Passive Cooling

Part I — Basic Principles

Cliff Mossberg

Though the climate of Belize is hot and humid, residents can use various passive techniques to create a cooler, more comfortable living environment.

Much of my early adult life was spent homesteading in the Alaskan bush. Winters are the predominant force there, and like most others in a northern or temperate zone climate, my main concern was keeping my living space warm. My location colored my entire world view. It never occurred to me that in some places in the world, the problem was to stay cool.

Most of the residents of the United States have similar problems of perception. Because of this necessary emphasis on heating, there is not a lot of information available on alternative methods of cooling. In 1980, I was fortunate enough to "retire" to the Central American country of Belize where I routinely encountered temperatures in the eighties and nineties, and humidity in the upper 30 percent of its range. 95°F (35°C) at 95 percent humidity will quickly draw your attention to the need to cool down.

In the United States and most other industrial nations, cooling is dealt with by refrigeration. Air conditioners are predominantly powered by electricity, which is usually produced by burning fossil fuels. Affluence allows us to condition our living space using an expensive fuel of convenience. Most "third world" nations only allow this luxury to the very well-off. Where grid power is available in Belize, it costs 25 cents per kilowatt-hour. This is far too expensive for the average person to use for cooling on a regular basis.

Cooling for the Humid Tropics

Over the years, I've studied the problem of low energy input cooling in the tropics worldwide. There are two very different environments that demand solutions to the cooling problem. Hot, arid landscapes may require cooling as much as hot, humid areas, but the principles used to address the two problems are quite specific.

In this series of articles, I will try to pass on what I have learned about using sun, wind, and the basic principles of heat transfer to create a comfortable living environment. I am specifically targeting the humid tropics, but many of the principles I will discuss are relevant to arid areas as well. I will emphasize passive techniques here—things that can be done without using any technically derived energy to move heat, or techniques using devices to control heat flow automatically.

This will be a multi-part article. In the first part, I cover the basic principles of heat transference, and try to explain how they interact and what type of effects they produce. Later, I will discuss materials and environmental factors. Also, I will specifically apply the basic principles to building design and construction.

Heat Fundamentals

Heat is the motion of molecules in a substance. The hotter the temperature, the more energetic the motion becomes. There is no such thing as "cold"—there is only more or less heat. Cold is our own subjective reaction to a condition of too little heat for the body to be in its comfort zone.

This is an important concept because there is no one perfect temperature at which we are all comfortable. The human comfort zone depends on several factors,

Methods of Heat Transmission

Method	Transmission Mechanism	Transmission Medium	Direction of Heat Movement
Radiation	Electromagnetic radiant energy	Vacuum or transparent medium	Any direction, line of sight from source
Conduction	Molecule to molecule mechanical transference	Any substantial material in contact	Any direction into material in contact
Convection	Physical relocation of a heated substance	Usually movement of a heated fluid	Usually upward, unless forced

not least of which is the human acclimatization to the specific environment we live in.

While temperature is proportional to the energy of vibration in molecules of a substance, heat quantity is a measure of the numbers of these molecules and the temperature at which they are vibrating. A large pan of boiling water has more heat in it than a small one does, even though they are at the same temperature.

As matter heats up, the molecules move farther apart—they expand. Thus for the same volume of matter, there are fewer molecules if the material is hotter. This means that the same volume of our hypothetical material weighs less per unit volume when it is hot and more when it is cold and dense. This is true of solids, liquids, and gasses that are unconfined.

Three Modes of Heat Transfer

There are three ways that heat can be transferred between a source and a receiver body. They are radiation, conduction, and convection.

They all accomplish the task of imparting heat energy to a receiver body, and they do so in proportion to the difference in temperature between the sending source and the receiving body (called "delta t" and written "Δt"—Δ means "the change in"). The higher the difference in temperature between a heat source and a heat receiver, the faster heat will flow into the receiver and the faster its temperature will rise.

Radiation

When we talk about the electromagnetic spectrum, all we're talking about is "radio" waves—waves of magnetic energy that can propagate through a vacuum in space, thus transferring energy from the sun, stars, and galaxies to our earth. We are familiar with AM radio and the higher frequencies of FM radio and TV, but the radio spectrum contains many other waves of much higher frequencies. Visible light is a series of radio waves that our bodies can detect directly.

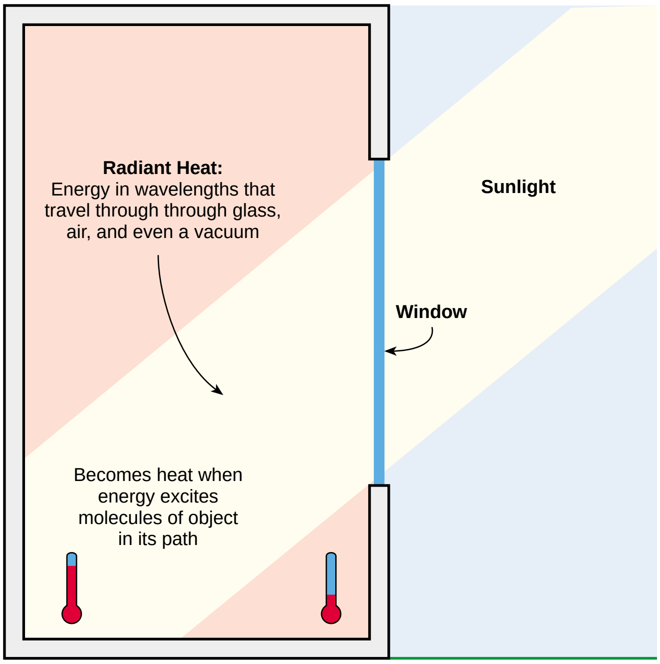
Other frequencies such as infrared (lower in frequency than visible light), ultraviolet (above the frequency of visible light), and x-rays (very, very high frequency) are undetectable by the human eye. Yet these frequencies transfer energy as surely as the visible light frequencies, and we are affected directly by them. Infrared radiation from the sun produces the feeling of heat on our skin when the sun's rays hit us. Ultraviolet radiation causes sunburn, and x-rays can kill or mutilate our body's cells.

Infrared radiation is the vehicle of heat transference that is most important to life on earth. It is heat radiation transmitted directly to the earth by the sun. It is one of the principles that allows a woodstove or a bonfire to radiate heat that warms at a distance.

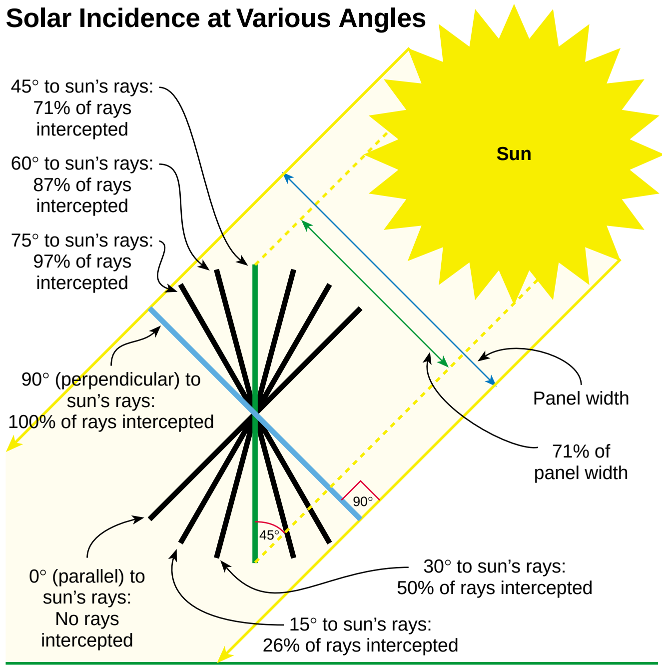
Visible wavelengths can be converted to infrared radiation when they fall on an absorptive surface, such as a roof or a photovoltaic panel. The energy in these light waves is absorbed by the surface, causing heating. This heating in turn causes re-radiation from the absorber as heat, or infrared light. This is the reason hot water collector panels are self limiting in their efficiency. The collector panel heats up the water until the water re-radiates as much energy back to the sky as it takes in. At this point, there is no further gain in collection of radiant energy possible.

A roof heats up in the sun's rays until it re-radiates infrared heat energy down into the house as well as out

Heat Transmission through Radiation



Solar Incidence at Various Angles



Absorbtance Characteristics for Common Building Materials

Surface	*Solar Absorptance*
Asphalt Shingles	
Dark	95%
White	75%
Rough Wood	
Dark	95%
White	60%
Smooth Wood	
Dark	90%
White	50%
Glazed or Enameled Surfaces	
Dark	87%
White	37%
Stucco	
Dark	90%
White	50%
Unpainted Brick	
Dark	85%
White	65%
Concrete Block	
Dark	95%
Unpainted	77%
White	55%

into the air. If the ceiling has no barrier to radiant energy, this radiation will heat up the ceiling surface, which in turn will re-radiate the heat directly into the living area of the structure. Radiant energy is the principle vehicle for moving heat in a downward direction into a structure.

Effects of Solar Incidence

There are several factors that affect the ability of a surface to absorb or radiate infrared energy, and one of the most important is the angle at which the radiation hits the absorbing surface, known as the angle of incidence. If you want to absorb energy at the maximum efficiency, radiation should fall on a collection surface that is exactly perpendicular to that radiation.

The diagram above shows a variety of panel angles in relation to the sun's rays. When the panel is perpendicular to the sun's rays, the most energy is intercepted. When the panel is set at 45 degrees to the sun's rays, only about 70 percent of the available energy is captured.

Absorption & Reflectance

Another factor that affects the amount of radiation converted to thermal energy on a hypothetical earth "panel" is the color and texture of the surface. This is so fundamental to our experience that the concept is understood intuitively. Dark surfaces absorb heat and energy, while light surfaces reflect them. Rough surfaces absorb energy, while smooth surfaces reflect it. What is not so intuitive is that colors and textures that absorb energy well, also radiate energy well.

Reflective metallic foils take advantage of this. They are actually conductors, but when specifically engineered into buildings to control radiant energy, they are as much as 95 percent effective at blocking radiant energy absorption. They are also very resistant to re-radiating absorbed energy.

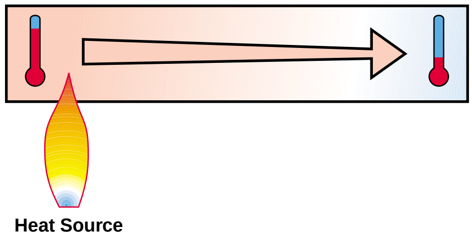
To be this effective, a radiant barrier must be installed with an air space on one or both sides of the material. Its mirror surface will then reflect any infrared energy rather than absorbing it and conducting it as heat.

