Can Roofs Breathe?

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School of Architecture
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D. Arch Project Committee
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We certify that we have read this D. Arch. Project and that, in our opinion, it is satisfactory in the scope and quality as a D. Arch. Project for the degree of Doctorate of Architecture in the School of Architecture, University of Hawai'i at Manoa.

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ABSTRACT

This research investigates using the principles of cross ventilation, stack effect, solar roof, and solar chimney techniques into a single roof design to possibly increase the internal air velocity and lower the internal temperatures for residential structures located in hot-humid climates. The environmental conditions common in hot-humid climates include low wind velocity, increased humidity levels and high ambient temperatures. The most beneficial way to provide thermal comfort for the occupants living in these climates is to increase air velocity across the body, to lower humidity levels, and to lower internal temperatures.

The goal is to design a roof system incorporating passive cooling and solar-induced cooling principles which will potentially increase the potential thermal comfort while outperforming conventional residential roof systems without using mechanical systems. The design in this research was tested using physical modeling with data collection and computational simulation using CosmosFlo Computational Fluid Dynamics (CFD) software. The software was used for the computational analysis used to estimate air velocity within the roof testing modules.

The preliminary testing results demonstrate a decreased internal temperature using the proposed design over those internal temperatures using typical roofing methods. The air velocity test data from the physical models has proved unreliable due to location of the physical testing modules which were influenced by higher wind speeds associated with the trade wind flow inherent in Hawai‘i. The temperature differences proved large enough between the air inlet vents, interior space, and air cavity to provide increased air movement in the interior of the test modules. The outcome of this research is encouraging and shows promise that the proposed design could possibly be beneficial to increase the thermal comfort levels for residential structures in the hot-humid climates. Further exploration and a large amount of research and development are still needed to make this design more efficient and cost effective for possible wide spread use.

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INTRODUCTION

Research Background

Traditionally, when selecting a new roof three: things are considered cost, durability, and aesthetics.[1] But there are other factors which should be considered such as the roof's performance and environmental impacts. Roofs are generally built to keep the occupants shaded, dry, and secure. Why can't roofs do more than these three basic needs?

In fact, while looking back at the history of roofs there are examples of roofs that catch water for later use and roofs that permit the growth of vegetation (the ancestors to the modern green roof). In current roof designs, one can witness more water catchment designs, green roof configurations, and other energy generating options which are becoming increasingly popular.

The roof is commonly the largest and most exposed part of any structure constantly being bombarded by the extremes of heat, cold, wind, and moisture especially in the hot-humid latitudes. In hot-humid climates the roof surface becomes the hottest surface on the structure which can and often will transfer this heat to the interior spaces there by disturbing the comfort level for the occupants. To mitigate this heat, many structures rely on thick insulating layers, reflective roof coatings and increasing air flow either naturally or mechanically, employing cooling fans or air conditioning. The most common approach used to cool the interior spaces is by installing air conditioning, but that also requires high initial and operating costs limiting its potential use for low-income residential projects.

The other alternative is by incorporating passive cooling into the design of the residential structure. Passive cooling is utilized very successfully in many parts of the world, but it is difficult to achieve the same human comfort level in hot-humid climates. The main factors limiting the benefits of passive ventilation in hot-humid climates are the high temperature levels, high humidity levels and low air velocities inherent to those regions. One example is the data from the Malaysian Meteorological Service Department demonstrating the mean outdoor air velocity is between approximately 3 ft/s to 5 ft/s (2.04 mph. to 3.40 mph) at 30 feet high.[2] The problem is that air velocity reduces closer to ground level and in many cases it becomes calm. To combat this problem there is a need to design a system which will increase the air velocity using a passive system providing human comfort levels in a residential structure.

Human comfort in this context relates to thermal comfort or how a person positively reacts, interprets, or feels in a given thermal environment. The two main factors that affect thermal comfort are:

- Environmental factors which include air temperature, relative humidity, air movement and radiation.
- Subjective factors which include activity levels, age, sex, clothing skin color, human size, health condition, food and drink, and clothing.

To graphically represent the human thermal comfort level, two charts are commonly used in the architecture and engineering professions. The first is the Bioclimatic chart which indicates zones of comfort in relation to climatic conditions. The second is the Psychometric chart which indicates how the climatic properties relate to each other. These charts demonstrate that in hot-humid climates if the temperature and/or humidity levels cannot be lowered, the only way to provide additional human comfort is by increasing the air velocity across the skin. This process is called psychological cooling and it uses the processes of convection and evaporation to cool the body. It has been said by Md. Rajeh that the acceptable range of air velocity for human comfort can be achieved by introducing 3ft/s air velocity.[3]

The term passive ventilation used in describing the ventilation of buildings without the introduction of mechanical systems. Passive ventilation systems rely on the naturally occurring properties (physics) to move air. For passively ventilated systems to work the air outside must be cooler than the air inside or there must be a difference in air pressure. Natural ventilation cooling is where higher air temperatures are offset by increased air motion (by increasing air velocity by 0.4921ft/s or 0.03mph compensates for a 1.8˚F or 1˚C decrease). There are two major types of passive cooling ventilation systems: cross ventilation and the stack ventilation.

Cross ventilation occurs when wind is drawn into and through an interior space and across the occupants' skin aiding in the natural cooling effect. This is normally accomplished by the proper placement and sizing of windows to catch the prevailing winds. For cross ventilation to be effective, the plan of the structure needs to be rather narrow with minimum partition walls or obstacles. Cross ventilation can be used in rooms without windows on opposing sides but with only limited results. Cross ventilation has several significant benefits:

- Greater magnitude and effectiveness
- Readily available (natural occurring force)
- Relatively economic implementation
- User friendly (when provisions for control are provided for

occupants)

Since cross ventilation relies on wind and air pressures, it becomes ineffective during light or calm winds which are prevalent in the hot-humid climates.

Stack ventilation uses the principle of convective air flow where the warm air rises and the cool air sinks. This system uses very low openings to let the cooler air into the interior and very high openings to let the warm air escape from the interior. Although stack ventilation does not move as much air as cross ventilation, it does work even with light or calm winds. Most roof ventilators use the combination of the cross and stack principles to move the warmer air out of the space.

A solar roof system typically uses a double roof system to trap heated air before it enters the interior space, then uses this air to draw warm air out of the interior. Many solar roofs are configured horizontally with outlet vents located in the center and inlet vents located around the perimeter of the upper interior space. This design has been proven to only move a small volume of air 0.98 ft/s which is not enough to increase human thermal comfort levels.[4]

The solar chimney typically uses a tall air chamber which is heated by the solar radiation to promote a convective air flow. The outlet is at the top of the chimney and the inlet is at the bottom. The taller the chimney the more air velocity can be created. One proven drawback of a solar chimney is the added heat gain transferred into the interior spaces increasing the cooling load. There is much interest and experimentation of solar chimneys, and their efficiency levels are constantly being increased.

Problem Statement

There are three major climatic issues that affect both internally and externally the design of residential structures in hot-humid climates; temperature, wind velocity, and solar radiation levels. The amount of heat generated by solar radiation on the roof surfaces of many residential structures increases the cooling loads needed to create comfortable living conditions. Using the heat (energy) created by the impact of solar radiation on the roof surface to generate a convective air movement thus ventilating the interior space. This would remove the internal heat gain, reduce the internal temperatures, and increase the internal air velocity. This produces an added psychological cooling effect which would increase the human comfort level.

Research Questions

The following questions will be addressed in this experiment:

1. Can the proposed roof design create increased air velocity to cool occupants?
2. Is there a beneficial difference between using radiant barrier vs. wood louvers in the design's louver construction?
3. Can the proposed roof design lower temperatures better than typical asphalt roof construction and without using insulation?
4. Does the proposed roof design cool the interior better than typical roof construction with cross ventilation?
5. Is the proposed roof design a viable passive ventilation option for hot-humid climates?

Research Objective

The primary goals of this experiment are to compare the temperature differences and air velocities capabilities of the proposed roof design for use in hot-humid climates.

Other goals of this experiment include:

- To design a passive roof system that out performs existing passive cooling systems for hot-humid climates.
- To develop a roof system prototype that improves air movement for use in both new houses and in the retrofit of existing residential structures.

Scope and Limitations

The scope of this experiment is to test the effectiveness of using solar radiation to passively move air at higher velocities and to lower the internal air temperatures in residential structures. The computational models and the physical models were set at the same scale to reproduce as accurate test data as possible. The testing was carried out by both computational software (CosmosFlo) and physical means and thus is constrained by certain limitations. These limitations are due the location of the physical models (due to local climatic conditions) and by the newly gained knowledge of the CFD program.

Importance of Research

The expectation of this research is to show an increase in the air velocity in the interior space using solar induced passive ventilation. The study is also expected to show the design can lower the interior temperatures without the use of added insulation or reflective roof surfaces. This design could be an additional passive ventilation design strategy increasing human thermal comfort and improving health of the interior space by increasing the air circulation and air changes. The research of this experimental design is only the first stage in developing a roof system for widespread use in new and existing residential structures in the hot-humid climates.

Organization of This Research Report

This project report is divided into five sections that are summarized below.

The **Introduction** explains the main issues of the project and includes the research background, problem statement, research questions, research objectives, scope and limitations, importance of research, and the structure of the report.

The **Literature Review** is composed of three main sections; The Factors, The Roof, and Passive Ventilation.

