat exchanger and returns through separate piping to the bottom of the collectors to begin the process again. In another more common instance, the warm water in the collectors rises and is directed in

piping to the top of the storage tank. A pipe from the bottom of the storage tank directs cold water down to the bottom of the collectors. A check valve in the return pipe to the bottom of the collector prevents reverse thermosiphoning at night, at which time the warm water from the tank would flow in the opposite direction, stealing heat from the tank. Placing the tank no less than 18 inches (46 cm) above the top of the collectors will often eliminate reverse thermosiphoning at night, without need for a check valve.

Thermosiphoning systems are open systems in which potable water from the storage tank is pumped directly through the collectors and then returned. Advantages of this type of system configuration are simplicity and lower operating costs. There are fewer moving parts than in a closed system and better thermal efficiency is achieved because there is no exchanger between the collector and storage tank. The main disadvantage of an open system is the general inability to operate in freezing weather.

An additional advantage of the thermosiphon system is the stratification of storage which results in better service and collector efficiency. The main disadvantage of the system is that the storage must be located above the collector subsystem. This means that the tank will have to be located on the roof or in the attic. A typical 250-liter tank weighs about 310 kg, posing possible structural complications. Another disadvantage is poor access to the water heater. The user would have to go onto the roof or into the attic to close the shutoff valves and open the draincocks whenever the temperature dropped below freezing. For this reason, thermosiphon systems are rarely used in freezing climates.

Exhibit 6-6 illustrates various commercially available therosiphon design water heaters.



Direct Heating, Thermosiphon Circulating Solar Water Heater. (SOL-1)

EXHIBIT 6-5

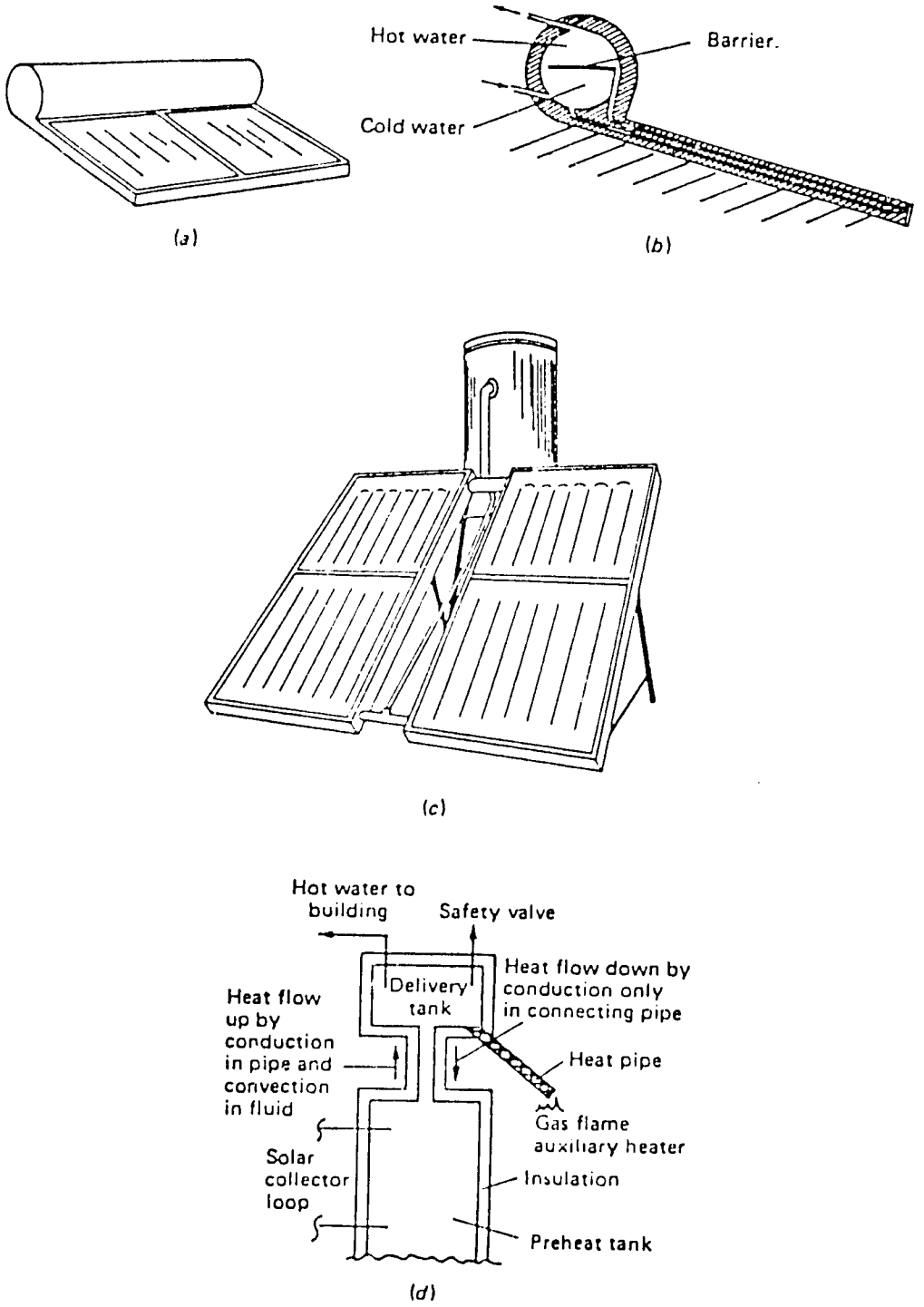


EXHIBIT 6-6. Thermosiphon Water Heaters: (a) Australian compact model, isometric view, (b) Australian model, section view showing fluid compartments; (c) Israeli tank-andcollector assembly; (d) deWinter system using gravity return heat pipe for auxiliary heating and thermal diode between preheat tank and delivery tank. (KRE)

6.2.2.2 Implementation Issues

The thermosiphon is the most common solar DHW system in nonfreezing climates. The collector is single glazed and ranges in area from 2.8 to 7.4 m^2; a typical insulated tank ranges from 150 to 300 liters. In sunny climates, the hot water requirements of a four-person family can usually be met with a system in this size range.

A system of this type can be designed to operate at supply line pressure or as an unpressurized system. For unpressurized systems, a float valve can be installed in the storage tank or a float-controlled elevated heat tank can be utilized. Unpressurized systems utilize gravity flow from the hot water tank to hot water faucets unless an automatically actuated pump is installed to pressurize the hot water line.

This system only operates when solar energy is received. Thus, the system is self-controlling. The higher the isolation level, the greater the heating and the more rapid the circulation rate will be. In a typical system, a temperature rise of 8°C to 11°C commonly occurs in one pass.

The storage tank is usually piped in series between the cold water supply and the conventional domestic hot water tank located elsewhere in the building. This type of system is an open-loop system, and can only be used where freezing is not a problem, since the water in the collectors, tank, and plumbing is subject to freezing. The back of the collector, the storage tank itself, and the pipes should all be insulated to reduce heat losses, which can be very high as the the tank is located in an unheated area. If used in an area with severe winter conditions, the system should be designed so that it can be fully drained before the first freeze.

If water is not drawn from the storage tank and the temperature and pressure in the system rise to a high level, a combination temperature/pressure relief valve is placed at the highest point in the system. An automatic air vent is also included to keep air bubbles from hastening corrosion in the collector risers.

When a heat exchanger is used across the top of the collectors, an antifreeze can be used as the heat transfer fluid. This will protect the collectors from freezing, but not the water in the heat exchanger. The closed loop in the collector is filled with a water-glycol mixture and will require an expansion tank and fill valve in addition to the air vent and temperature/pressure relief valve.

The heat exchanger eliminates the heat losses to ambient from the storage tank and reduces the size of the collector profile so that it is more visually attractive. The use of an antifreeze solution reduces collection efficiency, and the heat exchanger reduces it further, but only the plumbing line to the heat exchanger needs to be drained in freezing weather. The heat exchanger can either be plumbed between the cold weather supply and the conventional tank (with a bypass loop)when city water pressure is available, or as a loop from the conventional tank, with its own circulating pump. In the latter case, the system is no longer totally passive, but is a hybrid system as the collection loop is passive and the storage loop uses a circulating pump.

6.2.3 Phase-Change Systems

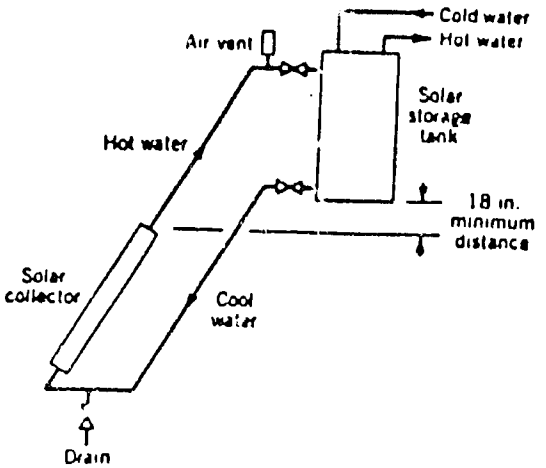
Phase change collectors use a heat-transfer fluid that changes from a liquid to a gas when heated by the sun. The gas bubbles rise in the collector, pass over the heat exchanger and condense to a liquid again as they give up their latent heat. This condensed fluid flows by gravity to the bottom of the collector to rise again (this is illustrated in Exhibit 6-7).

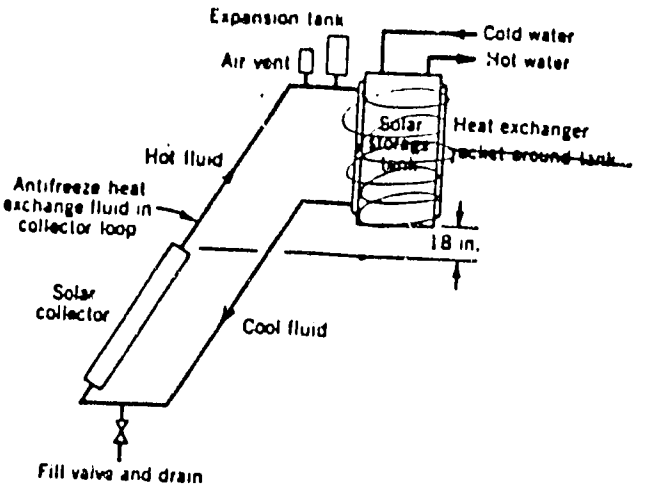
As the fluid, usually a refrigerant, is able to change phase and store latent heat, it has a higher efficiency than fluid used in thermosiphoning collectors, which can only store sensible heat. System manufacturers claim increased efficiencies of 30 to 40 percent. Although the collectors cannot freeze, the heat exchanger has the same problems as its counterpart in thermsiphoning collectors.

Most phase-change systems have the same major problem as the thermosipohon systems: the tank or heat-exchanger must be physically placed above the top of the collector. In addition, the use of a refrigerant means using silver solder for piping connections and incurring a corresponding additional increase in cost.

A new proto-type phase-change system is being developed in the United States that is totally passive and yet still allows the storage tank to be placed on a level below. The Geyser Pump^{tm} solar collector (Sunrise Research, Eugene, Oregon) uses a water-alcohol mixture that uses the phase-change to motivate the fluid through the loop, and <u>not</u> as a method of heat transfer between collectors and storage (as in traditional phase-change collectors). The fluid begins to boil, carrying a mix of gas and liquid to tubes at the top of the collectors (a diagram is provided in Exhibit 6-8). This creates a closed loop pressure differential which the system naturally tries to overcome. The liquid portion of the mixture flows down to the storage tank, gives up its heat in the heat exchanger, and is forced up again to the collectors because of the difference in pressure. The gaseous portion passes to the vapor condenser, where it condenses against the cooler liquid returning from the heat exchanger. The combined liquid is gravity fed to the bottom of the collectors. A check valve prevents backflow through the system.

The system is totally passive in collection and storage, with no pumps, controls, or sensors. It protects itself against freezing and stagnation, and is self-controlled. The biggest advantage architecturally and structurally is that the tank can be placed below the collectors.


Cold water
Hot water
Air vent
Solar storage tank
Hot water
18 in. minimum distance
Solar collector
Cool water
Drain


Expansion tank
Cold water
Hot water
Air vent
Solar storage tank
Heat exchanger
Hot fluid
Antifreeze heat exchange fluid in collector loop
18 in.
Solar collector
Cool fluid
Fill valve and drain

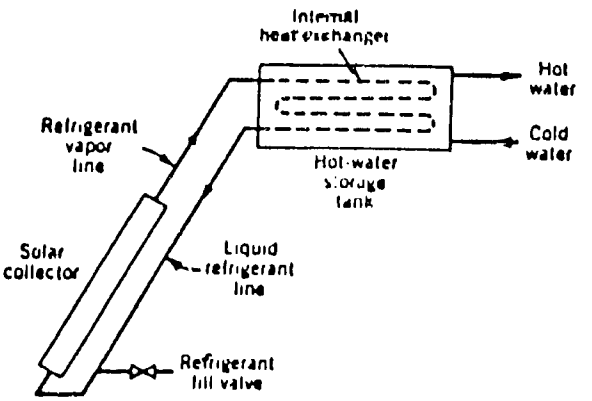
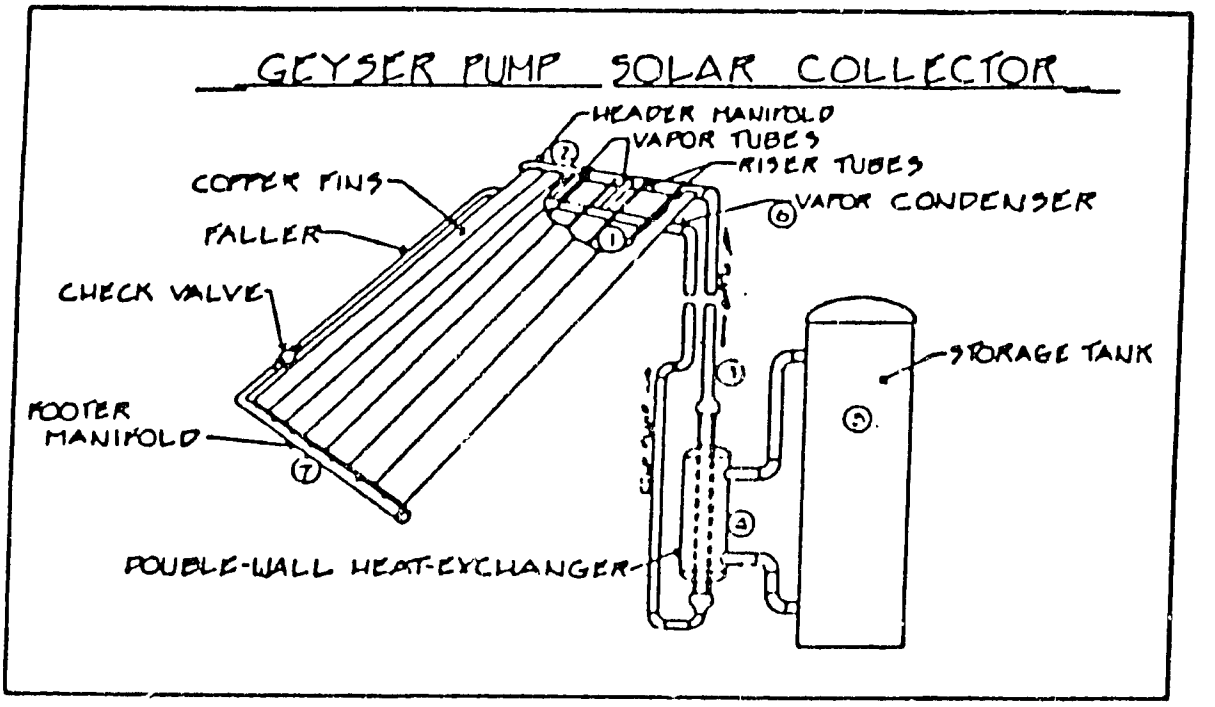

Internal heat exchanger
Hot water
Cold water
Refrigerant vapor line
Hot-water storage tank
Solar collector
Liquid refrigerant line
Refrigerant fill valve

EXHIBIT 6-7



The Geyser Pump Solar Collector. The top end of each riser tube (1) butts into a header that runs across the top of the collector (2). A mixture of gas and liquid bubbles up into the header from the risers. A pipe from one end of the header (3) allows the liquid to flow down to the heat exchanger (4), give up its heat to the storage tank (5), and flow back to the vapor condenser (6). Smaller pipes connect the vapor condenser and the header so that vapor flows directly into the condenser. When the cool liquid and hot vapor hit, the vapor condenses and the combined fluid flows down the faller to the footer manifold (7) at the bottom of the collector. A check valve prevents backflow up the faller.

EXHIBIT 6-8

Exhibit 6-9 is an illustration of another commercially available phase--change passive water heater. The illustrated unit incorporates a modular design enabling required components to function as a unit to produce hot water by passive means.

6.3 Active DHW Systems

6.3.1 Overview

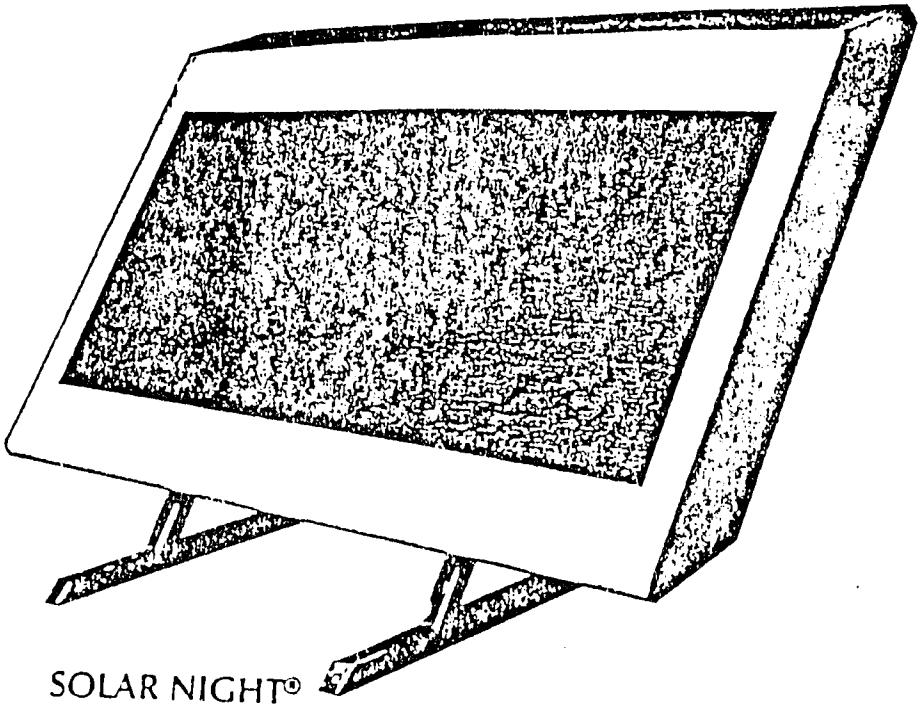
Active water heating systems are classified as either direct or indirect. These two main types are further subclassified according to operating principle. All active DHW systems consist of the following components:

1. **Collector panels:** Heat collection fluid.
2. **Circulation pump:** Forces cold fluid through the collector and to the storage tank.
3. **Storage tank:** Contains the heated fluid until it is used.
4. **Valves:** Controls the flow of fluid in the system.
5. **Thermostatic control:** Regulates the speed of the pump which determines the flow of fluid in the system.

6.3.2 Direct Heating DHW Systems

Direct heating systems utilize potable water which is directly heated in a collector and then transferred to storage. Exhibit 6-10 provides a schematic diagram of a direct-heating active solar DHW system.

Instead of insolation levels controlling fluid circulation (as in passive thermoisphoning type systems), in an active system, a temperature sensor actuates a small pump which circulates water through the collector-storage loop. To maximize utilization of solar energy,



SOLAR NIGHT®
Domestic Hot Water System
Series 1000

EXHIBIT 6-9. General Energy Technologies, Incorporated, Albuquerque, New Mexico. Phase-Change Water Heater.

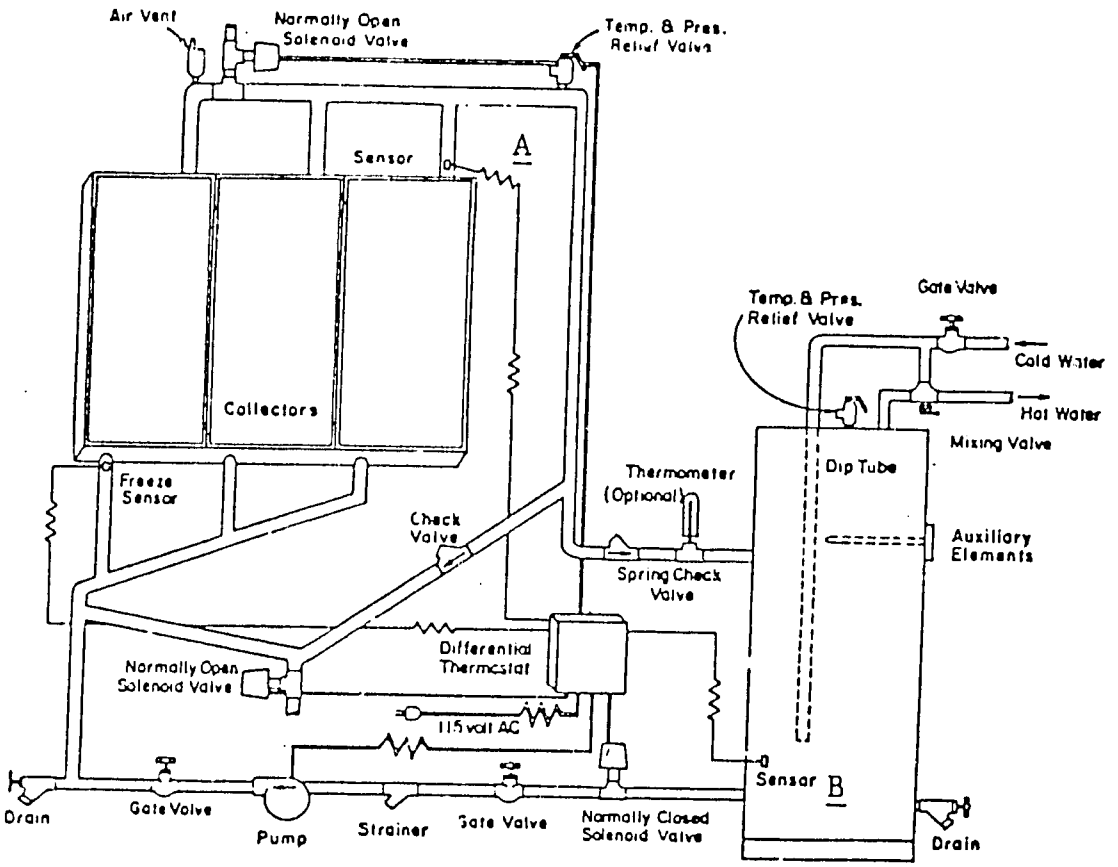


EXHIBIT 6-10. Direct Heating, Pump Circulation Solar Water Heater with Automatic Drain-Down. (Applicable also to a two-tank system) (SOL-1)

temperature control is based on the difference in temperature between water flowing into the collector and that of water flowing out of the collector. Whenever the temperature difference exceeds a specified set point, the pump is actuated. The sensor at the collector outlet must be located close enough to the collector so that it detects the fluid temperature even when the pump is not running. (See position A in Exhibit 6-10). Similarly, the sensor in the storage tank should be located in or near the bottom outlet where the water is supplied to the collector (See position B in Exhibit 6-10). When the temperature difference is lower than a preset lower differential limit, the pump is shut off and circulation ceases. Reverse circulation is prevented by a check valve located in the circulation line.

If domestic hot water use is not sufficient to maintain storage tank temperature at normal levels, boiling may occur in the collector line and circulation line. If a check valve is used to prevent reverse circulation, a relief valve must also be provided in the loop to allow the escape of steam and prevent system damage from boiling.

If a pump-circulation system is used in freezing climates, the collector must be drained when freezing temperatures and sub-freezing temperatures are encountered.

Drainage of the collector can be accomplished by automatic valves which provide water outflow to a drain and air inflow to the collector. One typical control arrangement provides for the opening of these two valves whenever the circulating pump is not running. For increased reliability, the valves should be driven mechanically rather than electrically. The main disadvantge to this system is the frequent exposure of collector tubing to air and possible resultant corrosion.

6.3.3 Indirect Heating DHW Systems

6.3.3.1 Classification

Indirect systems are two-fluid systems in which a nonfreezing, noncorrosive fluid is circulated through the collector and then utilized to heat potable water in a storage tank. (This is illustrated in Exhibit 6-11). There are two basic methods of indirect heating; the use of a nonfreezing liquid as the heat transfer fluid and the use of air. Indirect systems eliminate the need for drainage of fluids in freezing weather. Corrosion is also decreased because a noncorrosive fluid is used and because there is no free oxygen in the heat transfer medium.

6.3.3.2 Indirect Liquid Systems

The most commonly used liquid heat transfer medium in an indirect system is a solution of ethylene glycol in water (automobile antifreeze). A pump circulates this unpressurized solution to and through a liquid-to-liquid heat exchanger. Simultaneously, another pump circulates potable water from the storage tank through the same heat exchanger and back to storage.

If the heat exchanger is located below the bottom of the storage tank and pipe sizes and exchanger design are adequate, thermosiphoning circulation can be used and a pump can be eliminated from the potable water loop. In an unpressurized collector circuit, an expansion tank is needed in the collector loop, preferably near the high point of the system. This expansion tank must be vented to the atmosphere. If the collector is operated under postive pressure, an expansion tank with a pressure-balanced diaphragm may be located in the line near the solution pump.

The heat exchanger must be designed so that rupture or corrosion will not permit flow of the heat transfer fluid into the potable water supply (even if pressure on the water side of the exchanger drops below that on the antifreeze side). For this reason, a conventional shell-and-tube

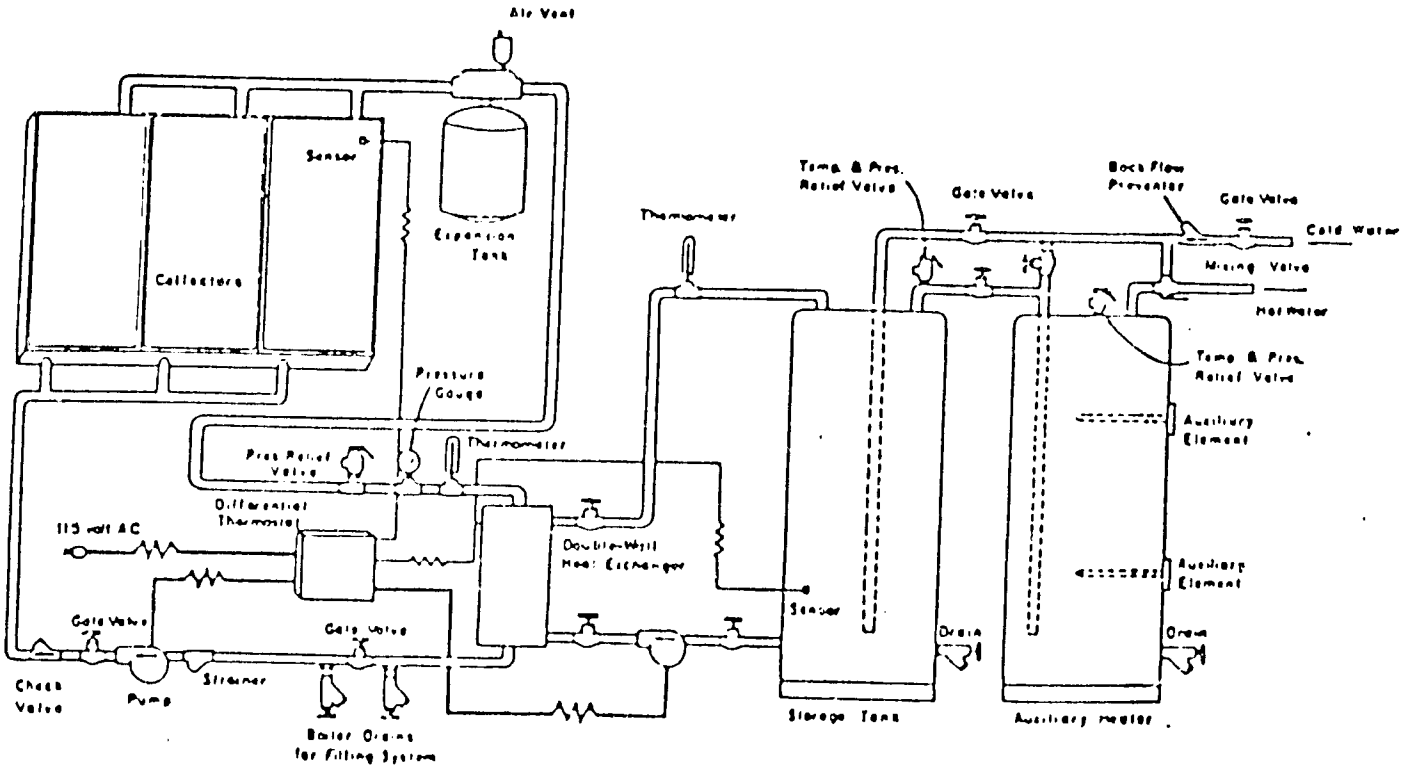


EXHIBIT 6-11. Indirect Heating, Pump Circulation Solar Water Heater with Liquid Heat Transfer Media. (SOL-1)

exchanger or a single pipe coil inside the storage tank would not be acceptable. Use of a design incorporating parallel tubes with metal bonds between them would ensure that perforation of one tube could not result in liquid entry into the other tube. Another possible design is a finned tube air-to-liquid heat exchanger which circulates the two liquids through alternate rows of tubes. In this case, heat transfer takes place by conduction through the fins.

Although aqueous solutions of ethylene glycol and propylene glycol are most commonly used, organic fluids such as silicone oil, Dowtherm J^{tm} and Therminol 55^{tm} can also be used as heat-transfer media. High price and high viscosity are primary disadvantages of these fluids, but chemical stability and high boiling points are advantages over the commonly used antifreeze solutions.

6.3.3.3 Indirect Air Systems

In this system, solar-heated air is used to heat domestic water in an air-to-water heat exchanger. A solar air collector is supplied with air from a blower. The heated air is then cooled in the heat exchanger through which potable water from storage is either pumped or circulated by natural means. Air is then recirculated back to the collectors. As in the other indirect systems, differential temperature control is used. Exhibit 6-12 provides a schematic diagram of an air-heated DHW system.

Obvious advantages of air as a heat transfer medium are the absence of corrosion in the collector loop, no toxic leakage into the potable water supply tank, freedom from freezing, boiling, and evaporation of collector fluid. Disadvantages are the need for larger fluid conduits between the collector and heat exchanger, the need for an additional air blower which results in higher power consumption, and necessity of larger collector surface area.

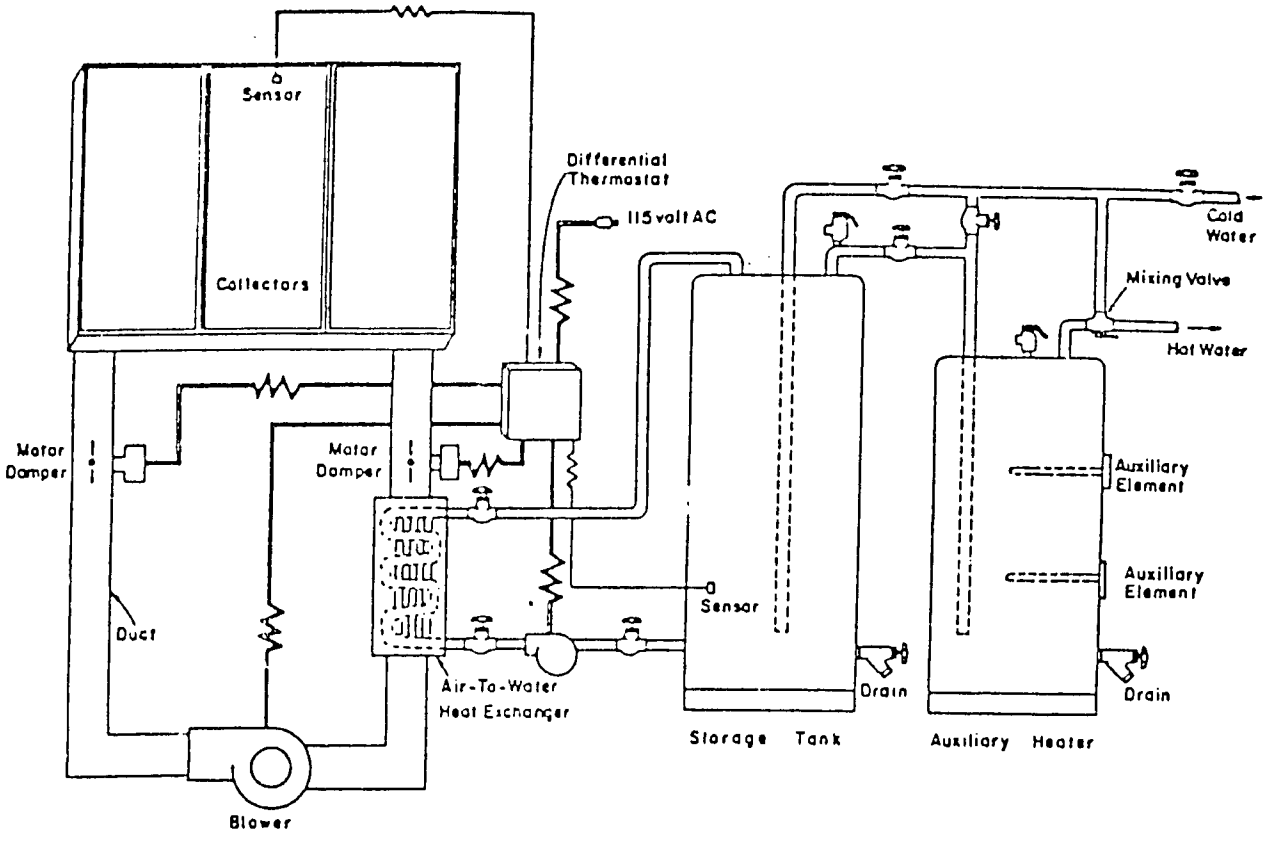


EXHIBIT 6-12. Solar Water Heaters With Air Collectors. (SOL-1)

6.4 Auxiliary DHW Systems

The demand for a reliable supply of hot water can require the use of auxiliary heat for supplementing the solar source.

6.4.1 Auxiliary Location

In order to maximize solar supply use and minimize auxiliary use, direct or indirect auxiliary heat input to the fluid entering the solar collector must be avoided. If auxiliary heat is added to the solar water storage tank so that the temperature of the fluid is above that normally supplied, collector efficiency is reduced because of higher heat losses from the collector. Thus, auxiliary heat should be placed beyond or downstream from the collector-storage system, making the solar storage tank a "preheat" tank for the auxiliary hot water heater.

6.4.2 Electric Resistance Auxiliary Heat

An electric resistance heating element is often used to provide backup energy to the hot water storage tank. The heater is generally located in the upper portion of the tank. Cold water arrives at the bottom of the tank and is drawn at the same level into the collector loop. Hot water comes back from the collector and flows into the tank below the resistance heater so that a supply of hot water is always available at the top of the tank. Since the electric element is heating the warmest layer of water, system efficiency is increased and storage requirement is reduced. If relatively hot water is needed, use of an auxiliary heater may cause an undesirable impact on collector efficiency due to mixing of layers in the storage tank.

6.4.3 Auxiliary Heat Using Gas or Oil

If gas or oil is used as auxiliary heat source, a two-tank system might be required, as burners are usually located at the bottom of the auxiliary storage tank. Auxiliary heat supplied from the bottom of the

tank raises the water temperature uniformly and promotes layer mixing. In such a case, collector efficiency is adversely affected if only one tank is used. Exhibit 6-13 illustrates the configuration of a two-tank system typical of some United States installations. The solar energy collected is used to preheat incoming cold water. The top layer in the preheat tank is then drawn to be heated in the second tank by an auxiliary gas or oil furnace.

6.5 System Maintenance

Corrosion represents the greatest maintenance problem in solar DHW systems. There are two main sources of corrosion: chemicals in water and galvanic action.

6.5.1 Water Supply

The chemicals occurring naturally in the water supply (e.g. sulfur, iron, calcium) form scales which clog aluminum or steel collector tubing. Because of this, copper tubing is used in most open solar systems. Even if copper tubing is used, it is recommended that, to prevent clogging, it never be less than 1.27 cm interior diameter (I.D.) Exhibit 6-14 contains a list of typical detrimental and beneficial water quality parameters. Collector field studies have indicated that a pH between 7.0 and 8.5 (slightly basic) is optimal for corrosion control. A pH value below 7.0 and the presence of chloride or sulfate ions will result in rapid corrosion.

6.5.2 Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals are used in the presence of aqueous working fluids. Corrosion results from the differences in electrochemical potentials. Exhibit 6-15 presents a list of elements that may be present in solar systems. The potential difference between any two elements is a measure of the tendency for the

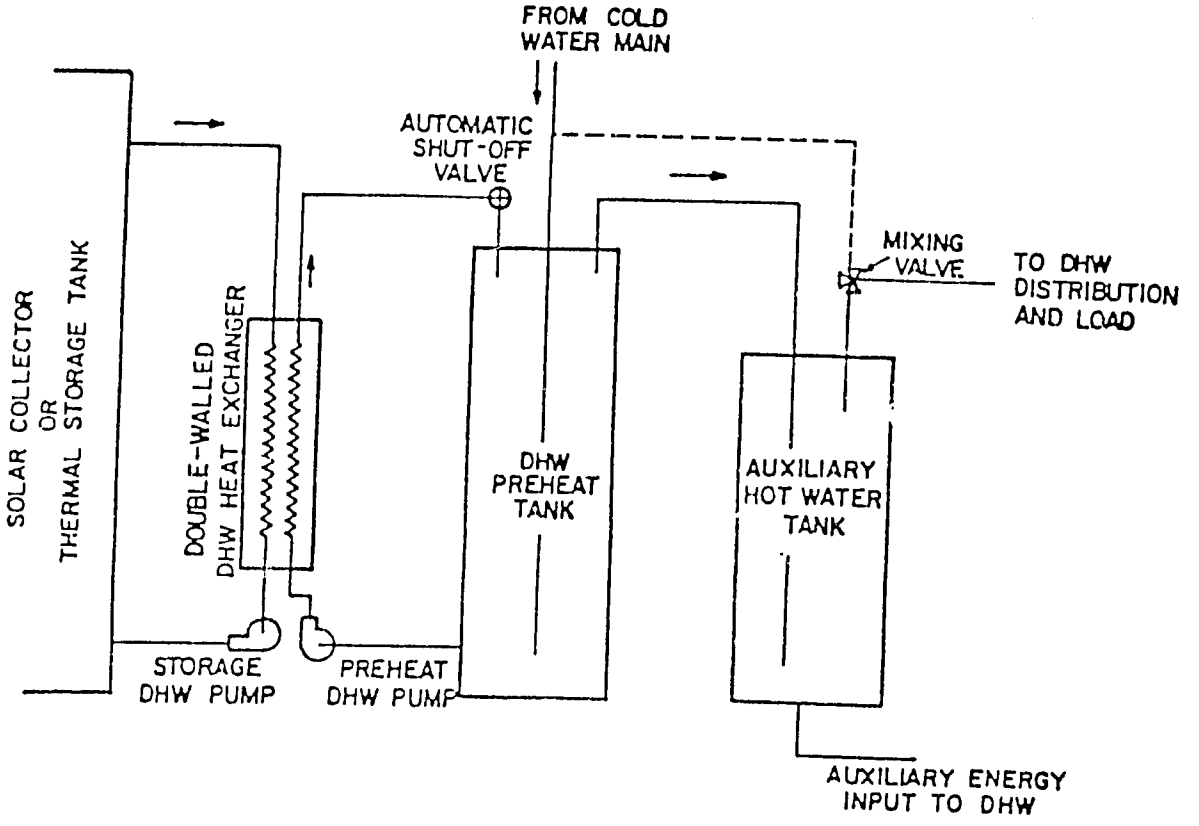


EXHIBIT 6-13. Schematic Arrangement of a Solar Domestic Hot Water Subsystem. (SOL-1)

reaction to occur. For example, from Exhibit 6-15 for a system made of aluminum and copper, the oxidation potential tending to promote the reaction is:

$$1.66V - (-0.34V) = 2.00V$$

Practicaly, the use of brass or bronze nipples to connect a steel tank to a copper water pipe will reduce this problem. Joints connecting steel to copper and aluminum to copper should be avoided to minimize galvanic corrosion.

Detrimental parameters	Beneficial parameters
Dissolved oxygen	Calcium ion
Sulfides	Bicarbonate ion
Tin	Metaphosphate ion
Magnesium ion (with Al)	Monohydrogen phosphate ion
Chloride ion	Silica (SiO_2)
Sulfate ion	Organic color
Nitrate ion	Borax (sodium borate decahydrate)
Carbonate ion	
Hydroxyl ion (high pH enhances corrosion)	
Hydronium ion (low pH enhances corrosion)	
Cupric ion	
Carbonyl ion	
Nickel ion	
Lead ion	

EXHIBIT 6-14. Water Quality Parameters and Corrosion Control. (KRE)

Element	Oxidation potential in 1-molal solution (V)
Sodium	+2.71
Magnesium	2.37
Aluminum	1.66
Zinc	0.76
Iron (to ferric ion)	0.44
Cobalt	0.28
Nickel	0.25
Tin	0.14
Lead	0.13
Hydrogen (reference)	0.00
Copper (to cupric ion)	−0.34
Bromide ion (to Br_2 gas)	1.09
Chloride ion (to Cl_2 gas)	1.36

EXHIBIT 6-15. Partial Electromotive Series For Solar System Components. (KRE)

7. DESIGN CONSIDERATIONS FOR ACTIVE SYSTEMS

7.1 Introduction

One of the main difficulties facing potential designers and users of solar systems is how to determine required system size. A solar system can be designed so that it provides for all of the heating, cooling, or domestic hot water load, whichever is desired. However, in most climates, the cost of such a system would not be cost effective.

System components such as pumps and storage tanks are selected on the basis of collector area. The main reason that the collector area is the primary design variable is that it is a primary factor in determining the amount of solar energy that can be collected. Rules of thumb are used to select heat exchangers, ducts, pumps, and tanks once the collector area is determined.

In order to determine the optimum solar system size or solar collection area, several systems need to be investigated to predict or determine the performance of each. Economic analysis will determine whether additional area and its resultant additional energy contribution justifies the added cost.

Several simulation and design methods have been developed to aid in predicting a solar system's performance. Most routines utilize the test slope and intercept from the ASHRAE 93-77 procedure ($-F_R U_L$, $F_R \tau \alpha$) in combination with the collector area to determine "f", the fraction of the user load that is supplied by solar.

Most of the simulation and design methods have been prepared for use with a computer or calculator. This is primarily because of the complex calculations, each of which has to be repeated several times. The

process being studied is unsteady; solar insolation, radiation geometry, and ambient temperatures all vary throughout the day as well as throughout the year. A number of available computer routines can aid in solar system analysis and design. Among them are TRNSYS, F-Chart, SOLCOST, SLR, SEU, and GFL.

Design routines can be classified as hourly simulations or correlation routines. The correlation routines were primarily derived from hundreds of hourly simulations. The primary disadvantage of correlations is that they apply accurately only for the system that was initially investigated. If the user has a different configuration from the initial basis, these correlations may not be accurate at all. On the other hand, hourly simulations also have their disadvantages. The basic disadvantage is the amount of data needed to conduct the simulations. Hourly insolation data, hourly temperature data, wind speed, humidity, frequency of rainfall, etc. for a whole year are not available for many locations. In addition, the time required to run the large number of simulations needed, is costly both in computer time and required manpower.

Methods of solar system design can also be classified in three general categories:

1. Systems in which the collector inlet temperature is known and the critical radiation level can be readily established. These methods primarily determine radiation levels above which useful energy can be collected. An example is the utilizability method.

2. Approaches that consist of correlations of the result of a large number of detailed simulations, usually correlated in terms of easily calculated dimensionless groups. Examples include the F-Chart.

3. Methods based on short-cut simulations, done using representative days of meteorological data. Results are related to long term performance. Examples are the SLR, relative areas, and most graphical methods.

There exist numerous methods to design an active solar system. This notebook will describe a few of them, including SLR, TRNSYS, and F-Chart.

7.2 SLR Method

The Balcomb-Hedstrom method (HJM) estimates for a given collection area the annual solar fraction of the heat load. This method is related to the load-collector ratio method (LCR) and consists of the following steps:

1. Determine the monthly degree days for the location in question.

2. Calculate the heat load for the building in terms of MJ/DD (°C).

3. Determine the average total horizontal solar radiation for each month of the year ($MJ/m^2/mo$).

4. Convert horizontal radiation to tilted radiation incident on the collector surface ($MJ/m^2/mo$).

5. Calculate SLR, the solar load ratio, for each month. This term represents the ratio of total solar energy incident on the collector surface to the total energy load of the building.

$$\text{Monthly SLR} = \frac{(\text{area})(\text{incident radiation})}{(\text{building load})(\text{DD/month})}$$

6. Determine the annual solar heating fraction from the SLR data.

$$F = \sum_{1}^{12} \frac{(\text{monthly DD})(x)}{(\text{annual DD})}$$

Where "x" equals:

$$x = 1.06 - 1.366 \exp(-0.55\ \text{SLR}) + 0.306 \exp(-1.05\ \text{SLR})$$

For SLR < 5.66

$$x = 1$$

For SLR $\geq$ 5.66

The following table, taken from (HIM) summarizes the standard parameters used to develop the Balcomb-Hedstrom model.

	Air System	Liquid System
Solar Collector		
# glazings	2	1
transmissivity	0.86	0.86
absorptance	0.98	0.98
emittance	0.89	0.89
insulation	R-12	R-12
fluid flow rate	0.61 $m^3/min*m^2$ (area)	.00082 $m^3/min*m^2$
heat capacity	10.2 $kJ/m^2*°C$	20.4 $kJ/m^2*°C$
heat trans. coeff. to collection fluid	81.8 $kJ/hr*m^2*°C$	613.2 $kJ/hr*m^2*°C$
tilt	lat + 10°	lat +10°
orientation	due south	due south
Collector Piping/Ducts		
ht. loss coeff. to ambient	2.0 $kJ/hr*m^2*°C$	.82 $kJ/hr*m^2*°C$
Heat Exchanger		
effectiveness	------	204 $kJ/hr*m^2*°C$
Thermal Storage		
heat capacity	306.6 $kJ/m^2*°C$	306.6 $kJ/m^2*°C$
ht. loss coeff.	0	0
dimensionless rock-bed heat transfer length	10	------
Heat Distribution		
temperature of distr.	------	49°C
building maintained at	20°C	20°C

7.3 TRNSYS

TRNSYS is an hourly simulation package that was developed at the Solar Energy Laboratory of the University of Wisconsin-Madison, in Madison, Wisconsin, USA. This package is modular in that each system

subcomponent is modeled separately and designated a particular subroutine. Components available include: collector, differential controller, pump, liquid storage tank, auxiliary heater, and packed bed energy storage tank.

TRNSYS is very accurate and its output is almost extensively used to generate generalized correlations. As was stated earlier, because of the facilities and expertise needed and the lack of necessary meteorological data, TRNSYS is mostly used for research and development applications rather than by the individual designer.

7.4 F-Chart

The most commonly used solar system design method is the F-Chart method dveloped by S. Klein and W. Beckman. The F-Chart package is designer-oriented and is ultimately derived from TRNSYS output. It estimates the fraction of total heating or domestic hot water load that can be supplied by solar energy for a given system.

F-Chart correlations have been developed for air-based systems and water-based systems used for domestic space heating and domestic water heating. These correlations relate the monthly solar fraction, f, provided by the solar system and two dimensionless parameters, X and Y.

X = Ratio of collector losses to user load.

Y = Ratio of collector gains to user load.

The primary design variable in the F-Chart method is the collector area. Secondary variables include collector type, storage capacity, fluid flow rates, and heat exchanger sizes.

The F-Chart program outputs the monthly performance of the solar system. For this reason, it is mainly applicable to analysis of long-term thermal performance of a particular solar system. Because it performs a correlation, the method has several limitations:

1. For domestic hot water systems assume a constant daily water usage distribution. (It does not account for periods when the system may not be used, i.e. vacations.)

2. In a water heating system, it is assumed that energy in water above the set temperature is not useful.

3. F-Chart does not take into account system degradation and leakage.

4. All liquid storage tanks are assumed to be fully mixed. (Both storage and preheat tanks) This leads to conservative estimates of long-term performance by overestimating collector inlet conditions.

5. All days are considered symmetrical about solar noon.

6. The most important limitation is that F-Chart is a correlation for a specified system and only accurately applies to that system. Using F-Chart to model a system which is vastly different from the originally specified system will result in inaccurate performance estimates.

As previously mentioned, this method correlates f, the fraction of the load supplied by solar energy, to two dimensionless groups, X and Y. [Taken from (BEC)]

$$X = \frac{(A_c)*(F_R')*(U_1)*(T_{ref} - T_a)(t)}{L}$$

$$Y = \frac{(A_c)*F_R'(\tau\alpha)*(H_T)*(N)}{L}$$

SYMBOL EXPLANATION

A_c collection area

F_R' collector heat exchanger efficiency factor

U_1	collector overall heat loss coefficient
t	number of seconds in a month
T_a	monthly average ambient temperature
T_{ref}	reference temperature, (100°C)
L	monthly total heat load for both space heat and domestic hot water applications
H_T	monthly average daily radiation incident on collector plane
N	number of days per month
$(\tau\alpha)$	monthly average transmittance absorptance product

These expressions can be rearranged as follows:

$$X = [F_R U_1]\ [F_R'/F_R]\ [T_{ref} - T_a]\ [t]\ [A_c/L]$$

$$Y = [F_R(\tau\alpha)_n]\ [F_R'/F_R]\ [(\tau\alpha)/(\tau\alpha)_n]\ [A_c/L]\ [H_T\ N]$$

The factors $F_R U_1$ and $F_R\ (\tau\alpha)_n$ are obtained from collector performance test results. The term (F_R'/F_R) corrects for temperature drops between collector and the storage tank. It is an indication of the penalty in collector performance incurred because a heat exchanger located between the collector and storage unit causes the collector subsystem to operate at higher temperature than it normally would.

If there is no heat exchanger between the collector subsystem and the storage medium, the term F_R'/F_R equals one. Refer to the reference (BEC) for situations in which this is not the case.

The term $(\tau\alpha)/(\tau\alpha)_n$ is the ratio of the average transmission/absorptance product to that at normal incidence. Klein (BEC) found that the value of $(\tau\alpha)/(\tau\alpha)_n$ during the winter months is nearly constant and equal to 0.96 for a one-cover collection subsystem. For collectors oriented toward the equator, and tilted at angle of latitude plus 15°, Klein suggests using the value of 0.96 for one-glazed systems and 0.94 for a two-cover system.

LIQUID-BASED SYSTEMS

The F-Chart correlation for liquid-based space heating systems is represented by the following expression:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3$$

The terms X and Y are calculated from the relations previously mentioned.

A correlation such as the F-Chart is derived by empirically fitting data obtained from a large number of detailed simulations. It has already been stated that one of the weaknesses of a correlation is that it applies to a specific set of conditions. If the conditions or the system studies are different from that used to develop the correlation, correction factors are required to provide accurate results. Examples include changes in storage capacity and changes in load heat exchanger size.

The storage capacity used to develop the F-Chart is 75 l/m^2 collection area. For other storage capacities, a correction factor is needed to adjust X, the parameter which relates collector heat losses to the total heat load. This factor X_c/X is calculated as follows:

$$\frac{X_c}{X} = \left[\frac{\text{Actual storage}}{75\ l/m^2}\right]^{-0.25}$$

for:

$$0.5 \leq \frac{\text{actual storage}}{75\ l/m^2} \leq 4.0$$

Another parameter which will affect the accuracy of F-Chart is the load heat exchanger size. If this heat exchanger is reduced in size, the storage tank temperature must be increased to supply the same amount of

energy. The consequences are higher collector temperatures and reduced collector output. A measure of the exchanger size required is the value of the group

$$\frac{e_1 C_{min}}{(UA)_h}$$

e_1	effectiveness of load heat exchanger
C_{min}	minimum fluid capacitance in load exchanger
$(UA)_h$	overall heat loss coefficient for building.

It has been observed that a significant reduction in performance results when $e_1 C_{min}/(UA)_h$ is less than one. Practical values for this factor are between 1 and 3. The F-Chart program for liquid systems was developed with a value of two. The following factor is required when values of $e_1 C_{min}/(UA)_h$ other than two are used.

$$\frac{Y_c}{Y} = 0.39 + 0.65\exp(-0.139 \frac{(UA)_h}{e_1 C_{min}}$$

for:

$$0.5 \leq \frac{e_1 C_{min}}{(UA)_h} \leq 50$$

AIR BASED SYSTEMS

The F-Chart correlation for air-based space heating systems is represented by the following relation:

$$f = 1.040Y - 0.065X - 0.159Y^2 + 0.00187X^2 - 0.0095Y^3$$

As in the liquid system case, correction factors are needed when certain system parameters vary from those values used to develop the correlation.

The first such factor is air flow rate. Air flow rate affects both X and Y. An increase in flow rate tends to improve system performance by increasing turbulence and therefore F_R; this increased efficiency affects the value of Y. However, an increase in flow rate decreases thermal efficiency by reducing thermal stratification in the rock storage bed; this decreased performance is reflected in the value of X. Overall, air flow rate produces the most profound effects upon the value of X. The following correlation factor is required when flow rates other than 10 l/s per square meter of collection areas are used.

$$\frac{X_c}{X} = \left[\frac{\text{actual air flow rate}}{10\ \text{l/s*m}^2}\right]^{0.28}$$

for:

$$0.5 \leq \frac{\text{actual flow rate}}{10\ \text{l/s*m}^2} \leq 2$$

The second factor which affects air-based systems is rock-bed storage capacity. Performance of an air-based system is less sensitive to storage capacity than that of liquid-based systems. Unlike liquid systems, air systems can operate in a collector-load mode in which storage is bypassed. The F-Chart for air systems is based on storage capacity of 0.25 m^3 rock per square meter of collection area, which corresponds to 350 kJ/m^2*^oC for typical void fraction and properties.

$$\frac{Xc}{X} = \left[\frac{\text{actual capacity}}{25\ m^3/m^2\ \text{area}}\right]^{-0.30}$$

for:

$$0.5 \leq \frac{\text{actual flow rate}}{25\ m^3/m^2} \leq 2$$

DOMESTIC HOT WATER SYSTEMS

For systems with DHW capabilities only, the F-Chart correlation for a liquid system is with a correction factor. Two temperatures are needed for the analysis:

T_m main water temperature, deg C

T_w minimum acceptable hot water temperature, deg C

$$\frac{X_c}{X} = \frac{11.6 + 1.8T_w + 3.86T_m - 2.32T_a}{(100 - T_a)}$$

This expression is based on a storage capacity of 75 l per square meter collection area; all temperatures are in degrees Celsius.

7.5 Rules of Thumb for Sizing Active Solar System Components

As was discussed in sections 4 and 6, one of the main difficulties facing potential solar users is the determination of the required system size. Most system components such as pumps, blowers, piping, tanks and ductwork are selected on the basis of collector area. The principal reason is that the amount of collection surface area determines the total thermal energy that can be delivered to the user's load.

This section provides basic "rules of thumb" to use when selecting subsystem equipment. These guidelines are for preliminary design only. Proper optimization techniques should be used when making final selections for heat exchanger, piping, ductwork, etc. For these rules, it has been assumed that an optimum collection area has already been selected by valid technical and economic analyses. All design suggestions are referenced to a unit area of collection surface, i.e. a storage capacity of 2 l per square meter (m^2) of collector. The following information has been compiled from these references: (BEC), (CEC-4), (KRE-3), (SOL-1), (SOL-2), (WIL), (HIM), (DOE).

LIQUID-BASED SPACE HEATING SYSTEM

COMPONENT	RECOMMENDED VALUE	RANGE OF VALUES
Collector orientation	true south, 0	$0° \pm 15°$
Collector tilt	latitude + 15°	(lat − 20°) to vertical (lat + 15) ± 15°
Collector fluid flow rate	0.0136 $l/s*m^2$	0.00679 − 0.0204 $l/s*m^2$ 0.010 to 0.020 $kg/s*m^2$
Water storage	81.6 l/m^2	40.8 to 102 l/m^2
Collector/storage heat exchanger	$F_R'/F_R = 0.97$	$F_R'/F_R > 0.90$
Load heat exchanger	$\frac{e_L C_{min}}{(UA)_L} = 2$	$1 < \frac{e_L C_{min}}{(UA)_L} < 5$
Pressure drop across collector		3.45 to 34.5 kPa/module
Approach temp for heat exchanger	5.6°C	
Water preheat tank capacity	1.5* (capacity of conventional heater)	

AIR-BASED SPACE HEATING SYSTEM

COMPONENT	RECOMMENDED VALUE	RANGE OF VALUES
Collector orientation	true south, 0	$0^\circ \pm 15^\circ$
Collector slope	latitude $\pm 15^\circ$	(lat + 15°) $\pm 15^\circ$
Collector air flow rate	10.2 $l/s*m^2$	5 - 20 l/m^2*s
Storage capacity	0.23 m^3/m^2	0.15 to 0.35 m^3 rock/m^2 collector
Pebble size (graded to uniform size)	0.019 - 0.038 m	0.01 to 0.03 m
Bed length, flow direction	1.83 m	1.25 to 2.5 m
Pressure Drops		
Pebble bed	0.0374 kPa,g	55 Pa minimum
Collector		50 to 200 Pa
Ductwork	0.065 kPa/100 m	10 Pa
Maximum entry velocity of air into pebble bed at 55 Pa delta P		4 m/s
Water preheat tank capacity	2*(DHW aux. tank)	1.5*conventional water heater
Duct insulation	2.54 cm fiberglass	R-4 to R-13 R-7 minimum

ACTIVE DOMESTIC HOT WATER SYSTEMS

COMPONENT	RANGE
Collector area rough approximation	0.0245 $m^2/l*day$
Storage capacity	61.2 to 81.6 l/m^2
Water equivalent collector flow rate	0.0204 - 0.0272 $l/s*m^2$
Heat exchange area	0.05 to 0.1 $\frac{m^2_{he}}{m^2_c}$
Collector tilt	latitude $\pm$ 5°
Expansion tank volume indirect system	12% of collector fluid loop
Heat rejector capacity	Equivalent to peak collection rate possible under clear sky conditions at heat rejection specified temperature
Controller turn on temperature difference	8.3 to 11.1°C
Controller turn off temperature difference	1.7 to 2.8°C
System operating pressure	To provide 20.7 kPa, gauge at topmost collector manifold

ACTIVE DOMESTIC HOT WATER SYSTEMS

COMPONENT	RANGE
Storage tank insulation	R-25 to R-30
Mixing valve set point	48.9° to 60°C
Pipe diameter	To maintain fluid velocity below 1.83 m/s and above 0.61 m/s

RECOMMENDED PIPE DIAMETERS FOR VARIOUS FLOW RATES (SOL-1)

Select pipe size English units	Flow rate Gal/min	liter/sec	Velocity ft/s	m/s	Pressure drop per 100 feet, PSI
3/8"	2	0.126	3.36	1.02	6.58
1/2"	4	0.253	4.22	1.29	7.42
3/4"	8	0.505	4.81	1.47	6.60
1"	15	0.948	5.57	1.70	6.36
1-1/4"	25	1.58	5.37	1.64	4.22

DIMENSIONS AND AIR VELOCITIES FOR VARIOUS ROCK BEDS (KRE-4)

Bed dimensions and air velocity	Rock diameter (cm) 0.64 cm	1.3 cm	1.9 cm	Design Basis
Bed height, m	1.04	1.80	2.26	Maximum allowable pressure (maximum height)
Bed area, m^2	25.6	14.8	11.7	
Air velocity, m/s	0.030	0.053	0.067	
Bed height, m	0.838	1.22	1.52	Intermediate Height
Bed area, m^2	31.6	21.7	17.4	
Air velocity, m/s	0.025	0.036	0.045	
Bed height, m	0.610	0.610	0.610	Minimum Height
Bed area, m^2	43.4	43.4	43.4	
Air velocity, m/s	0.018	0.018	0.018	

It must be emphasized that the preceding guidelines are only for preliminary system sizing. Final equipment specifications are obtained through rigorous design methods and subsequent economic optimization. The rules of thumb given are used to obtain an estimated system cost. At that point, a decision is made regarding feasibility of further study and implementation of the system. If the decision is favorable, detailed design routines would be utilized to analyze and specify all aspects of the system, i.e. pump type, pump size, pipe material, pipe sizes, and heat exchanger size.

7.6 Solar Collector Performance

7.6.1 Introduction

A solar collector "gathers" energy by converting incident solar radiation to energy in the form of a heated fluid. The conversion occurs when an absorber is heated by the sun's radiation and subsequently contacts a moving fluid either directly or indirectly.

Under steady conditions, the useful energy delivered by the solar collector is equal to the solar energy absorbed minus any heat losses. This principle can be stated as:

[Useful Energy from Collector] = [Area of Absorber] [Solar Radiation Absorbed] - [Heat Losses]

Using the terminology used by Duffie and Beckman, (BEC):

$$Q_u = A_c F_R \left[G_T \left(\tau\alpha\right) - U_L \left(T_p - T_a\right)\right]$$

Where (utilizing English or metric units throughout):

Q_u = Useful heat delivered by collector system (kJ/s, BTU/hr).

A_c	=	Total collection area (m^2, ft^2).
F_R	=	Heat removal factor, the ratio of the energy collected to that collected if the entire absorber plate were at the inlet fluid temperature.
G_T	=	Solar radiation incident on upper surface of collector per unit area ($kJ/s/m^2$, $BTU/hr/ft^2$).
α	=	Absorptivity, the fraction of incoming solar energy incident on surface which is absorbed, dimensionless.
τ	=	Transmissivity, the fraction of incoming solar radiation which reaches absorbing surface, dimensionless.
U_L	=	Overall heat loss coefficient of collector, ($W/m^2/°C$, $BTU/hr/ft^2/°F$).
T_p	=	Average temperature of the upper surface of absorber plate, (°C, °F).
T_a	=	Ambient temperature, (°C, °F).

7.6.2 Principal Design Factors

The goal of collector design is to maximize the amount of solar radiation that can be absorbed on the collector while simultaneously minimizing heat losses. Therefore, a collector designer has two options to improve collector performance: increase solar absorptance and/or decrease heat loss. A measure of performance is the collector's thermal efficiency, which indicates what fraction of incident radiation is converted to useful energy.

Heat loss from the collector occurs by radiation, convection, and conduction. If a bare metal plate serves as the collector, heat loss coefficients to the atmosphere range from 2 to 10 $BTUh/ft^2*°F$ (11.3 to 56.7 $W/m^2/°C$). As a result, rates of heat loss would be so large that an absorber plate temperature 25 to 50°F (13.9 to 27.8°C) above

atmospheric would be the maximum achievable under typical full solar insolation of 300 BTU/ft^2 (3403 kJ/m^2) (SOL-2). Under these conditions no useful heat would be delivered by the collector because heat loss would equal absorbed solar radiation.

Heat loss due to convection and radiation can be reduced by installing one or more transparent surfaces, such as glass, above the metal absorber. Glass, for example, will transmit as much as 90 percent of the incident solar radiation, as well as reducing the heat loss coefficient U_L. The reduction of U_L results from a stagnant air layer between the absorber plate and cover, which suppresses convection heat loss. In addition, long-wave thermal radiation emitted by the absorber plate is intercepted by the cover system because glass is opaque to long-wave radiation. Similar benefits are realized by the use of certain transparent plastics. In harsh climates, further reductions are gained when a second transparent cover is utilized.

Radiation losses can be cut further by use of selective coatings on the absorber and cover surfaces. Thermal radiation emitted by the absorber plate may be reduced by reflecting it downward from the lower cover plate. This is accomplished by applying an infrared-reflecting coating on the cover surface facing the absorber plate. For example, a very thin layer of tin oxide or indium oxide deposited on the glass will reduce losses by reflecting radiated energy back to the absorber surface. These coatings absorb a small fraction of the incoming solar radiation; usually, the reduced thermal losses offset the absorption losses.

Conduction losses are due to thermal gradients in the absorber plate. Such losses can be reduced by properly designed fluid flow patterns and passages. The absorber plate should be a material with a high thermal conductivity. Significant conduction losses occur through the back and sides of the collector. To remedy this, high-temperature insulation

should be used adjacent to the back side of the collector. Additional insulation is needed for the sides. For medium-temperature flat plate collectors, the R-value of the insulation should be at least 10 (English units).

As was previously stated, the thermal efficiency of a collector indicates what fraction of incident solar radiation on the collector is transferred as useful energy to the working fluid.

The collector efficiency is important because it is used in design calculations to determine the collector area required to provide a needed amount of useful thermal energy. Unfortunately, collector efficiency is not a constant value; it depends upon such parameters as average tempertaure of operation, solar insolation level, wind speed, collector flow rate, and ambient temperature. As a result, for example, the efficiency measured at noon on June 21 is not the same as the average daily efficiency for June 21 and that is not the same as the monthly efficiency for June.

The useful energy collected can be expressed as:

$$Q_u = A_c \; [G_T \; (\tau\alpha) - U_L \; (T_p - T_a)]$$

If the numerical value of all the terms above are known, the rate of useful energy delivery, Q_u, can be calculated. In addition to the design characteristics of the collector, ambient temperature, solar insolation, and average absorber plate temperature must be known. With the exception of plate temperature, these terms can be readily obtained. The absorber plate temperature, however, is seldom known and cannot be easily measured; it is affected by other collector operating conditions, and, more importantly, by the inlet temperature of collector fluid. In most instances this inlet fluid temperature is known or can be accurately estimated. For convenience, the above equation can be

modified by substituting the inlet fluid temperature for the absorber plate temperature and adding a correction factor. The resulting equation is:

$$Q_u = F_R A_c \left[G_T (\tau\alpha) - U_L (T_i - T_a) \right]$$

T_i	inlet collector fluid temperature
F_R	heat removal factor

The heat removal factor F_R is the ratio of collected energy to that collected if the absorber plate temperature were equal to the inlet fluid temperature. Theoretically, this temperature equality would be possible if the fluid were circulated through the collector at a large rate such that there would be a negligible rise in the fluid temperature as the fluid is circulated. The heat transfer coefficient for heat transfer between the absorber plate and collection fluid would be high so that a negligible temperature difference between the two would exist.

The above equation can be rewritten so as to define the collector efficiency, that is, the ratio of useful energy delivery to total solar insolation incident.

$$= \frac{Q_u}{A_c G_T} = F_R (\tau\alpha) - \frac{F_R U_L (T_i - T_a)}{G_T}$$

The efficiency can also be defined by:

$$= \frac{\dot{m} c_p \triangle T}{A_c G_T}$$

Where:

$\dot{m}$	mass flow rate of fluid through the collector
c_p	heat capacity of working fluid
$\triangle T$	temperature difference between inlet and outlet of collector fluid.

For a given collector operating at a constant fluid circulation rate, A_c, F_R, [illegible], [illegible], and U_L are nearly independent of temperature and insolation level. As it is defined, the collector efficiency decreases as the average fluid temperature increases.

Assuming that A_c, F_R, [illegible], [illegible], and U_L are constant, η_i, the thermal efficiency, is a linear function of the difference $(T_i - T_a)$. That is, the preceding equation represents a straight line of a plot of efficiency versus $(T_i - T_a)/G_T$. The y-intercept of this curve is F_R ( ) and the slope is $-F_R U_L$. If experimental data on collector energy delivery at various temperatures and solar conditions are plotted as $_i$ versus $(T_i - T_a)/G_T$, the best straight line through the data points is a complete representation of the collector performance over a wide operating range.

The y-intercept of the efficiency (the point at which the line intercepts the vertical axis) corresponds to the fluid inlet temperature being equal to the ambient temperature. At this point, collector efficiency is at its maximum. When the curve intercepts the horizontal axis, the thermal efficiency is zero. This situation corresponds to a very low insolation level, or a high fluid temperature so that heat losses equal solar absorption so that no useful energy is delivered. At this point, the temperature of the absorber plate is equal to the inlet fluid temperature, and is the maximum attainable for a particular ambient temperature and insolation level. This temperature is called the stagnation temperature of the collector.

The efficiency curve slope $-F_R U_L$ and intercept F_R ([illegible]) are used in many design procedures to characterize the collector's performance. Knowledge of these two parameters allows the collector's behavior to be characterized over a normal temperature operation range. Many methods have been synthesized to experimentally determine these two parameters.

Collector performance tests have been standardized and most test facilities use the ASHRAE 93-77 Standard Procedure. The basic test method is to expose the test collector to solar radiation and observe its performance.

Data recorded in a typical test include:

1. Wind speed
2. Radiation incident on collector surface
3. Ambient temperature
4. Inlet and outlet fluid temperature
5. Fluid mass flow rate

ASHRAE has three standardized test methods for liquid solar collectors, one for closed loop and two for open systems. These test methods have the following common features:

- Control of the inlet temperature of working fluid into collector. Tests are made at various inlet temperatures.
- Pyranometer on plane of collector to measure incident solar radiation.
- Instrumentation to measure mass flow rate of working fluid, inlet and outlet fluid temperatures, and ambient conditions.
- Instrumentation for pressure and pressure drop across the collector.

For air heating collectors, additional instrumentation is needed to specify conditions such as air flow rate, air mixing, air temperature, and pressure drop.

Most performance tests are done outdoors although tests can be done indoors with equipment to simulate solar radiation and ambient conditions.

A typical test procedure is as follows:

a) The collector is operated under steady conditions to determine Q_u (G_T, T_i, T_a are measured). Outdoor tests are usually peformed at midday, on clear days, and with beam radiation normal to collector surface.

b) Tests are done at various inlet temperatures, T_i.

c) "Instantaneous" efficiency $= \frac{Q_u}{A_c G_T}$

d) is plotted against $(T_i - T_a)/G_T$

e) If U_L, F_R, and $(\tau\alpha)_n$ are constant, the plot of efficiency versus $(T_i - T_a)/G_T$ is a linear relationship. The slope of the curve (straight line) would be $-F_R U_L$ and the intercept of F_R $(\tau\alpha)$.

However, U_L, F_R and $(\tau\alpha)$ are <u>not</u> constant. For instance, U_L varies with temperature, wind speed, and number of collector covers. Thus data is fitted to form a linear relationship. The parameters $-F_R U_L$ and F_R $(\tau\alpha)$ are used in design methods such as F-Chart to design and size systems.

7.7 Active/Passive Retrofit Guidelines

7.7.1 Introduction

Solar energy technologies have been used in the past primarily in new construction. Unless existing buildings are converted to solar, the benefits of solar technologies will be slow in coming and limited to a small segment of the population. Solar retrofitting need not be restircted to single family residential units. Businesses that use a large amount of hot water and apartment buildings are excellent candidates for solar domestic hot water applications. It is believed that just about any structure should be regarded as a potential retrofit.

7.7.2 Energy Conservation

Before any solar system is chosen, it is important to determine the current energy consumption due to space heating and domestic hot water. Detailed techniques for estimating DHW, heat, and cooling loads are described in (ASH-1). Other good references are (KRE-3), (SOL-1), (SOL-2), and (WIL).

7.7.2.1 DHW Conservation

There are several methods available which reduce the amount of energy required for domestic hot water. In the majority of cases, they involve simple changes in living habits or small expenditures. One simple measure is to reduce hot water consumption. This can be accomplished by altering some living habits; another method is to intall flow reducers in shower heads and faucets. Another important conservation measure which can save on the DHW load is to stop hot water leaks caused by dripping faucets. For example, a single hot water faucet leaking 1 drop per second can waste 10 gallons (37.8 l) per day or 3650 gallons (13,815 l) per year. This can account for 10 percent of an average four-person family consumption.

Additional conservation measures can reduce energy consumption for water heating. These particular methods will not affect water consumption but will reduce standby heat losses, thus saving fuel. Large heat losses occur when hot water is in storage and is not being used. These standby losses are reduced if the DHW thermostat is turned down. Another important measure is to insulate the hot water tank by wrapping 3 1/2 inch (8.9 cm) thick fiberglass batts around the outside of the tank and securing with tape. Reductions of up to 30 percent of the standby heat lossses are possible.

7.7.2.2 Space Heat Conservation

In general, space heat consumption can be reduced by putting less heat into the building, decreasing the flow of heat out of the building, and improving the efficiency of the heat source. Measures that can be taken are the following:

(a) Lower thermostat setting

(b) Stop air leaks by weatherstripping and caulking

(c) Insulate ceiling

(d) Insulate exterior walls

(e) Insulate windows--storm windows, drapes, insulating shutters, etc.

(f) Service furnace or heat source

(g) Turn off pilot lights in summer

7.7.3 Solar Prospecting

The first step in solar retrofitting is to reduce energy consumption by conservation measures. The previous section described possible routes to take. At this point, the amount of energy required for space heating and hot water has already been estimated. The next major step is to survey your house or building to see where you can locate the various parts of a solar energy system. This step, referred to as solar prospecting, consists of finding and evaluating potential collection areas and noting capabilities of existing equipment.

7.7.3.1 Possible Collection Areas

Possible collection areas are any generally south-facing walls, roofs, or fences that receive good sunlight and have areas of approximately 30 ft^2 (2.79 m^2) or greater. The ideal situation is one rectangular

uninterrupted area large enough to do the whole job. Unfortunately such as an area does not often exist. Passive collection areas can be divided more easily than active areas. Some passive retrofits are easier to do when remodeling at the same time, i.e. adding rooms or knocking out walls.

One option is the use of free standing collectors Free standing collectors can be mounted in yard areas, against south walls, and on roofs. Problems encountered with free standing collectors include the following:

1. Visibility--Collectors often protrude above the roof line of buildings.

2. Wind--Panels can act as sails and tear off their mounts. The structure must be capable of supporting a wind load of 15-20 lb/ft^2 (73.2 to 97.6 kg/m^2) collection area.

3. Earthquakes--Panels must have sideway bracing capable of resisting 1/5 of their weight.

4. Chimney and Vent Clearance--Free standing collectors can interfere with proper performance of chimneys and vents. Chimneys must extend 2 feet (61 cm) above any panel within a horizontal distance of 8 feet (2.44 m). Vents must extend 6 inches (15.2 cm) above the panel.

7.7.3.2 Shading

The issue of shading is just as important as a south-facing orientation. A south-facing collection area that is shaded during critical hours will not be very efficient. It is generally recommended that a potential collection area be exposed to direct sunlight between the hours of 9 a.m. to 3 p.m. It is difficult to precisely predict how much heat collection is reduced by shading. A good rule of thumb is that whatever percentage of collection area is shaded, the system will lose double that percentage in output (CEC). For example, for a collection area in which 50 percent is shaded during the critical hours of 9 a.m. and 3 p.m., the useful output will be virtually nothing.

When prospecting, keep the following in mind:

1. Buildings or trees to the south of your location can cast shadows on collection areas. This is worse in winter because of longer shadows.

2. Tall overhanging trees or building eaves cast shadows during the summer.

3. Use a sun viewer to estimate summer and winter shading from overhangs and other projections and obstructions.

In conclusion, the following are steps and decisions to make when prospecting for potential collection areas:

1. **Find true south**
   a. Compass method--Note: magnetic south is not true south. Check and find out the correction for your particular location.

   b. Solar noon method--The sun is in a true south direction at solar noon, which differs from clock noon because of daylight savings and location within a time zone.

2. **Orientation of surface**
   15 degrees east or west of south is acceptable.

3. **Obstructions & Other Considerations**
   a. Zoning--Some local restrictions may apply especially for room additions or greenhouses.

   b. Aesthetics--The willingness to alter the appearance of the building.

   c. Working conditions--Any surface which has a slope steeper than 30° requires time-consuming safety precautions. In addition, it is difficult to get materials to high or inaccessible surfaces.

   d. Existing roof materials--It is difficult to fasten collectors to slate or tile roofs; wood and asphalt shingle roofs present fewer problems.

4. **Existing equipment**
   a. Note whether water heater runs on electric or gas.

   b. Note the water supply pipe coming into the water heater, since it may be interrupted.

c. Note the type of fuel the heating system uses and how the system functions.

d. Some heating systems (floor furnaces, wall furnaces, and electric baseboard) deliver heat directly to the space. There is no way to tie a solar system into this type of equipment.

e. If a central heating system exists, look for:
   - forced air systems (supply and return ducts): possibilities of installing additional equipment on return side of furnace.
   - Water (hydronic) system: trace pipe runs and how water is pumped in and around the building.

7.7.4 Possible Space Heat and DHW Retrofit Options

7.7.4.1 Integral Collector Storage DHW Units

The units are sometimes called batch or breadbox water heaters. Storage and collector are combined into a single unit. They are usually constructed of an insulated, glazed-top box around a storage tank with the optional addition of reflectors to enhance energy collection. The heater should be installed in a sunny, south-facing location beside the building, as near as possible to the existing water heater. The cold water service to the existing heater is interrupted so that water is rerouted through the batch unit. Because of weight on the order of 500 lb (226.8 kg) for a 50-gallon (189.2 liter) unit, batch units are suited to ground-level installation. For other than ground level locations, proper mounting and support must be available.

7.7.4.2 Flat Plate Water Heater

Flat plate DHW systems require a relatively small area, 30 to 100 ft^2 (2.78 to 9.29 m^2). Collectors are generally mounted flush on the roof, although free-standing collectors can be used on flat roofs. This system uses a storage tank with a capacity of 1.5 to 3 gallons per square foot (61.1 to 122.2 l per square meter) collector. An ideal location for the storage tank is next to the existing water heater.

The flat plate DHW system does not require a pump. A thermosiphoning system can be used if the storage tank can be placed above the collector. Usually, the tank requires so much support that suitable elevated locations are rare. Another disadvantage of thermosiphon systems is that larger piping (from 1-1/4 inches (3.18 cm) diameter) between the collector and storage is needed.

7.7.4.3 Windows and Skylights

Windows and skylights can provide solar heat by direct gain if the glazing is sloped and oriented toward south. Before installing additional glazing area, it is important to check whether affected rooms already overheat on sunny cold days. If this is the case, no additional glazing area should be installed. If the affected rooms only overheat during summer, more glazing area can be intalled if overhangs are installed to keep out the summer sun.

It is possible to store some of the admitted solar energy if concrete or water walls are positioned such that sunlight strikes between 9 a.m. and 3 p.m. Since a single pane of glass is a poor insulator, the windows can lose more energy than they gain unless insulation is provided for nights and cloudy periods.