Conduction

Conduction is the most intuitively understood mode of heat flow. For conduction to occur, materials must be in contact with each other. For example, imagine a copper bar one foot long, two inches wide, and half an inch thick (30 x 5 x 1.3 cm)—a rather substantial piece of copper. If we support this bar, and place a candle or a Bunsen burner under one end, the bar will slowly heat up from one end to the other. Soon the whole bar will be too hot to touch. Heat is being transmitted by conduction throughout the bar.

Thermal Conduction

Conductive Heat:
Excited (hotter) molecules heat the molecules in contact with them



What is happening here is that the heat source is exciting the molecules in the copper to vibrate more enthusiastically, becoming more and more energetic as the temperature increases. As these copper molecules pick up physical motion from the heat energy, they continuously “bump” into the molecules next door.

This physical disturbance imparts energy to the adjacent molecules, causing them to increase their vibrational energy—they warm up. Heating progresses down the bar, away from the heat source, until the whole bar has reached a state of equilibrium based on the amount of heat supplied by the source.

Conductive Heat Flow

Radiant energy is one of the loss factors that draws heat from the bar. Another factor that allows the bar to lose heat is conduction to the medium surrounding it. This is a loss by physical contact with the fluid—air—surrounding the bar.

Different materials will move heat at different rates. Based on these rates, materials are classified as “insulators” if they retard the flow of heat, or “conductors” if they facilitate the movement of heat. These are far from absolute definitions. Most insulators are designed to retard heat flow in conduction, but there are some exceptions such as metallic foil radiant barriers.

Materials and their Conductivity

Material	*Conductivity (Conductance)**
Copper	220.000
Aluminum	122.000
Steel	25.000
Concrete	0.600
Water	0.350
Brick, red	0.270
Rubber, soft	0.100
Wood, pine	0.070
Corkboard	0.025
Rock wool	0.023
Air	0.014
Vacuum	0.000

*BTU per hour per sq. ft. per degree per foot thickness

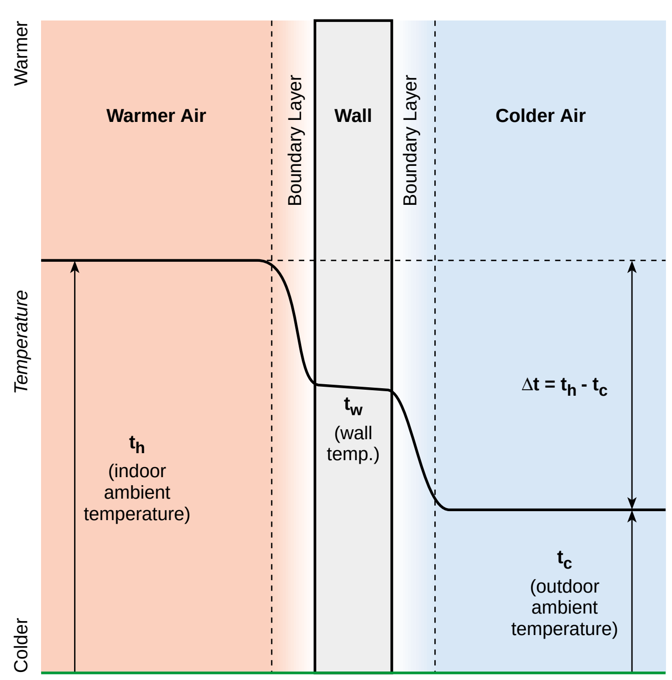
Air can be either an insulator or a conductor. For example, air is used as an insulator to slow down the transmission of heat in homes. It is the “dead” air space in fiberglass batt insulation that does the work. But air is also a cheap and relatively effective conductor of heat in electric motors, vehicle cooling systems, and many other applications. So while it is important to understand how material properties affect heat flow, you should also realize that these properties can be applied in many ways to achieve an engineering goal.

Boundary Layer

In conduction, heat flows through a substance because of tangible physical interaction between molecules. These same forces allow heat to flow between any substances that are in contact with one another. The boundary where one substance stops and another begins (between the copper bar and the air, for example) is known as the interface. Heat flow across an interface can be complicated by factors that are not obvious. The first of these factors is the variable rate of conduction by different materials. The second factor is the mobility that a fluid has, which results in convective flow.

Conductive heat flow is impeded when a fluid such as air is in contact with a heated surface such as a wall. This impediment is caused when a layer of stagnant air is changed in temperature and density by heat moving across the interface. The air in the layer next to the wall

Conduction through a Boundary Layer



will heat up more that the air some distance away. When this situation exists, the change in temperature (Δt) between the warm wall and the warm layer of air is reduced. This cuts back on heat flow.

The existence of the boundary layer and its removal is the essence of "wind chill." This is when it feels colder than the real ambient temperature because of the extra heat loss when the wind blows away the boundary layer around our bodies. This is undesirable when we are trying to keep warm, but very desirable when we are trying to cool down.

The conductivity of any material can be measured and quantified so that the relative qualities that make it an insulator or conductor can be examined in absolute terms. The conductivity table lists some materials and their conductivity. Even without knowing how to use the "soup" of units with which these materials are labeled, it is obvious that copper has a very high conductance value (220), while air is very low (0.014).

Convection

In its most generic form, convection involves the movement of heat by transporting some hot substance. Convective heat movement is usually associated with the movement of fluids. There are two common forms of convection—"forced" and "free." In forced convection, power is used to move a heated fluid from the source of heat to the heat destination. Vehicle radiator type cooling systems and hot water or hot air home heating systems are common examples of this.

Since we are interested in heat flow that occurs without any energy input from us, we will be concentrating on free convection to move our heat. Free unpowered convection happens due to the difference in density or molecular concentration per unit volume that occurs when a fluid is heated.

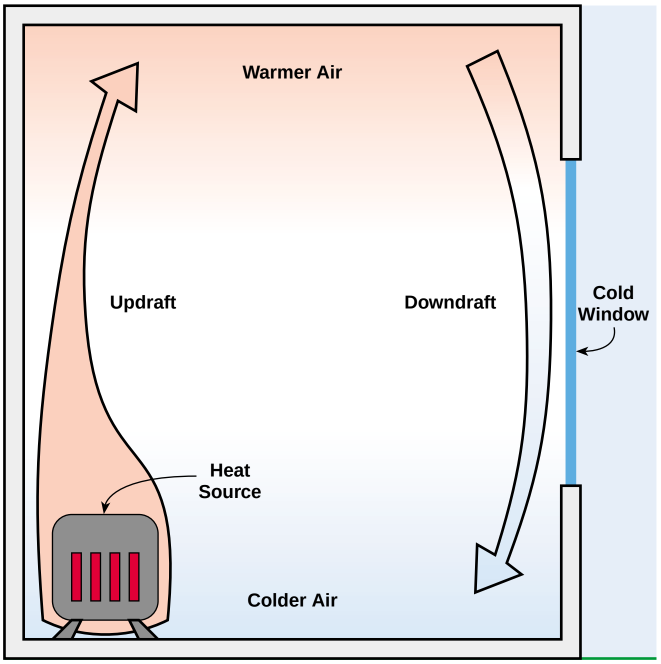
Molecular Density & Weight

The same volume of material weighs less per unit volume when it is hot and more when it is cold. Thus a "cold" (less hot) fluid packs more matter into the same volume than the same amount and type of fluid when it is heated.

The practical result of this change in density is that a hot fluid, being lighter, will "float" on a colder fluid. Conversely, a cold fluid will move downward under the pull of gravity until it finds the lowest level possible. These are dynamic processes. The fluid actually physically flows from one position to the next as its thermal status changes. Such flow results in the movement of heat.

If you put your hand over a heated stove burner, you can feel air rising off the burner. A hot air balloon

Thermal Convection in a Fluid



depends on the change in density between the hot air inside the balloon and the cooler air outside it to rise into the sky. On a warm summer day, the lake you swim in will have a warm layer at the top and cooler water underneath. These are all examples of fluid movement caused by a change in density that causes convective heat to rise.

Convection is the movement of the heat rather than the movement of the fluid. But the two are inexorably intertwined, so much so that we also call the fluid movement convective flow.

Stratification & the Greenhouse Effect

Hot air flows up; cold air flows down. This causes several familiar effects such as stratification. The warm water on the lake surface in the example above is a case of stratification. Water in the lake is heated by sunlight and rises to the top level, where it cannot go up any farther. Here it forms a layer. It gives off some of the sun-induced heat to the air above it, becomes more dense, and eventually sinks again.

Depending on the amount of solar energy available, this convection loop will stabilize so that approximately the same amount of water is constantly heated, rises, gives off its heat, and sinks back into the cold depths. Thus solar heat is moved from the lake to the air.

The conversion of visible light energy into re-radiated radiant energy contributes to what is called the "greenhouse effect." That's the label for the tendency of heat to build up in a greenhouse so that the air inside is much warmer than ambient outside temperature.

This happens because glass that is transparent to visible light waves impedes the re-radiation of infrared wavelengths. The trapped radiation heats the structure, fixtures, and air inside the building. This heated air is trapped inside the greenhouse by the glass (probably causing stratification), and cannot move the heat away by convection.

Chimney Effect & Boundary Layer Disturbance
Convection directly affects the comfort of our living space, and even the clothes that keep us warm. It also affects the boundary layer, which is made up of stagnant air that acts like an insulator.

If the Δt between the ambient air and the boundary layer is anything but zero, the boundary layer will attempt to rise or fall of its own accord, inducing convective heat flow. This can be the boundary layer around our own warm bodies on a cool day, chilled air flowing down a cold windowpane to create floor drafts in a dwelling, or heat rising off the inside of a solar heated wall.

Another convective phenomena commonly encountered is the "chimney effect." In most furnaces, exhaust gasses exit the combustion process under the influence of convection. The heated gasses are lighter than the ambient air, so they rise up the chimney, pulling air into the furnace or stove through cracks or through a controlled draft regulator. The hotter the flue gasses and the longer the chimney (within limits imposed by conductive heat loss), the faster the gasses will exit, so the stronger the gas column flowing up the chimney will be. Most stoves and furnaces would simply not work if this convective flow was not possible.

This chimney effect is not limited to chimney flues. It can be used in a building as a tool to move hot air out of the living space. The rising hot air can be supplied by solar energy. The resultant air movement is used to induce whole house ventilation where it might otherwise be difficult to achieve passively.

Wind as a Heat Mover
Under the right circumstances, warm lake water will heat the cooler air above it, inducing another fluid convection cell in the air. This air is heated, rises, cools, and circulates back down to the surface to be heated again. This process is much the same as the drafts settling off a cold window. It is much greater in volume, and we call this movement wind. Anything that can affect the heating of the air mass is important.