The Factors section introduces the overall factors present including an overview of climatic conditions associated with the hot-humid regions of the world, physical properties, and ways of quantifying human comfort levels. The Climatic Condition section explains the environmental factors which are present in hot-humid climates. The Physical Properties section explains the different properties of water flow and heat transfer which directly affect the building structure and the occupants. The Human Comfort section explains the factors that affect human comfort and introduce the Bioclimatic Chart and the Psychometric Chart both used in quantifying human comfort levels.

The Roof section introduces the History of Roofs, Roofing Types, and Roofing Materials. The History of Roofs section gives a brief history of how the roof has evolved over time and some problems associated with current roofing techniques in hot-humid climates. The Roofing Types section discusses current steep-slope roofing types widely used today and considerations to take into account when designing roofs for the hot-humid climates. The Roofing Material section different roofing materials are presented with their background, advantages, and disadvantages.

The Passive Ventilation section explains different types of roof ventilators and passive ventilation strategies including; cross ventilation, stack effect, solar roof, and solar chimney systems. This section also discusses potential problems for common roof ventilators and cross ventilation options.

The **Methodology** is divided into three sections: Combination of Passive Ventilation Strategies, Design, and Testing.

The Combination of Passive Ventilation Strategies section explains the different principles incorporated into the design. These principles include the proper sizing for cross ventilation, the minimum temperature difference for stack effect, the solar roof configuration, and the air cavity configuration of the solar chimney.

The Design section describes the proposed design, material choices, and methods of construction for both the physical and computational models. This section also explains the different roof testing module configurations used for physical testing.

The Testing section explains the testing methods and tools used for gathering data. This section discusses where the testing took place and the locations of the testing equipment within the roof testing modules. The results from the testing are presented and analyzed in the following Results and Analysis section.

The **Results and Analysis** section explains verbally and graphically the results of the testing. The physical temperature differences in the roof testing modules are compared and computational air velocity tests are examined. These results are then analyzed to discover if the proposed design has any merits for future exploration.

The **Summary and Conclusion** section summarizes the major findings of the testing and introduces considerations for future developments. This section includes proposed improvements for the testing and design of the proposed system.

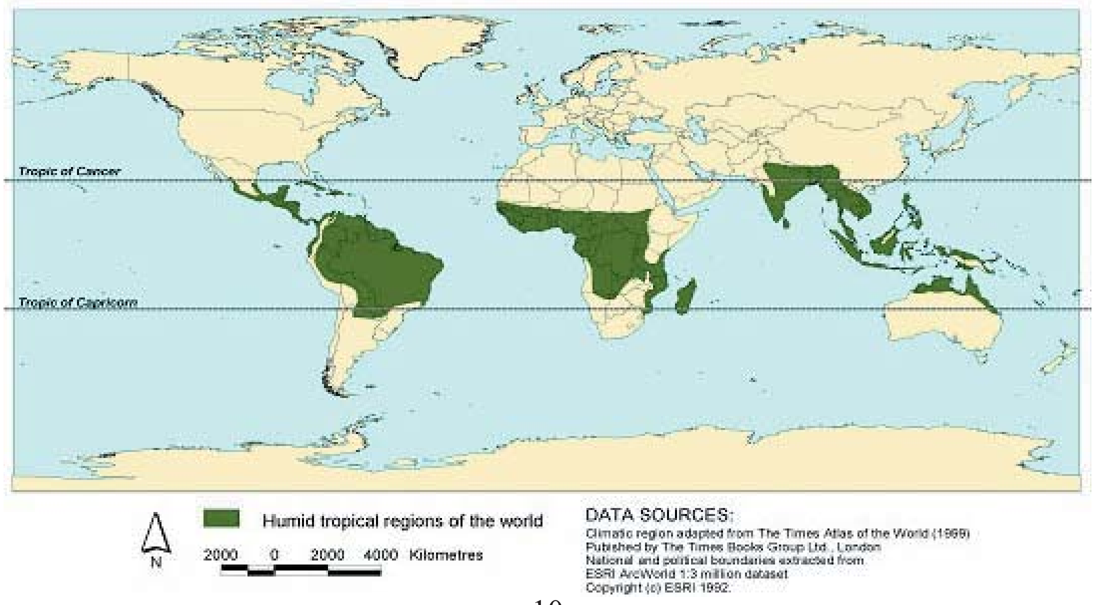
LITERATURE REVIEW

THE FACTORS

Climatic Conditions

For any architecture project to be successful, the designer must first take into consideration the climate where the project is to be located. Climates are often defined in terms of area, latitude, altitude, or other geophysical features. Although there are thousands of microclimate variations, climates can essentially be broken down into four basic types. Hot, moist climates feature high rainfall with often intense and rapid chemical weathering. Cold, moist climates still feature chemical weathering but because of the lower temperature, the rates are dramatically reduced from those encountered in hot, moist climates. Cold, dry climates feature the least weathering, but mechanical weathering (e.g., ice wedging) does produce slow landscape evolution. Hot, dry climates often have intense mechanical weathering pressures (e.g., wind, sand-blasting, etc).1

Figure 1: *This map shows the locations of the majority of tropical hot-humid climates on the planet. These locations are also seeing an increase in population levels and increased construction.*



DATA SOURCES:
Climatic region adapted from The Times Atlas of the World (1999)
Published by The Times Books Group Ltd., London
National and political boundaries extracted from
ESRI ArcWorld 1:3 million dataset
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The climatic conditions for buildings can then be divided into two sections: the external climate and the internal climate. The external climate can be defined by the average and variations of weather in a region over long periods of time. This can be quantified by using data such as: air temperature, air humidity, wind speed and direction, amount of sunlight, amount of rain, etc… The interior climate is more complex even though it uses the same type of data used for exterior climate. The influences and preceptions of the occupants have an effect on the internal climate since the interior climate is directly related to human comfort. This subject will be further addressed in the comfort section.

Since the proposed design is to be used in the Hot-Humid tropical climates the definition of what makes up this climate must be the starting point. In a hot-humid climate there is a high relative humidity (often 90 percent), heavy rainfall, and a mean temperature all the year round of over 64°F (17.77°C), but may reach almost 100°F (37.78°C) in the hot season.[2]

Some researchers further classify hot-humid climates as having:

- A 67°F (19.5°C) or higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or
- A 73°F (23°C) or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.[3]

The hot-humid climate continues to have an increased humidity level even during the dry season and a smaller variation in day and night temperatures (75-85°F. in the hot season, 50-70°F. in the cool season).[4] The small temperature range makes nights almost as warm as days which make it very difficult to obtain a restful sleep.[5] The increased humidity levels make creating human comfort very difficult by losing heat in the evaporative process. The bright sun shining through and reflecting off the clouds may increase solar radiation by 10% or more.[5]

Figures 2 & 3: *The hot--humid climate promotes an abundance of vegetative growth and extreme weathering of structures. These structures are located on the Mentawai Islands of the coast of Sumatra and are constructed out of the natural surrounding materials. Even though the materials weather quickly they are easily replaced and with little impact on the environment.*

In these hot-humid climates, everything is overdone from the blazing near vertical equatorial sun to torrential rains often wind driven and nearly horizontal. Wind speeds are normally light and may be blocked further by an overabundance of vegetation in these tropical regions, yet during storms the winds may blow in excess of 100 miles per hour. In these hot-humid climates the need for relief from the heat and humidity should be top priority in the design process. Air movement then becomes a very important component in the design of a passive cooling system.

To design in these extreme climatic conditions one must understand that certain designs work and others do not. An example of this is the early Hawaiian structures made with timber posts and beams, steep roofs, and large overhangs covered with thatching. These structures have little or no walls and the light winds flowed unimpeded through them. The structures were built for the occupants comfort with the climate in mind.

Figure 4: *This early Hawaiian structure which sheds water and promotes good air flow is actually nothing but a roof.*

Now take the types of structures built in Hawaii by the Missionaries. These were constructed out of concrete, rock, and timber with small openings in the solid walls and roofs with little or no overhangs. These structures were great for security but otherwise were very uncomfortable to occupy since they were built using common construction methods from the northeastern United States.

Figure 5: *The Baldwin House in Lahaina, Maui is an example of how the Missionaries built structures suited for the colder climates of the northeastern United States in the warm tropical climates of Hawaii. These structures had limited air flow and small roof overhangs causing the buildings to heat due to the solar impacts on the exterior walls.*

Even today many structures are built in Hawaii and in other locations around the world with little or no consideration to the climate where they are located. There seems to be a growing disconnect between humans and their environment. Can properly designed architecture aid in closing the gap between humans and environment?

Physical Properties

There are certain physical properties that cannot be overlooked in roof and roof ventilation design. These properties include the law of gravity, fluid dynamics, and thermodynamics. The following is a very brief overview of different physical properties that should be considered when designing a roofing system or component.

Figure 6: *Gavity holds the building on the ground and enables the rain water to be shed off the roof and away from the structure.*

Mainly, gravitational forces keep a structure on the ground and the components, including the roof, held together. Gravity is also responsible for the action of water shedding enabling a steep roof to work. The water uses the gravitational forces to drain off and away form the structure. The common principle that water flows downhill is due to gravity. But, there are other physical properties that can make water flow up hill and around corners. Both air and water are controlled by the properties of fluid dynamics. These properties include things such as capillary action, surface tension, and the Bernoulli Effect.