7.7.4.4 Thermal Wall

One basic method for adding storage capacity is to build a heavy wall behind south-facing glass. One basic disadvantage of this and other massive wall systems it that most floors cannot withstand their weight. If the existing floor is not strong enough, there are two alternatives. The first is to add a room with large south-facing glazing area on a well reinforced slab on grade. A massive wall will then be built on this slab forming the wall between the new room and the rest of the building. A second choice is to knock out a portion of the south wall and build a concrete foundation wide enough to accommodate drums or culverts and glazing.

Another version of the drum wall is a tube wall. A double glazed row of 6 to 12" (15.2 to 30.5 cm) diameter water-filled tubes are intalled over a blank area of south wall. In this design, the tubes act as both collector and storage. Heat is delivered to the buildings by blowing air past the back of the tubes with a fan.

A third possibility is a Trombe wall, a double-glazed south wall built with grout-filled concrete block, brick, stone, or solid concrete. Vents are provided to facilitate natural ventilation. The wall's weight requires an on grade foundation. For a wood-frame house, the south wall would be knocked out and replaced or a system would be incorporated into a room addition with south facing exposure.

7.7.4.5 Liquid-based Flat Plate Heating System

This type of system requires a central heating system; if one does not exist, it has to be installed in order to use this system. A large collector area is required to do a significant portion of the space heat requirements. Collectors are mounted either flush or freestanding. This type of solar system can essentially be viewed as a large solar water heating system plus delivery system for transfer of energy from storage to the load.

The delivery system can be connected into a forced air heating system by installing a heating coil in the return air duct. However, integrating with a hydronic system is much simpler. A few plumbing connections are all that is needed. Radiant floor slabs operate by pumping warm (80 to 110°F, 26.7° to 43.3°C) water through pipes in the concrete floor. The pipes then warm the concrete which in turn radiates energy into the rooms. Baseboard convector systems transfer energy to the house by pumping hot (120 to 160°F, 48.9° to 71.1°C) water through finned pipes that run along the room perimeters. Because high temperatures are difficult to achieve with a solar system, baseboard systems are not as well suited to retrofitting as radiant slabs.

Volume III of III Volumes

Active/Passive Technology
Reference Notebook

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RENEWABLE ENERGY RESOURCES
FIELD TESTING

VOLUME III OF III VOLUMES

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8. RESEARCH AND DEVELOPMENT THRUSTS

8.1 Active Space Heating

8.1.1 Overview

Active solar technology applications in the United States are primarily devoted to domestic water heating, pool heating, space heating, and space cooling for residential and commercial buildings. In addition, active technologies are used in agricultural applications (such as crop drying) and low temperature industrial heat.

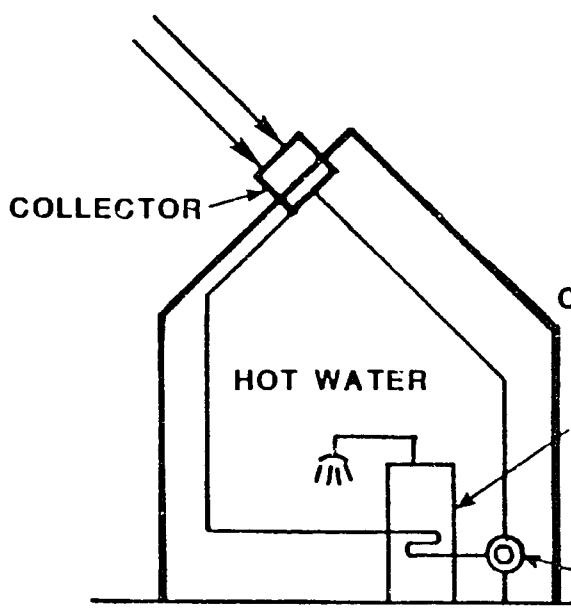
Typical domestic hot water (DHW) solar systems consist of 2 to 4 collectors (3.7 to 7.4 m^2). However, space heating systems can potentially be up to four times as large and will provide energy at a smaller rate, as excess energy is not utilized during the summer months (Exhibit 8-1 illustrates the size and complexity differences of these systems). Active space heating systems are not economically competitive, even though they are commercially available. The cost of copper absorbers and glass covers alone prevent space heating to be competitive. Research, however, is focusing on new low-cost materials for solar collectors to improve the cost competitiveness of active space heating.

8.1.2 Thin-Film Solar Collector

For several years, the United States Department of Energy (DOE) has funded research on thin-film polymeric flat plate collectors. These lightweight, large-area collectors are predicted to cost significantly less than standard flat plates. In 1983 DOE awarded Burton Energy and Solar Technology, Inc. (BEST) a contract to manufacture a version of this collector for DHW applications.

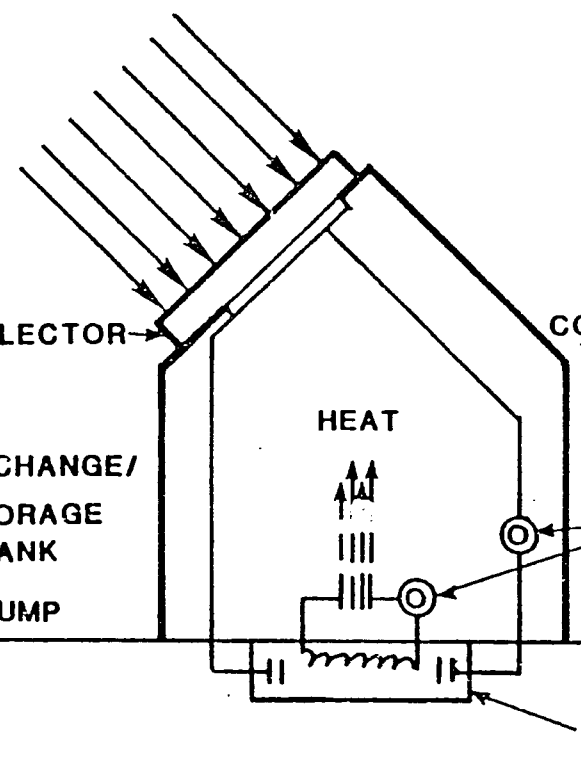
ACTIVE SOLAR SYSTEMS

WATER HEATING



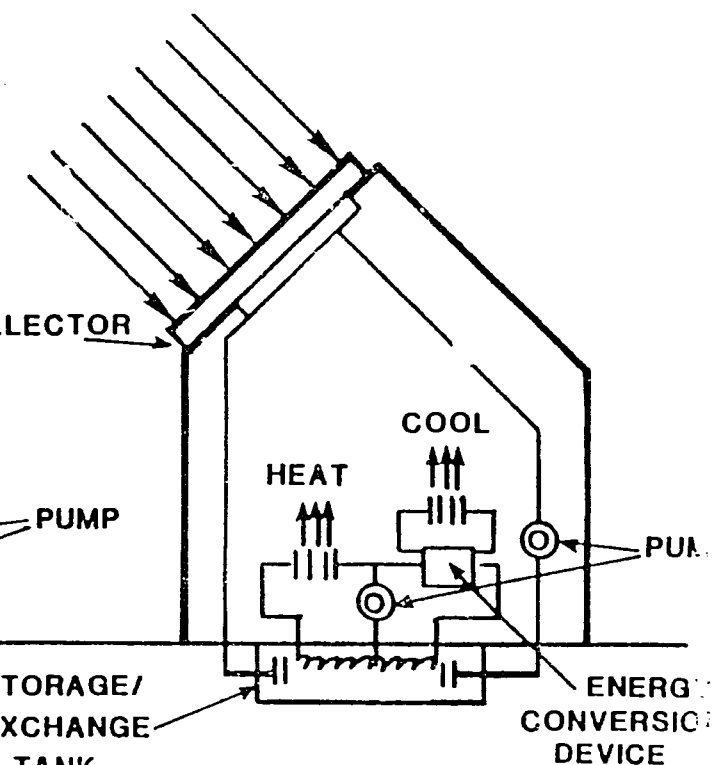
- SMALLEST COLLECTOR ARRAY
- SIMPLEST DESIGN
- LOWEST COST/EASILY RETROFIT

SPACE HEATING



- LARGE COLLECTOR ARRAY
- HEAT STORAGE REQUIREMENT

SPACE HEATING AND COOLING



- LARGEST COLLECTOR ARRAY
- ENERGY CONVERSION DEVICE
- HEAT STORAGE REQUIREMENT

EXHIBIT 8-1 (DOE-3)

The BEST collector has two sheets of highly specialized carbon-impregnated polymeric film for the absorber. BEST projects collector costs to be approximately one-fourth that of conventional copper flat plates. Also, since their weight is only 1/10th (10%) that of metal collectors, installation costs will be reduced. Exhibit 8-2 is a schematic diagram of a thin polymer film flat plate collector.

The Solar Energy Research Institute (SERI), supported by DOE, has been involved in identifying improved polymeric materials for thin-film glazings. SERI has found that surface fluorination can improve transmittance of inexpensive polymers by approximately 5% and polyester materials appear to have the greatest potential for glazing applications.

Exhibit 8-3 summarizes recent solar collector product trends.

8.1.3 Thickness Insensitive Paint

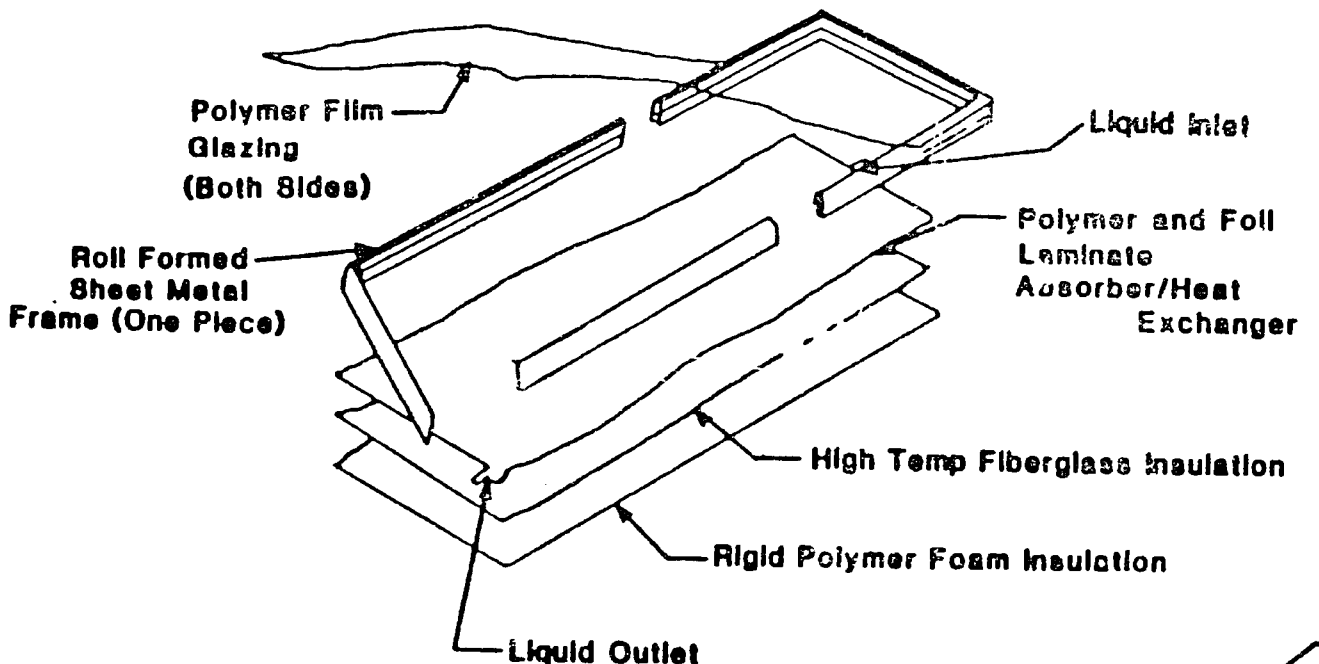
In this case, the objective is to develop an inexpensive selective paint that has optical properties comparable with more expensive coatings, i.e. having absorptivity greater than 0.9 and emissivity less than 0.1. This paint would then be applied to the absorber or storage materials.

Work done at Los Alamos National Laboratory has revealed that aluminum, copper, and brass flake materials show potential for achieving these properties. Although initial samples have only produced an absorptivity of 0.83 and an emissivity of 0.33, results continue to be encouraging.

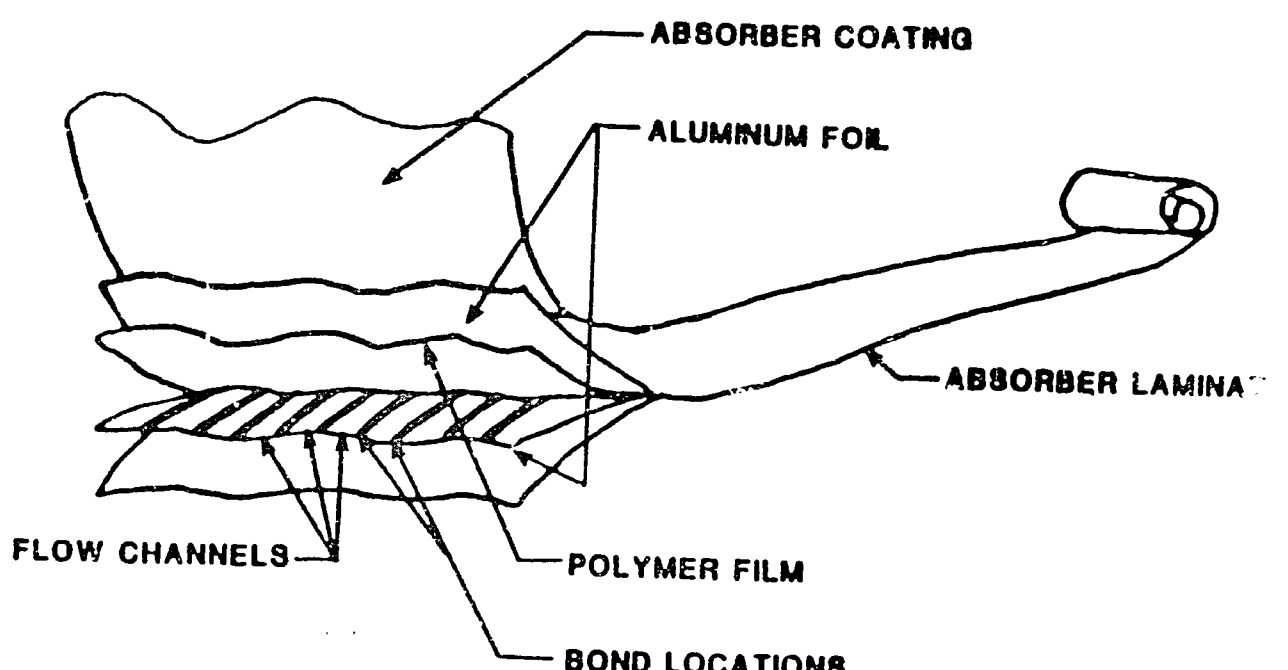
8.1.4 Packaged Residential Space Heat Systems

The incentive for developing advanced packaged residential space heating systems is to reduce system cost and increase reliability. Utilization of innovative materials, components, and system designs will reduce system cost, simplify installation and repair, and prolong system operating life. Testing and evaluation of these innovative systems will supplement the solar industry's knowledge base, leading to the development of cost-effective active solar space heating systems.

THIN POLYMER FILM FLAT PLATE COLLECTOR



BNL COLLECTOR DESIGN CONCEPT



LAMINATED ABSORBER

EXHIBIT 8-2

(DOE-3)

PRODUCT	SAMPLE SPECIFICATIONS	MANUFACTURERS
Refrigerant Charged Collectors		
- these collectors passively transfer heat from the collector absorber to an integrated or separate condenser/ heat exchanger.	Freon refrigerant, hermetically sealed collector, black chrome copper absorber, aluminum casing, tempered glass glazing, copper tube in shell heat exchanger, R-10 insulation, 3'x8' panel.	Dell Solar, Ying Manufacturing.
Thin-Film Plastic Collectors		
- lightweight polymer film absorber and glazing construction to produce a low-cost, large area collector.	Tedlar cover glazing, aluminized polyimide film absorber with semi-selective coating, galvanized steel frame, polyester backing, air and foam insulation, 60 sq. ft. panel.	ACME Solar Works and Burton Energy Systems expect to begin production in 1984.
Passive ICS Systems		
- integrated collector and storage components rely on thermosyphoning for heat transfer and thermal inertia, and insulation for freezing protection.	6" O.D. stainless steel absorber/storage tubes, selective paint surface, low-iron glass cover glazing, teflon inner glazing, aluminum casing, R-12 insulation, 38 gallon capacity, 19 sq. ft. panel.	Gulf Thermal, Solar Edwards, Fafco, Servamatic, Sun Systems.

EXHIBIT 8-3

Recent Collector Product Trends (SAI-2)

8.1.5 System Performance Monitoring

Solar system performance is monitored by the DOE supported National Solar Data Network (NSDS). Selected solar demonstration projects have utilized instrumentation installed with a standardized set of sensors to obtain high quality data. Under the program, monitoring instrumentation has been installed at over 170 solar sites, with a number of sites monitored for 3 years or more. During FY-1983, 12 active solar sites were monitored by the NSDS. Performance monitoring has provided some important information for designing active solar systems. For example, air systems were found to perform as well or better than liquid systems; system performance can be improved by keeping the ratio of collector area to load low; and good system performance is very dependent on proper installation and adjustment of the system.

8.2 Active Space Cooling

8.2.1 Overview

DOE supports the development of the following three solar space cooling technologies: absorption, Rankine, and desiccant. Active space cooling systems have the largest area and tend to provide less energy (on a per square meter basis) due to inherent inefficiencies of the systems. Operating experience has proven that, in most U.S. applications, state-of-the-art solar cooling systems are too costly for commercialization. To achieve signficant market penetration, cheaper collectors and systems with higher performance characteristics are needed.

8.2.2 Advanced Regenerative Absorption Chillers

The Lawrence Berkeley Laboratory (LBL), of the University of California, completed testing of an advanced double-effect regenerative air-cooled absorption chiller in FY-1983. Tests on this machine have confirmed flow stability in the regenerator and achievement of near-design performance (COP of 1.35 @ 137.8°C generator temperature). This success enabled LBL to proceed with final design and experimental testing of a

more advanced high efficiency single-effect regenerative absorption chiller. This single-effect regenerative design has a predicted COP of 1.3 to 1.5. The higher COP's will reduce required collector area and therefore reduce the cost of the solar cooling system.

8.2.3 Integrated Stationary Evacuated Concentrator Collector

An advanced version of the compound parabolic concentrating collector (the integrated stationary evacuated concentrator) has been designed at the University of Chicago to operate continuously at temperatures of 190.6°C or higher. This collector has achieved the best high-temperature performance ever measured with a stationary collector.

A recommended profile design, having a concentration ratio of 1.55 and an acceptance angle of $\pm 35°$, has been identified. Thermal and pumping losses have been reduced to acceptable levels, and two passive approaches for ensuring stagnation (no liquid flow) survival have been identified. The integrated stationary evacuated concentrator research will furnish a data base that industry can use to develop a high-temperature stationary collector for use in high-temperature solar cooling systems.

Exhibit 8-4 summarizes the status of absorption cooling systems and evacuated CPC collectors.

8.2.4 System Integration and Control

The Carrier Corporation's air-cooled 3-ton absorption chiller at Colorado State University (CSU) Solar House I was successfully tested and demonstrated near-design performance. The Arkla Corporation's evaporative-cooled 3-ton absorption chiller was tested over a complete cooling season in CSU's Solar House III.

TECHNOLOGY STATUS - ABSORPTION COOLING

COMPONENT/SYSTEM		CURRENT STATUS	5-YEAR GOALS
EVACUATED/CPC COLLECTORS	EFFICIENCY	60% @ 300°F (LAB)	60%-70% @ 300°F
	COST	$25-$35/SQ. FT.	$9-$12/SQ. FT. (PROJECTED)
	LIFE	>10 YEARS	>15 YEARS
CHILLER	COEFFICIENT OF PERFORMANCE	0.6-1.2	1.5
	COST	$700-$1000/TON (SINGLE EFFECT)	$1,000/TON (ADVANCED REGENERATIVE)
	LIFE	>10 YEARS	15 YEARS
SYSTEM	COEFFICIENT OF PERFORMANCE	0.2-0.4	0.8-1.0
	COST	$10,000-$12,000/TON	$3,000-$5,000/TON (PROJECTED)
	LIFE	>10 YEARS	>15 YEARS

EXHIBIT 8-4

(DOE-3)

In FY-1984 and FY-1985, Drexel University has plans to characterize the dynamic behavior of active solar systems, develop a simulation model to match the dynamic behavior, and then validate the model using data obtained in experimental system test at CSU's Solar House III. This project will enhance the understanding of interactions between components of a solar system and how to best control components to achieve maximum seasonal performance.

8.2.5 Rankine Cooling

Previous DOE research has developed Rankine chillers that operate at 93°C for residential and commercial applications. In addition, high temperature Rankine (149°C) chillers have been developed for commercial use. At this time, these state-of-the-art solar Rankine cooling systems are too costly for commercialization.

At the United Technologies Research Center (UTRC), laboratory tests were completed on an 18-ton second generation turbocompressor heat pump designated as the MOD-2; the unit under went endurance testing in Phoenix under the joint U.S./Saudi Arabia SOLERAS solar program. This pump provided 75% of the cooling load in the Hamilton Test Systems headquarters. The performance target of 0.7 COP with a 149°C generator temperature was achieved. This is a 15% improvement in performance over the first generation MOD-1 unit.

A design using a hybrid Rankine steam cycle to drive a conventional vapor compression chiller was developed at the University of Pennsylvania. In this design, steam feed water is preheated to 100°C by solar means and then superheated to 599°C by fossil fuel. Theoretically, the thermal efficiency of this hybrid steam Rankine cycle is more than double that of solar-powered organic fluid Rankine cycle operating at 93°C.

8.2.6 Desiccant Cooling

The difficulties encountered in reaching cost-competitiveness in solar absorption and Rankine systems have fostered increased interest in desiccant cooling. As with the other systems, the cost of collectors represents a major portion of the total desiccant system cost. However, desiccants can be regenerated at lower temperatures than those required for driving absorption and Rankine systems.

8.2.6.1 Solid Desiccant Systems

An analysis of experimental data taken in the SERI Desiccant Cooling Laboratory indicated that the adsorption and desorption properties of silica gel are not the same. In FY-1983, the first experimental test on the sorption hysteresis behavior of silica gel were completed at SERI.

Adsorption and desorption properties at 25°C and 40°C with air velocity in the range of 0.3 to 1.2 m/s and relative humidity in the range of 10-80% were tested. These test results are being used to validate theoretical models of heat and mass transfer in the desiccant particles. Characterizing the sorption kinetics of desiccant materials may lead to the development of improved desiccant materials with associated improvements of 10-20% in the performance of desiccant cooling systems.

At Argonne National Laboratory (ANL), supported by DOE and operated by the University of Chicago, it was discovered that water adsorbed into magnanese dioxide exhibited week adsorbate/adsorbent interactions. Work was begun to pursue the concept of incorporating manganese dioxide fibers into the structure of a silica gel body to aid water transport into the interior of large silica gel particles.

8.2.6.2 Liquid Desiccant Systems

During FY-1983, Lockheed Missiles and Space Co. evaluated the effectiveness of an open flow glazed solar collector for cooling in hot and humid climates. The glazing has the advantage of reducing the contamination rate of the liquid desiccant. A computer model was developed and showed favorable agreement between analytical results and experimental data.

At Arizona State University, an analytical model was developed for free--convection controlled heat transfer and mass transfer in open-flow liquid desiccant systems with inclined rough surfaces. It predicted that transfer coefficients for rough surface would be 50 to 80 percent higher than those for smooth surfaces. A roof collector was experimentally tested and various roughness conditions for natural convection heat transfer to inclined surfaces were studied. There is favorable agreement between analytical results and experimental data.

At the University of South Carolina, experimental testing of liquid desiccant systems in FY-1983 demonstrated that the open-cycle liquid desiccant solar heat pump system is technically viable and environmentally acceptable. These tests have proven that many of the materials used in the liquid desiccant system are corrosion resistant.

8.2.6.3 Hybrid Desiccant Systems

Hybrid desiccant/vapor compression heating and cooling systems show promise in competing with conventional designs. These systems will be evaluated over a range of climatic conditions for comparison with existing technologies. Some consider them to be the best near-term application of recently-developed active space cooling technology.

Exhibit 8-5 summarizes the technical status of desiccant cooling systems.

TECHNOLOGY STATUS - DESICCANT COOLING

COMPONENT/SYSTEM		CURRENT STATUS	5-YEAR GOALS
SOLID DESICCANT DEHUMIDIFIER	COEFFICIENT OF PERFORMANCE	0.6-1.0	1.3
	COST	$1,200 - $1,800/TON	$1,000/TON (PROJECTED)
	LIFE	>10 YEARS	>10 YEARS
SYSTEM	COEFFICIENT OF PERFORMANCE	0.2-0.4	0.6
	COST	$3,500/TON (ESTIMATE)	$2,000/TON (PROJECTED)
	LIFE	>10 YEARS	>10 YEARS

EXHIBIT 8-5
(DOE-3)

8.3 Passive and Hybrid Systems

8.3.1 Overview

Passive buildings are considered by leading architects and engineers to be a viable design approach, they tend to be accommodating to required design variations and to be readily adaptable to varying local conditions.

In the United States, heating by passive techniques is most advanced in single-family detached residential buildings. However, over the last few years, advances in nonresidental applications have been made. In the past few years interest in cooling techniques has emerged as well as interest in passive designs to enhance interior daylighting.

One can estimate passive solar energy's potential contribution to building design by considering only passive heating of single-family residential buildings. This technology is widely accepted in all climatic regions. Current passive heating techniques can competitively supply 30-40% of the heating demand. Considering that four times the amount of energy required to heat a home actually strikes that structure in the form of solar radiation, this estimated contribution can be considered conservative.

8.3.2 Low-Conductance, High Transmittance Materials

The objectives of research in this field are:

1. New low-emissivity materials that will be applicable to nonsealed windows.
2. High-clarity, high transmittance insulating materials.
3. Fenestration or the use of doors and windows in a building incorporating evacuated air spaces.

Other objectives will seek to reduce convection, conduction, and radiation in low-conductance aperture materials. The long-term goals are to produce durable gradient index films with optical properties approaching 0.1 emittance and 0.8 transmittance.

Another concept being developed is the conveyance of light to building interiors through optical fibers using technologies already developed for electronic communications. Fluorescent concentrators will also be investigated for the efficient collection of light from diffuse sources.

8.3.3 Thermal Storage Materials

Problems of overheating and design practices that dictate the use of lightweight building materials have mandated that consideration be given to more effective thermal storage materials. The objective is to enhance conventional materials through the development of new and improved latent and sensible heat storage materials.

The primary objective of this research is to develop thermal storage materials with melting points within the operating temperatures required for heating and cooling buildings. These properties would be high heat of fusion (at least 167.5 MJ/m^3); high thermal conductivity; and neither toxic or combustible properties when combined with conventional building materials. Current research includes investigating candidate materials such as pentaglycerin, alkyl hydrocarbons, and other phase change materials.

8.3.4 Thermal Transport Concepts and Materials

This research area seeks to double the performance of passive heating systems by employing more efficient means of transporting energy from the collection surface or aperture to the building interior. It is intended to overcome present limitations which confine passive apertures to southern orientations (in the northern hemisphere). The goal is for the entire exterior surface of the building to be considered the prospective collecting surface.

8.3.5 Systems Simulation and Analysis

This research activity addresses integrated residential systems studies, energy analysis code development and validation, and nonresidential building system studies. Passive heating system combinations will be simulated with validated numerical models to obtain performance data under a variety of conditions. This research is important because the widely used Solar Ratio calculation method (SLR) is a single-system design tool. As a result, it does not provide insight to combined system design and performance. This research and analysis will result in integrated systems design guidelines.

8.3.6 Daylighting Systems Research

Lighting accounts for approximately 25 percent of the energy used in nonresidential buildings. In addition, artificial light also contributes a substantial amount of unwanted heat to the building, increasing cooling loads. As a result, cooling and lighting are interrelated technologies; moderate reductions in either one can have substantial financial benefit.

Research will now be extended to the evaluation of daylight system alternatives to ensure that designers may achieve maximum benefits for a range of daylight system configurations, building requirements, and climatic conditions. Particular emphasis will be placed on the daylighting of the interiors of large nonresidential buildings. Emphasis will be placed on the development of aperture materials and systems for projecting natural sunlight deep into the building.

8.3.7 Heat Transfer Research

Heat transfer research in buildings focuses on three critical areas: surface convection effects, interzonal convection, and modeling.

In the area of interzonal natural convection, the research emphasis will begin to shift towards more complex room configurations, beginning with two zones. System studies will be performed using a major load analysis computer code. These studies will ensure that future research on complex configurations of two or more zones addresses only realistic and representative passive solar designs. System studies will also determine the sensitivity of building loads to state-of-the-art assumptions regarding radiation and conduction, as well as natural convection heat transfer.

8.3.8 Passive Cooling Research

Passive cooling systems research to date has focused upon an examination of the potential of individual technologies (i.e. ventilation, evaporation, dehumidification, and radiation) and the use of architectural elements to reduce cooling requirements.

Future research will begin to address systems integration and the development of engineering concepts for passive systems. Lawrence Berkeley Laboratory (LBL) will conduct research to determine the effectiveness of hybrid ventilation cooling strategies for commercial buildings, which are expected to be more common than strictly natural cooling approaches. The research will result in estimates of cooling energy use reductions and electric power requirements. Results will be compared to similar analyses conducted at Los Alamos National Laboratory (LANL) for practical evaporative cooling systems. LBL will also investigate engineering concepts for commercial building cooling systems. The research will result in schematic designs, detailed simulations of performance, and engineering design. Ventilation strategies coupled with thermal storage for heat reoval will be emphasized because they are most likely to be applied.

9.0 SPECIAL CONDITIONS FOR SOLAR ENERGY SYSTEMS IN EGYPT

Geographic location and climate combine to make Egypt one of the more favorable settings in the world for the application of solar thermal energy. Situated in the Northern hemisphere between 23°N and 31° N latitude and in the Sahara desert, the average annual solar energy intensity and daily duration of unblocked sunlight provide a very suitable climate for solar derived heating and cooling. There are, however, counteracting conditions, such as dust and pollution, which inhibit solar collection. Limiting factors such as these and other special conditions must be included in an objective analysis of relevant Egyptian environmental conditions.

9.1 Solar Insolation and Climatic Conditions

9.1.1 Insolation and Duration

Active and passive solar heating systems are both influenced by solar radiation intensity and daily duration. Compared to the populated world average, Egypt has a long and intense solar day. However, within the country, there exists a solar-day length gradient which provides the southern regions of Egypt with the best in-country locale for solar energy utilization. There are over 3400 hours per year of solar availability in the north and 3900 hours in the south. Exhibit 9-1 shows the January solar day length (in hours) for the entire country using a contour map. The range of 6.4 hours in Alexandria to 9.1 hours in the southerly positioned Kharga is typical of the day lengths for global locations between these latitudes in January.

During the summer period, Egypt has days averaging 14 hours in length and the sunshine duration over the country extends to 12.2 hours (87 percent of the possible duration). Exhibit 9-2 presents the variation in the sunshine duration with season and latitude in Egypt. The solar

SUNSHINE DURATION IN EGYPT DURING THE WINTER
(JANUARY)

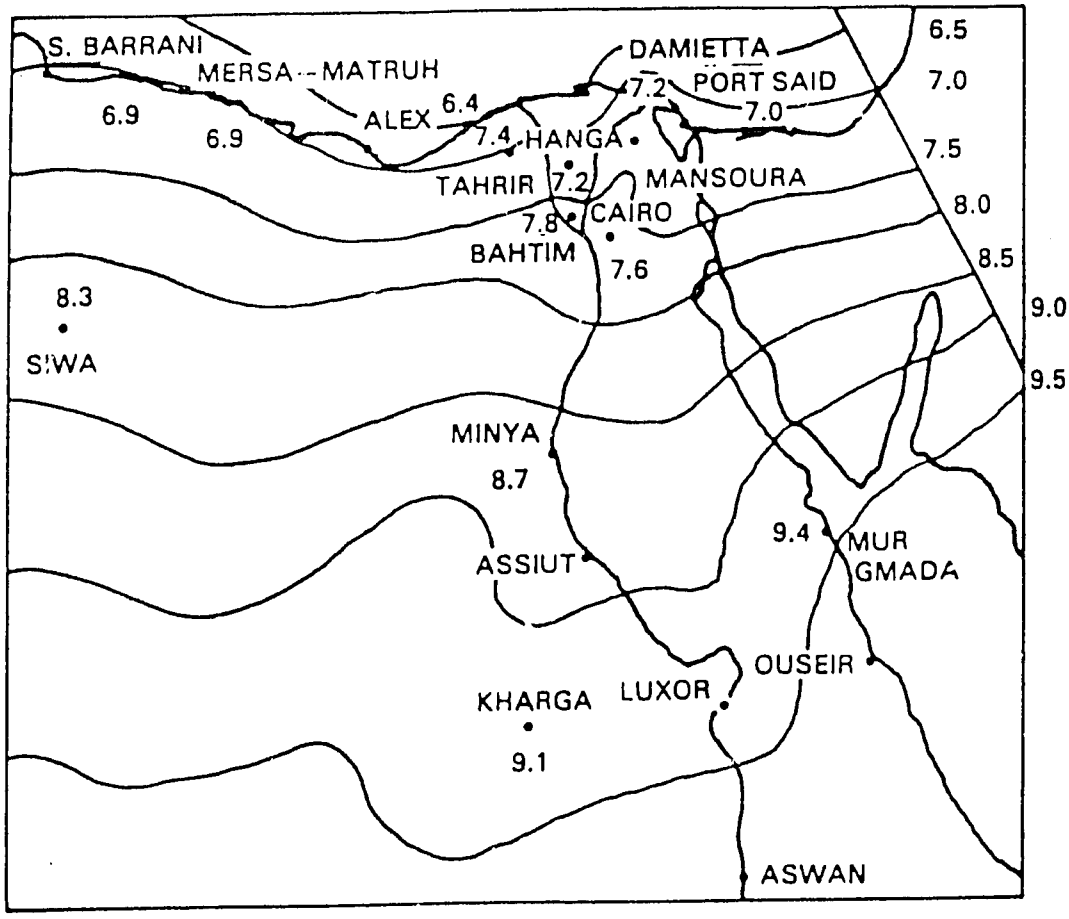


EXHIBIT 9-1

SUNSHINE DURATION AND SOLAR INSOLATION IN EGYPT

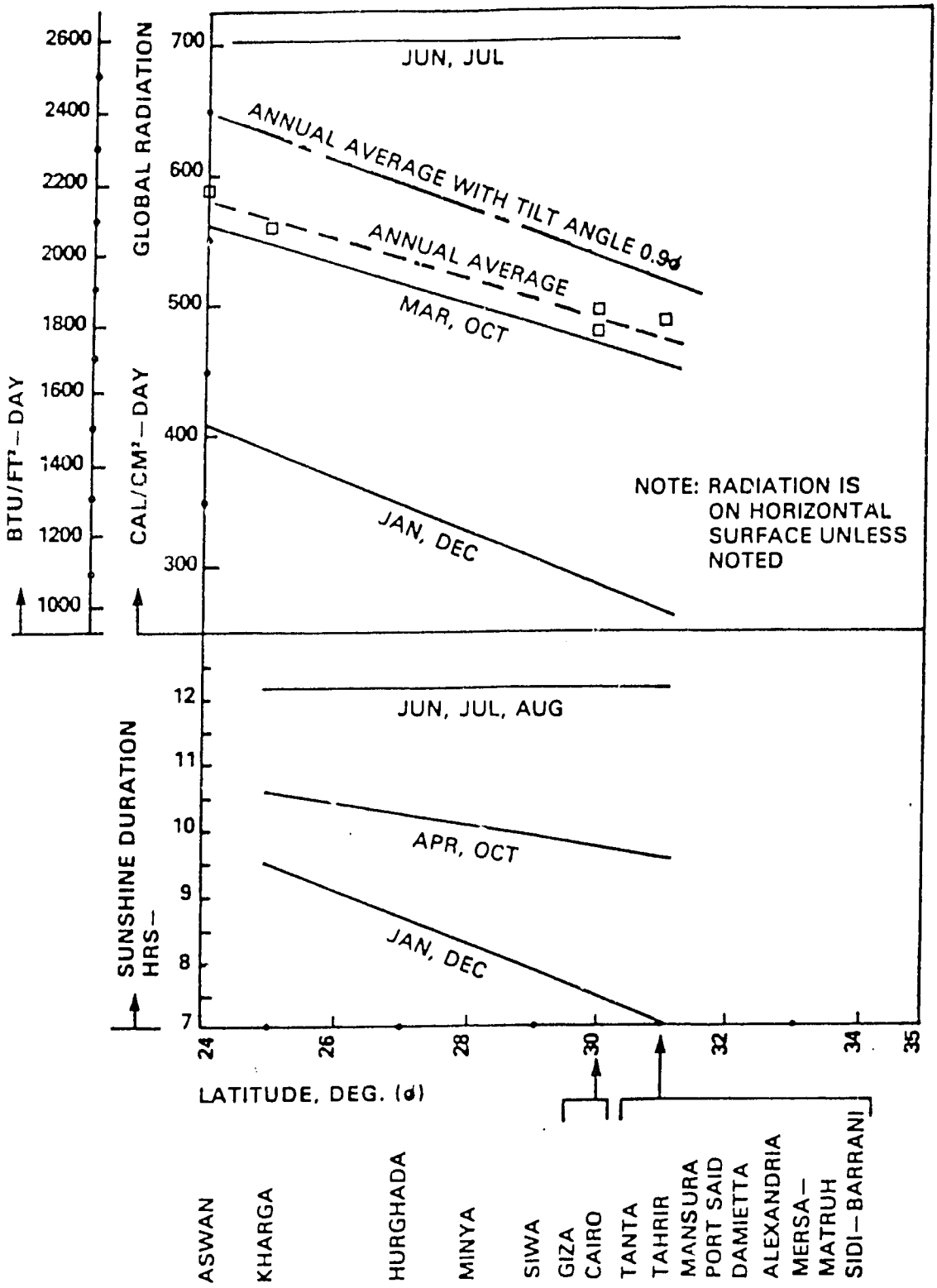


EXHIBIT 9-2

insolation varies from 420 cal/cm^2-day in winter to 710 cal/ cm^2-day in summer in Aswan or southern Egypt and it ranges from 260 cal/cm^2-day to 710 cal/cm^2-day in northern Egypt.

Cairo has a January solar day of 7.8 hours and a January average daily insolation of 12.9 MJ/m^2 (Bahteam, north Cairo data). This contrasts with Jacksonville, Florida, USA, at the same latitude, which has a January average daily insolation of 10.2 MJ/m^2. This represents 26% greater insolation for Cairo over another insolatitudinal city. The discrepancy is explained by climatic differences between the two locations. Jacksonville has a cloudy and humid climate which produces higher atmospheric solar absorption and reflection and a corresponding lower insolation.

Exhibit 9-3 is a table of total daily solar radition for Bahteam, Cairo HQ, and Giza.

9.1.2 Climatic Conditions

Climatic conditions in Egypt are characterized by a desert type environment. Rainfall is scarce and the relative humidity is low. Summer temperatures are consistently high and winter temperatures are very mild. The seasons are not pronounced in Egypt. Spring and fall are almost nonexistent and the year can be best described as a long and hot summer getting milder during the winter.

The climate in Egypt exhibits several regional variations. The main pattern is the important influence of the Mediterranean Sea on the northern delta area. For example, the Alexandria area receives almost 200 mm of rain per year compared to 20 mm per year in Cairo and 1.4 mm per year in Aswan. Humidity is also higher on the coast and progressively decreases further south.

EXHIBIT 9-3

DAILY TOTAL HORIZONTAL SOLAR RADIATION

$MJ/m^2/day$

MONTH	BAHTEAM	CAIRO HQ	GIZA
JAN	12.48	11.85	12.31
FEB	16.20	15.53	15.78
MAR	19.85	19.26	20.77
APR	23.91	23.28	24.16
MAY	27.05	26.29	26.84
JUN	28.84	28.14	28.56
JUL	28.30	27.26	28.39
AUG	26.21	25.33	25.96
SEP	22.69	22.07	22.57
OCT	18.93	18.09	17.37
NOV	13.85	13.28	13.40
DEC	11.64	11.27	11.27
ANNUAL	20.86	20.15	20.64

Exhibit 9-4 presents temperature, rainfall, and humidity data for Aswan, Cairo, and Alexandria. The data indicates a progression in average temperatures as locations progress inland, with Aswan exhibiting almost no winter heating need and having a very high temperature profile in the summer. On the coast the sea moderates these extremes.

9.1.3 Dust and Pollution

Solar energy utilization by active and passive systems is severely hindered by atmospheric dust and pollution. Solar collection efficiencies are adversely affected in such environments because:

1) For both active and passive systems, incoming radiation is both reflected and absorbed in the atmosphere, thereby reducing the total solar energy available for collection.

2) For active systems, collection plates become dirty. This results in further reduction in radiation availability via screening of the collection tubes.

In general, Egypt experiences quite dusty periods each year, normally in April and May. This is compounded in large metropolitan areas by the daily pollution levels. The pollution effects can be seen by contrasting the insolation of two locations of the same latitude and general proximity but of different pollution indexes. Katamiya, or south Cairo, has a May average daily insolation of 28.5 MJ/m^2. This contrasts with the Cairo Center solar radiation of 25.5 MJ/m^2 for the same period. The 12% difference is directly attributable to the higher dust and pollution levels near the city center. Comparison of data such as these is imperative during the analysis, selection, and sizing of solar collector technologies.

Exhibit 9-5 summarizes the annual frequency of weather phenomena in the selection of stations in Egypt.

EXHIBIT 9.4 CLIMATIC CONDITIONS FOR CAIRO, ALEXANDRIA AND ASWAN

DESCRIPTION	UNITS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	TOTAL
CAIRO														
MONTHLY AVG. TEMP.	deg C	13.2	14.2	16.6	20.2	24.2	26.7	28.2	27.8	25.4	23.4	19.2	14.8	
AVG. YEAR TEMP.	deg C	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	
RELATIVE HUMIDITY	%	76.0	73.0	63.0	55.0	52.0	55.0	61.0	67.0	67.0	70.0	75.0	78.0	66.0
RAINFALL	MM	5.3	4.7	0.9	0.3	1.1	0.0	0.0	0.0	0.0	0.3	2.0	5.6	20.2
ALEXANDRIA														
MONTHLY AVG. TEMP.	deg C	13.5	14.0	15.6	18.3	21.4	24.2	26.1	26.7	25.3	22.8	19.3	15.2	
AVG. YEAR TEMP.	deg C	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	
RELATIVE HUMIDITY	%	71.0	70.0	67.0	68.0	70.0	72.0	73.0	73.0	69.0	68.0	72.0	74.0	70.0
RAINFALL	MM	48.3	28.4	14.0	2.7	1.5	0.0	0.0	0.5	0.4	7.9	32.2	36.7	192.1
ASWAN														
MONTHLY AVG. TEMP.	deg C	16.8	18.6	22.4	27.2	31.9	33.6	34.0	34.2	32.0	29.6	24.0	19.8	
AVG. YEAR TEMP.	deg C	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	27.0	
RELATIVE HUMIDITY	%	35.0	27.0	21.0	17.0	15.0	15.0	18.0	20.0	22.0	26.0	33.0	39.0	24.0
RAINFALL	MM	0.1	0.0	0.1	0.3	0.6	0.0	0.0	0.0	0.0	0.2	0.1	0.0	1.4

ANNUAL FREQUENCY OF WEATHER PHENOMENA IN A SELECTION OF MET. STATIONS IN EGYPT

STATIONS	FOG	MIST	DUST OR SAND RISING	DUST OR SAND STORM	TOTAL ANNUAL
Meraa-Metruh	7.4	4.5	12.7	7.2	31.8
Alexandria	20.1	21.5	7.9	2.4	51.9
Port-Said	1.8	2.9	4.6	2.0	11.3
Cairo	19.7	25.1	11.1	3.2	59.1
Almaza	16.2	15.9	9.0	3.7	44.8
Minya	5.1	7.6	3.4	0.9	17.0
Assiut	2.0	3.4	5.0	2.0	12.4
Luxor	0.1	2.0	2.7	1.5	6.3
Hurghada	0.1	1.7	4.5	1.8	8.1

EXHIBIT 9-5

9.2 Active Systems

Egypt's climate is ideal for the operation of active solar systems. Not only does Egypt exhibit one of the highest amounts of solar hours per year of any site on earth, it also has a very low proportion of diffuse radiation versus direct radiation. Such conditions make the use of concentrating solar technologies very attractive.

Generally, most systems used for domestic space and water heating are based on flat plate technologies. In the case of active cooling technologies the requirement for higher operating fluid temperatures translates into the need for concentrating solar collectors. Thus, Egyptian solar insolation patterns are promising for active solar cooling.

Cooling accomplished via active solar technology is governed by essentially the same environmental factors which influence active heating systems. Active solar cooling utilizes a high vapor pressure refrigerant and its corresponding low heat of vaporization to extract heat from the warm space. The efficiency and performance of such technology is enhanced by long and intensive solar days and hindered by dust, pollution and other conditions that typically prevent solar heat from being optimally collected. Active chillers are additionally hindered by adverse environmental conditions in that, should the solar collection efficiency drop to a level such that the working fluid or refrigerant cannot boil, the chiller will cease functioning.

The location of active solar collectors is critical for optimum operation of the system. Exhibit 9-6 shows the variation in solar energy collected daily on surfaces facing south in Cairo with inclinations ranging from 0° to 70°. If the collector is horizontal (0°) the solar collection is minimal during winter and very high in the summer (when the sun's rays are almost perpendicular to the surface). If the angle is increased above the latitude, the solar collection improves during the winter but drops significantly in the summer. For Egypt, an inclination angle of 40° is optimal in order to balance out solar collection

over the year. Any smaller angle will increase collection during the summer and any larger angle up to about 60° will increase collection in winter.

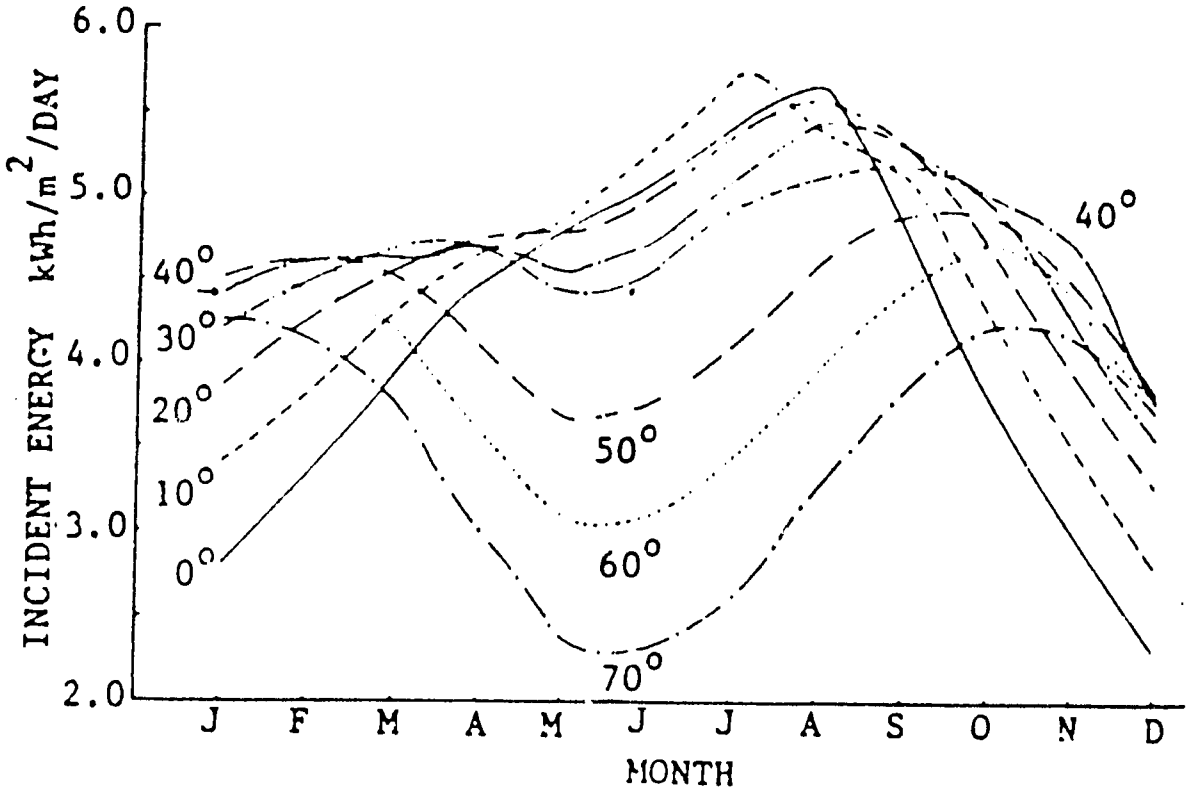
The panel tilt angle for the collection system will need to be chosen depending on the nature of the appilcation, i.e., whether it is a cooling or heating system and, more important, the months during which the peak demand occurs.

Exhibit 9-7 presents a graphical representation of the amount of solar collection by a flat plate under various configurations. Clearly, a system which tracks the sun biaxially will collect much more energy than either a fixed horizontal plate or a south-facing surface tilted by an angle equal to the latitute. The choice of the solar collection system will need to be based on the economic evaluation of the tradeoffs between increased system collection efficiency and the additional cost.

9.3 Passive Systems

There are a variety of methods which can be utilized to accomplish passive solar cooling. Shading is the most important and should be the first to be deployed to accomplish passive cooling. Natural shading, such as that derived from vegetation, is potentially available in Egypt, although for most metropolitan areas the existing city plans would require renovation to accommodate trees. A majority of the rural areas (e.g. small village) do employ vegetative shading. Artificial shading such as shutters, screens, and window glazing are easily implemented and are relatively inexpensive. Most Egpytian dwellings already employ these items.

The Egyptian climate offers hot, dry days followed by cool, dry nights. The constant low humidity and minimal cloud cover provide an excellent environment for night radiative cooling. Thus those architectures which encourage thermal, i.e. indirect gain, perform very well in the Egyptian ambient: heat storage during the day via thick insulated barriers,

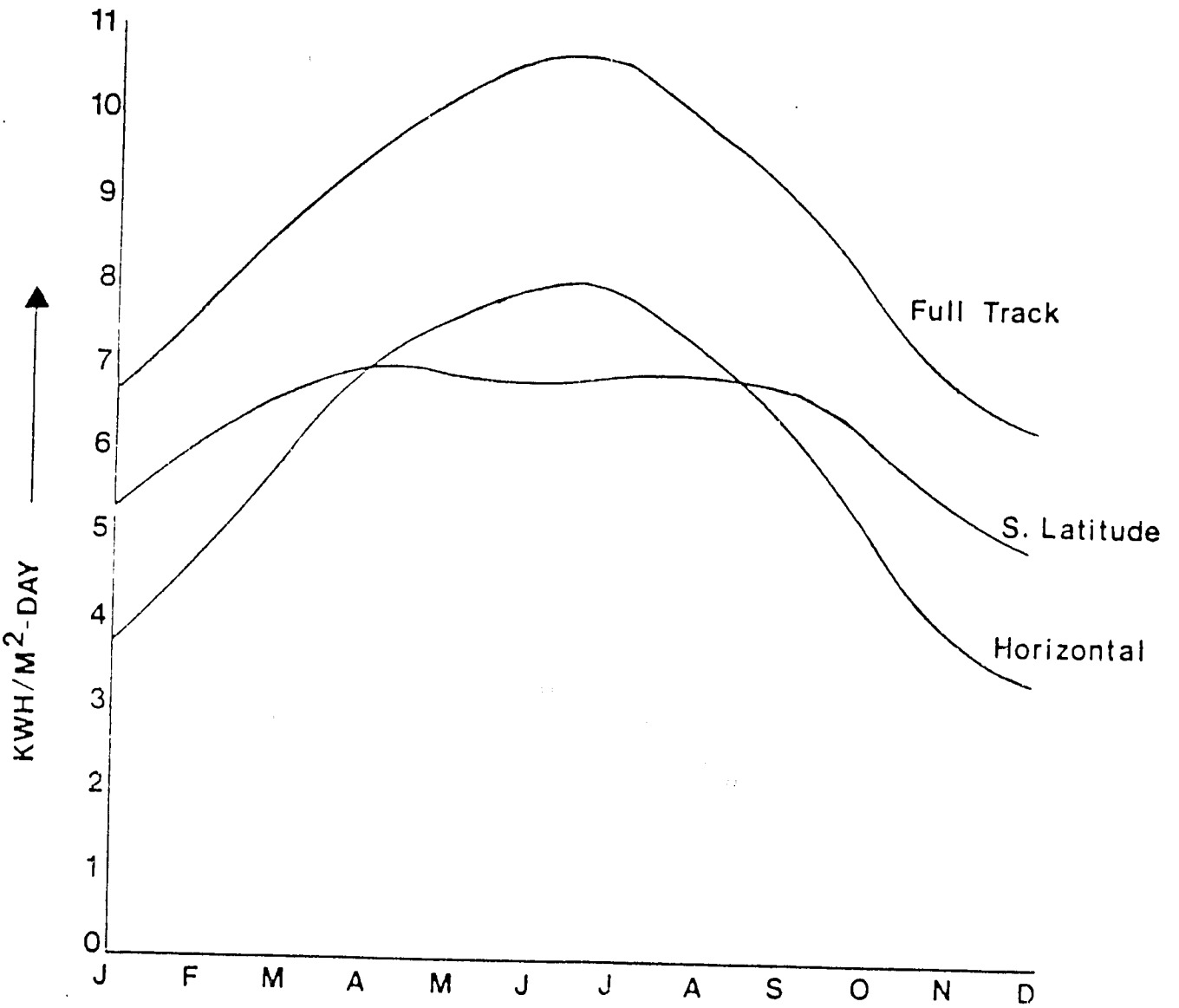


Solar energy received daily on surfaces with inclination from 0° to 70° facing south. (Latitude = 30°).

EXHIBIT 9-6

EXHIBIT 9.7

Comparison of Solar Energy Collection in Cairo by tilted, horizontal, and tracking surface



followed by heat release to the outdoors at night. Just as the sun disperses its heat through radiation, a building can radiate signficant amounts of heat through radiation, a building can radiate significant amounts of heat if correctly designed. The phenomena of night sky radiation has been exploited since the time of the ancient Persians, who made ice by exposing thin pools of water to the night sky even though ambient temperatures exceeded 0°C. In dry climates, pure radiative cooling can attain significant levels--up to 70 W/m at 6 degrees below ambient temperature. The traditional Islamic courtyard is cooled by nighttime radiation of the yard floor and this cooler air is then trapped by the courtyard shape and lasts well into the following day.

The alternative thermal mass type concepts such as the traditional thick walled Egyptian architecture (e.g. those of Hassan Fathi) perform as good as, or better than, the water-based designs. However, these designs are for single story, low density population buildings. Crowded, multiple story dwellings present a more difficult passive cooling scenario. Without major metropolitan renovation, other means will be needed to effect cooling. Currently the Egyptian government is promoting new and future building developments to employ appropriate passive cooling and heating designs.

Specific passive solar cooling techniques are presented in Exhibit 9-8. All of the cooling strategies listed are applicable to conditions in Egypt except for dehumidification, which is more appropriate for comfort improvement in more humid climates.

Shading and other methods of reducing solar gain are particularly appropriate for Egypt's sunny climate. The use of overhangs, louvers, shades, and reflective paints can shield a building from excessive solar radiation. The placement of windows and the orientation and shape of a building can also be optimized to minimize the absorption of solar radiation on and within a structure. Trees and trellissed vegetation can provide shading with the added cooling benefit of leaf evapotranspiration.

Passive Solar Cooling Techniques

Strategies	Techniques	Application
Minimize conductive heat flow	Insulation	Buildings that achieve lower indoor than outdoor temperatures through other means.
Delay periodic heat flow	Increase thermal mass Earth-sheltering	Where nighttime temperatures are significantly lower than daytime temperatures. Particularly suited to locations with large seasonal variations in temperature.
Promote ventilation	Stack effect Cross-ventilation Fans	Where heated air can rise and exit through a ceiling opening. Requires existing moderate wind conditions. Absence of adequate wind-driven ventilation.
Minimize solar gain.	Shading Building orientation Building shape	Trees, louvres, and indoor blinds are a few of the options.
Promote radiant cooling	Exposed emissive surfaces	Particularly suited to dry climates with clear nighttime conditions.
Promote evaporative cooling	Roof ponds Moistened roof surfaces Trees and ventilation	Lack of water in arid areas can be a major constraint.
Dehumidification	Ventilation	

EXHIBIT 9-8

Insulation can also be a very economical means of moderating indoor temperatures. Insulation reduces the transfer of heat absorbed by the walls and roof from incident sunshine and warm outside air into the interior of work or living space. Traditional insulation materials such as dried paint matter and synthetic insulation materials such as fiberglass can be used in structures ranging from village dwellings to modern high rise buildings.

9.4 Other Requirements

In addition to solar radiation, there are requirements for basic construction materials. Materials such as steel, concrete, glass, and aluminum are all manufactured in Egypt. The requirement for these materials is substantial since the utilization of solar energy resources requires considerable surface area with collection surfaces capable of withstanding severe environmental conditions.

Support structures, towers, and storage tanks are required in a functional passive solar design. These are similar in construction to conventional equipment. These systems require various skill levels in metal forming, welding, plumbing, mechanical assembly, site preparation, concrete pouring and other labor skills common to a range of conventional systems. These skill levels are readily available in Egypt. However, special training may be required for many aspects of design, manufacture, installation, operation, and maintenance.

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SAI-3 Fiscal Year 1983 Acive Solar Heating and Cooling Program Research Highlights, Science Applications, Inc., for the Office of Solar Heat Technologies, USDOE, August 1984.

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TRA Trane Air Conditioning Manual, The Trane Company, La Crosse, Wisconsin, 1968.

VAN Van Nostrand's Scientific Encyclopedia, Third Edition, D. Van Nostrand Company, Inc., Princeton, New Jersey, 1958.

WAR Warfield, George, ed., Solar Electric Systems, Hemisphere Publishing Corporation, New York, 1984.

WIL Williams, J. Richard, Design and Installation of Solar Heating and Hot Water Systems, Ann Arbor Science, Collingwood, Michigan, 1983.

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APPENDIX A

ACTIVE AND PASSIVE SOLAR VISIT BOOK

TECHNOLOGY AREA: DHW Active Drain-down System

PROJECT TITLE: LA Quinta Motor Inns, Inc.

LOCATION: Mobile, Alabama, USA

DESCRIPTION:

This system is designed so that when the water circulation pump stops, the collector fluid drains out of the system and down into the protection of an enclosed space. The hybrid version utilized is a drain-down with a heat exchanger. By using this heat exchanger, the buildup of minerals in the solar collector is eliminated. A certain amount of water is used on the solar loop of the system. As this water level drops, makeup water is introduced into the system. The amount of water introduced is extremely minor in comparison to the minerals which would be constantly introduced by a direct link between the storage vessel and the solar collectors.

SPECIFICATIONS:

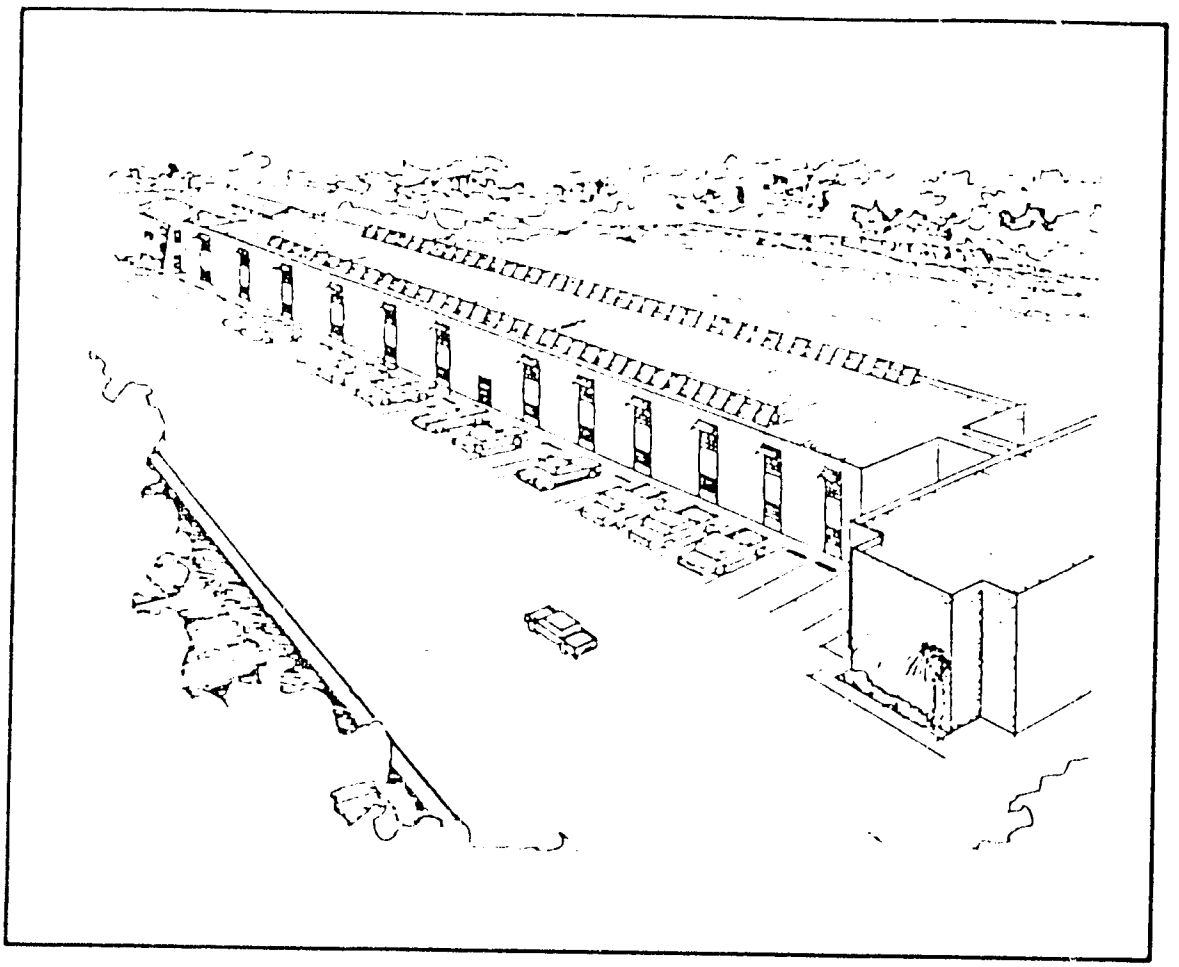
Active System Components:

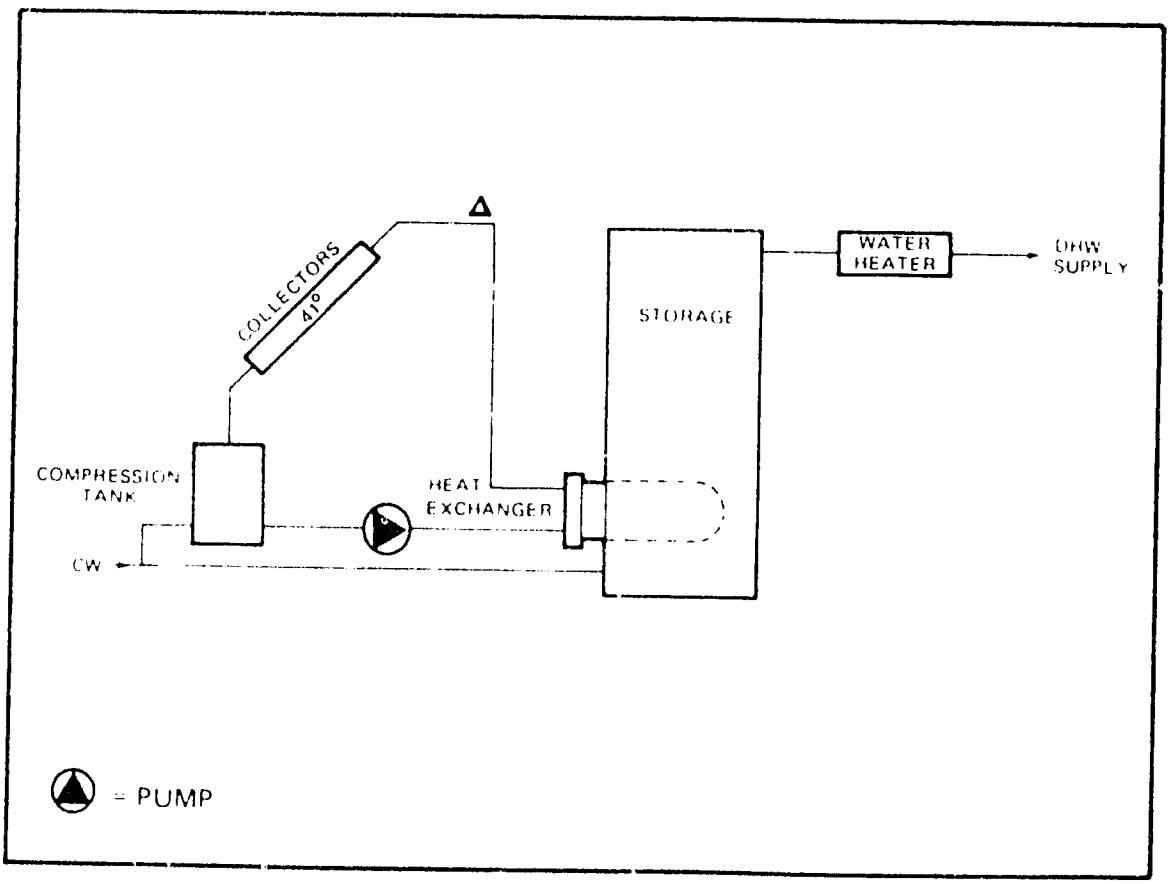
186 m^2 Revere Copper & Brass, Inc., liquid flat-plate collectors
6 m^3 underground steel water tank
Electric boiler for auxiliary

PERFORMANCE:

67% of DHW requirements

CONTRACT: Travis-Braun & Associates, Inc.




COLLECTORS
41°
STORAGE
WATER HEATER
DHW SUPPLY
COMPRESSION TANK
HEAT EXCHANGER
CW
= PUMP

TECHNOLOGY AREA: Active absorptive heating and cooling system

PROJECT TITLE: Radian Corporation

LOCATION: Austin, Texas, USA

DESCRIPTION:

This demonstration project consists of heating and cooling three offices in a new building. A 3-ton solar system is set up in parallel with a 3-ton conventional gas unit. This system utilizes gas fired and electric auxiliary systems.

SPECIFICATIONS:

Floor Area: 79 m^2 (conditioned space)

Active System Components:

ARKLA 3-ton absorptive heating and cooling unit

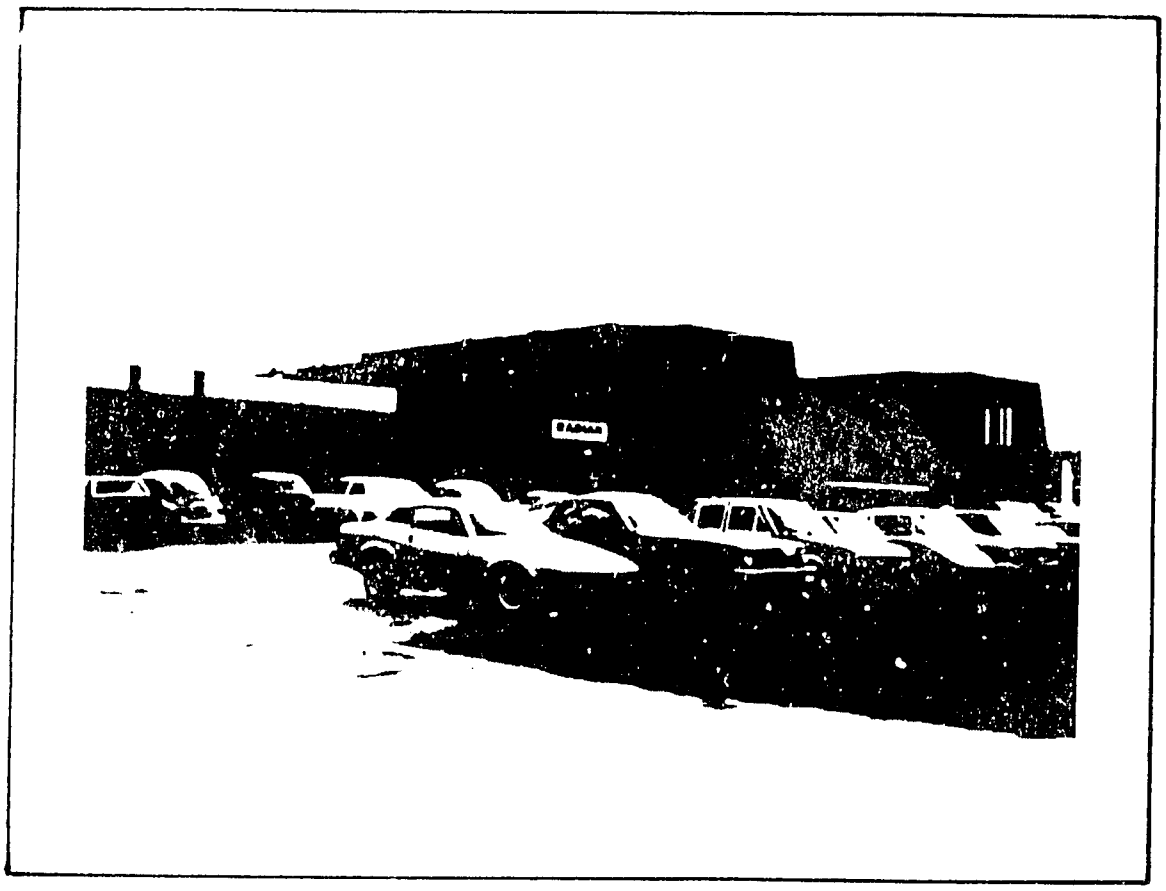
32.5 m^2 Northrup, Inc., linear concentrating and tracking Fresnel lens

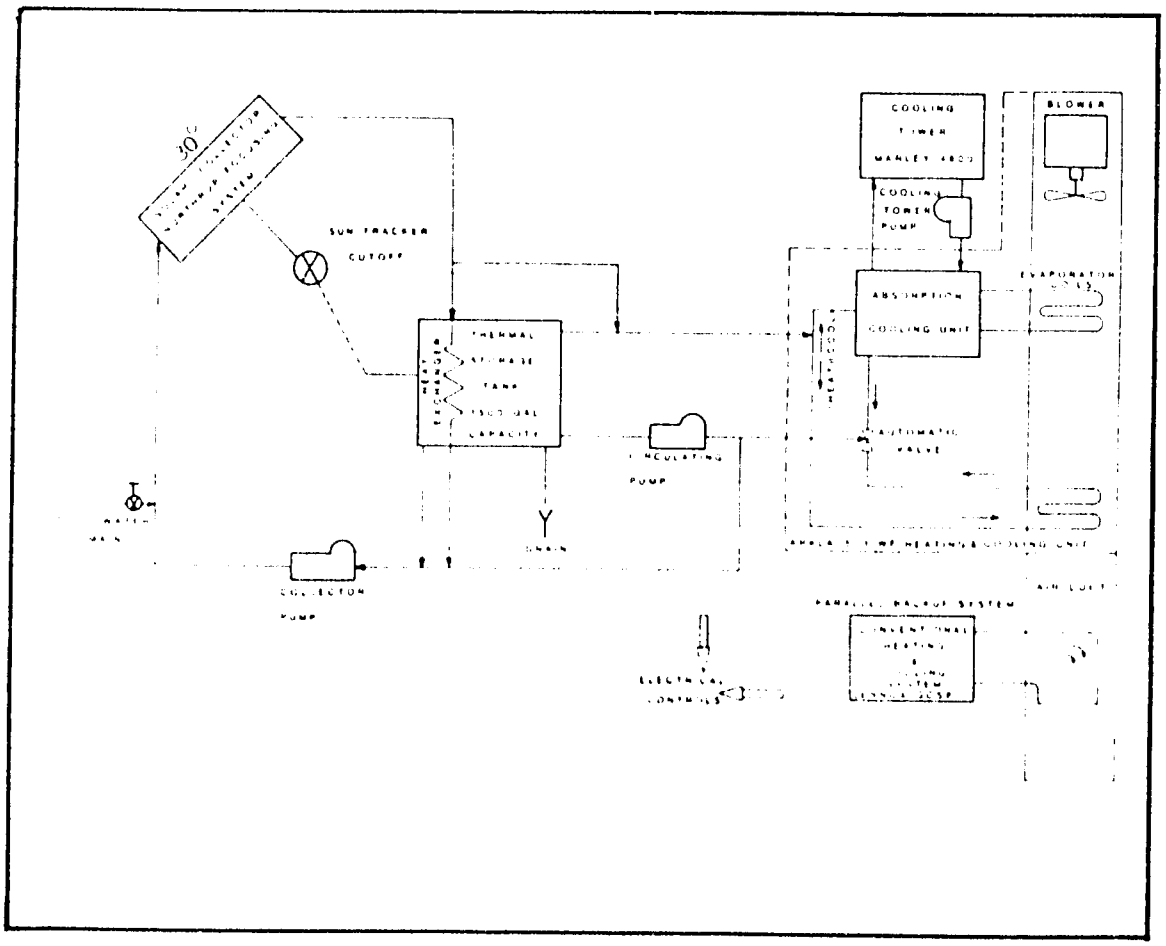
6 m^3 fibeglass above ground water storage tank

PERFORMANCE:

85% of the heating load and 75% of the cooling load

CONTACT: Radian Corporation




SUN TRACKER
CUTOFF
THERMAL
TANK
CAPACITY
PUMP
DRAIN
COLLECTOR
PUMP
COOLING
TOWER
PUMP
BLOWER
ABSORPTION
COOLING UNIT
EVAPORATOR
AUTOMATIC
VALVE
AIR OUT

TECHNOLOGY AREA: Evacuated Tube DHW System

PROJECT TITLE: Rodeway Inns of America & R. V. Development Company

LOCATION: Phoenix, Arizona, USA

DESCRIPTION:

The commercial building in this project is a low rise motel. The collectors for the system are located on the roof of the motel. The energy collected is transferred to a double bundle heat exchanger via a collector loop circulating pump. The energy is then transferred to a storage tank. The double bundle heat exchanger eliminates the danger of ethylene glycol leakage from the solar loop into the storage tank. An electric boiler provides auxiliary heat.

SPECIFICATIONS:

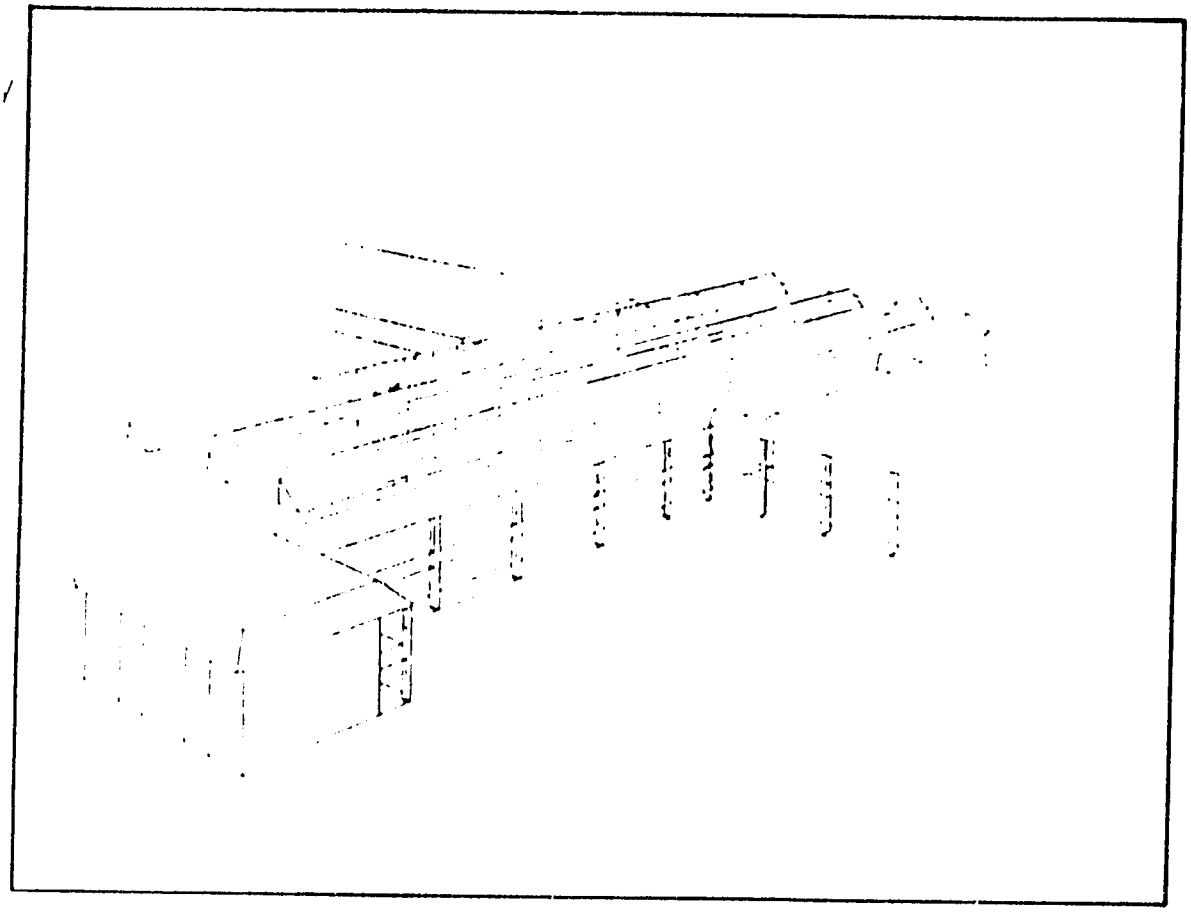
Active System Components:

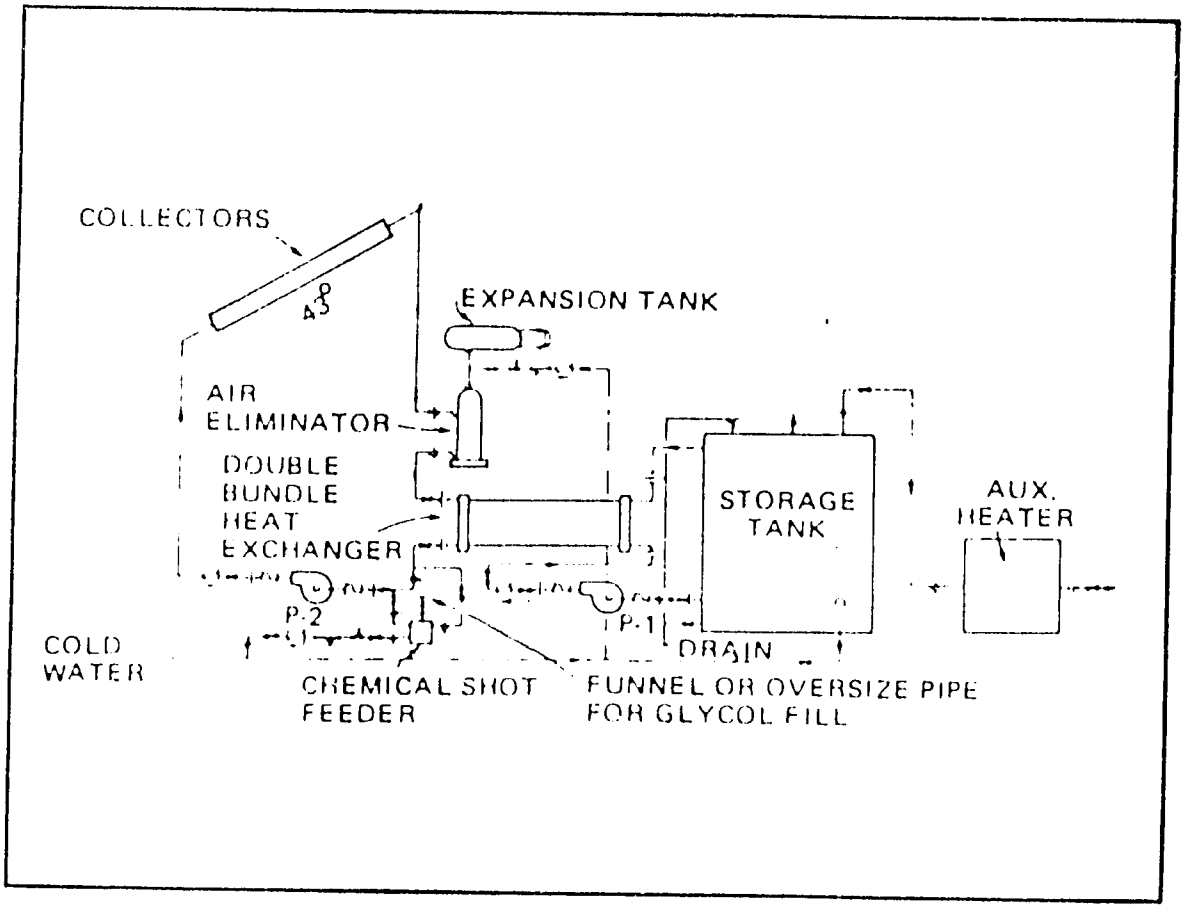
232 m^2 General Electric Company evacuated tubular collectors
11.4 m^3 insulated steel water tank as storage

PERFORMANCE:

59.5% of DHW requirements

CONTACT: Charter Builders, Inc.