Wind is our ally. We have limited ourself by definition to creating comfort passively in our living environment. We have cut ourselves off (or been cut off by circumstances) from the use of highly concentrated fossil fuel derived energy. Yet to move heat around to our advantage, it takes energy—sometimes large amounts of it. Wind is the one source of energy readily available to us that can do this job.

The differences in reflectance of the earth's surface is important to heat absorption wherever we are. Black basalt rock will absorb more solar energy than light silica sand. A farmer's pasture will absorb less heat energy than the concrete streets and building walls in a city. This brings us back to the basics of material, surface texture, and color.

We don't usually think of something like a parking lot affecting natural breezes. Yet such a man-made feature can have a vast effect on the microclimate that we are subjected to in our living spaces. A large black parking lot will absorb a lot of solar energy. This solar energy will be transmitted into the soil through conduction, re-radiated into the surrounding environment as radiant heat, and will heat the air above it, which can then rise convectivly.

This convective flow may induce local breezes where there would be none, or it may disrupt natural wind flow. The radiant energy will distribute itself outward from its source to all the surrounding areas adjacent to the lot, causing local heating and possibly destroying any benefits a locally induced breeze might produce. Conductive heating of soil will create a reservoir of heat that will continue to radiate to the surroundings long after the ambient air temperature should have become naturally cooler. All three factors as well as terrain and vegetative cover are interactive and each affects the other.

Humidity & Evaporation
No discussion of wind and weather would be comprehensive without understanding the role of humidity and evaporation. Wind and weather are formed as part of a large heat cycle driven by solar energy. One of the principle forces acting on this cycle is the addition or subtraction of heat through evaporation.

It takes one BTU (British thermal unit) to raise the temperature of one pound of water from 211 to 212°F (99.4 to 100°C), but 970.4 BTUs are needed to turn it to steam at 212°F. Those 970.4 BTUs are known as latent heat, measured under standard conditions of one atmosphere of pressure at sea level.

Water does not have to boil to absorb this latent heat. It will slowly evaporate at room temperature, requiring the same latent heat. Evaporation requires heat, and this heat, coming from surroundings, cools the environment considerably. The heat taken in or given off as this process occurs creates a very complicated thermal dance in everything from deserts to hurricanes.

Unless it is artificially dried, air contains water vapor suspended in molecule-sized droplets. The amount of water air can hold is determined by its temperature and density. Hot air can hold more moisture than cold air. So that there will be some common point of reference when talking about air moisture or humidity, figures for the water content are given as "relative humidity."

Relative humidity measurements are given in the percent of moisture that air holds relative to its maximum possible moisture content at a given temperature. The range runs from 0 percent for absolutely dry air to 100 percent for air that holds as much moisture as is physically possible. This is known as the saturation point. Anything greater than 100 percent relative humidity will lead to free water condensing out of the air as mist, fog, clouds, rain, or snow.

The amount of moisture that air can absorb under any condition is dependent on temperature and the amount of moisture it already contains. Thus air measuring 70 percent humidity can only absorb the equivalent of the remaining 30 percent moisture capacity. The lower the air humidity, the more potential moisture the air can still absorb.

The more moisture that can still be absorbed, the more potential there is for heat removal through evaporation. By evaporating moisture into the air as humidity, cooling can be produced. And the more moisture that can be absorbed, the more efficiently you can cool with evaporation. Humidity bears directly on the creation of the human comfort zone, since the body depends on evaporation through perspiration to rid it of excess heat.

Vegetative Cover

The black surface of an asphalt parking lot is a very good absorber of thermal energy. The dark green surface of vegetation is also a good absorber of thermal energy, yet the plants cool their microenvironment. How can this be?

Plants are designed to effectively trap solar energy. But instead of absorbing light and producing heat, they produce plant sugars through photosynthesis. Much of this solar energy has no chance to be turned into excess heat. It is directed to the plants' needs instead. Because of this, the use of green foliage to block sunlight striking a building is very effective. The advantage of such shade is obvious when it comes from trees, but the use of vining plants on trellises covering roofs and walls also works effectively to lower temperatures.

One of the products plant leaves give off is water vapor, a vegetative "breath" that is transpired from pores in the leaves. Transpiration is the process of taking in gasses (mostly CO_2) and sunlight, and giving off oxygen and water vapor. This evaporating water absorbs heat from the leaves and the surrounding air, cooling the local microclimate. The combination of transpiration and evaporation is called "evapotranspiration."

Local Breezes

Transpiration can also play a significant role in local breeze generation. The figure on the facing page is a scale cross section of the Barton Creek valley where I lived in Belize. The east side of the valley and the adjacent hill was cleared for pasture when the original settlers moved in. It is covered with low bushes and a dense fern covering that is locally called "tiger bush." It faces squarely into the afternoon sun, and the rate of vegetative transpiration is poor.

The west side of the valley was too steep to be cleared, so it is mostly covered with undisturbed jungle canopy. Direct morning sun hits this slope and is cooled by the vegetation, but late in the afternoon when the east slope is hottest, this west slope is taking the indirect (non perpendicular) sun's rays and is cooled still further. Air is heated on the east slope and rises, while it is cooled on the west slope by the tree canopy and sinks down into the valley.

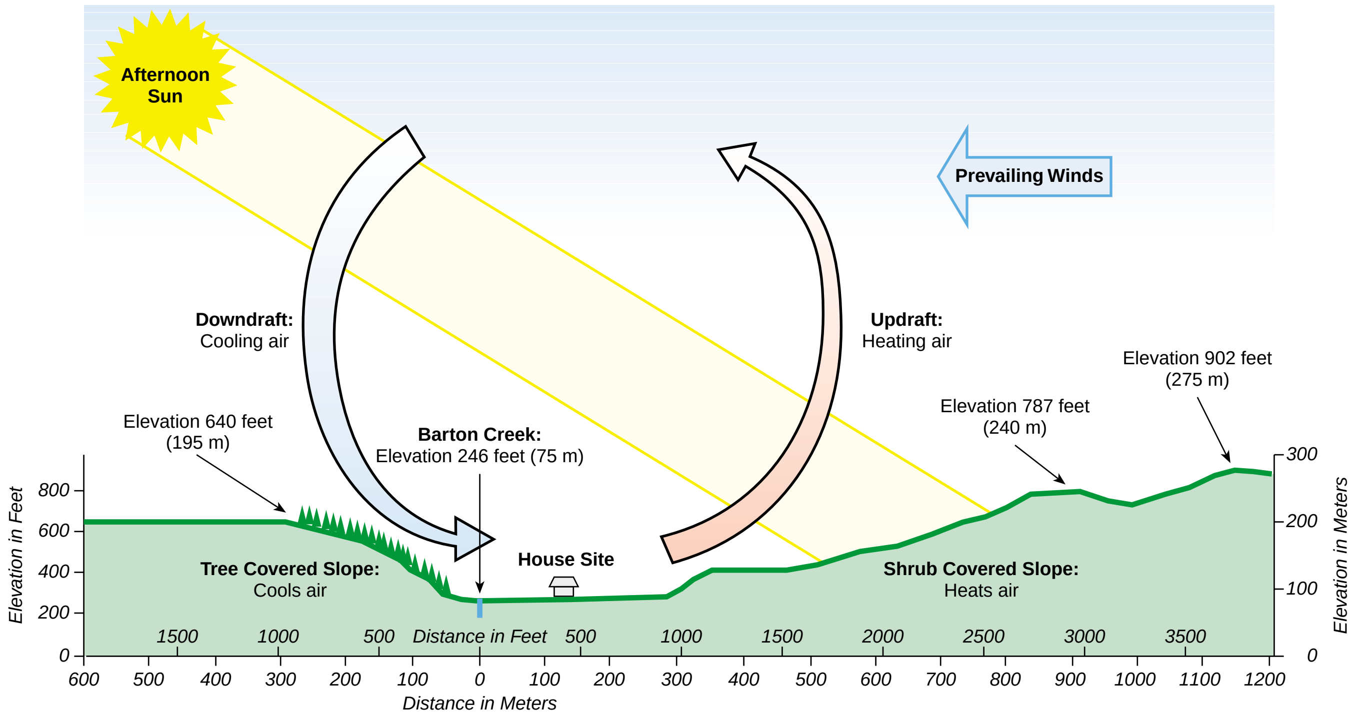
The net result of this differential movement is a strong afternoon breeze that blows straight across the valley in the hot dry season, contrary to the direction of the prevailing Caribbean trade winds. The existence of such a wind is completely counterintuitive, but very much appreciated because it is much more local and intense than the prevailing breeze. This illustrates how much significance local and regional factors, both natural and man-made, can have on ventilation and heat flow.

Terrain such as hills or mountains can act as deflectors to re-route prevailing winds, either creating a wind shadow or augmenting wind velocity. Up to a point, when you are trying to get cool, more is better, so astute selection of a house site with an emphasis on maximizing (or minimizing) local wind is important. A good site for wind will provide the energy needed to deal with uncomfortable temperatures either passively or actively.

Human Heat Physiology

In spite of any surplus heat from the environment, the body must maintain an internal temperature very close to 98.6°F (37°C). There are a great many mechanisms that we have evolved to effect this precise temperature regulation. All three mechanisms for transferring heat are at work—radiation, conduction, and convection. In addition to those three, the body also uses

Localized Winds in the Barton Creek Valley of Belize



perspiration—shedding excess heat through the latent heat of evaporation.

The high relative humidity typically encountered in the humid tropics (around 95–98%), will severely interfere with the ability to lose heat through evaporation. The air is already saturated and cannot hold more moisture. This is the great difference between a hot humid environment and a hot arid environment.

Where the humidity is low, the body has the cooling mechanism of evaporation at its disposal and the low air moisture considerably increases the efficiency of the process. This makes the designer's job much easier in such an environment.

Since I am targeting passive cooling in a hot humid climate, my emphasis will be on techniques for the humid tropics and subtropics. For those readers who are fortunate enough to have dry desert conditions as their design criteria, I direct you to two books by the Egyptian architect Hassan Fathy. These books are superb, clear, well illustrated, and relatively non-technical.

Acclimatization

When I moved from Alaska to Belize in 1980, I was adapted to the subarctic environment of interior Alaska. Winter temperatures plunged to -60°F (-51°C) routinely, while summers were "oppressively hot" at 80°F (27°C). I could work in shirtsleeves at 35 to 40°F (1.6–4.4°C) and be comfortable.

In five years in Belize, the coldest temperature I ever encountered was around 55°F (13°C). The typical high temperatures were 75 to 80°F (24–27°C) in winter, 90 to 95°F (32–35°C) in the wet season, and 95 to 108°F (35–42°C) in the hot, dry season. Getting used to these temperatures so that my body could regulate itself was difficult. I acclimated about 80 percent in the first year, and by the end of year two, I was 90 to 95 percent acclimated. I never reached 100 percent in the five years I lived there full time.