Capillary action occurs when the adhesion to the walls are stronger than the cohesive forces between molecules. The height to which capillary action will take water vertically is limited by its surface tension. The surface tension of water is 72 dynes/cm at 25°C and it takes a force of 72 dynes to break a surface film of water 1 cm long. Surface tension is caused by the polar nature of the water molecule.6

The Bernoulli Equation (Bernoulli Effect) is considered to be a statement of the conservation of energy principle appropriate for flowing liquids. This is the lowering of fluid pressure in regions where the flow velocity is increased. This is where the venturi effect and the principles governing the air foil of an airplane wing come from.

The heat and thermal properties are controlled by thermodynamics. The basic rule of thermodynamics deals with heat transfer where heat travels from a higher temperature

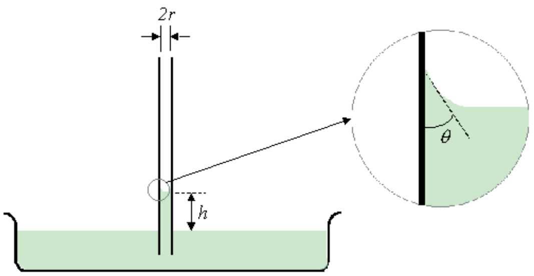


Figure 7: *Capillary action can cause water to flow vertically seeming to defy the law of gravity. (http://diracdelta.co.uk/science/souce/c/a/capillary%20action/source.html)*

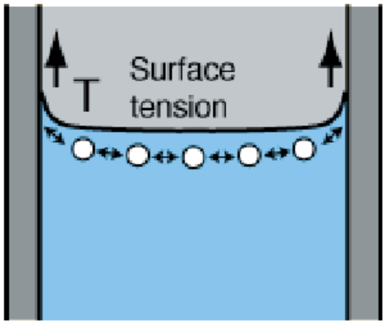


Figure 8: *Demonstrates how surface tention pulls the edges of water up the sides of the glass cylinder this is caused by the polar nature of the water molecules. (http;//hyperphysics.phy-astr.gsu.edu/hbase/fluids/imgflu/capi.gif)*

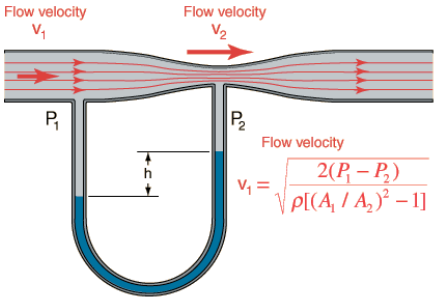


Figure 9: *An example of how the Bernoulli Effect reacts in a venturi. The increased flow at smaller diameter causes a lower pressure drawing fluid upward.(http://hyperphysics.phy-astr.gsu.edu/.../venturi.hm)*

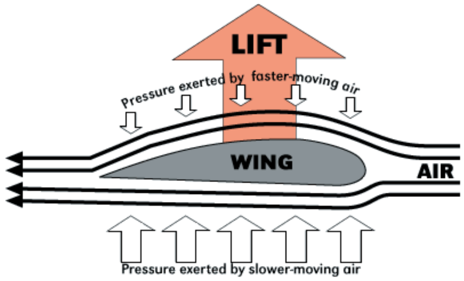


Figure 10: *An example of how the Bernoulli Effect works on an airplane wing. The air foil shape causes a negative pressure on the top and a positive pressure on the bottom of the wig creating lift.(http://people.bath.ac.uk/dab21/downforce_files/image008.gif)*

to a lower temperature. This flow of heat can be accomplished in four different ways by conduction, convection, radiation, and evaporation. The following are some simple definitions:

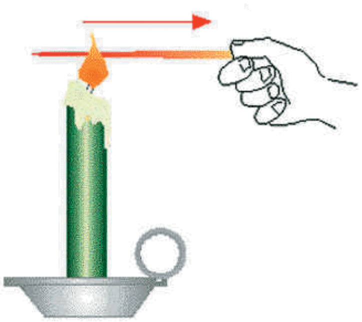


Figure 11: *Demostration of heat transfer by conduction. As the metal is heated by the candle the heat is transfered toward the cooler end.(http://www.etap.org/newsletter/newsletter_02_05/lesson3/conduction.gif)*

Heat transfer by conduction is caused by molecular agitation within a material without any motion of the material. An example of this is the metal handle of a pot or pan on the heated stove as the pan warms the heat is transferred through the handle. This also happens in building materials where the heat is introduced by the sun or other means and transferred into the occupied spaces.

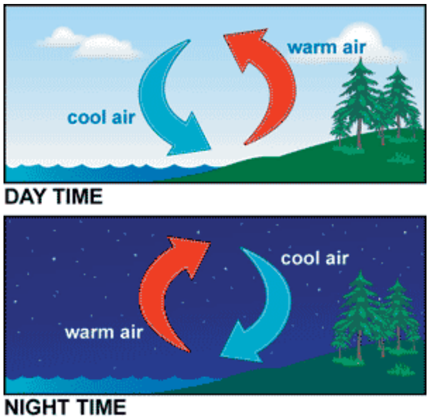


Figure 12: *The effects of convective air flow shows the changes in air flow caused by the land heating by day and cooling at night.(http://www.energyquest.ca.govt/story/images/chap01_convection.gif)*

Heat transfer by convection is caused by the mass motion of a fluid such as air or water, where the heated fluid is caused to move away from the source of heat, carrying energy with it. Convection above a hot surface occurs because hot air expands, becomes less dense, and rises. This causes currents in fluids since, the hot fluid rises and the cold fluid sinks. This principle is used in the stack ventilation systems in buildings where the warm air is drawn out of the buildings and the cool air is drawn in.[7]

Heat transfer by radiation is caused by the emission of electromagnetic waves which carry energy away from an emitting object. An example of this is the heat felt from sunlight on one's skin. This is the heat being radiated from the sun to ones skin. In buildings the impact from the sun radiation is extreme, especially on the roof of a structure. The roof is the first defense of any structure from the sun's heat caused by radiation and is the primary reason for covering roofs with materials that help block this intense heat.

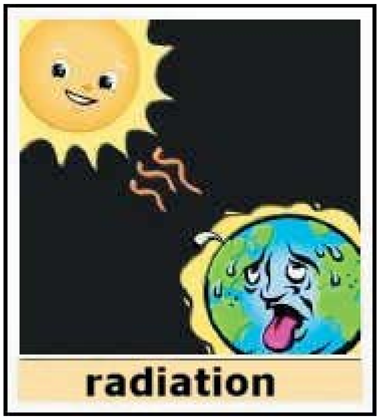


Figure 13: *Depicts the suns radiant heat impacting the surface of the earth. The same effect can be felt on one's skin while in strong sunlight.(www.vtaide.com/png/heat2.html)*

Heat transfer by evaporation is caused by a surface phenomenon where some molecules have enough kinetic energy to escape. This works when water molecules lift off a surface and carry the trapped heat away from the surface. This is the principle behind humans perspiring; the moisture evaporating off the skin carries the heat away from the body cooling the skin. Evaporation does not work if there is equilibrium - meaning the same number of water molecules escaping that there are returning to surface. The pressure of this equilibrium

Figure 14: *As sunlight heats the roof, the morning dew begins evaporating. The heat trapped in the water molecules is lifted away from the surface causing a cooling effect. The same process happens when one perspires.(http://www.pbase.com/graylady/varia_2003&page=5)*

is called the saturation vapor pressure. This is the reason evaporative cooling works in hot-dry climates but, not in hot-humid climates where the air is commonly saturated.

By understanding certain physical properties, one may use them as an advantage in the design process. By understanding how fluids (air and water) react in certain conditions one can begin to design roofs systems or roof components more efficiently. The idea of a roof that can breathe is directly related to the movements of both air and water with the possibility of directing these fluids toward the best possible outcome. Understanding the effects of heat and of heat flow will allow for new roof designs and materials that utilize these principles for blocking and carrying the heat away from the occupants, thus increasing human comfort.

Human Comfort

The human comfort in this context is the thermal comfort or lack of discomfort.[8] Three factors affect comfort: personal, measurable environmental, and psychological. The personal (or physical) are normally under personal control such as one's metabolism and one's clothing, the ability to move to a more comfortable place, or the intake of warm or cold foods and beverages.[9] The measurable environmental factors include: air temperature, air motion, humidity, and surface temperature. The psychological factors used in the measurement of comfort include: light, sound, color, texture, aroma and movement. While all three of these factors are important for human comfort the measurable environmental factors will be the primary focus.

The measurable environmental factors are based on air temperatures, surface temperatures, air motion and humidity and their relationship to heat transfer.

Heat Transferred by:	**Is Primarily Dependent on:**
Conduction	Surface temperature
Convection	Air temperature, air motion, and humidity
Radiation	Surface temperature, (and orientation to the human body)
Evaporation	Humidity, air motion, air temperature[10]

The term "comfort zone" refers to the combination of air temperature and air humidity level (relative humidity). There are charts depicting the comfort zone such as the bioclimatic chart and psychometric chart.