COLLECTORS
EXPANSION TANK
AIR
ELIMINATOR
DOUBLE
BUNDLE
HEAT
EXCHANGER
STORAGE
TANK
AUX.
HEATER
P-2
P-1
COLD
WATER
DRAIN
CHEMICAL SHOT
FEEDER
FUNNEL OR OVERSIZE PIPE
FOR GLYCOL FILL

TECHNOLOGY AREA: Absorption Cooling and Water Space Heating System

PROJECT TITLE: Scottsdale County Courthouse

LOCATION: Scottsdale, Arizona, USA

DESCRIPTION:

The building is a one-story county courthouse with stucco/block walls and insulated steel roof. The collectors are mounted on the flat roof at a very slight tilt angle and track the sun from east to west. The collectors supply hot water (104°C) to the 25-ton absorption chiller for cooling, to the hot water heating system (82°C), or to the thermal storage tank. Controls discriminate between heating and cooling and between the solar or auxiliary system. The solar system is expected to save $5000-$6000 annually, which represents 60% of the annual energy needed for both heating and cooling. Electric strip heat provides the auxiliary heat required.

SPECIFICATIONS:

Active System Components:

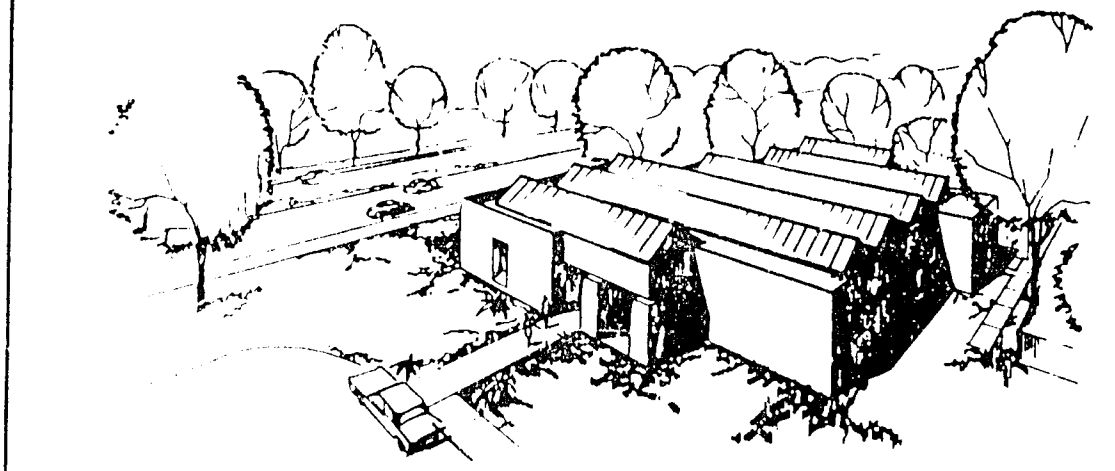
251 m^2 concentrating collectors

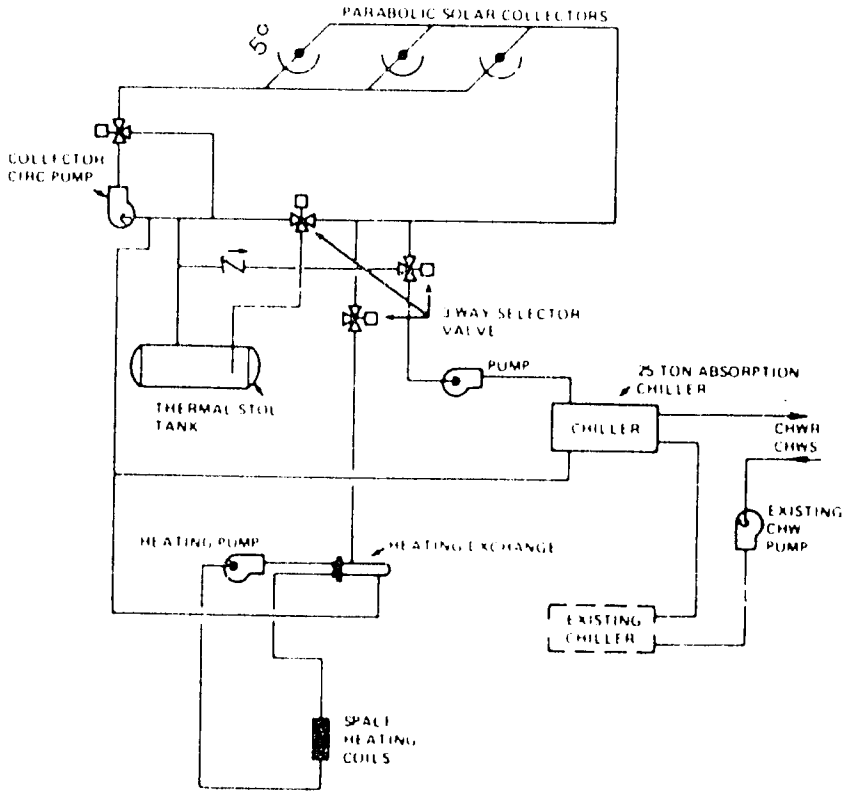
26.5 m^3 steel underground water tank for storage

PERFORMANCE:

100% of the heating load and 60% of the cooling load

CONTACT: Sullivan & Masson, Inc.




PARABOLIC SOLAR COLLECTORS
COLLECTOR CIRC PUMP
3 WAY SELECTOR VALVE
PUMP
25 TON ABSORPTION CHILLER
THERMAL STOR TANK
CHILLER
CHWR
CHWS
EXISTING CHW PUMP
HEATING PUMP
HEATING EXCHANGE
EXISTING CHILLER
SPACE HEATING COILS

TECHNOLOGY AREA: Hybrid Space Heating and DHW System

PROJECT TITLE: Tempe Union High School District 213

LOCATION: Tempe, Arizona, USA

DESCRIPTION:

The Corona Del Sol High School has a solar system that provides for space heating and DHW needs. Southwest Standard liquid flat-plate roof-top collectors face south at an angle of 32°.

Additional passive designs include earth berming at perimeter walls, concentration of building mass, extensive use of insulation throughout the building, and use of natural landscaping surrounding the perimeter and interior court of the facility. Heated water from the buried storage tank will be pumped into heat exchangers transferring the energy to a four-pipe heating/cooling system with air handlers. The building has an electric auxiliary energy source.

SPECIFICATIONS:

Active System Components:

1858 m^2 Southwest Standard liquid flat-plate collectors
176 m^3 insulated partially buried steel water tank for storage

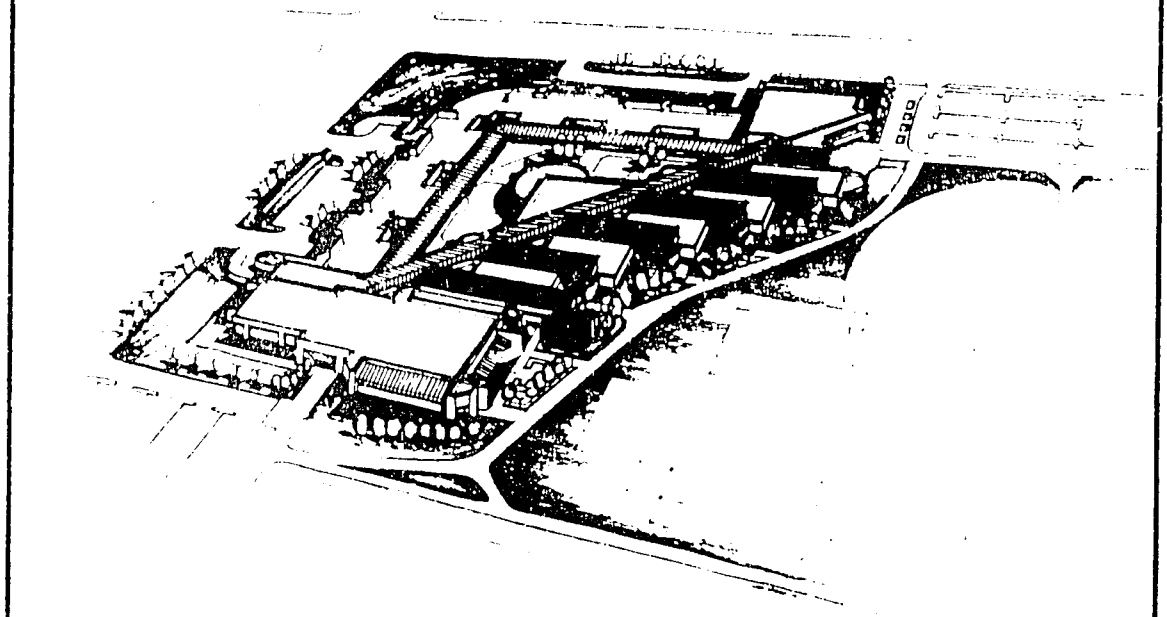
Additional measures:

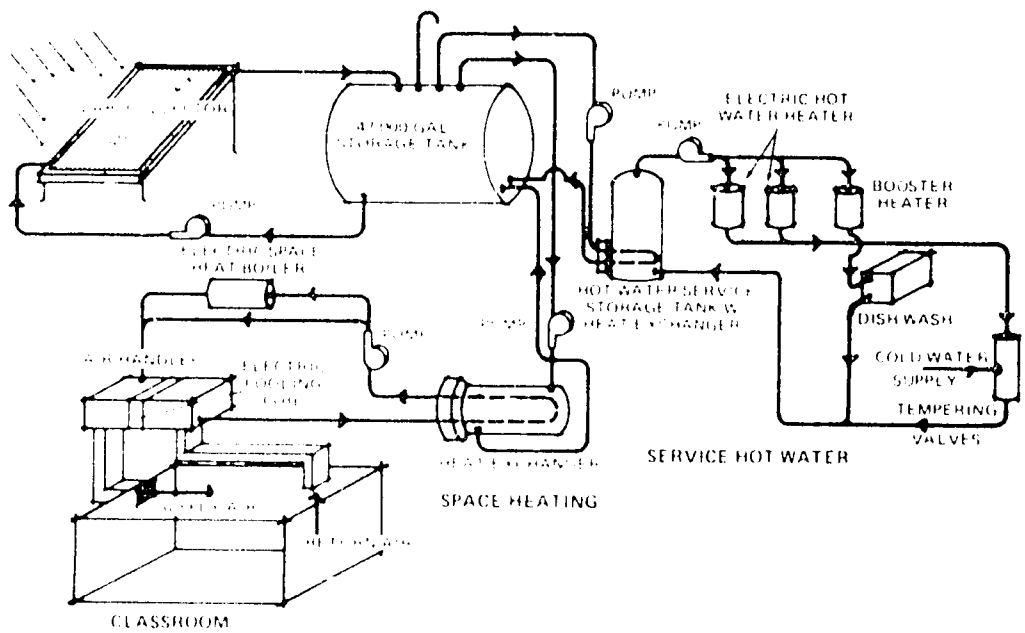
Earth berming at perimeter walls, concentration of building mass.

PERFORMANCE:

83% of the heating load and 90% of DHW requirements

CONTACT: Mardian Construction Company




PUMP
ELECTRIC HOT WATER HEATER
BOOSTER HEATER
DISH WASH
COLD WATER SUPPLY
TEMPERING VALVES
SERVICE HOT WATER
SPACE HEATING
CLASSROOM

TECHNOLOGY AREA: Active Space Heating, Cooling, and DHW System

PROJECT TITLE: Brandon Swimming Association

LOCATION: Brandon, Flordia, USA

DESCRIPTION:

The building is a sports/medical center. The solar design incorporates solar collectors which provide hot water for space heating, domestic hot water, pool heating, and a solar air conditioning unit. Potable water is used in the space heating and space cooling systems. If there is no demand for either space heating or hot water, the solar-heated water is used for swimming pool heating. In the low range of insolation, the collectors are used for pool heating only.

The collectors are tube-in-strip modular solar collectors installed on the 28° south-facing slope of the gymnasium roof. An electric boiler is used for auxiliary heat.

SPECIFICATIONS:

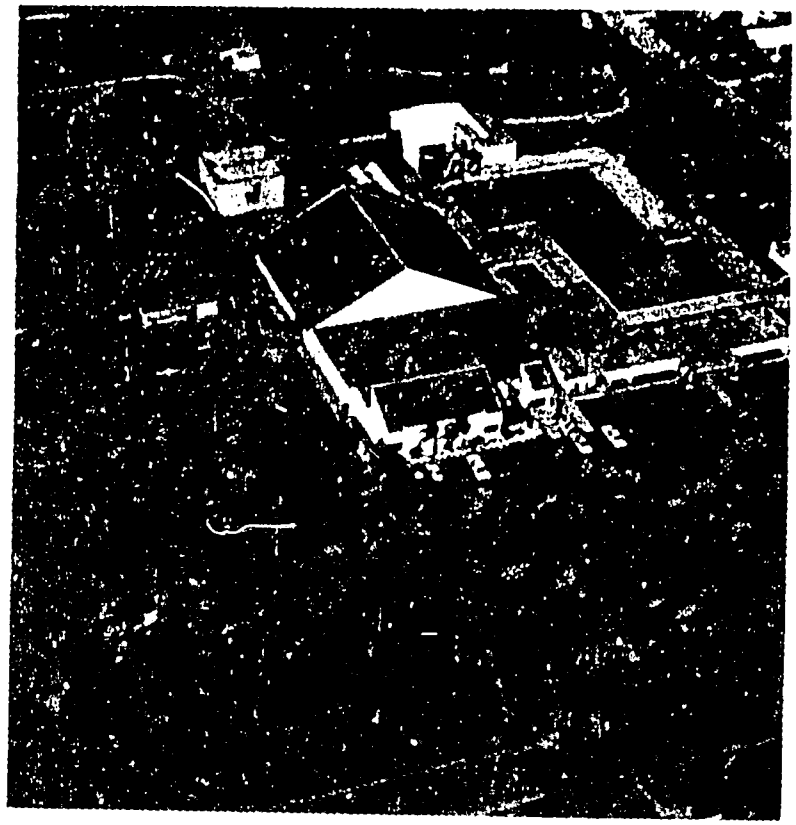
Active System Components:

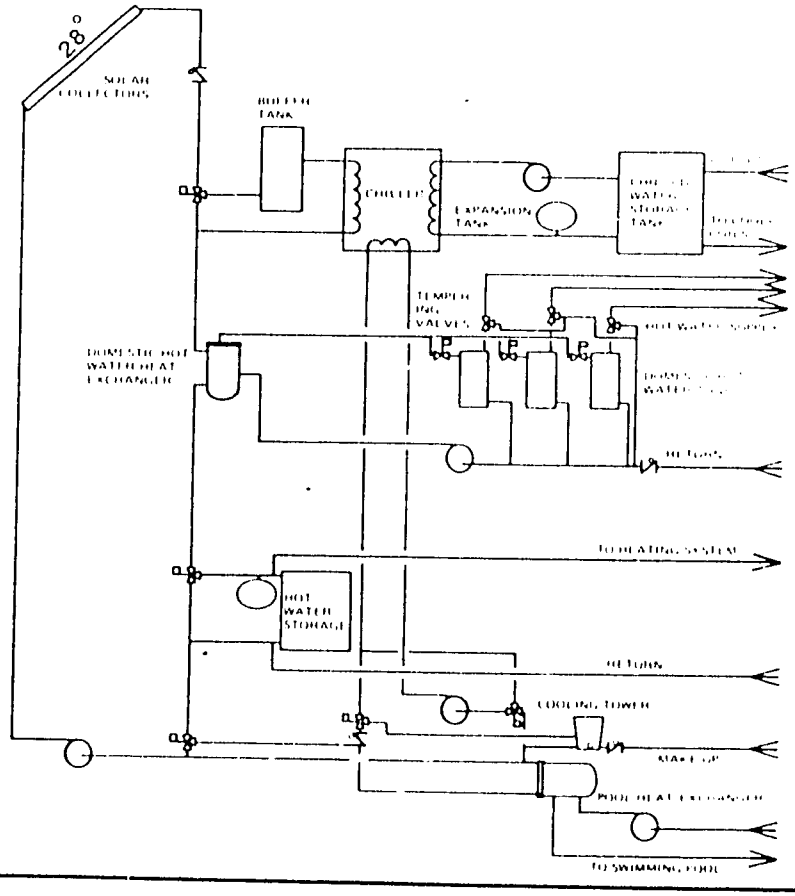
492 m^2 Revere Copper & Brass Inc., liquid flat-plate collectors
ARKLA-Servel, Solarie-300, 25 ton air conditioning unit
21 m^3 hot water storage and 34 m^3 chilled water storage (both above ground)

PERFORMANCE:

90.5% of the heating load and 89% of DHW requirements, and 59% of the cooling load.

CONTACT: Independent Living, Inc.




28°
SOLAR COLLECTORS
BOILER TANK
CHILLER
EXPANSION TANK
TEMPER ING VALVES
DOMESTIC HOT WATER HEAT EXCHANGER
HOT WATER STORAGE
TO HEATING SYSTEM
RETURN
COOLING TOWER
MAKE UP
POOL HEAT EXCHANGER
TO SWIMMING POOL

TECHNOLOGY AREA: Active Space Heating, Cooling, and DHW System

PROJECT TITLE: San Diego Unified School District

LOCATION: San Diego, California, USA

DESCRIPTION:

The building is a 17187 m^2 high school of which 3716 m^2 will be space cooled. The solar collector field will be located on a south-facing hill which forms a backdrop for the four one-story buildings. For maximum utilization of solar energy, this design calls for a central heating and cooling plant adjacent to the collection field. An enthalpy-controlled economizer cycle will be used in each building. Air handling units with variable volume air valves will condition each space. A time clock system ensures that the buildings will not be heated or cooled when not occupied. A one-half to one-hour morning preheat cycle closes off the outside air make-up and recriculates 100%. The return air passes through lighting units which lessens heat gain from the fixtures.

SPECIFICATIONS:

Floor Area: 17187 m^2, 3716 m^2 will be cooled

Active System Components:

1364/216 m^2 respectively of parabolic/concentrating collectors. Manufactured by Solartec Corporation/Northrup, Inc.

379 m^3 underground steel water tanks for storage

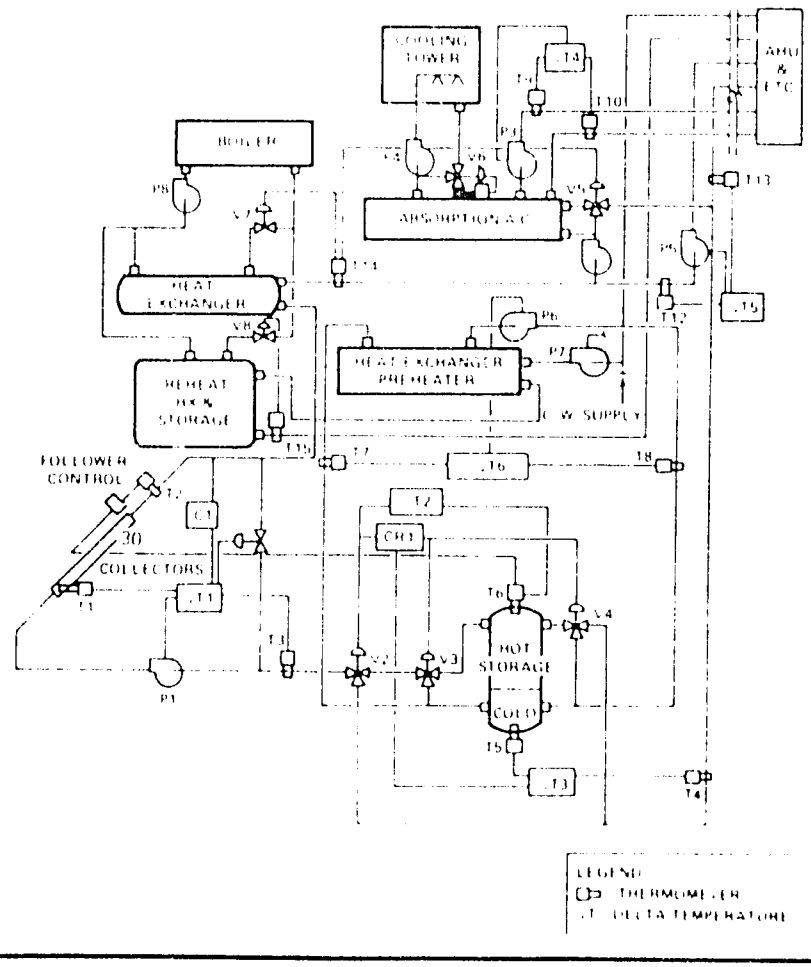
Convertible gas and oil fired boilers and electric back up air conditioning are auxiliary units.

PERFORMANCE:

90.5% of the heating load and 89% of DHW requirements, and 59% of the cooling load.

CONTACT: Hugh Carter Engineering

Photograph not available



TECHNOLOGY AREA: Active Space Heating, Cooling, and DHW System

PROJECT TITLE: Reedy Creek Utilities Co., Inc. (Walt Disney World)

LOCATION: Lake Buena Vista, Florida, USA

DESCRIPTION:

The building is an office; sixteen modular solar collectors are joined together along the ridge lines to form the insulated roof. The longitudinal axes of the reflective suface run in a east-west direction. The solar roof replaces the usual trusses, corrugated decking, and insulated concrete roof.

Each collector is a AAI Corporation solar concentrator that consists of a concave cylindrical reflective surface and an absorber. The collectors use water as a heat transfer medium and are linear tracking. An absorption chiller provides space cooling.

SPECIFICATIONS:

Floor area: 595 m^2 of conditioned space

Active System Components:

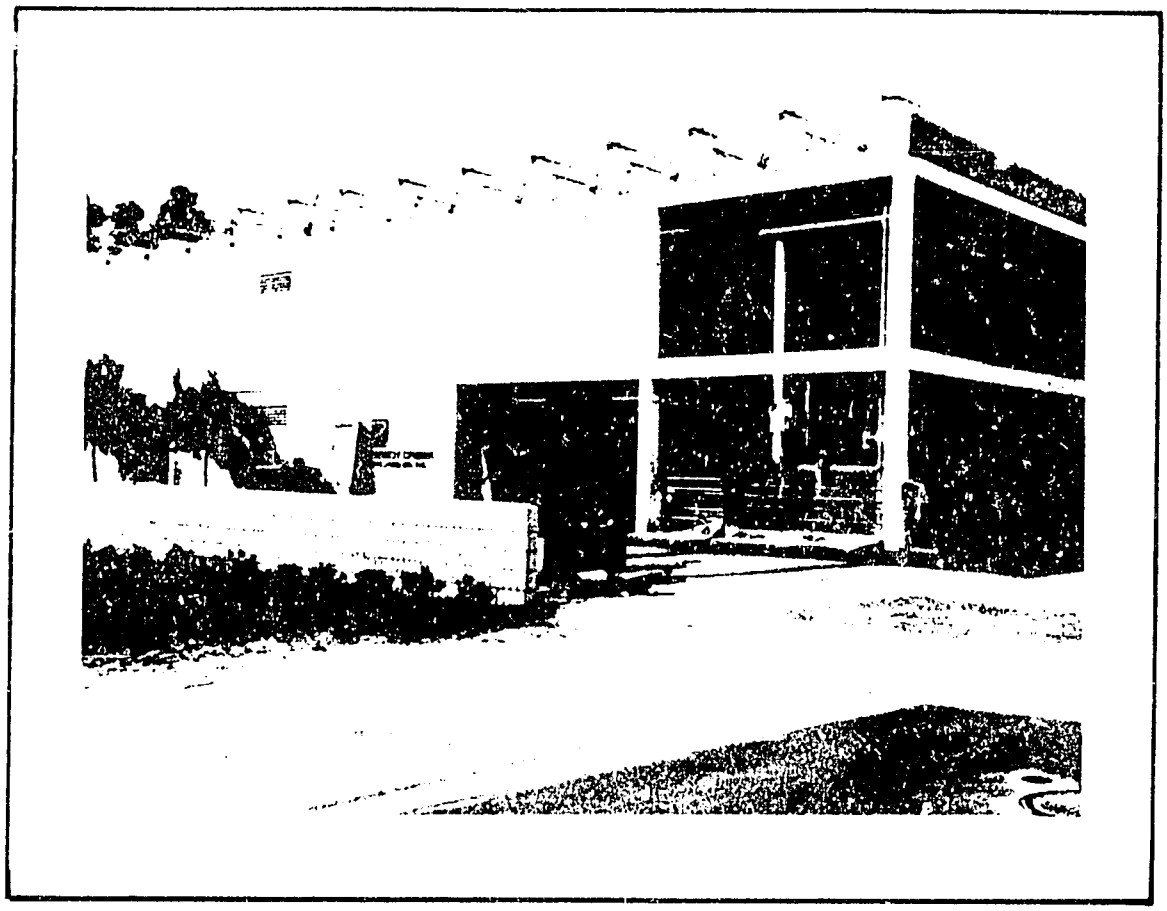
353 m^2 AAI Corporation linear tracking solar concentrators

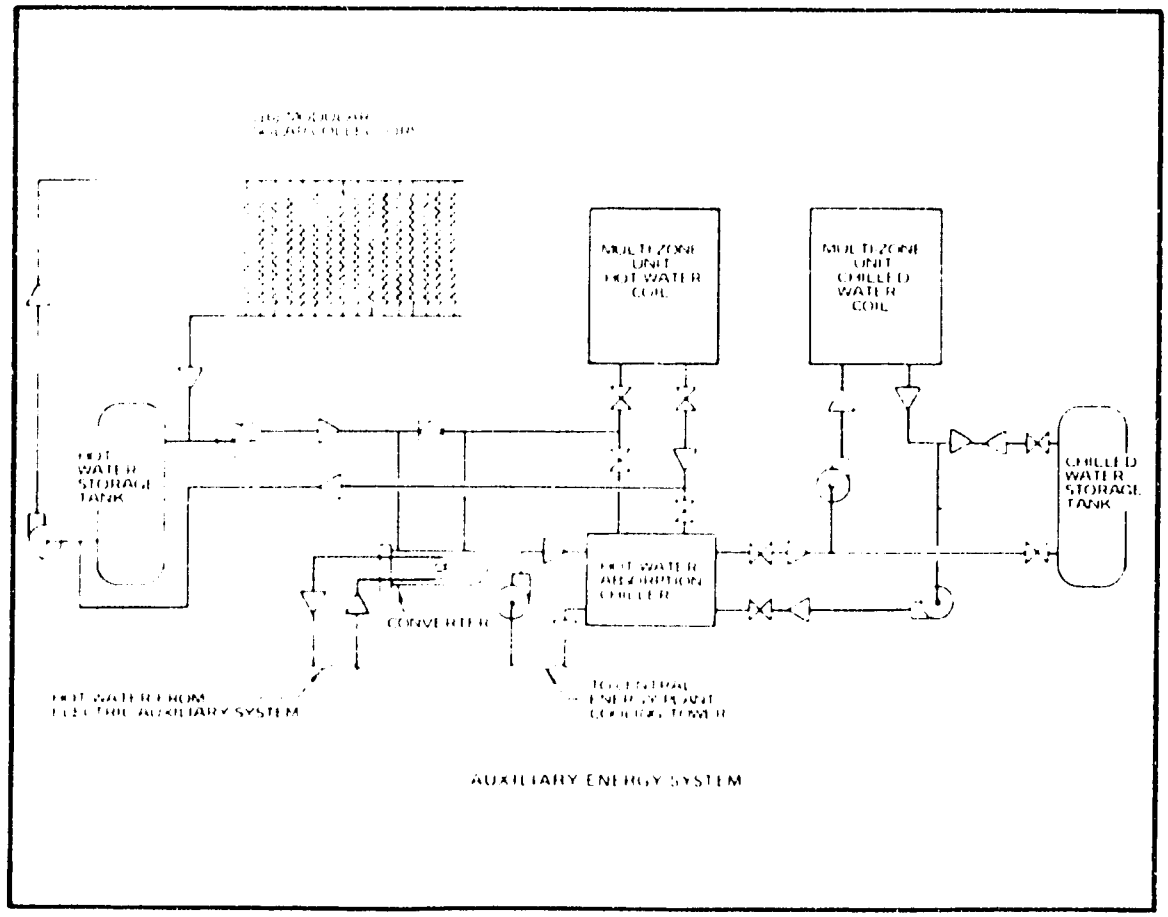
38 m^3 hot water storage and 38 m^3 chilled water storage (both above ground)

PERFORMANCE:

99% of the heating load and 100% of DHW requirements, and 80% of the cooling load.

CONTACT: Buena Vista Construction Company





AUXILIARY ENERGY SYSTEM

TECHNOLOGY AREA: Active Space Cooling, and DHW System

PROJECT TITLE: Dade County

LOCATION: Coral Gables, Florida, USA

DESCRIPTION:

The building is a two-story elementary school which will utilize solar energy from roof-mounted flat-plate collectors and three storage tanks. These tanks are buried in earth berms adjacent to the first floor perimeter walls. The berms have a 20% gradient and are sodded. Space cooling is accomplished from four 25-ton ARKLA chillers operated in unison or from a 125-ton centrifugal chiller.

SPECIFICATIONS:

Floor area: 6503 m^2 conditioned space

Active System Components:

1858 m^2 PPG Industries, Inc. liquid flat-plate collector
277 m^3 water storge (underground)
ARKLA 25-ton chiller unit and 125-ton centrifugal chiller.

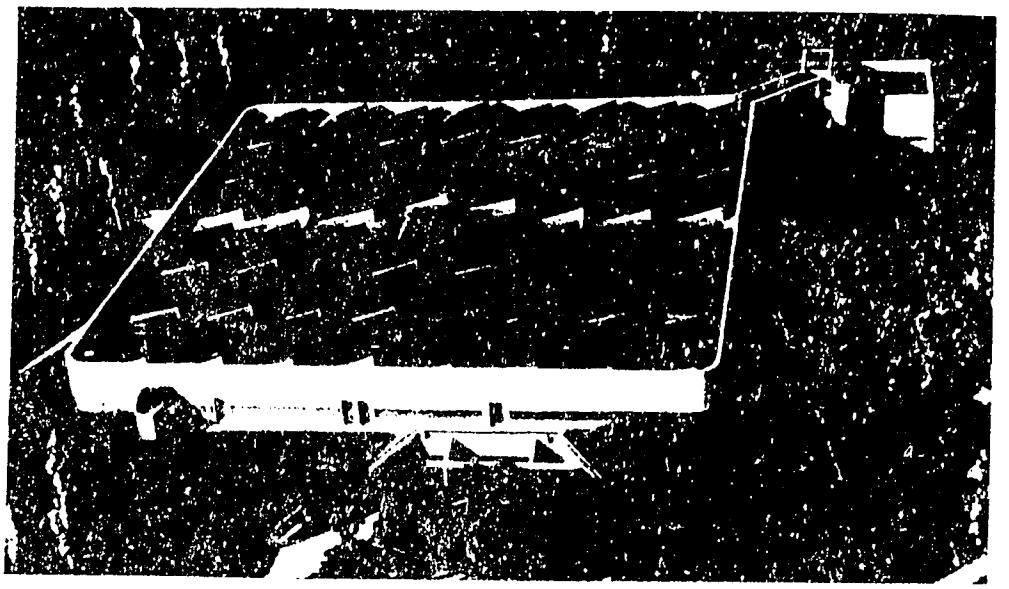
Additional Measures:

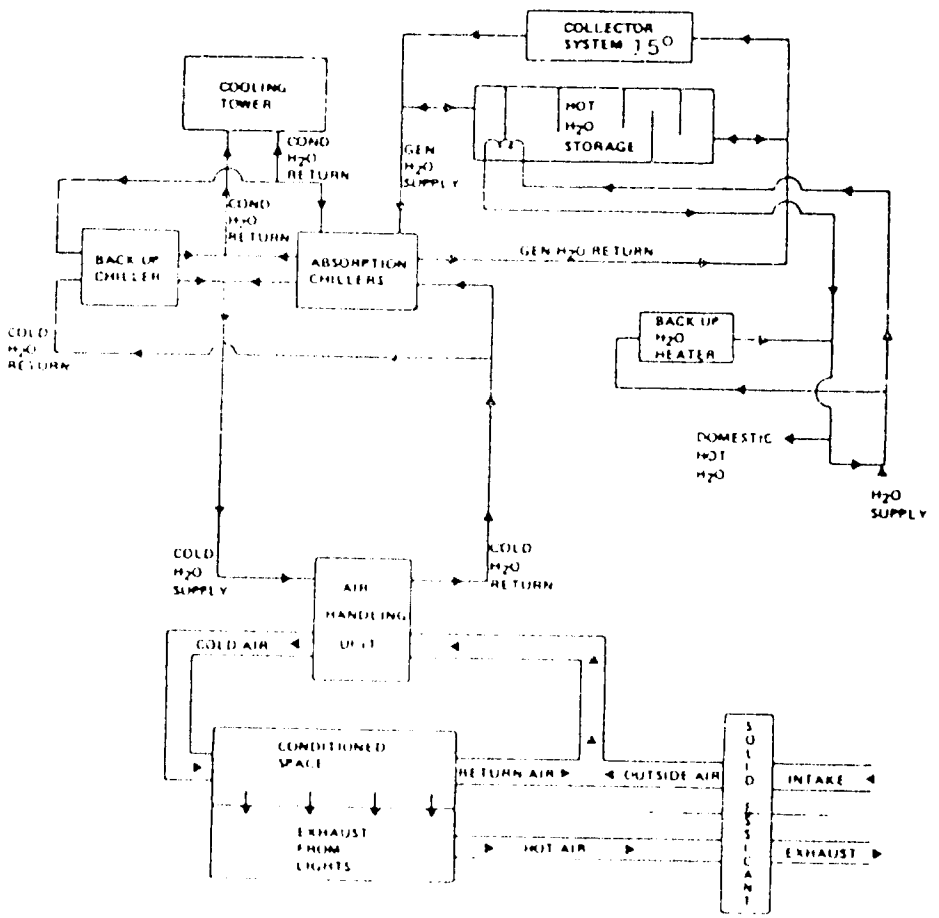
Earth berms, minimal fenestration, and a 3.3 m^3/sec desiccant wheel.

PERFORMANCE:

90% of DHW requirements and 70% of the cooling load.

CONTACT: School Board of Dade County, Florida




COLLECTOR SYSTEM 15°
COOLING TOWER
HOT H2O STORAGE
COND H2O RETURN
GEN H2O SUPPLY
COND H2O RETURN
BACK UP CHILLER
ABSORPTION CHILLERS
GEN H2O RETURN
COLD H2O RETURN
BACK UP H2O HEATER
DOMESTIC HOT H2O
H2O SUPPLY
COLD H2O SUPPLY
COLD H2O RETURN
AIR HANDLING UNIT
COLD AIR
CONDITIONED SPACE
RETURN AIR
OUTSIDE AIR
INTAKE
EXHAUST FROM LIGHTS
HOT AIR
EXHAUST
SOLID DESICCANT

TECHNOLOGY AREA: Active space cooling and heating system

PROJECT TITLE: Florida Solar Energy Center

LOCATION: Cape Canaveral, Florida, USA

DESCRIPTION:

The building is an office of a single-story concrete block construction on a concrete slab and having a flat roof of built-up tar and gravel composition. The roof has 1.8 m overhangs on the east, west, and south sides.

The space heating system is operated with evacuated tubular collectors. For air conditioning applications, stored heat drives a lithium bromide-water absorption chiller. Hot water storage will be placed between the collectors and the absorption chiller and the heating coil, and there will be chilled water storage between the chiller and the cooling coil. The entire solar system is backed up by the existing HVAC system.

SPECIFICATIONS:

Floor area: 1486 m^2 of heated space and 483 m^2 of air conditioned space.

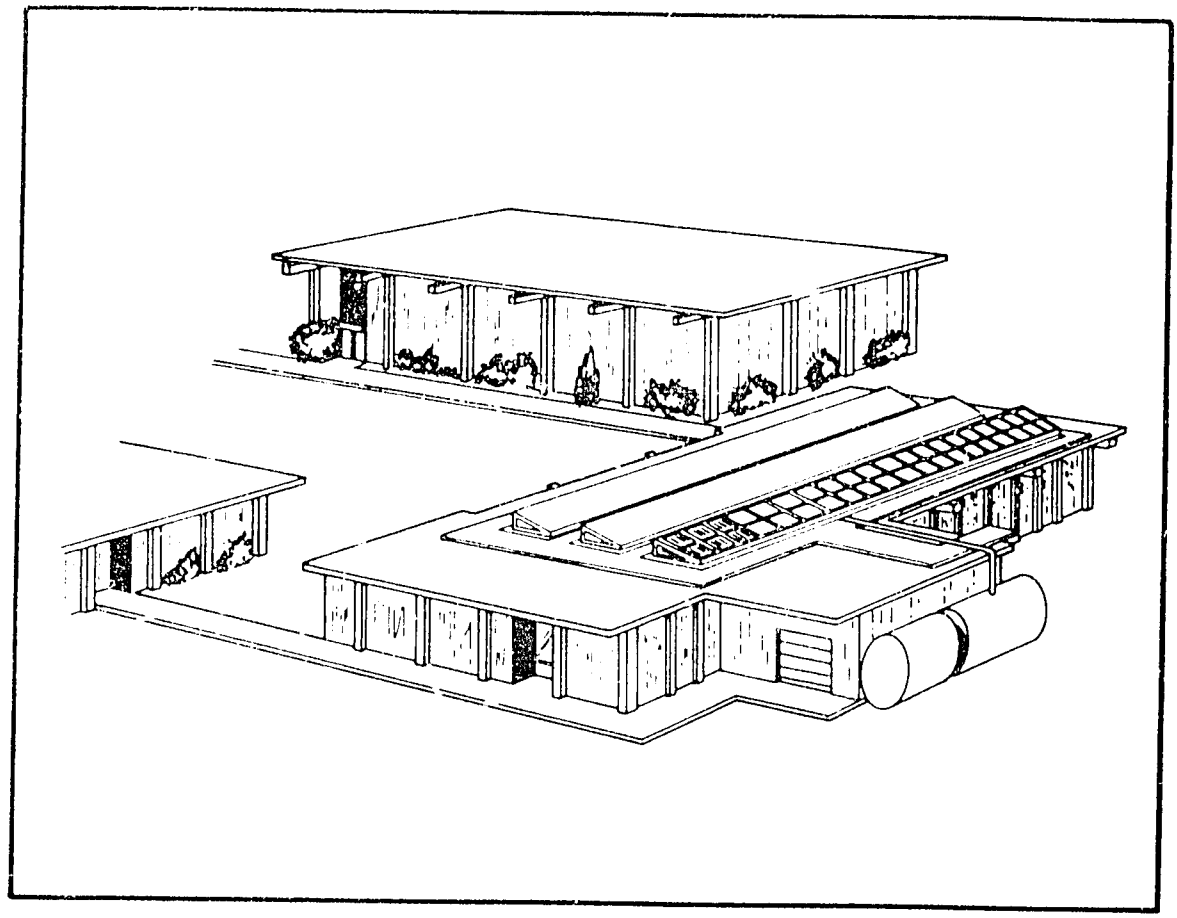
Active System Components:

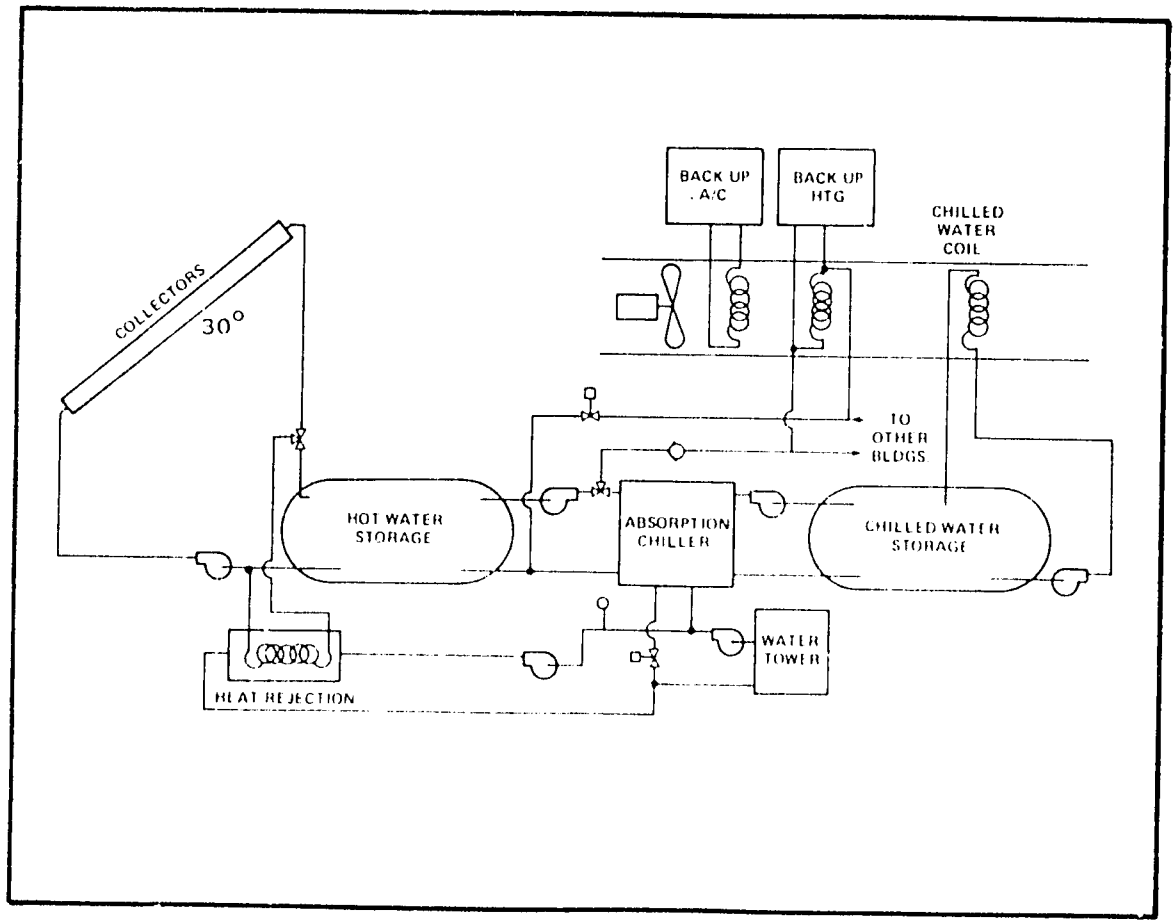
165 m^2 General Electric Company evacuated glass tubular collectors

11 m^3 hot water storage and 23 m^3 chilled (both above ground)

Auxiliary includes an oil-fired boiler, and vapor compression A/C.

CONTACTS: Florida Solar Energy Center




BACK UP
A/C
BACK UP
HTG
CHILLED
WATER
COIL
COLLECTORS
30°
TO
OTHER
BLDGS.
HOT WATER
STORAGE
ABSORPTION
CHILLER
CHILLED WATER
STORAGE
WATER
TOWER
HEAT REJECTION

TECHNOLOGY AREA: DHW System

PROJECT TITLE: Days Inn of America, Inc.

LOCATION: Clermont, Florida, USA

DESCRIPTION:

This solar system is designed to collect 90% of the total hot water requirements for one 24-hour day during one complete solar-day. The solar loop is a closed loop system, utilizing an antifreeze solution, with rust inhibitors, for the heat transfer fluid. Potable water will be heated by the transfer fluid via a heat exchanger Circulation pressure developed by a thermo-mainwater syphon will force the solar-heated potable water into the building system through the building's hot water system.

SPECIFICATIONS:

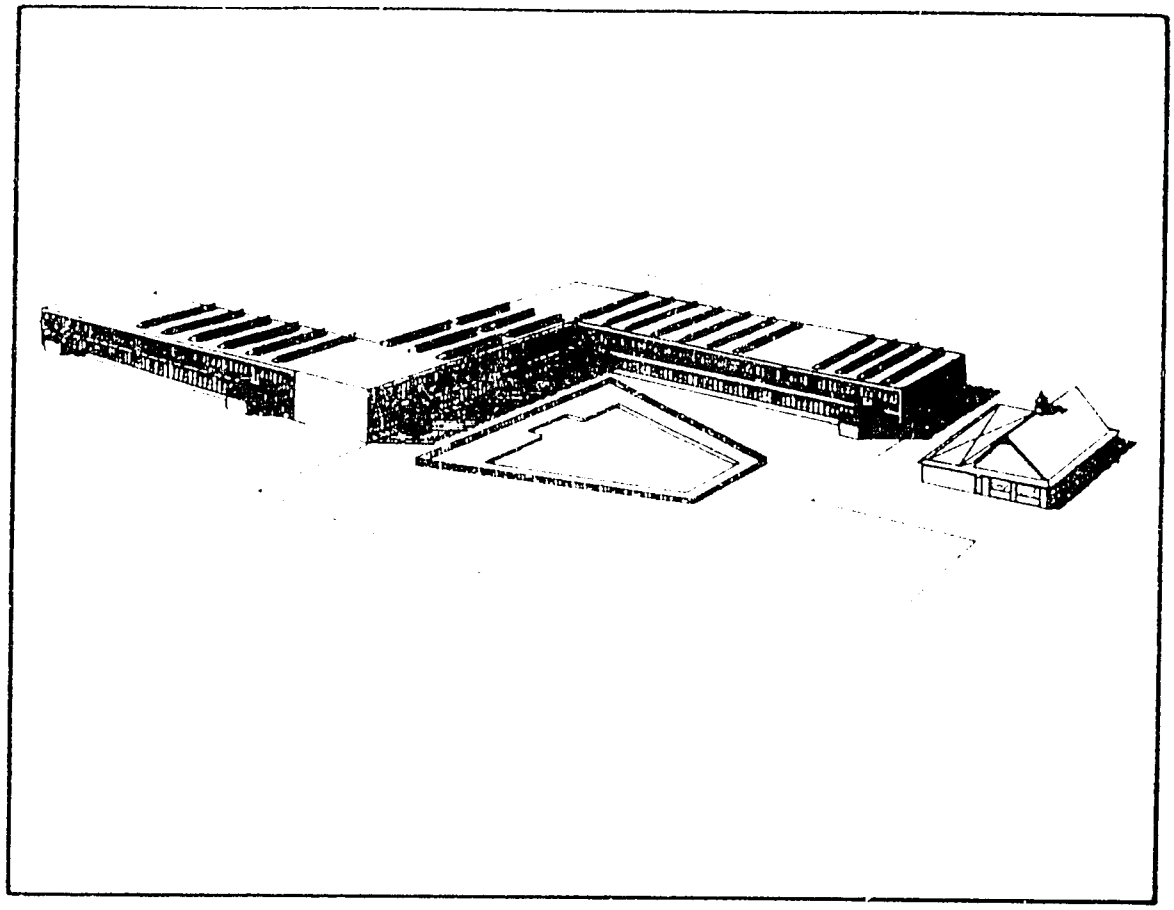
Active System Components:

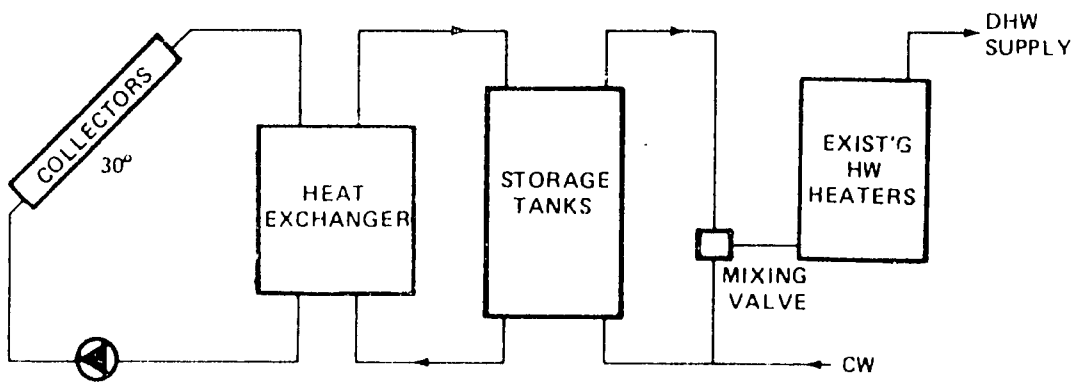
750 m^2 of Energy Systems, Inc., liquid flat-plate collectors
55 m^3 of glass-ceramic lined above ground water tank for storage
Electric hot water heaters for auxiliary

PERFORMANCE:

90% of DHW requirement

CONTACT: Solar Engineering and Equipment Company





HOT WATER SCHEMATIC –
TYPICAL OF THREE SEPARATE SYSTEMS

= PUMP

TECHNOLOGY AREA: Thermoponds

PROJECT TITLE: Lloyd A. Bell/American Ornamental Metal Company

LOCATION: Austin, Texas, USA

DESCRIPTION:

The building is for a combination factory/office which has tilt-up, load-bearing concrete walls with polystyrene exterior insulation. The capacitance of the concrete is varied to obtain different thermal time lags for unlike exposure to transient thermal flow.

Sun screens on south-facing windows decrease summer heat gain while allowing winter heat gain. The installation has 30 cm-deep thermoponds which provide 265 m^3 of water storage over the roof deck. This is supported by bar joists spaced approximately 1.2 m apart on centers. Plastic films are used as a black liner over the roofdeck for transparent thermopond covers.

During summer months, moveable insulation panels are closed during the day with comfort conditions resulting from radiation of body heat to the 75° ceiling. At night, the panels are opened and the interior heat is reradiated to the night sky. During the summer humid period, indirect evaporative cooling will be obtained by flooding the thermoponds. An air cell is used over the bags to maximize heat collection in cooler months.

SPECIFICTIONS:

Floor Area: 1068 m^2

Area of Collection Medium: 818 m^2 of thermoponds

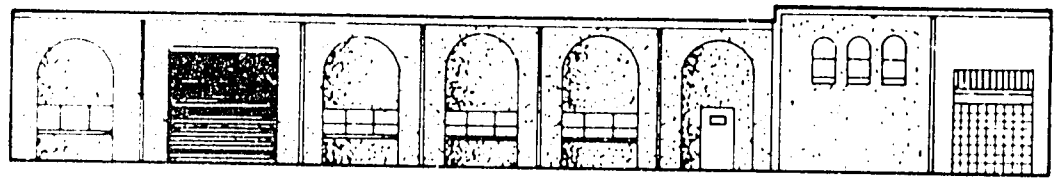
Capacity of System: 265 m^3 of water

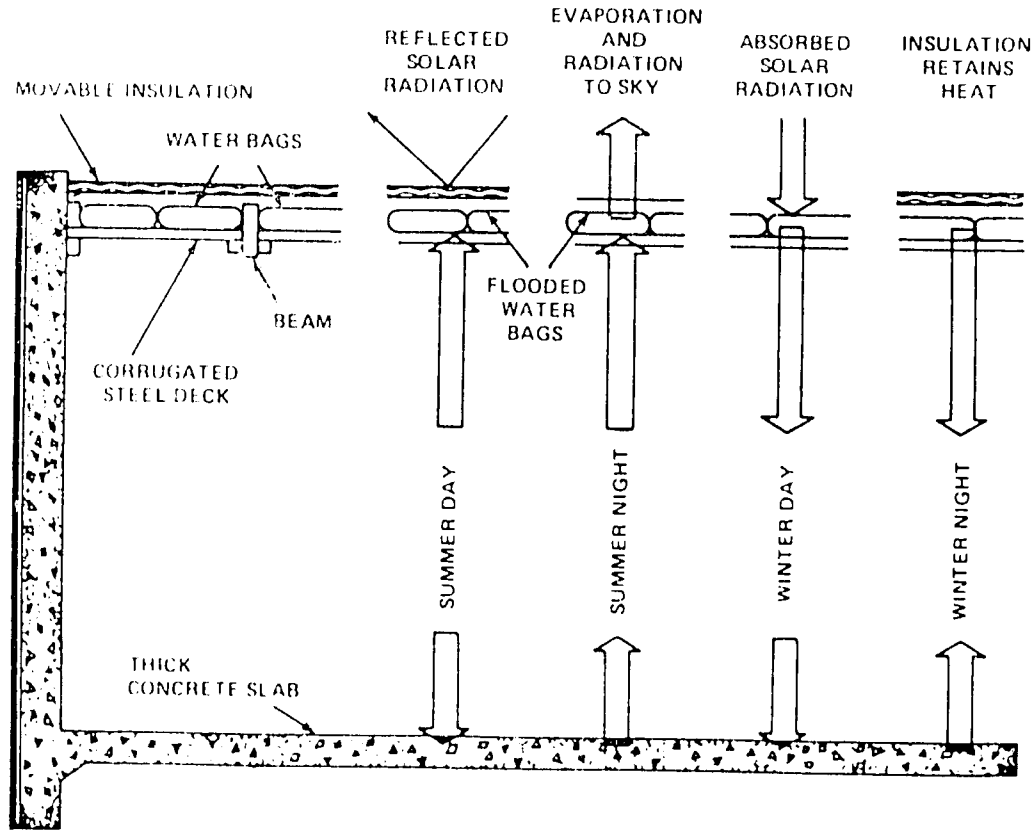
Heat pump for auxiliary

PERFORMANCE:

100% of the heating load and 90% of the cooling load.

CONTACT: American Ornamental Metal Company




MOVABLE INSULATION
WATER BAGS
BEAM
CORRUGATED STEEL DECK
REFLECTED SOLAR RADIATION
EVAPORATION AND RADIATION TO SKY
ABSORBED SOLAR RADIATION
INSULATION RETAINS HEAT
FLOODED WATER BAGS
SUMMER DAY
SUMMER NIGHT
WINTER DAY
WINTER NIGHT
THICK CONCRETE SLAB

TECHNOLOGY AREA: Passive direct gain and greenhouse

PROJECT TITLE: H. E. Crane, owner

LOCATION: Flagstaff, Arizona, USA

DESCRIPTION:

This residential building lies on an east/west axis. The north and west walls of this earth-sheltered home are built of block; east and south walls are of frame construction. Direct gain provides most of the required heat; 11 m^2 of windows cover the south-facing side of the wing. The concrete floor and block wall of the 1.5m-wide corridor store heat. There is a greenhouse adjacent to the living room. The greenhouse floor heats up as it absorbs sunlight striking 14 m^2 of windows. Four 0.2 m^3 water-filled drums in the rear of the greenhouse also store energy. The greenhouse can heat the rest of the room when the French doors between them are open. A wood stove and gas furnace provide auxiliary heat.

SPECIFICATIONS:

Construction: Wood frame and masonry, slab on grade

Floor Area: Total: 226 m^2; Heated: 215 m^2

Solar Aperture: 24 m^2

Aperture/Floor Area Ratio: 0.11

Primary Thermal Mass: Filled concrete block

PERFORMANCE:

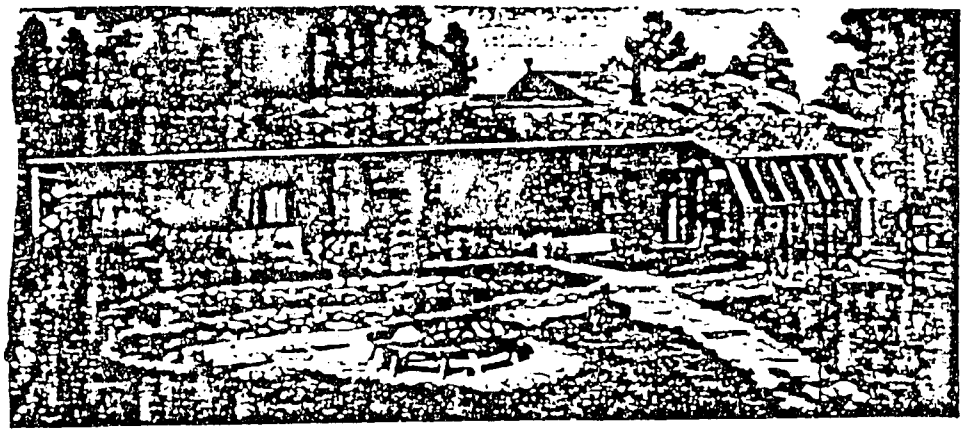
Reported Average Indoor Temperature: 20°C

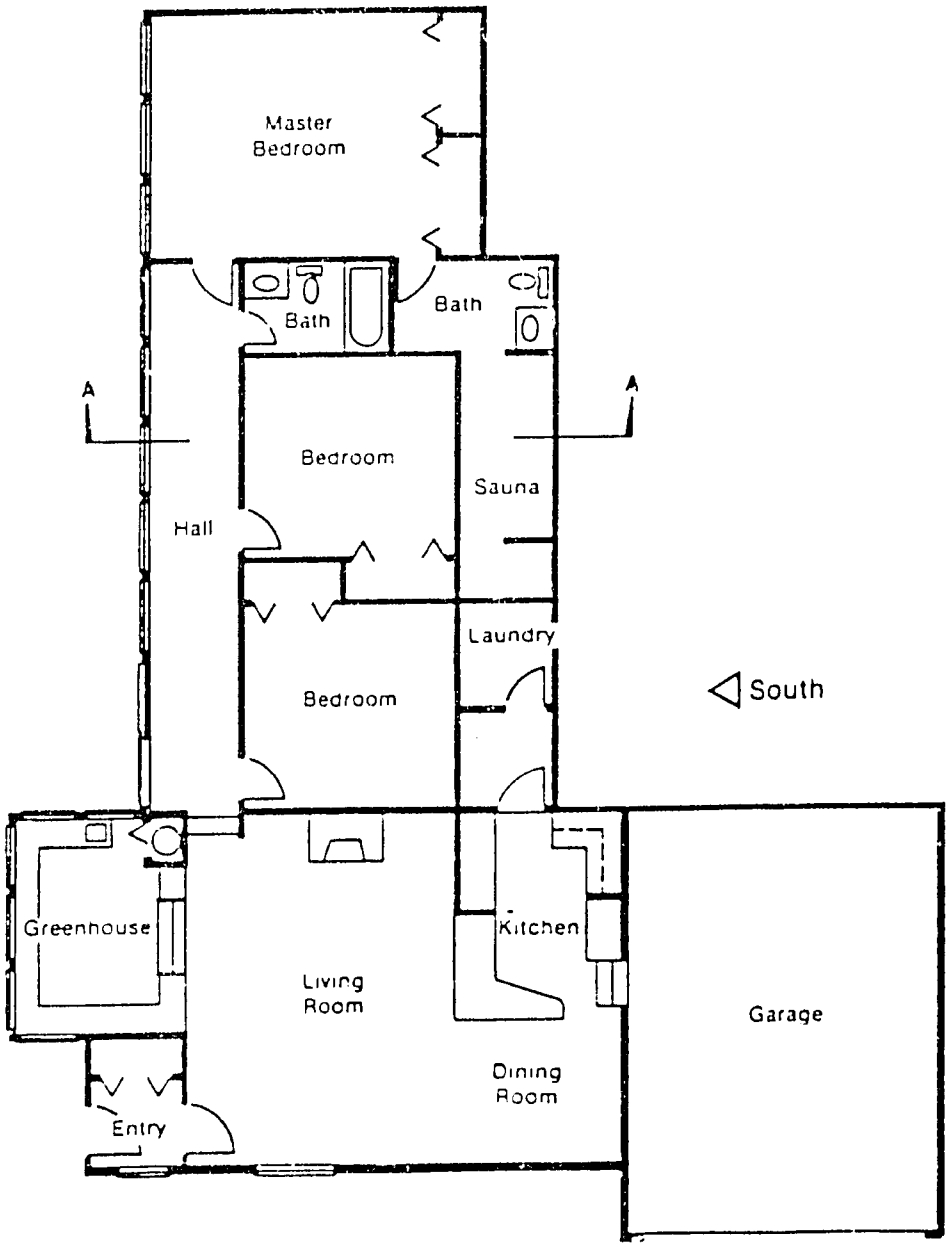
1979-80 Total Nonsolar Enegy Consumed per Square Meter:
$31.7*10^4$ kJ/m^2

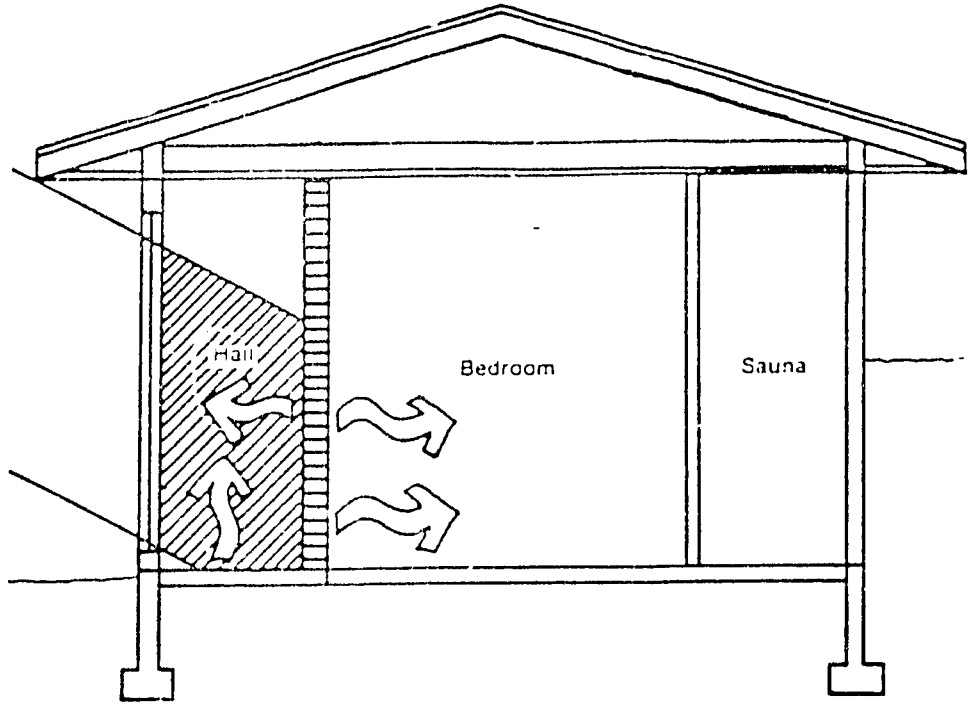
Calculated Net Heat Loss Coefficent: 299 W/°C

Estimated Infiltration Rate: 2/3 air changes/hr

CONTACT: H. E. Crane and Herb Wade




Master Bedroom
Bath
Bath
A
A
Bedroom
Sauna
Hall
Laundry
Bedroom
South
Greenhouse
Kitchen
Living Room
Garage
Dining Room
Entry


Hall
Bedroom
Sauna

TECHNOLOGY AREA: Passive direct gain and thermosiphon solar collector

PROJECT TITLE: Don Booth, Community Builders

LOCATION: Canterbury, New Hampshire, USA

DESCRIPTION:

Two passive systems provide heat for this building. The main system is the direct gain system on the first floor. Collection is accomplished via 15 m^2 double-glazed patio doors spanning the south wall. A floor and interior wall, both concrete, serve as thermal mass. A vent in the floor of the family room allows heat to rise to the second floor. Moveable insulation is placed on all doors at night to reduce losses.

The secondary system is a thermosiphon air panel on the lower gambrel roof. This system provides heat to the second floor during the day. The sun strikes the collector and heats the air, which then rises to the top of the collector and back into the building. A wood stove and small electric heater function as auxiliary energy sources.

SPECIFICATIONS:

Construction: Wood frame, slab on grade

Floor Area: Total: 152 m^2; Heated: 152 m^2

Solar Aperture: 21 m^2

Aperture/Floor Area Ratio: 0.14

Primary Thermal Mass: Concrete slab and first floor walls

PERFORMANCE:

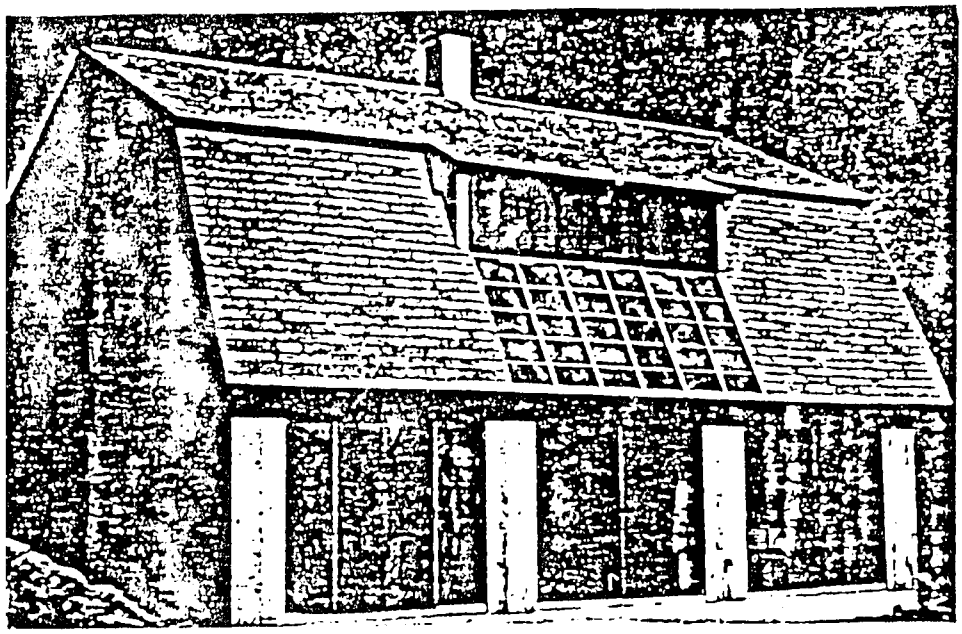
Reported Minimum Indoor Temperature: 15°C

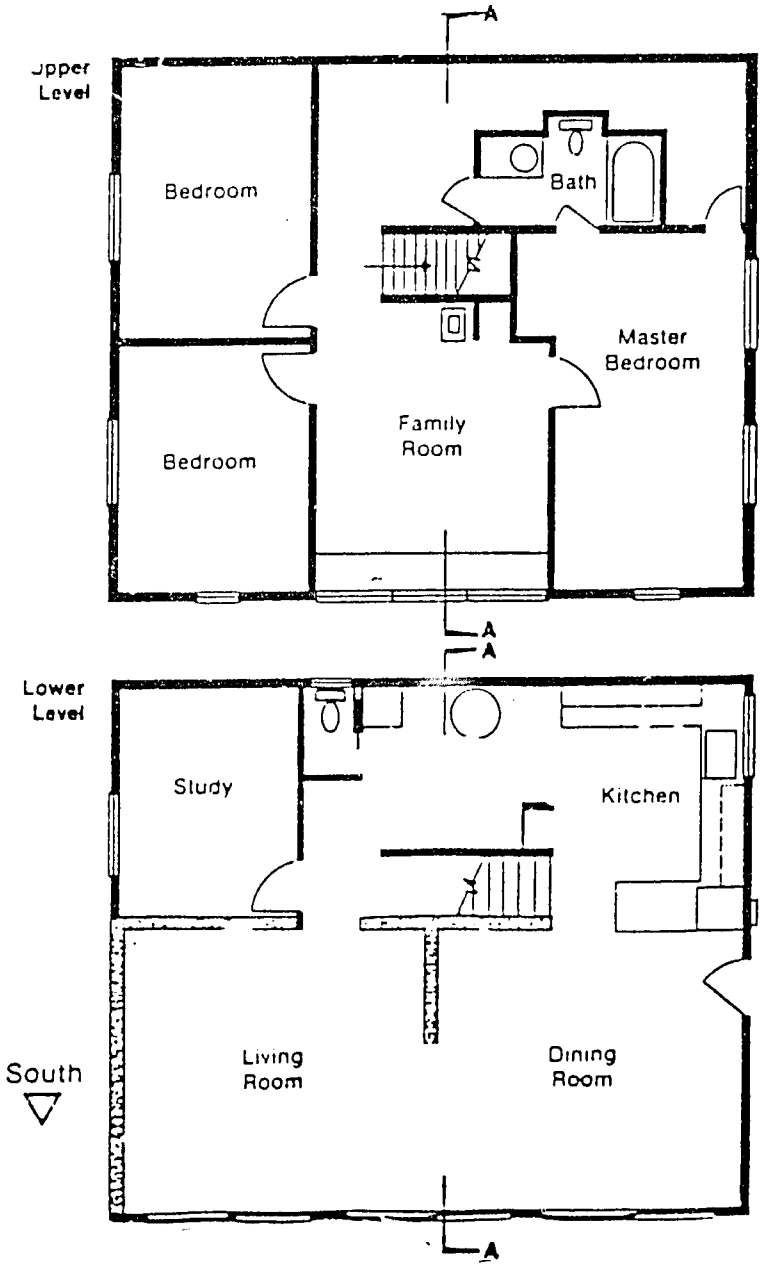
1981 Total Nonsolar Energy Consumed per Square Meter: $29.1*10^4$ kJ/m^2

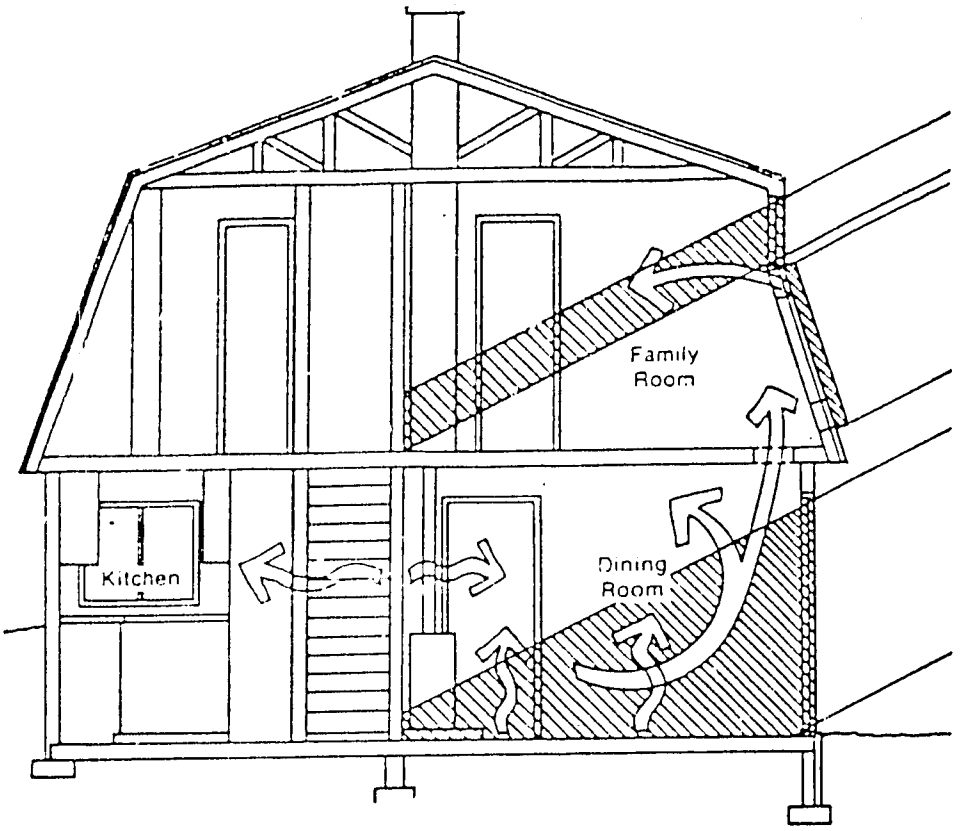
Calculated Net Heat Loss Coefficient: 181 W/°C

Estimated Infiltration Rate: 2/3 air changes/hr

CONTACT: Don Booth Community Builders
Canterbury, New Hampshire




A
Upper Level
Bedroom
Bath
Master Bedroom
Family Room
Bedroom
A
A
Lower Level
Study
Kitchen
Living Room
Dining Room
South
A


Family
Room
Kitchen
Dining
Room

TECHNOLOGY AREA: Passive sunspace with rock storage

PROJECT TITLE: Weather Energy Systems

LOCATION: Falmouth, Massachusetts, USA

DESCRIPTION:

This building is an old two-story inn converted into a private residence. During the winter, all but one wing is shut off; this wing is used for living quarters for the residents. A sunspace has been added to this wing. Sunlight enters through 17 m^2 of double-pane windows and then strikes black roller shades that cover the back wall. The heated sunspace air is then blown directly into the living areas or to a 5-m^3 bin containing 4536 kg of crushed rock for heat storage. When the indoor tempeature drops, fans direct the heat stored in the rock bed back into the living areas. A wood stove supplements the heat. An advantage of this design is that is adds 23 m^2 of living space.

SPECIFICATIONS:

Construction: Wood frame, house has basement, sunspace has crawl space.