If you live in Phoenix, Arizona where the temperatures go to 125°F (52°C) in August, and you are used to a 72°F (22°C) air-conditioned environment, you will never acclimate to the heat because you are not forced into it. But if you are out in the heat as it gradually increases over the spring and summer, you will find yourself growing accustomed to an environment that would have seemed impossibly hostile before. If you are acclimated to the local climate, whether hot or cold, it will take much less energy input to remain in the comfort zone under adverse conditions.

The Comfort Zone

The comfort zone is defined as those combinations of conditions of humidity, temperature, and air motion under which 80 percent of the population experiences a feeling of thermal comfort. In temperate zones, this is from 68 to 80°F (20–27°C), and 20 to 80 percent humidity.

Different conditions can redefine this zone of comfort. Air motion or breeze can extend it to almost 98 percent humidity and 90°F (32°C). Evaporative cooling can extend the highest comfort temperature up to 105°F (41°C) at lower humidities. High thermal mass (such as rock or concrete) acts like a thermal flywheel, remaining cool into the day, and warmer at night than ambient air. Thermal mass alone can extend the comfort zone up to 95°F (35°C), while thermal mass cooled by nighttime ventilation can extend this zone all the way up to 110°F (43°C). Combinations of techniques are even more effective.

Evaporation (Perspiration) & Air Motion

At higher humidity and temperature, most of the excess body heat is lost through perspiration. Air motion can increase the boundaries of the comfort zone up to 98 percent humidity. This boundary would be 80 percent in still air.

Research with a large sample of people shows that comfort can be maintained at 100 percent humidity and 82°F (28°C), if air velocity across the skin is maintained at around 300 feet per minute. This is the approximate velocity of a good ceiling fan on high speed. At lower humidities (50 percent or less), temperatures of around 90°F (32°C) are comfortable at this velocity. Because of this relationship, the designer’s goal is to create or preserve air velocity in the dwelling whenever possible.

A breeze blowing against our bodies removes heat through two mechanisms—convection and latent heat transfer. When convection occurs, the skin heats the air and this heated air is carried away by the breeze. With latent heat transfer, perspiration evaporates, soaking up heat from the skin in the process. Moving air aids the process of evaporation at higher humidities, as well as removing the boundary layer on the skin. This dead air layer acts as an insulator to block thermal transfer from the skin to the air.

The boundary layer also blocks evaporative transfer from the skin to the air. This layer heats up and reduces the Δt between the skin and the air, slowing down heat exchange. It also absorbs moisture from the skin, but is unable to immediately pass this on to the surrounding air. The boundary layer thus rises in humidity, reducing the difference in humidity between the skin and the air. This slows down skin evaporation and the exchange of heat to the air. Air movement shifts this boundary layer of warm, moist air, allowing the skin to come in contact with drier, cooler air that can cool more efficiently.

Summary

In Part 1, I’ve taken a look at the basic principles governing the movement of heat, and tried to give you a feel for the way these forces interact with the environment. We’ve looked at comfort, and found that the experience of thermal comfort is largely subjective to the individual.

In the next article, I will move from the general to the specific. I’ll try to apply these principles of thermal design to the goal of creating a comfortable, passively cooled house in the Barton Creek valley of tropical Belize.

Access

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Resources for Further Study:

Building for the Caribbean Basin and Latin America; Energy-Efficient Building Strategies for Hot, Humid Climates, Kenneth Sheinkopf, 1989, Solar Energy Research and Education Foundation, 4733 Bethesda Ave. #608, Bethesda, MD 20814 • 301-951-3231 Fax: 301-654-7832 • plowenth@seia.org www.seia.org

Air Conditioning: Home and Commercial, Edwin P. Anderson and Roland E. Palmquist, Theodore Audel & Co., a division of Howard W. Sams & Co., Inc., Indianapolis, Indiana, 1978. Any library should have a comparable book on air conditioning that will treat this subject thoroughly.

Architecture For the Poor, 1973; and *Natural Energy and Vernacular Architecture, Principles and Examples with Reference to Hot Arid Climates,* 1986, Hassan Fathy, both published by The University of Chicago Press, Chicago. These books can be hard to find. I was able to locate them through my regional inter-library loan program and have them brought to my local library.

Passive Cooling

Part II — Applied Construction

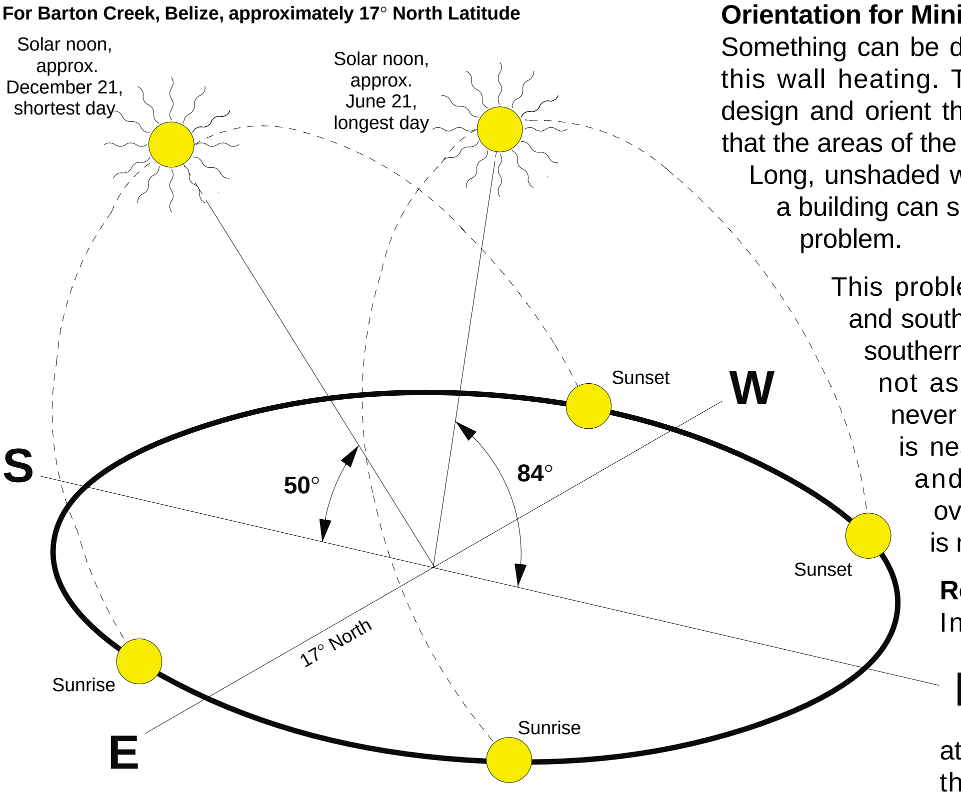
Cliff Mossberg

In Part 1 of this series (see *HP82,* page 84), I outlined the three modes of heat transfer, and tried to integrate this knowledge with the factors of human comfort. This information is basic to any design or construction geared towards minimizing the discomfort of living in the tropics.

In Part 2, I would like to show some of the design techniques for dealing with the effects of heat and humidity in a dwelling located in what we know as "the humid tropics." This label differentiates this climate from that of a hot, arid, desert type of environment. The desert might ultimately be hotter than the conditions found in the humid tropics. But the low humidity found in the desert makes it practical to use some techniques of dealing with the heat that we cannot use in more humid locations.

Figure 1: Seasonal Variation of the Solar Path

For Barton Creek, Belize, approximately 17° North Latitude



Solar Incidence as a Design Element

The sun is the primary engine of heat gain in a tropical dwelling. It is not usually ambient air temperature that causes heat discomfort, but the radiant energy of sunlight, either directly or re-radiated in long wave infrared. The first line of defense against heat buildup in a building is to minimize the surfaces that sunlight can fall on.

It is obvious that the building's roof is going to be the main absorber of solar energy. If the roof is designed to block heat flow down into the dwelling, and made large enough to cover and shade the walls, the builder should be successful at reducing unwanted heat. This simple concept is more difficult to accomplish that it seems at first.

If the sun was always in the high-noon position, the job would be simple, but it's not. In the morning, it starts out shining low in the eastern sky. It can heat up a building's walls for many hours before it rises high enough for the roof's shadow to shield the east wall from radiant energy. In the afternoon, the sinking sun has the same effect on the western wall.

Orientation for Minimum Incidence

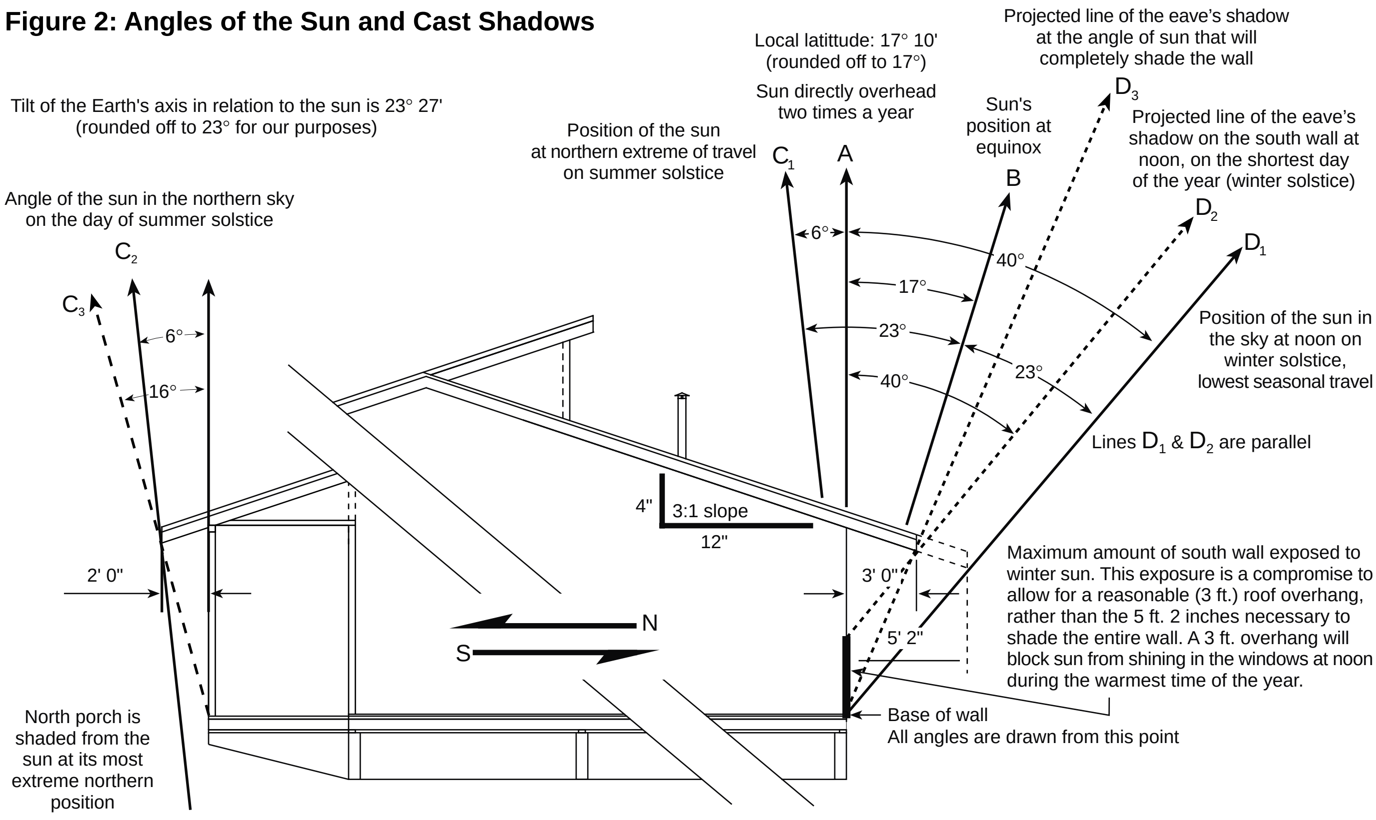
Something can be done at the design stage to reduce this wall heating. The very first effective step is to design and orient the structure on the building site so that the areas of the east and west walls are minimized. Long, unshaded walls on the east and west sides of a building can significantly contribute to the heating problem.