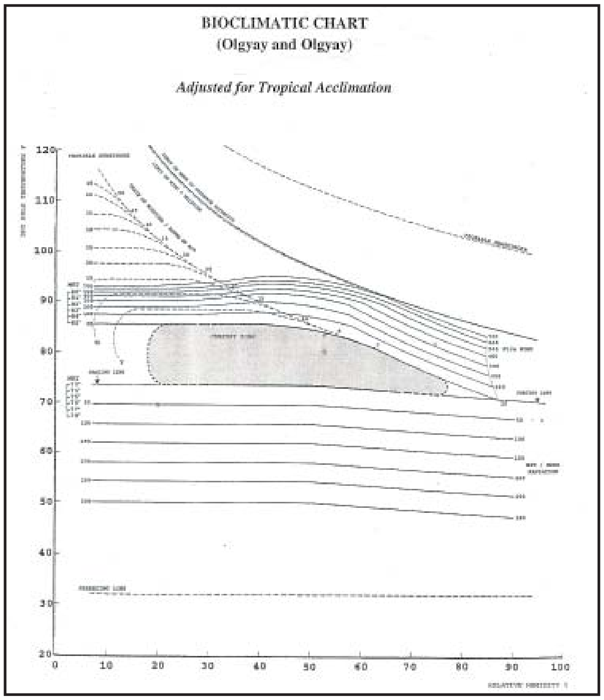


Figure 15: *The Olgyay Bioclimatic Chart aids designers, architects, and engineers in designing buildings that work with the local climatic conditions. The chart represents comfort levels at different temperatures and air velocities and can be adjusted for different climates.*

The Olgyay Bioclimatic chart was developed in the 1950's to incorporate the outdoor climate into building design. The chart indicates the zones of comfort in relation to ambient temperature and humidity, mean radiant temperature (MRT), wind speed, solar radiation, and evaporative cooling. This chart can be adjusted to specific climates (hot-humid or cold-dry) or seasons (summer or winter) to take into account acclimation.

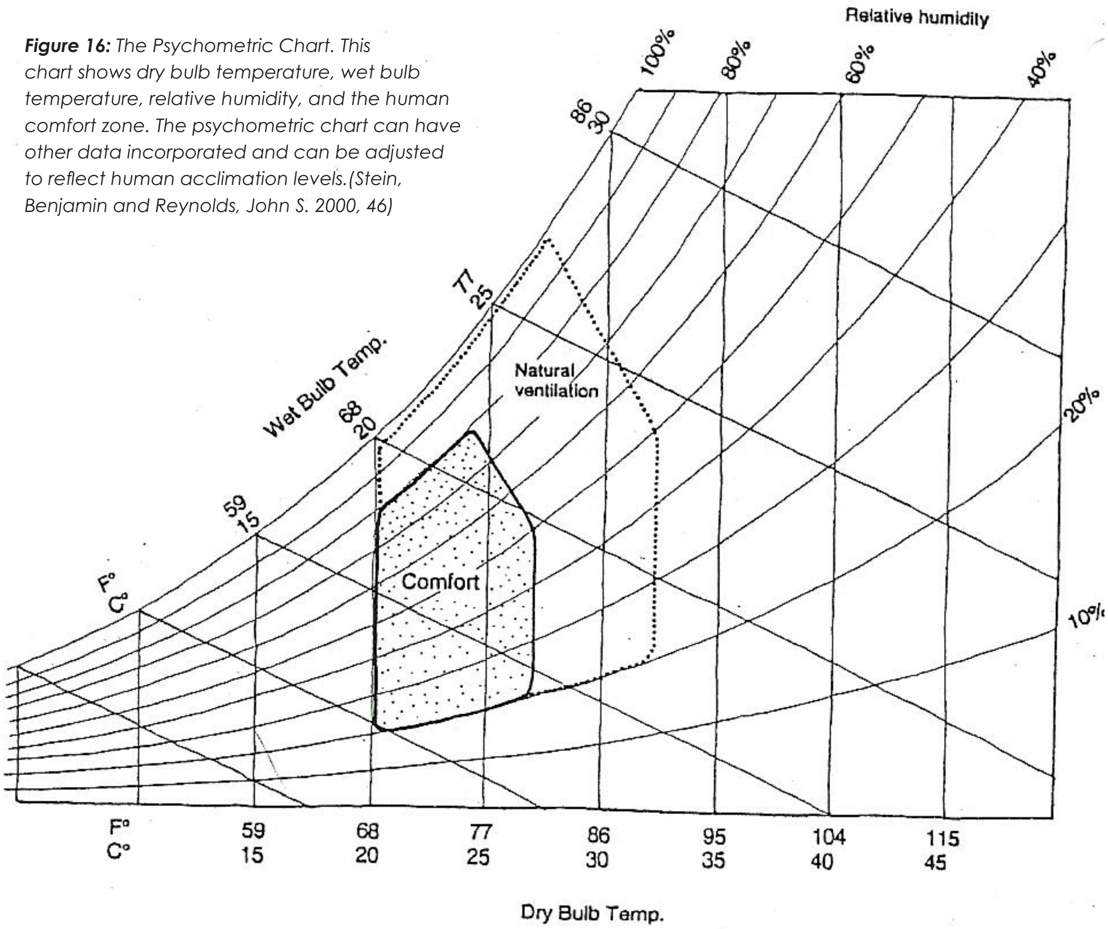


Figure 16: *The Psychometric Chart. This chart shows dry bulb temperature, wet bulb temperature, relative humidity, and the human comfort zone. The psychometric chart can have other data incorporated and can be adjusted to reflect human acclimation levels.(Stein, Benjamin and Reynolds, John S. 2000, 46)*

The Psychometric Chart is a graph of the physical properties of moist air at a constant pressure (often equated to an elevation relative to sea level). The chart graphically expresses how various properties relate to each other.

The different thermophysical properties found on most psychometric charts are:

Dry Bulb temperature (DBT) determined by an ordinary thermometer, the thermometer bulb being dry

Wet-Bulb temperature (WBT) determined by a thermometer whose sensing bulb is covered with water

Dew point temperature (DPT) which is the temperature at which moist air would reach the saturation level

Relative Humidity (RH) ratio of the mole fraction of water vapor to the mole fraction of saturated moist air at the same temperature and pressure

Humidity Ratio (also known as Moisture Content, Mixing Ratio, or Specific Humidity) the proportion of mass of water vapour per unit mass of dry air at the given conditions (DBT, WBT, DPT, RH, etc.)

Specific Enthalpy symbolized by h (also called heat content per unit mass) sum of the internal (heat) energy of the moist air in question, including the heat of the air and water vapor within

Specific Volume, also called Inverse Density, volume per unit mass of the air sample

By using these charts architects and designers can begin to address specific comfort goals to incorporate in building design. The small diurnal temperature differences in the hot-humid climate eliminate the efficiency of high-mass cooling and because of the high humidity levels evaporation cooling is not an appropriate cooling option. In passively cooled buildings located in these hot-humid climates the design must both increase the air flow and lower the interior temperatures to increase the human comfort levels. By using proper shading techniques, by choosing materials and insulation that reduce the solar heat gain, and by reducing MRT on the interior, the increased air flow effects might be adequate to keep residential buildings passively cooled in hot-humid climates.

THE ROOF

History of Roofs

Since the beginning of human existence, humans have always gravitated to some type of shelter to protect themselves from the harsh natural elements (sun, wind, rain, snow, insects, predators, and the extremes of hot and cold). When people think of shelter, a roof is one of the first building components that come to mind. The first human shelters were nothing more than naturally formed roofs such as caves, cliff overhangs, or dense foliage. Many early shelters were nothing more than a roof.

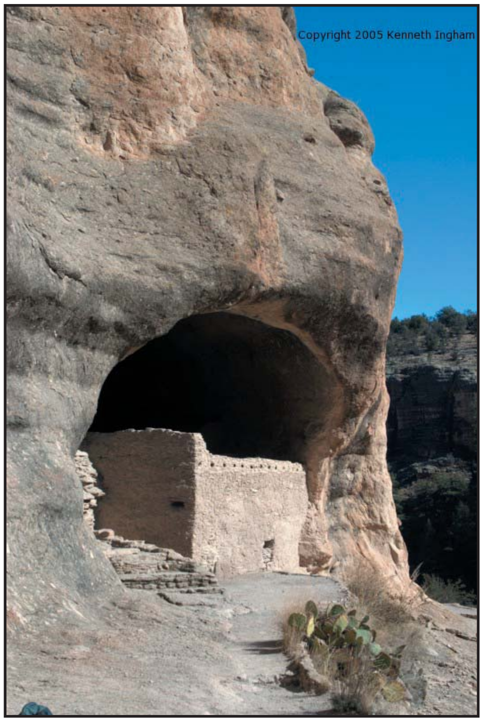


Figure 16: *Caves were used as early natural roofs to provide shelter. The cave would keep the mud brick walls dry enabling them to last longer than if they were exposed to the weather. (http://www.explorenm.com/hikes/GilaCliffDwellings/Overview/crw_6053.jpg)*

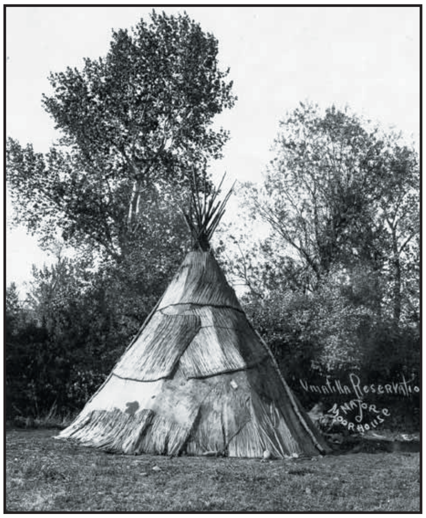


Figure 17: *This is a Native American Tipi. These structures were made of timber poles and layered skins to create a water shedding shelter. (http://www.nps.gov/archive/whmi/images/history/tipi.jpg)*