Floor Area: Total: 313 m^2; Heated: 116 m^2

Solar Aperture: 21 m^2

Aperture/Floor Area Ratio: 0.18 (based on winter floor area)

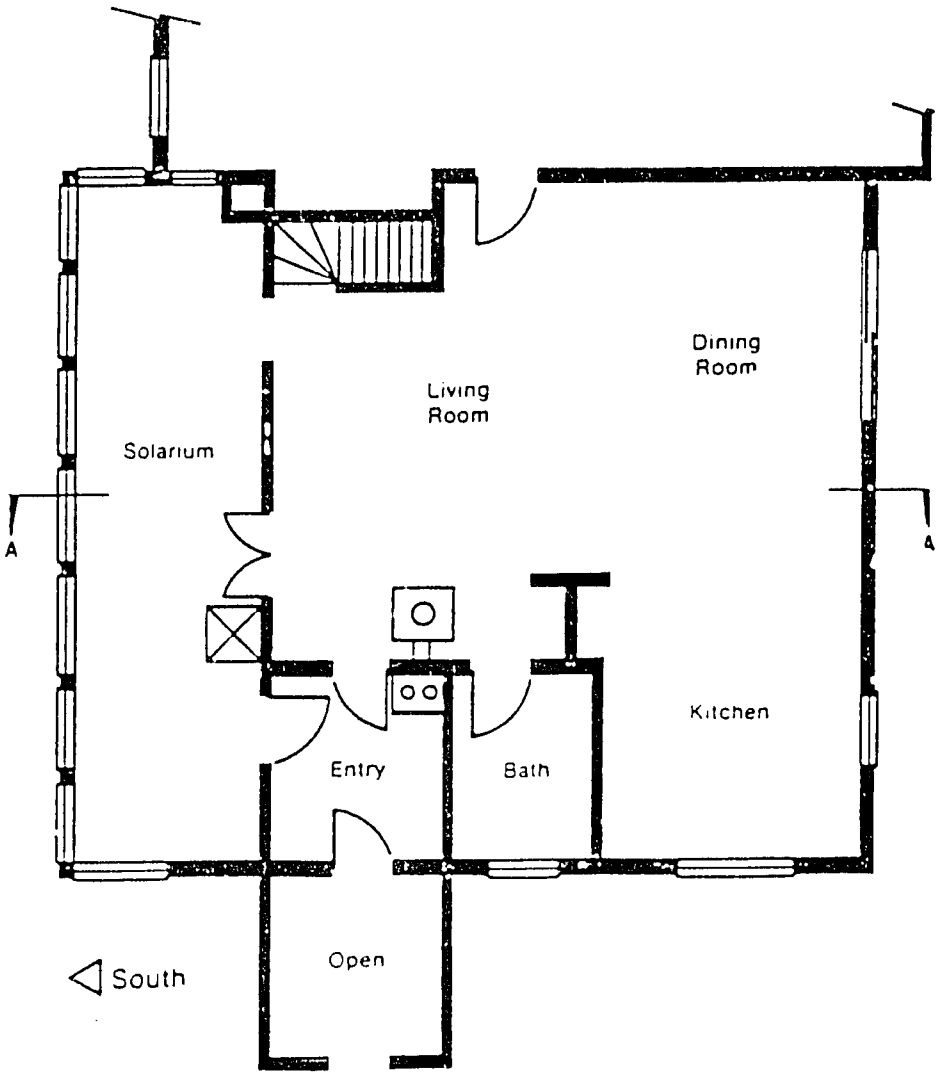
Primary Thermal Mass: Rock bed

PERFORMANCE:

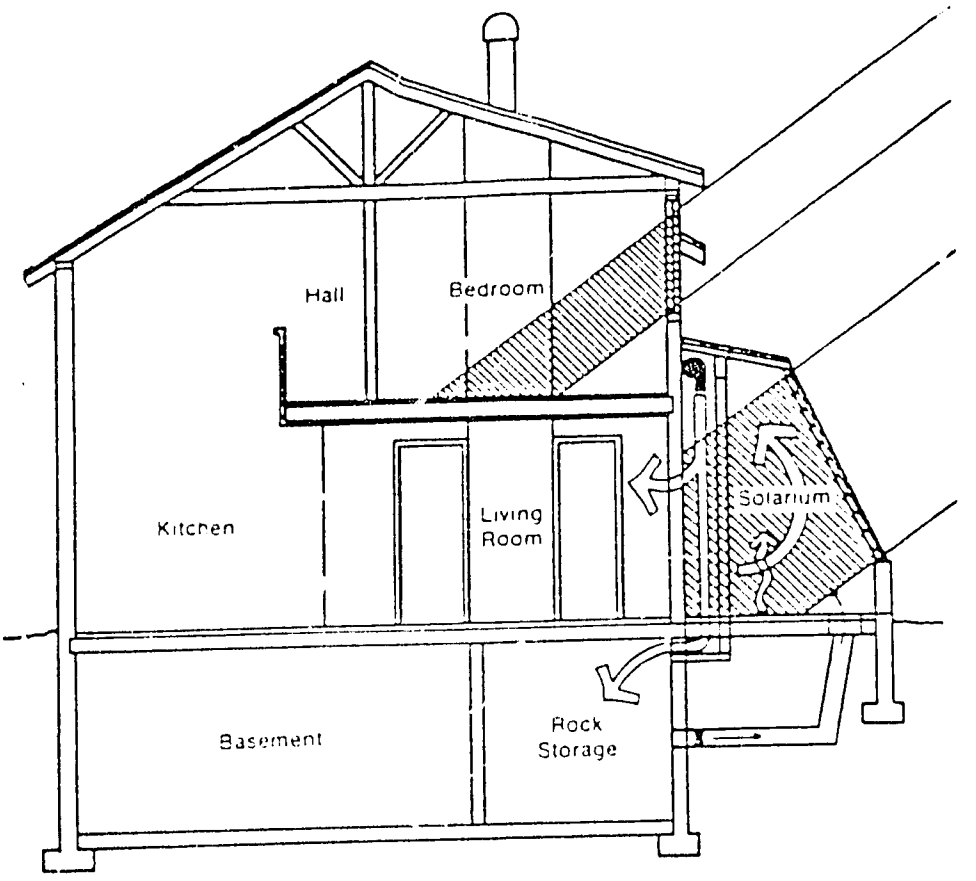
Reported Average Indoor Temperature: 18°C

Estimated Infiltration Rate: 1-1/4 air changes/hr

CONTACT: Weather Energy Systems, Pocasset, Massachusetts


Dining
Room
Living
Room
Solarium
A
A
Kitchen
Entry
Bath
Open
South

(SER-3)


Hall
Bedroom
Kitchen
Living
Room
Solarium
Basement
Rock
Storage

TECHNOLOGY AREA: Passive direct gain

PROJECT TITLE: Design Associates, Washington, Connecticut

LOCATION: New Milford, Connecticut, USA

DESCRIPTION:

This building is a 129 m^2 shed-roof-style home. It is designed with several thermal buffers: it is built into a hillside and has a north-facing garage. The lower floor has concrete block walls and the upper floor is frame type construction. Sunlight enters the building through windows along the south side, primarily those in the living room. Heated air from the living room is ducted into the storage system. The floor of the first story is constructed of concrete blocks laid so that air can pass through their hollow cores. A layer of concrete covers these blocks. These blocks form a duct area under the entire lower floor. The blocks function as a thermal storage medium. This heat is released slowly up through the floor. The insulated interior walls and masonry chimney also serve as thermal storage. Overheating is prevented by overhangs that shade the summer sun.

SPECIFICATIONS:

Construction: Masonry, slab on grade

Floor Area: Total: 129 m^2; Heated: 129 m^2

Solar Aperture: 31 m^2 of double glass

Aperture/Floor Area Ratio: 0.24

Primary Thermal Mass: Concrete slab with tile, plaster walls

PERFOFMANCE:

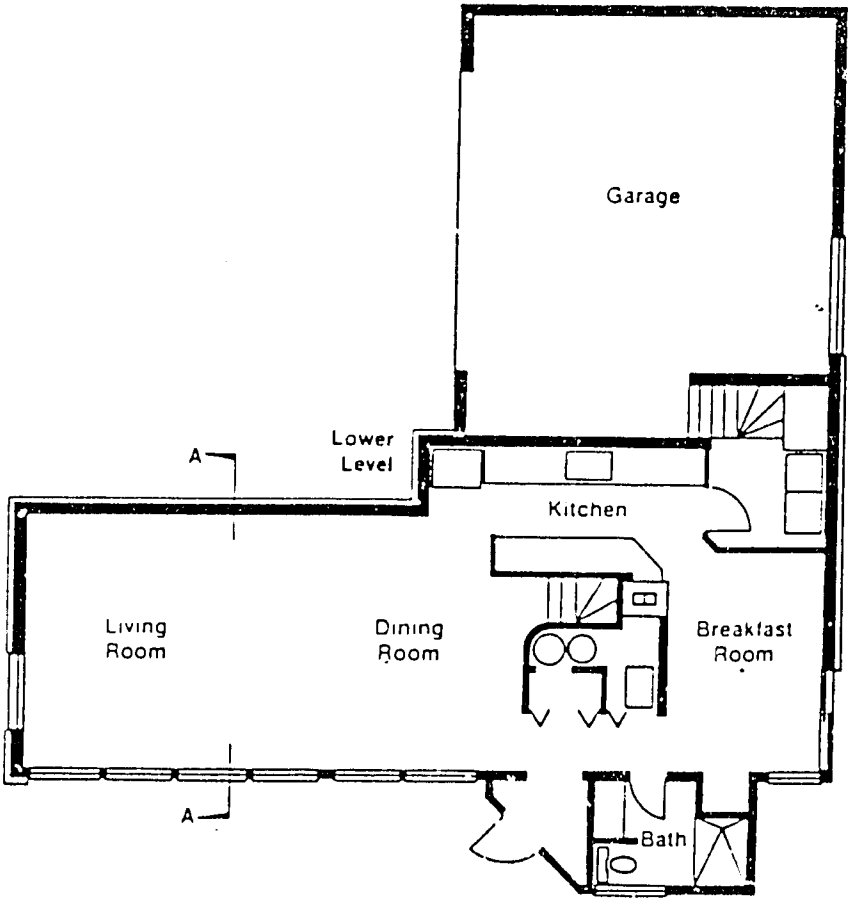
Reported Average Indoor Temperature: 17°C day, 13°C night

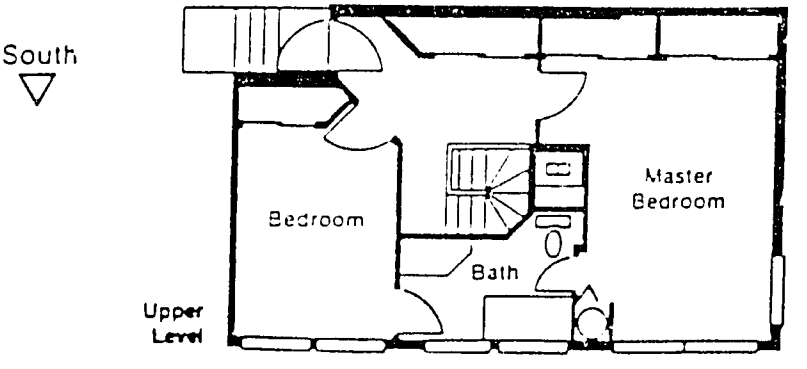
1979-80 Total nonsolar energy consumed per square meter:
$35.8*10^4$ kJ/m^2

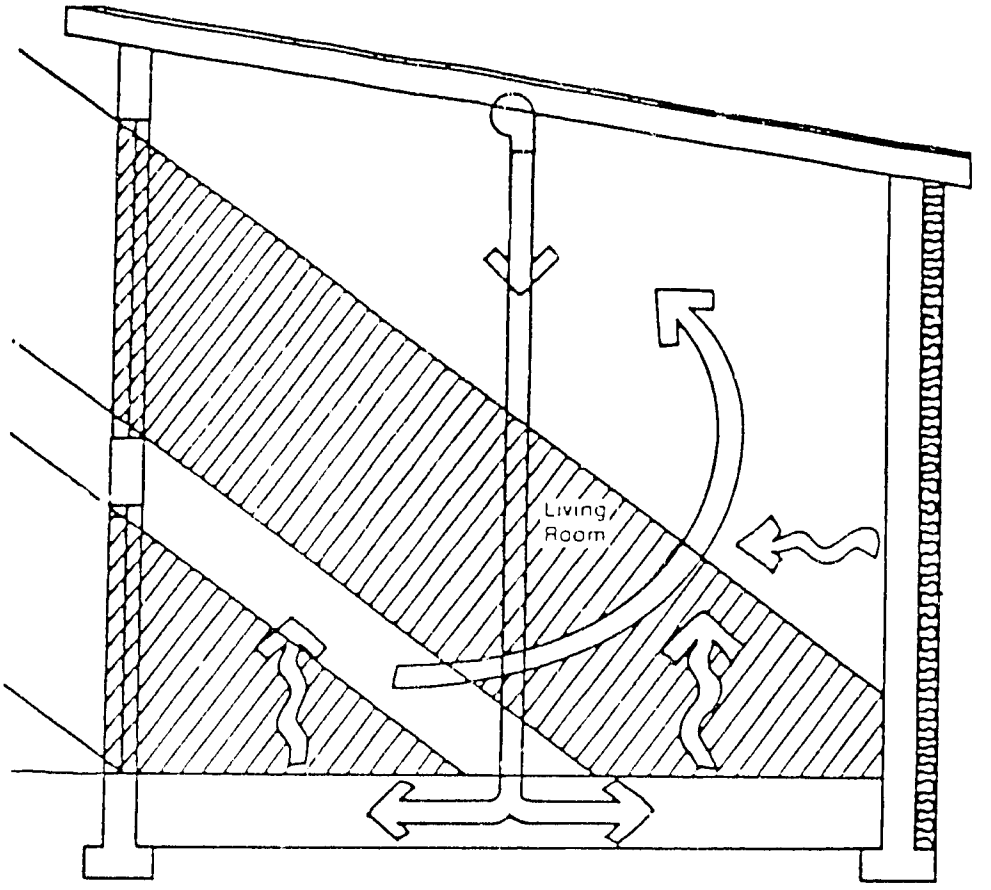
Calculated net heat loss coefficient: 173 W/°C

Estimated Infiltration Rate: 1/2 air chnages/hr

CONTACT: Designer, Stephen Lasar, New Milford, Connecticut


Garage
Lower Level
A
Kitchen
Living Room
Dining Room
Breakfast Room
A
Bath


South
Master Bedroom
Bedroom
Bath
Upper Level


Living
Room

TECHNOLOGY AREA: Passive direct gain with mass wall

PROJECT TITLE: Bert Seyfarth, East Lansing, Michigan

LOCATION: East Lansing, Michigan, USA

OBJECTIVE: To provide space heating

DESCRIPTION:

This residential building has six levels plus a back porch deck. The passive solar system combines 19 m^2 of glazing associated with an isolated mass wall and direct gain system with 9 m^2 of double-paned windows. The mass wall covers the south side of the garage and extends up into the living room. Sunlight enters the living room through the glazing above the storage wall, which directly heats the living area and the level above. Heat from the mass wall is transferred to the living areas by warmed air flowing up from the lower levels. Night losses are minimized by a reflective curtain below the wall and the glass. Ventilation from twin vents at the base and top of the mass wall and in the main bedroom cools the house in the warm months.

SPECIFICATIONS:

Construction: Wood frame, heated crawl space and basement

Floor Area: Total: 150 m^2; Heated: 150 m^2

Solar Aperture: 29 m^2 of double glass

Aperture/Floor Area Ratio: 0.19

Primary Thermal Mass: Concrete block wall packed with sand

PERFORMANCE:

Reported Average Indoor Temperature: 18°C day, 17°C night

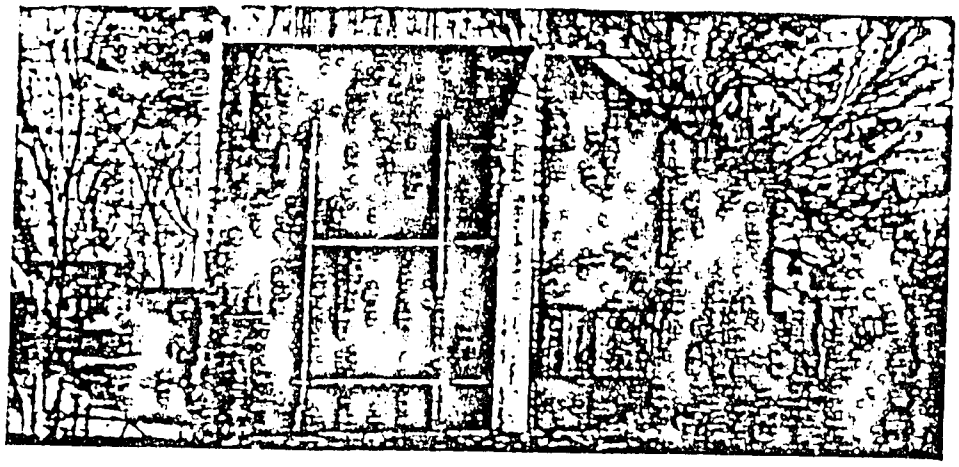
1981-82 Total nonsolar energy consumed per square meter:

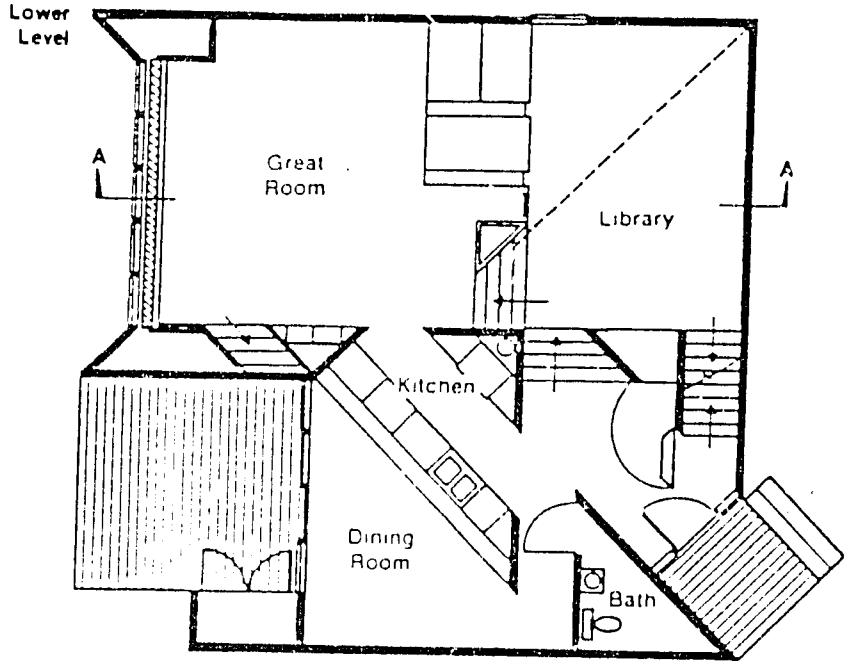
$88.2*10^4$ kJ/m^2

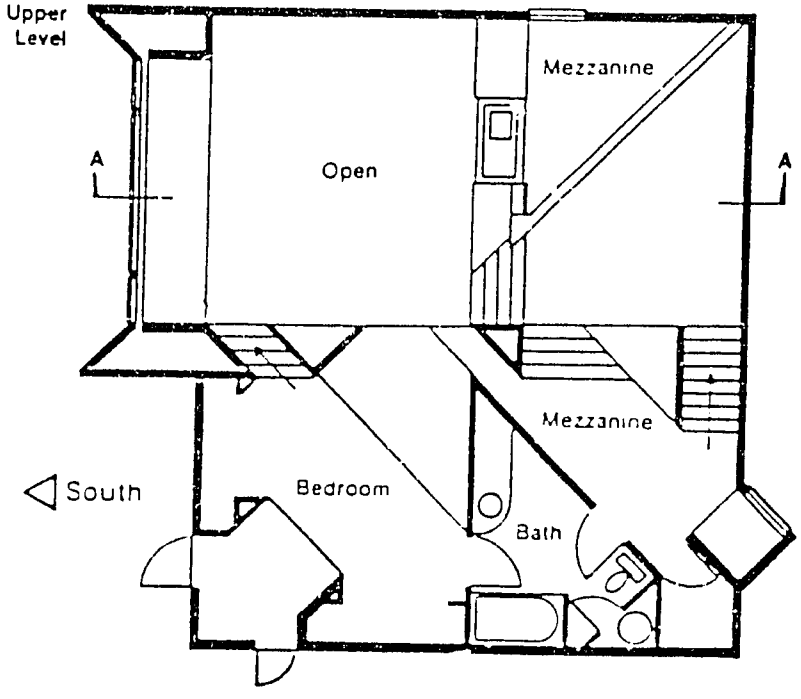
Calculated net heat loss coefficient: 284W/°C

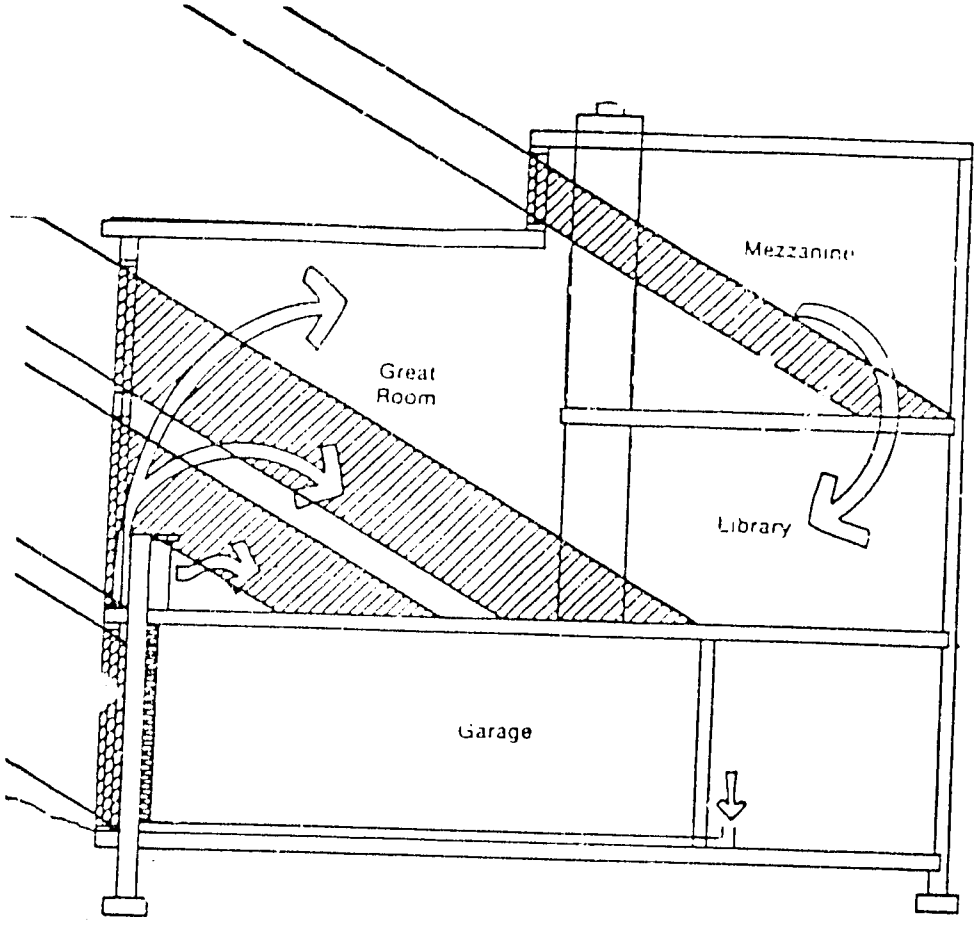
Estimated Infiltration Rate: 1/2 air changes/hr

CONTACT: Bert Seyfarth, East Lansing, Michigan




Lower Level
A
Great Room
Library
A
Kitchen
Dining Room
Bath


Upper Level
Mezzanine
A
Open
A
Mezzanine
South
Bedroom
Bath


Mezzanine
Great
Room
Library
Garage

TECHNOLOGY AREA: Passive greenhouse and attic ventilation cooling

PROJECT TITLE: Mad Dog Design and Construction

LOCATION: Tallahassee, Florida, USA

DESCRIPTION:

This 196 m^2 wood home features many widnows and a large greenhouse on the south side. This design incorporates both a passive solar heating system and an attic ventilation cooling system. A greenhouse also serves as an airlock entry to the house. The greenhouse has 15 m^2 of vertical windows and 16 m^2 of sloped windows. Heat is stored in 0.2 m^3 water-filled drums as well as the walls and in the concrete floor slab.

The house is ventilated by several methods: a small fan in the greenhouse vents the unwanted heat that builds up; natural cross-ventilation vents the attic space; and a whole house ventilator evacuates the entire building. Roof overhangs and white shingles help reduce summer heat gain.

SPECIFICATIONS:

Construction: Wood frame, slab on grade

Floor Area: Total: 196 m^2; Heated: 178 m^2

Solar Aperture: 32 m^2 of double wall acrylic

Aperture/Floor Area Ratio: 0.18

Primary Thermal Mass: Water-filled 0.2 m^3 drums in greenhouse

PERFORMANCE:

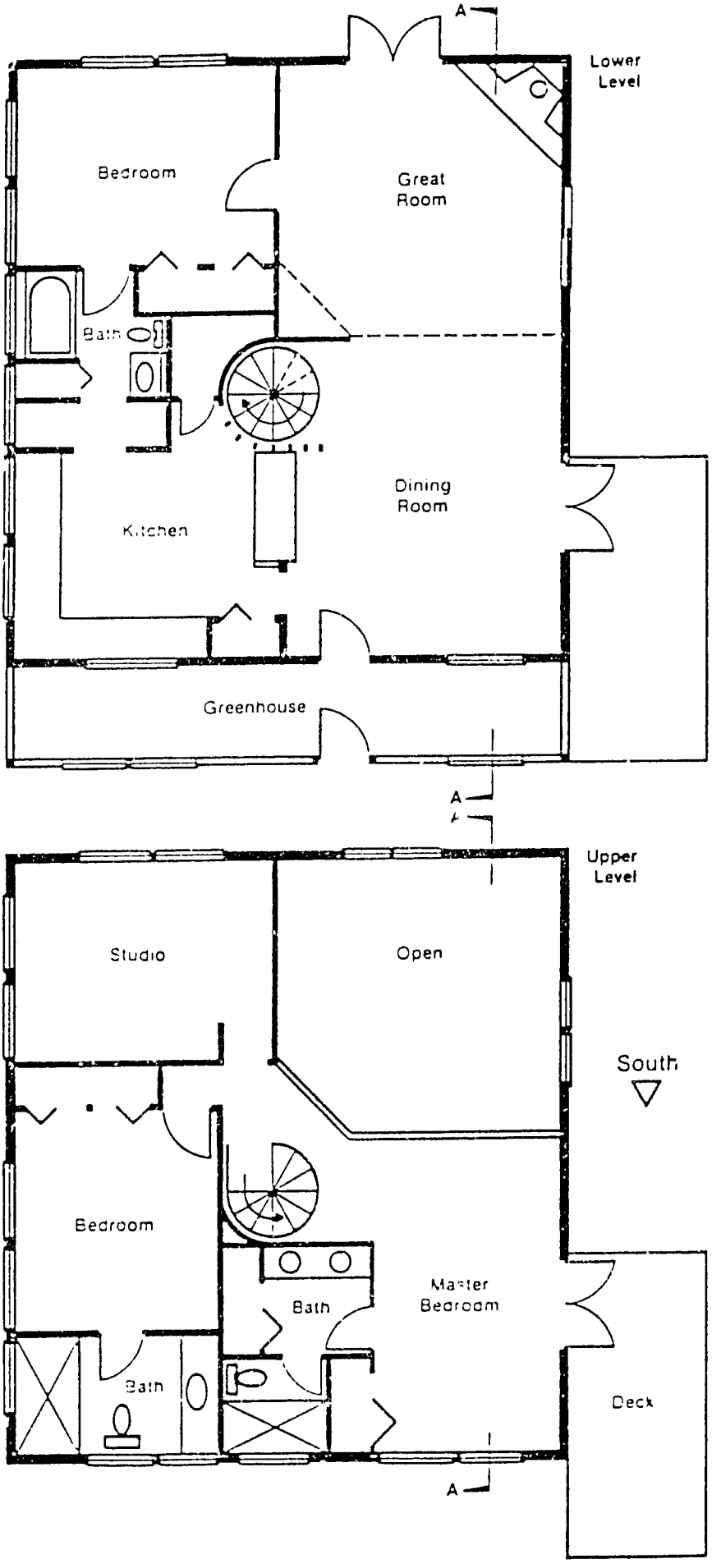
Reported Average Indoor Temperature: 24°C

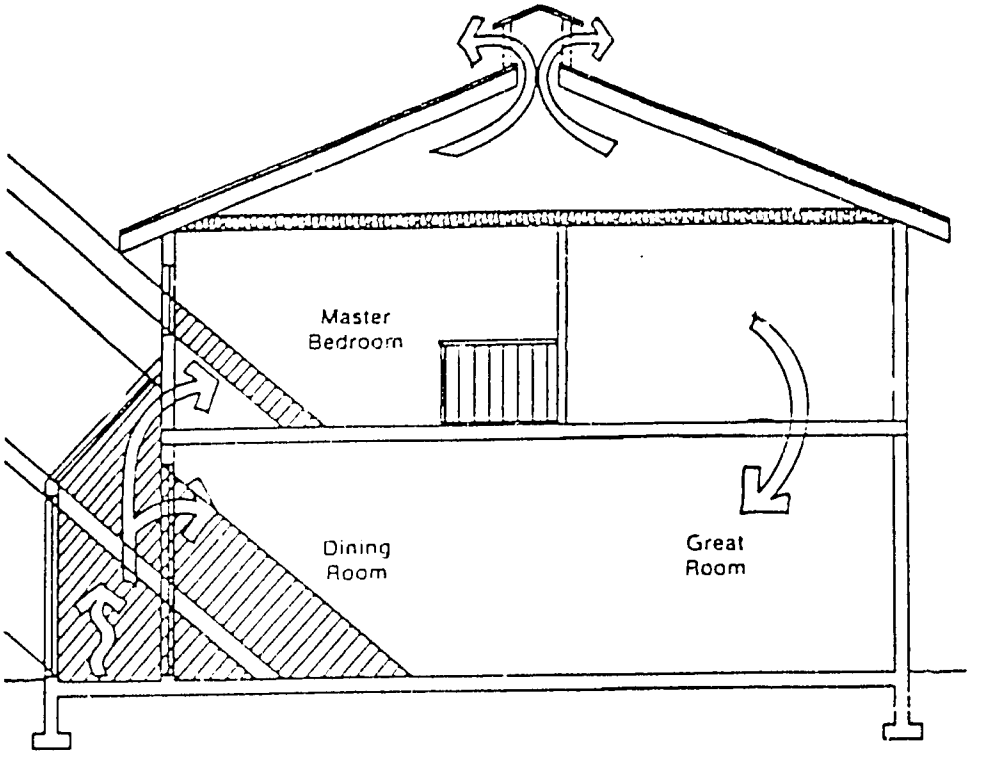
1981-82 Total nonsolar energy consumed per square meter:
$49.9*10^4$ kJ/m^2

Calculated net heat loss coefficient: 499 W/°C

Estimated Infiltration Rate: 3/8 air changes/hr

CONTACT: Mad Dog Design and Construction


A
Lower Level
Bedroom
Great Room
Bath
Dining Room
Kitchen
Greenhouse
A
Upper Level
Studio
Open
South
Bedroom
Master Bedroom
Bath
Bath
Deck
A


Master
Bedroom
Dining
Room
Great
Room

TECHNOLOGY AREA: Passive Home for Hot Desert Climate

DESIGNER: Edward Gorman

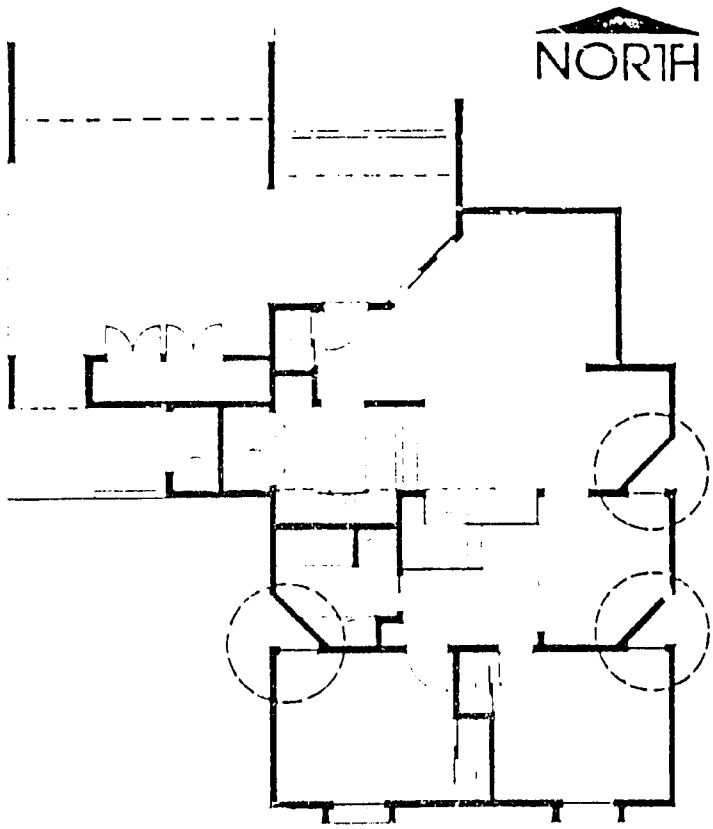
LOCATION: El Centro, California, USA

DESCRIPTION:

This house is built in a hot desert climate. All windows and doors are shaded from the summer sun. The roof and stucco exterior are a very light color, and all sides of the house have some earth berming for added insulation. The south-facing walls are angled to reflect light into the windows, providing natural light while eliminating heat gain.

CONTACT: Edward Gorman
Environmental Systems
San Diego, California

(CEC-2)



TECHNOLOGY AREA: Direct Gain and Indirect Passive Solar Features

DESIGNER: Sinan Sabuncuoglu and Jim Fong

LOCATION: West Oakland, California, USA

DESCRIPTION:

This 149 m^2 residential building has a north-south orientation and two stories. A vestibule on the north side minimizes heat loss from the entryway. The passive heating system incorporates both direct and indirect gain features. Direct gain is from south-facing windows and clerestories (Note: A clerestory is a vertical window placed high in wall near eaves, used for light, heat-gain and ventilation.); indirect gain is from two-story Trombe or Solar Mass walls.

During the winter months, the sun enters the main living space through south-facing glass. The concrete slab floor stores heat, which radiates into the room later in the day. South-facing clerestory windows allow light and heat to enter the north side living spaces. The Trombe wall (24 m^2) provides both direct and indirect heating. Top vents allow the solar-heated air to flow into the living spaces while bottom vents draw cold room air to be heated. These vents have manually-operated dampers to prevent reverse circulation. Heat loss is minimized by 2.5 cm thick rigid insulation installed below grade at the perimeter of the foundation walls.

During the summer months, the south-facing clerestory vents are opened to let hot air out while cooler air is drawn in from the northern windows at an intermediate level. Cool air is drawn across the rooms through the lower Trombe wall vents of each level and leaves through the opened exterior ve . Summer solar gain is reduced by overhangs, roll-up shades, and curtains.

SPECIFICATIONS:

Floor Area: Total: 149.2 m^2

Solar Aperture:

Trombe wall glazing, 24 m^2

Clerestories, 77 m^2

Slab with 22 m^2

Primary Thermal Storage:

Trombe wall, 30 cm thick, and concrete slab 15 cm thick

Ventilation System:

0.3 m^2 vent opening in Trombe wall for night ventilation.

Vents low on north side and high in ceiling for night ventilation.

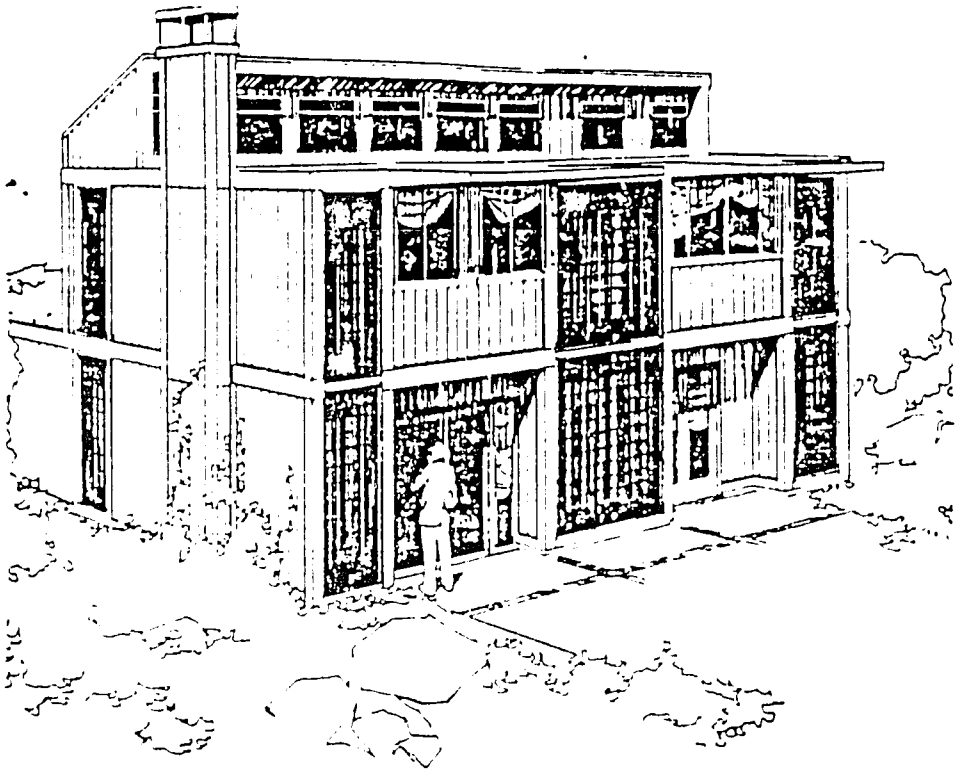
Operable windows

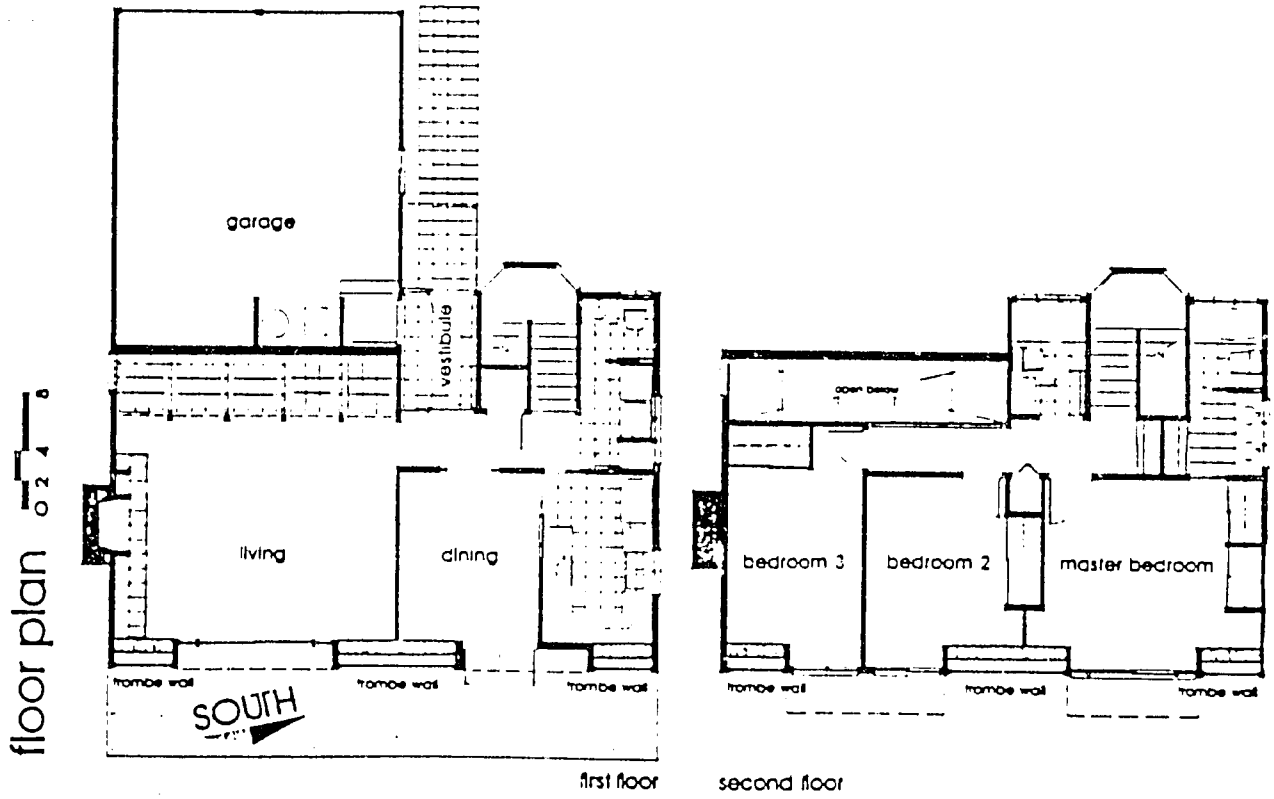
PERFORMANCE:

Solar Heating Fraction: 0 79

Solar Cooling Fraction: 0.74

CONTACT: Sinan Sabuncuoglu and Jim Fong
4368 Benevides Avenue
Oakland, California 94602

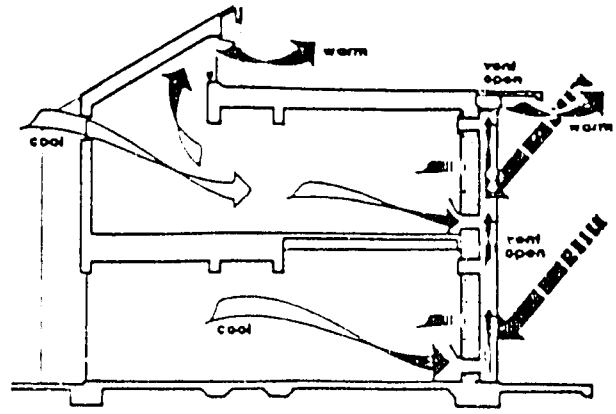



floor plan
0 2 4 8
garage
vestibule
living
dining
trombe wall
trombe wall
trombe wall
SOUTH
first floor
open below
bedroom 3
bedroom 2
master bedroom
trombe wall
trombe wall
trombe wall
second floor

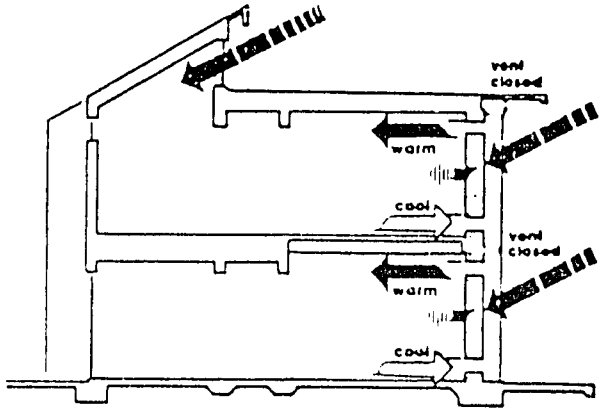
(CEC-2)

system sections

cooling



heating



(CEC-2)

TECHNOLOGY AREA: Direct Gain Passive Solar Features

DESIGNER: Robert Colyer, Architect
S. Pearl Freeman

LOCATION: Oakland, California, USA

DESCRIPTION:

This design is a multi-family unit. Unique features include earth-filled planter boxes for thermal mass in the solariums. Rain water for irrigation is collected and stored in a cistern equipped with a hand pump. On cool days, all exterior solarium vents can be closed to retain the maximum amount of solar radiation. The energy received is stored in 30-cm thick concrete block walls between the solarium and living area, in the second floor earth planter and prestressed floor slab, and in the insulated earth mass and slab on the first floor. Living spaces receive this heat via vents in the solarium or by thermal radiation from the mass wall.

During hot weather, the solariums are shaded by extending exterior roll-down shades and cooled by opening exterior vents. Cooler night air enters lower vents on each floor and hot air is exhausted through the top vents. The rest of the living space is shaded by closing interior venetian blinds on the south-facing windows.

SPECIFICATIONS:

Floor Area: Total: 123 m^2

Solar Aperture: South-facing windows and solarium, 94 m^2

Primary Thermal Storage:

Solarium concrete block mass walls and concrete floor

Ventilation System:

Operable windows and stack-effect chimneys

Vents in solarium and wall partitions

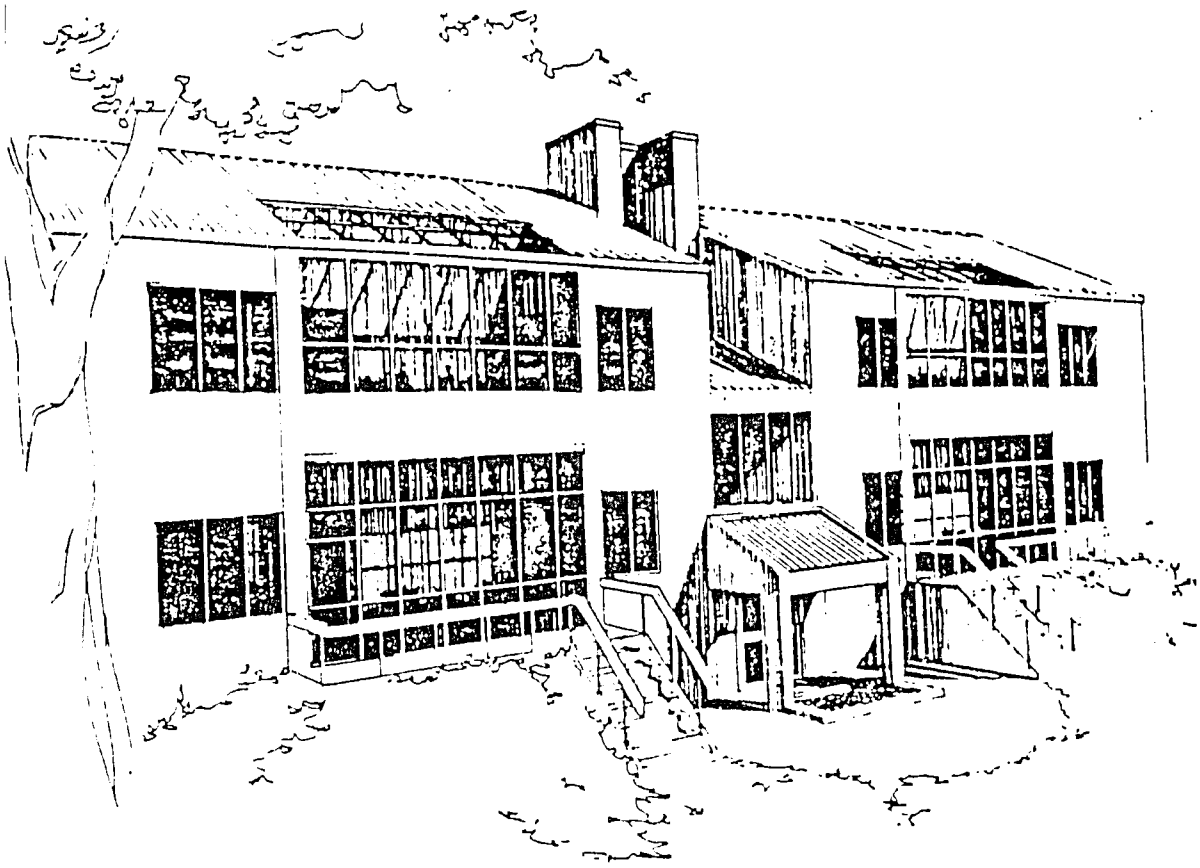
PERFORMANCE

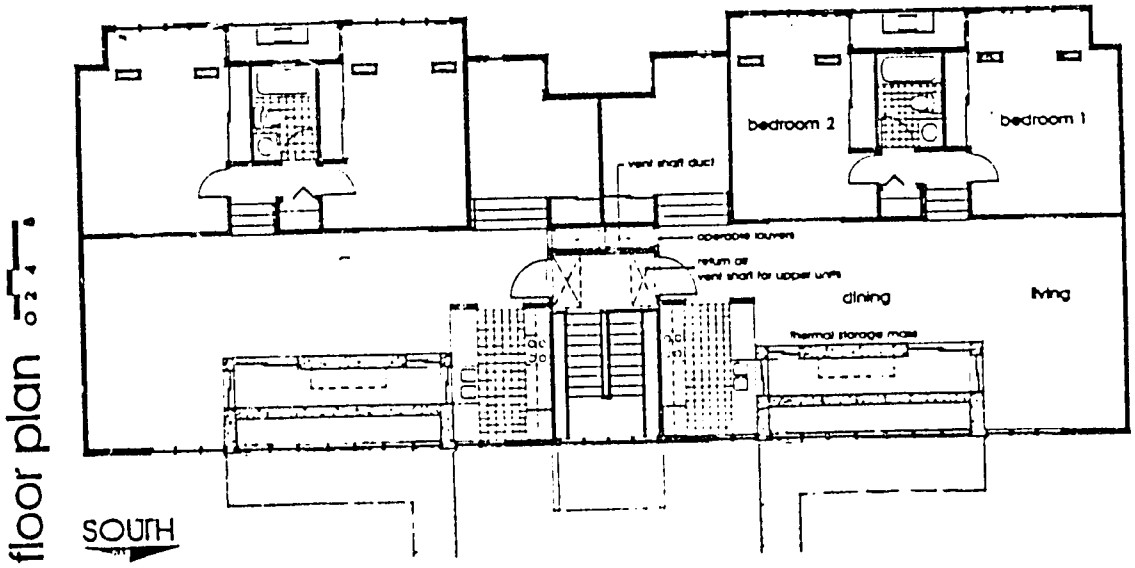
Solar Heating Fraction: 0.73

Solar Cooling Fraction: 0.75

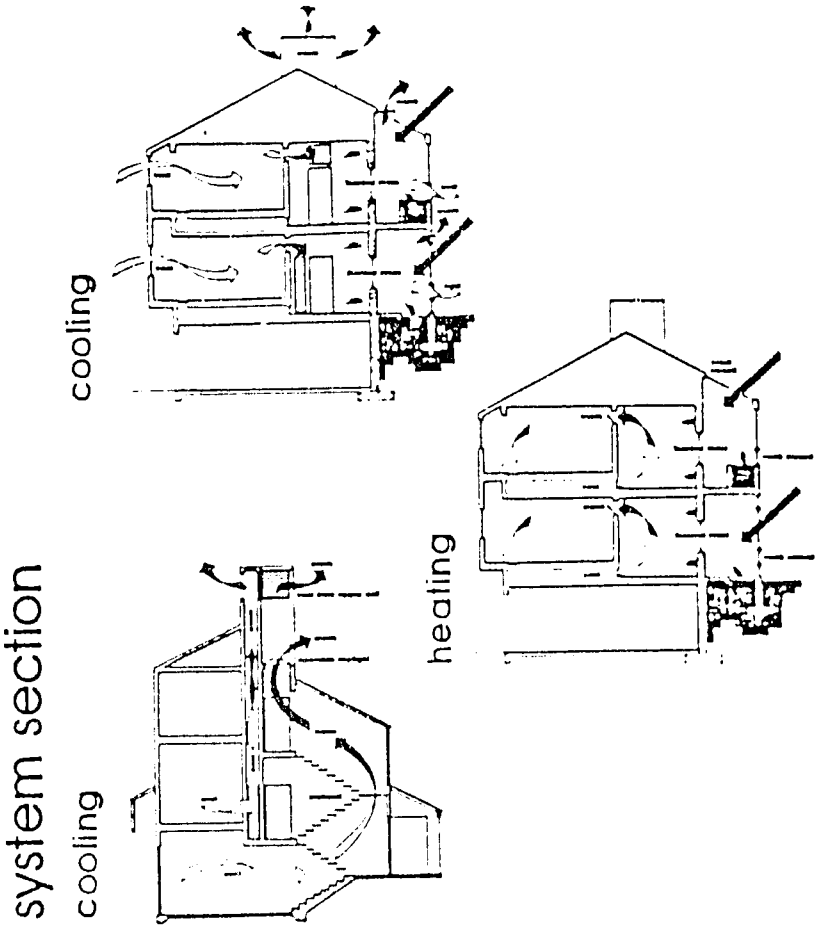
CONTACT:

Robert Colyer, Architect
S. Pearl Freeman
The Coyler/Freeman Group
1945 Eddy Street
San Francisco, California 94115




bedroom 2
bedroom 1
vent shaft duct
operable louvers
return air
vent shaft for upper units
dining
living
thermal storage mass
floor plan
SOUTH

(CEC-2)



(CEC-2)

TECHNOLOGY AREA: Direct Gain and Trombe Wall System

DESIGNER: Shepley, Bulfinch, Richardson, Abbott, Inc., Architects

LOCATION: Braintree, Massachusetts, USA

DESCRIPTION:

This project is part of Massachusetts' Multi-Family Passive Solar Program, and is housing for the elderly. The site is large and open, which is ideal for good solar access. Eight two-story buildings stretch east to west on the site. Small exterior stairs and interior vestibules serve four or six apartments each. In each apartment, frequently used areas such as bedrooms or living rooms face south; kitchen and bathrooms face north.

Fifty-two of the 58 one-bedroom apartments have direct gain windows and unvented Trombe walls for passive solar heating. In addition, the apartments have R-20 walls, R-40 Roofs, and R-10 perimeter insulation to the footing. All windows are triple-glazed (R values are in English units.)

SPECIFICATIONS

Construction: Wood frame with clapboard siding

Floor Area: 76 m^2 (Per apartment)

Solar Aperture:

Direct gain triple-glazed windows, (4.4 m^2)

Trombe wall (9.8 m^2 total, 8.3 m^2 glazed), 8-inch (20 cm) block, triple-glazed, unvented, canvas awnings for summer shading.

Primary Thermal Storage:

Concrete masonry heat storage wall (6-inch thick, 15 cm) perpendicular to direct gain aperture.

Ventilation System:

Kitchens are partially opened to living room, allowing natural ventilation; good cross ventilation

PERFORMANCE

Building Heat Loss Coefficient: 112 BTU/hr-°F, 59 W/°C

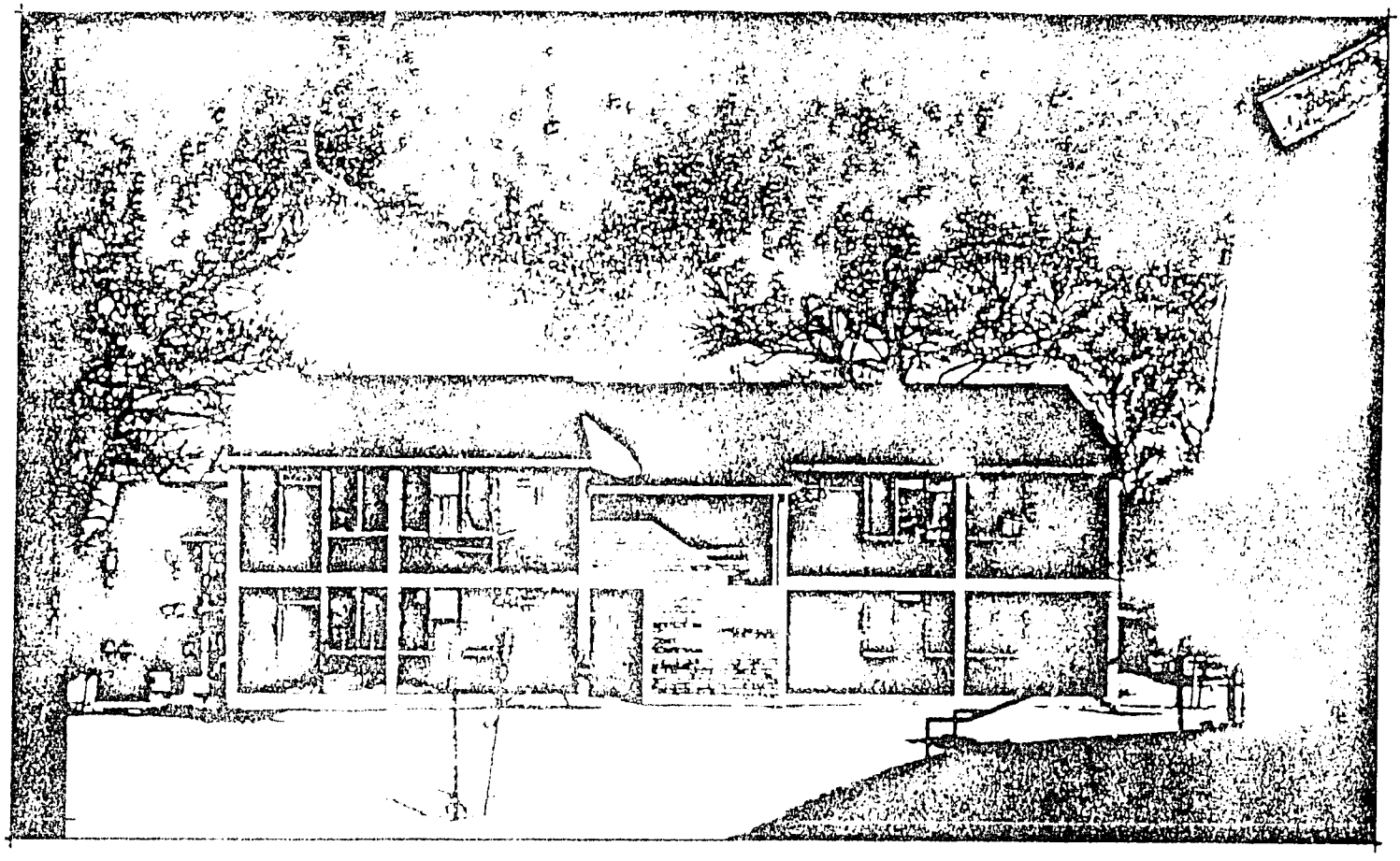
Solar Contribution: 65% if vented at 75°F, 24°C

CONTACT:

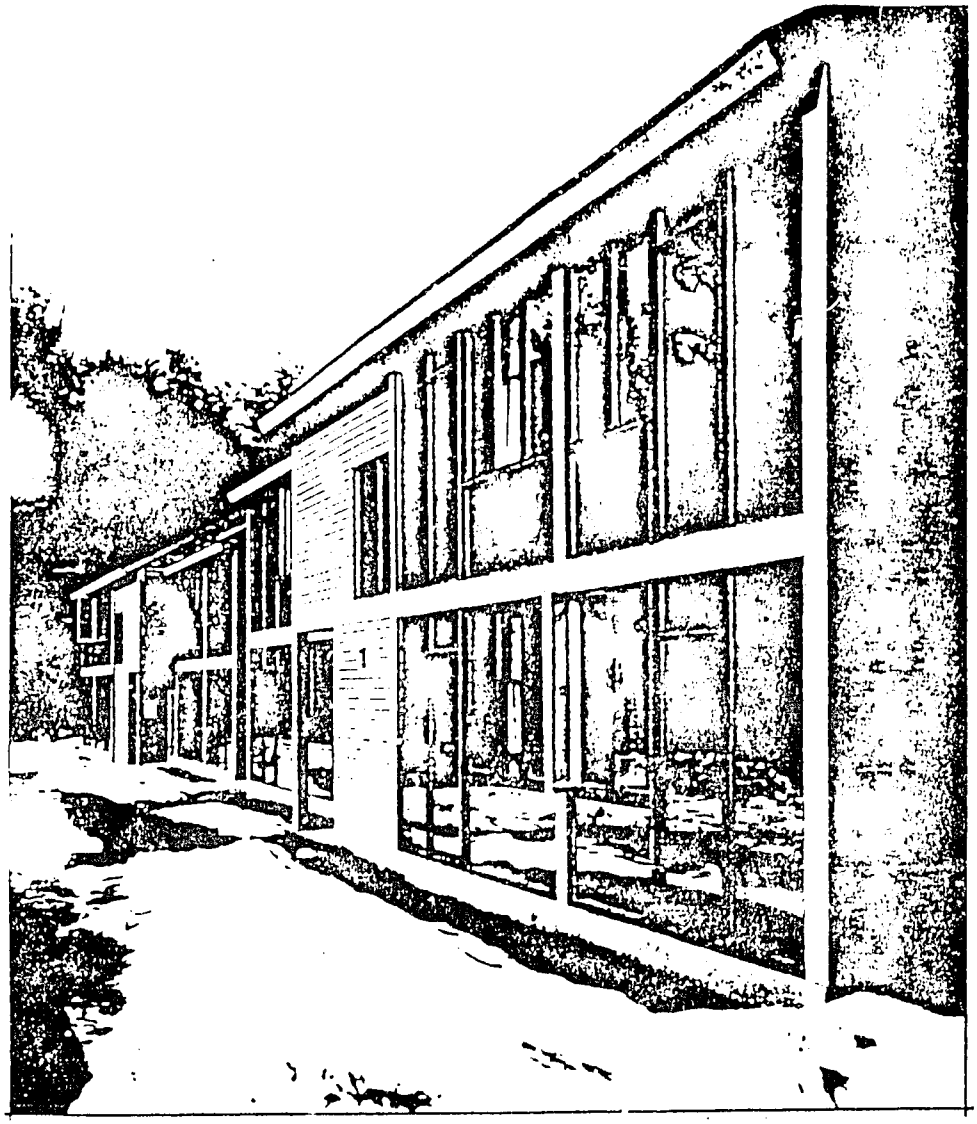
Marlene M. Hoey,
Executive Director
Braintree Housing Authority

or

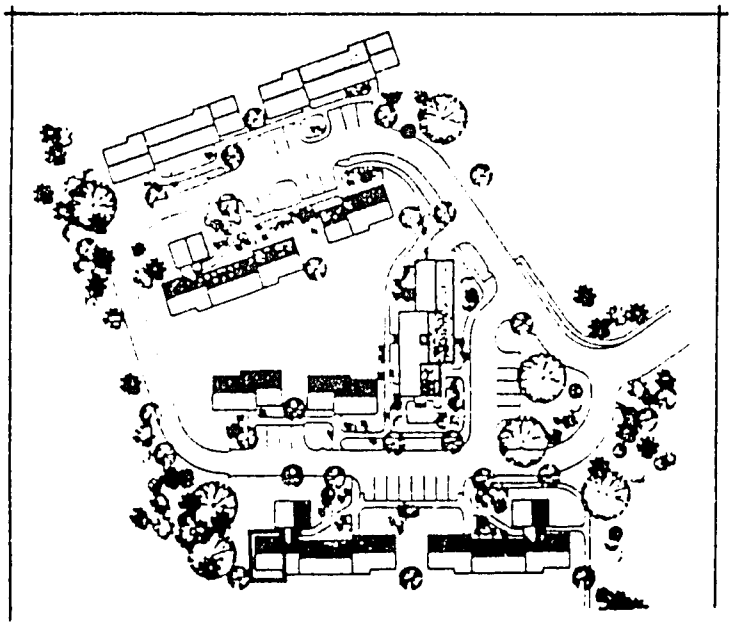
Architects.

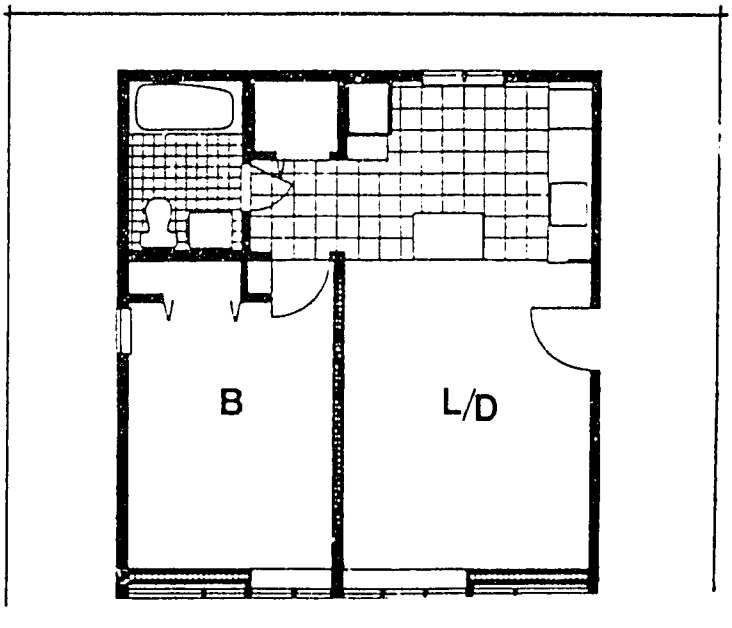


Braintree, Massachusetts (ROU)



Braintree, Massachusetts (ROU)





TECHNOLOGY AREA: Trombe wall, direct gain, and corridor sunspace.

DESIGNER: Haldeman and Goransson Associates, Inc., Architects.

LOCATION: Fall River, Massachusetts, USA

DESCRIPTION:

This project is part of Massachusett's Multi-Family Passive Solar Program and is housing for the elderly. The building is a steel frame mid-rise that occupies a semi-urban site in downtown Fall River, Massachusetts.

The building contains 54 apartments. Its east-west wing is single-loaded (having apartments on one side) with a sunspace/corridor facing south. At the east end of this wing, four apartments occupy the south side, blocking the sunspace. These aprartments use Trombe walls and direct gain windows for heat.

In addition, the building has R-25 walls, R-40 Roofs, and R-10 perimeter insulation to the footing. All windows are triple-glazed (R values are in English units).

This building is a relatively complex passive design; four different passive/hybrid systems are utilized.

The stair tower at the end of the north/south wing is a sunspace collector. Its south facade is a triple-glazed, thermal break curtain wall. When the temperature of the stair tower rises above 27°C, hot air is ducted off the stair tower and is fed through the ceiling plenums of apartments with only partial solar access. The top of each plenum is a 2.5-inch (6 cm) thick concrete floor slab and the bottom of each plenum

is a doubled gypsum board ceiling. Hot air from the sunspace warms the concrete and the heat is gradually transferred to the apartments above and below. Cool air is then returned to the bottom of the stair tower.

The west wall of the building is jogged to include both west and south-facing glazing. Even though the south-facing glazing is shaded for over half the day, it performs more efficienctly (i.e. collects more useful winter heat and less unwanted summer heat) than an equal area of west facing windows.

A total of twelve apartments have combined Trombe/direct gain systems. These walls are unvented and slatted metal overhangs help control overheating.

The corridor/sunspace provides heat for sixteen apartments. A fan circulates air through the ceiling plenum whenever the sunspace temperature rises above 32°C.

SPECIFICATIONS:

Construction: Steel frame midrise

Floor Area: 65 m^2 (Per apartment)

Solar Aperture:

- o Corridor sunspace: (Serves 16 apartments), 11 m^2 sunspace glass, 2.2 m^2 direct gain glazing, forced storage in ceiling in plenum.
- o Trombe wall/direct gain: (Serves 12 apartments), 3 m^2 direct gain glass; 3 m^2 Trombe wall glass; slatted metal overhangs. (25 cm thick concrete block for storage)
- o Jogged west facade: (Serves 16 apartments), 1.5 m^2 south facing glass.
- o Stair tower sunspace: (9 to 16 apartments), fan-forced heat storage in ceiling plenum

PERFORMANCE:

Building Heat Loss Coefficient: 68 BTU/hr-°F, 36 W/°C

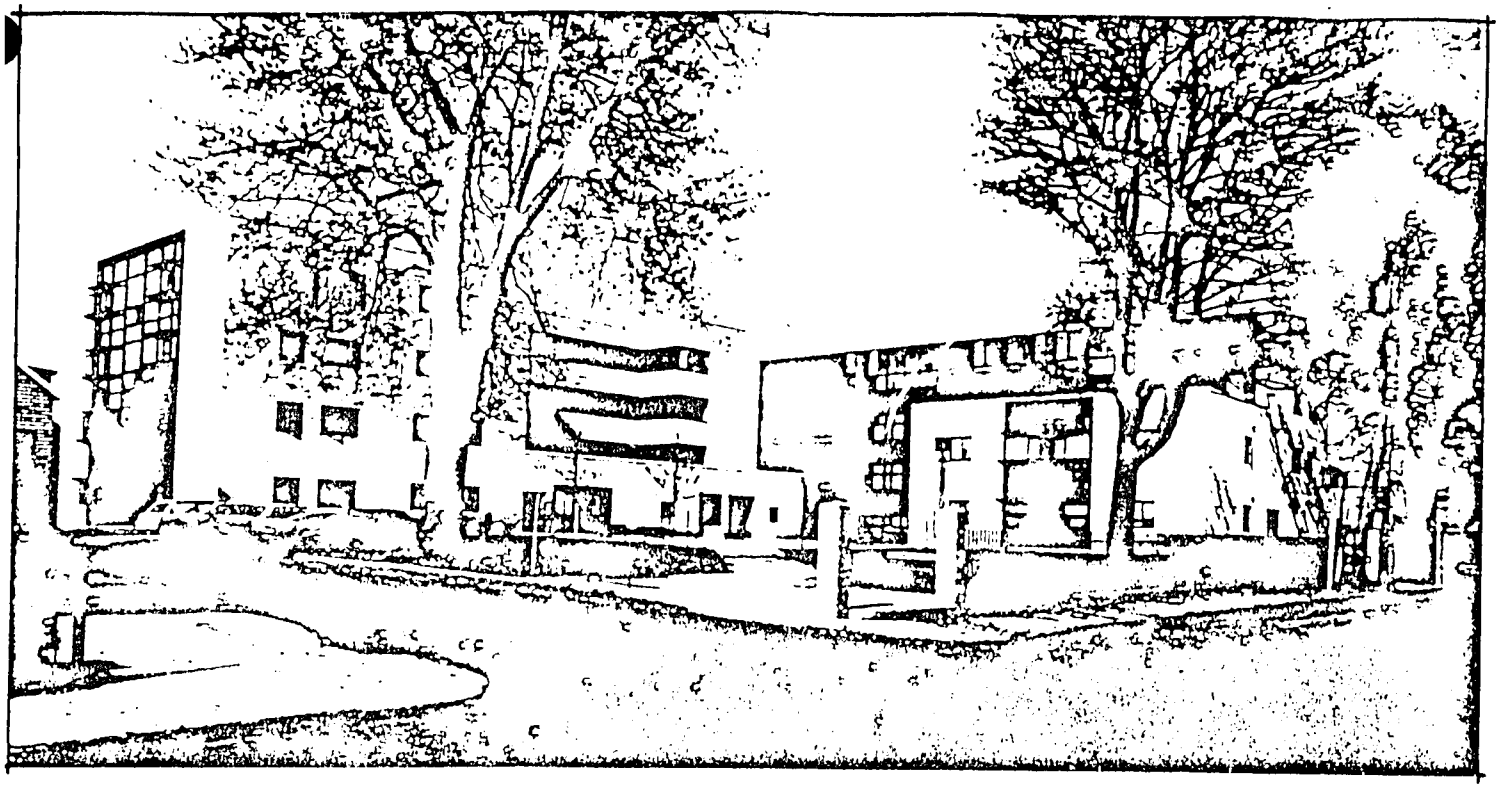
Solar Contribution: 76% if vented at 75°F, 24°C (8.3 m^2 sunspace glass; 2.2 m^2 apartment glass).

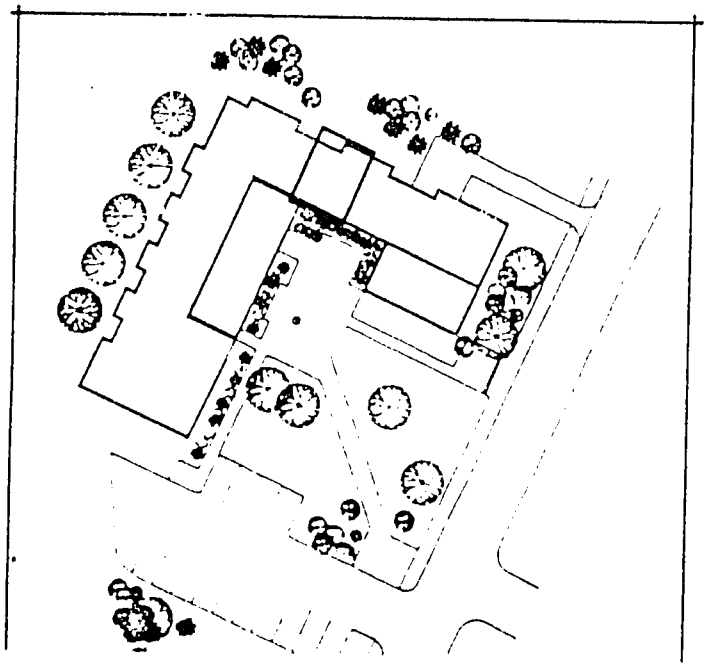
CONTACT:

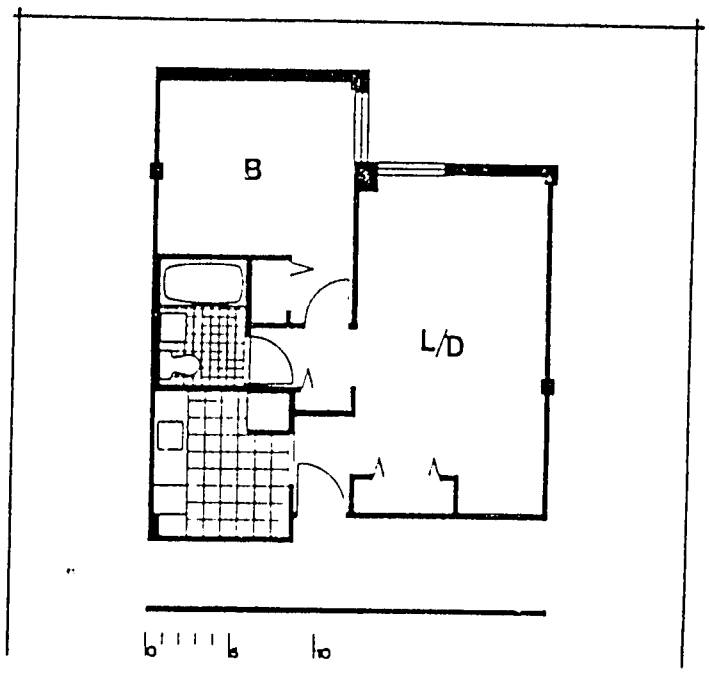
Leonel V. Garanta
Executive Director
Fall River Housing Authority
Chor Bishop Eid Apartments

or

Architects.







Fall River, Massachusetts (ROU)

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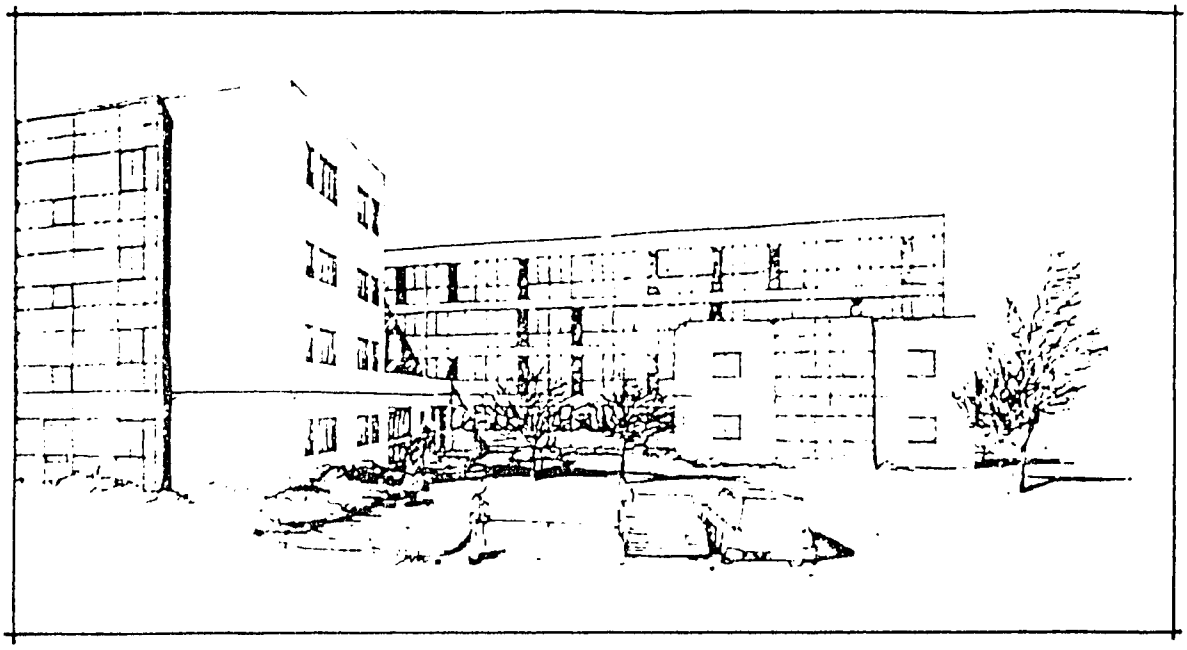
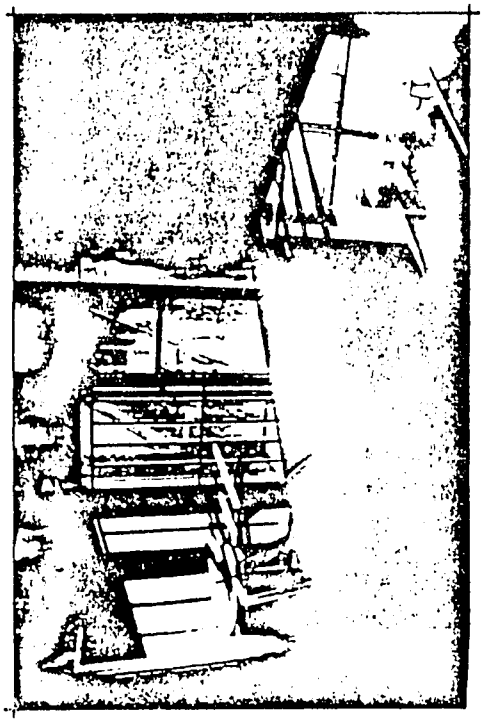
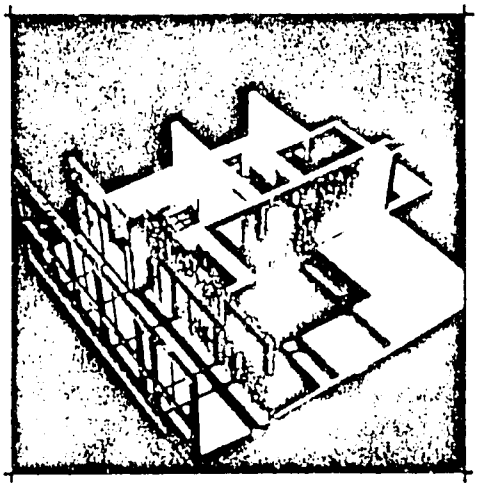






(ROU) Fall River, Massachusetts

TECHNOLOGY AREA: Direct gain, Trombe walls, and sunscoops

DESIGNER: Juster Pope Associates, Architects

LOCATION: Amherst, Massachusetts, USA

DESCRIPTION:

This project is part of Massachusett's Multi-Family Passive Solar Program, and provides congregate housing for people with severe mobile disabilities. The site is small and stretches north-south, thus limiting solar access.

The building's south-facing walls are a combination of direct gain windows and vented Trombe walls. Solar clerestories rise above the single-story roofline, funneling sunlight deep into the apartments.

In addition, the building has R-28 walls, R-40 roofs, and R-10 perimeter insulation to the footing. All windows are double-glazed. (R values are in English units.)

The Trombe walls are double-glazed and vented. Canvas covers shade the wall during the summer to prevent overheating.

The clerestories were designed to illuminate corridors, dining rooms, and kitchens, which would be otherwise deprived of solar light and heat. They are triple-glazed and are fitted with motorized insulating shades that will provide summer shading.

SPECIFICATIONS:

Floor Area: 130 m^2 (Per apartment, gross)

Solar Aperture:

- Direct Gain, 7 m^2 double-glazed glass, slab on grade storage.
- Trombe walls, 8-inch block (20 cm), 10.5 m^2 double-glazed glass, laced-on covers for summer shading.
- Clerestories, 2.2 m^2 triple-glazed glass, paddle fan to cut stratification, summer powervent.