This problem is not as severe on the north and south walls. The sun will be lower in the southern sky in winter when wall heating is not as big a problem. But the sun will never be as low in the southern sky as it is near sunrise and sunset in the east and west, so engineering roof overhangs to block the southern sun is much easier.

Roof Overhangs

In Figure 2, angle **A** represents directly overhead. Angle **B** has its pivot point at the base of the south wall. It is plotted at the local angle of north latitude. At that angle, the sun would appear

Figure 2: Angles of the Sun and Cast Shadows



directly overhead at the equator on the days of the solar equinox. **A** is easy to find—it is straight up. **B** is easy to compute graphically once local latitude is known. Once you have **B,** you have a baseline.

If we swing an angle north 23° from **B**, we will have the northernmost angle of the sun's travel in the sky in Belize. In this case, it is an angle of 6° north of vertical, or 84° vertical declination from level ground, pointing north (Figure 1). I have labeled this line $\mathbf{C_1}$. If $\mathbf{C_2}$ is drawn at the exact same angle as $\mathbf{C_1}$, but touching the edge of the roof overhang on the north wall, the lower extension of $\mathbf{C_2}$ will indicate the path of the sun's rays on the north side of this building.

In this case, the sun will not ever touch the base of the north wall. $\mathbf{C_3}$ is the position the sun would have to travel to for it to begin to heat the base of the wall. $\mathbf{C_3}$ is an imaginary angle, since the sun is never that far down in the northern sky at this time of day and this location in Belize. This shows us that a standard 2 foot (0.6 m) overhang on the north edge of the roof is sufficient to shade this north wall at all times of the year at this location.

Returning to our baseline **B**, we need to turn another 23° angle, south from **B** this time, just as we turned north before. This will produce line $\mathbf{D_1}$, the angle of the sun's rays at its extreme southern sky position. It is immediately obvious that $\mathbf{D_1}$ does not touch both the base of the south wall and the edge of the roof overhang. We know from this that the roof overhang is insufficient, even at 3 feet (0.9 m), to completely shade the south wall.

The south roof overhang would have to be extended all the way out to 5 feet 2 inches (1.6 m) to completely shade the wall. This large overhang would be structurally weak in high winds, and would also hang down far enough to block the view out of windows on the south wall. A compromise between 100 percent shade, vision, and structural rigidity will be necessary.

There are at least two possible solutions to this need for compromise. In Figure 2, I have chosen to construct $\mathbf{D_2}$ as a line parallel to $\mathbf{D_1}$ but moved over enough so that it touches the south roof overhang. If it is extended down to intersect the wall, the lower projection of $\mathbf{D_2}$ represents the limit of the south wall shading. Above the intersection with the wall will be shaded; below will see direct sun at this time of the year. The line of shade appears here to be sufficient to keep the sun's rays out of the window openings.

Vegetation

Trees and shrubs that shade the structure are one approach to blocking sunlight. From a practical standpoint, it is difficult and extremely expensive to add mature trees of any size to a building design. The usual procedure is to plant smaller ones and tolerate the sun

A wall of decorative concrete block allows ventilation and provides shade, transmitting only muted light.

until the smaller trees are big enough to produce shade. Unfortunately this can take ten years or longer. Where possible, keep what you have.

Vining plants are a good alternative to trees, with one serious caveat. One of the goals of a tropical house design is the exclusion of termites from the wooden parts of the structure. This can be done by building elevated columns with termite collars on top. Any vegetation planted on the ground and close enough to the structure to touch it will provide a path for termites to circumvent the exclusion features of the design. Without the termite problem, it would be effective to use a trellis on the east and west walls. Vining plants such as passion fruit can intercept the sunshine and put it to good use growing flowers or edibles.

Wall Shading with Architectural Elements

It is possible to use architectural elements to moderate direct sun on the walls. Properly designed architectural screens can be made to block and modulate sunlight to good advantage. The photo above illustrates the use of such a screen, here composed of simple decorative concrete blocks placed together into a pleasing texture. This very effectively opens up a whole wall to air and muted sunlight.

This screen can conceal wooden or metal louvers fitted with insect screens. These can be opened for the warm dry weather, but closed for storms. In this design, the concrete screen is integrated as part of an upscale-style Belizian house. It will take a substantial foundation to support such a screen. Such massive architecture is not necessary.

Hassan Fathy describes a traditional screen used throughout the Middle East that is made up of round turned spindles arranged into a rectangular grid. It is known as a mashrabiya. The same term is used to describe vertical louvered blinds that can be adjusted to shade an entire wall.

Both of these devices allow conditioned light to enter the building for illumination, while blocking the strong exterior sunlight. The harsh contrast of the sun beating on the outside of the screen blocks outsiders from seeing through the screen to the inside. But it allows someone on the inside to easily see out into the bright exterior.

Window Shading Devices

There are two problems to deal with if you wind up with sunshine on your outer walls. There is the re-radiation of the solar energy into the interior from the walls. I'll deal with that next. But first I want to deal more thoroughly with the problem of solar energy directly heating the interior space through the window openings. Where this is a problem, the windows themselves can be constructed to block the sun's rays through reflective glass coatings and through the use of solar screens.

Jalousie windows are commonly used in the tropics. They use single panes of glass to form the louvers. These single panes have virtually no insulation value. In contrast, double and triple pane argon-filled glass used in the colder regions are designed primarily to block conductive and radiant heat flow outward, not to facilitate natural ventilation inward. They would be valuable in an air conditioned house.

While air conditioning has a role in tropical cooling, it is not going to be a factor in our passive design focus. We want to foster good air circulation and a design that excludes solar radiation. Jalousie windows glazed with glass that uses reflective films can do this.

Glass can be made with a permanent reflective coating deposited on one face. This is conventionally either bronze or aluminum in color. This coated glass can block up to 80 percent of the heat energy in incoming sunshine. Films that can be applied to uncoated glass are also available for this purpose, and provide approximately the same excellent result. The downside to reflective coatings is a reduction in the amount of visible light entering a house for general illumination.

Louvered "jalousie" windows are coated with a reflective surface to block sun. They also readily facilitate ventilation.

Solar screens that go on the outside of the windows in place of conventional insect screens are also very effective, reducing the incoming heat energy by up to 60 percent. Using both of these strategies produces a tropical window that is extremely effective at blocking invading radiant energy, while still providing excellent ventilation. The cost is higher than uncoated glass and normal screening, but it is worth the money.

There are many traditional methods available for blocking solar heat from infiltrating the inside of a house through the window openings. As a general rule, external devices such as awnings, louvers, and roll shades are more effective than inside devices such as venetian blinds and roll shades. The efficiency of each device is a function of its material, color, and texture.

Radiant Barriers

The material of choice for blocking both visible light and infrared is a shiny sheet of polished metal. Aluminum foil is one of the best materials, reflecting up to 95 percent of both wavelengths. This foil is a very good conductor of heat energy, but it is a very poor radiator of radiant heat energy. It has a maximum emission inversely proportional to its reflectance.

In English, that means that a highly polished aluminum foil might only re-radiate 5 percent of the radiant heat energy falling on it. It is an ideal blocker of radiant energy. Used in this way, these foils are known as radiant barriers. Under peak sunshine conditions, a radiant barrier can reduce heat inflow by as much as 40 percent or more.

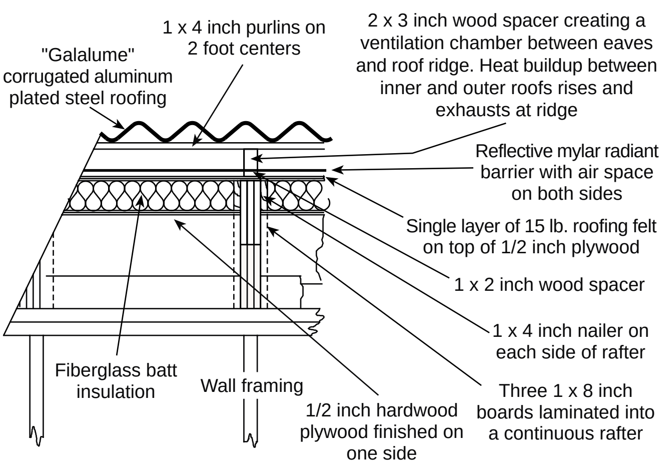
For a radiant barrier to be effective, it must have an air space on one or both sides. Aluminum is a very good conductor of heat. Without this air space, the foil would simply move heat from whatever substance is on one side of it to whatever is on the other. It would do this very efficiently. When it is installed with an adjacent air space, the air (which is a good insulator for heat transfer in the conduction mode) blocks conduction of heat from the foil, while the poor emissivity of the foil blocks heat transfer through the process of radiation.

Roof Design & Radiant Barriers

The roof is the most critical heat blocking device in your arsenal. It can operate passively, blocking radiant energy from moving downward into the house using a radiant barrier. It restricts conductive flow of heat through the roofing materials. And it can be designed to use thermal convective flow to carry off air heated by the roofing.

The roof design I prefer is actually two roofs sandwiched together. The upper roof blocks wind and rain. It also contains convective air channels (see Figure 3) between spacers over the structural joists. These cavities form ducts so that air heated by the hot roofing can rise and exhaust at the high point through thermal convection. Below these vent channels is a layer of radiant barrier material. This barrier blocks the heat that is radiated by the metal roofing, keeping it out of the dwelling.