As men became nomadic they had to become more resourceful, and begin creating temporary shelters. This is where the invention of tents and other mobile structures began. These structures were formed with animal skins stretched over branches which created a roof system where both the walls and the roof were one unit. It can be speculated that the first manufactured roof systems were water shedders, such as overlapped tree boughs, or thatch, or animal skins stretched over wood frames. A water shedding system relies on the gravity-induced flow of water.12

As humans began building more permanent structures the pit dwellings emerged where a shallow excavation would be covered with a simple roof made of branches and skins. To increase the headroom of these shelters the selection of bowed shaped branches were used to give a slight pitch which would increase the rain water run off and improve the quality of the environment within the shelter. This moved into the simple 'cruck' frame where two curved pieces of timber standing on the ground at one end and meeting at the top. Across several of these 'crucks' were tied horizontal members onto which, again, were fixed skins or, as time progressed, simple thatch.13

Figure 18: *This is an image of a Tateana pit shelter where a pit is dug into the ground and crucks are used to form the roof shape which is covered with thach.*
(http://dougukan.jp/archive/tateana.jpg)

The next development in roofing design was the roof as a separate unit from the wall, where the roof was built on the top of a mud, timber, or masonry wall. This basic form of a roof was called a coupled roof with two lengths of timber bearing against each other at the peak with the base resting on the wall or wall plate. At the peak the timbers were held together with pegs or dowels and at the base, they were

Figure 19: *An example of a early structure where the roof and walls are separate components joined together. This particular structure was built by the Isneg tribe. They are known for their boat building skills and the layered bamboo roof mimics the shape of a boat.*
(http://www.filipinoheritage.com/images/arts/architecture/early-beginnings2.jpg)

attached to the wall plate similarly. The term ‘couple’ was used until the fifteenth century when the terms ‘spar’ or ‘rafter’ started to be used. The term rafter, of course, is still used to describe the piece of timber in a roof spanning from ridge to the wall plate.[1] This is the beginning of what we know today as the common pitched roof or steep-slope roof which is well suited for smaller structures and is widely used in residential buildings.

Roof designs have evolved considerably in the last few centuries and now have been categorized into two distinct groups the steep-slope roof and the low-slope roof. One major reason for roof design to be split into groups is, as buildings became larger the spans needed for the roof also increased. As these spans increased the structural loading on the walls also increased with the loading directed both downward toward the ground and outward. The increased costs for the construction and materials for this increased loading were found to be impractical. The low-slope roof was found to be a better and more cost effective alternative for larger spans. Both of these roof designs have their advantages and disadvantages for certain applications and, since this research is based upon residential building roofs, the focus will be on steep-slope designs.

When researching any early roof designs, one discovers that in the hot-humid climates many roofs are build out of timbers with steep pitches and covered with thatching (due to the local availability of materials). Upon closer inspection one realizes that most indigenous houses are void of a ceiling. The ceiling or what might be considered a ceiling, is actually the underside of the roofing assembly. This permits the warm air and the smoke from cooking to rise away from the occupants. (This smoke is often used to cure the underside of thatching to prevent insect and fungus growth.)

This is very different to what many westerners have built in the hot-humid climates. Many of these structures have been built with drop ceilings which are insulated as would be done in a temperate or colder climate. This is understandable if mechanical cooling such as air conditioning are to be used as this would lessen the amount of air needed to be conditioned within the space, but in a naturally ventilated and/or passively cooled structure the ceiling is holding air in the upper cavity and not permitting the warm air to lift away from the occupants.

During a warm day in a building without air conditioning with an eight foot high ceiling if one lifts their arm toward the ceiling they can feel the increased temperature near the ceiling level. This is why spaces with higher ceilings feel so much cooler. So, why not learn from earlier roof designs and eliminate the ceilings altogether in a hot-humid climate? There are many different steep-slope roof designs and even a more diverse selection of materials currently being used on steep-slope roofs which (along with their individual history) will be discussed further in the Roofing Types and Materials section.

Roofing Types

As there are many differences between low-slope roof design and steep-slope roof design there are also differences in the types and forms used for these roof designs. The materials used on low-slope roofs are considered water barriers, capable of waterproofing a structure even though water will gather and stand on the roof surface. The materials for steep-slope roofs are considered water shedders and rely on the forces of gravity created by the slope of the roof to move the water off and away from the roof and structure. Low-slope roofs are typically used in commercial construction and, since the focus of this project is in the residential applications, the steep-slope roofing will be the focus. There are many types of steep-slope roof configurations and roofing materials such as thatch, slates, tiles, asphalt shingles, wood shingles, and metal roofing. Each of these will be explained further in the Roofing Material section with their different characteristics followed by a matrix used for comparisons.

First, steep-slope roofs come in many shapes, sizes and configurations and with some of the most commonly used in residential construction being:

- ***Gable.*** The Gable roof is one of the most popular roof types. It is easy to build, sheds water well, provides for ventilation, and is applicable to a variety of house shapes and designs.

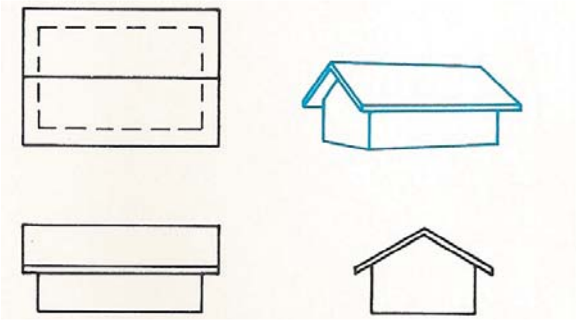


Figure 20: *Gable Roof (Kicklighter, Clois E. 1984, 292.)*

- ***Hip.*** The hip roof is slightly more difficult to build than a gable roof, but is still a popular choice. It does not provide for ventilation as well as some other designs and increases the chance for leakage due to the hips and valleys. (this design shades and protects the walls better than most all other roof designs)

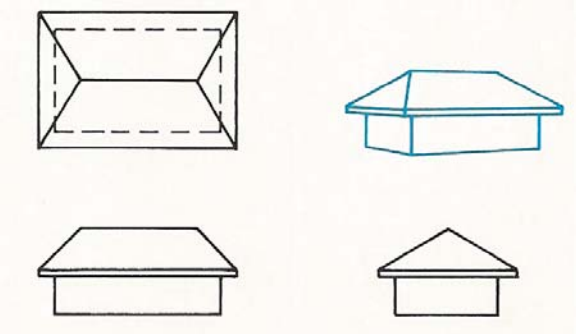


Figure 21: *Hipped Roof (Kicklighter, Clois E. 1984, 292.)*

- ***Butterfly.*** The butterfly roof has not been widely used in the past, but seems to be gaining in acceptance. It has the advantage of providing plenty of light and ventilation, but drainage is a problem. Flashing should extend far up each slope along the valley to prevent leaking. (This design is very useful in collecting rainwater for later uses but leaves the walls exposed to direct sunlight and rain.)

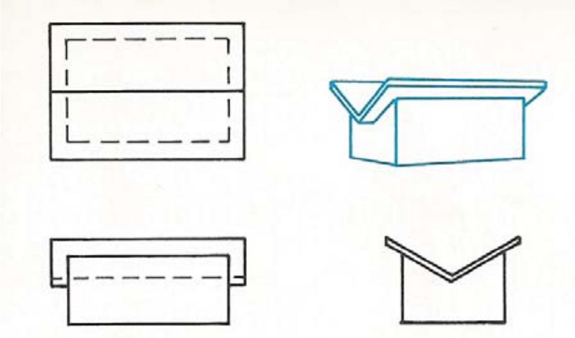


Figure 22: *Butterfly Roof (Kicklighter, Clois E. 1984, 292.)*

- ***A-Frame.*** The A-Frame provides not only a roof but the walls as well. Originally, it was used for cottages, but in recent years it has been applied to homes, churches, and other structures. (This design is closest to the early roof design where the wall and roof were one unit.)

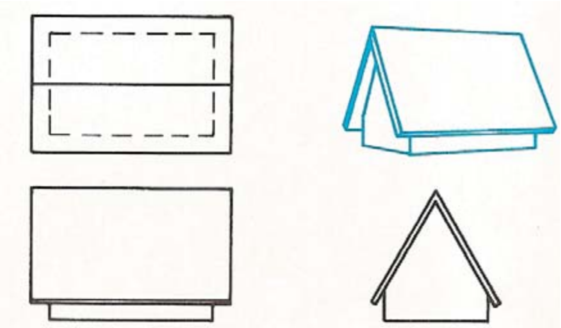


Figure 23: *A-Frame (Kicklighter, Clois E. 1984, 292.)*

- ***Folded Plate.*** The Folded Plate roof is a contemporary design which is finding limited application in residential buildings. However, it is quite popular for motels and small commercial buildings. Modular, prefabricated roof units are being produced which will probably increase the popularity of this design.