PERFORMANCE:

Building Heat Loss Coefficient: 342 BTU/hr-°F, 180 W/°C

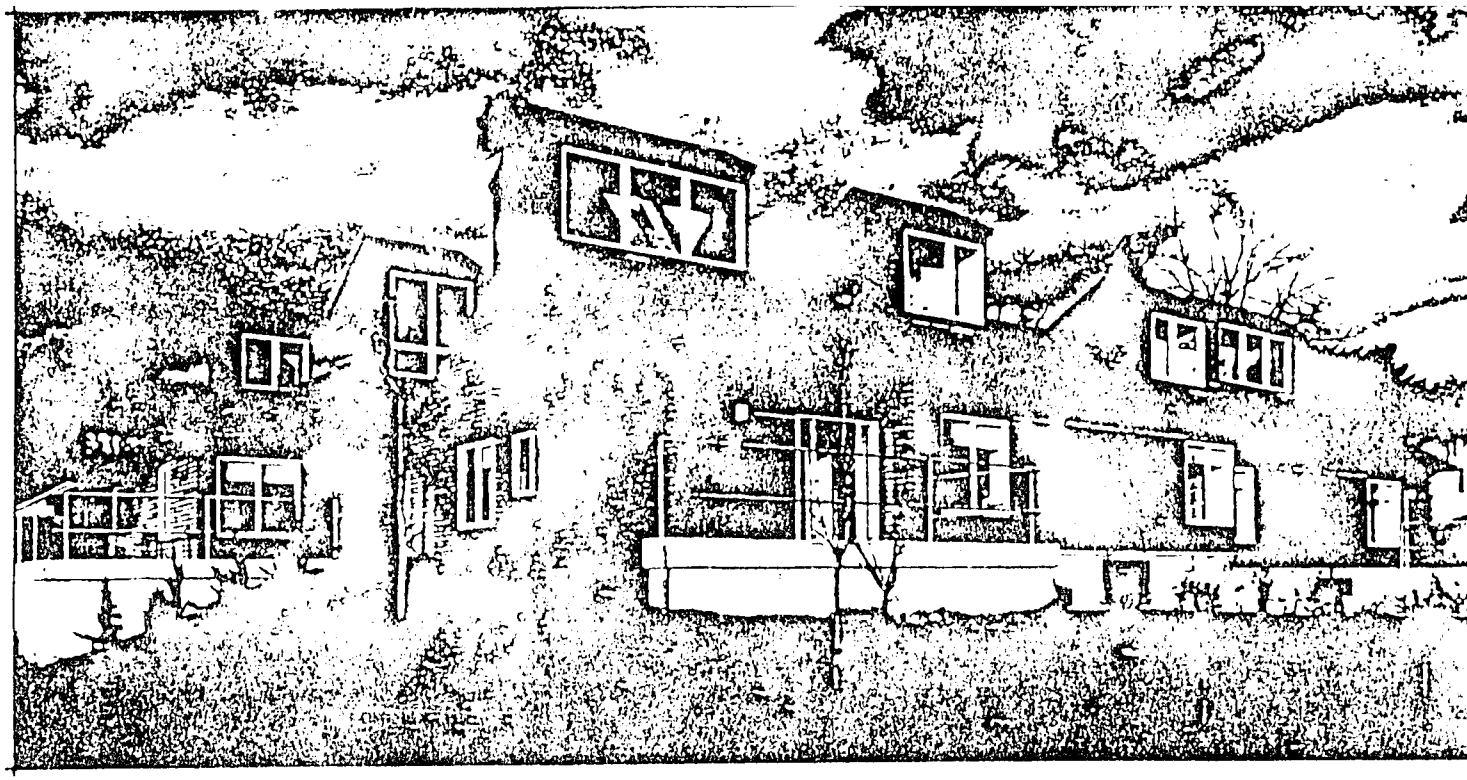
Solar Contribution: 38% if vented at 75°F, 24°C

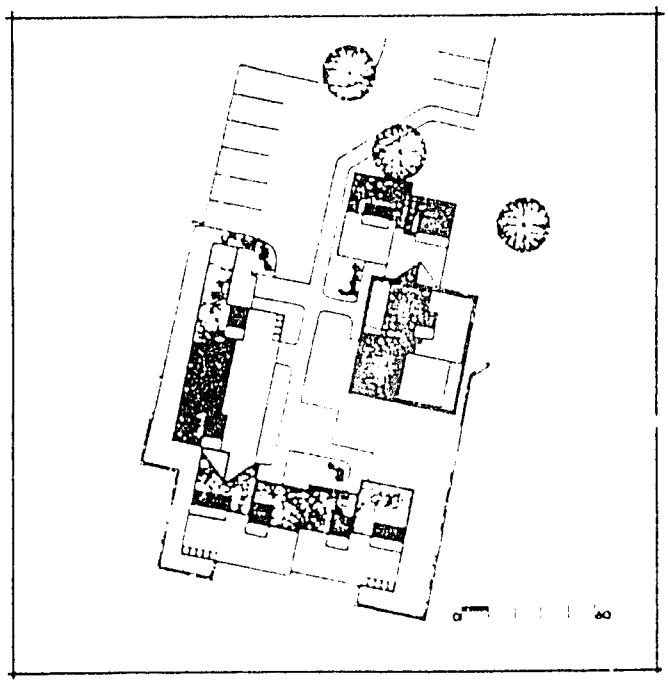
CONTACT:

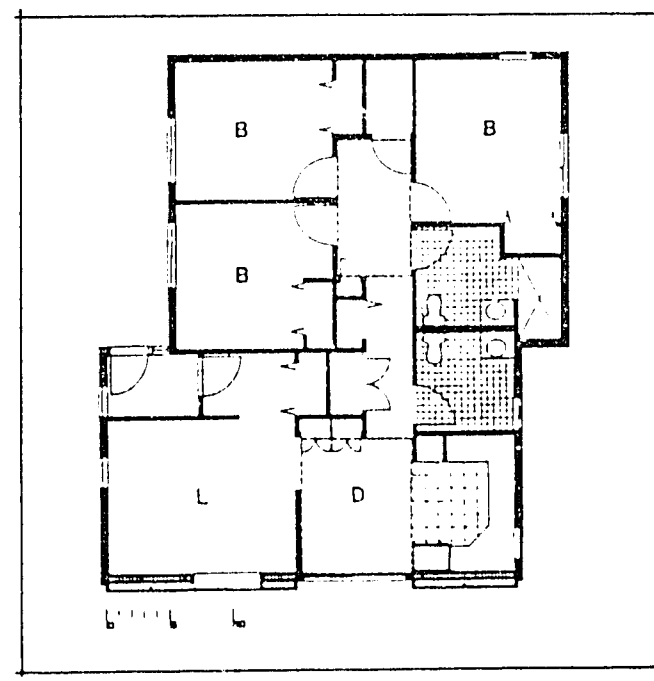
Carole E. Collins
Executive Director
Amherst Housing Authority
John Nutting Apartments

or

Architects.







Amherst, Massachusetts (ROU)

APPENDIX B

CONVERSION FACTORS

CONVERSION FACTORS AND USEFUL INFORMATION

International Metric System – Le Systeme International d'Unites (SI Units)

Base Units of the International Metric System (SI)

Quantity	Name of the Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	Kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd
Amount of substance	mole	mol

Recommended Decimal Multiples and Submultiples and the Corresponding Prefixes and Names

Factor	Prefix	Symbol	Meaning
10^{12}	tera	T	One trillion times
10^{9}	giga	G	One billion times
10^{6}	mega	M	One million times
10^{3}	kilo	k	One thousand times
10^{2}	hecto	h	One hundred times
10	deca	da	Ten times
10^{-1}	deci	d	One tenth of
10^{-2}	centi	c	One hundredth of
10^{-3}	milli	m	One thousandth of
10^{-6}	micro	μ	One millionth of
10^{-9}	nano	n	One billionth of
10^{-12}	pico	p	One trillionth of
10^{-15}	femto	f	One quadrillionth of
10^{-18}	atto	a	One quintillionth of

Some Derived Units of the International Metric System (SI)

Quantity	Name of the Unit	Symbol	Equivalence
Frequency	hertz	Hz	$1\ Hz = 1\ s^{-1}$
Force	newton	N	$1\ N = 1\ kg \times m \times s^{-2}$
Pressure	pascal	Pa	$1\ Pa = 1\ N \times m^{-2}$
Energy	joule	J	$1\ J = 1\ N \times m$
Power	watt	W	$1\ W = 1\ J \times s^{-1}$
Quantity of electricity	coulomb	C	$1\ C = 1\ A \times s$
Electrical potential or electromotive force	volt	V	$1\ V = 1\ W \times A^{-1}$
Electric resistance	ohm	Ω	$1\ \Omega = 1\ V \times A^{-1}$
Electric conductance	siemens	S	$1\ S = 1\ \Omega^{-1}$
Electric capacitance	farad	F	$1\ F = 1\ C \times V^{-1}$
Magnetic flux	weber	Wb	$1\ Wb = 1\ V \times s$
Magnetic flux density	tesla	T	$1\ T = 1\ Wb \times m^{-2}$
Inductance	henry	H	$1\ H = 1\ Wb \times A^{-1}$
Luminous flux	lumen	lm	$1\ lm = 1\ cd \times sr$
Illumination	lux	lx	$1\ lx = 1\ lx \times m^{-2}$
Wave number		υ	

Some Suggested SI Units for Air Pollution Control

Volume flow: Litres per second (l/s)

Velocity (gas flow): Meters per second (m/s)

Air to cloth ratio: Millimeters per second (mm/s)

Pressure: Kilopascals (kPa)

Conversion from ppm to g/m^3 at STP

$$T_{std} = 273.15°K$$

$$P_{std} = 1\ atm$$

$$\frac{g}{dscm} = \frac{ppm \times M.W.\left(\frac{g}{g\text{-mole}}\right)}{22.414\ \frac{liters}{g\text{-mole}} \times 10^{-3}\ \frac{m^3}{10^3 l}\left(\frac{293.15°K}{273.15°K}\right)} \times \frac{1}{1 \times 10^6\ ppm}$$

Conversion Between Different Units

We have gathered below quantities of the English and engineering systems of units that are commonly found in the literature on air pollution. Our intention is to list them in such a way that their equivalent in the MKS system of units can be found quickly. Quantities which are listed in each horizontal line are equivalent. The quantity in the middle column indicates the simplest definition or a useful equivalent of the respective quantity in the first column.

1 acre	1/640 mi^2	4.047×10^3 m^2
1 Angstrom (Å)	10^{-8} cm	10^{-10} m
1 atmosphere (atm)	1.013×10^6 dyn/cm^2	1.013×10^5 N/m^2
1 bar (b)	10^6 dyn/cm^2	10^5 N/m^2
1 barrel (bbl)	42 gal, U.S.A.	0.159 m^3
1 boiler horsepower	3.35×10^4 Btu/hr	9.810×10^3 W
1 British Thermal Unit (Btu)	252 cal	1.054×10^3 J
1 Btu/hour	1.93×10^6 erg/sec	0.293 W
1 calorie (cal)	4.184×10^{-7} erg	4.184 J
1 centimeter of mercury (cm Hg)	1.333×10^4 dyn/cm^2	1.333×10^3 N/m^2
1 cubic foot, U.S.A. (cu ft)	2.832×10^4 cm^3	2.832×10^{-2} m^3
1 dyne (dyn)	1 g-cm/sec^2	10^{-5} N
1 erg	1 g-cm^2/sec^2	10^{-7} J
1 foot, U.S.A. (ft)	30.48 cm	0.3048 m
1 foot per minute (ft/min)	1.829×10^{-2} km/hr	5.080×10^{-3} m/sec
1 gallon, U.S.A. (gal)	3.785×10^3 cm^3	3.785×10^{-3} m^3

Conversion Factors

Equivalents	Multiply	by	to obtain
Energy, Heat, and Work:			
1 Btu = 252.0 cal	Btu	252.0	cal
	cal	0.003968	Btu
1 Btu = 0.2520 kg-cal	Btu	0.2520	kg-cal
	kg-cal	3.968	Btu
1 therm = 100,000 Btu	therm	100,000	Btu
	Btu	0.00001	therm
1 Btu = 778.2 ft-lb	Btu	778.2	ft-lb
	ft-lb	0.001285	Btu
1 Btu = 1055 Joules	Btu	1055	Joules
	Joules	0.0009478	Btu
1 cal = 4.187 Joules	cal	4.187	Joules
	Joules	0.2388	cal
1 hp-hr = 2544 Btu	hp-hr	2544	Btu
	Btu	0.0003930	hp-hr
1 kwh = 3412 Btu	kwh	3412	Btu
	Btu	0.0002931	kwh
1 hp-hr = 1,980,000 ft-lb	hp-hr	1,980,000	ft-lb
	ft-lb	0.0000005051	hp-hr
1 kg-m = 7.233 ft-lb	kg-m	7.233	ft-lb
	ft-lb	0.1383	kg-m
Power and Heat Flow:			
1 kw = 1.341 hp	kw	1.341	hp
	hp	0.7457	kw
1 hp = 550 ft-lb/sec	hp	550	ft-lb/sec
	ft-lb/sec	0.001818	hp
1 hp = 42.41 Btu/min	hp	42.41	Btu/min
	Btu/min	0.02358	hp
1 Btu/sec = 1.055 kw	Btu/sec	1.055	kw
	kw	0.9478	Btu/sec
1 kw = 3412 Btu/hr	kw	3412	Btu/hr
	Btu/hr	0.0002931	kw
1 hp = 2544 Btu/hr	hp	2544	Btu/hr
	Btu/hr	0.0003930	hp
	Btu/min	0.01757	kw
	kw	56.92	Btu/min
	Btu/min	0.001	lb/hr (steam)
	lb/hr steam	0.454	kg/hr (steam)
	Mega watts	1360	kg/hr (steam)
	Boiler Hp	33,479	Btu/hr
	Boiler Hp	9,803	kw

Pressure

From \ To	mmHg	in Hg	in H_2O	ft H_2O	atm	lb/in^2	Kg/cm^2
mm Hg	1	0.03937	0.5353	0.04460	0.00132	0.01934	0.00136
in Hg	25.40	1	13.60	1.133	0.03342	0.4912	0.03453
in H_2O	1.868	0.07355	1	0.08333	0.00246	0.03613	0.00254
ft H_2O	22.42	0.8826	12	1	0.02950	0.4335	0.03048
atm	760	29.92	406.8	33.90	1	14.70	1.033
lb/in^2	51.71	2.036	27.67	2.307	0.06805	1	0.07031
Kg/cm^2	735.6	28.96	393.7	32.81	0.9678	14.22	1

Volume

From \ To	cm^3	liter	m^3	in^3	ft^3
cm^3	1	0.001	1×10^{-6}	0.06102	3.53×10^{-5}
liter	1000	1	0.001	61.02	0.03532
m^3	1×10^{-6}	1000	1	6.10×10^{-4}	35.31
in^3	16.39	0.01639	1.64×10^{-6}	1	5.79×10^{-4}
ft^3	2.83×10^{-4}	28.32	0.02832	1728	1

Temperature

°C = 5/9 (°F-32)	°F = 9/5 °C+32
°K = °C+273.2	°R = °F+459.7

Equivalents	Multiply	by	to obtain
Heat Flux:			
1 cal/hr sq cm = 3.687 Btu/hr sq ft	cal/hr sq cm	3.687	Btu/hr sq ft
	Btu/hr sq ft	0.2712	cal/hr sq cm
1 watt/sq cm = 3170 Btu/hr sq ft	watts/sq cm	3170	Btu/hr sq ft
	Btu/hr sq ft	0.0003154	watts/sq cm
Thermal Conductivity:			
$1 \frac{\text{Btu ft}}{\text{hr sq ft °F}} = 12 \frac{\text{Btu in.}}{\text{hr sq ft °F}}$	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	12	$\frac{\text{Btu in.}}{\text{hr sq ft °F}}$
	$\frac{\text{Btu in.}}{\text{hr sq ft °F}}$	0.0833	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
$1 \frac{\text{Btu ft}}{\text{hr sq ft °F}} = 14.88 \frac{\text{cal cm}}{\text{hr sq cm °C}}$	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	14.88	$\frac{\text{cal cm}}{\text{hr sq cm °C}}$
	$\frac{\text{cal cm}}{\text{hr sq cm °C}}$	0.0672	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
$1 \frac{\text{watt cm}}{\text{sq cm °C}} = 57.79 \frac{\text{Btu ft}}{\text{hr sq ft °F}}$	$\frac{\text{watts cm}}{\text{sq cm °C}}$	57.79	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$
	$\frac{\text{Btu ft}}{\text{hr sq ft °F}}$	0.01731	$\frac{\text{watts cm}}{\text{sq cm °C}}$
Heat Content:			
$1 \frac{\text{Btu}}{\text{lb}} = 0.556 \frac{\text{cal}}{\text{gm}}$	heat content in Btu/lb	0.556	heat content in cal/gm
	heat content in cal/gm	1.80	heat content in Btu/lb
$1 \frac{\text{Btu}}{\text{lb °F}} = 1 \frac{\text{cal}}{\text{gm °C}}$	specific heat in Btu/lb °F	1	specific heat cal gm °C

Useful Information

Energy equivalences of various fuels:

Bituminous coal	–	22.4×10^6 Btu/ton, 1971-1973
	–	21.9×10^6 Btu/ton, 1974
Anthracite coal	–	26.0×10^6 Btu/ton
Lignite coal	–	16.0×10^6 Btu/ton
Residual oil	–	147,000 Btu/gal
Distillate oil	–	140,000 Btu/gal
Natural gas	–	1,022 Btu/ft^3

1 lb. of water evaporated from and at 212°F equals:

0.2844 Kilowatt-hours
0.3814 Horsepower-hours
970.2 Btu

1 cubic foot air weighs 34.11 gm.

Miscellaneous Physical Constants

Avogadro's Number	6.0228×10^{23}	Molecules/gm-mole
Gas-Law Constant R	1.987	Cal/(gm-mole) (°K)
	1.987	Btu/(lb-mole) (°R)
	82.06	(cm^3) (atm)/(gm-mole) (°K)
	10.731	(ft^3) (lb) (in^2)/(lb-mole) (°R)
	0.7302	(ft^3) (atm)/(lb-mole) (°R)

Over-Rate Firing (Common Practice):

Cast iron sectional boilers	125 percent rating
Steel fire tube and brick set horizontal return tube (HRT)	150 percent rating
Scotch marine boilers (conventional type)	200 percent rating
Water tube boilers (small)	300 percent rating
Water tube boilers (large, power type)	600 percent rating

1 Sq Ft of Equivalent Direct Radiation (EDR):

= 240 Btu/hr for steam heating

= 150 Btu/hr for hot water heating (open system)

= 180 Btu/hr for hot water heating (closed system)

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Weight of O_2, N_2 and Air

		Pounds	Tons	SCF Gas
1 POUND	Oxygen Nitrogen	1.0	0 0005	12.08 13.80
1 TON	Oxygen Nitrogen	2000.0	1.0	24,160 27,605
1 SCF GAS	Oxygen Nitrogen	0.08281 0.07245	0.00004141 0.00003623	1.0

Air Density = 1.293 g/l at 1 atm 0°C
= 0.0808 lb/ft^3 at atm 32°F

Gram Mole = 22.414 liters at 0°C, 1 atm

1 lb. Mole = 359.05 ft^2 at 32°F, 1 atm

1 Boiler Horsepower:

= 33,475.3 Btu/hr heat to steam

= 34.5 lbs steam evaporated per hr from and at 212°F

= 44,633 Btu/hr fuel input for 75 percent overall efficiency

= approximately 10 sq ft of boiler heating surface (basis for boiler ratings)

= 139.4 sq ft of equivalent direct radiation

Overall Boiler Efficiency, Percent:

$$= \frac{\text{(lb steam/hr)} \times \text{(heat content of delivered steam - heat content of feed water)}}{\text{(fuel input rate)} \times \text{(gross heating value of the fuel)}} \times 100$$

Conversions – Dust Loadings in Flue Gas (Approximate)

Grains per standard cubic foot	× 1.87	=	lbs. per 1000 lbs. of flue gas
Grains per standard cubic foot	× 2.20	=	lbs. per 1,000,000 Btu input
Grains per cubic foot of 500° F flue gas	× 3.45	=	lbs. per 1000 lbs. of flue gas
Pounds per 1000 lbs. of flue gas	× 0.53	=	grains per standard cubic foot
Pounds per 1000 lbs. of flue gas	× 0.29	=	grains per cubic foot of 500° F flue gas
Pounds per 1000 lbs. of flue gas	× 1.18	=	lbs. per 1,000,000 Btu input
Pounds per 1,000,000 Btu input	× 0.45	=	grains per standard cubic foot
Pounds per 1,000,000 Btu input	× 0.85	=	lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 0 Waste	× 1.01	=	lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 1 Waste	× 1.30	=	lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 2 Waste	× 1.84	=	lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 3 Waste	× 2.80	=	lbs. per 1000 lbs. of flue gas
Pounds per 100 lbs. of Type 0 Waste	× 0.54	=	grains per standard cubic foot
Pounds per 100 lbs. of Type 1 Waste	× 0.70	=	grains per standard cubic foot
Pounds per 100 lbs. of Type 2 Waste	× 0.90	=	grains per standard cubic foot
Pounds per 100 lbs. of Type 3 Waste	× 1.50	=	grains per standard cubic foot
Pounds of flue gas per hour	× 0.22	=	standard cubic feet per minute
Standard cubic feet per minute	× 4.50	=	lbs. of flue gas per hour

NOTE:

Grains is a measure of weight; 7000 grains = 1 pound. In these Standards, all expressions of particulate emissions (dust loadings) are given with the total flue gases (products of combustion) corrected to 50 percent excess air.

All factors are based on properties of flue gas approaching those of dry air.

For ease of calculations any small differences are ignored and "corrected to 50 percent excess air" and "corrected to 12 percent CO_2" are considered equal.

Standard cubic feet is air at 70° F, and 29.92 inches of mercury.

APPENDIX C

PROPERTIES OF MATERIALS

SOLAR ABSORPTANCE OF VARIOUS MATERIALS*

(PAS-1)

Optical flat black paint	.98
Flat black paint	.95
Black lacquer	.92
Dark gray paint	.91
Black concrete	.91
Dark blue lacquer	.91
Black oil paint	.90
Stafford blue bricks	.89
Dark olive drab paint	.89
Dark brown paint	.88
Dark blue-gray paint	.88
Azure blue or dark green lacquer	.88
Brown concrete	.85
Medium brown paint	.84
Medium light brown paint	.80
Brown or green lacquer	.79
Medium rust paint	.78
Light gray oil paint	.75
Red oil paint	.74
Red bricks	.70
Uncolored concrete	.65
Moderately light buff bricks	.60
Medium dull green paint	.59
Medium orange paint	.58
Medium yellow paint	.57
Medium blue paint	.51
Medium Kelly green paint	.51
Light green paint	.47
White semi-gloss paint	.30
White gloss paint	.25
Silver paint	.25
White lacquer	.21
Polished aluminum reflector sheet	.12
Aluminized mylar film	.10
Laboratory vapor deposited coatings	.02

This table is meant to serve as a guide only. Variations in texture, tone, overcoats, pigments, binders, etc. can vary these values.

Thermal Properties of Metals and Alloys

Material	k, [Btu/(h·ft·°F)] 32°F	212°F	572°F	932°F	c [Btu/(lb$_m$·°F)] 32°F	ρ (lb$_m$/ft^3) 32°F	α (ft^2/h) 32°F
				Metals			
Aluminum	117	119	133	155	0.208	169	3.33
Bismuth	4.9	3.9	–	–	0.029	612	0.28
Copper, pure	224	218	212	207	0.091	558	4.42
Gold	169	170	–	–	0.030	1203	4.68
Iron, pure	35.8	36.6	–	–	0.104	491	0.70
Lead	20.1	19	18	–	0.030	705	0.95
Magnesium	91	92	–	–	0.232	109	3.60
Mercury	4.8	–	–	–	0.033	849	0.17
Nickel	34.5	34	32	–	0.103	555	0.60
Silver	242	238	–	–	0.056	655	6.6
Tin	36	34	–	–	0.054	456	1.46
Zinc	65	64	59	–	0.091	446	1.60
				Alloys			
Admiralty metal	65	64					
Brass, 70% Cu, 30% Zn	56	60	66	–	0.092	532	1.14
Bronze, 75% Cu, 25% Sn	15	–	–	–	0.082	540	0.34
Cast iron							
Plain	33	31.8	27.7	24.8	0.11	474	0.63
Alloy	30	28.3	27	–	0.10	455	0.66
Constantan, 60% Cu, 40% Ni	12.4	12.8	–	–	0.10	557	0.22
18-8 Stainless steel,							
Type 304	8.0	9.4	10.9	12.4	0.11	488	0.15
Type 347	8.0	9.3	11.0	12.8	0.11	488	0.15
Steel, mild, 1% C	26.5	26	25	22	0.11	490	0.49

Thermal Properties of Some Nonmetals

Material	Average temperature (°F)	k [Btu/(h·ft·°F)]	c [Btu/(lb$_m$·°F)]	ρ (lb$_m$/ft^3)	α (ft^2/h)
		Insulating materials			
Asbestos	32	0.087	0.25	36	~0.01
	392	0.12	–	36	~0.01
Cork	86	0.025	0.04	10	~0.006
Cotton fabric	200	0.046			
Diatomaceous earth, powdered	100	0.030	0.21	14	~0.01
	300	0.036	–		
	600	0.046	–		
Molded pipe covering	400	0.051	–	26	
	1600	0.088	–		
Glass wool					
Fine	20	0.022	–		
	100	0.031	–	1.5	
	200	0.043	–		
Packed	20	0.016	–		
	100	0.022	–	6.0	
	200	0.029	–		
Hair felt	100	0.027	–	8.2	
Kaolin insulating brick	932	0.15	–	27	
	2102	0.26	–		

(KRE-3)

Thermal Properties of Some Nonmetals (*continued*)

Material	Average temperature (°F)	k [Btu/(h·ft·°F)]	c [Btu/(lb$_m$·°F)]	ρ (lb$_m$/ft^3)	α (ft^2/h)
Kaolin insulating firebrick	392	0.05	–	19	
	1400	0.11	–		
Magnesia, 85%	32	0.032	–	17	
	200	0.037	–	17	
Rock wool	20	0.017	–	8	
	200	0.030	–		
Rubber	32	0.087	0.48	75	0.0024
		Building materials			
Brick					
Fire clay	392	0.58	0.20	144	0.02
	1832	0.95			
Masonry	70	0.38	0.20	106	0.018
Zirconia	392	0.84	–	304	
	1832	1.13	–		
Chrome brick	392	0.82	–	246	
	1832	0.96	–		
Concrete					
Stone	~70	0.54	0.20	144	0.019
10% moisture	~70	0.70	–	140	~0.025
Glass, window	~70	~0.45	0.2	170	0.013
Limestone, dry	70	0.40	0.22	105	0.017
Sand					
Dry	68	0.20	–	95	
10% water	68	0.60	–	100	
Soil					
Dry	70	~0.20	0.44	–	~0.01
Wet	70	~1.5	–	–	~0.03
Wood					
Oak ⊥ to grain*	70	0.12	0.57	51	0.0041
∥ to grain	70	0.20	0.57	51	0.0069
Pine ⊥ to grain	70	0.06	0.67	31	0.0029
∥ to grain	70	0.14	0.67	31	0.0067
Ice	32	1.28	0.46	57	0.048

Properties of Liquids

Name or Description	Specific Heat (Cp)		Specific Gravity or Density (ρ)		Thermal Conductivity*	
	Btu/lb (deg F)	Temp F	lb/ft³	Temp F	k	Temp F
Acetaldehyde			48.9	64.4		
Acetic acid	0.522	79–203	65.49	68	0.099	68
Acetone	0.514	37–73	49.4	68	0.102	86
Alcohol-ethyl	0.680	32–208	49.27	68	0.105	68
Alcohol-methyl	0.601	59–68	49.40	68	0.124	68
Allyl alcohol	0.655	70–205	53.31	68	0.104	77–86
Ammonia	1.099	32	43.50	−50	0.29	5–86
n-Amyl alcohol			51.06	59	0.094	86
Aniline	0.512	46–180	63.77	68	0.100	32–68
Benzene	0.412	68	54.9	68	0.085	68
Bromine	0.107	68	194.7	68		
n-Butryic acid	0.515	68	60.2	68	0.094	54
n-Butyl alcohol	0.563	68	50.6	68	0.089	68
Calcium chloride brine (20% by wt)	0.744	68	73.8	68	0.332	68
Carbon disulfide	0.240	68	78.9	68	0.093	86
Carbon tetrachloride	0.201	68	99.5	68	0.062	68
Chloroform	0.234	68	92.96	68	0.075	68
Decane-n	0.50	68	45.6	68	0.086	68
Ethyl acetate	0.468	68	52.3	68	0.101	68
Ethyl chloride	0.368	32	56.05	68	0.179	33.6

Name or Description	Specific Heat (Cp)		Specific Gravity or Density (ρ)		Thermal Conductivity*	
	Btu/lb (deg F)	Temp F	lb/ft³	Temp F	k	Temp F
Ethyl ether-	0.541	68	44.61	68	0.081	68
Ethyl iodide	0.368	32	120.35	68	0.214	86
Ethylene bromide	0.174	68	136.05	68		
Ethylene chloride	0.301	68	77.10	68		
Ethylene glycol			69.22	68	0.100	68
Formic acid	0.526	68	76.16	68	0.104	33
Glycerine (glycerol)			78.72	68	0.113	68
Heptane	0.532	68	42.7	68	0.0741	68
Hexane	0.538	68	41.1	68	0.0720	68
Hydrogen chloride			74.6	b.p.		
Isobutyl alcohol	0.116	68	50.0	68	0.082	68
Kerosine	0.50	68	51.2	68	0.086	68
Linseed oil			58	68		
Methyl acetate	0.468	68	60.6	68	0.093	68
Methyl iodide			142	68		
Naphthalene	0.402	m.p.	60.9	m.p.		
Nitric acid	0.42	68	94.45	68	0.16	68
Nitrobenzene	0.348	68	75.2	68	0.96	68
Octane	0.51	68	43.9	68	0.084	68
n-Petane	0.558	68	39.1	68	0.066	68
Petroleum	0.4–0.6	68	40–66	68		
Propionic acid	0.473	68	61.9	68	0.100	54
Sodium chloride brine						
20% by wt	0.745	68	71.8	68	0.337	68
10% by wt	0.865	68	66.9	68	0.343	68
Sodium hyroxide and water						
15% by wt	0.864	68	72.4	68		
Sulfuric acid and water						
100% by wt	0.335	68	114.4	68		
95% by wt	0.635	68	114.6	68		
90% by wt	0.39	68	113.4	68	0.22	68
Toluene ($C_6H_5CH_3$)	0.404	68	54.1	68	0.090	68
Turpentine	0.42	68	53.9	68	0.073	68
Water	0.999	68	62.32	68	0.348	68
Xylene [$C_6H_4(CH_3)_2$]						
Meta	0.400	68	54.1	68	0.90	68
Ortho	0.411	68	55.0	68	0.90	
Para	0.393	68	53.8	68		
Zinc sulfate and water						
10% by wt	0.90	68	69.2	68	0.337	68
1% by wt	0.80	68	63.0	68	0.346	68

(MAZ)

Glazing: Physical Properties

	Thermal Expansion	Ease of Handling	Weather-ability	Estimated Lifetime	Shading Coef.
GLASS					
Single Glazed Float Glass	.47	P	E	25+	1.0
Double Glazed Float Glass	.47	P	E	25+	.79 -.90
ACRYLIC					
Plexiglas (Rohm & Haas)	4.10	E	E	10-20	
Lucite (Du Pont)	3.90	E	E	10-20	
Exolite (CY/RO)	4.00	E	E	10-20	
POLYCARBONATE					
Lexan (G.E.)	3.75	E	F	15-17	
Tuffack Twinwall (Rohm & Haas)	3.30	E	F	5-7	
Cyrolon SDP (CY/RO)	4.00	E	F		.83
FIBERGLASS REINFORCED POLYESTER					
Lascolite (Lasco Industries)	1.60	VG	G	10-20	
Filon w/Tedlar (Vistron Corp.)	2.30	VG	G	10-20	
Sunlite Premium II (Kalwall)	1.36	E	G	20	
POLYESTER FILM					
Mylar Type W (Du Pont)	1.50	F	F	4	
Flexiguard(3M)		F	G	10	
POLYETHYLENE FILM					
Monsanto 602 (Monsanto)		F	P	1	
Teflon (Du Pont)	30.00	P	E	25	
POLYVINYL FLUORIDE FILM					
Tedlar (Du Pont)	2.80	F	E	10-20	

(PAS)

Glazing: Physical Properties

	Thickness	U-Value	Solar Trans.	Infrared Trans.	Maximum Operating Temperature
GLASS					
Single Glazed Float Glass	.090 -.125	1.13	.91	.01	400
Double Glazed Float Glass	.625	.52 -.65	.77 -.85		
ACRYLIC					
Plexiglas (Rohm & Haas)	.125	1.06	.90	.02	180-200
Lucite (Du Pont)	.125	1.06	.92	.02	180-200
Axolite (CY/RO)	.630	.58	.83	.02	160
POLYCARBONATE					
Lexan (G.E.)	.125	1.05	.81 -.89	.02	250-270
Suffack Twinwall (Rohm & Haas)	.220	.62	.77		195
Tyrolon SDP (CY/RO)	.630	.58	.74		240
FIBERGLASS REINFORCED POLYESTER					
Lascolite (Lasco Industries)	varies	.73	.86		200-300
Filon w/Tedlar (Vistron Corp.)	varies	.95	.86		200-300
Sunlite Premium II (Kalwall)	.040	.55	.87	.02	200-300
POLYESTER FILM					
Mylar Type W (Du Pont)	.003 -.014	1.05	.85	.16 -.32	350
Flexiguard(3M)	.007		.89	.095	275
POLYETHYLENE FILM					
Monsanto 602 (Monsanto)	.004		.85	.70	140
Teflon (Du Pont)	.001		.96	.57	300
POLYVINYL FLUORIDE FILM					
Tedlar (Du Pont)	.004		.95	.30	225

(PAS)

Material[a]	Nominal density (lb/ft³)	Temperature limitation (°F)	Mean temperature thermal conductivity °F	(Btu·in)/(h·ft²·°F)[b]	Federal specification compliance	Producer	Standard sizes (variable)	Cost[c] ($/bd ft)
					Mineral wool			
Insulation								
No. 10	10.0	1200	200 350 500	0.26 0.32 0.375	HH-I-558 B, form A, class 4	Forty-Eight Insulations	2 ft × 4 ft (board) THK: 1–3 in (¼ in increments)	0.125–0.14 (dist)[d] Carload: 30,000 bd ft
LTR	8.0	1000	200 350 500	0.27 0.32 0.385	HH-I-558 B form A, class 4	Forty-Eight Insulations	2 ft × 4 ft (board) THK: 1–4 in (¼ in increments)	0.105–0.115 (dist) Carload: 30,000 bd ft
I-T	6.0	550	200 350 500	0.27 0.34 0.45	HH-I-558 B form A, class 3	Forty-Eight Insulations	2 ft × 4 ft (board) THK: 1–4 in (¼ in increments)	0.095–0.10 (dist) Carload: 30,000 bd ft
MT-board								
MT-10	10.0	1050	200 350 500	0.25 0.333 0.445	HH-I-558 B form A, class 1, 2, 3	Eagle-Picher	2 ft × 4 ft (board) THK: 1–3 in (¼ in increments)	0.13–0.14 (dist) Carload: 36,000 bd ft
MT-8	8.0	1050	200 350 500	0.255 0.350 0.470	HH-I-558 B form A, class 1, 2, 3	Eagle-Picher	2 ft × 4 ft (board) THK: 1–4 in (¼ in increments)	0.107–0.12 (dist) Carload: 36,000 bd ft
MT-6	6.0	1050	200 350 500	0.270 0.373 0.495	HH-I-558 B form A, class 1, 2, 3	Eagle-Picher	2 ft × 4 ft (board) THK: 1–4 in (¼ in increments)	0.085–0.10 (dist) Carload: 36,000 bd ft
					Industrial felt[e]			
Thermafiber								
SF-234	8.0	1000	200 350 500	0.27 0.36 0.48	HH-I-558 B form A, class 1, 2, 3	United States Gypsum	THK: 1–2 in (N.I.) Length: 60 in THK: 1–2½ in (Ind.) Length: 48 in	0.131 (dist) 7,000–38,000 bd ft
SF-240	6.0	1000	200 350 500	0.27 0.37 0.50	HH-I-558 B form A, class 1, 2, 3	United States Gypsum	THK: 1–2½ in (Tex.) Length: 90 in THK: 1–3½ in (Ind.) Length: 48 in	0.095–0.113 (dist) 7,000–38,000 bd ft
SF-250	4.5	800	200 350 500	0.29 0.415 0.55	HH-I-558 B form A, class 1, 2	United States Gypsum	THK: 1–4 in (Tex.) Length: 90 in THK: 1–5 in (Ind.) Length: 48 in	0.081–0.10 (dist) 7,000–38,000 bd ft
SF-252	4.0	800	200 350 500	0.30 0.435 0.59	HH-I-558 B form A, class 1, 2	United States Gypsum	THK: 1–4 in (Tex.) Length: 90 in THK: 1–5 in (Ind.) Length: 48 in	0.07–0.087 (dist) 7,000–38,000 bd ft
SF-256	3.5	600	200 350 500	0.33 0.47 0.62	HH-I-558 B form A, class 1, 2	United States Gypsum	THK: 1–4 in (Tex.) Length: 90 in THK: 1–6 in (Ind.) Length: 48 in	0.066–0.084 (dist) 7,000–38,000 bd ft
SF-260	3.0	500	200 350 500	0.35 0.50 0.65	HH-I-558 B form A, class 1, 2	United States Gypsum	THK: 1–4 in (Tex.) Length: 90 in THK: 1–6 in (Ind.) Length: 48 in	0.064–0.82 (dist) 7,000–38,000 bd ft
SF-270	2.5	400	200 350 500	0.39 0.56 –	No data provided	United States Gypsum	THK: 1–4 in (Tex.) Length: 90 in THK: 1–5 in (Ind.) Length: 48 in	0.06–0.078 (dist) 7,000–38,000 bd ft

(KRE-3)

Insulation Data (*continued*)

Material[a]	Nominal density (lb/ft³)	Temperature limitation (°F)	Mean temperature thermal conductivity °F	Mean temperature thermal conductivity (Btu·in)/(h·ft²·°F)[b]	Federal specification compliance	Producer	Standard sizes (variable)	Cost[c] ($/bd ft)
				Foamglas and Fiberglas insulation[f]				
Foamglas[g]	8.5	600	200 350 500	0.46[i] 0.58 0.74	HH-I-551 D (Fed) ASTMC 552-73	Pittsburgh Corning	1 ft × 1.5 ft (board) 1½ ft × 2 ft (board) THK: 1½–4 in (½ in inc)	0.22–0.24 (Corning)[h] Carload: 36,000 bd ft
Fiberglas[i]								
701	1.6	450	200 350	0.33 0.51	HH-I-558 B form A, class 1 HH-I-558 B, type 7 form B, class 7	Owens-Corning Fiberglas	2 ft × 4 ft (board) THK: 1½–4 in (½ in inc)	0.07–0.08 (dist) Carload: 30,000– 35,000 bd ft
703	3.0	450	200 350	0.30 0.41	HH-I-558 B form A, class 1, 2	Owens-Corning Fiberglas	2 ft × 4 ft (board) THK: 1–2 in (½ in inc)	0.14–0.15 (dist) Carload: 30,000– 35,000 bd ft
705	6.0	450	200 350	0.27 0.38	HH-I-558 B form A, class 1, 2	Owens-Corning Fiberglas	2 ft × 4 ft (board) THK: 1–2 in (½ in inc)	0.25–0.27 (dist) Carload: 30,000– 35,000 bd ft
Thermal insulating wool[j]								
Type I	1.25	1000	200 350 500	0.41 0.65 0.85	HH-I-558 B form B, type 1, class 6	Owens-Corning Fiberglas	Rolls Width: 2 or 3 ft THK: 2, 3, 4 in Length: 76, 52, 38 ft	0.04–0.06 (Corning) Half carload: 35,000 bd ft
Type II	2.4	1000	200 350 500	0.30[j] 0.44 0.60	HH-I-558 B form B, type 1, class 7, 8	Owens-Corning Fiberglas	2 ft × 8 ft 2 ft × 4 ft (board) THK: 1–3 in (½ in inc)	0.08–0.09 (Corning) 0.14–0.15 (dist) Carload: 35,000 bd ft
IS board[i]	4.0	800	200 350 500	0.30 0.44 0.61	HH-I-558 B form A class 3	Owens-Corning Fiberglas	2 ft × 4 ft, 3 ft × 4 ft 4 ft × 8 ft (board) THK: 1–6 in (½ in inc)	0.10–0.13 (Corning) 0.18–0.20 (dist) Carload: 35,000 bd ft

[a] All insulations listed will not cause or aggravate corrosion and will absorb less than 1% moisture. All insulations listed appear as semirigid board composed of silica base refractory fibers bonded with special binders for service in indicated temperature ranges.

[b] Units are consistently employed within the insulation industry. Conductivity measurements consider a test specimen 1 in thick and 1 ft² in normal area.

[c] Cost data current through October 30, 1975. Costs are based on carload purchases and include freight where necessary to move insulation to Houston.

[d] Cost from Houston distributors noted by (dist).

[e] Industrial felt is preformed mineral fiber felt, which will not cause or sustain corrosion. It absorbs less than 1% moisture by weight and is rated noncombustible. Insulation to be ordered in varying thicknesses and lengths; standard width of 24 in employed (see column 8).

[f] All codes in specification compliance column are federal specifications unless otherwise noted.

[g] Foamglas is an impermeable, incombustible, rigid insulation composed of completely sealed glass cells with no binder material. Its rigid form may allow for Foamglas being implemented as the collector box.

[h] Cost from Corning Houston warehouse noted by (Corning); cost from Houston distributor noted by (dist).

[i] Insulations are made of inorganic glass fibers preformed into semirigid to rigid rectangular boards (TIW I in blankets). Insulations will not accelerate or cause corrosion and will absorb less than 1% moisture (by volume).

[j] The units of the mean temperature thermal conductivity for Foamglas and Fiberglas insulation are (Btu·in)/(h·ft·°F).

(KRE-3)

Time Lag of Heat Flow through Walls and Roofs

Construction			Time Lag (hours)
Walls:			
Brick:	4-inch		2.3
	8-inch		5.5
	12-inch		8.0
Concrete, solid or block:		2-inch	1.0
		4-inch	2.6
		6-inch	3.8
		8-inch	5.1
		10-inch	6.4
		12-inch	7.6
Glass:	window		0.0
	block[1]		2.0
Stone:	8-inch		5.4
	12-inch		8.0
Frame:	wood, plaster/no insulation		0.8
		insulated	3.0
	brick veneer, plaster/no insulation		3.0
		insulated	5.5
Roofs:[2]			
Light construction			0.7 to 1.3
Medium construction			1.4 to 2.4
Heavy construction			2.5 to 5.0

NOTES: 1. Glass block transmits, in addition to delayed conducted load, an instantaneous sun load which for smooth-faced block is about 0.45 times that of plain window glass, and for diffusing block about 25% of plain glass transmission.

2. Where applicable, the lags for wall materials can be used for roofs. Lags of materials added to a built-up structure are additive.

(MAZ)

APPENDIX D

SUNPATH DIAGRAMS

TAKEN FROM (KRE-3)

A description of the method for calculating true solar time is given together with meteorological charts for computing solar altitude and azimuth angles. (*a*) Description of method; (*b*) chart, 25°N; (*c*) chart, 30°N; (*d*) chart, 35°N; (*e*) chart, 40°N; (*f*) chart, 45°N; (*g*) chart, 50°N.

(*a*) Description of the Method

The altitude and azimuth of the sun are given by

$$\sin a = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \tag{1}$$

and

$$\sin \alpha = -\frac{\cos \delta \sin h}{\cos a} \tag{2}$$

where a = altitude of the sun (angular elevation above the horizon)
ϕ = latitude of the observer
δ = declination of the sun
h = hour angle of sun (angular distance from the meridian of the observer)
α = azimuth of the sun (measured eastward from north)

From Eqs. (1) and (2) it can be seen that the altitude and azimuth of the sun are functions of the latitude of the observer, the time of day (hour angle), and the date (declination).

Description and charts are based on the *Smithsonian Meteorological Tables* with permission from the Smithsonian Institute, Washington, D.C.

A series of charts are used, one for each 5° of latitude (except 5°, 15°, 75°, and 85°) giving the altitude and azimuth of the sun as a function of the true solar time and the declination of the sun in a form originally suggested by Hand.* Linear interpolation for intermediate latitudes will give results within the accuracy to which the charts can be read.

On these charts, a point corresponding to the projected position of the sun is determined from the heavy lines corresponding to declination and solar time.

To find the solar altitude and azimuth:

1 Select the chart or charts appropriate to the latitude.

2 Find the solar declination δ corresponding to the date.

3 Determine the *true solar time* as follows:

(a) To the *local standard time* (zone time) add 4 minutes for each degree of longitude by which the station is east of the standard meridian or subtract 4 minutes for each degree west of the standard meridian to get the *local mean solar time*.

(b) To the local mean solar time add algebraically the equation of time; the sum is the *true solar time*.

4 Read the required altitude and azimuth at the point determined by the declination and the true solar time. Interpolate linearly between two charts for intermediate latitudes.

It should be emphasized that the solar altitude determined from these charts is the true geometric position of the center of the sun. At low solar elevations, terrestrial refraction may considerably alter the apparent position of sun. Under average atmospheric refraction the sun will appear on the horizon when it actually is about 34′ below the horizon; the effect of refraction decreases rapidly with increasing solar elevation. Since sunset or sunrise is defined as the time when the upper limb of the sun appears on the horizon, and the semidiameter of the sun is 16′, sunset or sunrise occurs under average atmospheric refraction when the sun is 50′ below the horizon. In polar regions especially, unusual atmospheric refraction can produce considerable variation in the time of sunset or sunrise.

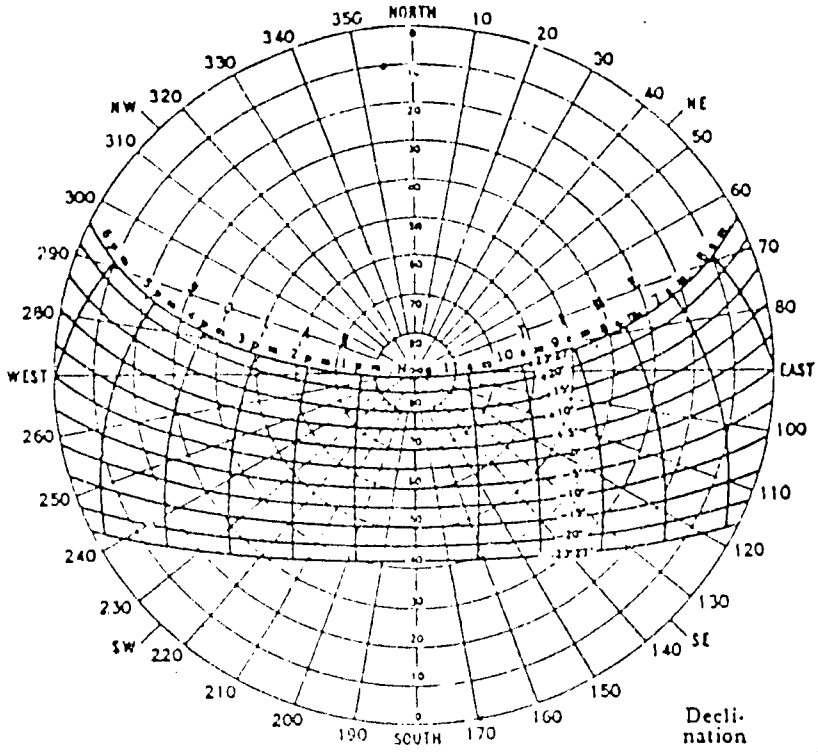
The 90°N chart is included for interpolation; the azimuths lose their directional significance at the pole.

To compute solar altitude and azimuth for southern latitudes, change the sign of the solar declination and proceed as above. The resulting azimuths will indicate angular distance from *south* (measured eastward) rather than from north.†

*I. F. Hand, *Heating and Ventilating*, vol. 45, p. 86, 1948.

†Note that the angular convention used by the Smithsonian differs from that used in Chap. 2 and elsewhere in this book.

Chart for 25° N



Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22

Chart for 30° N

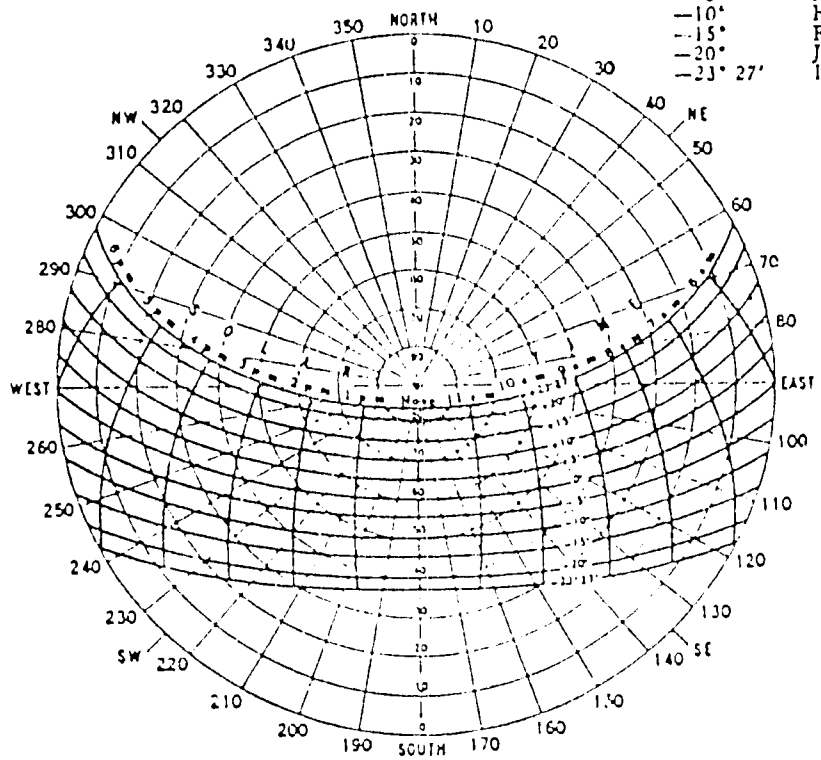
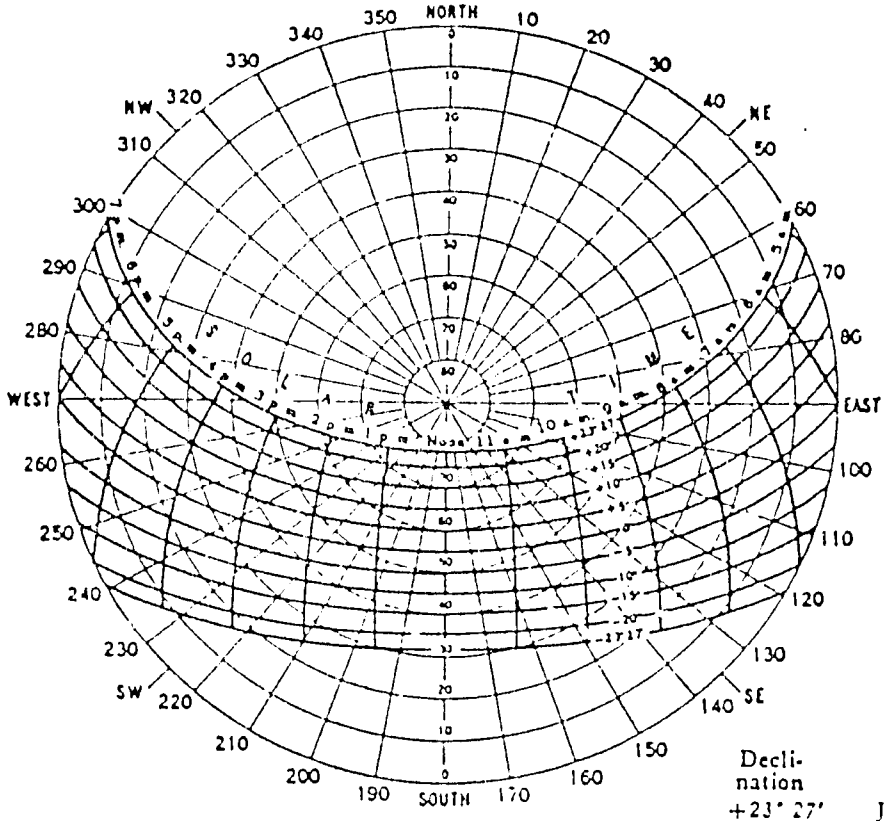


Chart for 35° N



Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22

APPENDIX E

SPACE CONDITIONING AND PERCEIVED HUMAN COMFORT

TAKEN FROM (ALT)

SPACE CONDITIONING AND PERCEIVED HUMAN COMFORT

The important factors involved in space conditioning systems include:

1. Temperature control
2. Humidity control
3. Air movement and circulation
4. Air filtering, cleaning and purification.

Complete space conditioning systems provide control of the above factors for all outdoor weather conditions encountered both summer and winter seasons. A complete system must heat or cool the air, increase or decrease the humidity, control air movement, and clean the air.

Air

Because conditioning deals with air, it is important that the structure and the properties of air be thoroughly understood.

The atmosphere surrounding the earth is reported to be about 400 miles thick (644 km). The atmosphere is divided into several layers: the ionosphere, the extreme outer portion of the atmosphere; the stratosphere, between 50,000 ft (15.3 km) and up to 200 miles (322 km); and the layer between sea level and 50,000 feet (15.3 km). We are most interested in this last layer closest to the earth's surface.

The air in this layer consists of a mixture of gases. Each of these gases behaves as though it alone occupied the space (Dalton's Law). The mixture is composed of gases listed in Exhibit E-1.

Because oxygen (O_2) is a heavier gas as compared to other constitutents in air, it has a higher percentage by weight than by volume. Hydrogen (H_2) is a very light gas, and it therefore does not appear in the weight percentage but is shown in the volume column.

		DRY AIR		AVERAGE AIR	
Name	Chemical Symbol	Amount by Weight %	Amount by Volume %	Amount by Weight %	Amount by Volume %
Nitrogen	N_2	75.47	78.03		
Oxygen	O_2	23.19	20.99		
Carbon dioxide	CO_2	.04	.03		
Hydrogen	H_2	.00	.01		
Water	H_2O			X*	X*
Dust				X*	X*
Rare Gases		1.30	.94		

*Variable

Table showing the amount of the various gases and substances that make up normal air.

EXHIBIT E-1

(ALT)

Amounts of water and dust (all foreign bodies) are so variable in the air that they cannot be given any definite value in a table. However, these two substances in the air are of considerable importance in air conditioning (heating and cooling).

Water exists in air under all conditions of temperature. It is in the vaporous form. It is present in the air even at temperatures below freezing, because it behaves as though it occupied the space alone, and therefore it is operating under extremely low pressures. For example, at 0.013 in Hg (0.33 torr, 44 Pa) (very close to a perfect vacuum), steam can be made at -20°F (-29°C), and at 100°F (38°C) the pressure in 1.9 in. Hg (48 torr, 6399 Pa). The amount of water in air is relatively small. For example, air at 72°F (22°C) and one half saturated with water vapor has 58 grains of water for each pound dry air (8.3 g/kg dry air). As 7000 grains are equal one pound, it follows that water vapor accounts for approximately less than one percent of the air.

Impurities in air come in a great variety of forms. Some of the different items which make up these impurities are:

1. Dust (solid particles 1 to 150 microns in diameter)
2. Fumes (0.2 to 1 micron in diameter)
3. Smoke (less than 0.3 microns in diameter)
4. Bacteria

Air has a comfort effect, a health effect, and a psychological or emotional effect on human beings. Therefore, effective air conditioning will become more and more important.

Air is practically invisible, but nevertheless it has weight, inertia, and density. It presses against the earth at sea level with an absolute pressure of 14.7 psi (101.3 kPa). It has a density of .0725 lbs/ft^3 (11.6 kg/m^3). Because of the mass of the air, it requires energy to move it, and it can exert pressures above atmospheric pressures. Additionally, air requires energy to alter its direction of motion.

Air Temperature

The human body temperature is normally 98.6°F (37°C). Since in the temperature zones the average atmospheric temperatures are below body temperature, clothing is worn to conserve body heat.

As heat is continually being generated in the body, heavy clothing in the winter insulates the body to retain heat and maintain bodily warmth.

In the summer while the atmosphere is warm, it is difficult for the body to radiate sufficient heat as heat is generated.

The only way the human body can lose heat during those times when the air temperature exceeds 37°C is by evaporation of body perspiration. This temperature change requires heating the air in some instances (winter and very cool earth zones) and cooling the air in some instances (summer and in torrid zones).

Dry Bulb Temperature

Because human comfort and health depend not only on the air temperature but also on humidity and dust content in the air, one should not speak only of the air temperature but also of these other factors. In air conditioning the air temperature is listed more accurately as the dry bulb temperature (db) as this temperature is taken with the sensing element of the thermometer in a dry condition. Unless otherwise noted, all air temperatures are dry bulb temperatures.

Air Moisture

The atmosphere we live in always has a water vapor content. Because the human body releases considerable moisture through its pores and by breathing (the body's respiratory system), it is important that one understand how air can absorb this moisture, and how the moisture in the air affects the release of moisture from our breathing mechanism and our pores.

Moisture in the air is in water vapor form. It is important to remember that this vapor can exist in the air at temperatures below freezing.

The vapor behaves as if it existed or occupied the atmosphere all by itself. Therefore it has a temperature pressure curve like all volatiles. It also has a latent heat of vaporization (this is illustrated in Exhibit E-2).

As indicated in Exhibit E-2, heat in water vapor is considerable, especially that amount of heat necessary to change the water or ice to steam and vice versa. The amount of heat is measured from 0°F (-18°C). Note that there is more heat in the vapor than there is in dry air.

Air is seldom saturated with water vapor. If it were, the human body could not lose heat by evaporation of moisture. Additionally, the vapor in the air would be ready to condense if it contacted any material having a marginally lower temperature than that of the air. Moisture would collect (condense) on clothing, on walls, on grass, etc. People in this atmosphere would be covered with perspiration and their clothes would be damp at all times.

Luckily the atmosphere rarely becomes saturated. To find out how much moisture is in the air, or how close it is to being saturated with water vapor, one may use a polished or shiny surface that can be slowly cooled. As this surface is cooled, it finally reaches a temperature at which a film of moisure appears on the surface (dew). If the temperature at which the surfaces "fogs" is noted, this temperature is the saturation temperature for the air sample. In nature, dew is the result of air becoming cooled to a temperature near its dew point temperature, and then as this air passes over the leaves and grass, small air currents and the pressure of the surface cause moisture to collect on cooled surfaces.

Temp.	ICE, WATER, WATER VAPOR Sat.Press. in Hg.	Heat in Liquid B.T.U./lb.	Total Heat after Vaporization B.T.U./lb.	Vol. of Water Vapor cu.ft./lb.	DRY AIR Volume cu.ft./lb.	Specific Heat B.T.U./lb.	Amount of Water Vapor Saturate Grains
-40	3.790(10)-3	-177.1	1043.4	1.343(10)5	10.567	-9.61	.5508
-30	7.503(10)-3	-172.7	1047.8	7.441(10)4	10.820	-7.21	1.018
-20	1.259(10)-2	-168.2	1052.3	4.237(10)4	11.073	-4.81	1.830
-10	2.203(10)-2	-163.6	1056.7	2.475(10)4	11.326	-2.40	3.206
0	3.764(10)-2	-159.0	1061.1	1.481(10)4	11.579	0.00	5.480
10	6.286(10)-2	-154.2	1065.5	9060	11.832	2.40	9.161
20	.1027	-149.4	1069.9	5662	12.085	4.81	14.99
30	.1645	-144.4	1074.3	3608	12.338	7.21	24.07
32	.1803	-143.4	1075.2	3305	12.389	7.69	26.40
35	.2034	0.0	1076.5	2948	12.464	8.41	29.80
40	.2477	8.0	1078.7	2445	12.591	9.61	36.34
45	.3002	13.1	1080.9	2037	12.717	10.82	44.14
50	.3624	18.1	1083.1	1704	12.844	12.02	53.40
55	.4356	23.1	1085.2	1431	12.970	13.22	64.36
60	.5216	28.1	1087.4	1207	13.096	14.42	77.29
65	.6221	33.1	1089.6	1022	13.223	15.62	92.51
70	.7392	38.1	1091.8	868.0	13.349	16.83	110.4
72	.7911	40.1	1092.6	814.0	13.399	17.31	118.4
75	.8751	43.1	1093.9	740.0	13.475	18.03	131.3
80	1.0323	48.1	1096.1	633.0	13.602	19.23	155.8
85	1.2136	53.1	1098.3	543.3	13.738	20.43	184.4
90	1.4219	58.0	1100.4	467.9	13.854	21.64	217.6
95	1.6607	63.0	1102.6	404.2	13.981	22.84	256.4
100	1.9334	68.0	1104.7	350.2	14.107	24.04	301.5
120	3.4477	88.0	1113.3	203.2	14.612	28.85	569.0
140	5.8842	108.0	1121.7	123.0	15.117	33.67	1071.
160	9.6556	128.0	1129.9	77.27	15.622	38.48	2090.
180	15.295	148.0	1137.9	50.22	16.128	43.30	4598.
200	23.468	168.1	1145.8	33.64	16.632	48.12	16053.
212	29.921						

EXHIBIT E-2

The vapor pressure, volume and heat values for water-vapor and low temperatures. Also the volumes and specific heat of dry air.

(ALT)

The dew point temperature can be measured or determined by placing a volatile fluid in a bright metal container and stirring this fliud with an air aspirator. A thermometer will indicate the temperature as a mist or fog appears on the outside of the metal container. The slower the temperature is lowered, the more accurate the reading. One must be careful not to use flammable, toxic, or volatile fluids for this experiment.

The dew point temperature may be obtained more accurately by using instruments made especially for this purpose.

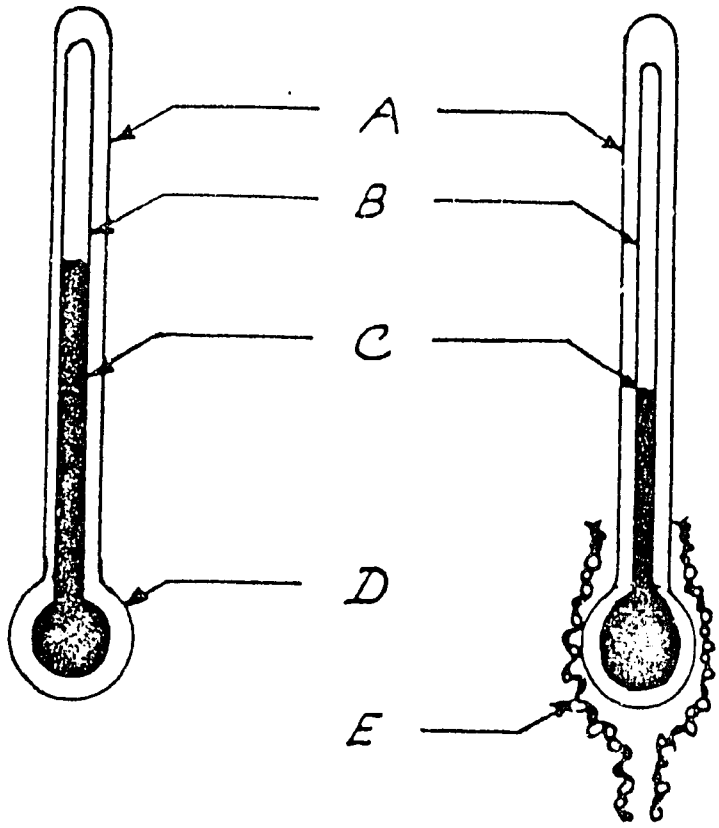
Wet Bulb Temperature

Another way to determine the moisture content of air is to use a wet bulb thermometer. This is a regular or standard thermometer except that this sensitive element (bulb) is covered with a clean white cloth (wick), and this wick is wet with clean water, as illustrated in Exhibit E-3.

When the air is saturated with moisture, no water will evaporate from this bulb, and its temperature will be the same as a dry bulb thermometer near it.

However, if the air is not saturated, water will evaporate from the wick, the wick temperature will be lowered and therefore the sensitive bulb temperature. The heat will now flow from the air to the wet thermometer bulb.

The heat change is adiabatic; that is, no heat is gained or lost from outside sources (radiation losses must be kept to a minimum). The total heat at saturation or at wet bulb temperature therefore equals the total heat in the original sample.



A dry bulb thermometer and a wet bulb thermometer. A. Thermometers; B. Mercury column; C. Wet bulb column distance below dry bulb reading; D. Dry bulb; E. Wick over wet bulb.

EXHIBIT E-3

(ALT)

The accuracy of the wet bulb reading depends on how fast the air passes over the bulb. Speeds up to 5000 ft/min (25.4 m/s) or 60 mi/hr (96.6 km/h) are best but can be dangerous if the thermometer is moved at this speed. The wet bulb should be protected from radiation surfaces at temperatures above normal (radiator, sun, electric heat, etc.). Errors as high as 15 percent may be made if the air movement is too low or if too much radiant heat is present.

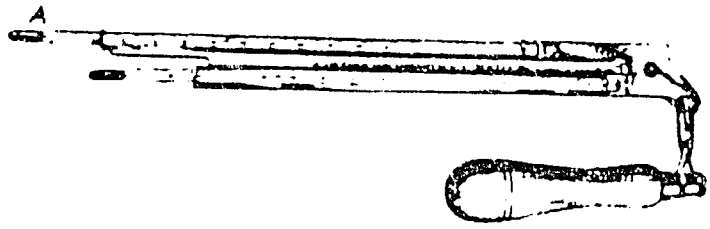
Relative air movement is usually obtained by whirling the thermometers on a single handle provided for this purpose. Exhibit E-4 illustrates a pair of thermometers (wet bulb and dry bulb) assembled in this manner. This is called a psychrometer. The wick on such a unit should be clean and white.

There are certain conditions and locations, such as narrow passages, in which it is difficult to spin the psychrometer. To obtain accurate results in these places an aspirating psychrometer is used as pictured in Exhibit E-5.

HUMIDITY

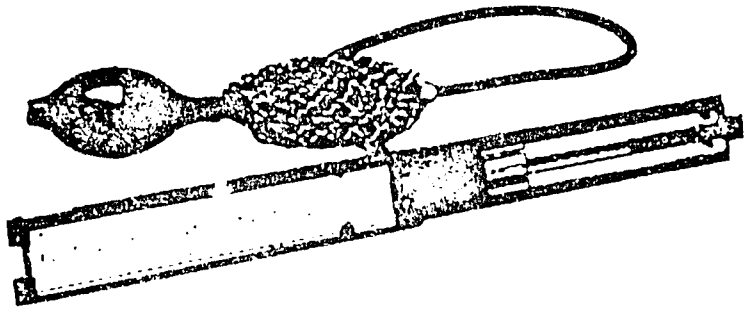
Humidity is a term used to describe the presence of moisture or water vapor in the air. The amount of moisture that the air will hold depends upon the temperature of the air. Warm air will contain more moisture than cold air. The amount of humidity in the air affects the rate of evaporation of perspiration from the body. Dry air causes rapid evaporation, which cools the surfaces of bodies and makes them feel cool. Moist (humid) air prevents rapid evaporation of perspiration; thus one feels warm although the indicated temperature may be the same for dry and humid conditions.

EXHIBIT E-4



A sling psychrometer. The wet bulb wick is mounted on the thermometer that extends the farthest (A) to the left.
(Friez Instrument Div., Bendix Aviation Corp.)

EXHIBIT E-5



An aspirating psychrometer. Note the handy calculating slide rule incorporated in the case.
(Friez Instrument Div., Bendix Aviation Corp.)

(ALT)

526

Air movement is an important part of the humidity effect on human comfort. Moving air will improve perceived comfort even through the humidity is high. Also, if there is no air movement, the air around the body will have a higher humidity than the rest of the air in the room, and a person will feel more uncomfortable.

Humidity is defined in two ways:

1. Absolute humidity
2. Relative humidity

Absolute (Specific) Humidity

Absolute humidity represents the actual amount of moisture in the air. This is measured as that moisture that is contained in each kilogram of dry air.

Absolute humidity is measured in grains of moisture; one grain is equal to 1/7000 of a pound (15.43 grains = 1 gram). It can also be measured in terms of vapor pressure such as in inches of Hg or in psia or kilo Pascals.

Relative Humidity

Relative humidity is a term used to express the amount of moisure in a given sample of air in comparison with the amount of moisture the air would hold if saturated at the temperature at which the sample was taken. Relative humidity is expressed in a percentage as 30 percent, 75 percent, etc.

Referring to Exhibit E-6, air at conditions denoted by Point B contains 111 grains of moisture per pound of dry air. Air at the saturated condition denoted by Point C for the corresponding temperature (85°F, 29.4°C) will hold 185 grains of moisture per pound of air. The relative humidity for air at Point B = 111/185 x 100 = 60 percent.

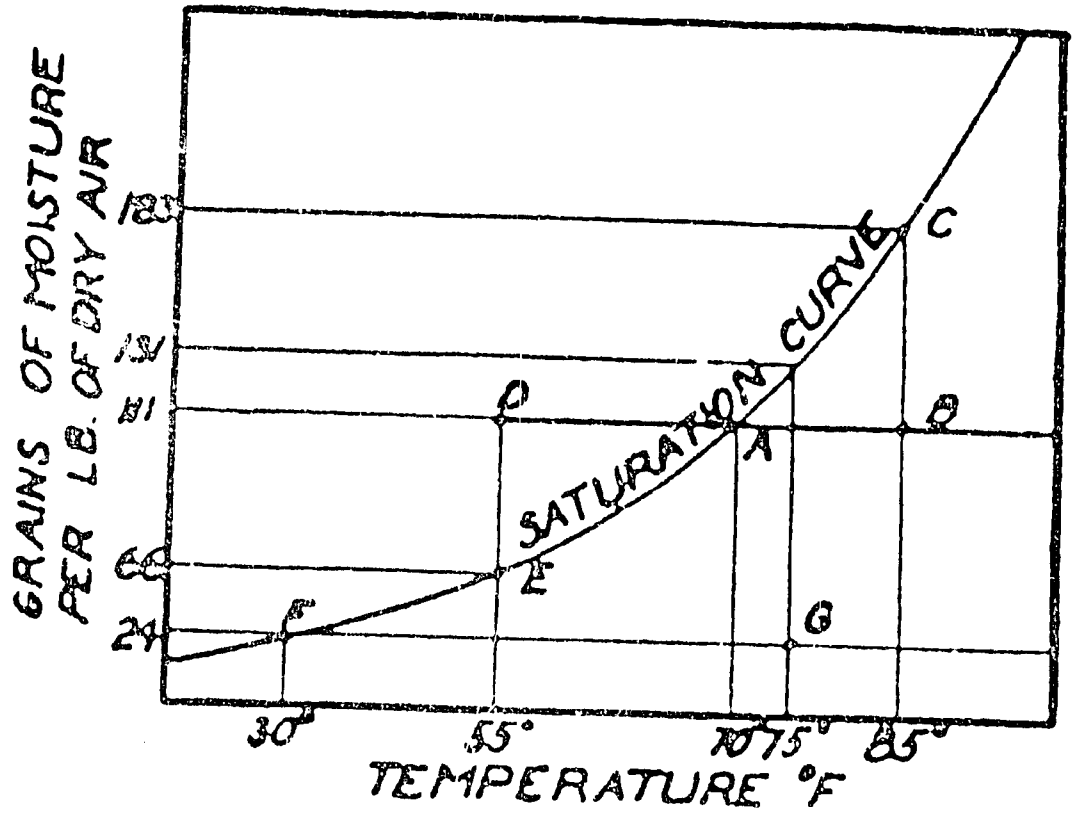


Illustration of a typical water vapor saturation curve for air. Note that as the temperature increases, the amount of moisture that the air will hold also increases.

EXHIBIT E-6

(ALT)

The line between points A and B represents what happens when saturated air is warmed. Point D represents what happens when saturated air is cooled. The moisture represented by the distance between points D and E is condensed out of the air, as air at the temperature corresponding to Point D (55°F, 12.8°C) will hold only 66 grains of moisture. Therefore the amount condensed is 111 - 66 = 45 grains

A typical winter condition is represented by Point F. Saturated air is taken indoors at 30°F (-1.1°C) and 100 percent relative humidity. It holds 24 grains of moisture at those conditions. If this air is heated to 75°F (23.9°C) and no moisture is added, its new condition will be represented by Point G. The amount of moisture in the air at this condition would be 131 grains. As the air contains only 24 grains at point F, the corresponding relative humidity is 4/131 = 18.3 percent. This is too dry for comfort, as evaporation will take place rapidly from the body and nasal passages, and one is likely to feel cold. Actual winter conditions in homes are often much worse than this, as relative humidities of 8 percent to 10 percent are common.

Air movement is also an important factor affecting comfort. If cool dry air is circulated past a warm body, the heat flow from the body will be increased. This actions tends to cool the body. In winter when a considerable difference in temperature exists indoors and outdoors, if there is no air movement within a room, the air may tend to stratify; that is, the cooled air will sink to the floor and the warmer air rise to the ceiling. By providing a certain amount of air movement in the room the air will be agitated so that a basically uniform temperature will exist throughout the room. Air movement can usually be accomplished by means of fans located in air-conditioning units or in air ducts.

Psychrometric Properties of Air

Psychrometry is the science and practice of dealing with air mixtures and their control. It deals primarily with the properties of dry air and water vapor mixtures, including specific heat, specific volume,

liquid heat of vaporization or condensation, and the specific heat of steam in reference to moisture mixed with dry air.

Tables and charts have been developed to show the pressure, temperature, enthalpy, and volume of air and its water vapor content. The tables and charts are based on the one pound of dry air plus the water vapor to produce the air conditions being studied.

Psychrometric Chart

The psychrometric chart is a graph representing the temperature-pressure relationship of air. The horizontal scale (abscissa) represents temperature, while the vertical scale (ordinate) is the pressure scale.

The values along horizontal lines represent dry bulb temperatures in °F. The values along vertical lines represent grains of moisture per pound of dry air. This psychrometric chart may be used in connection with the wet and dry bulb thermometers to determine relative humidity under any conditions.

This chart should be studied extensively because it illustrates the various air conditioning cycles and the results of mixing air of various properties.

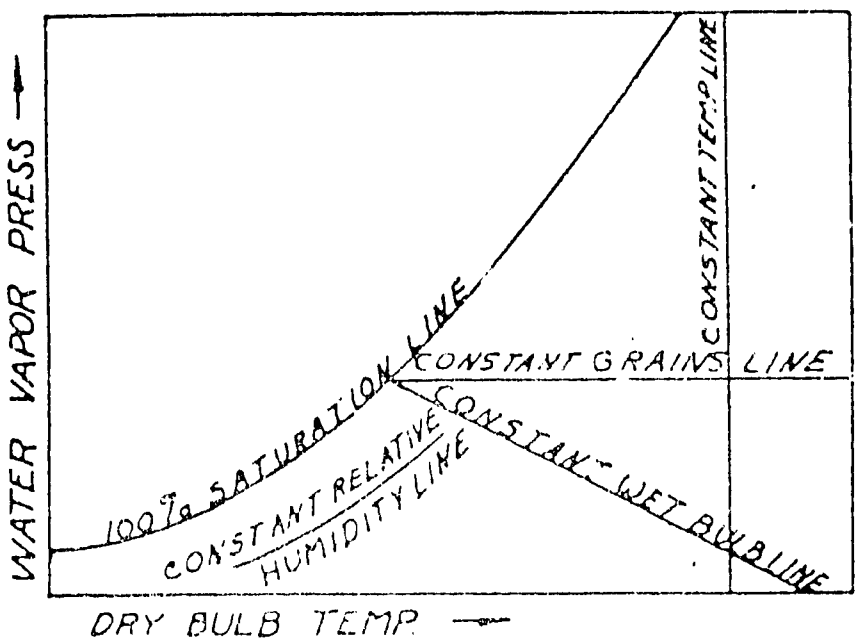
The various constant value lines are shown in Exhibit E-7.

Psychrometric Tables

The psychrometric table values permit much more accurate results because the values are accurate to four and five places. However, considerable arithmetic must be used to determine humidity and other properties for air that is not saturated.

EXHIBIT E-7

(ALT)



Psychrometric chart line nomenclature.

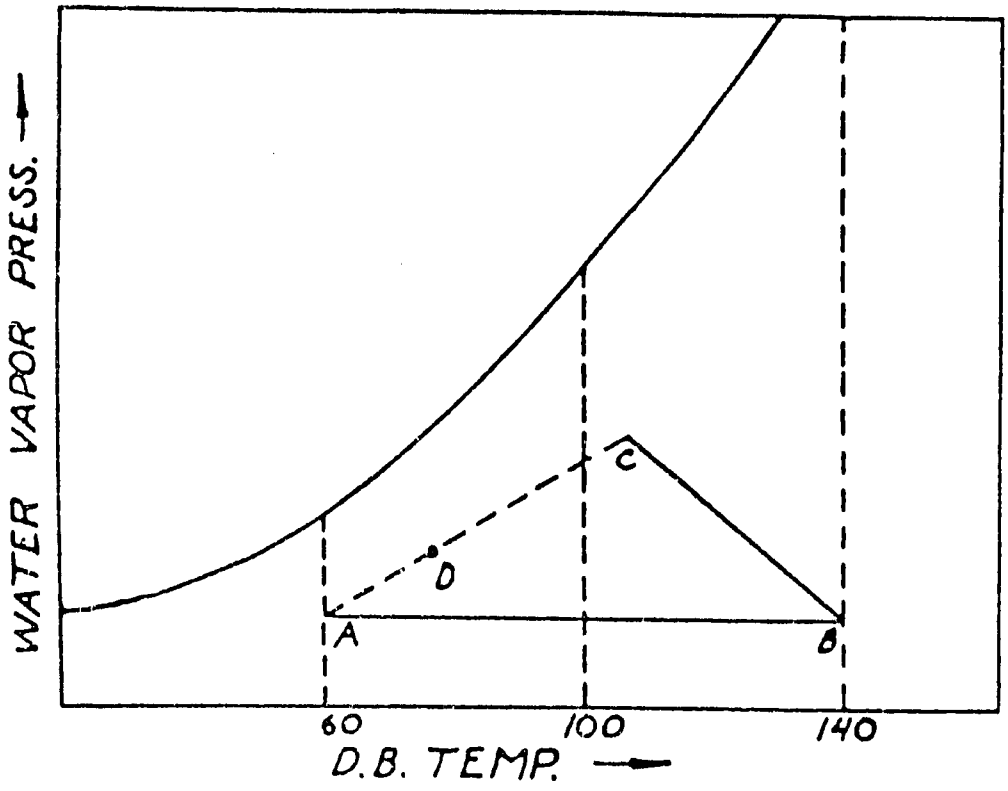
Heating Cycle

Heating a certain space is defined as the warming of air in the space from outside to the correct indoor conditions.

In a typical warm air heating device, a heating cycle can be illustrated by assuming that the return air to the furnace is at 60°F (15.6°C) and 25% R.H., that the furnace heats the air to 140°F (60.0°C), that a humidifier adds moisture to the warmed air, and, finally, that this heated air mixes with the air in the room. As illustrated in Exhibit E-8, the line from point A to point B represents heating the air. The line between points B and C represents warm air passing over the humidifier (total heat is constant). Between point C and point A the heated, humdified air is mixed, and the final result is represented at point D.