Figure 3: Cross Section of a Roof in the Tropics



The lower sandwich contains the structure as well as fiberglass batt insulation to block conductive heat flowing downward into the living area. As mentioned in Part I, radiant heating is the principal mode of heat flow downward. Conductive heat does not move as readily downward through materials.

Where the roof is built of standard sheet roofing over rafters, installing the radiant barrier is quite simple. It can be tacked to the underside of the rafters, above the ceiling joists. For this use, radiant barrier is available in several different designs.

Radiant Barrier in the Walls

Walls can also easily incorporate a radiant barrier. Where double-wall construction is used, the barrier material can be installed on the inside with the foil material facing the outer wall. In areas where insulation is to be used in the wall, more care must be taken so that there is an air space between the insulation and the barrier material.

One method of utilizing the radiant barrier material requires that it be installed on the outside of the sheathing. Spacers are then nailed over the barrier material, and a second, vented skin is installed on the outside. Vents at the top and bottom of this second building skin form a solar chimney, allowing heated air to exhaust from the wall by convection. This tactic works with either open single-wall construction or insulated double-wall construction.

Building Insulation

Many materials have been developed to do the job of holding air as an insulator. From sawdust, thatch, and straw, to high tech materials such as aero-gells and ceramic foams, all materials have pros and cons. The first materials I've mentioned are organic, and subject to biological degradation. The second two are ridiculously expensive for home use. Good home insulating materials should be cheap, effective, and stable.

The ideal building insulation is nothing. The nothingness of the vacuum in space is a case in point. Heat flow due to conduction or convection simply cannot occur in a vacuum because it depends on the interaction between molecules of a substance to move the heat. No substance equals no heat movement. But a vacuum is not easily maintained.

Among commonly available materials, air is a very good insulator. It is cheap and efficient, but air has a tendency not to stay in one place when it is heated. We need to stop convective air movements by trapping it.

Stability in Insulation Materials

Many insulating materials are available that do this successfully. Sawdust is one of the earliest and cheapest insulators. One of the great drawbacks of using sawdust is that it can absorb water from rain or moisture in the air, or even from the building interior. Water absorption will degrade the insulation value, and may lead to bacterial, fungal, or insect damage.

Sawdust is also subject to settling. Even the mechanical vibrations a building may be subject to can cause settling of the sawdust, opening up large cavities above the insulating material where convective heat flow can occur. A good insulator must be more than efficient; it must be stable too, maintaining its original volume and material properties.

Insulation Toxicity

To be a stable building insulator, a material must contain as much air as possible, trapped in a matrix of inert material. Rock wool is one of the oldest commercial insulators available in batt form. It is still used around heating systems where resistance to flame or high heat is desirable.

Rock wool is manufactured from inert materials that have been heated and spun out into fine fibers. It is then fabricated into batts containing innumerable small air spaces. It is a brittle material with friable fibers that can break down easily during handling. These fibers can be a severe irritant to the human body, both to the lungs and to the skin.

So besides being stable, a good building insulator should be benign to the people who must install it and live around it. Asbestos is the classic example of the perfect insulation material that is also supremely toxic.

Materials such as glass wool—fiberglass—and several types of closed-cell foams are non-toxic and non-irritating to a greater or lesser degree. Fiberglass is less benign than other materials, but not nearly as irritating as rock wool.

Fire Retardant Qualities

Another material that is common in the residential building trades is cellulose insulation. This is manufactured out of ground-up paper, frequently newspaper. It has fire retardant added, and sometimes materials to make it resistant to insect damage. Cellulose is a very efficient, non-toxic insulator, but it has a tendency to settle in vertical cavities, just as sawdust does. Because of this, it is primarily used as loose fill above ceilings. If it is kept dry, it works very well.

Foam boards and foamed-in-place urethanes are excellent insulators, but they do not like heat. Under high heat conditions, they can produce toxic gases that are lethal. Under sustained heat conditions such as those found under a tropical roof, they can break down and outgas, losing their closed-cell foam structure, and seriously degrading their insulation ability.

The material I prefer for insulation in the tropics is glass wool, most commonly known as fiberglass. It is available in the U.S. in either batts or loose fill that can be blown into place. Fiberglass is similar to rock wool in its physical construction. Since it is “spun” out of fine strands of real glass, it is inert to heat, resistant to airborne moisture in the form of high humidity, and is a very effective insulation. It is slightly more physically irritating to handle than some other insulations, but new materials are better than aged materials in this respect.

Shipping Cost

Since all of the commonly accepted thermal insulations are light and bulky, they are expensive to ship long distances. The cost of shipping this type of product is based on its volume rather than its weight. That can be substantial.

Fiberglass suffers from the same drawback that other insulating materials do. It is difficult to obtain in Belize and other tropical areas because it frequently must be shipped in from more developed nations. Many nations place a high customs duty on imported goods such as these.

Where it is available, two-component urethane foam insulation is very convenient because the resin to manufacture it can be shipped by the barrel, in concentrated form. With modest equipment, the two-part resin can be combined and applied directly. It will then expand in place. Keep in mind that this foam does not like high heat.

How Much Insulation?

Some people define “R” values as “resistance” to the flow of heat. This is a good way to think of R-values. R-values can be added together, and they are a directly proportional measure of heat resistance. The chart at right lists common building materials, including insulation materials, and their associated R-values.

Where there is little difference between inside and ambient temperatures, and where air movement through natural ventilation is the goal, uninsulated walls and floors are acceptable. In a temperate climate, where winter heat and summer air conditioning expense is an important factor, a well-insulated house envelope is required. R-values in the floors, walls, and ceilings are specified by the location of the house in specific climate zones.

The type of energy used to heat or cool a building affects recommendations too, with higher R-values specified for electric heat than for fossil fuels, for

R-Values of Common Building Materials

Material	*R-Value*
Insulation	
Polyurethane, per inch	7.00
Polystyrene, extruded (blue board), per inch	5.00
Polystyrene (bead board), per inch	3.85
Rock wool, per inch	3.45
Fiberglass batt, per inch	3.35
Masonry	
Concrete blocks, 8 inches	1.11
Brick, common, 4 inch	0.80
Concrete blocks, 4 inches	0.71
Stucco, 1 inch	0.20
Concrete, per inch	0.08
Siding	
Wood bevel siding, 3/4 inch	1.05
Wood shingles	0.87
Wood bevel siding, 1/2 inch	0.81
Aluminum siding	0.61
Roofing	
Wood shingles	0.94
Asphalt shingles	0.44
Felt paper, 12 lb.	0.06
Wall Covering	
Insulation board sheathing	1.32
Cement board, 1/4 inch	0.94
Gypsum board (drywall), 5/8 inch	0.56
Gypsum board (drywall), 1/2 inch	0.45
Windows	
Sealed double glazing	1.92
Single thickness glazing	0.91
Wood	
Common construction softwoods, 3-1/2 inches	4.35
Common construction softwoods, 1-1/2 inches	1.89
Common construction softwoods, 3/4 inch	0.94
Plywood, construction grade, 3/4 inch	0.93
Maple, oak, or tropical hardwoods, 1 inch	0.91
Particleboard, 5/8 inch	0.82
Plywood, construction grade, 5/8 inch	0.78
Hardwood finished floor, 3/4 inch	0.68
Plywood, construction grade, 1/2 inch	0.62
Plywood, construction grade, 1/4 inch	0.31
Tempered hardboard, 1/4 inch	0.31
Regular hardboard, 1/4 inch	0.25

example. Additionally, fiberglass batts are only available in certain thicknesses, so recommendations usually adhere to what is available. 3-1/2 inch (9 cm) thick batts are rated R-11, 5-1/2 inches (14 cm) at R-19, etc.

Dead Air Spaces Used as Thermal Blocks

There are other ways of designing to resist heat flow from solar-heated walls besides radiant barriers and insulated surfaces. In new construction, during the design phase, it's necessary to be aware of potential heating problems. It is cost effective to design cabinets, closets, garages, or other unoccupied or infrequently occupied spaces along those walls that are sources of interior heating due to exterior solar radiation. This practice creates a double wall with an interior dead air space to resist heat moving across that space into the living environment.

Mass Used as a Thermal Flywheel

From the adobe pueblos of the southwest Indians to the rock walls in the ancient stone city of Great Zimbabwe, many indigenous forms of architecture have taken advantage of the thermal storage inherent in large mass. This mass can store heat, and can also even out the temperature fluctuations in a hostile living environment. The modern equivalent of these classic examples is the Trombe wall.

Using mass to mitigate temperature swings in a dwelling only works well where the temperature differential between the mass and the tempering heat source is fairly large. If you try to adapt the Trombe wall or other less passive applications of thermal mass storage to cooling in the humid tropics, you are limited by environmental factors.

Solar-driven temperatures inside a poorly designed building can go up to 125°F (52°C) in the heat of the day. This gives you a nice temperature differential to drive heat exchange, but such a gain is never desirable! But you do need a significant temperature difference to move much heat from the hot interior mass to the cooler outside nighttime air. In a passively cooled house in the humid tropics, there is no concentrated source of "cold" that can drive such a cooling heat flow the way there is with solar heating.

Convection

In Passive Cooling—Part 1, I covered the theory of convection, the movement of heat carried by the flow of a fluid such as air or water. Here I will try to explain how the designer or builder can use the building envelope to force convective flow to occur passively—without any input of energy other than what is applied to the fluid through natural influences.

I should say here that I do not personally subscribe to the need for *entirely* passive designs. Where the energy is available or where you can create it efficiently, there are good arguments for the use of active designs. Low voltage DC ceiling fans are a good example.

The key to good design is the word "efficiently." Both passive and active cooling systems can be designed that are so expensive to install that it could well be more efficient, all things considered, to run a generator and an air conditioner. So when I talk about efficiency of design, I am factoring in the overall cost of the design, not just operating costs.

Chimney Effect Ventilation

Hot air is less dense and therefore lighter than cool air. It rises or floats on the heavier, cooler air. As with all forms of heat flow, "hot" and "cold" are qualities that are relative to the temperature of a human body—98.6°F (37°C). There is no absolute quantity known as "hot" or "cold."

The important consideration is the difference in temperature between one heat source and another, not whether it is hot or cold. This concept is known technically as Δt (delta t), shorthand for the change in, or the difference in temperature.

Δt governs all things thermal, including radiation of energy from one hot body to another, conduction through a substance, or how easily hot air will float on cooler air. If Δt is high, hot air is more buoyant and will rise faster. If Δt is small, there is less tendency for a heated mass of air to move upwards. I am using air here as a familiar example, but technically, any fluid from air to water to molten metals will support convective heat flow.