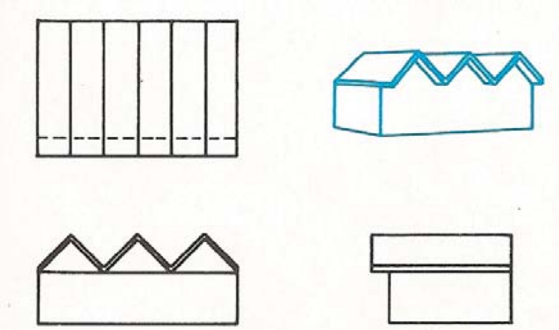


Figure 24: *Folded Plate (Kicklighter, Clois E. 1984; 292.)*

- ***Curved Panel.*** Curved Panel roofs are similar to the folded plate in style and application. Thus far they have had only limited use in home construction. They

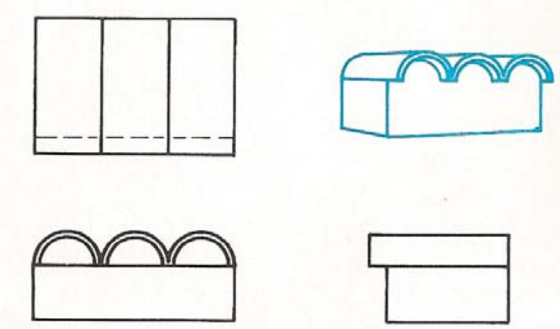


Figure 25: *Curved Panel (Kicklighter, Clois E. 1984, 292.)*

too are being produced in prefabricated modules.14

- ***Hawaiian Hipped.*** Some also refer to this type as a Dutch Hip or Dutch Gable. This design is a combination of the gable roof and a hipped roof they traditionally are without a dropped ceiling and the vents at the gabled ends ventilate the interior space. Many of these roofs have been built purely for aesthetic reasons without gable vents and with drop ceilings eliminating the functionality of this design.

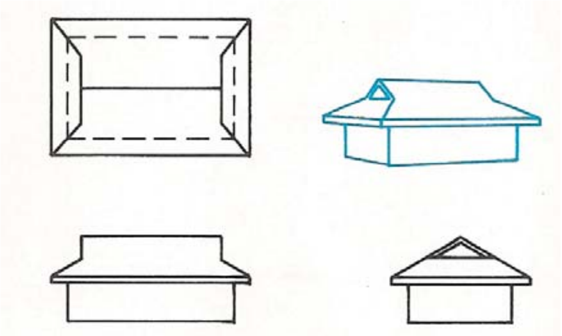


Figure 26: *Hawaiian Hip (Kicklighter, Clois E. 1984, 292.)*

There are many variations to these roof designs including several combinations of these types. The best roofing types for the hot-humid climates are the steeper sloped designs with large overhangs. These designs work best due to their ability to quickly shed the water from the heavy monsoonal rains and their ability to shade the exterior walls from the harsh sunlight which heats the interior spaces. The most commonly used roofing types tend to be the gable, hipped, and the A-frame in hot-humid climates. These also will be the types of roofs focused on for the proposed roof design.

Roofing Materials

Thatch

A thatch in this context can generally be defined as any vegetation used to roof a structure. A thatched roof is covering a roof with vegetation such as straw, water reed, sedge, rushes and heather. It is probably the oldest roofing material and has been used in both tropical and temperate climates. Roof thatching is one of the oldest crafts in the building industry still practiced today dating back 500 BC. Thatch is still employed by builders in developing countries, usually with low cost and local vegetation. By contrast in some developed countries it is now the choice of well-to-do people who want their home to have a rustic look.[15]

Thatched roofs have been built on every continent except Antarctica (due to the lack of local resources), and thatching materials range from plains grasses to waterproof leaves found in South American rainforests and on South Pacific islands. European thatch dates back to before the Middle Ages when the first small, permanent villages were established. The creation of villages brought with it the need for readily available, inexpensive, and durable building material. One of these materials was thatch. Early settlers to the New World used thatch as far back as 1565, but Native Americans had already been using thatch for generations. When settlers arrived in Jamestown in 1607, they found the Powhatan Indians living in houses with thatched roofs. The colonists used the same thatch on their own buildings.[16]

The type of vegetation used for thatching normally depends on what is available locally. In Europe, most thatched roofs are made of reed since it is more durable than one made of straw. Particular favorites are the Norfolk reed found along coastal areas in the Southeast of England and along the west coast of Scotland. In other parts of the world different varieties of reeds are used and are commonly referred as "water reed." The local vegetation dictates the choice in materials and this can be seen in the structures. Reeds are used in coastal areas, straw is used in inland areas, and palm fronds are mainly used in island areas.

__Figure 27:__ This is the edge or eave of a water reed thatch roof. The thickness of the material and the air pockets in the reeds make this a thermally insulated roof suitable for colder climates.

There are several types of construction techniques used for thatching roofs. Some are passed down from generation to generation; others are adapted from older indigenous styles. Even with these diverse techniques there are quite a few similarities across the board. First, for a thatched roof to perform properly the roof must have a minimum slope of 45° to drain the water and slow any absorption. Second, most thatching does not need any underlayment or roof sheathing (Thatch can be attached directly to the battens.) This lessens the amount of materials used (especially timber) in the construction process and even though the roof is waterproof it still lets the water vapor permeate out from the interior. Although, the layering of thatched roofs is similar, the thicknesses vary with some in colder climates being 12”-30” thick (used to insulate and shed snow) and those in tropical regions being only 1”-6” thick (used to block sun and shed water).

***Figure 28** This is an example of a thatch palm roof in a hot-humid tropical climate. The thatching is only 1-2 inches thick and is made of palm fronds. This structure is located in Sumatra, Indonesia.*

***Figure 30:** This shows the underside of a palm thatch roof. Since the palm thatching is light in weight, the structure can also be very light weight.*

***Figure 29:** This shows the preassembled thatched palm panels which will be installed on the roof. These panels are easily repaired and replaced.*

Thatch Advantages:

- Long lasting roofing option lasting upwards of 30-50 years without maintenance
- Uses natural materials and does not consume scarce and expensive energy resources
- Uses local materials which aid the structures in blending with their surrounding locations (although there are companies starting to ship manufactured thatched panels)
- The thatching process is a labor-intensive activity and, therefore, of practical economic value where unemployment among the lower income groups is common
- A thatch roof functions as both the roof and the ceiling reducing the amount of materials needed in construction
- A properly thatched roof is an excellent insulator that keeps the structure cool in the summer and warm in the winter, since thatch has a high insulation value (In technical terms the thermal transmittance, or U-value, for thatch 150 mm thick is 0.65 W/m2/°C for downward heat flow (i.e. from external sources), and 0.67 W/m2/°C for upward heat flow (i.e. from internal sources). The corresponding figures for 200 mm-thick thatch are 0.50 W/m2/°C and0.52 W/m2/°C. Comparative figures for a galvanized sheet-steel roof with a 6 mm-thick gypsum plasterboard ceiling, insulated with 38 mm-thick mineral wool are 0.68 W/m2/°C and 0.73 W/m2/°C.)

Thatch Disadvantages:

- More vulnerable to fire risk than those covered with other materials, and it is therefore imperative that precautions be taken to reduce this risk. (There are special treatments to help retard the risk of fire on thatched roofs.)
- Being an organic material, thatch is susceptible to decay and decomposition. In warm wet areas, it is prone to fungal growth.
- Can harbor vermin, but such infestation does not usually reach significant proportions. (Proper treatment can be used to keep the pests away.)
- Thatching is a labor intensive activity increasing the construction costs significantly.
- Not recommended for water catchment systems due to bacteria and fungus that may be present. Also, the chemicals used to retard the spread of fire and decay may be potentially dangerous.

Thatch Overall

The aesthetic beauty of a thatched roof is hard to beat especially in rural areas and on residential applications. The benefit of the low impact on the environment (being made from a sustainable resource and from locally available materials) cannot be under estimated. The drawbacks of the initial expense of construction and the vulnerability of fire and pests have kept thatched roofs from being as widely used today as they were historically. The sustainable principles and thermal properties of a thatched roof are still valid today and should be used as a benchmark for future roofing designs. The traditional thatch roof is the predecessor of the modern shingled roof design.

Shingles

The term “shingle” as used in the roofing industry means a thin piece of composition (asphalt), wood (shake), slate, tiles (clay and concrete) or metal which are applied (laid) in overlapping layers with staggered vertical joints to cover the roofs or walls of buildings.[17] The use of a shingle type system can be traced back to the time when skins and branched were layered with overlapping edges to drain the water and keep the interior dry. Shingles are considered water shedders and use the force of gravity to remove water from the roof surface. Shingle roofs are very popular in part because of the smaller sizes (easier to handle and install), ease of repair (Portions can be repaired without re-roofing.), and most are relatively inexpensive.

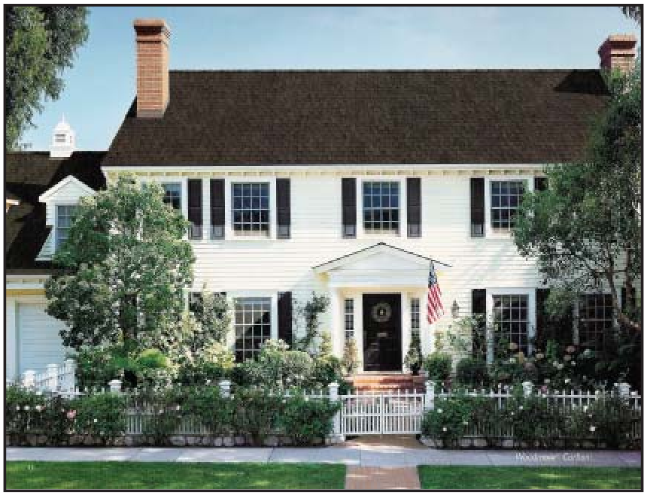


Figure 31: *This is a typical asphalt shingle roof on a traditional home in the United States. Asphalt shingles usually last 15-20 years before they need replacement.*

Asphalt Shingle

The most commonly used roofing material on North American residences is the asphalt shingle covering over 90% of all residential buildings.[18] The popularity is due to their relatively light weight, comparatively low cost, ease of installation, and low maintenance requirements. Asphalt has been used in the building industry for thousands of years. It was used in ancient times as mortar and between bricks as a waterproofing in canals.