Cooling Cycle

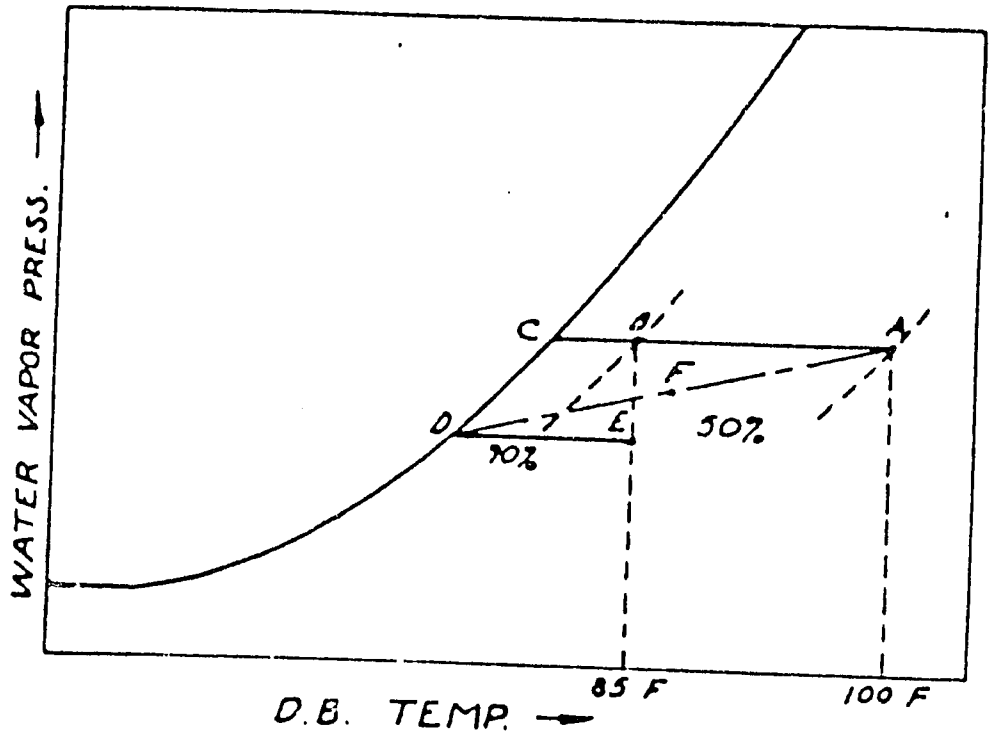
A cooling cycle involves lowering the temperature (db) of the air. When this happens, as illustrated in Exhibit E-9 and the line from point A to point B the relative humidity increases. Some moisture must therefore be removed. This moisture can be removed by using chemicals to dehydrate the air or by cooling the air to the saturation curve and then removing the moisture by condensing moisture on the cooling surface (traversal from point B to point C, then to point D). The distance from point C to point D represents the drop in vapor pressure or grains of moisture removed. Reheating to point E along a horizontal line from point D will decrease humidity. However, what more often happens is the air leaving at point D is mixed with room air, which is at some intermediate condition between 85°F and 100°F (29.4° and 37.8°C). The mixture meets on the line between point D and point A. If one third of the air by weight is pased through a cooling coil, the mixer temperature will be one third of the way from point D to point A, that is, to point F.



A recirculating warm air heating cycle on the psychrometric chart. A. Cold air return; A to B heating in the furnace; B. to C. Humidifying the air; C. to A. Mixing of air with room air; D. Final conditions after mixing.

EXHIBIT E-8

(ALT)



The cooling cycle on the psychrometric chart. A. Condition of outside air; B. Partly cooled air; C. Air cooled to saturation; D. Air cooled to remove some moisture; E. Dehydrated air reheated; F. Result of mixing treated and untreated air.

EXHIBIT E-9

(ALT)

Comfort

Heat Balance on the Body

Individual comfort depends on how fast the body is losing heat. The human body may be compared to a furnace using food as fuel. Food is composed largely of carbon and hydrogen; enegy contained in food is released by oxidation. The oxygen comes from air, and the principal products of combustion are carbon dioxide and water vapor. Physicians call this process metabolism.

The body is essentially a constant temperature device. Its internal temperature is kept at 98.6°F (37°C) by a delicate temperature regulating mechanism with the body.

The object of air conditoning is to assist the body in controlling its cooling rate. This is true for both winter and summer conditions. In summer, the body's job is to increase its cooling rate; in winter, its job is to decrease the cooling rate.

It is possible to compile a heat balance for the human body and study the ways in which the body's cooling rate can be controlled.

As mentioned previously, metabolism is the process by which the body produces heat. This will be shown on the left side of the equation. On the right side will be the ways the body loses heat.

Heat produced = Heat loss

$$M = \pm q_s \pm q_r + q_l$$

where

- M = metabolism, Btuh, kJ/s
- q_s = sensible heat loss, Btuh, kJ/s
- q_r = radiant heat loss, Btuh, kJ/s
- q_l = latent heat loss (evaporation), Btuh, kJ/s

Two things can cause the body temperature to rise: fever or continuous heavy activity. The body temperature will drop in freezing weather if it is not properly protected.

The left side of the heat balance represents basal metabolism. This is the amount of heat generated by an unclothed human at rest in an air temperature of about 70°F (21.1°C). For an individual of average weight and body build the basal metabolism is about 240 Btuh (70.3 J/s).

Except for design work relative to clinics and hospitals, the air conditioning engineer has only a passing interest in basal metabolism. The people he must keep comfortable are clothed and have various degrees of activity. So the left side of the heat balance becomes the actual metabolic level of the individual. This is the heat generated by the individual; it varies from 390 to 1500 Btuh (114 J/s to 439 J/s). The metabolic level for certain activities can be found in Exhibit E-10.

The right side of the heat balance represents the heat loss from the body. These terms represent the ways the body is able to keep itself at a constant temperature. This is quite a remarkable feat, considering that activity may vary from sleeping to heavy work and that activity may occur in an air conditioned atmosphere or in the hot sun. Each of the relevant heat loss terms will now be discussed.

Sensible Heat Loss

Note the "plus-and-minus" sign in front of the sensible heat term in the heat balance. This means the body can either lose or gain sensible heat. The key to this is air temperature. If the air temperature is below skin temperature, the sensible heat term is "plus"--the body is losing sensible heat to the air. If the air temperature is above the skin temperature, the sensible heat term is "minus"--the body is gaining sensible heat from the air.

Some of the heat liberated in a furnace is transmitted through the air surrounding the steel furnace walls. Similarly, some of the heat

EXHIBIT E-10

(TRA)

Table

Heat Gain from Occupants of Conditioned Spaces[1]

DEGREE OF ACTIVITY	TYPICAL APPLICATION	TOTAL HEAT ADULTS, MALE BTU/HR	TOTAL HEAT ADJUSTED[2] BTU/HR	SENSIBLE HEAT BTU/HR	LATENT HEAT BTU/HR
SEATED AT REST	THEATER-MATINEE	390	330	200	130
	THEATER-EVENING	390	350	215	135
SEATED, VERY LIGHT WORK	OFFICES, HOTELS, APARTMENTS	450	400	215	185
MODERATELY ACTIVE OFFICE WORK	OFFICES, HOTELS, APARTMENTS	475	450	220	230
STANDING, LIGHT WORK; OR WALKING SLOWLY	RETAIL AND DEPARTMENT STORES	550	450	220	230
WALKING; SEATED	DRUG STORE	550	500	220	280
STANDING; WALKING SLOWLY	BANK	490	550	240	310
SEDENTARY WORK	RESTAURANT[3]	800	750	240	510
LIGHT BENCH WORK	FACTORY	900	850	270	580
MODERATE DANCING	DANCE HALL	1000	1000	330	670
WALKING 3 MPH; MODERATELY HEAVY WORK	FACTORY	1500	1450	510	940
BOWLING[4]	BOWLING ALLEY	1500	1450	510	940
HEAVY WORK	FACTORY				

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NOTES.

[1] Tabulated values are based on 78 F for dry-bulb temperature.

[2] Adjusted total heat gain is based on normal percentage of men, women, and children for the application listed, with the postulate that the gain from an adult female is 85 per cent of that for an adult male, and that the gain from a child is 75 per cent of that for an adult male.

[3] Adjusted total heat value for sedentary work, restaurant, includes 60 Btuh for food per individual (30 Btu sensible and 30 Btu latent).

[4] For bowling figure one person per alley actually bowling, and all others as sitting (400 Btuh) or standing (550 Btuh).

liberated within the body is transmitted to the air in contact with the skin. Although the deep body temperature remains at 98.6°F (37°C), the skin temperature varies. The skin temperature will vary from 40°F to 105°F (4.4°C to 40.6°C) according to the temperature, humidity, and velocity of the surrounding air. If the temperature of the surrounding air decreases, the skin temperature will also decrease.

The range of skin temperatures, at any location on the body, is comparatively small. A change of 10 degrees in room temperature does not produce a corresponding change of 10 degrees in skin temperature. for instance, in one series of tests reported, forehead temperatures ranged from 93°F (33.9°C) in air at 64°F (17.8°C),, to 100°F (37.8°C) in air at 96° (35.6°C). So, as the temperature of the air rises, the difference in temperature between the skin and the air decreases. At normal indoor winter temperature, there is a steady of flow of sensible heat from the skin to the surrounding air. The amount of this sensible heat depends upon the temperature difference between the skin and air. If this difference decreases as the temperature of the surrounding air rises, less sensible heat will be transferred to the surrounding air. When the surrounding air is at a temperature of about 70°F (21.1°C), most people lose sensible heat at such a rate that they are comfortable. If the air temperature rises to 80°F (26.7°C), the sensible heat loss drops to zero. The reason is that 80°F (26.6°C) is an average skin surface temperature for an adult human. This is when he/she is indoors during the heating season and wearing comfortable clothing. If the air temperature continues to rise, the body will gain heat from the air.

Radiant Heat Loss

The body gains or loses heat by radiation according to the difference between two temperatures:

1. The body surface (bare skin and clothing) temperature, and

2. The mean radiant temperature.

Mean radiant temperature is abbreviated as MRT. It is a weighted average of the temperature of all the surfaces in direct line of sight of the body.

If the mean radiant temperature is below the body temperature, the radiant heat term (q_r) in the heat balance is "plus". Then the body is losing radiant heat to a surface it can "see". If the MRT is above the body temperature q_r is "minus"---the body is gaining radiant heat. It should be kept in mind that the body loses sensible heat and radiant heat according to its surface temperature. For a comfortable adult normally dressed, the weighted average temperature between bare skin and clothed surfaces is 80°F (26.7°C).

Surface temperatures have a pronounced effect on comfort. Suppose, that during the heating season, a person is working at a desk facing the center of a room with his back 5 ft (1.52 m) from the outside wall. The wall surface temperature is 59°F (15°C). Assume the air distribution in the room is almost perfect--74°F. at 2 in. (23.3°C, 5.1 cm) below the ceilings, 73°F (22.8°C) above the floor, and 73.5°F (23.0°C) all around including the space between the person's back and the wall. Will he be comfortable? Probably not. His radiant heat loss is so high, he will feel chilly. What can be done to correct this situation? The temperature of the wall surface cannot conveniently be changed. The position of the desk might be changed so the person's back is against an inside wall. The surface temperature of the inside wall will be near the air temperature--probably 73°F (22.8°C). So the radiant heat loss will be onethird of what it was. If the desk cannot be moved, what else might be done? The temperature of the air might be increased by turning up the thermostat. Increasing the air temperature will decrease the sensible heat loss from the body. Suppose air temperature is to be maintained at 77°F (25°C). This will decrease the sensible heat loss by the same amount the radiant heat loss was decreased by moving the desk from the outside wall. This balances the heat loss from the body. However, the trouble is that everyone else in the room is too warm.

Exactly the same thing might be true during the cooling season. One might be too warm because of the radiant heat the body gains from a warm outside wall or window. Now the sensible heat loss from the body should be increased by decreasing the air temperature. This puts body heat loss in balance, but everyone else in the room is too cool.

There is an important point to this discussion. It was assumed the air distribution was excellent; it was also assumed the air temperature could be raised or lowered at will. Even if these assumptions are true, everyone in the room will not be comfortable all the time. This means there is more to comfort than the effects of mechanical equipment. Good equipment properly operated will provide comfort in most instances. Building construction, building orientation, and the type of occupancy all influence comfort.

Latent Heat Loss (Evaporation)

The last term in the heat balance is latent heat or perspiration. This is always positive. Even at rest the human body requires about 100 Btuh (29.3 J/s) to evaporate moisture into inhaled air to keep the lungs moist. If it were not for this fact, lung tissues would stick together and insufficient air would enter the lungs to sustain the body's life. It is possible to "see" the breath when exhaling on a frosty morning. This provides evidence that the air leaving the lungs has a high moisture content.

Evaporative heat regulation is the body process that sustains life outside an air conditioned space. Suppose one goes outside when the air temperature is 100°F (37.8°C). The sensible heat loss is "minus" because the body is gaining heat from the air. The MRT is much higher than the body surface temperature; the sidewalk, street, building walls, and everything the body "sees" is above surface temperature. Thus, the second term is also "minus" because the body is gaining radiant heat. To maintain its heat balance the body must lose energy by evaporation. Nature takes care of this by automatically by opening the sweat glands.

Moisture on the body surface then evaporates. Most of the heat required to convert the moisture to vapor comes from the body. As long as the air will carry away the water vapor, the skin temperature will remain cool. This in turn keeps the deep body temperature at nearly 98.6°F (37°C).

Moisture lost by the body, whether in exhaled air or from the skin, is in the form of steam at extremely low pressure. The body supplies the necessary latent heat to evaporate the moisture that it loses.

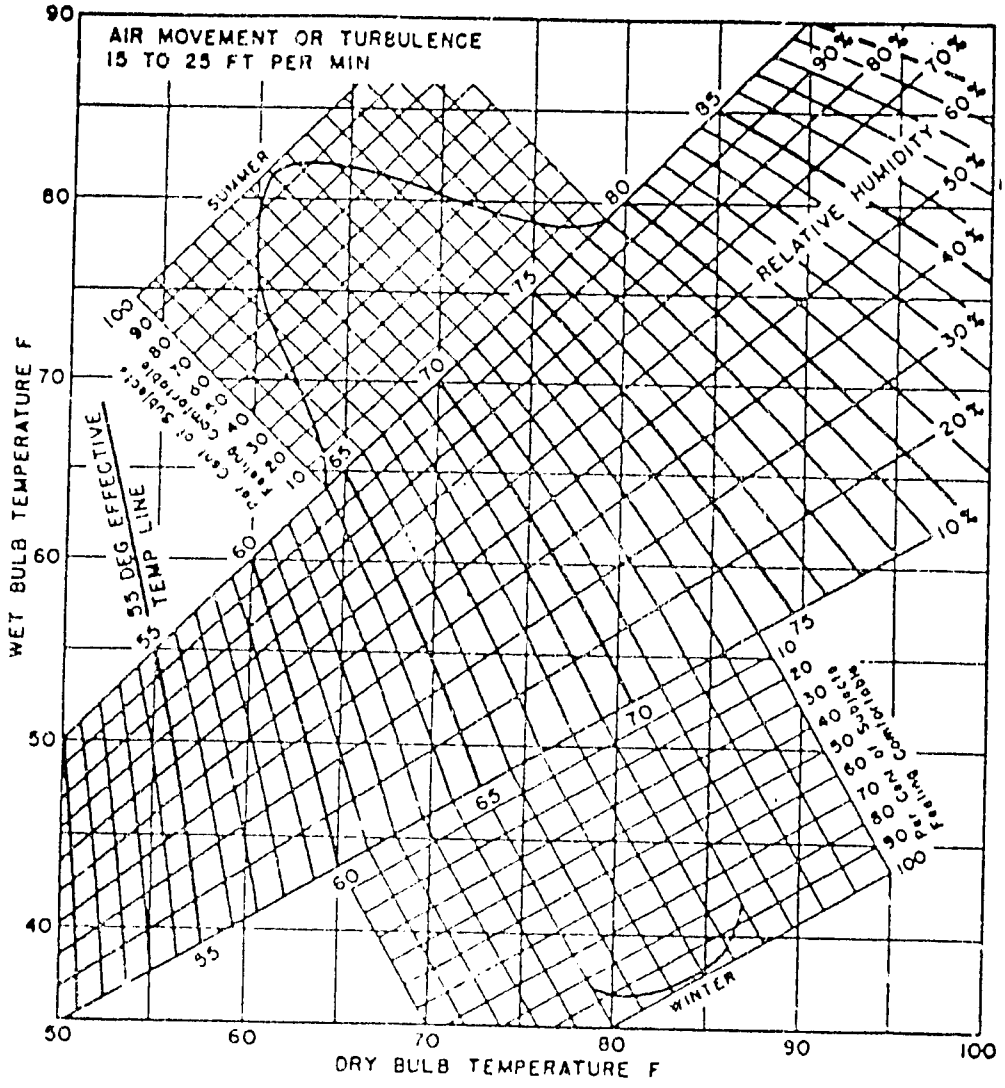
Comfort and Effective Temperature

There appears to be no rule as to the best atmospheric conditions for comfort for all people. Under the same conditions of temperature and humidity, the healthy young man is slightly warm while the elderly woman is cool.

The comfort of an individual is affected by many variables. Health, age, activity, sex, food, and acclimatization all play their part in determining the elusive "best comfort conditions" for any paritcular person. "Hard and fast" rules that will apply to all conditions and to all people cannot be given. The best that can be done is to approximate those conditions under which a majority of the occupants of a room will feel comforable.

The graph in Exhibit E-11 is based on the results of a test in which people were subjected to air at various temperatures and humidities. The coordinates of this chart are dry bulb temperature and wet bulb temperature. The straight lines sloping upwards from left to right are lines of constant relative humidity corresponding to various combinations of dry and wet bulb temperatures. The short, curved lines drawn across the humidity lines, and approximately perpendicular to them, are lines of constant effective temerature (ET).

Effective temperature is not an actual temperature in the sense that it can be measured by a thermometer. It is an experimentally determined



[a] *Note.*—Both summer and winter comfort lines apply to inhabitants of the United States only. Application of winter comfort line is further limited to rooms heated by central systems of the convection type. The line does not apply to rooms heated by radiant methods. Application of summer comfort line is limited to homes, offices and the like, where the occupants become fully adapted to the artificial air conditions. The line does not apply to theaters, department stores, and the like where the exposure is less than 3 hours. The summer comfort line shown pertains to Pittsburgh and to other cities in the northern portion of the United States and Southern Canada, and at elevations not in excess of 1000 ft above sea level. An increase of one deg ET should be made approximately per 5 deg reduction in north latitude.

[b] Dotted portion of winter comfort line was extrapolated beyond test data.

A graphical representation of a comfort zone.
(American Soc. of Heating and Air Conditioning Engrs.)

EXHIBIT E-11

(ALT)

index of various combinations of temperature, humidity, and air movement which induce the same feeling of warmth. In summer, most people who have been in a conditoned atmosphere for more than three hours will feel just about as cool at 75°F DB (23.9°C) and 60% humidity as at 79°F DB (26.1°C) and 30% humidity because both conditions are equivalent to 71°F ET. Studies conducted by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in areas having relative humidities betwen 30 and 70 percent indicate that 98 percent of the subjects were comfortable when the wet bulb and dry bulb temperatures fell on the 71°F ET (21.7°C) line. None of the test subjects were comfortable when the laboratory conditions were held at 64°F ET and 79°F ET (17.8°C and 26.1°C).

People doing physical work need a lower effective temperature for comfort. Naturally, the greater the activity and the more clothing worn, the lower temperature must be the effective temperature for comfort. Although the latent heat liberated by people engaged in any physical activity rises markedly, the sensible heat liberated remains approximately the same. For example, and average man seated at rest in a room at 80°F DB (26.7°C) gives off 180 Btuh (52.7 J/s) of sensible heat and 150 Btuh (43.9 J/s) of latent heat, or a total of 330 Btuh (99.6 J/s). Now if he does light bench work he will liberate 220 Btuh (64.4 J/s) as sensible heat and 530 Btuh (155.2 J/s) as latent heat. Note that with light activity the sensible heat increased about 20 percent but the latent heat increased about 250 perent. Thus, the degree of activity must be taken into account in arriving at an effective temperature for comfort.

A portion of the latest work to come from the ASHRAE laboratory is shown in Exhibit E-12. Here four lines are marked "slightly cool", "comfortable", "silghtly warm", and 'warm", and are called lines of equal thermal sensations. If the new data agreed with the comfort chart, the lines of equal sensation would be parallel to ET lines.

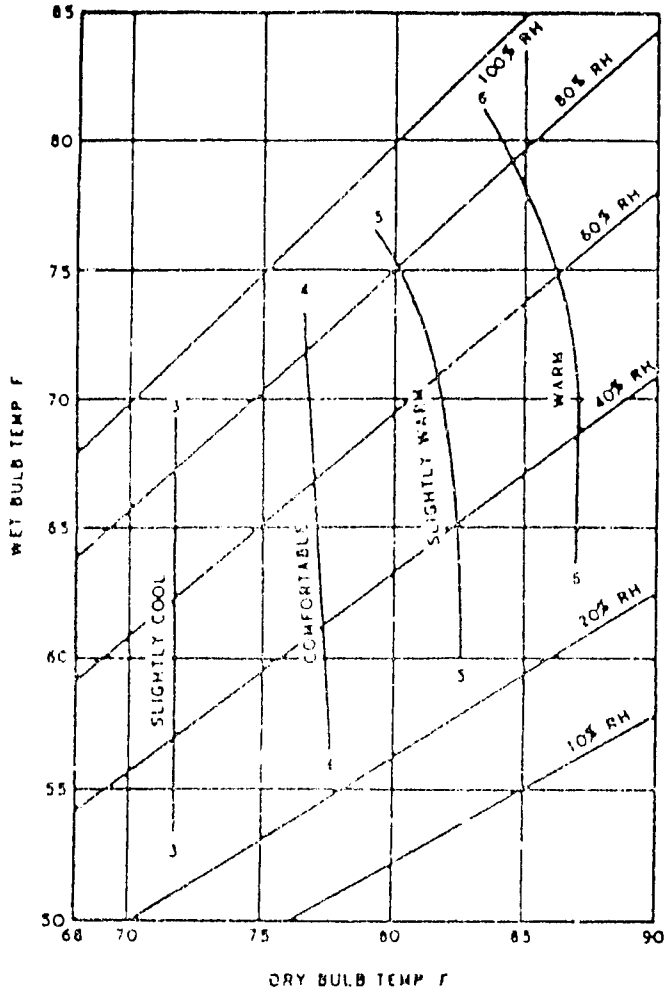
Along the "comfortable" line a rise in relative humidity from 30 to 90 percent calls for a decrease in dry bulb temperature of slightly less than 1.1°C. Looking at the 71°F ET (21.7°C) line on the comfort chart it can be seen that the same change in relative humidity gives a decrease in dry bulb temperature of about 3.9°C. It is interesting to note that, from this, relative humidity does not seem to have as much to do with human comfort as people thought it did 35 years ago.

Air Distribution

Air introduced into a conditioned space should be distributed in such a way that within the occupied zone (floor level to 6 ft (1.83 m) above the floor) there are only minor horizontal or vertical temperature variations and that the proper quantity of air is delivered to different sections of the occupied space without drafts. A draft may be defined as a noticeable air current. Drafts are objectionable, but there must be air motion in the occupied space or the occupants will feel uncomfortable. Heat and moisture must be carried away from the body as they are liberated or a stagnant film of warm, moist air would envelop each occupant. The type of occupancy, the physical arrangement of the room, the acceptable noise level, and the degree of occupant activity all have a bearing on the permissible air velocity in a conditioned space. Generally a velocity of 15 to 25 fpm (.0762 to .127 m/s) is considered to be "still" air while air moving at 65 fpm (.330 m/s) would constitute a draft to most people.

In order to cool an air-conditioned space the supply air is usually introduced into the room at 12 to 30°F (6.7 to 16.7°C) below the required room air temperature and at a velocity considerably above 15 fpm (.0762 m/s). Suppose a room were to be maintained at 78°F (25.6°C) and the conditioned air supply were introduced at 60°F and 500 fpm (15.6°C and 2.54 m/s). A good air distribution system for this room must do the following:

1. Entrain enough room air with the cold supply air that upon reaching the occupied zone the air stream will be warm enough not to be objectionable.



FIGURE

LINES OF EQUAL THERMAL SENSATIONS

EXHIBIT E-12

(TRA)

2. Reduce the air velocity before reaching the occupied zone to the point that there will be freedom from drafts.
3. Provide a turbulent, eddying motion within the entire occupied zone.
4. Keep air noise from the supply outlets and return grilles below the objectionable level.

While it may seem that these requirements are stringent, it should be pointed out that an air conditioning system may have the very best mechanical components (compressor, controls, etc.) and yet, from the owner's standpoint, be unsatisfactory if the air distribution is not providing comfort for the occupants.

Outdoor Air

A certain amount of outdoor air should be delivered to a conditioned room in order to prevent noticeable odors. Wherever humans gather, odors will inevitably appear. Sufficient outdoor air must be introduced to dilute the room air and keep these odors below the limits or perception. In addition to the odor problem, there is also the problem of keeping the atmosphere reasonably clear in rooms where smoking is permitted. The smoke problem is, as a rule, more difficult than the problem of odors.

APPENDIX F

EQUIPMENT MANUFACTURERS

TAKEN FROM (KRE-3)

EQUIPMENT MANUFACTURERS

The following list does not include all manufacturers, nor does it necessarily include all of the product lines of those that are listed. Listing of a manufacturer does not constitute an endorsement of its products. For more information on solar equipment manufacturers, contact the Solar Energy Industries Association, 1001 Connecticut Avenue, NW, Suite 800, Washington, DC 20036, (202)293-2981.

Alpha Energy
7038 Convoy Ct.
San Diego, CA 92111
(714)292-7811
Controls

American Solar King Corp.
7200 Imperial Dr.
Waco, TX 76710
(817)776-3860
Liquid-heating flat-plate collectors; evacuated-tube collectors; pumps; heat exchangers; heat pumps

Ametek Power Systems Division
1025 Polinski Rd.
Ivyland, PA 18974
(215)441-8770
Liquid-heating flat-plate collectors; controls; solar thermal storage units

Aquatherm, Inc.
541 Main St.
S. Weymouth, MA 02190
(617)337-4114
Heat exchangers; solar thermal storage units

Arco Energy Corp.
Sunburst Div.
7917 A Fruitridge Rd.
Sacramento, CA 95820
(916)383-4117
Liquid-heating flat-plate collectors; heat exchangers

Armstrong Pumps Inc.
93 East Ave.
N. Tonawanda, NY 14120
(716)693-8813
Pumps; heat exchangers

Artech Corp.
2901 Telestar Ct.
Falls Church, VA 22042
(703)560-3292
Solar thermal storage units

Bally Case & Cooler Inc.
P.O. Box 98
Bally, PA 19503
(215)845-2311
Solar thermal storage units

Bio-Energy Systems Inc.
221 Canal St.

Ellenville, NY 12428
(914)647-6700
Liquid-heating flat-plate collectors; heat exchangers; heat pumps; controls; solar thermal storage units

Campbell Scientific Inc.
815 W. 1800 North
P.O. Box 551
Logan, UT 84321
(801)753-2342
Controls

Compool Corp.
1708 Stierlin Rd.
Mountain View, CA 94043
(415)964-2201
Liquid-heating flat-plate collectors; controls

Delford Industries
82-88 Washington St.
Middletown, NY 10940
(914)342-3901
Evacuated-tube collectors

Doucette Industries Inc.
P.O. Box 1641
York, PA 17405
(717)845-8746
Heat exchangers

Easco Aluminum/New Jersey Aluminum
P.O. Box 73
North Brunswick, NJ 08902
(201)249-6867
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; evacuated-tube collectors

Enerdyne Corp.
Hanover Ind. Airport
Ashland, VA 23005
(804)798-1575
Liquid-heating flat-plate collectors

Energy Control Systems
3324 Octavia St.
Raleigh, NC 27606
(919)851-2310
Air-heating flat-plate collectors; controls

Energy Materials Inc.
2622 S. Zuni St.
Englewood, CO 80110
(303)934-2444
Solar thermal storage units

Energy Transfer Systems
5001 West Waters Ave.
Tampa, FL 33614
(813)885-7656
Liquid-heating flat-plate collectors; controls

Fafco, Inc.
255 Constitution Dr.
Menlo Park, CA 94025
(415)321-3650
Liquid-heating flat-plate collectors

F.E.C. Inc.
4489 Goodland Park Rd.
Madison, WI 53711
(608)222-3264
Controls

Ford Products Corp.
Ford Products Rd.
Valley Cottage, NY 10989
(914)358-8282
Solar thermal storage units

Grundfos Pumps Corp.
2555 Clovis Ave.
Clovis, CA 93612
(209)299-9741
Pumps

Halstead & Mitchell Co.
P.O. Box 1110
Scottsboro, AL 35768
(205)259-1212
Liquid-heating flat-plate collectors; heat exchangers

Heliodyne, Inc.
700 S. Fourth St.
Richmond, CA 94804
(415)237-9614
Liquid-heating flat-plate collectors; controls

Heliotherm
W. Lenni Rd.
Lenni, PA 19052
(215)459-9030
Liquid-heating flat-plate collectors; pumps; heat exchangers; controls; solar thermal storage units

Heliotrope General
3733 Kenora Dr.
Spring Valley, CA 92077
(714)460-3930
Controls

Hordis Brothers Inc.
825 Hylton Rd.
Pennsauken, NJ 08110
(609)662-0400
Air-heating flat-plate Collectors; liquid-heating flat-plate collectors

Horizon Enterprises, Inc.
710 NW Tenth Ave.
Homestead, FL 33030
(305)245-5145
Liquid-heating flat-plate collectors; pumps; controls; solar thermal storage units

Hydro-flex Corp.
2101 NW Brickyard Rd.
Topeka, KS 66618
(913)233-7484
Heat exchangers

Insolarator Solar Energy Products
7926 Convoy Ct.
San Diego, CA 92111
(714)292-1857
Liquid-heating flat-plate collectors; controls

JBJ Controls Inc.
1680 Foote Dr.
Idaho Falls, ID 83402
(208)522-2200
Controls

KTA Solar, Inc.
13856-A Park Center Rd.
Herndon, VA 22071
(703)471-5405
Liquid-heating flat-plate collectors

Lane Maxwell Enterprises
4303 Rawhide Rd.
Pueblo, CO 81008
(303)544-0278
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; controls; solar thermal storage units

Lennox Industries Inc.
P.O. Box 400450
Dallas, TX 75240
(214)783-5429
Liquid-heating flat-plate collectors; heat exchangers; controls; solar thermal storage units

McClintock Corp.
7000 SW 62nd Ave.
Miami, FL 33143
(305)666-1300
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; controls

Morning Star MFG., Inc.
138 Industrial Loop W.
Orange Park, FL 32073
(904)264-2649
Liquid-heating flat-plate collectors

Noranda Metal Industries Inc.
Forge-Fin Division
Prospect Dr.
Newton, CT 06470
(203)426-4431
Heat exchangers; heat pumps

Novan Energy, Inc.
1630 N. 63rd St.
Boulder, CO 80301
(303)447-9193
Liquid-heating flat-plate collectors; controls

One Design, Inc.
Mountain Falls Rte.
Winchester, VA 22601
(703)877-2172
Solar thermal storage units

Owens-Illinois, Inc.
One Seagate
Toledo, OH 43666
(419)247-5000
Evacuated-tube collectors

Pace Corp.
555 Two Mile Rd.
Appleton, WI 54911
(414)731-5281
Air-heating flat-plate collectors; controls; solar thermal storage units

P. & S. Hardware
905 W. Fifth St.
Reno, NV 89503
(702)329-1392
Liquid-heating flat-plate collectors; pumps; heat exchangers; controls

Phelps Dodge Solar Enterprises
1590 South Sinclair St.
Anaheim, CA 92806
(714)978-1122
Liquid-heating flat-plate collectors; pumps

Precision Bending MFG., Inc.
P.O. Box 4917

Liquid-heating flat-plate collectors; controls

Solar Manufacturing Corp.
30958 Industrial Rd.
Livonia, MI 48150
(313)522-6223
Heat exchangers; controls

Solar Products Manufacturing Corp.
1 Alcap Ridge
Cromwell, CT 06416
(203)635-0266
Liquid-heating flat-plate collectors; pumps; heat exchangers; controls; solar thermal storage units

Solar Research Div., Refrigeration Research Inc.
525 North Fifth St.
P.O. Box 869
Brighton, MI 48116
(313)227-1151
Liquid-heating flat-plate collectors; heat exchangers

Solar Research Systems
2116 S. Yale St.
Santa Ana, CA 92704
(714)540-4292
Liquid-heating flat-plate collectors; controls

Solar Span Corp.
285 Queen St.
Southington, CT 06489
(203)621-6728
Liquid-heating flat-plate collectors; controls

Solartrac Inc.
Zero Herbert St.
P.O. Box 670
Beacon, NY 12508
(914)831-6435
Pumps; heat exchangers; controls; solar thermal storage units

Solar Unlimited Inc.
37 Taylor Island
Huntsville, AL 35801
(205)534-0661
Liquid-heating flat-plate collectors; pumps; heat exchangers; controls; solar thermal storage units

Solar Usage Now, Inc.
420 E. Tiffin St.
P.O. Box 306
Bascom, OH 44908
(419)937-2226
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; heat exchangers; controls

Solatherm Corp.
1255 Timber Lake Dr.
Lynchburg, VA 24502
(804)237-3249
Heat exchangers

Solex Corp.
187 Billerica Rd.
Chelmsford, MA 01824
Liquid-heating flat-plate collectors; heat exchangers

Sungrabber Energy, Inc.
5010 Cook St.
Denver, CO 80216
(303)825-0203
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; controls; solar thermal storage units

Sunmaster Corp.
35 W. William St.
P.O. Box 1077
Corning, NY 14830
(607)937-5441
Evacuated-tube collectors; heat exchangers; controls; solar thermal storage units

Sun-Ray Solar Equipment Co. Inc.
Four Pines Bridge Rd.
Beacon Falls, CT 06403
(203)888-0534
Liquid-heating flat-plate collectors; heat exchangers; controls; solar thermal storage units

Sunsav, Inc.
640 S. Union St.
Lawrence, MA 01843
(617)687-0044
Liquid-heating flat-plate collectors; solar thermal storage units

Sunshine Unlimited, Inc.
900 N. Jay St.
Chandler, AZ 85224

Miami Beach, FL 33141
(305)672-3191
Heat exchangers

Pyramid Controls
421-16 N. Buchanan Cir.
Pacheco, CA 94553
(415)827-0160
Controls

Ramada Energy Systems Limited
1421 S. McClintock Dr.
Tempe, AZ 85281
(602)273-4300
Liquid-heating flat-plate collectors; pumps; heat exchangers; controls; solar thermal storage units

Raypak Inc.
3111 Agoura Rd.
Westlake Village, CA 91361
(213)889-1500
Liquid-heating flat-plate collectors

Revere Solar and Architectural Products, Inc.
P.O. Box 151
Rome, NY 13440
(315)338-2401
Liquid-heating flat-plate collectors

Rheem Water Heater Division
5780 Peachtree-Dunwoody Rd. NE, Suite 400
Atlanta, GA 30342
(404)256-2037
Liquid-heating flat-plate collectors; solar thermal storage units

Rho Sigma, Inc.
Subsidiary, Watsco Inc.
1800 W. Fourth Ave.
Hialeah, FL 33010
(305)885-1911
Controls

Rom-Aire Solar Corp.
1909 E. 28th St.
Lorain, OH 44055
(216)277-5600
Air-heating flat-plate collectors; heat exchangers; controls

Sealed Air Corp.
3433 Arden Rd.
Hayward, CA 94545
(415)887-7000
Liquid-heating flat-plate collectors; controls; solar thermal storage units

Solar Control
2525 W. Sixth Ave.
Denver, CO 80204
(303)534-4133
Heat exchangers; controls

Solar Corporation of America
105 North Hanks
Rome, GA 30161
(404)291-6956
Liquid-heating flat-plate collectors; pumps; heat exchangers; heat pumps; controls; solar thermal storage units

Solar Dakota, Inc.
520 20th Ave. SW
Minot, ND 58701
(701)852-2431
Air-heating flat-plate collectors; controls; solar thermal storage units

Solar Design Associates, Inc.
205 W. John St.
Champaign, IL 61820
(217)359-5748
Liquid-heating flat-plate collectors; pumps; heat exchangers; heat pumps; controls; solar thermal storage units

Solar Energies of California, Inc.
11421 Woodside Ave.
Santee, CA 92071
(714)448-4300
Air-heating flat-plate collectors; liquid-heating flat-plate collectors

Solar Energy of Colorado, Inc.
4230 Fox St.
Denver, CO 80216
(303)433-8761
Liquid-heating flat-plate collectors; pumps; heat exchangers; heat pumps

Solar Energy Sales, Inc.
2499 N. Main St.
Walnut Creek, CA 94596
(415)939-8838
Liquid-heating flat-plate collectors; controls; solar thermal storage units

Solar Industries, Inc.
2300 Highway 34
Manasquan, NJ 08736
(201)223-8100

(602)963-3878
Liquid-heating flat-plate collectors; heat exchangers; solar thermal storage units

Sunwest Solar Systems, Inc.
4024 E. Broadway Rd., Suite 1001
Phoenix, AZ 85040
(602)243-6171
Liquid-heating flat-plate collectors; controls

Sunworks, Div. Sun Solector Corp.
P.O. Box 3900
Somerville, NJ 08876
(201)469-0399
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; evacuated-tube collectors; heat exchangers; heat pumps; controls

Technitrek Corp.
34701 Seventh St., Bldg. 1B
Union City, CA 94587
(415)794-8400
Liquid-heating flat-plate collectors

Thermal Energy Storage Inc.
10637 Roselle St.
San Diego, CA 92121
(714)453-1395
Heat exchangers; heat pumps; solar thermal storage units

Tritec Solar Industries Inc.
711 Florida Rd.
P.O. Box 3145
Durgano, CA 81301
(313)247-8497
Air-heating flat-plate collectors; heat exchangers

Turbonics, Inc.
11200 Madison Ave.
Cleveland, OH 44102
(216)228-9663
Heat exchangers

United States Solar Industries, Inc.
5600 Roswell Rd. NE, Suite 380
Atlanta, GA 30342
(404)252-1870
Air-heating flat-plate collectors; liquid-heating flat-plate collectors; pumps; heat exchangers; controls; solar thermal storage units

Vulcan Solar Industries, Inc.
Six Industrial Dr.
Smithfield, RI 02917
(401)231-4422
Liquid-heating flat-plate collectors; controls; solar thermal storage units

Western Solar Development, Inc.
1236 Callen
Vacaville, CA 95688
(707)446-4411
Liquid-heating flat-plate collectors; pumps; controls; solar thermal storage units

Wilkes Sun Energy Systems, Inc.
P.O. Box 1842
Hobe Sound, FL 33455
(305)286-5602
Liquid-heating flat-plate collectors

Ying Mfg. Corp.
125 W. 157th St.
Gardena, CA 90278
(213)770-1756
Liquid-heating flat-plate collectors; solar thermal storage units

Zomeworks Corp.
1221 Edith Blvd. NE
P.O. Box 25805
Albuquerque, NM 87125
(505)242-5354
Heat exchangers; pumps; controls

SOLAR PRODUCT MATRIX

	Cntrl	Liqfl	Evac.	Pumps	H.E.	Hpump	Store	Airft	Conc.	Track	Chill	ICS	Phase
Acro Energy Corp.		X											
Acurex Solar Corp.									X	X			
Alpha Energy	X												
Alpha Solarco		X							X				
American Solar King		X	X	X	X	X							
Amtek Power System	X	X					X						
Aquatherm Inc.					X		X						
Arco Energy Corp.		X			X								
Armstrong Pumps				X	X								
Artech Corp.							X						
Atlantic Solar Group		X											
Bally Case & Cooler							X						
Bio-Energy Systems	X	X			X	X	X						
Campbell Scientific	X												
Compool Corp.	X	X											
Cornell Energy Inc.												X	
Dulford Industries			X										
Doucette Industries					X								
Easco Alum./NJ Alum.		X	X					X					
Energdyne Corp.		X											
Energy Control Syst.	X							X					
Energy Harvestor									X				
Energy Materials Inc							X						
Energy Transfer Syst	X	X											
F.E.C. Inc.		X											
Ford Products Corp.							X						
General Energy Tech.													X
Grundfos Pumps Corp.				X									
Halstead & Mitchell		X			X								
Heart Sun Track Cntr										X			
Heliodyne Inc.	X	X											
Heliotherm	X	X		X	X		X						

SOLAR PRODUCT MATRIX

	Cntrl	Liqfl	Evac.	Pumps	H.E.	Hpump	Store	Airft	Conc.	Track	Chill	ICS	Phase
Heliotrope General	X												
Hordis Brothers, Inc	X							X					
Horizon Enterprises	X	X		X			X						
Hydro-flex Corp					X								
Insolarator Sol Prod	X	X											
JBJ Controls Inc.	X												
Joule Solartron								X					
Koldwave, Div H.E.						X							
KTA Solar Inc.		X											
Lane Maxwell Enter.	X	X					X	X					
Lennox Industries	X	X			X	X	X						
Mann-Russell Electr.										X			
McClintock Corp	X	X						X					
McDonnell Douglas									X				
Noranda Metal Indus.					X	X							
Novan Energy Inc.	X	X											
One Design Inc.							X						
Owens-Illinois Corp			X										
Pace Corp.	X						X	X					
P. & S. Hardware	X	X		X	X								
Phelps Dodge Solar		X		X									
Precision BendingNFG					X								
Pyramid Controls	X												
Ramada Energy Systems	X	X		X	X		X						
Raypak Inc.		X											
Revere Solar & Arch.		X											
Rheem Water Heat Div		X					X						
Rho, Sigma Inc.	X												
Robbins Engineering										X			
Ros-Aire Solar Corp	X				X			X					
Sealed Air Corp	X	X					X						

SOLAR PRODUCT MATRIX

	Cntrl	Liqfl	Evac.	Pumps	H.E.	Hpump	Store	Airft	Conc.	Track	Chill	ICS	Phase
Solarcone												X	
Solar Control	X				X								
SolarCorp of America	X	X		X	X	X	X						
Solar Dakota Inc.	X						X	X					
Solar Energies of CA		X						X					
Solar Energies of CO		X		X	X	X							
Solar Energy Sales	X	X					X						
Solar Industries Inc	X	X											
Solar MFG. Corp.	X				X								
Solar Products MFG	X	X		X	X		X						
SolResearchDiv frig		X			X								
Sol Research Systs.	X	X											
SolResourcesInternat									X				
Solar Span Corp	X	X											
Solartrac Inc.	X			X	X		X						
Solar Unlimited Inc.	X	X		X	X		X						
Solar Usage Now Inc	X	X			X			X					
Solatherm Corp					X								
Solex Corp		X			X								
Solway Corp												X	
Sungrabber Energy	X	X					X	X					
Sunmaster Corp	X		X		X		X						
Sun-Ray Solar Equip	X	X			X		X						
Sunsav, Inc.		X					X						
Sunshine Unlimited		X			X		X						
Sunwest Solar Systs.	X	X											
Sun Solector Corp	X	X	X		X	X		X					
Technitrek Corp		X											
Thermal Energy Systs					X	X	X						
Tritec Solar Indus.					X			X					
Turbonics, Inc.					X								

SOLAR PRODUCT MATRIX

	Cntrl	Liqfl	Evac.	Pumps	H.E.	Hpump	Store	Airft	Conc.	Track	Chill	ICS	Phase
U.S. Solar Indus.	X	X		X	X		X	X					
Vulcan Solar Indus.	X	X					X		X				
Western Solar Dev.	X	X		X			X						
Whiteline Inc.									X				
Wilkes Sun Energy		X											
Yazaki Corp		X									X		
Ying MFG. Corp		X					X						
York Div Borg Warner											X		
Zomsworks, Inc.	X			X	X								

NOTE:

Cntrl:	Solar system controls
Liqfl:	Flat plate liquid collector
Evac.:	Evacuated tubular collector
H. E.:	Heat exchanger
Hpump:	Heat pump
Store:	Thermal storage unit
Airft:	Flat plate air collector
Conc.:	Concentrator collector
Track:	Tracking system for concentrating collector
Chill:	Absorption Chiller
ICS:	Integral collector storage DHW heater
Phase:	Phase change collector

SOURCES:

1. Williams, J. Richard, Design and Installation of Solar Heating and Hot Water Systems, Ann Arbor Science, Ann Arbor, Michigan, 1983.

2. The Spec Guide: Energy Product Specifications 1985, SolarVision, Inc., 1985.

APPENDIX G

SYSTEM IMPLEMENTATION AND OPERATION

G. SYSTEM IMPLEMENTATION AND OPERATION

PASSIVE SYSTEMS

Direct Gain/Sunspaces

Direct gain systems and sunspaces are the easiest of the passive solar energy systems to build and operate. Is is during the design stage that careful attention must be given to placement, glazing selection, building integration, mass, shading, and venting. Once properly designed, these systems require only standard conventional construction practices.

During construction, special attention should be given to the tightness of the building envelope and proper installation of building insulation. Glazing should be installed according to manufacturer's instructions.

Little or no maintenance is required beyond that required for the rest of the building's exterior (periodic cleaning of the glazing and perhaps painting of exterior wood or occasional roof repairs). Seasonal tasks such as opening and closing moveable insulation panels or installing and removing exterior awnings may be necessary.

The exterior surface should be cleaned with a masonry cleaner before painting. Although any dark color may be used on particularly rough textured walls, flat black paint is preferred.

Glazing should be installed according to the manufacturer's instructions. It must be airtight and water resistant.

As with direct gain and sunspace, Trombe walls require little or no maintenance beyond periodic cleaning of the glazing.

Trombe (Mass) Walls

Trombe walls also require careful planning during the design stage. A few additional considerations are discussed here.

As with direct gain systems and sunspaces, construction of these walls requires general contracting skills. The junction between the inner storage wall and the adjoining surfaces, including foundation, floors, adjacent side walls, and roof, should be treated as normal construction. However, details that permit direct conduction of heat to masonry or metal exposed to the weather should be changed or eliminated. The concrete wall should be thermally isolated from the metal frame of the glazing system by wooden blocking and from adjacent conventional concrete construction by preformed vinyl or rubber control joints. Foundations directly below Trombe walls should be protected with rigid insulation in the same way as perimeter heating systems in slab-on-grade construction.

The interior finish of the Trombe wall should not prevent heat from reaching the room. It can have a conventional architectural concrete finish, such as exposed aggregate, and sandblasted or brushed surfaces may be used. The surfaces may be sealed and painted any color. A plastic skim coat or plaster may be used. However, sheet materials, such as wood or hardwood paneling, should not be used. Gyspum board can be used only if excellent continuous contact between the board and the wall can be obtained, which is difficult. Concrete finishing work may require subcontractors on the job site at other than normal times.

ACTIVE SYSTEMS

Preinstallation

As a rule, all major components of most active systems are specified by the system designer or kit manufacturer. Before beginning the installation, the following information and answers should be obtained:

The Supplier

Has the supplier of the major systems components been selected? Is help from the supplier readily available? Are replacement parts easily available? Is the suppiler's deilvery schedule reliable? Some of this information may be available from the supplier's other customers.

Legal Preparations

Has a building permit, if required, been prepared and approved? Have zoning requirements, if any, been met? Which building codes will require inspection of this installation? Will a licensed plumber be required to connect the plumbing system? Will a licensed electrician be required to make the electrical connections?

System Siting

The collector array should be placed where it will receive the maximum amount of sunlight available. A roof mount is the most common because it reduces the changes of shading and keeps the collectors out of the way. If a good roof area is not available, collectors may be ground-mounted. To minimize energy losses, outdoor pipe runs should be kept to a minimum.

Collector Orientation

It is desirable to mount collectors to capture as much of the sun's daily rays as possible. Ideally, collectors should be aimed as nearly as possible to true south, not magnetic south. However, vaiations of up to 15° east or west of true south will have little effect on performance if the system is running properly. It is not worth the added expense to build a special mounting frame to point collectors true south if the roof is pointed within the ±15° limits. Beyond 15°, additional calculations must be performed to determine if the expense is justified.

Collector Tilt

Collector tilt (the angle the surface of the collector makes with the horizon) is also an important factor in system performance. Ideally, collectors should be as nearly perpendicular to the sun's hottest rays as possible.

Collector Shading

No more than 5% of the collector area should be shaded between 9:00 A.M. and 3:00 P..M. local Standard Time, when the greatest solar potential occurs. One of the major sources of shading is trees. Chimneys, dormers, other buildings, new construction, and even fences may also shade the collector array. By knowing the altitude (angle of the sun above the horizon) and the azimuth (angle between true south and a point on the horizon below the sun) of the sun throughout the year, shading problems can be determined accurately.

Other Factors to Consider

Collectors should be placed near or slightly below, the mid-line of pitched roofs for best appearance. A location close to the ridge of the roof exposes the collector array to increased wind loading and heat losses.

Check to see if glare from the collector array will annoy neighbors or cause traffice hazards (particularly with ground-mounted collectors). A matte finish glazing material will help alleviate this problem. Collector boxes should be dark anodized if bare aluminum boxes create a reflection problem.

If the back of the collector is visible, an enclosure may be desirable to improve appearance, reduce heat losses, and protect the collector array from wind loading.

Mounting Procedures

Hoisting Roof Mounted Collectors

A typical collector weights between 34 and 91 kg (75 and 200 pounds). A method of hoisting the collectors to the roof should be planned well in advance of the intallation.

There are several types of load lifting devices that could be used, such as a bucket truck, cherry picker, crane, or fork lift. A simpler device is a roof hoist which may be temporarily mounted on the roof.

Manually lifting the collectors is possible, but it will require at least two people. One method is to use two parallel ladders with two people walking one collector up at a time. If the collector is outfitted with flanges, temporary handles may be attached.

The so-called "push and pull" method utilizes one ladder as a steep inclined plane. A rope is attached to one end of a collector. A person on the roof hoists the collector while another lifts and guides it up the ladder to prevent it from swinging out of control.

Precautions for Working on Roofs

Mounting procedures should be planned carefully to minimize the number of trips over the roof. Gravel roofs are more fragile than they appear, and the source of a leak in a gravel roof is not easy to locate. Walking must be done carefully. Planks or plywood should be put down in heavy traffic areas on gravel roofs.

Specially designed roofer's shoes are recommended on asphalt shingle roofs. Shoes with heavy lug soles should be avoided because they can damage shingles, especially in warm weather.

Wind Loads

It is generally recommended that the mounting structure be built to withstand wind velocities of at least 60 km/hr, (which impose a wind load of 40 pounds per square foot on a vertical surface or an average of 25 pounds per square foot on a tilted roof). Flat-plate collectors mounted flush with the roof surface should be constructed to withstand the same wind loads.

When mounted on racks, the collector array becomes more vulnerable to wind gusts as the angle of the mount increases. Collectors can be uplifted by wind striking the underside surfces. This wind load, which is in addition to the equivalent roof area wind loads, should be determined according to accepted engineering procedures. All mounting racks should be cross-braced.

Positioning Collectors

The collector array must be parallel with the ridge of the roof. Distance from the top of the collector array to the ridge line should be measured at each end and checked with a bubble level. A chalk line makes a useful guide. The array must be sloped toward the inlet to facilitate drainage at the minimum rate of 1/8 inch per foot (1 cm per meter). A spacing of at least 1/4-inch (0.6 cm) between collectors should be allowed for expansion and contraction which could loosen the mounting.

Collectors with weep holes should be mounted with weep holes at the bottom. These holes allow moisture to escape because condensation can damage some absorber surfaces. Holes should be loosely blocked with glass fiber that will prevent entry of dirt or insects but will allow a flow of air.

Installing Spacers

On retrofit installations, collectors should be at least 1.5 inches (4 cm) above the roof to avoid damage to shingles. Without that space, moisture buildup could cause growth of fungus, mold and mildew.

Spacer blocks of rot-resistant wood, such as redwood or cedar, should be used between the collector and roof surface. Other types of wood can be used if pressure treated with a preservative such as creosote or pentachlorophenol. Blocks of Plexiglass[R] or other UV-resistant plastic also can be used. Silicone sealant or fibrous roofing cement should be applied liberally between the spacer and roof sufface, or use a neoprene pad (this is illustrated in Exhibit G-1).

Instead of a block spacer, a mounting angle or clip can be used. It should be made of a metal compatible with the metal of the collector box and fastened directly to the collector box or flange, and bolted to the roof with a compatible metal fastener.

Spanner Mounting

If the attic is accessible, a spanner mounting is recommended because the uplift force of wind of the collector array will be evenly distributed to the roof framing members. 2" x 4" (5 x 10 cm) spanners should be screwed or nailed directly to the rafters inside the attic, perpendicular to the rafters. At least two, and preferably three, spanners should be used. Holes should be pre-drilled through the roof. Spacers large enough to accept the thru-bolts should be carefully mounted; they must not be split. It may be easier to drill holes and insert thru-bolts before securing spanners to assure proper alignment of holes.

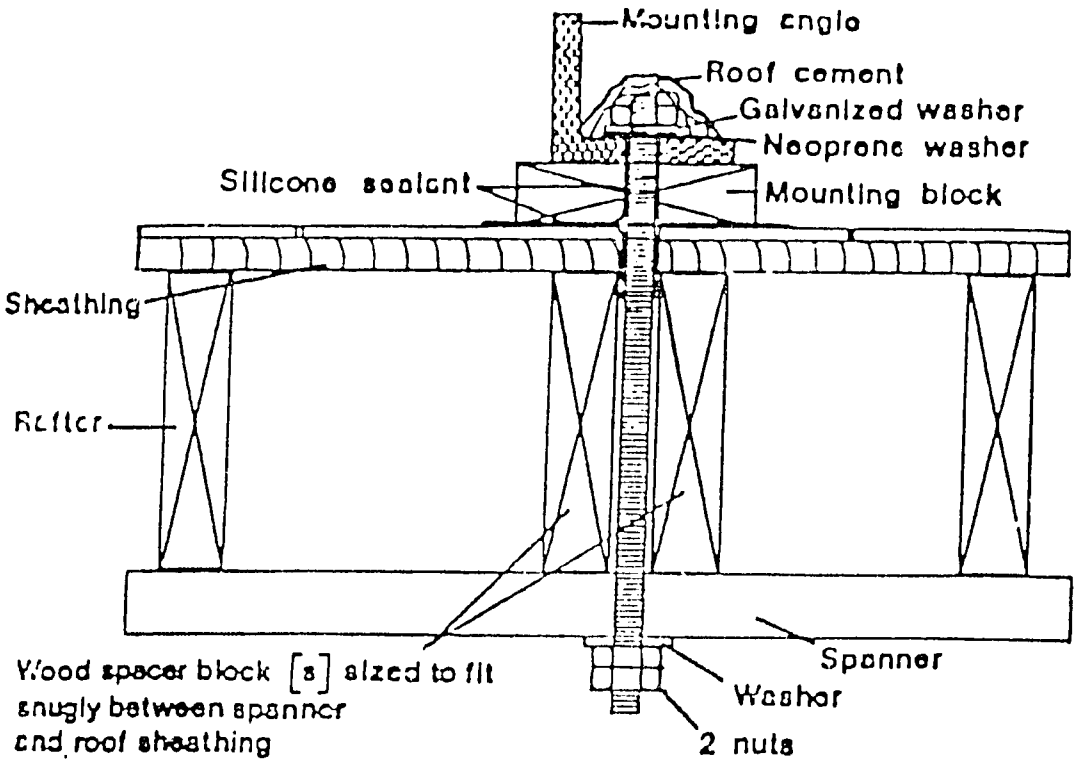


EXHIBIT G-1

Spacer Block with Spanner Mount

Rack Mounting

Collectors may be mounted on racks or standoffs to achieve the optimum tilt angle. If the holes or clips on the collectors do not line up with rafters or trusses, collectors can be mounted on a rack and the rack can be fastened properly to the framing members.

The rack should be constructed of slotted angle rails at least 12 gauge and about 1-1/2" by 1-1/2" in dimension (3.8 by 3.8 cm); normally used to fabricate warehouse shelving. The rails can be cut to any length and bolted together. The collectors should be bolted to the rail framework. Galvanic corrosion must be prevented here. The framework is lag-bolted or spannermounted to the roof, and roof penetrations carefully sealed. Asphalt tape may be used between the rack and the roof.

Mounting Techniques for Flat Roofs

On flat roofs, collectors can be mounted on uprights which are then fastened to the roof. The base of the upright is placed in a pitch container and both are simultaneously bolted onto the roof, by either the spanner or the lag bolt method (as illustrated in Exhibit G-2). The container should have a lip to accept flashing, which is extended down onto the roof surface. The container is then filled with pitch or roofing cement. Pitch pots require frequent inspection and do not have lasting watertight qualities.

Plumbing

The favored plumbing for active solar systems is sweat-soldered, type L copper tubing. Type M copper tubing is also acceptable if it is allowed by local building codes.

All joints in copper tubing in and near the collector array should be soldered with 95-5 tin-antimony solder to avoid joint failure at

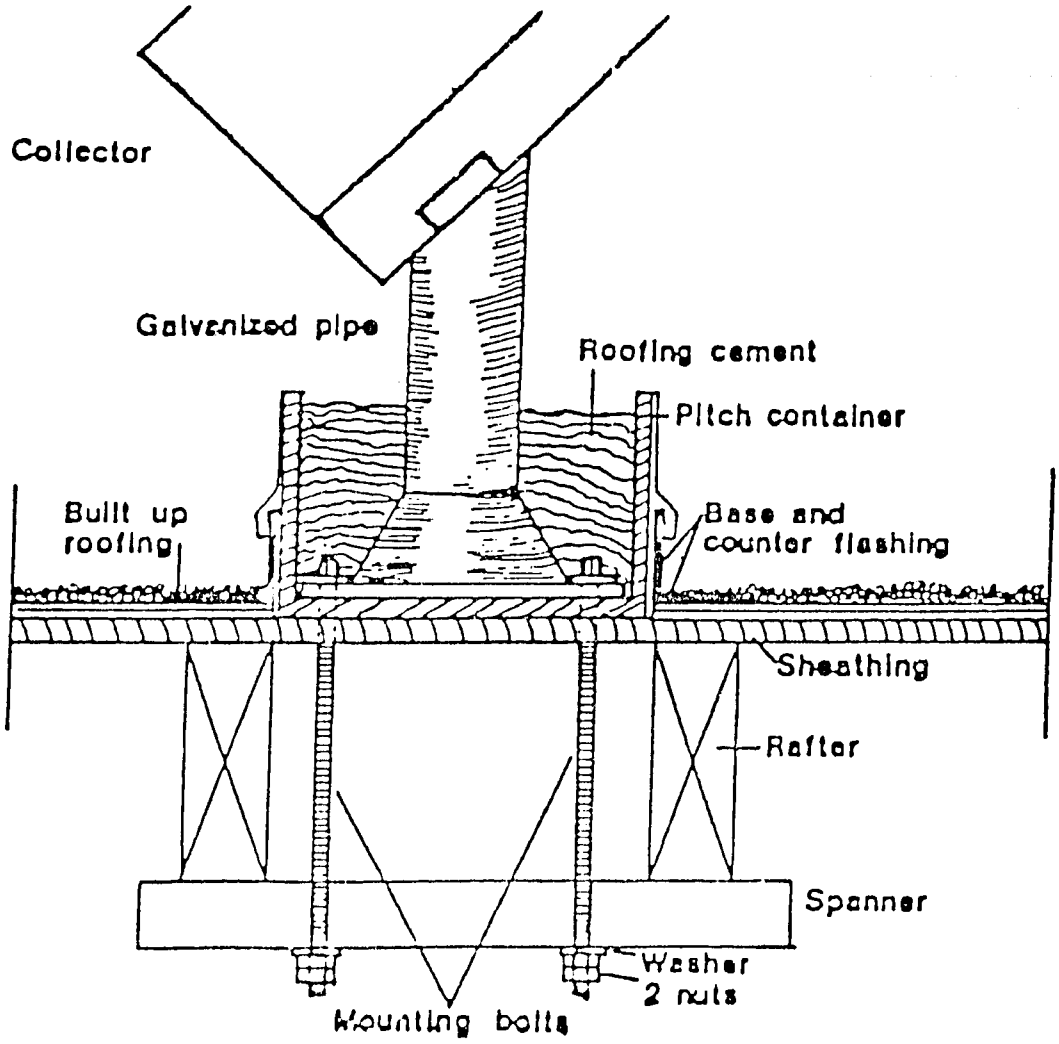

Collector
Galvanized pipe
Roofing cement
Pitch container
Built up roofing
Base and counter flashing
Sheathing
Rafter
Spanner
Washer
2 nuts
Mounting bolts

EXHIBIT G-2

stagnation temperatures. While 95-5 solder could be used throughout the rest of the system and should be used in a silicone system, 50/50 tin-lead solder can be freely substituted in those parts of the system that will be subjected to the extremes of stagnation temperature. Silicones and glycols demand well-soldered joints.

Plastic Pipe

Polyvinyl chloride (PVC) pipe should not be used for hot water applications. PVC pipe will sag at about 160°F (71°) if not adequately supported. This sagging prevents proper drainage or draindown of systems, make flushing out of nondraindown systems more difficult, and prevents air bubbles from venting properly. Polybutylene pipe will begin to sag at about 200o F (93°F). In general, extra care should be exercised when using plastic pipe.

Pipe Runs

Long pipe runs increase heat losses, pressure drops, installation costs, and may require installation of larger pipe. Pipe chases from rooftop collectors should be run through closets and between wall partitions. If pipes must be routed through rooms, they should be run as near to walls as possible, remembering that there must be a 2 inch (5 cm) gap between two pipes or between pipes and walls, for insulation. Pipes that have to be brought into the house from ground-mounted collectors should be routed as directly as possible, minimizing sharp bends and ells.

Expansion

All pipe should be hung or anchored loosely enough so that it can expand and contract with temperature changes. A 100 foot (30.5 m) length of copper pipe will expand approximately 1 inch (2.5 cm) with a 100°F (56°C) temperature rise. Using silicone hoses as expansion joints is

advised in arrays where there is no room for pipe expansion. Standard corrugated joints made of copper alloy are also available. Elbows will allow for some expansion.

Sizing

Typically, 1/2-inch (1.3 cm) pipe is used in systems utilizing up to three collectors, but certain fittings (for pumps, etc.) will have to be adapted to larger sizes. If total pipe runs are longer than 100 feet (30.5 m) 3/4-inch (1.9 cm) pipe may be required. Headers connecting the collectors should be of sufficient diameter to ensure equal flow rates through each individual collector.

Installation Type

Insides of all tubes or pipes must be kept clean. The ends of all pipes and tubing should be reamed out. Sandpaper or emery cloth should be used to clean the outside surface of the ends of copper tubing and the inside surface of all copper fittings before soldering. Surfaces must have a bright finish. Copper tubing should be bent (provided it is annealed or bending temper tubing) rather than use elbows or other fittings. This will reduce friction losses. Sharp bends must be avoided and bending tools should be used. Eccentric reducers are encouraged to join horizontal pipe of different sizes to avoid trapping air.

Reverse Return Hookups

It is desirable to connect collectors in a parallel reverse return mode. In this mode, the distance the heat transfer fluid travels is equalized. Balancing valves can be added for additional flow control if deemed necessary by the engineer.

Series Hookups

Collectors connected in a series mode obtain higher temperatures, thereby reducing collector efficiency. Series hookups are not recommended for solar DHW systems unless specificed by the engineer.

Insulation

Insulating active system plumbing prior to system startup is an important part of the installation procedure. Pipe insulation can typically be of the closed-cell foam type. All exposed pipes in the collector loop and all parts of conventional DHW systems, except the city cold water supply, must be insulated. All elbows, tees, valves, silicone hoses, pumps, and plumbing require insulation, butting right up to the collector array and storage tank. Insulation can be gouged out or pieced to fit over plugs and other hard-to-fit components. The pump motor housing, tempering valves, tops of air vents, and openings in vacuum breakers and relief valves should not be insulated.

The type of insulation best suited to a given installation depends on local costs, availability, job requirements, and insulating qualities of the materials. For pipe under 1-inch (2.5 cm) diameter, insulate at R-4; for pipe over 1-inch (2.5 cm) diameter, insulate at R-6.

Pumps

In an active solar system, the pump is usually a low-horsepower centrifugal circulator of about 1/4 to 1/25 horsepower. This pump may be specified by the engineer or included as part of a total parts package.

Pump Installation

The pump(s) must be electrically connected on a separate 15-amp service line to prevent any possibility of overload and pump failure. The pump should be located on the supply side of the collectors, as close to the

supply as possible, and below the top of the tank to retain its prime. Pump manufacturers' literature should be consulted for proper operating positions. Bearings on some pumps will wear out rapidly if the motor shaft is not in a horizontal position. Position of flow arrows on the pump must be checked to verify that flow is in the proper direction. The pressure gauge also will indicate if the impeller is running in the right direction. Some pumps can easily be installed backwards. Make sure adequate support is required on both sides if the pump is heavy enough to need support. Pump location should facilitate maintenance. The pump can be insulated, but the motor housing must not be, or the life of the pump will be greatly shortened. A strainer with a brass or stainless steel screen must be installed ahead (upstream) of the pump to remove metal filings, sediment, etc. that might damage the pump, clog collector passages, or cause galvanic corrosion in the system.

Valves and Gauges

Special attention must be given to the selection and placement of valves. The system may have a collector loop separate from the regular plumbing and may use toxic or nonpotable heat transfer fluids. A variety of valves and components are often needed; they will vary slightly from one packaged system to another.

Check Valve (One-Way Valve)

Check valves are designed to permit liquid flow in only one direction. They should be installed in closed-loop systems to prevent reverse thermosiphoning of heated water from the storage tank into the collector array.

Pressure Relief Valves

If the system is not operating and the collectors reach stagnation temperature, the pressure relief valve will permit steam to escape and prevent damage to the system. The relief valve may be installed anywhere

along the closed loop, but the general practice is to install it in the return side of the loop near the expansion tank and on the suction side of the pump. There should be a relief valve installed between all valves that can be closed manually or automatically. Collectors must not be allowed to be isolated without a relief valve in the line. The relief valve should be installed either after pressure testing or plugged during the test.

Tempering or Mixing Valves

This valve is used to add cold water to water from the storage tank that exceeds a present temperature, usually between 120°F and 140°F (49°C and 60°C). In DHW systems, this allows the collection of hotter solar-heated water while protecting users from being scalded. It should be installed 12 inches (30.5 cm) below the hot water outlet, with cold water entering from the bottom.

Air Vents

Air vents eliminate air bubbles from the system. Vents are installed at the high points in the system, usually in the collector manifold and above the air eliminator.

Automatic float vents are most commonly used. The cap on the automatic air vent must not be tightened; it should sit loosely on the threads. It is there only to prevent entry of dust or water which would clog the port. The vent must be mounted vertically on the top surface of the pipe or manifold.

Air Eliminator (Air Separator)

An air eliminator also removes air from the heat transfer fluid. The fluid flows across a series of baffles that causes air to bubble up out of the fluid stream. Air is then eliminated through an automatic air

vent. Eliminators are usually installed above the expansion tank and include threaded fittings that will mate with most tanks that would typically be used.

Balancing Valve

A balancing valve can be used to control the flow of heat transfer fluids through each collector panel in those systems that do not have a reverse return piping arrangement. A proper flow velocity though each collector is necessary for optimum efficiency. The simplest and least expensive type of balancing valve is the square head cock, which is installed between each collector an the manifold, downstream from the pump to prevent cavitation. Ball valves or globe valves are also commonly used. A gate valve must not be used for balancing.

Vacuum Relief Valves

Vacuum relief valves are used in draindown systems and are installed at the high point of the system above the collector. This valve permits the system to drain by admitting atmospheric pressure into the return piping. It is sometimes installed above the cold water inlet of storage tanks to eliminate vacuum conditons that could collapse the tanks.

Isolation Valves (Shutoff Valves)

Isolation valves should be installed to permit certain components to be serviced without having to drain and refill the system.

Isolation valves should be placed at the following locations:

1. One on each side of the circulator pump and its associated strainer.
2. One at the cold, or city water, supply inlet (to shut down the entire system).

3. One on either side of an external heat exchanger for servicing.
4. One on each side of the screen or strainer (ahead) of a pressure regulator.

Isolation valves should not be installed in a way that could isolate collectors from pressure relief valves or temperature and pressure relief valves, and the expansion tank. If this occurs, collectors could burst during stagnation conditions.

Boiler Drain Valve

There should be one boiler drain valve at the bottom of the storage tank for draining and periodic cleaning. There should also be two on the collector loop near the storage tank. These two valves are used for "charging up" the system using a pump and they should be separated by an isolation valve, which can be closed for system charge-up until the air is purged. After the system is charged and capped, remove the valve handles and label the valves with the charge-up date.

Pressure Gauge

A suitable preessure gauge should be installed on the collector loop or on the top of the air eliminator.

Expansion Tank

An expansion tank is a necessary component of a system which has a closed circulation in the collector loop. As the temperature of the heat transfer fluid in the loop rises, the volume of fluid expands. The apparent expansion rate per degree of temperature rise will depend on the heat transfer fluid.

Installation

The expansion tank should be placed on the suction side of the pump in the collector loop. A diaphragm tank can be installed either upward or downward without seriously affecting performance. Downward installation is preferred to reduce heat loss. A pressure gauge should be provided by the manufacturer for installation with the expansion tank. The valve must not be adjusted. The air side of an expansion tank is prepressurized by the manufacturer. If it is necessary to change the air charge in the tank, this can be done via a threaded valve on the tank bottom. Butyl rubber diaphragms will deteriorate when in contact with oils or water/glycol heat transfer fluids. If glycols are being used, the diaphragm should be of neoprene or some other suitable material. Oils require a nondiaphragm expansion tank.

Storage Tanks

Water is by far the most common storage medium in an active solar system.

Single-Tank vs. Two-Tank Systems

A backup conventional domestic hot water (DHW) heater can be installed as part of a solar DHW storage tank or connected in series with it. For example, a single-tank solar DHW system can be made from an adapted electric water heater of sufficient size by disconnecting the lower of the two electrical heating elements from the power source. There are also tanks now available with one element in the middle for solar applications. In draindown and drainback systems, the collector supply line outlet is generally located in the lowest third of the storage tank to draw out the coldest water and circulate it through the collectors so they will work at highest efficiency. Combining both auxiliary and solar DHW storage in one tank does reduce the system's storage volume. A one-tank solar DHW system will probably require a larger tank than conventional DHW systems.

In a two-tank system the solar DHW tank serves as a preheat and has a cold water inlet. Supplemental heating takes place in the conventional DHW tank. Two tanks require more floor space, and standby losses will be greater. However, in a two-tank installation collectors often will receive lower inlet temperatures, improving their efficiency.

The source of auxiliary heat is also a consideration. Because a gas hot water heater will not stratify, two tanks may be more desirable. An electric backup with the lower element disconnected may function better in a one tank configuration.

Inspecting Storage Tanks

After the tank is delivered to the job site, it must be thoroughly checked for obvious signs of damage. It may be wise to pressure test it before putting in in final position, because the tank may be difficult to move once properly placed. Check the condition of the the in-tank heat exchanger, if there is one. If the heat exchanger coil is suspended in the tank, bouncing around during shipment may have damaged it. Damaged tanks must be rejected.

Placing Storage Tanks

The best optimum storage tank location is near the existing components with protection from moisture and cold, near the point of use, and in an area where drainage, leakage, or valve-venting will not cause damage. In most cases, this would probably be in a cellar or an enclosed porch. Tanks should never be installed in areas where flammable liquids are stored.

Installation

When installed, the storage tank should be leak-tested before insulation is added.

System Controls

The task of the controller is to enable the system to collect as much useful heat as possible and deliver this heat to meet the demands of the system's users. The three basic components of a controller are the sensor subsystem, the differential thermostat, and the output subsystem.

Sensor Subsystem

Sensors measure temperatures in various parts of the system and send signals to the differential thermostat. Several types of sensors are used in solar applications. Sensors should be able to withstand collector stagnation temperatures. Because the controller generally is calibrated for a particular sensor, the sensors supplied by the manufacturer should be used. One sensor is mounted at the bottom of the preheat storage tank and the other on the collector absorber plate or on the outlet pipe. Proper sensor location must be verified.

Differential Thermostat

The differential thermostat receives signals from the sensors and uses this input to control the system. It is usually factory-set for high and low temperature differentials to maximize the amount of heat energy collected and stored, and to minimize excessive cycling. This reduces wear on pumps, blowers, and relays and minimizes the amount of power necessary to operate the system.

Output subsystem

The output subsystem delivers the appropriate control voltages from the differential thermostat to appropriate pumps.

Switching is done either with conventional relays or with solid state relay circuits. Conventional relays withstand momentary overloads caused by accidental shorting or by close lightning surges.

Mounting the Control Panel

All controls and equipment must be properly grounded and plug-in connectors should have built-in grounds. All equipment requiring electrical connectors over 50 volts should have a positive means of disconnect adjacent to and in clear sight of the controller and other equipment.

The system should ideally be installed on a separate unswitched circuit or, if necessary one with a very light load. Failure of the controller because of an overloaded circuit could result in expensive damage to the system. Power supply to the controller is usually 120 volts. The control system wiring is low voltage, usually 24 volts, and 20- or 22-gauge thermostat or bell wire is normally used. Shielded wire should be used if there is evidence of high voltage interference with the low voltage signal.

System Startup

When installation is completed, the system must be checked for leaks before it is charged for use. The type of system will determine what leak test and charge-up procedure should be followed. Collectors must be kept covered; manufacturer's printed instructions should be closely followed.

Closed-Loop System-Hydrostatic Test

All elastomeric pipe insulation must be pulled back from joints and component connections and held by clamps during leak testing. All gauges, relief valves, and expansion tanks must be removed and their

openings plugged. These components may be damaged if tested at pressures greater than their design limits. All fill and drain valves must be closed.

The collectors must be covered (they must be at a constant temperature). The system should be filled with water and brought up to test pressure. For best results, the system should be tested for not less than one hour at 1-1/2 times maximum design pressure.

If leaks are observed during a check of joints, leaking joints must be tightened or resoldered and the system should be retested. After the test, the testing media must be drained completely into a container in order to measure the system volume. This will determine the proper amount of heat transfer fluid needed (or the amount of glycol needed to make another batch of antifreeze mixture) to refill the collector loop.

Charging the System

After the system is leak tested, it must be flushed out and then charged. The collector loop can be filled either manually from the roof or by pumping from the lowest point in the system.

Flushing the System

All metal filings, solder, silt, and other contaminants not cleaned out of the system during hydrostatic and drain line testing must be flushed out. Collectors must still be covered and the controller must be off (inoperative).

Fill and drain valves are to be opened and the isolation valve between them closed. A small hi-head self-priming pump (of the type used to pump out cellers) should be connected to the fill valve in the direction of flow with the feed line hose in a large bucket filled with water. This fill hose can be attached directly to the water supply. Another

hose can be attached to the drain valve and routed to a drain. The pump should run for 10-15 minutes. After this point, the strainer screens must be removed and cleaned. Water cannot be used to flush out any systems or parts of systems that use hydrocarbon or silicone heat transfer fluids.

Filling From the Bottom

To fill, the flushing procedure is repeated with a bucket of heat transfer fluid. The pump should be operated for about 20 minutes to purge air from the system by recirculating the same fluid. The drain valve should be closed and the system allowed to pressurize. At this time, the return drain valve should be closed and the isolation valve should be opened. After the valve is opened, the pump is shut down and the drain is capped and tagged with fluid type, fill date, and emergency procedures. This information should be displayed on a wall chart by the switch box. At this time, operation of the controller is resumed in automatic mode and collector covers can be returned.

Maintenance

All active systems should be inspected at least once yearly in addition to any periodic maintenance that may be required for the components. A log of all system maintenance should be kept.

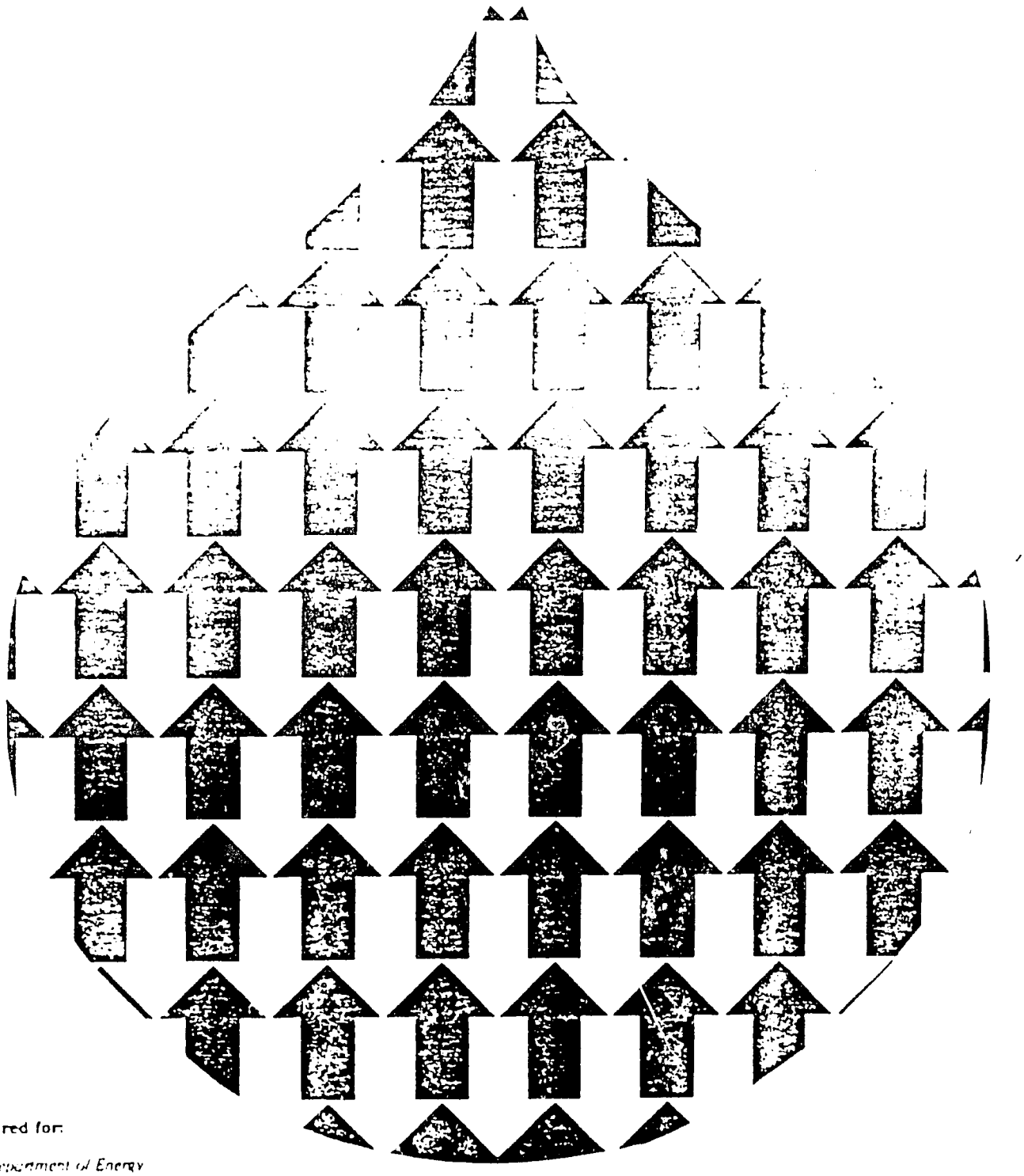
The outer glazing of collectors should be cleaned regularly. The collector sensor should be inspected periodically to be sure it is making good thermal contact. If the glazing is broken, the system must be shut down immediately and the collector array must be covered with a sheet, tarp, or opaque plastic drop cloth until the glazing can be replaced.