Solar chimneys are structures designed to heat air with solar energy. This heated air then rises in a duct, just as furnace-heated air in a stovepipe rises. Under most conditions, stand-alone solar chimneys cannot justify their cost with their performance. Solar-enhanced ventilators (roof panels that are designed into new construction) may have a slightly better cost/benefit ratio, but as a general rule, their performance is disappointing. They are especially ill-suited to the humid tropics.

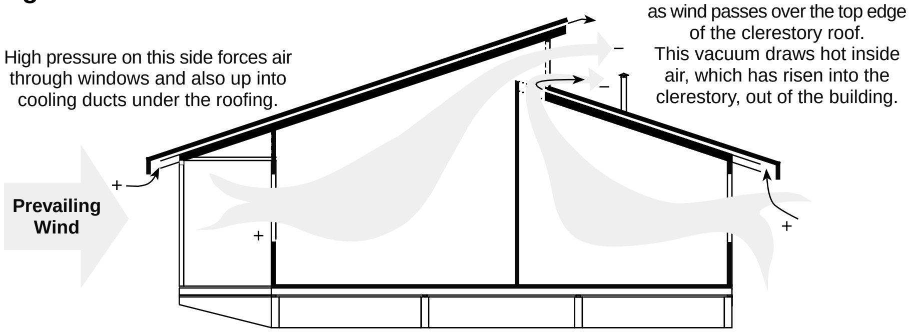
Roof Venting

In Part 1, I described heat buildup in the attic air space under a hot roof, and I showed how this buildup transfers heat to the ceiling and then down into the living space. If we return to that example, we can now discuss the role convection will play.

In the example above, the hot roof will attain temperatures of around 140°F (60°C) maximum. In the living space, the desirable temperature is around 72°F (22°C). There is a Δt between the roof heat source and the ceiling of 68°F (20°C). That is sizeable.

Suppose now that we open the roof up and allow the hot air, which has risen to the highest point of the roof, to keep rising and escape? This air removal technique is known as roof venting, and it is highly recommended for any enclosed roof or attic space.

Figure 4: Ventilation Paths



Of course, for air to flow out of a cavity, there must be provision for replacement air to flow in. The hot air flows out, creating a very slight vacuum, which draws cooler air in from some other place, usually around the roof eaves or gables.

As this replaces the hot air with much cooler air, the Δt between the attic air space and the ceiling membrane is considerably reduced. The Δt between the roof and the attic air is increased, allowing more heat to transfer from the roof surface to the attic air, which is vented outside to the ambient air. This reduces the roof temperature. Clearly, convection can be useful.

Whole House Venting

The type of convective heat removal described above is not just useful in attics and roofs. It is also useful for whole house ventilating under certain conditions. The point of whole house ventilation is to completely change the air inside the living envelope periodically.

Large fans are typically used for whole house ventilation in hot climates. These are installed in the ceiling, and thermostatically controlled to respond to overheating of the living space. This is typical for houses without refrigeration-type air conditioning that encounter seasonal high temperatures. For our purposes, we must try to accomplish the same end goal, but without the fan. (When practical, a whole house system is an excellent application for a solar-powered fan.)

Whether you employ a fan or rely only on convection for whole house ventilation, it is desirable to achieve about twenty air changes per hour, or 0.33 air changes each minute. The volume of the structure can be found by multiplying the floor area by the wall height. For the house in Figure 4, it works out to about 6,850 cubic feet (194 m^3). So the resulting airflow desired is around 2,260 cubic feet (64 m^3) per minute (0.33 x 6,850 = 2,260.5).

Disadvantages of Convection Alone

In Figure 4, the outer wall of the house is around 8 feet (2.4 m) tall, while the roof over the clerestory windows in the center is over 14 feet (4.3 m) tall. The interior of this house has a cathedral ceiling that rises to a high point above the clerestory. Hot air can flow out at this high point to drive whole house venting. Calculating the ventilating airflow under the best of conditions gives about 300 cfm—not very good! Here we are assuming no wind augmentation, just the induced circulation due to hot air rising and exhausting.

The reality is that we are not going to be able to ventilate this dwelling without the help of solar energy. Either we will need it to run an active fan system, or at a minimum to heat up the building so there is differential temperature gain that can be put to work moving air. But the last thing you want to do is introduce hot air just to get rid of the hot air! Convective cooling alone is not possible in this house under these rainy-season conditions. During the dry season, some air exchange is possible using convection.

Buried Cooling Tubes

Another idea that frequently creeps into conversations about passive cooling is the use of earth tubes as air intakes for solar chimney driven ventilation. The principle here is that pipes are buried in the cooler earth to draw air into the structure. The intake air cools down to earth temperature as it is drawn in, cooling the building.

Where a source of forced ventilation is available, such as an electrically driven blower, this can be made to work. Even then, there are potential problems with moisture build-up in the tubes, which can lead to introducing mold and mildew into the structure. Without using a powered blower to force air through the cooling tubes, non-circulation or even reverse circulation (pulling heated air into the structure from a hot source) is a possibility.

It is important to remember that stack-effect ventilation requires that the *average* temperature in the air column be higher than the cooler surrounding air. If the air column is 85°F (29°C) in the dwelling, 100°F (38°C) in the stack 10 feet (3 m) above, and 70°F (21°C) 10 feet below, down inside the cooling tubes, we have an average column temperature of 85°F. Ambient air temperatures outside would have to be lower than 85°F for upward movement of the air column to occur.

Wind Used for Ventilation

Wind is a form of convective air movement driven by the sun. It is a concentrated form of energy. Every time you double wind velocity, you increase wind energy eight times, because wind energy is a cubic function of velocity.

Wind will act on a building, whether we intend it to or not. Contrary winds can and do drive heated air backwards in solar ventilating ducts. They can allow cold air infiltration into a heated building envelope, and they generally do unexpected things in a structure not well thought out to resist wind dynamics.

Where a reliable breeze is available, you can use it to good advantage to drive air exchange through the envelope of a building. A considerable amount of information is available about how wind interacts with the planes and curves of a building structure.

The U.S. Federal Emergency Management Administration (FEMA) has thoroughly explored the dynamics of wind/structure interaction, seeking a better understanding of hurricane damage to buildings. Figure 5 and 6 are taken from FEMA course material, and illustrate the envelope dynamics of a building very well. This information is basic to understanding how the forces developed by wind can be used to foster local area and whole house ventilation.

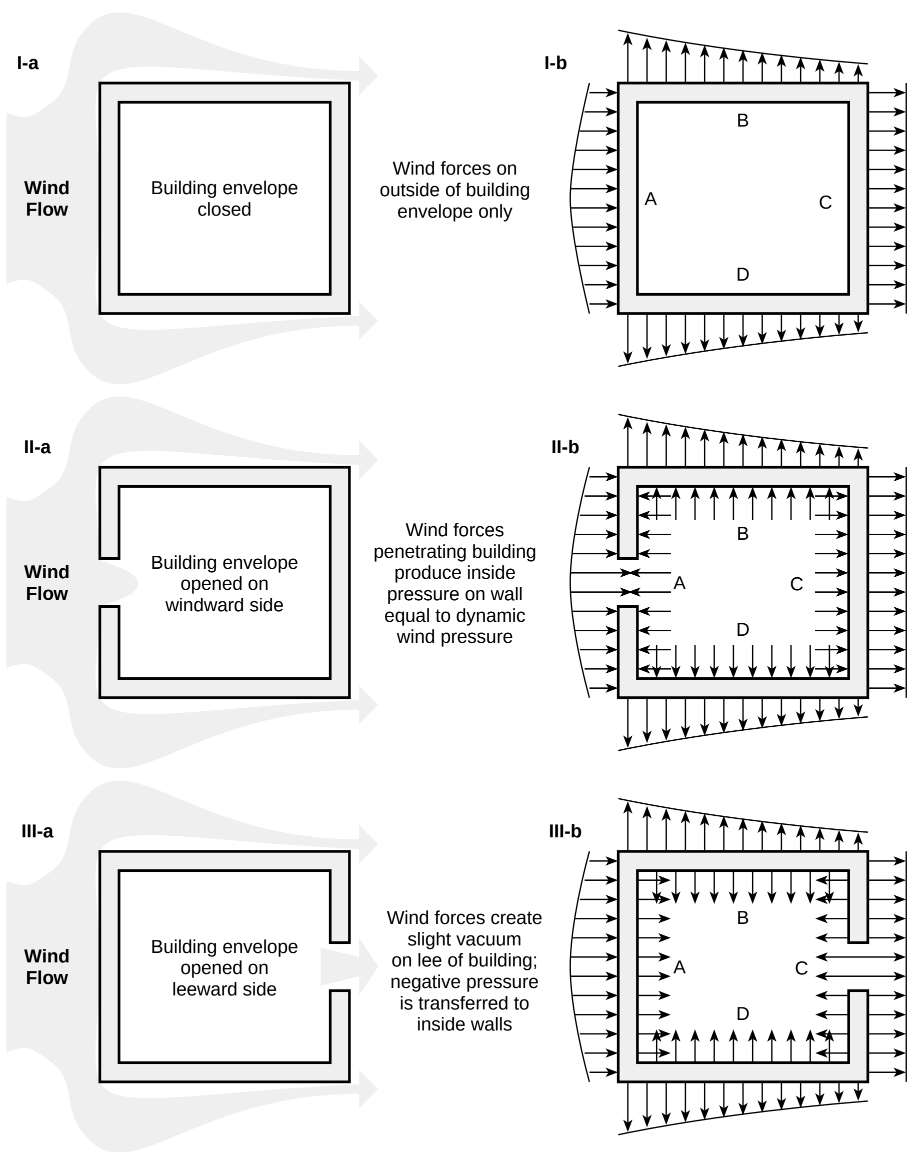
Wind blowing against the walls and roof of a building is forced along the planes of the surfaces. When it reaches the limit of a surface—the corner of the wall or the edge or peak of the roof—it continues to blow in the direction in which it has been flowing. This is a property of the inertia of the mass of the air in the wind current.

As it passes the edge of a building panel, wind does not turn the corner and follow the building planes. Instead, it lifts away from those flat sides, creating an area of lower pressure just past the edge. Technically, it makes a transition from smooth laminar flow along the panel to turbulent flow away from the second panel.

Air Flow Around Walls

Figure 5 illustrates wind flow as if we were looking down from above on the floor plan of a rectangular building. On the left is a pictorial schematic of the path of the wind flow. On the right is a schematic diagram of the vector forces of pressure and vacuum induced by the wind pattern on the left. Arrows pointing inward at the wall represent pressure. Arrows pointing outward,

Figure 5: Wind-Induced Pressure Vectors Under Different Conditions of Building Ventillation



away from the wall, represent vacuum. The curved lines are a rough representation of a graph of the pressure/vacuum forces, showing how they vary in different locations.