The introduction of asphalt roofing in the United States began with roll-roofing which consisted of long strips of asphalt-coated felt with a top layer of finely crushed stone. This type of asphalt roofing material has been manufactured in the U.S. since 1893. In 1903, Henry M. Reynolds began marketing asphalt shingles cut from the rolled roofing material. By the 1920's asphalt shingles were so popular they were being sold through mail-order catalogs. By the 1950's the asphalt shingles looked similar to today's product including the tab-forming cutouts.

Asphalt roll-roofing and shingles were originally produced with organic felt as the base material holding the roll and shingles together. Beginning in the late 1950's, manufacturers developed inorganic base materials as alternatives to the traditional organic felt. The reasons for switching to the inorganic base materials is due to the fact they are more fire resistant than the organic base and they absorb less asphalt during the manufacturing process making them lighter in weight. Great improvements in these inorganic base materials occurred in the 1970's with the use of fiberglass matting which is still the most popular base material used in asphalt shingles today.[19]

Figure 32: *Asphalt shingles come in a wide variety of shapes and colors which are fairly inexpensive as compared to other roofing materials. They can be applied over all types of roof designs by any contractor or handyman.*

Asphalt shingles are considered composite shingles due to the compositions of materials used to manufacture them. A typical asphalt shingle is made from a base material, asphalt, stone or ceramic, and thermoplastic. The base material made from either organic or inorganic materials is formed into sheets. The sheet then is coated with a special asphalt material. The asphalt is a very thick hydrocarbon substance which is either obtained from naturally occurring deposits or more commonly from the byproducts of crude oil refining.

The asphalt must first be oxidized by a process called “blowing” which is done by bubbling air through the asphalt and adding certain catalysts and additives. These additives can include a mineral stabilizer such as fly-ash or finely ground limestone making the material more durable and fire resistant. After the base has been coated with the asphalt mixture, various colors of ceramic-coated mineral granules are used as a top coat to protect the asphalt from the sun’s ultraviolet rays, to increase their resistance to fire, and to add an aesthetic finish. Some shingles for use in humid locations may include copper-containing granules to inhibit the growth of algae. The bottoms of the shingles are normally coated with fine sand, talc, or other fine powders to keep the shingles from sticking together. The final material applied to a asphalt shingle are spots or strips of a thermoplastic adhesive which once installed will heat up from the sun and bond the overlapping shingles together for increased wind resistance.

Today the typical size for an asphalt shingle is 12-18” (30-40cm) wide and 36-40” (91-102cm) long. There are several different cutout patterns being used from two to five tabs, but the most commonly used is the three tab design. They are commonly sold bundled in a “square” meaning the amount able to cover 100 square feet. The majority of asphalt shingles must be installed on slopes of 3:12 or greater.

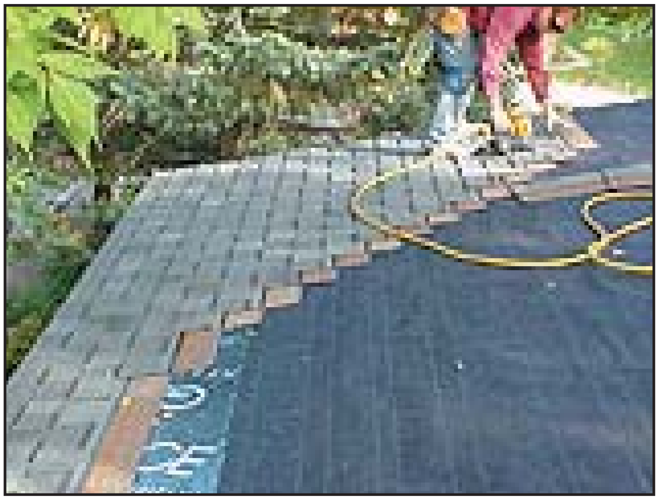


Figure 33: *Shingles being applied over asphalt felt underlayment. The shingles are started at the eave and are staggered up the roof to the ridge.*

Figure 34: *Pneumatic air guns are now being used instead of hammers to install the shingles which cuts the installation time in half.*

Due to the thinness of asphalt shingles they must be applied (laid) over roof decking and/or sheathing which has be covered with a minimum of 30lbs felt or equivalent underlayment. The thickness of the decking and/or sheathing depends on the spans (spacing) between the rafters. This must be calculated to eliminate any sagging of the roof surface that can become highly visible through the shingles. The shingles are commonly attached to the roof deck or sheathing using galvanized roofing nails or staples. The shingles are overlapped in rows starting from the bottom eave of the roof and working toward the ridge.

Asphalt Shingle Advantages:

- Inexpensive compared to other roofing products (especially in the United States)
- Available in a wide selection of sizes, styles, and colors
- Available at most lumberyards and home improvement stores
- Easy to install and can be done by Do-It-Yourselfers
- Relatively low maintenance
- Durable and resistant to fire, weather, and moisture
- Relatively light in weight compared to other shingle systems

Asphalt Shingle Disadvantages:

- Relatively short life span as compared to other shingle types
- Begin to deteriorate early in their life-cycle by shedding the protective granules
- Notorious for being adversely affected by high winds
- If not properly maintained are susceptible to mildew, moss, and fungal growth
- Environmentally unfriendly due to limited recycling facilities. (The National Association of Homebuilders Research Center estimates that 20 billion pounds of asphalt roofing is taken to landfills every year.)
- Very limited thermal protection
- Can be damaged by the heat and sun by curling on the edges blistering, and by scaring
- Not a viable material to be used in water catchment systems due to the leaching of the petroleum compounds into the water

Asphalt Shingle Overall

Asphalt shingles have been an extremely popular choice for residential roofs in the United States for over a century. The low cost, ease of installation, and availability of this roofing material has convinced more people to cover their residential roofs with asphalt (petroleum) shingles than any other material in the U.S. While examining other countries one notices the complete lack of asphalt roofing in most residential applications. When the question of, “Why don’t other countries use asphalt roofing?” was posed to Glenn Murcutt, he responded, “Using asphalt roofing which is made of petroleum is too expensive to be used as roofing material in most countries. There are better materials to use for roofing and better uses for petroleum than purely placing it on the roof.” The thermal characteristics of asphalt shingles increase the interior temperature of buildings in hot climates and reversely release heat from a building’s interior in colder climates. The negatives associated with petroleum based products, the thermal characteristics, and the increasing costs of asphalt shingles discourage further investigation for future design applications in hot-humid regions. The more environmentally friendly option for the asphalt shingle roof is the wood shingle and wood shake design.

Wood Shingles and Shake

Wood has been used as a roofing material in some fashion for thousands of years. Some of the oldest wooden roofs are an evolution from using branches or layered bark to shed water and create shelter. With the invention of tools that could cut and split wood, the wood shingle and wood shake roof was born. A wood shingle is cut and the wood shake is split. Many people today call any wood covered-roof a "shake roof," and, for the purpose of this research, the term "wood shake" will be used to describe both wood shingle and wood shake applications. The aesthetic quality of a wood roof is one reason why so many houses are covered with them. Because of the natural qualities, wood roofed houses tend to ground themselves into their environment better than other roofing materials.

Wood roofs were the most popular water-shedding roof system before the invention of asphalt roofing. In some areas they are still among the most commonly used roofing materials. Many types of woods have been used as wood roofing, the best being white cypress, red cedar, and redwood. Other woods such as white and yellow pine and spruce have also been used for wood roofing, although less successfully. Most wood roofs today are constructed with cedar, a relatively strong wood

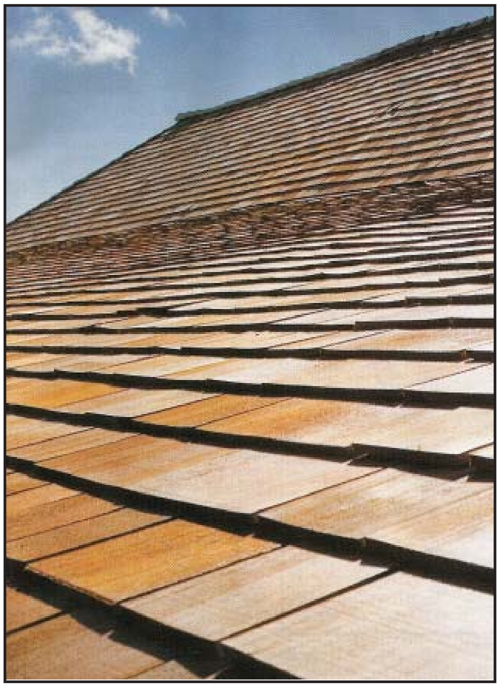


Figure 35: *This is an example of a typical wood shake roof. As the roof ages the wood will change color from a golden brown to light grey color.*

given its light weight and low rate of expansion and contraction. Cedar contains natural oils and rosins that resist rot and certain insects making it superior to many other types of softwood. Wood shingles are typically smoother due to the cutting process and wood shakes are usually rougher in texture and thicker due to the splitting process.