APPENDIX H

MOISTURE AND HOME ENERGY CONSERVATION

MOISTURE AND HOME ENERGY CONSERVATION

How to Detect, Solve and Avoid Related Problems



Prepared for:

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Small Scale Technology Branch
Alternate Technologies Division

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ECTION I

AT THE ROOT OF THE PROBLEM

Moisture problems can be tricky to solve, yet with an understanding of the basic controlling forces one can usually predict where, how, and when a moisture problem could occur. In this section, the roots of most moisture problems are explained, including climatic differences and the physical forces that can affect moisture. How weatherization affects moisture's behavior is emphasized, and the range of general solutions to moisture problems is covered, to allow the reader to relate basic principles described in this section to actual building practice.

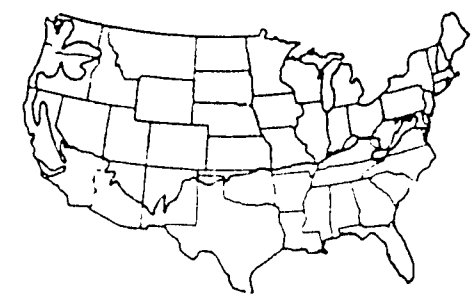
Moisture Problems Can Vary by Region or Climate

Although moisture problems can surface almost anywhere in the United States if conditions are right, certain climate zones and regions are more prone to particular problems.

More than half the country is moderately or highly prone to wood decay due to outdoor humidity levels (see Figure 1). In many of these areas, mold, mildew, and rot are constant problems. High outdoor humidity can also lead to considerable summertime cooling and dehumidification expense, as well.

In locations where January temperatures average 35°F or below, wintertime condensation problems can occur (see Figure 2). Buildings in this region need special treatment to avoid condensation damage to building materials.

Although climate differences provide a framework for looking at the forces that control moisture, building design and construction and occupant behavior also play critical roles with moisture troubles.

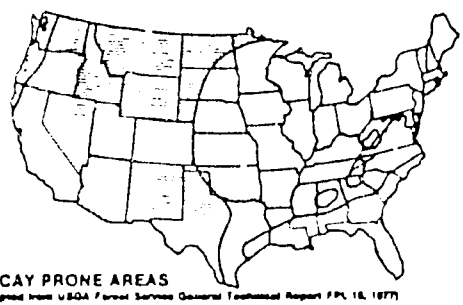


WINTER CONDENSATION ZONE

(Adapted from USDA Forest Service Information Bulletin No. 273, USGPO)

AVE. JAN. TEMPERATURES OF 35°F OR BELOW (AREAS WHERE VAPOR RETARDERS ARE RECOMMENDED)

FIGURE 2



DECAY PRONE AREAS

(Adapted from USDA Forest Service General Technical Report FPL 16, 1977)

HIGH

MODERATE

LOW

FIGURE 1

Moisture Transfer Methods

Moisture can be present in a home in three different forms: as a vapor (gas), liquid or solid. Thus, a number of physical factors influence moisture's behavior in a home. Water vapor travels in two principal ways—air movement and diffusion. Liquid water travels by capillary action (see Figure 3).

Air movement is the major water vapor transfer method, in that more moisture is moved by this means than by the others. Air movement is largely determined by several factors, including vapor pressure, wind, convection and temperature differences that set a "stack effect" in motion (see Figure 4).

In climates that require home heating in winter, *high water-vapor pressure* may be created indoors when moist air is heated. (Water-vapor pressure is the contribution made by water to the total atmospheric pressure.) Because high vapor pressure always seeks to move moisture toward areas of lower vapor pressure, this warm, moist air tends to be driven through cracks and holes in the building, where it can condense if temperatures are right, causing the potential for deterioration of building materials. In warm, humid climates that demand interior cooling, the high vapor pressure can come from the outdoors, pushing moist air toward the interior of the house.

As *wind* strikes a building, it creates additional air pressure effects. The upwind side of the building (the side hit by the wind) experiences higher pressure, with the wind pushing toward and into the building. Walls on the low-pressure or downwind side of the house may show more signs of moisture because the warm, moist air is being drawn to the outdoors through that section.

The *stack effect* illustrates the fact that warm air always rises. The higher the temperature of the air, the greater the upward thrust or buoyancy of that air. As warm air rises and escapes through the upper regions of the house, it creates a lower pressure situation in the lower areas. Cooler outdoor air is then pulled into the low pressure areas, and the cycle continues as this air is warmed and rises.

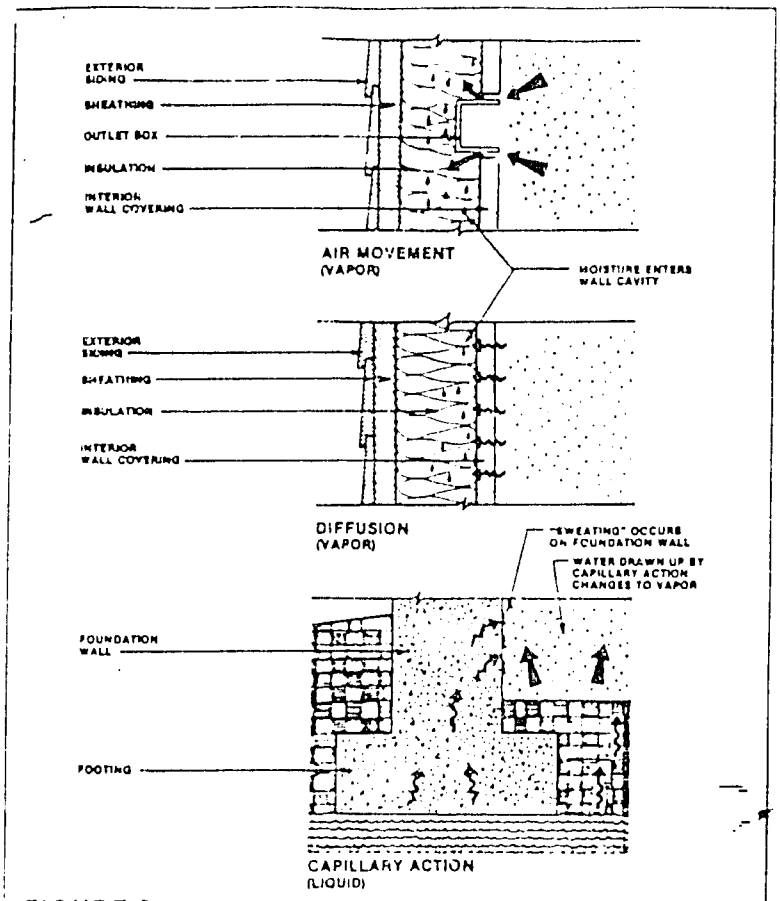


FIGURE 3: MOISTURE TRANSFER METHODS

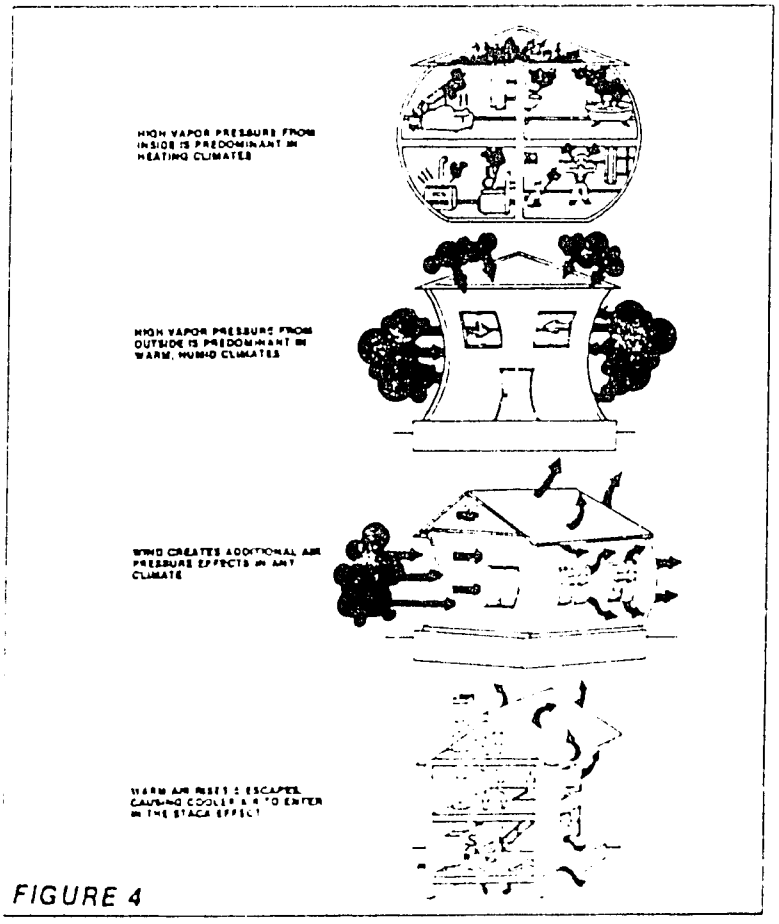


FIGURE 4

Convection describes the action of warm air moving upward until it is cooled or strikes cooler surfaces, such as windows. As the air is cooled, the amount of water vapor it can hold decreases, and condensation can take place. The cooled air then falls until it is reheated, and the process begins over again. Convection currents occur throughout the interior space of the home, powered by temperature differences. Air movement through convection can also happen in wall cavities and other enclosed areas of the building, which can reduce the thermal effectiveness of the insulation, as well as cause moisture problems (see Figure 5).

In cold climates, after a house has been weatherized by sealing, caulking and weatherstripping air leaks, air movement is reduced, and less heat and moisture escape. Tighter homes usually have greater comfort levels and lower fuel bills. However, if there are a significant number of moisture sources in a tight home, ventilation may not be great enough to remove moisture as fast as it is produced. And, in extremely tight houses, controlled ventilation through heat-recapturing devices, such as air-to-air heat exchangers, must be employed to remove normal moisture build-up and potential indoor air pollution.

After a house has been thoroughly sealed, moisture transfer through *diffusion* becomes more important. Because the amount of water vapor that escapes through air movement has been cut to a minimum, water vapor must find another avenue of exit. Water vapor always attempts to move from high vapor pressure areas to low vapor-pressure areas; thus, water vapor will pass directly or "diffuse" through building materials. Water vapor that penetrates a surface may be cooled to the point where it turns to liquid or ice, which creates the potential for damage.

Vapor retarders (also known as vapor "barriers") are allowed to slow diffusion through building materials. Good vapor retarders allow very little water to pass through them; they should always be located on the *warm side* of the wall, ceiling or floor surface. With some of the new cold-climate building technologies, vapor retarders are used to slow both air movement and water vapor diffusion. If used in this manner, the vapor retarder must be installed with great care; any air leakage points that remain will experience relatively greater vapor pressure, as water vapor works to escape through the easiest route.

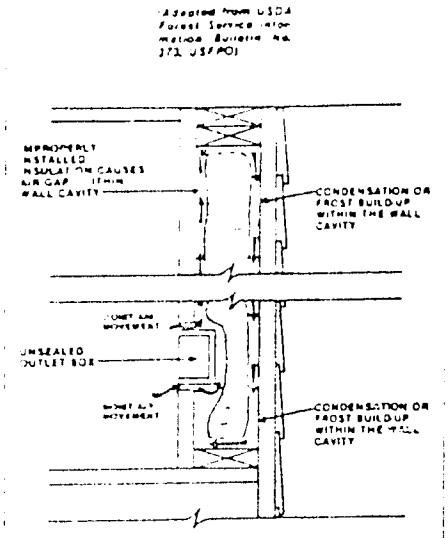


FIGURE 5: HOW CONVECTION CURRENTS BRING MOISTURE INTO WALLS AND REDUCE INSULATION EFFECTIVENESS.

Vapor retarders also are used to reduce moisture transfer from *capillary action*, which involves liquid water being pulled from a source through a porous material, such as soil, that provides pathways for water transfer. In this use, vapor retarders don't actually stop the capillary action, but rather they prevent moisture from entering the air, which can then enter the house.

Relative Humidity and Dew Point

When designing an insulation job for new construction or retrofit for climates in the condensation zone (locations where January temperatures average 35°F or below), care must be taken to use vapor retarders effectively. This demands knowledge of the concepts of relative humidity and dew point temperatures.

Air temperature determines how much water vapor air can hold. Warmer air is capable of holding much more moisture than cooler air. The temperature at which air has been cooled to the point where water vapor condenses to liquid is called the "dew point."

One goal with vapor retarders is to keep the warm, moist air in the house from coming in contact with temperatures below the dew point. This is why vapor retarders are located on the warm side of the surface. The cold side of these surfaces must be backed with materials that can breathe, to allow any moisture that does not pass through to escape.

To determine the dew point temperature requires that one know the air temperature and relative humidity. Relative humidity describes the amount of moisture air holds relative to the maximum it could possibly hold at any given temperature. (Relative humidity should not be confused with *absolute humidity*, which simply describes the total amount of water vapor in the air.)

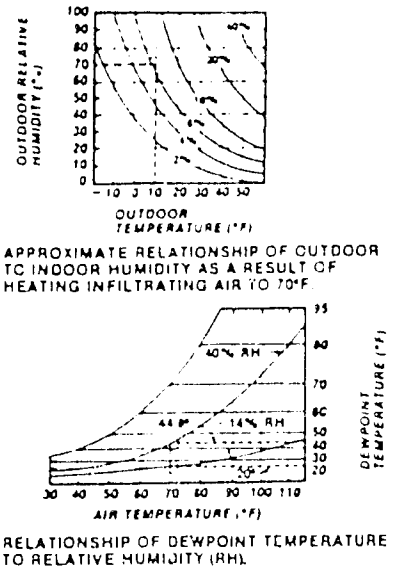
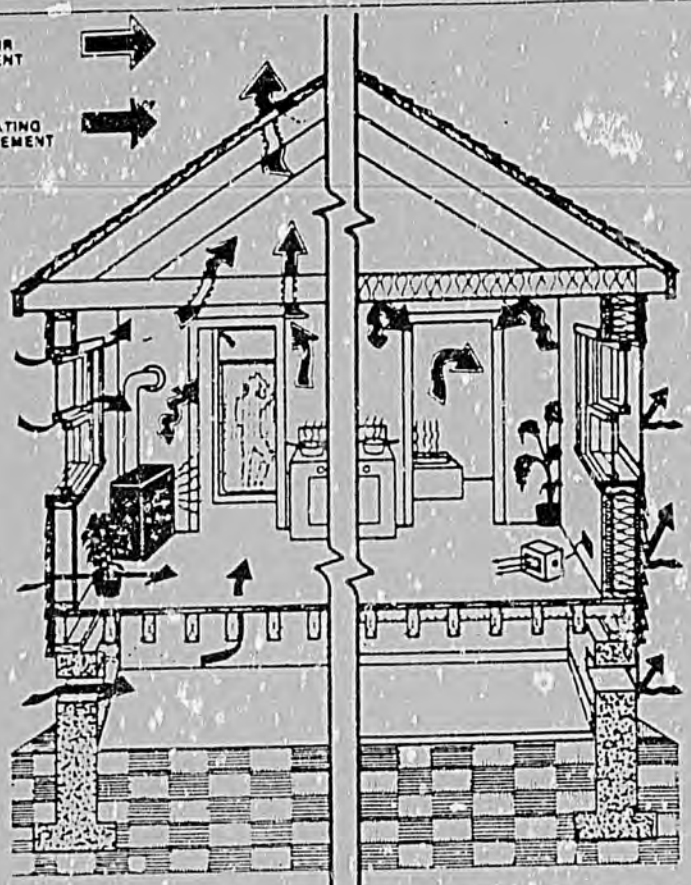


FIGURE 6

For example, assume that the outdoor air has a temperature of 10°F and 70 percent relative humidity. If this air enters a house where it is warmed to 70°F, the air's relative humidity would fall to 6 percent, because the warm air can hold so much more moisture than the cold 10°F air (see Figure 6). Cool, outdoor air will generally have higher relative humidity than warm, indoor air, yet the indoor air could have much higher absolute humidity.

The higher the relative humidity, the higher the dew point temperature. If a house has an air temperature of 70°F and the relative humidity is 40 percent, the surface temperature at which moisture will condense is 44.6°F. If the relative humidity falls to 14 percent, the dew point temperature would fall to 20°F.

These examples illustrate that the higher the relative humidity in a house, the greater the chance that some surface will be cool enough (even in moderate or warm climates) to cause condensation. For this reason, keeping indoor relative humidity below about 45 percent, if possible, is a good way to avoid many moisture problems that may be related to constantly high indoor relative humidity.



BEFORE WEATHERIZATION

- HIGH AIR INFILTRATION
- LOW HUMIDITY

AFTER WEATHERIZATION

- LOWERED AIR INFILTRATION
- INCREASED HUMIDITY

FIGURE 7

The relative humidity concept also explains why indoor air may become uncomfortably dry in cold climate homes during the winter. If the house has significant air infiltration, cool, outside air will be drawn into the house through cracks and leaks, where it will be warmed. Similarly, warm, indoor air will be pushed out of the house. The cool, outdoor air can absorb additional moisture as it is warmed, and it draws moisture from the air, surfaces, skin and other moisture sources. Thus, stopping air leaks in a house can save energy both from saved heat and the energy used to run humidifiers (see Figure 7).

On the other hand, this drying action can have a positive effect in humid climates. The process of drying air or wet surfaces involves four main actions: the intake of dry air, the warming of that air, the circulation of the air and the exhausting of the warm, moist air. The intake air must be drier than the air inside the house for drying to take place.

Effective drying involves good circulation and ventilation or exhaust. If air circulation is poor, moist air can become trapped and may not reach exhaust points in the house. Heat may not reach certain areas of the home, allowing some surfaces to cool to the point where moisture will condense and cause problems. Homes with good circulation can generally maintain somewhat higher indoor relative humidity without significant problems.

Obviously, a certain level of whole-house *ventilation* is needed to remove normal moisture and indoor air pollutant buildup from the usual activities of daily living. If the overall ventilation rate is too low, moisture problems may be the first sign that indoor air quality is less than adequate. However, localized ventilation in kitchens, baths and other high moisture areas can solve many moisture problems. If this spot ventilation is used regularly and a home still has significant moisture problems, the home probably has some major moisture sources that have been overlooked. Enclosed areas that are not heated or cooled, such as attics, crawlspaces, porches or basements need adequate ventilation and circulation to provide drying that helps avoid moisture build up and condensation damage.

The Moisture Balance

Four factors dictate whether a home's moisture balance will become uneven enough to cause problems. These four balancing factors are *source strength, temperature, moisture transfer rate,* and *circulation-ventilation rate.* In a home without moisture problems, these forces are typically in balance. These factors are critical to understanding and solving home moisture problems.

Source strength is often the most important factor, in that moisture problems can't exist without sources of moisture. Controlling the source of a moisture problem is usually the most productive and cost-effective approach to solving the dilemma. Examples of indoor source-reduction solutions include fixing plumbing leaks, reducing moisture from domestic activities and reducing humidifier use. Outdoors, source-reduction solutions include improving drainage, fixing leaks, and being aware of soaking and puddling from sprinkling. If sources can't be reasonably or affordably controlled, then it's time to try another route.

Temperature differences that promote unwanted condensation should be remedied. Temperature solutions include: bringing warm air to cold surfaces through improved heating patterns, insulating the surface against cold temperatures, installing vapor retarders, and simply being aware of temperature differences and not allowing warm, moist air to contact surfaces, such as walls in basements or crawlspaces.

The *moisture transfer rate* in a home can be altered in several ways. These moisture transfer solutions include sealing air leaks from inside the home, weatherizing before insulating, use of vapor retarders on the warm side of the wall or surface, use of ground-cover vapor retarders in crawlspaces, stopping all exterior leaks and puddling of water, and increasing the moisture resistance of exterior wood.

The *circulation-ventilation rate* of a home can be adjusted to help solve moisture problems. Venting moisture out of enclosed areas is a basic, common solution. Increased circulation and ventilation are also back-up options when internal moisture sources can't be reduced sufficiently. Circulation and ventilation solutions include installing properly sized vents located to promote circulation, using materials that can "breathe" on the cool side of moisture-resistant surfaces, using spot ventilation of high moisture areas such as baths and kitchens, using small, efficient fans to move internal air through a house, or use of air-to-air heat exchangers to exhaust moisture but reclaim heat or coolness.

SECTION II

SYMPTOMS, CAUSES AND BASIC SOLUTIONS TO EXCESS MOISTURE

Recognizing and diagnosing moisture problems is the first step in solving them. Once the symptoms and source of moisture have been positively identified, the problem usually can be approached in several ways. Some moisture problems can best be handled by a change in occupant habits or lifestyle, while other problems demand structural repair or other improvements that are best handled by a skilled person.

In this section, the common symptoms of excess moisture are identified, and the most common moisture sources, both inside the house and outside, also are listed. Following each moisture source, possible solutions to the problem are presented, to make the reader more familiar with the range of solutions that could be applied to each problem. Also, DOE project examples are given to illustrate how grantees discovered, dealt with or solved various moisture-related troubles.

Detailed information on tackling specific moisture problems is presented in the next section, *Fixing the Problems*.

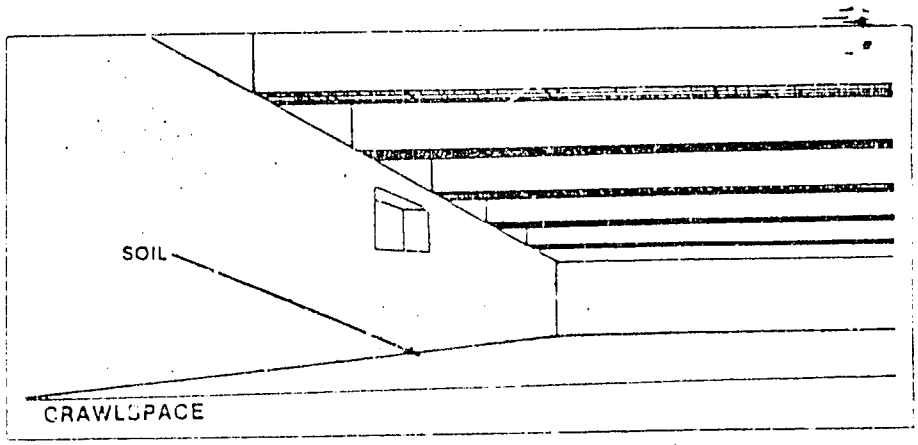
Defining the Problem: Symptoms of Excess Moisture

Symptoms of excessive moisture can usually be sensed in some way, though the process of detection can sometimes be difficult. Some symptoms are easily seen, while others demand the use of our senses of smell, touch or hearing. Successful detection is based on becoming aware, doing a thorough search and using all one's senses.

Many symptoms of excess moisture are readily apparent and not easily overlooked. Thus, focusing on the less-obvious symptoms is a good habit to adopt. Bear in mind that some moisture symptoms may be seasonal and may not be evident during the time of inspection. For example, the soil in a crawlspace may appear dry in mid-winter; however, the subsurface could have a high moisture source from summer irrigation, drainage, or ground water. One clue, in this situation, might be a damp feeling when entering this area.

One of the major challenges in solving excess moisture problems is that one symptom can have several causes. Conversely, one moisture source could be causing a large number of seemingly unrelated symptoms.

The following list describes the major symptoms commonly encountered in homes with moisture problems:



- **Odors**—Odors increase in intensity with high relative humidity. Musty odors may signal mold, mildew or rot. Also, odors from everyday household activities that seem to linger too long may be a signal of less-than-adequate ventilation.
- **Damp feeling**—The sensation of dampness is common in areas with high relative humidity.
- **Mold, mildew**—Growths of mold or mildew can often be seen in the form of a discoloration, ranging in color from white to orange, from green to brown to black. If they can't be seen, they may often be noticed as a musty odor. Mold and mildew are surface conditions that may indicate that conditions favoring decay are present.
- **Discoloration, staining and texture changes**—These are usually indicative of some degree of moisture damage, no matter what the material. These changes may appear as black or dark streaks or lines, which border a discoloration. The area in question may not be wet at the time of inspection, but it obviously has been subject to some moisture source.
- **Rot, decay**—Rot and wood decay indicate advanced moisture damage. Unlike surface mold and mildew, wood decay fungi penetrate the wood and make it soft and weak. Look for any type of rot or fruited bodies (mushroom-like growths). (Refer to the Pick Test in Appendix A for more information on detecting wood decay.) Decay fungi grow in a temperature range from just above freezing to 100F. Wood decay usually happens at a fast rate in the middle temperature range, 50°F to 75°F if wood is more than 30 percent saturated with moisture. Fungi growth is slow below 50°F and above 90°F. At below freezing, fungi go dormant, and at 150°F, most spores are killed.
- **Water-carrying fungus**—This fungus is special—it carries water across surfaces, sometimes to distant locations. It looks like a fan, with vine-like strands emanating from it. These growths are papery,

and usually have a dirty, white color with a tinge of yellow. This fungus fan can spread over moist or dry wood, and can be found under carpet, behind cupboards, on framing between subfloors or on damp concrete foundations.

- **Fogging windows**—Condensation on windows and other smooth surfaces can be a sign of excess moisture, or the need to insulate or warm the surface in question. Another possibility is a faulty heating plant, or some other flame-fired appliance, which is causing excess moisture and combustion gases to enter the living space. Physical symptoms include frequent headaches, drowsiness, or other unexplainable illnesses. This possibility should be checked at once.
- **Sweating pipes, water leaks and dripping**—Water vapor may be condensing on cold pipes, or the pipes may be leaking.
- **Frost and ice**—Roof ice dams occur both in roof valleys (where two roof lines meet) and along the eaves. They frequently occur when there is insufficient ceiling or attic insulation and poor ventilation in the roof, problems that are aggravated by the freeze-thaw cycle. Snow or ice melts as the sun strikes the roof and as the interior roof surface is warmed from within. This moisture freezes again when temperatures drop, forming dams that impede drainage. Ice can build up under shingles, which eventually can result in moisture penetrating into the attic when temperatures rise. Frost or ice on any surface is an indication of possible trouble.
- **Paint peeling, blistering or cracking**—Moisture may be working from outside or inside the home to damage paint. A major signal of moisture-caused paint damage is when the raw surface is exposed between cracks or under blisters.
- **Corrosion**—Corrosion, oxidation and rust on metal is a sure clue that moisture is at work.
- **Deformed wooden surfaces**—Wood swells when it becomes wet, and it warps, cups, and cracks when allowed to dry. Shrinking, warping wood can cause new air leaks in the home, making it less energy efficient.
- **Concrete and masonry efflorescence and chipping**—Concrete or masonry may show sign of "efflorescence"—a white, powdery substance or line—after moisture has moved through it. Freeze-thaw cycles speed the process of deterioration, causing chipping and crumbling.

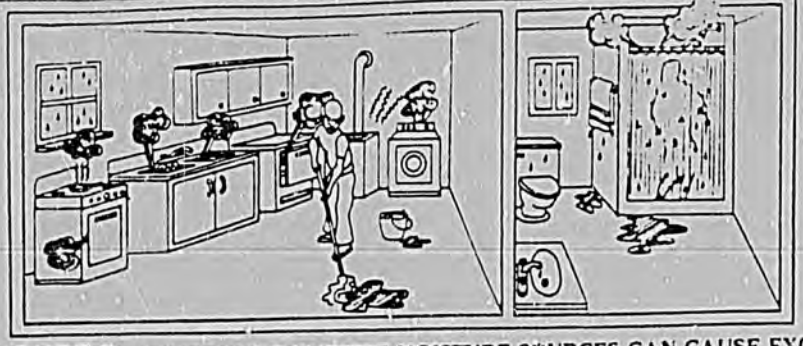


FIGURE 8: NUMEROUS DOMESTIC MOISTURE SOURCES CAN CAUSE EXCESS MOISTURE AND HIGH INDOOR RELATIVE HUMIDITY.

Common Causes and Basic Solutions to Moisture Problems

Sources of moisture can be found both inside and outside the home. Outdoor moisture sources usually stem from three main causes: poor drainage, blocked air circulation and high outdoor relative humidity. Indoors, the situation is more varied and complex; sources range from cooking habits to poor circulation. By focusing on the more common moisture sources and possible solutions to each problem, the reader can become familiar with the problems to be experienced in the home.

Indoor Causes

Continually High Relative Humidity Indoors—Many sources of excess moisture can lead to continually high indoor relative humidity levels. Prolonged high indoor relative humidity—above about 45 percent—can cause a wide variety of problems. Check each possible moisture source, and take corrective action. If in doubt, test for relative humidity, using the Relative Humidity Test described in Appendix A.

Too Many Occupants; Small Buildings—People, pets and domestic activities generate moisture; buildings under 800 square feet tend to be more prone to moisture problems. Check how many occupants (both people and pets) live in the building. If there is less than 250 square feet of living space per person or pet, there could be a problem. Also watch for seasonal changes in occupancy.

Possible Solutions: If occupancy exceeds the above guidelines, step up circulation and ventilation. Consider dehumidification. Alert occupants to try to reduce interior moisture sources in any reasonable manner. Look for moisture damage in attics, around windows and doors and other likely areas, and take action if needed.

Too Many Internal Sources from Domestic Activities—Unvented bathrooms and kitchens are a common problem; cooking without lids, open-flame heating and cooking appliances, bathing, and hanging wet clothing and towels inside to dry can produce excessive moisture (see Figure 8). Low-volume shower heads save energy, but generate greater amounts of water vapor. In addition, houseplants and aquariums without covers can produce a considerable amount of moisture. Don't vent clothes dryers to the indoors; air pollution may result from lint and laundry products, and excess moisture may become a problem. Drying firewood inside the home may produce excess moisture.

Possible Solutions: Use existing exhaust equipment in kitchens and bathrooms. Vent clothes dryers to the outdoors. Install exhaust fan vents in the kitchen and bath if they aren't present. If appropriate, ask occupants to become aware of moisture-generating activity and voluntarily reduce moisture production. Step up overall ventilation, if necessary, through windows, whole-house or local exhaust fans, or consider installing an air-to-air heat exchanger if appropriate.

Inadequate Circulation and Ventilation—Moisture becomes trapped when air circulation and ventilation are inadequate. Inside the home, poor circulation of heat can lead to condensation problems, and inadequate ventilation of high moisture areas such as kitchens and baths can lead to damage. If the house has inadequate ventilation overall, moisture problems may be the first clue. In attics, crawlspaces and other unconditioned structural spaces, poor circulation or ventilation can cause a variety of problems. For instance, roof ice dams as well as attic condensation problems may be caused by trapped air when ceiling insulation touches roof sheathing, without allowing for proper circulation.

Possible Solutions: Install externally venting fans in kitchens and baths if needed. For localized moisture problems in the home, especially unstoppable condensation, try aiming a small fan at the area to better circulate warm air. Provide circulation and ventilation inside the home by opening windows, considering cross-ventilation, and similar strategies. An air-to-air heat exchanger should be considered if the house has been built or retrofitted with an air-tight vapor retarder. If a significant amount of ventilation is needed, a central exhaust fan could also be considered. Install any needed vents in attics and crawlspaces or other structural spaces. Check insulation for any needed repair or re-installation.

Improper Temperature Differences, Lack of Insulation—When warm, moist air hits a cold surface, condensation can sometimes cause water or frost damage, or lead to the growth of mold or mildew. Rooms shut off from heating sources or used only intermittently (such as bedrooms or closets) are prime problem areas. Uninsulated walls and windows in heating-season climates, and wall, ceiling or floor areas where insulation is missing or has shifted are other key locations for this type of problem (see Figure 9).

Possible Solutions: In heating-season climates, seal the infiltration leaks first, then insulate, employing proper vapor retarder techniques. Check existing insulation. Insulate windows with additional glazing or treatments that seal around all edges. If insulation is impossible, continuous circulation of air with a fan in the problem area will help prevent condensation. For closets or other out-of-the-way places, better air and heat circulation can be achieved by leaving doors open or installing louvered doors.

Lack of or Improper Placement of Vapor Retarders—If you are in a climate where vapor retarders are called for, action may be needed. New, tightly built and well-insulated homes or homes that have been thoroughly weatherized have a greater need for a durable vapor retarder that has been carefully installed on the warm side of the surface to stop moisture transfer through building materials. If the vapor retarder is installed haphazardly, every point subject to air leakage will experience pressure, and condensation may be damaging. Improper placement of vapor retarders is not uncommon. For example, if a building material that is, in fact, a vapor retarder has been installed on the cold side of the wall surface, moisture may be condensing in the walls. If a low-perm vapor retarder is used on two sides of a wall surface, moisture may build up without an avenue of escape. In areas of high ground water, the lack of a gound-cover vapor retarder in the crawlspace may allow water vapor to constantly enter the dwelling, leading to a variety of problems.

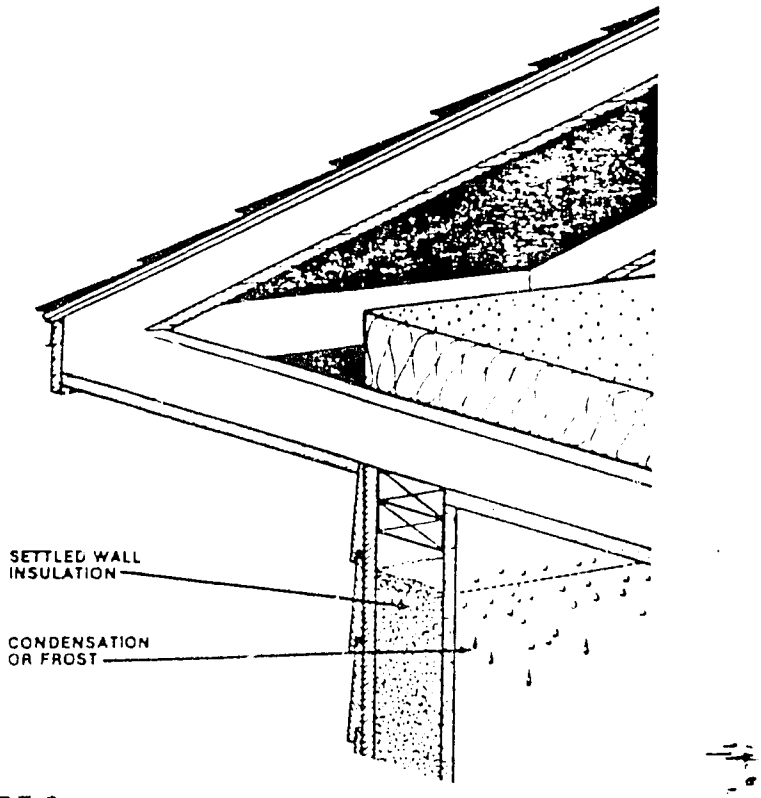


FIGURE 9: SETTLED WALL INSULATION CAN LEAD TO CONDENSATION OR FROST ON COLD SURFACES.

Possible Solutions: Inspect materials on the cold side of the home's envelope to determine whether a sheathing or siding may be acting as an unwanted vapor retarder. Search for places where the vapor retarder may not have been installed, such as the rim joists, between floors. Install vapor retarders where they are needed, in conjunction with insulation work. Always use materials that can breathe on the cool side of walls, ceilings or floors once vapor retarders are in place.

Examples: *A Nebraska Department of Energy Appropriate Technology grantee experimented with a double-wall, pole frame home construction system, to create a wall cavity that would hold from 8 to 10 inches of insulation. A polyethylene vapor retarder was employed on the inside, or warm, surface of the walls. However, joints and penetrations in the vapor retarder were not sealed. The result was that air infiltration caused a serious heat loss. If a vapor retarder is used to stop both moisture transfer and air leakage, the retarder must be installed with great care, making sure that all penetrations, joints and other breaks are sealed.*

A number of grantees reported installing vapor retarders on both sides of a wall surface. One grantee used this method when retrofitting a multi-unit row house. A 4-mil polyethylene vapor retarder was used as a sound insulator on both sides of a party wall, between units. The seal with the vapor retarder was not airtight, thus moisture could accumulate in the wall cavity. Double vapor retarders must be avoided, if moisture is to be controlled. This involves using vapor retarders on the warm side of the wall, ceiling or floor surface and a breather material on the cool side, to allow any moisture that passes through to escape. Generally, vapor retarders should not be used in party walls.

New Construction, Retrofit or Remodeling—New foundations, concrete floors, brick fireplaces, taping of sheetrock, painting, green lumber, wet wood or uncured masonry materials contain an enormous amount of moisture until the dwelling has dried. New, tightly constructed homes are more prone to this problem and m longer to dry.

Possible Solutions: To facilitate the drying process, increase ventilation and circulation, both during the building process, if possible, and during the first year of occupancy. Avoid humidifier use.

Example: *A Vermont Appropriate Technology grantee, working with air-to-air heat exchanger, reported that construction drying can be speeded by installing and using the heat exchanger before construction is complete. In one test, an air-to-air heat exchanger was installed in one house on a multi-house construction site, and it was operated to reduce interior humidity from the newly installed gypsum board. The grantee reported that the walls of the house with the heat exchanger in use were dry and ready for paint in one-quarter to one-fifth the time required by the other houses (see Figure 10).*

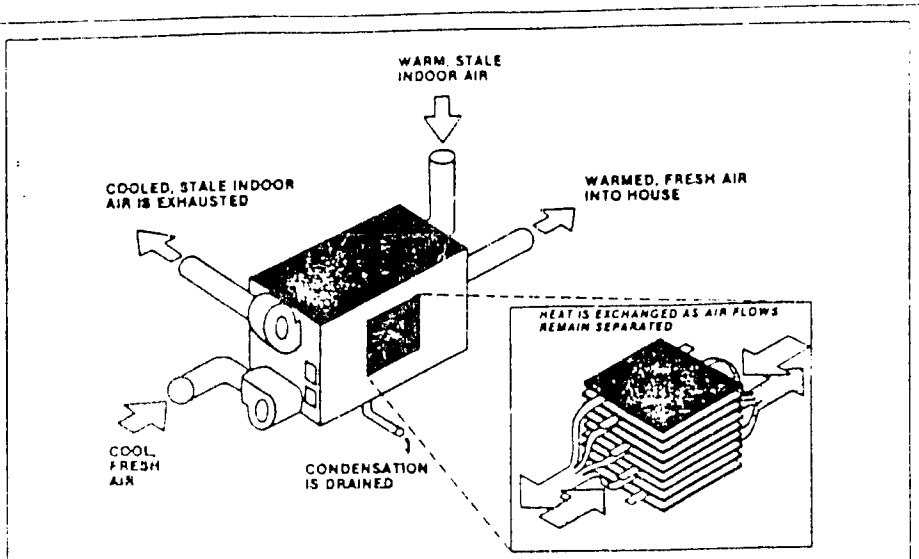


FIGURE 10: AIR-TO-AIR HEAT EXCHANGERS RECAPTURE HEAT FROM THE STALE EXHAUST AIR AND CAN REDUCE INDOOR HUMIDITY.

Faulty or Problem Flame-fired Heating Plants—Faulty flame-fired appliances used for heating, water heating or cooking can be sources of moisture problems. Without adequate combustion air, these appliances can spill water vapor and deadly, odorless carbon monoxide gas into the living area. Incomplete combustion is revealed by an excessively yellow or wavy flame, and can cause drowsiness, recurring headaches or even death. Windows that fog for no apparent reason are another clue. Other types of heating systems may also influence moisture's behavior in the home. Note that liquid propane gas produces more moisture during combustion than other systems. If wood heat is used, wood stored inside the home may be producing excess moisture. And, in tightly built all-electric homes that have no chimneys, normal internal moisture sources can occasionally present problems.

Possible Solutions: Check for blocked furnace vents, a chimney blockage, a chimney that is too short, insufficient combustion air or whether the system is vented at all (unvented gas and kerosene heaters). If you suspect the flame-fired heating plant is faulty in any way, call for help from the local utility or a contractor. Don't wait. If wood heat is used, store wood outside the home, when possible.

Example: *The family of one Ohio Appropriate Technology grantee began experiencing unusual colds and frequent headaches. The grantee's house was extremely tight, and he traced the problem to his gas hot water heater. After the grantee isolated the water heater with insulated walls and ducted in outdoor combustion air, the family's symptoms ended.*

Problem Cooling Systems and Humidifiers—Evaporative coolers (commonly known as "swamp coolers"), humidifiers and air conditioning units all can be sources of excess moisture or moisture problems. A swamp cooler operates by drawing outside air through louvers in the cabinet where it passes water soaked pads. The water in the pads absorbs the heat from the air. Water is automatically metered into the cooler to replace evaporation losses, thus a swamp cooler is a constant source of moisture. The process of evaporation cools the air, while increasing indoor relative humidity. These coolers are effective in dry climates, but they may cause major excess moisture problems in humid, warm locations. Used in a new or newly retrofitted house, humidifiers only add to construction moisture. Also, humidification after a house has been weatherized or tightened to reduce air leaks can cause trouble. With air conditioners, condensation is sometimes a problem on ductwork or in floors.

Possible Solutions: For swamp coolers, avoid use in high humidity climates. If internal moisture or relative humidity becomes too high, discontinue use. Use humidifiers only when needed. Otherwise, avoid them. An unnecessary central humidification system can be disconnected, saving energy. The main overall action for air conditioners is to keep the thermostat setting at 75°F or above, to help save cooling dollars and to keep surface temperatures above the dew point. Drain air conditioning condensation to the sewer system or the outdoors, not the crawlspace. Check for adequate crawlspace ventilation. Check for air conditioning ducts, and seal, insulate and add vapor retarders where needed.

Plumbing Leaks—The best way to check for plumbing leaks is to run each part of the system for 10-15 minutes and watch and listen for leaks. Check all accessible connections, and thoroughly inspect the house during the process. Leaking pipes may be buried in a concrete slab floor or hidden in the walls. Find and fix all leaking plumbing.

Attached Horticultural Greenhouses— Because of its many moisture sources, the attached greenhouse can cause moisture problems indoors. Plants prefer relative humidity levels under 70 percent; higher levels cause greater leaf production at the expense of the fruit or vegetables. Check relative humidity in the greenhouse over time. Attached greenhouses can cause moisture problems in the wall they are attached to, through condensation. In addition, drainage may be a problem.

Possible Solutions: Above all, provide adequate circulation and ventilation in the greenhouse. If greenhouse relative humidity is high, avoid venting into the home. Provide proper exterior drainage away from the house and the greenhouse. Avoid excess watering of plants. Use proper vapor retarder and insulation techniques.

Example: *A Vermont Appropriate Technology grantee, developed a simple concentric tube air-to-air heat exchanger for greenhouses that may have applicability for residential greenhouse use. This type of heat exchanger could be employed to deliver low-humidity warm air to the living space, thus avoiding moisture problems that stem from direct venting of greenhouse air into the home.*

Outdoor Causes

Poor drainage—This is the major exterior moisture dilemma. With bermed or earth-sheltered construction and for foundations in general, proper drainage is especially critical. If drainage problems cannot be properly corrected, try increasing resistance to moisture through the use of wood preservatives, dampproofing and waterproofing. General solutions to each problem are described below (see Figure 11).

Surface water: Poor drainage of water and moisture from rain and snow, and irrigation of nearby foliage and lawns is common, especially in locations with clay-type soils.
Possible Solutions: Check for blocked downspouts and gutters, or lack of rain gutters. Check for cracks in foundations, and install proper dampproofing. Check for proper soil slope away from the house. In new construction, use proper perimeter footing drain.
Example: *A Kansas Appropriate Technology grantee wanted to build a bermed house on a hillside. The grantee noted that homes in the vicinity suffered from flooding problems from surface water. Most homes employed sump pumps equipped with a battery powered back-up, in case of power outages. However, even with the sump pumps, some homes in the area still experience basement flooding.*

To avoid the flooding problems and reduce energy consumption, the grantee built a successful passive drainage system that involved installing drain pipe under and around the base of the foundation, sloping soil away from the house, installing proper gutters, down pipes and extender pipes. The below-grade drain pipe slopes down the hill to provide good gravity flow. (Similar construction details are illustrated in the next section.)

Ground Water—If excess ground water (high water table) is a suspect, try the following solutions. To determine if moisture is wicking up through the ground or coming from the interior space, use the Capillary Test found in Appendix A.
Possible Solutions: Add a ground water retarder in the crawlspace. Ventilate the crawlspace. Fix basement drainage through use of drain tiles, drain pipe or sump pump. Try fixing cracks in the foundation and use foundation waterproofing or dampproofing. In new construction, lay down a moisture barrier before pouring concrete slab floors.

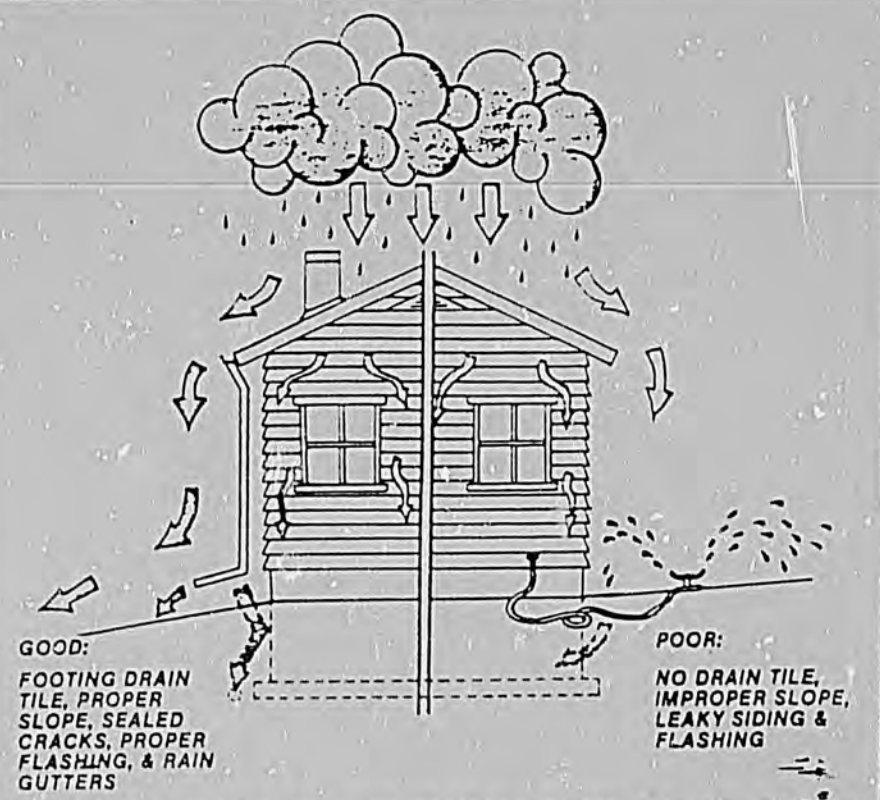


FIGURE 11: PROPER OUTDOOR DRAINAGE IS ESSENTIAL FOR REDUCING MOISTURE PROBLEMS.

Example: *An Ohio Appropriate Technology grantee found that many homes in the area had damp basements. When he built his new solar home, he used a variety of good drainage techniques to avoid the problem. These included exterior insulation and water barrier, proper soil slope, gutters and downspouts, drain tile around the foundation, and footings built on high-drainage gravel. The grantee also drilled weep holes in the base of the hollow concrete block wall that allowed moisture to drain properly to the gravel base. His concrete floor featured a gravel base, covered with a vapor-water barrier, over which rigid insulation was laid before concrete was poured. The grantee reported that his foundation walls have remained dry.*

Soil Problems—Clay-type soils that expand when wetted can cause cracks in the foundation.
Possible Solutions: Provide for drainage away from the foundation with the proper slope and through the use of gravelly soil backfill, thereby reducing pressure.

Poor Construction Details—Flat ledges, places for moisture to puddle, and inadequate drip edges and flashing all can cause troubles.
Possible Solutions: Repair poor construction details before insulating, to avoid moisture problems that could damage insulation or otherwise cause problems. Check all places where water drains for proper slope down and away from the house. Install flashing where needed or repair current flashing or drip edges. Or extend the protective overhang of the roof. Caulk and seal to save energy and stop leaking water.
Example: *A Connecticut Appropriate Technology grantee studied the feasibility of weatherization and solarization of a public building. One problem noted was that the building's flat roof and 11 skylights were a constant water problem, a problem that had been repaired unsuccessfully several times during the building's 16-year history. To ensure a positive result, the grantee proposed that the skylights be removed and the roof thoroughly repaired before energy conservation work is attempted.*

Note Seasonal Changes—Rain, irrigation and ground water table all can change seasonally, potentially creating a problem that shows only at certain times in the year. Other factors that can change seasonally include soil moisture content, foliage, rain, snow, surface water and relative humidity. If the moisture problem occurs only seasonally, it might not be of a magnitude that require immediate remedial action. But, seasonal water problems can sometimes cause great damage. Check on the situation several

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times during the year. Watch for seasonal change periods: spring and fall.

High Outdoor Humidity—Consistently high outdoor humidity can cause a variety of problems, particularly higher cooling costs and constant mold, mildew and decay. Ventilating crawlspaces, attics and interior living spaces with this high humidity air can aggravate all existing moisture problems, or even cause new ones.

Possible Solutions: On the exterior of the home, take measures to increase resistance of wood to moisture, using pressure-treated wood or wood that has been treated with a fungicide preservative. Caulk and seal to stop moisture transfer and reduce heating or cooling costs. In cooling climates, tighten up the home with weatherization techniques, provide dehumidification, and avoid ventilating crawlspaces in times of high outdoor humidity and temperature.

Example: *An Iowa Appropriate Technology grantee wanted to use cool basement air to reduce his air conditioning costs during the summer. High outdoor relative humidity was a problem, however, causing discomfort, sweating of walls and pipes in the basement and mold and mildew.*

The grantee developed a system that circulates warm, humid air from the upstairs to the basement, where the air was mechanically dehumidified and then cooled by contact with the basement wall and floor surfaces. The cool air is then pumped back to the living space through the ductwork for the heating system. Before installing his system, the grantee reported reduced relative humidity in the 40 percent range. The grantee found his system to be a successful way to reduce cooling costs and increase comfort, through dehumidification. Note that this technique may not be advisable in areas where soil radon levels are high unless the basement is first monitored for radon.

Blocked Exterior Circulation—Foliage close to the dwelling or items stored next to the house (such as firewood), can block air circulation and lead to mold, mildew and other moisture damage.

Possible Solutions: Cut back foliage to allow for circulation. Move firewood or other stored items away from the house to avoid reducing circulation. High moisture areas can be treated with zinc oxide paint to avoid mold and mildew problems, but use of this type of paint should be kept to a minimum as it isn't as long-lasting as some other types of exterior paint.

ECTION III

IXING THE PROBLEMS

Once moisture problems are correctly diagnosed, choices must be made on how best to remedy them. Some problems can be tackled with a low-cost change in living habits, such as using existing bath and kitchen exhaust fans to reduce indoor humidity levels. But, more complex problems demand careful evaluation and inspection to solve, and substantial action to fix.

This section illustrates a number of techniques to correct and prevent moisture problems in the home, including:

- *How to evaluate the use of vapor retarders and breathable materials, in attics, walls, floors and crawlspaces;*
- *How to determine ventilation requirements for attics and crawlspaces, as well as ventilation requirements for kitchens and baths and high moisture areas;*
- *When to avoid ventilation of crawlspaces and basements with outdoor air, including a discussion of dehumidification options;*
- *Evaluating drainage problems, including details for controlling surface and ground water, and insulation of basements and foundations;*
- *How to protect the home from the elements, including preserving exposed wood and avoiding and solving moisture-caused paint problems.*

Vapor Retarders

Vapor retarders have been used in conjunction with insulation in colder climates for the last several decades. The familiar term "vapor barrier" has recently been replaced with the term "vapor retarder" to avoid the misconception that vapor barriers stop all moisture transfer, when they actually only reduce the rate of moisture transfer.

In cold-climate locations, vapor retarders have traditionally been employed to avoid condensation by stopping water vapor from diffusing outward under pressure through building materials. But, new information shows that much more moisture is transferred by air movement than through diffusion. Thus, to truly block most moisture transfer, the vapor retarder must be carefully installed to stop air leakage, as well as diffusion. Vapor retarders that stop air leakage are a major feature of the new, energy-efficient construction and retrofit applications.

Vapor retarders should always be located on the warm, or high-vapor pressure, side of the wall surface. The cold side of the wall must be allowed to breathe, to allow any moisture that does not pass through to escape (see Figure 12).

Wall and ceiling vapor retarders are not recommended in areas outside the condensation zone (see Figure 2) because if both wintertime heating and considerable summer cooling are called for, the vapor retarder may be on the wrong side most of the time. In addition, in warm climates the temperature difference across the insulation tends to be less, thus less moisture will migrate through the surface, and it is less likely that condensation will occur because dew point temperatures will be higher.

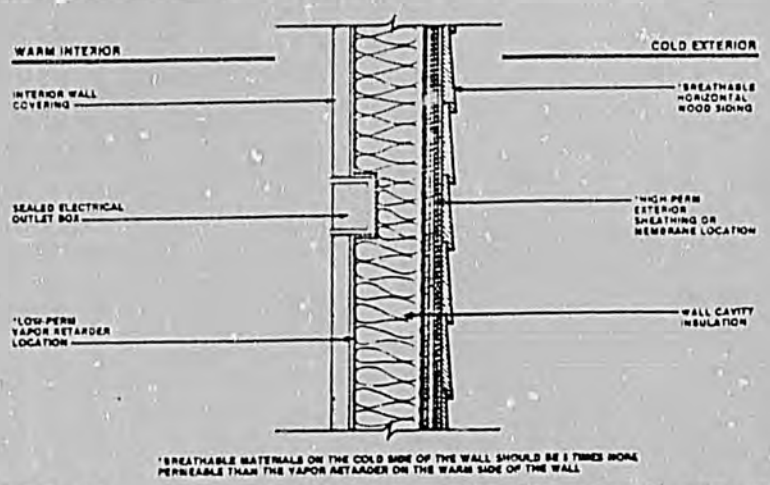

FIGURE 12: THE LOCATION OF VAPOR RETARDING AND HIGH PERMEABILITY MATERIALS IN COLD CLIMATE REGIONS IS AN IMPORTANT CONSIDERATION.

Using Perm Ratings

Vapor retarder effectiveness is measured in "perms," which stands for the permeance of the material; one perm equals one grain (or drop) of water per square foot per hour per unit vapor pressure difference. The lower the perm rating of a material, the better the material is at slowing moisture transfer.

Knowing the perm rating of a material is critical when choosing materials for walls. To allow any moisture that does pass through the vapor retarder to escape, the outer skin of the wall should be at least *five times more permeable* than the vapor retarder. This 1:5 ratio should be applied when choosing a vapor retarder and also when choosing sheathing materials for the outer skin of the house (see table, Generic Perme-

ance of Materials to Water Vapor).

In the past, materials with a perm value of 1 or less were considered to be vapor "barriers." However, the current state of the art is to use vapor retarders of 0.1 perm or less. For the reason, polyethylene films, which have extremely low perm ratings in the [illegible] range, are generally the material of choice.

Asphalt-coated laminated papers and kraft-backed aluminum foil were once commonly used, but installation problems, lack of flexibility, and the breakdown of some of these materials when exposed to high humidity tend to make them less effective and popular than polyethylene films.

Special Problems with Vapor Retarders

While vapor retarders are meant to avoid condensation problems, improper placement, installation errors and incomplete use of vapor retarders can cause moisture problems. Common errors include:

- *Vapor retarder installed on the wrong side of the wall surface.* If low-perm products are used on the exterior side of a wall and in low-humidity climates, they can become trapped inside the wall. Examples of low-perm exterior use products include vinyl or metal sidings, insulating sheathings with foil coverings and low-perm plastics that are substituted for breathable building papers. Low-perm sidings are typically outfitted with small vents or perforations that allow moisture to escape, but sometimes these points can become blocked or are intentionally closed off. In colder climates, condensation problems are more likely when metal siding is used on an uninsulated home that has no vapor retarder. Low-perm, high R-value sheathings can experience condensation during times of very cold temperatures. Manufacturers' instructions for use of these types of sheathings should be followed exactly to avoid moisture problems. Finally, low-perm plastics should not be substituted for higher-perm sheathing papers.
- *Double vapor retarders, or vapor retarders on both sides of a wall.* Using a low-perm product on both sides of a wall or foundation can result in moisture buildup. The cold side of the wall or foundation must be able to breathe. Vapor retarders are not meant for use in party walls; both sides of the wall are conditioned, and water vapor can enter any leakage points and become trapped in the wall. Several HOUSE grantees inadvertently installed double vapor

GENERIC PERMEANCE OF MATERIALS TO WATER VAPOR

Perm ratings for a given generic product will vary, depending on manufacturing techniques used and other variables. Permeance is measured in two ways—wet cup and dry cup testing. Wet cup testing exposes the material to greater amounts of moisture. A material's perm rating will be lower in dry cup testing than wet cup, which means wet cup ratings are best when choosing a vapor retarder for an extremely wet location.

The following table gives the dry cup perm ratings for a representative sample of standard building components. The ratings shown in the table will permit comparisons and should be used only for general reference. For specific applications and materials, selection of vapor retarder materials should be based on values obtained from the manufacturer or from recognized laboratory test results.

Perm ratings in the table are given for the thickness of material shown. When a material is followed by the notation "perm-in," which means perm value per inch, the permeability for greater thicknesses can simply be estimated by dividing the perm-in by the number of inches. (For example, to determine the perm value of concrete 8 inches thick, divide the perm-in value of 3.2 by 8. This gives a perm value of 0.4 for 8 inches of concrete.)

Basic Materials Used in Construction	Permeance (Perm)
Concrete (1:2:4 mix)	3.2 (Perm-in)
Brick masonry (4" thick)	0.8
Concrete block (8" cored, limestone aggregate)	4
Tile masonry, glazed (4" thick)	0.12
Plaster on metal lath (3/4")	15.0
Plaster on wood lath	11.0
Gypsum wall board (3/8" plain)	50.0
Hardboard (1/8" standard)	11.0
Hardboard (1/8" tempered)	5.0
Plywood (douglas fir, exterior glue, 1/4" thick)	0.7
Plywood (douglas fir, exterior glue, 3/4" thick)	1.9
Thermal Insulations	
Air (still) (1")	120.0
Cellular glass	0.0
Cork board (1")	2.1-2.6 (Perm-in)
Expanded Polystyrene - extruded	1.2 (Perm-in)
Expanded Polystyrene - beads	2.0-5.8 (Perm-in)
Expanded Polyurethane (R-11 blown, board stock)	0.4-1.6 (Perm-in)
Plastic and Metal Foils and Films	
Aluminum foil (1 mil)	0.0
Aluminum foil (0.35 mil)	0.05
Polyethylene (1 mil)	0.8
Polyethylene (6 mil)	0.06
Polyethylene (8 mil)	0.04
Polyethylene (10 mil)	0.03
Polyethylene cross laminated high density (4 mil)	0.02
Building Papers, Felts, Roofing Papers	
Papers sheet, asphalt laminated, aluminum foil one side	0.002
Stabilized and coated rolled roofing	0.05
Kraft paper and asphalt laminated, reinforced 30-120-30	0.3
Blanket thermal insulation back up paper, asphalt coated	0.4
Asphalt saturated and coated vapor barrier paper	0.2-0.3
15 lb/sq ft felt	1.0
15 lb/sq ft felt	4.0
Single kraft, creped	31.0
Cloth, aluminized, backed by polyethylene film	94.0
Liquid Applied Coatings	
Commercial Latex Paints	
Vapor retarder primer paint	0.4
Primer, gloss paint	0.29
Vinyl-modified alkyd primer	7.12
Vinyl-acrylic primer	8.62
Semi-gloss vinyl-acrylic enamel	6.61
Exterior acrylic house & trim	5.47
Paint - 2 coats	
Aluminum varnish on wood	0.3-0.5
Enamels on smooth plaster	0.5-1.5
Various primers plus 1 coat flat oil paint on plaster	1.0-3.0
Paint - 3 coats	
Exterior paint, white lead and oil on wood siding	0.3-1.0
Exterior paint, white lead zinc oxide and oil on wood	0.9

SOURCE: Adapted from ASHRAE Handbook, 1981 Fundamentals

NOTE: Perm ratings for this product were supplied by the manufacturer.

Best Available Document

retarders in walls, party walls and foundations, a practice that they later discovered could lead to problems.

• *Incomplete installation of vapor retarders.* If some areas of the house are missed or avoided during vapor retarder installation, these areas can become escape routes for water vapor. If the home has constantly high indoor humidity, these areas can suffer deterioration over time. A typical example is when the vapor retarder is installed over walls and ceilings, but not rim joists (see Figure 13).

• *Haphazard installation of vapor retarders.* Vapor retarders are not effective if they are not tightly installed. If used to stop air infiltration as well as moisture transfer, the installation must be extremely conscientious. With polyethylene sheeting, this means sealing seams completely with non-hardening sealant (acoustical sealant is recommended) and taking care to carefully seal all breaks caused by electrical and plumbing runs.

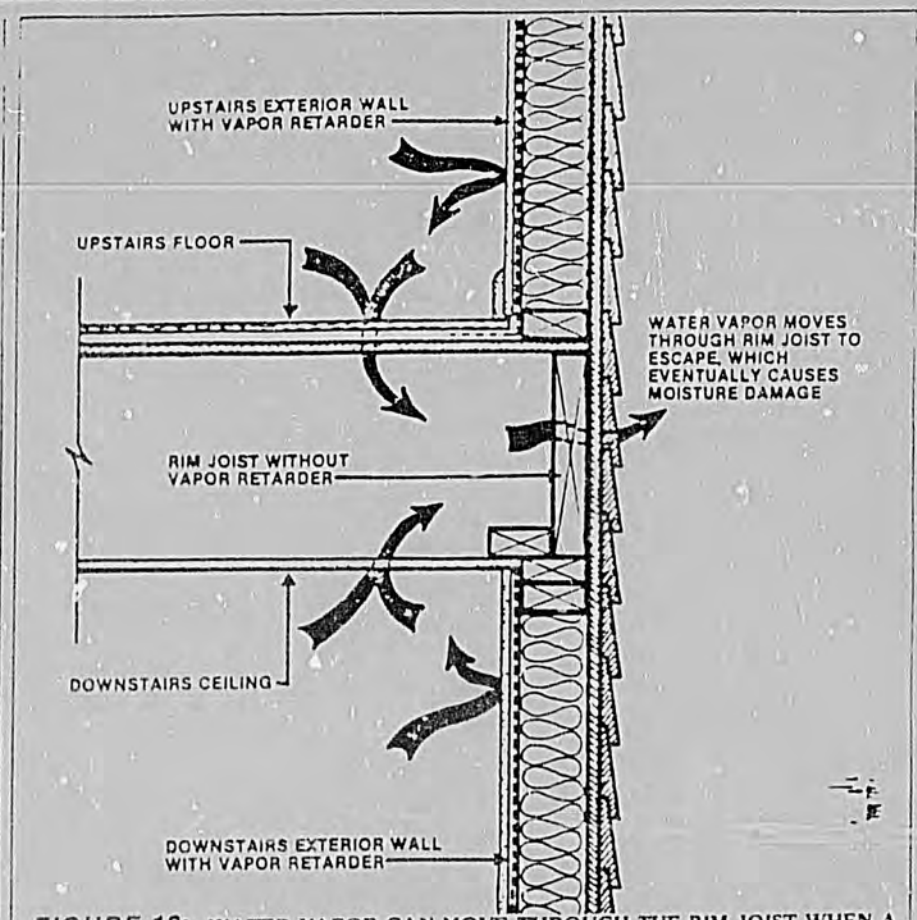

FIGURE 13: WATER VAPOR CAN MOVE THROUGH THE RIM JOIST WHEN A VAPOR RETARDER IS NOT INSTALLED.

Conventional Insulation Retrofits

Walls

Millions of houses have had wall cavities retrofitted with insulation in the last decade, usually with the insulation being blown in and no vapor retarder added. The question of the need for vapor retarders was raised by utilities and other agencies who were sponsoring insulation work. A number of studies have found that while condensation does occur, usually next to the cold inner surface of the exterior sheathing, wood rot and decay problems seem to be dependent on local climatic conditions and are not prevalent.

Researchers note that if moisture buildup within an insulated wall isn't extreme, it tends to correct itself. As the insulation gets wet, the insulating power decreases, and heat losses increase. The temperature inside the wall then increases, and this slows further condensation and steps up evaporation.

Wet insulation can pose problems in severe cases. First, insulating power can decrease dramatically if moisture content is high. In addition, wet insulation touching electrical fixtures may cause a fire hazard, and some researchers are finding evidence that moisture may rob cellulose insulation of its flame retardancy as the moisture evaporates away.

Remember that water vapor moves into wall cavities both by air movement and diffusion, but air movement is the more powerful force. For this reason, air leakage points should be sealed from the *inside* of the house as a first step in a conventional wall insulation job. This means sealing penetrations around windows, doors, where the wall meets the ceiling and floor, and any cracks or holes in wall surfaces. Once air leakage points are closed off, then vapor retarder paint can be applied to give wall surfaces some resistance to water vapor diffusion (see Figure 14).

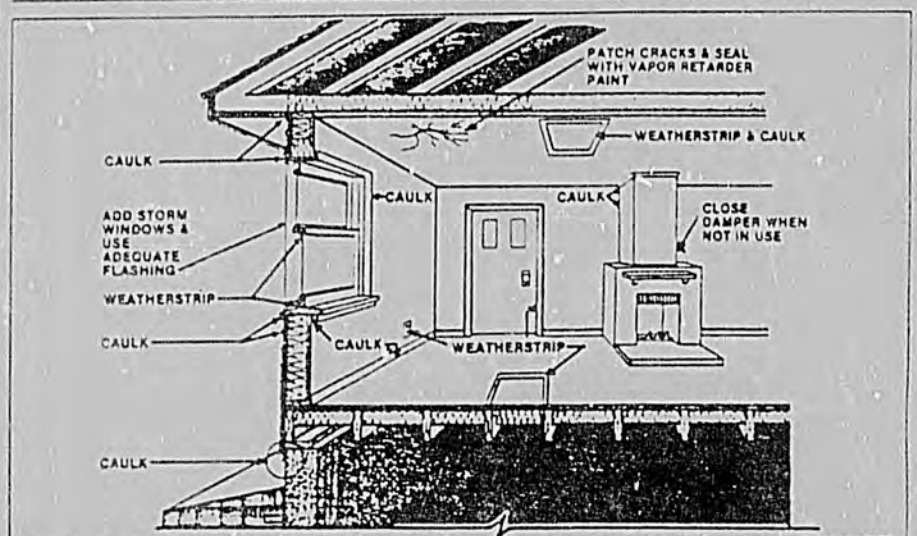

FIGURE 14: FIRST SEAL THE INSIDE, THEN SEAL THE OUTSIDE TO REDUCE AIR MOVEMENT AND MOISTURE TRANSFER.

Attic and Ceilings

Attic ventilation is the main strategy to avoid moisture problems in attics, and until recently, it has been common not to use tightly installed vapor retarders with attic insulation, except in the coldest climates. The reason for this was that if a good

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vapor retarder was used in the walls, too much moisture might accumulate in the house if the ceiling also had a vapor retarder. Any water vapor that passes through the ceiling insulation would then be vented away through attic vents.

However, with the move toward using vapor retarders to stop both air and moisture transfer, tightly installed ceiling vapor retarders are becoming more common in all condensation-zone locations for new construction and sometimes in comprehensive retrofits. And, a carefully installed vapor retarder is the only way to avoid moisture damage if attic ventilation is likely to be inadequate, particularly with flat roofs or cathedral ceilings.

With conventional attic insulation retrofits, batt insulation with attached vapor retarders can be carefully and tightly stapled to the rafters. For loose fill attic insulation, polyethylene can be cut into strips and tightly fitted between the joists (see Figure 15). Existing vents at the eaves must not be blocked during the insulation retrofit.

With greater thickness of attic insulation, care must be taken to provide additional ventilation at the eaves. Rigid vent troughs can be installed on the underside of the roof sheathing to provide this ventilation and prevent thicker levels of insulation from blocking air flow (see Figure 16).

If a vapor retarder isn't used in the attic or ceiling, attic ventilation must be greater than when a vapor retarder is used.

Crawlspaces and Floors

In all climate regions, ground cover vapor retarders are needed to stop moisture migrating up from the soil in the crawlspaces. A tough, puncture-resistant material (often 6-mil polyethylene) is simply laid over the soil, and held in place with weights or bricks. For additional protection from damage from foot traffic, a layer of sand can be put over the vapor retarder. As with attic ventilation, crawlspace venting can be less if a good, soil cover vapor retarder is used.

Floor vapor retarders can be used in conjunction with insulation in both cold and hot climates to stop condensation. These vapor retarders should not be substituted for ground cover vapor retarders, but rather used in addition to them. In cold climates, the vapor retarder is, as usual, on the warm side of the floor. In warm climates where long periods of air conditioning occur, the warm side is the bottom of the floor (see Figure 17).

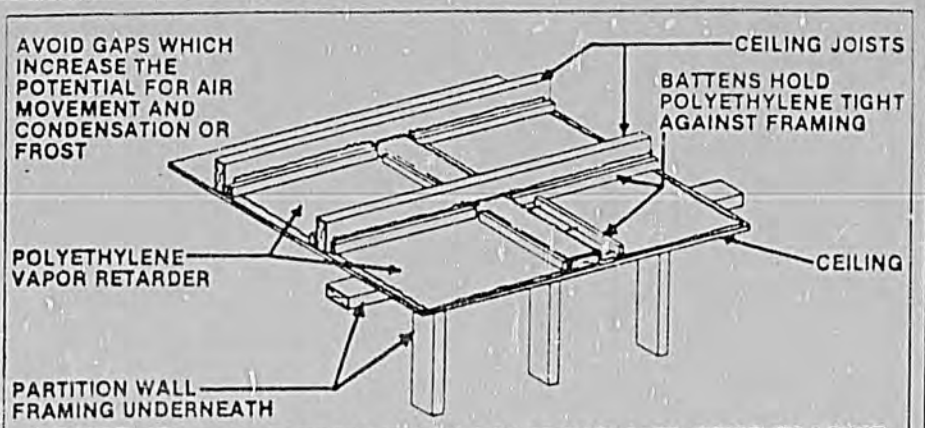

FIGURE 15: POLYETHYLENE STRIPS CAN BE INSTALLED PRIOR TO LOOSE-FILL OR BLOWN-IN ATTIC INSULATION.

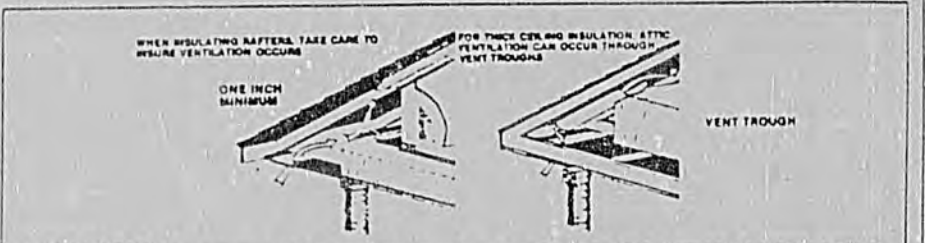

FIGURE 16: INSULATION WORK SHOULD NOT BLOCK ATTIC VENTILATION AT THE EAVES.

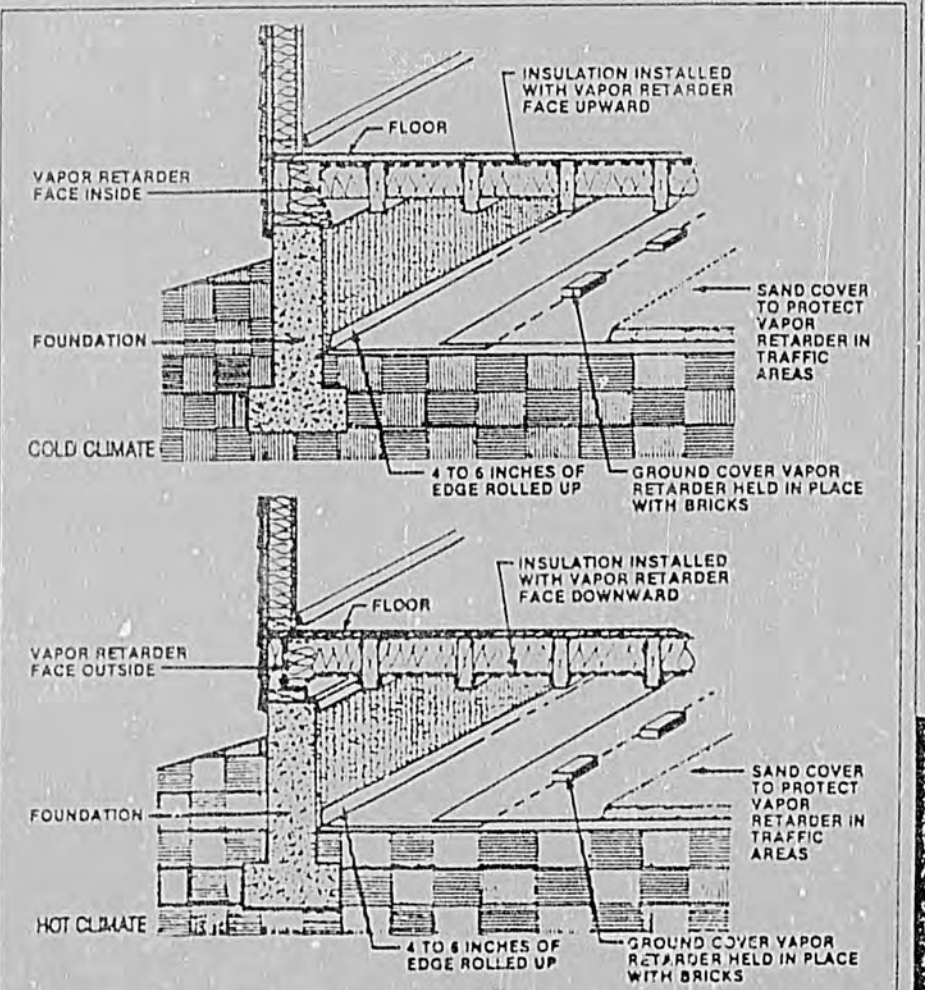

FIGURE 17: VAPOR RETARDER LOCATIONS FOR CRAWLSPACES AND FLOORS DIFFER DEPENDING ON CLIMATE.

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Windows

The same concept of putting a tightly installed vapor retarder on the warm side of the surface applies to storm windows, which act as both air and vapor retarders as well as additional insulation. Condensation can result when the outer sash is tighter than the inside window.

A good rule of thumb with older windows is to always tighten the existing window first with weatherstripping and caulk. If an outer storm window is being added, a product with small weep holes at the bottom is recommended to allow moisture to escape. With interior-side storm windows, make sure that the seal is tight around all edges.

If storm windows are properly installed and fogging and icing still happens, indoor humidity levels may be too high, or the window may need still another glazing layer. In the coldest climates, triple-glazing is recommended. Newer window insulation products that have a built-in vapor retarder must provide for a tight seal around all edges to avoid condensation problems. Similarly, traditional drapery and blinds can aggravate window condensation because the window surface gets colder, heat circulation is impeded and the window covering doesn't provide for a tight seal.

Vapor Retarders for New Construction and High-R Retrofits

In new construction or substantial retrofit in colder climates, great care should be taken when installing a continuous vapor retarder that is intended to stop air infiltration as well as moisture transfer. Care must be taken to provide an unbroken vapor retarder between floors, ceilings and interior walls (see Figure 18). If these locations are left open to moisture, degradation can occur because these are the only open paths for moisture's transfer.

An excellent insulation and vapor retarder installation will result when a polyethylene vapor retarder is used over insulation that is friction-fit between the framing. Like any vapor retarder, polyethylene film's perm value will increase dramatically if holes caused during installation are left unrepaired. Thus conscientious installation is essential to avoid damage.

Seams in the vapor retarder must be overlapped and carefully sealed with acoustical sealant, making sure that seams fall over a solid surface to facilitate a good, strong bond. Special attention must be given to sealing all breaks caused by electrical and plumbing runs. Inadvertent tears in the vapor retarder can be patched with acoustical sealant and polyethylene. One popular way to seal gaps around windows, doors and plumbing is to foam the area with polyurethane.

A number of new products have been developed to help achieve a tightly sealed vapor retarder. These include special plastic pans for use with electrical and plumbing fixtures, and new, tougher polyethylene blend plastics for vapor retarder use. In addition, new products known as "air barriers" are being employed in place of felt paper under the siding to reduce air movement in the insulation, thus maintaining the insulation's effectiveness. These air barriers, made of olefin (a high-density spunbound polyethylene fiber), have extremely high perm ratings, thus moisture easily passes through while air movement is curtailed. Consult references listed in Appendix B for additional information about these new vapor retarder installation techniques and products.