Illustrations I-a and I-b in Figure 5 show a building with sealed walls and roof. In this theoretical illustration, there are no paths for pressure to be transmitted into the envelope. Every time a building design creates an impediment to smooth airflow, it will induce a high pressure area. And every time airflow is forced over a hard edge with nothing behind it, a modest vacuum will be created.

Figure 5, illustrations II-a and II-b show a building with a breach in its windward wall. This can be a door, window, or just siding torn off under high wind forces. There are no other openings in the walls, so pressure builds up inside the building until it exactly equals the dynamic force of the wind entering the windward wall. The air is actually compressed somewhat, causing a rise in the static pressure against all of the inside walls.

Once the inside static pressure and the dynamic wind pressure equalize, it is just like a balloon that's been blown up. No more air can blow into the building because it is balanced by the force pushing out by pressure of compression. As II-b illustrates, the pressure inside this building is exactly equal to the highest pressure developed on the windward wall. This is because the wall opening is located in the area of highest pressure.

If the wall opening were moved over to an area with less pressure (near the corner), that lesser pressure would be what is transmitted to the inside of the building. Wall C is subject not only to the force developed by the mild vacuum pulling on the outside, but also to the force of the static pressure inside. These forces add up. In hurricane winds, a building can explode under these forces.

The designer should be sensitive to the areas of wind-induced high and low pressure in a structure. Maximum interior air flow value can be achieved by allowing pressure into a building envelope at points of highest dynamic wind pressure. Conversely, air can be drawn from inside a building most efficiently by strategic placement of exit venting at points where the wind has developed negative pressure. Combining both strategies gives a very effective push/pull effect. It is desirable to have the outflow openings larger than the inflow. A six to one ratio of outflow to inflow area is optimum.

Air Flow Over Roofs

Figure 6 shows buildings in cross section to illustrate the dynamics of airflow over different roofs. The flat roof and the low-pitched gable roof are subject to negative forces trying to lift up on them. Roofs with pitches over 40° do not have sufficiently sharp eaves to cause the flowing air to pull away from the roof as it moves along. Consequently, the windward side of the roof receives a substantial impact from the direct wind. So there are positive pressures on one side of this building, including the roof, and negative pressures on the downwind side.

These are the notes of the tune we want to play. Now we must put the notes together into a melody. If you open a building up to ventilation on the windward side only, you will have no ventilation. The inside and outside pressures cancel each other out, and that's that. This illustrates that you must have both an inlet and an exit for air to flow. Air must flow out of the envelope as fast as it can flow in or there will be pressure build-up that will restrict inflow.

Figure 6: Wind-Induced Pressure Vectors Over Different Roof Configuartions

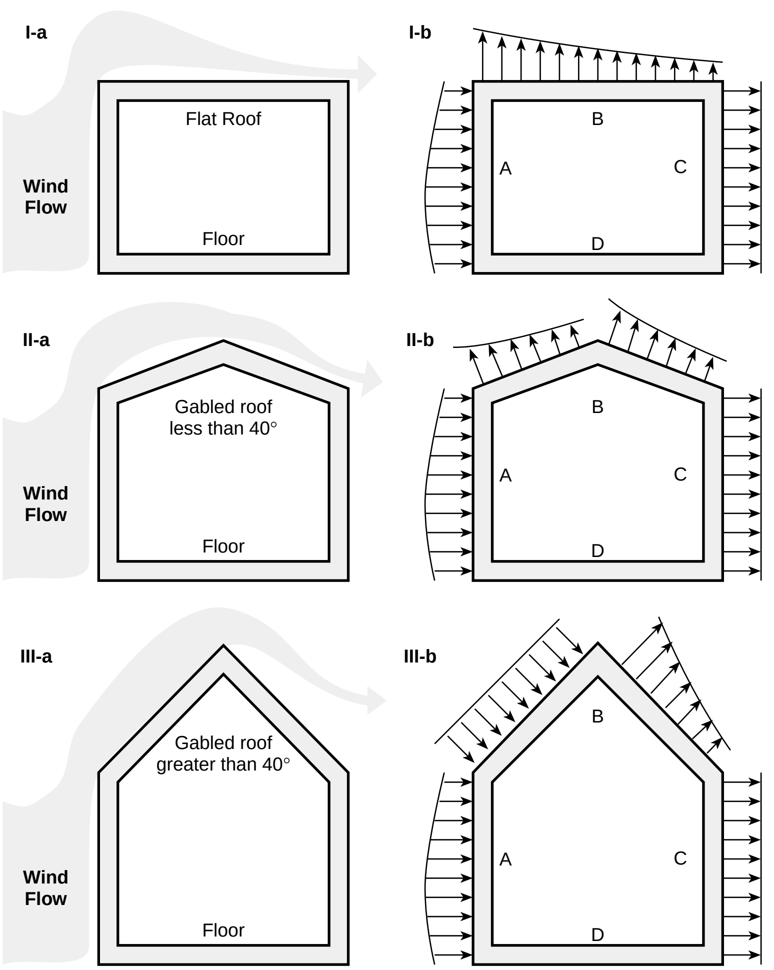
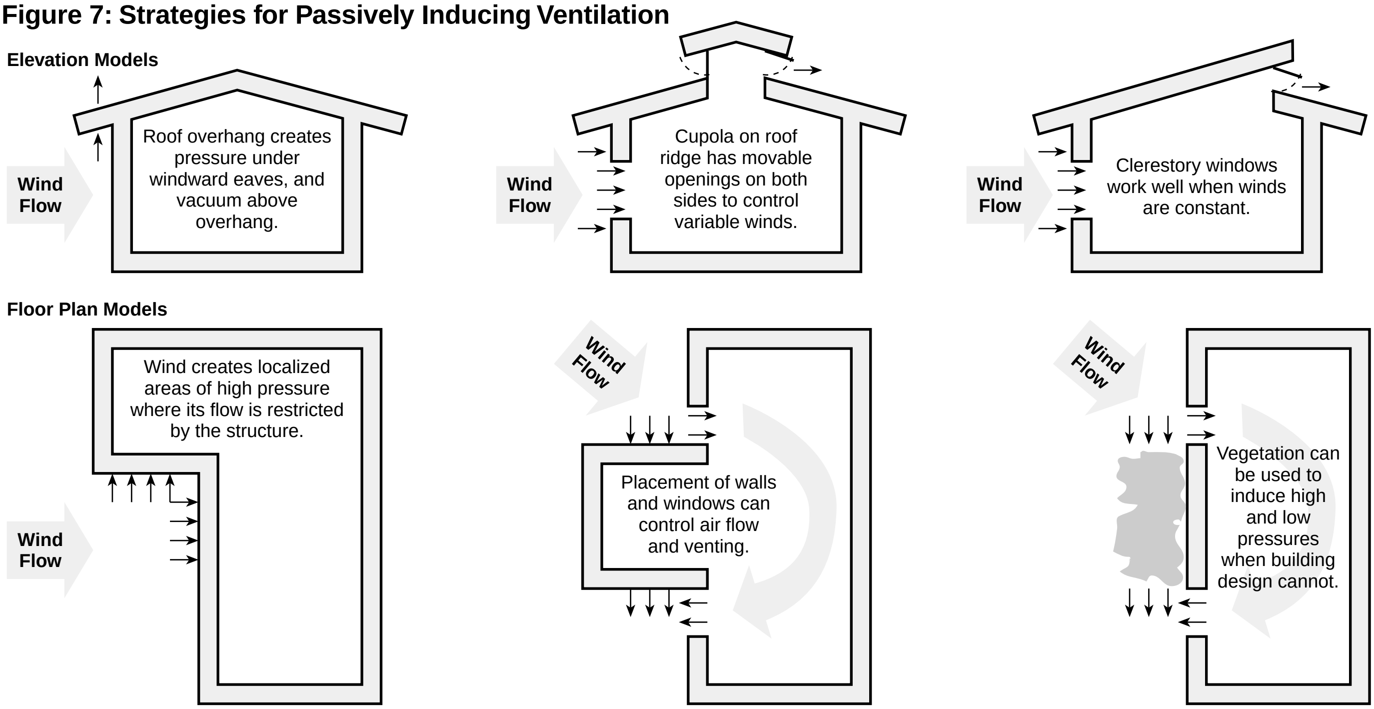


Figure 7: Strategies for Passively Inducing Ventilation



Direct Action on Building

Figure 7 illustrates some specific building treatments that are effective in fostering passive building ventilation. The important concept here is that even under moderate wind loads, there are pressure differentials on the outside walls and roof of the structure. If the designer takes advantage of these, it is possible to induce significant forced ventilation circulation through a structure. Under the right conditions, this ventilation will equal or exceed what you could obtain with an electric fan.

Vent windows placed high on the downwind wall allow negative pressure to extract hot air from inside.

Conclusion

In Passive Cooling Part 1—Basic Principles, I described the three basic mechanisms of heat transfer. I also related the transfer of heat to the sensation of comfort that people seek.

In Passive Cooling Part 2—Applied Construction, I have tried to relate the basic information in Part I to the world of wood, concrete, and glass. Here, to a limited degree, I have shown specific building techniques for thwarting the penetration of heat into a living environment. I've covered the principles and pitfalls of using natural forces to create that comfort envelope we seek in order to keep the effects of excessive heat at bay.

I have also tried to list other, more extensive sources of information on the subject of passive cooling, for the enthusiastic reader. I hope this has been of some help to people trying to live comfortably in the humid tropics. It can be done.

Access

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Resources for further study:

Architecture For the Poor, 1973, and *Natural Energy and Vernacular Architecture, Principles and Examples with Reference to Hot Arid Climates,* 1986, by Hassan

Fathy, both published by The University of Chicago Press, Chicago. These books can be hard to find. I was able to locate them through my regional inter-library loan program.

Building for the Caribbean Basin and Latin America; Energy-Efficient Building Strategies for Hot, Humid Climates, Kenneth Sheinkopf, 1989, Solar Energy Research and Education Foundation, 4733 Bethesda Ave., #608, Bethesda, MD 20814 • 301-951-3231 Fax: 301-654-7832 • plowenth@seia.org www.seia.org

Radiant Barriers: A Question and Answer Primer, by Ingrid Melody • Florida Solar Energy Center www.fsec.ucf.edu/Pubs/EnergyNotes/En-15.htm

Low Energy Cooling; A Guide to the Practical Application of Passive Cooling and Cooling Energy Conservation Measures, Donald W. Abrams, Van Nostrand Reinhold Company, New York, 1986 Apparently no longer in print, but check with used bookstores and inter-library loan.

Passive Cooling, 1989, edited by Jeffrey Cook, US$55 from The MIT Press, 5 Cambridge Center, Cambridge, MA 02142 • 800-356-0343 or 617-625-8569 Fax: 6l7-625-6660 • mitpress-orders@mit.edu http://mitpress.mit.edu