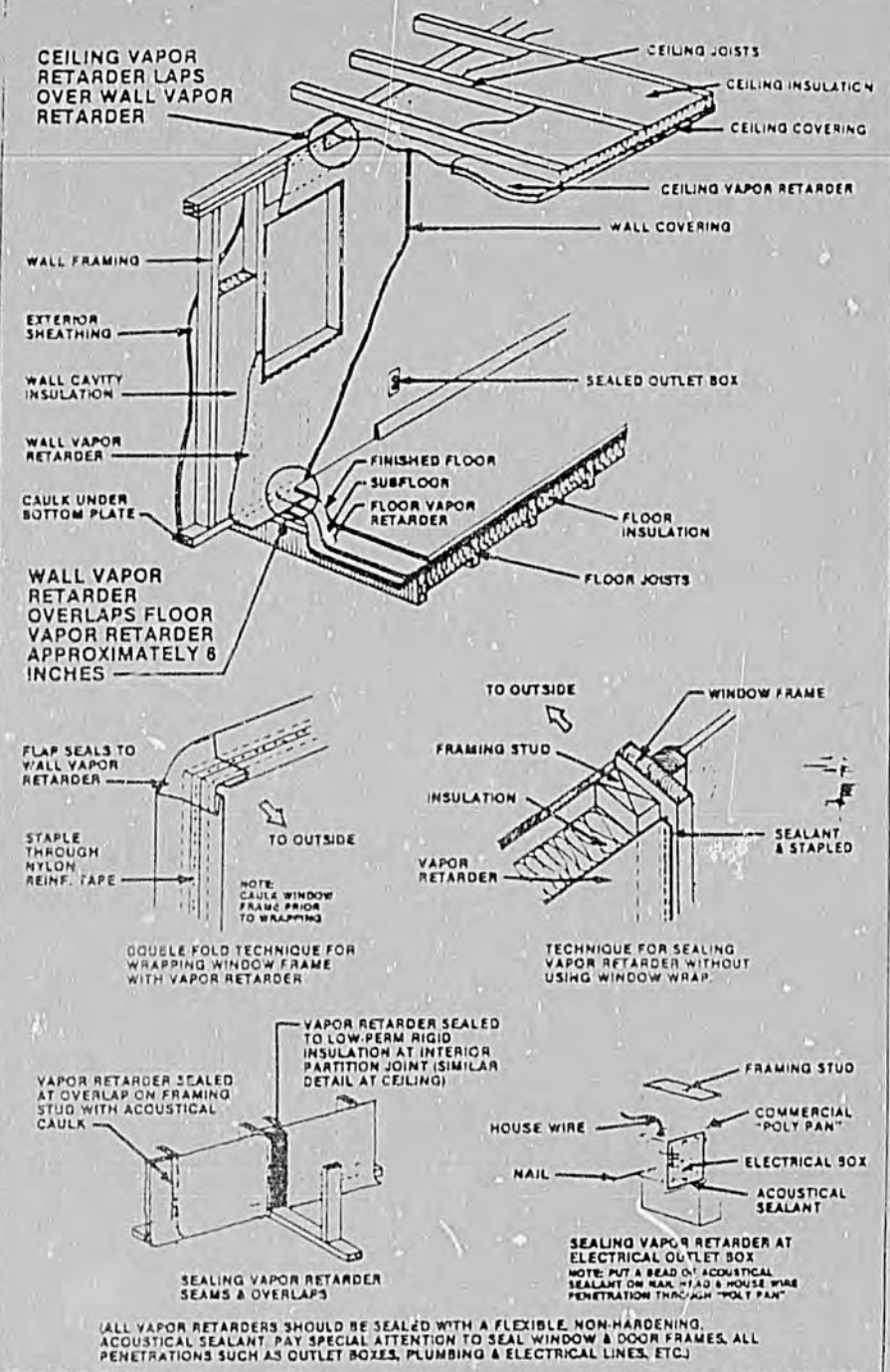

FIGURE 18: INSTALLATION OF A CONTINUOUS VAPOR RETARDER INVOLVES ATTENTION TO DETAIL.

Ventilation

Ventilation and circulation with outdoor air is a major moisture control strategy, and this section deals with a variety of ventilation options and requirements. Passive ventilation is important for crawlspaces and attics and other unconditioned spaces, and mechanical localized ventilation is needed in kitchens, baths and sometimes other areas of the home. In extremely tight homes, mechanical whole-house ventilation with an air-to-air heat exchanger is advised.

During warm, humid weather, ventilation with outdoor air can cause condensation in basements and crawlspaces. And, sometimes dehumidification is necessary, either mechanically or with chemicals.

Controlling Moisture in Attics and Crawlspaces with Ventilation

The basic rule-of-thumb is that an unconditioned space shouldn't be under-ventilated: when in doubt, go to the next largest vent size. These spaces should be ventilated with passive vents that are located to promote good air circulation. (Using a fan for attic ventilation is not cost effective and can draw moisture from the dwelling into the attic.) The following recommendations reflect *minimum* vent requirements, given current practice.

Sizing Attic and Crawlspace Vents

Vent sizing depends on four factors: area to be vented, type of vent obstructions (screens or louvers), where the vents are placed and whether a vapor retarder is used.

If a vapor retarder isn't used, more vent area is needed. The rule of thumb is to multiply square footage to be vented by .0067 (or 1/150). Then, note what type of obstruction (screens, louvers and the like) is used on the vent, and multiply the answer you just obtained by the number shown in the chart below.

If a vapor retarder is used, multiply the total area to be vented by .0034 (or 1/300). Then, multiply the answer by the number shown in the chart.

Steps to Determine Attic Ventilation Needs

1. Measure area to be vented.
2. Multiply this number by either .0067 (no vapor retarder) or by .0034 (vapor retarder in place).
3. Note what type of obstruction is covering the vents, and multiply by the appropriate number to obtain total gross vent area needed.
4. Determine where vents should be located (see Figure 19).

Steps to Determine Crawlspace Ventilation Needs

1. Measure square footage to be ventilated.
2. *If ground cover vapor retarder is not used*, multiply the square footage by .0067 (or 1/150) to determine needed vent space. Then, consult the obstructions chart, and multiply venting by the number given for the type of material used.

   If ground cover vapor retarder is used, multiply squre footage by .0067 (or 1/150), then multiply needed venting by number shown on the obstructions chart.
3. Determine location of needed vents (see Figure 20).

For example, say you have a 595 square foot attic to be ventilated. No vapor retarder is used. Multiply 595 times .0067 = 3.99 square feet of vent needed. If a ⅛-inch mesh screen is used to cover the vent, multiply 3.99 by 1.25 = 4.98. Rounded up to the nearest foot, 5 square feet of vent area would be the minimum needed in this case. Then, the vent area would be divided (depending on the design of the house and attic) between several vents located to promote good cross-ventilation and circulation.

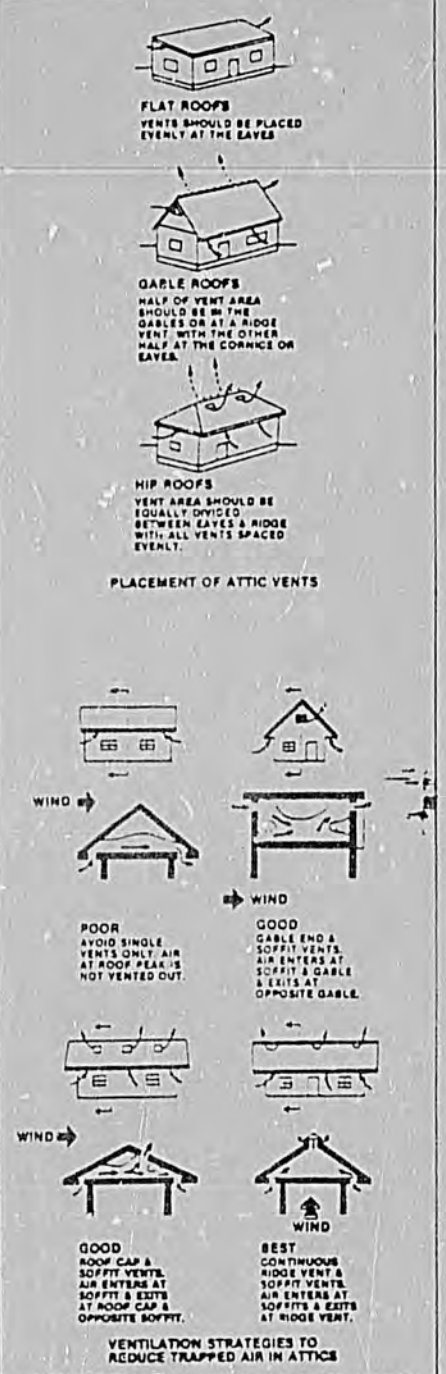

FIGURE 19: ATTIC VENTILATION IS CRITICAL TO AVOIDING MOISTURE PROBLEMS.

SIZING VENTS WITH OBSTRUCTIONS

OBSTRUCTIONS IN VENTILATORS, LOUVERS AND SCREENS[1]	TO DETERMINE TOTAL GROSS AREA OF OF VENT, MULTIPLY AREA IN SQUARE FT. BY:
¼ inch mesh hardware cloth	1
⅛ inch mesh screen (8 mesh screen)	1¼
No. 16 mesh insect screen (with or without plain metal louvers)	2
Wood louvers and ¼ inch mesh hardware cloth[2]	2
Wood louvers and ⅛ inch mesh screen	2¼
Wood louvers and No. 16 mesh insect screen	3

[1] In crawlspace ventilators, screen openings should not be larger than ¼ inch; in attic vents no larger than ⅛ inch.
[2] If metal louvers have drip edges that reduce the opening, use same ratio as shown for wood louvers.

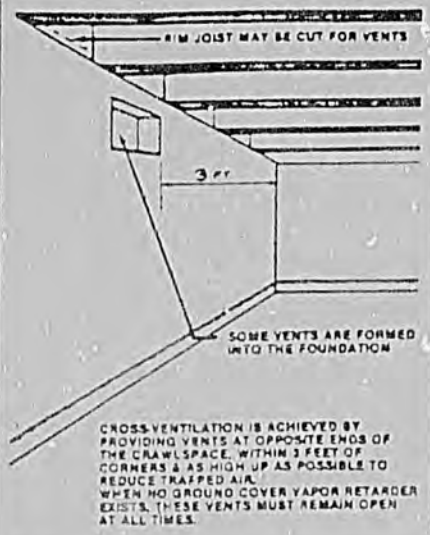

FIGURE 20: CRAWLSPACE VENTILATION IS ESPECIALLY IMPORTANT WHEN A GROUND COVER VAPOR RETARDER ISN'T EMPLOYED.

USING OUTDOOR TEMPERATURE AND RELATIVE HUMIDITY TO REDUCE MASONRY SWEATING

Outside Air Temperature (°F)	Outside Percent Relative Humidity less than	Dew Point Temperatures (°F) (Basement/crawlspace surfaces must be above these temperatures to not have condensation)
90	80	83
	60	75
	40	63
80	80	74
	60	63
	40	54
70	80	64
	60	56
	40	45
60	80	54
	60	47
	40	36
50	80	45
	60	37
	40	28
40	60	35
	40	28
		20

Crawlspace Venting and Sweating of Masonry Walls

Ventilation of crawlspaces and basements may cause sweating of concrete or masonry walls below grade because these surfaces stay at a constant, cooler temperature and outdoor air may hold enough moisture to cause condensation. Beyond the routine action of installing a ground cover vapor retarder in the crawlspace, other actions may be needed to avoid causing this problem.

Condensation can be avoided by closing off vents when outdoor temperatures and humidity become too high. The goal is to keep warm, moist air from contacting surfaces (masonry walls) below the dew point temperature. The chart below shows the relationships between outdoor temperature, relative humidity and dew point temperatures.

For example, assume the basement/crawlspace temperature is 50°F on the masonry surfaces. Below-grade ventilation would be recommended when outside temperature is 60°F or less and outdoor relative humidity is below 60. The dew point for the wall would be 47°F in this instance, and condensation will be avoided because the surface temperature of the masonry is 50°F.

For more detail on determining dew point temperatures, consult the psychrometric chart in Appendix A.

Ventilation for Kitchens, Bathrooms, and High Moisture Areas

The major preventative and corrective action with kitchens and baths is to install and use direct fan venting systems that pull moisture out quickly. The 1981 standard of the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) recommends providing the capacity for ventilation of 50 cubic feet per minute (cfm) in baths and 100 cfm in kitchens. The higher rate for kitchens reflects the possibility of gas cooking appliances, which need greater ventilation rates if indoor air pollution and moisture buildup are to be avoided.

Ductless kitchen and bath recirculating units that simply filter air, not remove it, are not suitable for removing moisture. Where moisture and indoor air pollution aren't major problems, these devices can work well enough. Another popular tactic for reducing condensation in bathrooms is to install an overhead infrared heat lamp. These lamps are sometimes combined with a blower to help circulate the warm air. Obviously, these heat lamps do not remove moisture, but they reduce visible signs of condensation. An exhaust fan is a better solution to remove moisture.

Clothes dryers should always be vented to the outdoors to avoid excess moisture and possible indoor air quality problems from laundry additives. If the home's relative humidity is consistently high, wet towels from bathing and hand washing should be hung outdoors or dried in a dryer.

If it is impossible to install the required vents in kitchen and bath, another option is to install an exhaust fan in a central location as close as possible to the humidity source and duct it to the outdoors. For automatic control of unwanted moisture, any of these vent fans can be successfully connected to a dehumidistat that operates the fan automatically.

Air-to-air Heat Exchangers

Another mechanical method of ventilation and dehumidification is the use of an air-to-air heat exchanger. In today's tightly built cold-climate homes, the air-to-air heat exchanger serves as a heat-recovery ventilation system—a system that recovers heat in outgoing stale air and uses it to warm the fresh, cold air coming into the house. Heat exchangers also need defrosting in very cold climates, and some exchangers on the market have an automatic defrost cycle. Small wall- or ceiling-mounted heat exchangers are available for use in place of bathroom exhaust fans.

Some heat exchangers will do little or nothing to solve moisture problems, because they allow moisture to pass into the fresh air stream. These exchangers, called

"enthalpy" models, should be avoided if excess moisture is a problem. Another problem with heat exchangers that pass moisture is that some indoor air pollutants readily dissolve in water, and these contaminants would then be passed into the fresh air stream.

Air-to-air heat exchangers are necessary in any home that is tightly sealed with a continuous air-vapor retarder. The best heat exchanger systems are ducted to all areas of the home. Tightly constructed, well-insulated homes that employ centrally ducted heat exchangers can tolerate somewhat higher humidity levels, because circulation and ventilation are constant and uniform.

Dehumidification

When high relative humidity is a constant problem, one option is to dehumidify the air. This can be accomplished by mechanical or chemical methods.

Mechanical dehumidifiers are typically the refrigerator type that remove moisture by cooling the air. Moist air is drawn into the device where it is pulled past refrigerator coils, which are cooler than the dew point. The dry air is then exhausted back into the house. Water vapor condenses on the cooling coil, then drips into a collection pan.

At cooler room temperatures of 65°F or below, frost or ice will form on the cooling coils, and dehumidification stops until the unit is defrosted. Some units have an automatic defrost cycle, while others must be manually defrosted by shutting the unit down until the ice melts.

For good circulation, place the dehumidifier in the center of the room. For maximum effectiveness, close off the area to be dehumidified. Clean and empty the drainage pan regularly.

Chemical Dehumidifiers

Chemical dehumidifying agents, known as "desiccants," absorb moisture out of the air. Desiccants are a good option for small, confined places like closets, but they can be used in larger rooms, as well. Some desiccants are very corrosive and must be handled with extreme care. Others are reusable and non-toxic, but hands should be washed thoroughly even after handling the non-toxic variety. Below is a chart that details characteristics of the two major types of desiccants.

Evaluating Drainage Problems

Drainage problems often obstruct insulation and weatherization work, especially with basements and foundations, which are major heat losers in heating season climates. Common sources of drainage problems include excess surface and ground water and clay-type soils. When combined with poor construction details, drainage problems can quickly cause moisture damage, from roof to basement.

In the construction of bermed or earth-sheltered housing, special attention to proper drainage details is critical. See references on drainage in Appendix B for references on this topic. And, in all new construction, foundations need proper design and protection if a long-lasting dwelling is to result.

Some drainage improvements are fairly simple, such as adding downspouts and replacing flashing. Others are extremely costly for retrofit applications, such as excavating around the basement walls to get at the source of a severe ground-water problem. Because of the expense, some basement and foundation moisture problems, simply cannot be remedied and insulation must be foregone. Many factors must be taken into account when evaluating basement and foundation water problems, and thought should be given to choosing the lowest-cost option that best meets the homeowner's needs.

Surface Water

Basement and foundation water problems can sometimes be simply solved by improving drainage of surface water from precipitation and irrigation. Adding soil around the foundation to achieve a good slope is a basic solution. A 6-inch slope over a 10-foot run is recommended. Where cost and lack of room prohibit meeting the recommended slope, try to channel moisture away, as well as sloping the soil as much as possible. Another option is to install drain gutters on the roof eaves with long extension spouts to channel water away from the dwelling, as well as inspecting and repairing flashing details all around the house (see Figure 21).

However, in some locations where surface water typically causes basement flooding due to terrain and seasonal run-off, more radical action may be needed, including actions that are traditionally used to control excess ground water (high water table). These actions include adding sump pumps and dry wells, installing additional or new floor drains, laying a new basement floor over a waterproofing layer, and installing a drain tile. In new construction and comprehensive retrofit, another basic preventative measure is to install a sloped drain pipe along the footings with use of gravelly soil next to the foundation.

In the optimal situation, the best course of action is always to tackle the water problem from the outside of the wall surface. In new construction, this is easily possible by employing good construction techniques suited to the location. In most retrofit applications, however, excavation of the exterior of the basement or foundation wall is too costly for consideration. In these cases, interior retrofit action is usually the only available route, but it may not pro-

DESICCANTS FOR DEHUMIDIFICATION

Desiccant	Characteristics	Application Guide
Silica gel or activated alumina	• Not harmful to fabrics • Can be placed in paper containers (i.e. paper bag) • Uses: Hung with clothes, placed in containers or shelves, floor basement • Reuseable • Suitable for above-freezing application	• Place in suitable container that is porous or open at top • Close off areas to be dehumidified for maximum effectiveness • Dry silica gel is a blue color and pink when wet • Reuse by drying in oven at 300°F for a couple of hours
Calcium Chloride	• Corrosive to clothes, metal, burns skin, etc. • Keep away from vegetation • Wash surfaces after contact (i.e. metal, skin, clothes) • Uses: Basements, crawlspaces • Turns to a liquid as it absorbs water • Suitable for above-freezing application	• Place calcium chloride salt in non-corrosive container (i.e. glass, some plastics) • Close off area to be dehumidified for maximum effectiveness • Larger areas (i.e. basements or crawlspaces) use several 25 lb. containers • Dispose of the corrosive liquid and replace with new calcium chloride daily or as needed

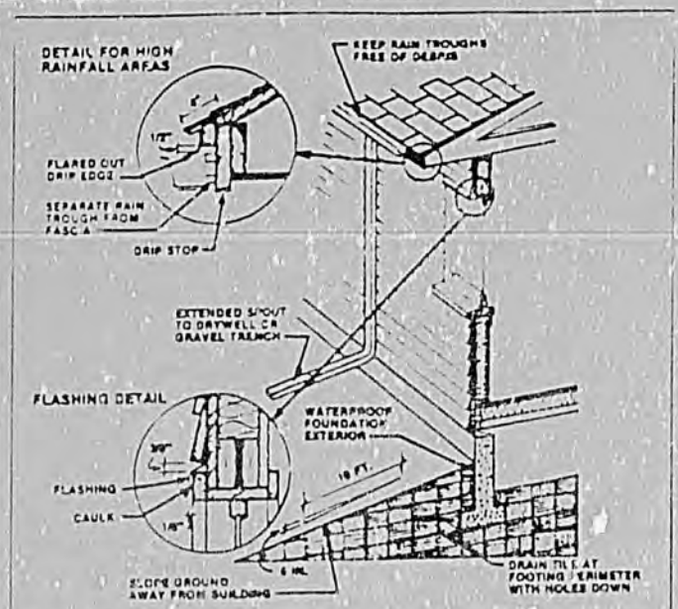

FIGURE 21: PROVIDE PROPER DRAINAGE AND PREVENT SEEPAGE INTO STRUCTURE TO AVOID DAMAGE.

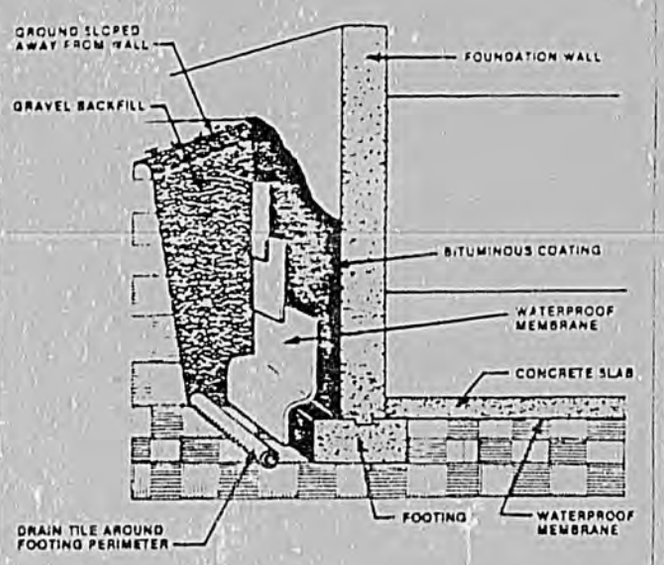

FIGURE 22: EXTERIOR WATERPROOFING IS OFTEN REQUIRED FOR "SEVERE" GROUND WATER MOISTURE PROBLEMS.

only available route, but it may not produce satisfactory results in severe situations. The main problem with interior retrofit action to stop water is that the wall may become fully saturated with water, causing a variety of problems.

Assessing the Problem

To choose the proper solution, one must first know the extent of the moisture problem. Remember that concrete can be an adequate vapor retarder, but when subject to standing water or ground water pressure, capillary flow can occur. Waterproof coatings should be used with concrete in high ground water situations, or special additives can be mixed with concrete when it is poured to retard leaking. The wetter the concrete is poured, the higher its permeability.

If the problem is *severe, waterproofing* the basement or foundation walls and slab floors is recommended. This is an exterior operation usually limited to new construction, but it can be adapted for a radical retrofit, if necessary. Waterproofing stops the direct flow of water, and it often consists of built-up membranes layered several times. A variety of waterproofing products are currently in use, and contractors dealing with earth-sheltered construction differ over which method and products are the best.

Severe moisture problems are typically found in locations near swamps, rivers and lakes, which are prone to ground water pressure. In these cases, water pressure won't be relieved by standard drainage methods such as footing tiles, which drain to storm sewers. A variety of preventative measures should be used in these locations, including impermeable exterior waterproofing. Minimum property standard codes call for waterproofing (at least the equivalent protection of 2-ply hot-mopped felts, 6-mil polyvinyl chloride or 55-pound rolled roofing) that is carefully applied and sealed at all seams. Waterproofing should extend from the edge of footings to the finished soil line, as well as under basement and ground slabs (see Figure 22).

If the problem is moderate, *dampproofing* may suffice. Dampproofing products interrupt the capillary action of the moisture, but are not intended to totally stop water penetration. (See chart below for examples of common dampproofing products.) Dampproofing is a common solution for basement or foundation retrofits, but it cannot be expected to handle severe water pressure problems. If the problem is moderate, dampproofing in conjunction with other actions can do an adequate job.

DAMPPROOFERS FOR INTERIOR FOUNDATION SURFACES

A. Ready-mix Paints	• Hydrocarbon solvent base (mineral spirits) pigments, portland cement (to increase solids content) and a form of synthetic rubber as a binder. • Convenient to use, good choice, competitively priced and can be quite effective. May require more than one coat.
B. Ready-mix "Latex" Paints	• Water base, pigments and synthetic rubber binder. • Easy to clean up, no flammable solvents, safer and easy to use and give off less odors. May not be as effective as other types. May require more than one coat.
C. Ready-mix Solvent Based Paints	• Contains portland cement, pigments, resins and linseed oil. • Cleans with solvents. May require more than one coat.
D. Two-Part Epoxy Paints Solvent or Water-Base	• Require careful mixing, are more costly than most other products, may require more than one coat, but are usually more effective.
E. Portland Cement Based Powders	• Mix with water. • Require the most work to mix and apply, dries quickly, making application difficult, requires constant rewetting during application. Least costly, may require more than one coat. Some staining may result. Reasonably effective.

NOTE: BE PARTICULAR REGARDING CORRECT SURFACE PREPARATION AND APPLICATION. FOLLOWING THE MANUFACTURERS' DIRECTIONS AND SUGGESTIONS CAN MAKE THE DIFFERENCE BETWEEN SUCCESS WITH A POORER PRODUCT OR THE FAILURE WITH A SUPERIOR PRODUCT. EXPERIMENTING WITH DIFFERENT TYPES PRIOR TO A TOTAL COMMITMENT SHOULD BE CONSIDERED.

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Unlike severe moisture problems, *moderate* moisture problems define situations where water pressure can be relieved by drain tiles at the footings. However, heavy rains may cause seasonal back-up of storm sewers, and if soil is heavy, it may retain water for long periods of time even though high ground water isn't a normal problem.

In general, if the soil type is sandy and gravelly, and ground water is below the foundation level, drain tiles at the footings are unnecessary because the soil's natural drainage will be adequate. However, seasonal changes and terrain may dictate that previously discussed preventative actions should be considered. Remember that when exterior waterproofing is required, a backfill of crushed gravel should be considered, especially for areas where soil is the clay type and expands when wetted.

Excessive moisture pressure, which can cause buckling of walls and slabs, should be relieved. In the floor, consider the addition of a dry well and a sump pump to reduce pressure from ground water (see Figure 23). In addition, commercially available mixtures can be applied to the interior masonry wall to make it less permeable. These mixtures must fill the surface pores to be most effective.

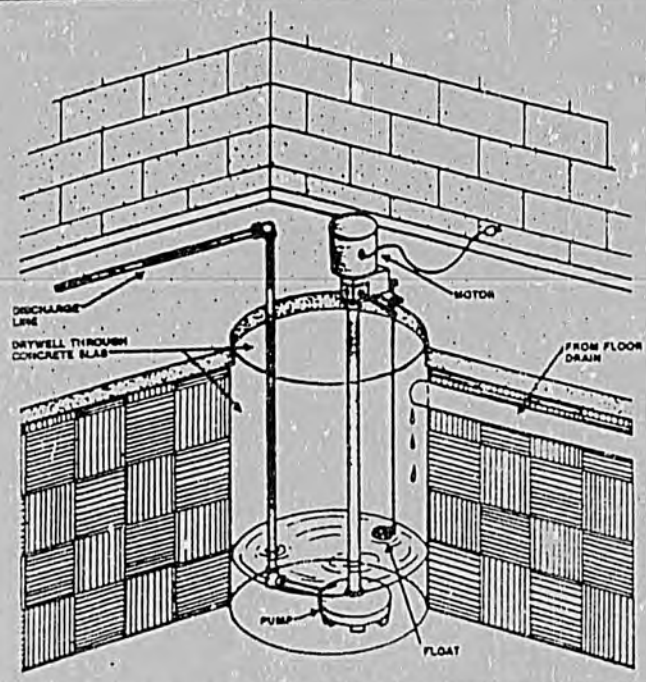

FIGURE 23: A DRYWELL AND SUMP PUMP ARE OFTEN NECESSARY IN AREAS OF HIGH GROUND WATER OR PROBLEMATIC SURFACE WATER.

Exterior Insulation Options

Foundation and basement walls can be insulated on the outside to reduce condensation and save energy, and insulation should be a part of cold-climate retrofit or new construction waterproofing or dampproofing. Insulating on the outside is the superior method, because it protects the wall or foundation from the freeze-thaw cycle.

When insulating on the exterior, use rigid insulation that does not deteriorate in below-grade applications (typically high-grade extruded polystyrene) and cover the insulation to protect it from ultra-violet rays and damage. In new construction, the rigid insulation should extend from the top of the foundation to the footings. In retrofit applications, the rigid insulation should extend from the top of the foundation to at least two feet below grade (see Figure 24).

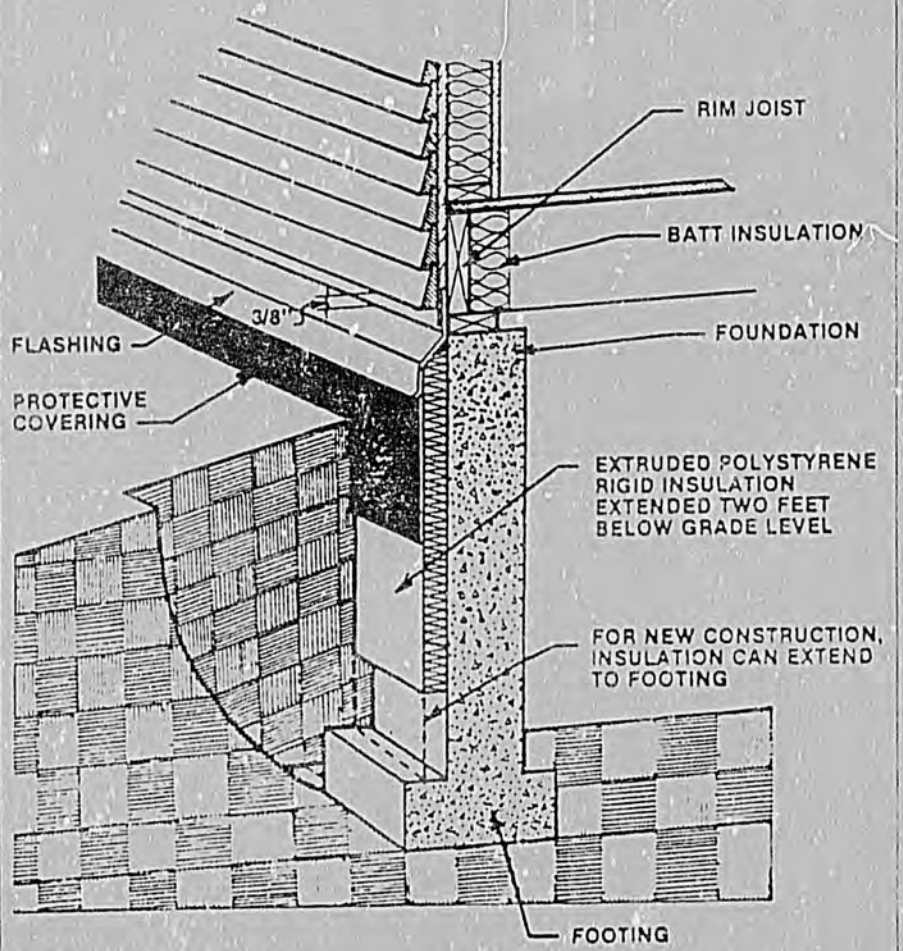

FIGURE 24: AN EXTERIOR RETROFIT INSULATION JOB CAN HELP REDUCE HEAT LOSS THROUGH EXPOSED CONCRETE WALLS.

Interior Insulation Options

Remember that most interior water-stopping action deals with the symptoms of the problem more than the cause. Generally, when it isn't possible to tackle severe mois-

ture problems from the exterior, basement walls should not be insulated. Attempts can be made at controlling the moisture problem with the use of dampproofing, drainage and sump pumps, as previously illustrated. If moisture cannot be controlled, add a vapor retarder and insulation to the ceiling instead of the walls, in order to stop moisture migrating to the living space above.

With moderate moisture problems, wall dampness can be reduced with the application of a cement-base dampproofing or an epoxy or latex paint. Before insulation is added, the moist or wet wall must be thoroughly dried. The drying process for a wet basement wall, whether from new construction, an outside source or from interior condensation, may take weeks or even months. For new construction, it's often common to wait through one heating season to allow the foundation to dry.

To insulate on the inside involves either building a new frame wall and adding batts and a vapor retarder, or using the simpler method of installing rigid insulation directly to the dry concrete walls with construction adhesive. Note that with the rigid insulation option, electrical installations are limited to the ceiling or surface mounting on the walls. The rigid insulation should be covered with an airtight vapor retarder and fire-rated board to reduce fire hazards associated with foam board insulations (see Figure 25).

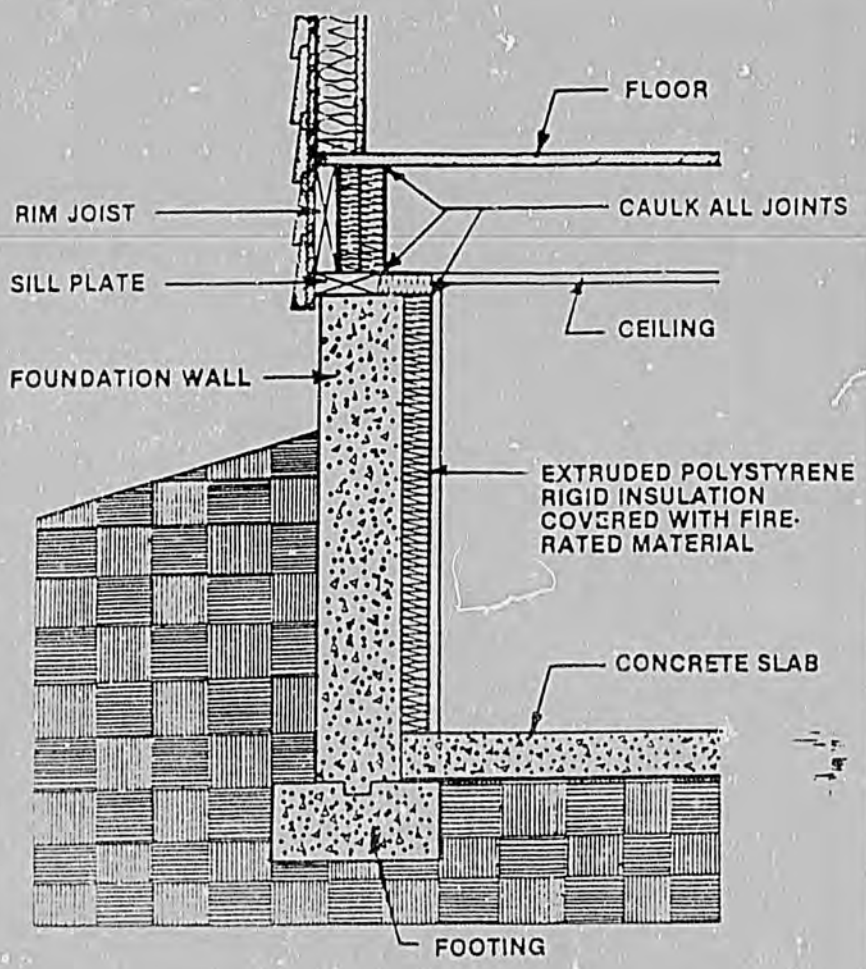

FIGURE 25: AN INTERIOR RETROFIT INSULATION JOB MAY BE A SUITABLE OPTION IF SOIL MOISTURE PROBLEMS ARE NOT SEVERE.

Increasing Resistance to Moisture

When moisture sources cannot be sufficiently reduced or in areas of high outdoor humidity, high rainfall, or constant wetness, increasing wood's resistance to moisture is the major prevention and correction option. In this section, wood preservatives and water repellents are discussed, and moisture-caused paint problems are examined.

When Wood Needs Protection

In general, wood should be protected if:

- it is in contact with soil;
- it is in or around masonry or concrete within 18 inches of the ground;
- it is an exposed, structural member subject to wetting, such as porches, decks and steps or;
- it is a joint end grain or water-trapping area that is unprotected from moisture.

Water Repellants and Preservatives

Pressure-treated wood is a good option where wood will be exposed to extreme moisture conditions. Chemicals are impregnated through the wood under pressure to protect it from decay and insects. Some preservatives can't be painted over. For more information on wood preservatives and related federal standards, see references in Appendix B.

A water repellent penetrates the wood and seals it from absorbing moisture. A preservative contains an additional toxic fungicide that resists decay and insects. Repellents are good choices for above-ground applications, while preservatives are recommended for below-ground locations and areas subject to constant wetting.

Penta (Pentachlorophenol) is the most common fungicide preservative in use. Copper napthanate is another, less toxic choice, but it does have an undesirable odor. A coating of spar varnish will reduce odor problems. Dipped, brushed or sprayed repellents do not have the strength of pressure-treated wood, but they do provide substantial protection. Preservative solutions made with mineral spirits or turpentine can usually be painted when the solution dries. Refer to the manufacturers' instructions for application details.

Paint Isn't a Preservative or a Repellent

Paint isn't an effective preservative or repellent because it only coats the surface. A true repellent or preservative soaks into the wood and seals the interior of the wood cells. A cracked, painted surface will readily take in moisture, while slowing the evaporation process. Thus, a cracked, painted surface is a perfect climate for decay.

Water repellents or preservatives should be liberally applied before painting or finishing a surface. And, if the surface is exposed to constant wetting, a better protection method than paint should be considered.

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Decayed wood won't benefit from preservatives. Decayed wood should be replaced, along with wood up to two feet on either side of the decayed area to make sure all the infection has been removed.

Paint Problems

Peeling, blistering, or cracking paint can point to a moisture problem, especially if the raw surface or wood is visible under paint blisters or cracks. Moisture inside or outside the dwelling can attack paint. Paint problems are usually most visible after the heating season, but before spring rains (see Figure 26).

Moisture-caused paint problems are most common on the coldest side of the building or areas subject to heavy wetting through rain or sprinkling. Often, paint problems are severe on outside walls of rooms with high humidity. Unfortunately, some paint problems are not recognized as moisture-related, and sometimes the problem is simply covered up with new vinyl or metal siding. Of course, some paint problems are strictly linked to poor application of the paint, or use of a paint that wasn't meant to do a particular job.

Like other exterior-use products, paint should shed water, but should still be breathable to allow moisture to escape. For this reason, latex paints with vinyl or acrylic polymers are often the best choices because they breathe, yet protect. High-luster oil-based paints are the least porous. When choosing paint, ask the dealer for advice on the right paint for the job, and follow the manufacturers' instructions to the letter.

Gable ends of heated buildings often have paint problems if the attic is uninsulated, poorly vented, without a vapor retarder or if the dwelling has excess moisture. Treat these problems, and the paint problem should be alleviated.

Fascia board may be the site of difficulties if poor drainage is being caused by undersized, plugged or leaking gutters, or design or construction errors with eaves, shingles or soffits. Also, ice dams will contribute to paint deterioration. Inadequate ventilation at the eaves is another possible culprit.

Solutions to fascia paint problems are numerous. Clear debris from the roof area, such as leaves, pine needles and other damming items. Unplug rain gutters, and repair them to stop leaks. Sometimes, increasing the size or number of downspouts is the answer. For eave/rake or flashing/drip edge dilemmas, consider increasing the length of the shingle drip edge or install a new metal drip edge under the shingles, leaving a gap between the drip edge and the fascia for drying purposes. The drip edge should extend at least one-half inch below a butting wood member.

Soffits suffer problems similar to fascia board and gable ends. Generally, all the above-mentioned remedial actions should be considered.

Paint can deteriorate below windows on both the exterior and the interior. Watch for poor seals around exterior window trim that allows water to get behind siding. Cracked or deteriorated window sills will also cause difficulties. Note all places around windows where water or water vapor can

Making Your Own Wood Preservatives

Wood preservatives are available commercially, or they can be made from common household supplies. The key in application is to concentrate on the end grain, or any holes or cuts in the wood. (Note that the end grain absorbs moisture much more readily than the side grain.) These areas require multiple treatment if the wood will be used in an area where it will be exposed to constant wetting.

The following repellent recipe is not as toxic as most preservatives, and it can be painted after drying. It is lower in cost than most preservatives and is a good choice for above-ground exposed wood, such as furniture, decks, railings and playground equipment.

Water Repellent Recipe—Makes One Gallon

[illegible] cups boiled linseed oil

(or 3 cups exterior grade varnish)

4 ounces paraffin wax

Solvent (turpentine, mineral spirits or paint thinner) to make one gallon

Mixing: Mix the solution in a well-ventilated area, and wear rubber gloves and goggles or mask. Melt the paraffin in a double boiler. Have the solvent at room temperature (60-80°F). Stir the solvent vigorously while slowly pouring in the melted wax. Add linseed oil (or the varnish) and blend well.

Uses: A 3-15 minute dip is the superior method of use. The repellent also can be sprayed or brushed liberally, especially at the board ends and joints. Allow two warm days drying time after brushing or spraying it on, and allow a week for drying dipped pieces. The repellent will keep, but ingredients may separate at cooler temperatures. Warm to room temperature and stir before re-use.

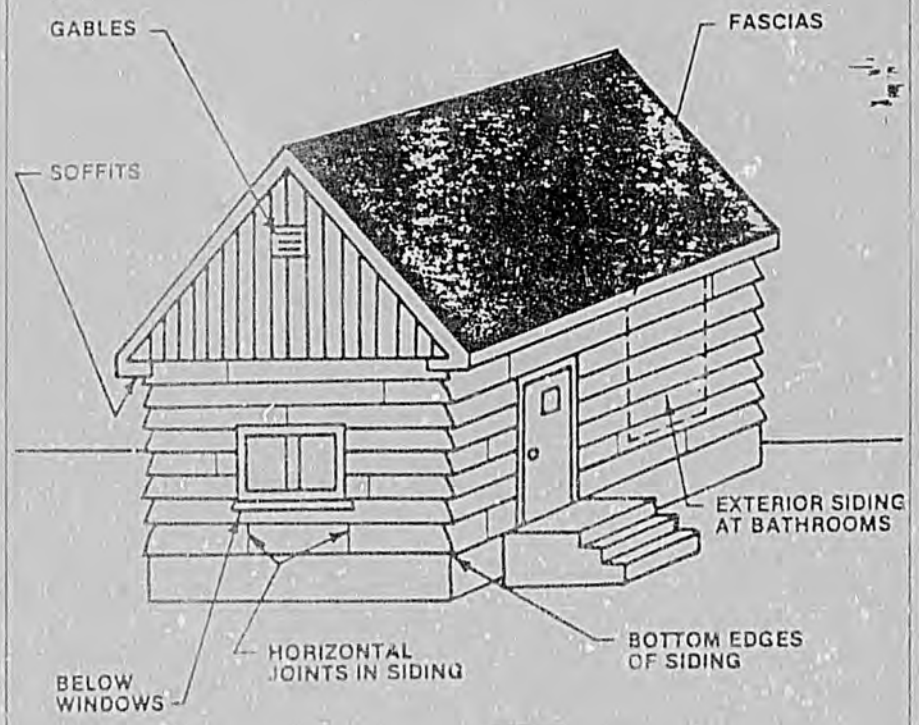

FIGURE 26. EXTERIOR PAINT DETERIORATION CAN OCCUR IN MANY LOCATIONS AND IS OFTEN A SIGN OF MOISTURE PROBLEMS.

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enter. Another good move is to replace or seal the flashing above the window.

The Double-hung Window Dilemma

A special and hard-to-spot problem can occur with double-hung windows. Warm, moist air can enter the cavities, through the holes where the pulley-sash cord is located or from the sides of the interior window trim, and condense on the cold weights inside the cavities. Frost and ice can build up on these weights, and when it melts, it can leak into the wall cavity.

Two solutions: either caulk around the interior window trim where it meets the wall and seal the pulley holes, using one of the new sealing devices that allow the cords to still operate; or remove the weights, seal the cavities, and seal the pulley openings. To keep the window operable with the second option, install low-cost spring clips. (Note that these clips may not work on extra large windows.) With the remove-the-weights option, a good weatherstripping job is possible because the sash cords are out of the way (see Figure 27).

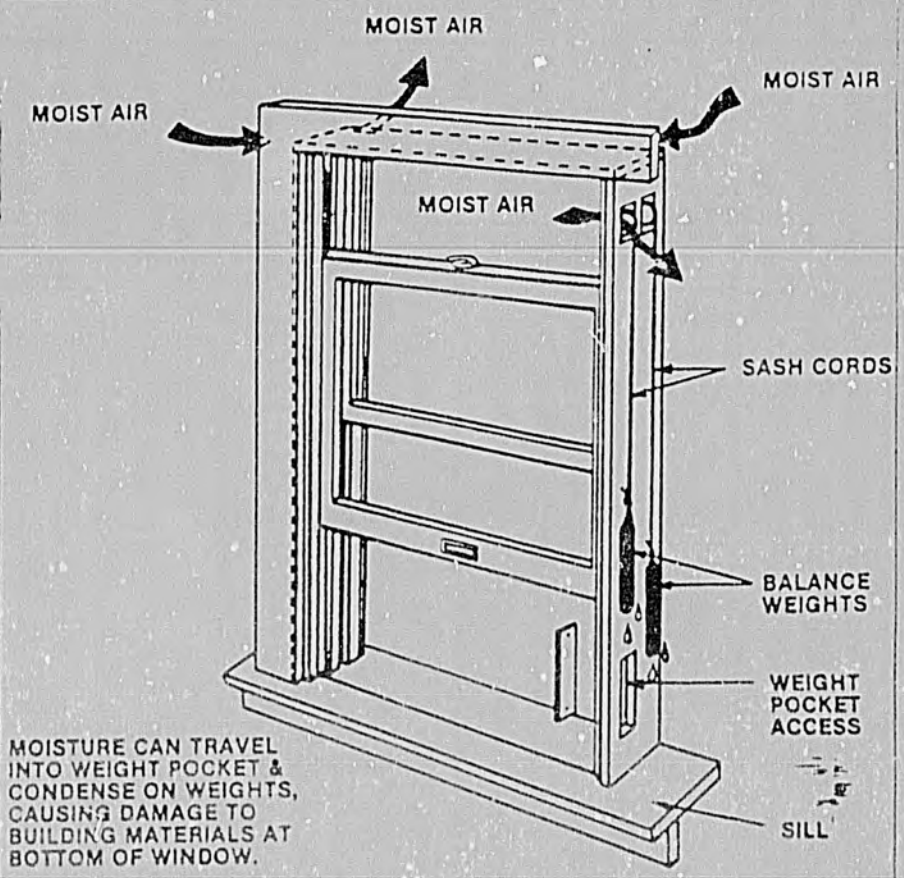

FIGURE 27: DOUBLE-HUNG WINDOW BALANCE WEIGHTS MAY CONTRIBUTE TO MOISTURE DAMAGE.

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SECTION IV

A MOISTURE AUDIT PROCESS

The process described in this section is a generalized method for conducting a moisture audit on a home. It is not all-encompassing; a process is presented rather than a comprehensive "cook book." Simple forms are included to provide a systematic framework and to give the reader a handy place to keep notes. The reader should be familiar with the material in the preceding sections before using this audit.

The audit process follows five main steps: I. Identify the Symptoms, II. Get the History, III. Start Searching, IV. Define the Solutions, and V. Select Corrective Measures.

The following tools will be useful as you conduct this audit.

- ☑ Coveralls, hat or hardhat, cotton gloves
- ☑ Magnetic compass
- ☑ Pocket knife or awl
- ☑ Tape measure
- ☑ Flashlight and spare bulb/batteries
- ☑ Step ladder
- ☑ Sling psychrometer and charts
- ☑ Thermometer (electronic is fast and best choice)
- ☑ Duct tape
- ☑ Polyethylene film 6-1½' x 1½'
- ☑ Camera, flash, film (optional)
- ☑ Clipboard, paper, pencil(s) and eraser
- ☑ Binoculars for multi-story buildings (optional)
- ☑ Calculator (optional)
- ☑ Hair blow dryer

I. IDENTIFY THE SYMPTOMS

The first step in the moisture audit process involves noting symptoms of excess moisture and identifying their locations considering the entire house, both inside and out. The following checklist can help identify locations where moisture problems may exist. Try to be as specific as possible when describing the location.

Typical Symptoms	Locations
☑ Strong or musty odors	
☑ Damp sensation	
☑ Mold and mildew	
☑ Discoloration, staining or texture changes on wood or masonry surfaces	
☑ Rot or decay	
☑ Water-carrying fungus	
☑ Fogging windows	
☑ Condensation or sweating	
☑ Frost or ice build-up	
☑ Paint peeling, blistering or cracking	
☑ Corrosion or rust on metal surfaces	
☑ Leaks or dripping noise	
☑ Deformed wooden surfaces	
☑ Concrete or masonry chipping	
☑ Drainage problems (interior and exterior)	

II. GET THE HISTORY

After the obvious symptoms of moisture problems have been identified, the next step is to obtain as much information as possible about the structure and its use patterns, both from inspection and from the building occupants. Except in rare cases, moisture problems don't appear overnight, and this historical information will help to interpret the symptoms and diagnose the causes of moisture problems.

A. Building Components and Operation

The mechanical and structural components of a home all help to define its moisture balance. These questions will aid in identifying important factors in this moisture balance.

1. What type of heating system is used? (Circle all appropriate answers)
System Type:
Central Forced Air
Central Hot Water
Central Steam
Fireplace
Wood Stove
Portable Space Heater
Fuel Type:
Electricity
Natural Gas
Propane (LPG)
Fuel Oil
Coal
Wood
Kerosene
(Electric homes without chimneys may have higher indoor relative humidity levels.)

2. Are any rooms in the home closed off with only intermittent heat? YES NO
Comments: _____

3. What is the normal thermostat setting?
Day _____ Night _____
(When warm moist air contacts cold surfaces condensation can take place.)

4. Does the heating system have poor distribution?
Are there any cold spots? YES NO
Comments: _____

5. If you use wood for fuel do you store it inside or directly against the side of your home outdoors? YES NO
(Wet wood contains a lot of moisture and can contribute to home moisture problems if not stored properly outdoors away from the side of your house.)

6. Is a dehumidifying device ever used? YES NO
- Type: Central_____
  Portable_____
- Season(s) used: _____
  hours/day_____
- Location of use: _____
- Percent relative humidity setting_____

7. Is an air conditioner ever used? YES NO
- Type: Central_____
  Portable_____
- Seasons(s) used: _____
  hours/day_____
- Temperature setting _____°F
- Location of use and comments: _____

8. Is a humidifier ever used? YES NO
- Type: Central_____
  Portable_____
- Season(s) used: _____
  hours/day_____
- Percent relative humidity setting _____
- Location of use and comments: _____

9. Is an evaporative cooler (swamp cooler) ever used? YES NO
- Type: Central _____
  Portable _____
- Season(s) used: _____
  hours/day _____
- Machine setting—High _____ Med. _____ Low _____
- Location of use and comments: _____

(Humidifiers and evaporative coolers can contribute large amounts of moisture to the home.)

10. Is propane or natural gas used for cooking: YES NO
If yes, is a vented range hood provided? YES NO
(Cooking with propane and natural gas discharges water vapor to the living space.)

11. Do any windows have single glazing? YES NO
Comments: _____
(Single glazed windows may be a simple remedy.)

12. Do windows fog up even though they have two or more layers of glazing? YES NO
(Generally, this is a reasonable indication that indoor relative humidity is too high.)

13. Is circulation or ventilation of indoor air curtailed in any way? YES NO
Comments: _____

14. Does the attic and/or crawlspace have inadequate ventilation? YES NO
Note total vent area: attic_____
crawlspace_____

15. Does the attic or ceiling insulation touch the roof sheathing, leaving no gap for circulation? YES NO
(Note: Further information on how to determine whether attic and crawlspace ventilation is adequate is provided in the text in Section III.)

16. Are vapor retarders present in the home? YES NO
Where are they located?_____
Are they properly installed? YES NO
Comments: _____

17. Are vapor retarders located on both sides of the same wall in any locations? (This is an invitation to moisture problems.) YES NO
Comments: _____

18. Is a ground cover vapor retarder used over the soil in the crawlspace? YES NO
(Further information on vapor retarders is found in the text in Section III.)

B. Modifications to the Building Structure

Modifications to a home can sometimes lead to changes in ventilation and air circulation, which can affect moisture transfer patterns. Have any building changes been made in the last year or two? Yes answers to the following questions should be noted for further analysis.

19. Have any of the following energy conservation/weatherization activities been recently conducted?

- Caulking/weatherstripping YES NO
- Insulation YES NO
- Vapor retarder installation YES NO
- Storm Windows YES NO

20. Has any remodeling recently been done? YES NO

Comments: _____

21. Has an attached solar greenhouse been added? YES NO

Comments: _____

22. Have any modifications to the heating/cooling system been made? (For instance, has a new humidifier, air conditioner or furnace been installed?) YES NO

Comments: _____

C. Occupant Behavior

The lifestyle of the building occupants can also have a significant impact on the moisture balance. Yes answers to these questions indicate that moisture is being contributed to the home from sources that can easily be controlled through behavior changes if a home's moisture balance is out of adjustment. See Section II for further information.

23. Is there now or was there in the past more than one occupant for every 250 sq. ft. of floor area in the home? YES NO

(Home water use is generally proportional to the number of building occupants.)

24. Does bathing take place without the use of an exterior vented exhaust fan? YES NO

25. Are wet towels hung in a confined area indoors to dry? YES NO

26. Does cooking take place without an exterior vented exhaust fan? YES NO

27. Does cooking take place without lids on pots? YES NO

28. Are clothes dried on a line indoors or with a clothes dryer vented into the living space. YES NO

29. Are floors frequently mopped? YES NO

30. Are large open terrariums or aquariums present? YES NO

31. Are there large numbers of house plants present? YES NO

III. START SEARCHING

Now that background information has been obtained and the obvious symptoms of moisture problems in the home have been identified, it's time to initiate a thorough search and begin diagnosing problems. You will need to draw heavily on the principles which have previously been described in the text. You must also be careful and thorough because a single symptom of excess moisture may have multiple causes, and multiple symptoms may result from a single cause.

A. The most important tool for the analysis of moisture problems is the moisture balance principle discussed in detail in Section I.

- *Sources* of moisture must be identified—where they come from, when and how they appear and whether they need to be reduced or eliminated.
- *Temperature* plays a major role in the moisture balance. As was previously noted, the amount of moisture that air can hold depends on its temperature. Are temperature and/or temperature differences causing moisture problems?
- *Moisture transfer* must be analyzed. Should it be increased or decreased?
- *Ventilation and circulation* play a part in the moisture balance. Is moisture in a home being properly swept away by ventilation, or is moist air stagnating and causing problems?

B. Begin searching for the causes of the symptoms of moisture problems you have already identified. The search must be thorough and systematic. Make sure you have obtained the answers to all the questions in Section II of the audit. Start looking for causes at the location of the symptom, and move systematically away from it. For example, work in a clockwise direction, or start upward and move downward, or move from the exterior to interior. Do the same for every symptom of moisture problems you have identified. Make sure you have covered the entire house from attic to basement or crawlspace inside and out before you have finished. You may find other previously unidentified symptoms of moisture problems along the way. Sometimes it is better to focus on a single problem until it is diagnosed before addressing another, because the process can become complex.

C. As you search, use the "water hose method." *Pretend* you are washing the surface you are looking at with a hose in a systematic manner. Leaky locations are obvious sources of liquid moisture and water vapor. But, this method will also call attention to less obvious symptoms and their solutions.

D. *Use all your senses* to help diagnose the causes of moisture problems. *Walk* the perimeter of each room as well as the exterior perimeter of the dwelling. Usually, unevenness, slope, warpage and so forth, can be detected simply by walking over a surface. Use the *Tap Test* (Appendix A) to identify signs of decay. Sound wood will normally present a clear ringing sound. *Look* for signs of discoloration or changes in texture on all surfaces. Check behind furniture, drapes, shades, and foliage. Note any strong or musty *odors*. Be particularly sensitive to any *damp sensation* in the air.

E. The moisture tests (relative humidity, dew point, capillary, and wood deterioration) in Appendix A will aid you in your search for symptoms and causes. Don't be afraid to investigate and experiment. Moisture problems are often complex to solve. Often

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bits of information from several different sources will be required to come up with a solution.

F. Special or unusual problems will demand even more careful searching. If a moisture source is eluding you, look for the following:

- Look for hidden passages to upper or lower levels of the dwelling. Open wall cavities, on the exterior or interior, may extend from the basement or crawlspace to the upper levels. Balloon framing, partition walls, vents, shafts and ducts can all be sources of moisture transfer between floors.
- Certain moisture problems are seasonal in nature. Some complex roof designs (roofs with valleys) are conducive to ice dams, which are present only in the winter. Also, roof drainage problems may not be readily visible if it is not raining. Be aware of the season while doing your audit.
- With mobile homes, unusual water stains may appear along the outside corner where the wall meets the ceiling. This is caused by moist interior air condensing on the sheet metal roof. The moisture then follows the roof curve down to where the ceiling and roof join. The problem can be solved with an airtight ceiling vapor retarder, more attic ventilation and more ceiling insulation. The principles for controlling moisture in mobile homes are generally similar to those of site-built homes, although the techniques for resolving problems are sometimes different.
- Occasionally, mistakes can create serious moisture sources. Dripping water from recessed electrical fixtures after a ceiling insulation job calls for fast action. Never insulate over these fixtures or old knob and tube wiring, as dangerous levels of heat can build up. The solution is to replace recessed fixtures or old wiring before insulating with surface-mounted light fixtures, then install a vapor retarder and ceiling insulation.

IV. DEFINE SOLUTIONS

Once the sources of home moisture problems have been identified, the next step is to define solutions to the problems. Again, the solutions relate to adjusting the home's moisture balance. The following list of corrective and preventive options for moisture problems will be useful in defining solutions.

A. Reduce the sources: Stop water and plumbing leaks; repair or increase drainage; change home occupant behavioral habits, try dehumidification, passive or mechanical drying techniques.

B. Watch temperature differences: Warm up cold surfaces with circulation or ventilation; try insulating cold surfaces, such as walls, windows, ceilings, basements, and crawlspaces. Use local heating with space heaters to help warm surfaces. Make sure temperatures are above the dew point to avoid condensation of moisture.

C. Check moisture transfer rate: Seal inside surface air leaks. Stop capillary action with ground moisture vapor retarders. Consider using tightly installed vapor retarders where needed (heating climates) in attic or crawlspace or when adding insulation. Protect and seal exterior surface cracks and leaks and provide moisture proofing. Increase moisture resistance with wood preservatives and proper finishes.

D. Increase air circulation and ventilation: Eliminate or reduce trapped moisture or damp air. Increase circulation first, using natural or mechanical means, to accelerate drying and curtail the environment for deterioration. Allow enough room when placing home furnishings for proper air movement. Allow the cool side of insulated walls, ceilings, floors and basements to breathe with the use of proper materials and venting. In heating climates, in homes with reduced ventilation, consider the use of air-to-air heat exchangers. Another option is to connect a dehumidistat to an exhaust fan so that moist air is automatically exhausted.

V. SELECT CORRECTIVE MEASURES

Fill in the attached chart as you proceed through the audit. After you have completed the audit and filled in the chart, you need to prioritize the tasks necessary to solve the moisture problems you identified. Remember the following considerations:

A. Start with the easiest, lowest-cost remedies that address the most pressing problems.

B. Lifestyle modifications are often cheap and easy to make. They are sometimes ideal ways to reduce moisture sources.

C. If lifestyle changes do not solve the problem, make any necessary mechanical adjustments or repairs to reduce moisture sources and improve the moisture balance.

D. As a last resort, make any structural changes that are necessary to halt moisture problems (retrofitting vapor retarders, dampproofing foundation walls, and the like).

MOISTURE AUDIT FORM

PROBLEM/ SYMPTON	LOCATION	SOURCE/ CAUSE	REMEDY	COST ESTIMATE

NAME: _____
ADDRESS: _____
TELEPHONE NUMBER: _____
DATE: _____
ENVIRONMENTAL CONDITIONS: _____

Appendix A

MOISTURE TESTS AND TOOLS

The following is a group of tests that can help pinpoint moisture problems. The tests include: Relative Humidity and Dew Point Tests (for determining when high RH is a problem and discovering dew point temperatures to avoid condensation), the Capillary Test (for determining where moisture is coming from) and Wood Deterioration Tests. In addition, information is provided to help you clean and calibrate a humidistat.

RELATIVE HUMIDITY AND DEW POINT TESTS

The best method for determining relative humidity (RH) is to use a sling psychrometer made for that purpose (see Figure 28). If a sling psychrometer is not readily available, the RH can still be determined to within 5 percent by using a standard bulb thermometer.

Relative Humidity and Dew Point Determination with a Standard Bulb Thermometer

1. Set the thermometer with a small fan blowing across it until temperature stabilizes and record as dry bulb air temperature.
2. Wrap bulb with small piece of thin cotton gauze wetted with water, preferably distilled water.
3. Again turn on the fan and record the wet bulb air temperature when it stabilizes. Note: With two thermometers the test is completed more quickly and is probably more accurate, but the two thermometers must read the same before the test.
4. Use the dry bulb and wet bulb temperatures and the psychrometric chart to determine RH.
5. Next, use the RH and dry bulb temperature to determine dew point temperature from the psychrometric chart.

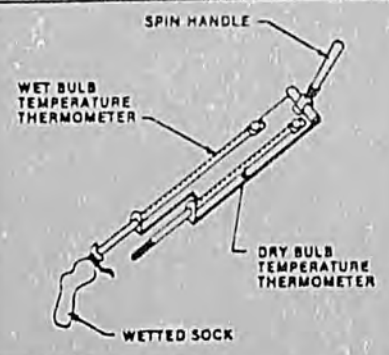
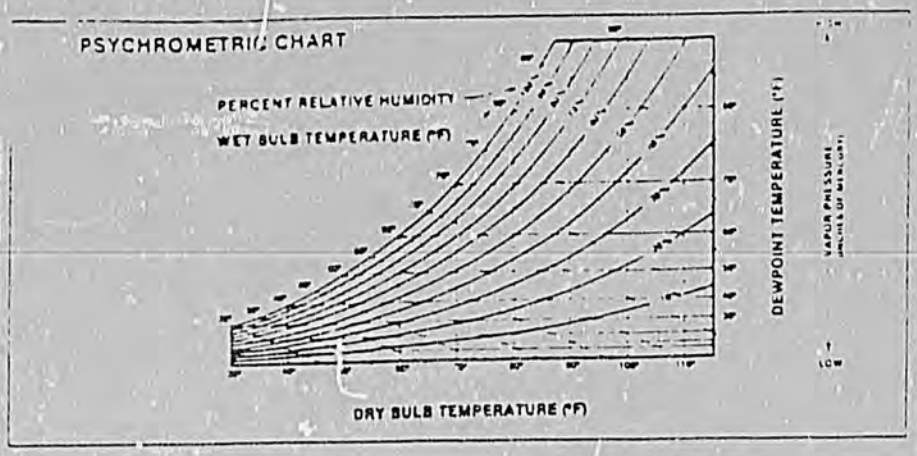


FIGURE 28: A SLING PSYCHROMETER IS A HANDY TOOL IN DETERMINING INDOOR RELATIVE HUMIDITY.



A Low-Cost RH Indicator

A simple low-cost tool is available for determining indoor relative humidity (see Appendix B). It consists of a cardboard gauge that is color sensitive to humidity. By simply mounting this indicator to the wall, humidity can be monitored.

CAPILLARY TEST

Capillary rise of soil moisture is upward movement of water through the soil. To determine whether this moisture is coming through the foundation walls or floor to the inside or whether moisture is coming from inside the dwelling itself, do the following:
1. Identify the damp interior surface. Note that testing of multiple locations on the floor or walls may be necessary to locate external sources of moisture.
2. Dry a portion of the damp area approximately 18 inches square. (A hair blow-dryer can quickly dry this surface.) Note that lower areas below grade may be more prone to high moisture content.
3. Cover the dried area with a vapor retarder, preferably polyethylene, firmly attached and sealed with tape around the edges (see Figure 29).
4. Check the underside of the vapor retarder after a couple of days. If there are beads of moisture under the vapor retarder, there is water seeping or wicking through the surface into the dwelling. However, if the vapor retarder is wet on the room side and dry underneath, the dampness is due from another source of moisture, such as plumbing leaks or poor ventilation. The condensation is forming due to warm moist air cooled to its dew point by the cold masonry surface. It is possible for both sides to be damp indicating both external seepage and internal condensation problems.

NOTE: This test is sometimes difficult to interpret. Seasonal variations in surface water flow patterns and the ground water table can cause confusion. You may need to seek further professional advice.

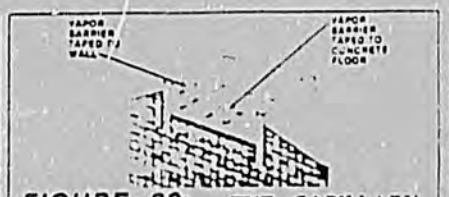


FIGURE 29: THE CAPILLARY TEST IS AN INEXPENSIVE WAY TO DETERMINE THE SOURCE OF MOISTURE IN BASEMENTS.

WOOD DETERIORATION TESTS

Decayed wood is more permeable to moisture and, therefore, more subject to further damage and decay. Recognizing wood decay is a skill that comes with practice, but several symptoms do stand out.

White rot is probably the worst form of wood decay, and often it is the most difficult to recognize. Wood infected with white rot appears somewhat whiter than normal, sometimes with dark lines bordering the light discoloration. Because the wood doesn't visibly shrink or collapse, people sometimes miss the fact that wood with white rot is seriously weakened and possibly ready to collapse. In advanced stages, some cracking across the grain occurs with white rot.

In contrast, brown rot readily shows as a brown color or brown streaks on the face or end grains. In advanced stages, the wood appears very damaged, with surface shrinking and collapse, as well as cracks across the grain. Both white and brown rot are serious forms of wood decay that deserve treatment and/or wood replacement.

Soft rot and blue stain are less damaging forms of wood decay that tend to be more active on the surface. Soft rot is recognizable because the wood surface appears soft and profusely cracked, resembling driftwood in color. The soft rot decay is slower acting than white or brown rot. Blue stain indicates somewhat weakened wood, with a blue, brownish black, or steel-gray colored staining. The discoloration actually penetrates the wood cells and is not a surface stain.

The following tests can help you determine if the wood decay process has start

PICK TEST

This test is a simple means for detecting the toughness of wood fibers and testing for hardness. One of the first indications of wood decay is reduced toughness. It is most reliable on thoroughly wetted wood.

1. A sharp pointed instrument of tough steel (ice pick, small chisel, sharpened screwdriver) is jabbed into the wood across the grain and pried up (see Figure 30).

2. The resistance to prying and the characteristics of the sliver when it breaks are indicators of the wood's toughness. Wetted wood in good condition lifts with a long sliver or breaks by slivering. Decayed wood breaks out with less resistance and lifts/breaks as two relatively short lengths breaking abruptly across the grain without splintering. Wood surfaces that have reduced toughness may also appear rough or fibrous.

SAW TEST

Cutting a piece of wood (board or timber) will produce a rougher finish cut on wood even in the early stages of decay than non-infected wood. This is a good test for purchase of lumber, logs for construction, and so forth.

JAB TEST

Wood decay can also be detected by jabbing or scraping the surface with a sharp pointed instrument. Start at ground level or below, and work up. Note areas that appear soft for other symptoms of decay, such as wood color and texture changes.

TAP TEST

Tap the surface of wood to detect sound differences. A sharp, clear, almost ringing sound is typical of good, dry wood. A dull, dead, soft sound is characteristic of wet or decaying wood.

CALIBRATING HUMIDISTATS AND DEHUMIDISTATS

Humidistats and dehumidistats measure the moisture content of the air through sensing devices. They are designed to control the relative humidity in confined spaces. The element that controls the device is a material that expands as it absorbs moisture and contracts when drying, thus opening and closing the electrical circuit of the humidifier or dehumidifier mechanism. When the elements become dirty, lengthened or shortened, these devices may no longer be accurate (See Figure 31).

Cleaning the contact points is easily accomplished by drawing a piece of clean paper between the points to remove oxidation.

The element can be cleaned gently with a very soft bristle brush and distilled water. Allow the element to dry out before trying to calibrate the device.

To adjust the device, first determine the relative humidity of the air where the control device is located using the previously described techniques.

While watching the point contacts, turn the humidity control knob to the relative humidity that was just determined. If the points do not close or prematurely close at the setting, turn the adjusting screw until points are adjusted properly.

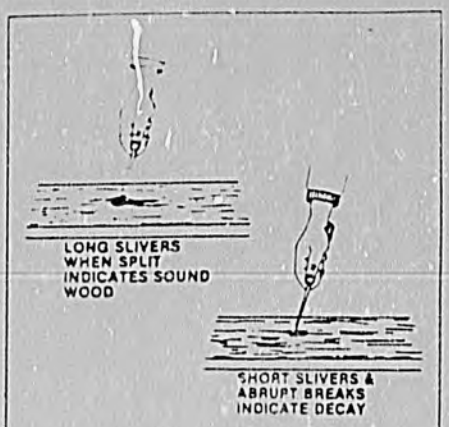


FIGURE 30: THE PICK TEST IS A SIMPLE WAY TO DETECT WOOD DECAY.

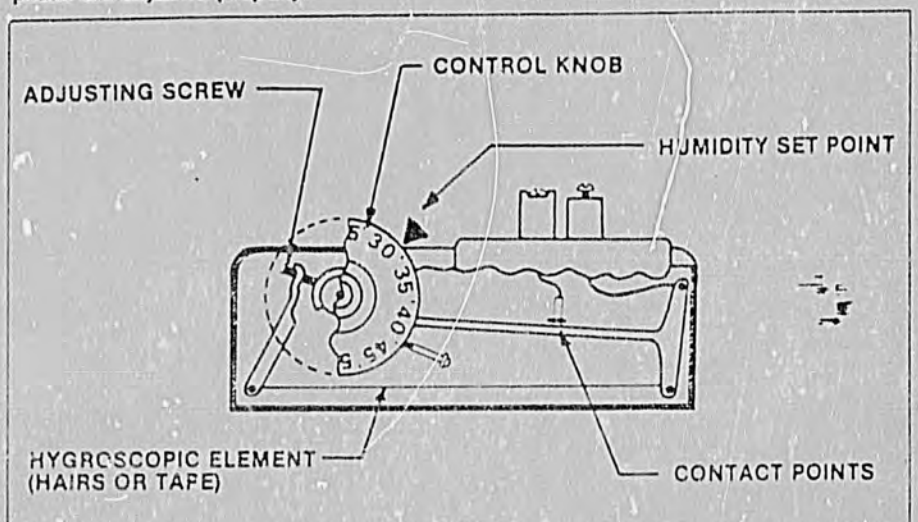


FIGURE 31: LEARNING ABOUT THE COMPONENTS OF A TYPICAL HUMIDISTAT CAN HELP WHEN CALIBRATING THESE DEVICES.

Appendix B

SUGGESTED READINGS, NEW PRODUCTS AND FURTHER REFERENCES

VAPOR RETARDERS

Eyre, D. and Jennings, D., *Air Vapor Barriers*, 1981. Available from Canadian Oil Substitution Branch, Room 1120, Killeany Bldg., 460 O'Connor St., Ottawa, Ontario K1S 5H3. 613/995-1118.

Marshall, Brian and Argue, Robert. *The Superinsulated Retrofit Book*, Renewable Energy in Canada Publishers, Toronto, Ontario, 1981.

VENTILATION

H.C. Products Co., *Fundamentals of Residential Attic Ventilation*, Princeville, IL, 1974.

Shurcliff, William A., *Air-to-Air Heat Exchangers*, Brick House Publishing Co., Cambridge, MA, 1980.

DRAINAGE AND WATERPROOFING METHODS FOR FOUNDATIONS

Jones, R.A., Kapple, W.H., and Leadrum, J.T., *Basements*, Small Homes Council, University of Illinois, Champaign, IL, 1953.

Underground Space Center, *Earth Sheltered Housing Design—Guidelines, Examples and References*, University of Minnesota, Minneapolis, MN.

"Basement Waterproofers," *New Shelter*, pp. 39-48, April 1981.

Sarah Fitz-Hugh, "The War Against Water," *New Shelter*, pp. 30-32, January 1982.

WOOD FINISHING AND DECAY

U.S. Department of Agriculture, *Wood Finishing: Water Repellants and Water Repellant Preservatives*, Forest Service Research Note FPL-0124, Madison, WI, 1978.

U.S. Department of Agriculture, *Wood Handbook: Wood as an Engineering Material*, USDA Handbook No. 72, Madison, WI, 1974.

U.S. Department of Agriculture, *Principles for Protecting Wood Buildings From Decay*, Forest Service Research Note FPL-190, Madison, WI, 1973.

Drisko, R.W., *Paint Failures—Causes and Remedies*, Techdata Sheet 82-08, Naval Civil Engineering Laboratory, Port Hueneme, CA, 1982.

Specific information on wood preservative treatment can be obtained from: American Wood Preservers' Association, 1625 Eye St. NW, Washington, D.C. 20006. 202/931-8180; and American Wood Preservers' Institute, 1651 Old Meadow Rd., McLean, VA 22101. 703/893-4005.

SPECIALTY PRODUCTS

The following product list is provided to help the reader locate new, unusual or hard-to-find products that relate to moisture control or measurement. Reference to a company or product name does not imply approval or recommendation to the exclusion of others that may be suitable.

VAPOR RETARDER AND BREATHER MATERIALS

A new type of tough polyethylene has been developed especially for use as an air-vapor retarder. Known as TU-TUFF, it is available from:

Sto-Cote Products, Inc.
P.O. Box 310
Richmond, IL 60071
800/435-2621

Acoustical sealant is a special sealant used to stop sound transfer. However, it has also become the major sealant for polyethylene vapor retarders because testing revealed that it stays flexible and does not make the plastic disintegrate. This type of acoustical sealant is available from:

Tremco
10701 Shaker Blvd.
Cleveland, OH 44104
216/229-3000

Special plastic pans (also called "polypans") to protect the integrity of the vapor retarder around electrical and plumbing runs are available from:

Solatech
7726 Morgan Ave. S.
Minneapolis, MN 55423
612/866-7672

High-perm exterior paper that breathes, yet stops air movement is being used to enhance insulation effectiveness in high-R new construction and retrofit. This product is available from:

PARSEC
P.O. Box 38534
Dallas, TX 75238
800/527-3454

Product name: TYVEK
E.I. DuPont, Fibers Dept.
Centre Road
Wilmington, DE 19898
800/441-7515

A variety of products are available for fixing moisture problems related to weights in double-hung windows. These products and their distributors include:

(Sash-cord pulley seal)
Anderson Pulley Seals, Inc.
920 West 53rd Street
Minneapolis, MN 55419
612/827-1117

(Double-hung window position control—spring clips)
Grovco Sales Company, Inc.
537 Easton Road
Horsham, PA 19044

Wright Products Co.
2515 Wabash Street
St. Paul, MN 55114

(Position control with window jamb channels)
Quaker City Manufacturing Co.
701 Chester Pike
Sharon Hills, PA 19079
215/586-4770

Specialty instruments for measuring humidity are available from:

Humidial Corp.
P.O. Box 464
Colton, CA 92324
714/825-1793

Brooklyn Thermometer Company, Inc.
90 Verdi Street
Farmingdale, NY 11735
516/694-7610

Preservation Resource Group, Inc.
5619 Southampton Drive
Springfield, VA 22151
804/323-1407

FURTHER REFERENCES

These publications were also instrumental in the production of this document.

Anderson, L.O. and Sherwood, G.E., *Condensation Problems in Your House: Prevention & Solution* USDA Forest Services Bulletin No. 373, U.S. Government Printing Office, Washington, D.C.

Brown, E.J., Kapple, W.H. and Percival, D.H., Technical Note #9, *Construction for Attic Ventilation*, Small Homes Council, Building Research Council, University of Illinois.

Jones, R.A., *Crawlspace Houses*, F. 4.4 Council Notes, Vol. 4, No. 2, Small Homes Council—Building Research Council, University of Illinois at Urbana, Champaign, IL, 1980.

U.S. Department of Energy, Office of Assistant Secretary for Conservation and Solar/Office of Building and Community Systems, *Residential Conservation Service (RCS) Auditor Training Manual*, Chapter 7, Moisture Control, Washington, D.C., 1980.

"Condensation in Attics: Are Vapor Barriers Really the Answer?" G.S. Dutt, May 15, 1979, *Energy and Buildings*, Vol. 2, #4, 1979, p. 251-258. (Study from Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.)

American Society of Heating, Refrigeration and Air Conditioning Engineers, *ASHRAE Handbook 1981 Fundamentals*, New York, 1981.

Control of Condensation in the Walls and Ceilings of Retrofitted Houses, report by Special Ad Hoc Task Group under contract to National Bureau of Standards for Division of Building and Community Systems, Department of Energy, Dec. 29, 1978.

Duff, John E., *Moisture Conditions of a Joist Floor over an Insulated and Sealed Crawlspace*, Forest Service Research Paper SE-206, Southeast Forest Experiment Station, Asheville, NC, 1980.

Tsongas, George A., and Sieton, John and Odell, Inc., *Field Study of Moisture Damage in Walls Insulated Without a Vapor Barrier*, Prepared for the Oregon Department of Energy ORNL/SUB-78 97726 1, Dist. Category UC-95d, Contract No. W-74-5-Eng-26, Oak Ridge National Lab, Oak Ridge, TN, 1980.

Selvagg, John A., *Residential Humidification Versus Energy Consumption*, Research Products Corp., Madison, WI.

Rowley, R.B., Algren, A.B., Lund, C.E., "Condensation of Moisture and Its Relation to Building Construction and Operation," Bulletin No. 18, *Bulletin of the University of Minnesota Engineering Extension Station*, Vol. 18, No. 56, Sept. 10, 1941.

H.R. Trechasel Associates, *Problem Definition Study of Requirements for Vapor Barriers in the Building Envelope*, CR 83.D06, Germantown, MD, 1982.

Sherwood, Gerald E. and Tenwolde, Anton, *Moisture Movement and Control in Light-Frame Structures*, Forest Products Lab, Madison, WI, 1982.

Appendix C

INFORMATIVE DOE A.T. GRANTS RELATED TO MOISTURE

The National Center for Appropriate Technology has drawn upon the experiences of numerous DOE Appropriate Technology grantees to develop this publication.

Listed below are selected final reports which proved to be particularly informative in addressing specific moisture-related problems. This data is current through May 1983. Final reports and additional information about these grants can be obtained from NCAT upon request.

KANSAS

A 1,600 square-foot passive solar house with an attached greenhouse was constructed. The design also incorporated the use of a trombe wall. A 6-mil vapor retarder prevented moist, interior air from penetrating the 15½ inches of fiberglass insulation in the roof. Rigid insulation was used on the exterior of this earth-bermed, high-mass building. A woodstove was the source of back-up heat. The purpose of this project was to demonstrate how various building technologies could be integrated into a single dwelling to conserve energy.

Grantee:
Ross and Carolyn Duffy
224 Circle St.
Topeka, KS 66606
DOE Contract #:
DE-FG47-79R701014
ATMIS ID:
KS-79-005

NORTH CAROLINA

A demonstration house that employed both solar and energy-conserving building technologies was constructed on the campus of the North Carolina State University in Raleigh. The design included a sunspace that could easily be isolated from the living space, thereby reducing both the heating and cooling load. The results of 1½ years of monitoring indicated a yearly heating and cooling bill of under $40. A polyethylene vapor retarder was attached to the interior wall underneath the sheetrock to halt the migration of moisture from the house into the insulation.

Grantee:
Herbert Eckerlin
Department of Mechanical and Aerospace Engineering
North Carolina State U.
Box 5246
Raleigh, NC 27650
DOE Contract #:
DE-FG44-80R410141
ATMIS ID:
NC-79-008

OHIO

The grantee constructed a passive solar house, which integrated massive thermal storage and a wood back-up system into a forced-air heating system. Large amounts of insulation and infiltration-reduction techniques were also incorporated into the design. The grantee used an effective foundation drainage system that helped avoid typical basement moisture problems experienced by others in the vicinity.

Grantee:
Timothy Kimpel
2051 Chandler S. Ville Rd.
Roseville, OH 43777
DOE Contract #:
DE-FG02-79R510146
ATMIS ID:
OH-79-005

VERMONT

A prototype, residential-scale heat exchanger was designed, built and tested. This innovative system includes a defrost cycle which has been successfully tested in northern climates. The heat exchanger can effectively remove moisture from energy-efficient, airtight houses. The product of this research has since been commercialized.

Grantee:
The Memphremegog Group
Box 456
Newport, VT 05855
DOE Contract #:
DE-FG41-80R110348
ATMIS ID:
VT-80-004