Figure 37: *The traditional tools used to split wood shakes for roofing. Now machines are used to cut and split the wood shakes.*

Wood shingles and shakes are classified into four grades:

- **#1 Blue Label** are 100% heartwood, these are stronger and more stable than the sapwood of the perimeter of the tree. They are 100% clear and have 100% edge grain. The grain should run straight down the length of the shingle or shake without curves. These are found most commonly on residential roofs.
- **#2 Red Label** has some sapwood and some flat grains which are susceptible to drying causing splitting and curling. These are occasionally used in residential work or more commonly in secondary buildings such as sheds and garages.
- **#3 Black Label** has less than 50% clear and contain flat grain and sapwood. These are commonly found in secondary building or mixed with #2 Reds on some home applications.
- **#4 Undercoursing** has numerous knots and surface defects. These are used for starter courses and shims and are not suitable for normal roofing material.

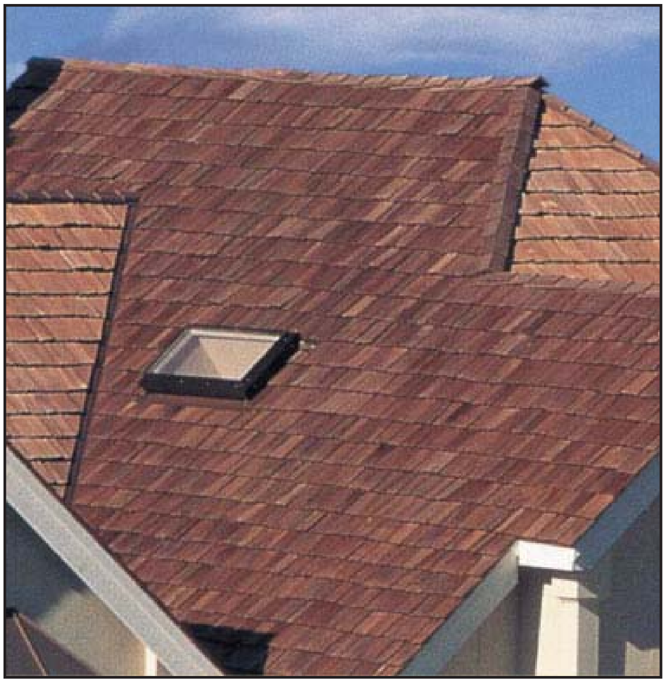


Figure 36: *A wood shake roof is one of the most attractive roof coverings, but their high cost keeps many homeowners from installing them.*

The typical size of wood shingles and shakes are 16-24" long and 8-13" wide although some codes specify different sizing. The typical thicknesses range from 0.4-0.5" measured at the bottom edge. Wood shingles and shakes are normally applied to slopes 3:12 or greater. They are generally applied over roof decking or sheathing commonly covered with a minimal underlayment of 30lbs felt or equivalent. The thickness of the roof decking/sheathing depends on the span (spacing) between the roof rafters. The wood shingles or shakes are fastened to the roof decking or sheathing with galvanized, stainless steel, aluminum, or copper nails or staples. To avoid splitting the wood the fasteners should be at least ¾" from the sides and 2" above the butt line of the overlaying shingle. The shingles and shakes should be layered over each other with a 5-7" exposure and a 6-9" head lap starting at the eave and working toward the ridge.

Wood Shake Advantages:

- Offer a beautiful aesthetic quality and weather to a soft grey anchoring them in their environment
- Made from natural renewable resources
- Have very good thermal insulating qualities
- Allow water vapor escape preserving the roof structure
- Easily repaired and replaced
- Long lasting, if maintained, will last 30-50+ years
- Resistant to weather, insects, and the sun’s ultraviolet rays
- Trap air and provide a degree of conductive insulation

Wood Shake Disadvantages:

- More expensive than many other roofing options
- Require periodic maintenance including cleaning and wood treatments to limit effects of moisture, algae, and fungus growth
- Very flammable if not treated properly
- Usually require professional installation
- Not recommended for water catchment systems due to the leaching of chemicals, oils, and bacteria into the water

Wood Shake Overall

Wood shingles and wood shakes are some of the most attractive roof materials due to their inherent natural beauty. By using a wood roof a house tends to look more like a home. The qualities of a wood roof range from being a naturally made material to its thermal qualities in keeping the occupants of the building comfortable. The visual qualities of a wood roof reflect the same qualities as those of a thatched roof. Wood roofs were great during the era of plenty of forests and plentiful resources but, as these resources become scarcer, the need for alternatives emerges. The benefit of being a natural resource is often diminished when chemicals are applied to the wood as a fire retardant or preservative. The wood roofs then will not break down naturally and will leave traces of the chemicals behind in the landfills.

New types of simulated wood shingles and wood shakes are currently being marketed. Some are made with the same materials as asphalt shingles, and others are made out of rubber. The uses for wood shingles and wood shakes in hot-humid areas are limited due to the moisture content which will quickly cause decay and lead to the formation of mold, moss, and fungus on exposed wood products. Another environmentally friendly option that resists the formation of mold, moss, and fungus is the slate roof.

Slate

Slate is a naturally occurring material created when clays and fine silts were deposited on ancient ocean floors. Over thousands or even millions of years the geographical pressures transform these clays and silts into hardened stone. This hardened slate comes in a variety of colors (gray, blue-gray, black, green, purple, and red) depending on the mineral content of the stone. This quarried slate has two distinct characteristics which allow it to be formed into roof shingles by the quarrier: the slate grain and the slate cleavage.[20] This stone then can be hand-split along the grain and cleavage forming roof shingles. These roof shingles can be cut to a variety of different shapes and sizes depending on the look or application where they are to be used. After the desired sizes have been cut, holes are punched in the top of the shingles. The shingle will be attached to the roof structure through the holes.

Figure 40: *The slate shingles on this roof are huge. They must be at least 2'x2' if not larger. This is an old slate roof dating back well over one hundred years. (http://www.photoseek.com/05ALP_3303-Arolla-Valley-slate-roof.jpg)*

Slate roofing is classified into three groups:

- **Standard slate.** Commercial grade slate, commonly used for slate roof systems, approximately 3/16- to ¼- in thick. Standard slate has a smooth finish and is uniform in length and width, with square ends and sides.
- **Textural slate.** Has a rough or textured surface due to the composition of the slate which, upon splitting at the manufacturing facility, separates not in a clean and smooth surface layer, but into a rough surface.
- **Graduated slate.** Can have either a smooth or textured surface, made from textural slates. The slates graduate in size, thickness, or both, with larger and thicker slates installed at the bottom eave, decreasing in size and thickness as courses are laid to the ridge top.[21]

Slate roofing has been used in Europe for centuries and is predominantly used in the Northeastern United States close to the Appalachian mountain chain were much of the slate is quarried. Slate roofing is also used in China, South America, and in different locations throughout the U.S. Currently, due to the increasing cost of slate for roof application there seems to be more slate roof repair and renovation than the specification for new slate roofs. Slate roofs are also heavy so the roof structure must be able to support this increased load. Some applications specify 2"x12" rafters centered at 16" covered with ¾" tongue and groove decking. Even with this added expense, the longevity of a slate roof might offset the costs of initial construction; some slate roofs have lasted over 200 years without any repairs or leaks.

Even though slate is a long lasting natural stone it still will eventually deteriorate, flake, and delaminate. This usually happens due to the formation of gypsum within the cleavages of the slate caused by the wet-dry and hot-cold cycles.[2] Since gypsum is an absorbent material, it expands when moisture is introduced. This facilitates the flaking and delaminating. Slate can also be damaged by extreme weather (heavy winds and hail) and by walking on the roof deck which causes the shingles to prematurely crack and eventually leak. Many slate roofing companies require inspections yearly and after storms to maintain their warranty.

Slate roofs are normally installed by slate roof masons or members of the Slate Roofers Contractors Association. Slate roofs should be applied only on slopes of 4:12 or greater and need a heavier-than-normal roof framing and decking. Slate roofs require an underlayment of at least 30-45lbs. (or similar type of water-barrier) depending on the type of slate chosen. The slates are then attached to the roof with copper or stainless steel nails or fasteners. (Only nonferrous fasteners and flashings should be used with slate roofs.) The proper slate lap depends on the slope and usually ranges from 2”-4” with slate exposure ranging from 3”-11”. Even though slate roofs are long lasting repairs are sometimes required. The rule of thumb advises that, if only 20-25% needs repairing, it will be less expensive and worth the repair. Commonly, shake roofs are replaced when they only need repair.

Slate Advantages:

- Considered one of the best aesthetic roofing materials available
- Naturally occurring material and can be returned to the earth after its useful life with out any negative effects
- Natural stone and is more durable than most man-made materials
- Fireproof and completely non-combustible
- Waterproof because of its high density and will not absorb water (except for gypsum formations)
- Permanent and therefore enhances building value
- Lowers net energy costs (in colder climates) because of its insulating capability and reflectiveness
- Requires little to no maintenance
- Resists climatic and seasonal change
- Acceptable for water catchment systems

Slate Disadvantages:

- One of the most expensive roofing materials
- Requires specialized installation
- Very heavy material increasing structural loads and increasing shipping and handling charges
- Requires frequent maintenance to preserve the integrity of the system
- Considered a non-walkable surface do to cracking and possible damage (this creates problems for inspections and maintenance)
- Underlayment often fails before the slate causing leaking.
- Stores the heat from the sun and releases this heat with a lag time (not beneficial in a hot-humid climate)

Slate Overall

Slate is an excellent roofing material especially in colder climates even with its increased initial costs. Slate is better suited for structures located near the natural material to lessen the amount of embodied energy costs associated with transporting the material. The longevity of the material and the fact that it is a sustainable material are also very beneficial. The fact that the structural system needs to be built stronger with more materials to support the increased load may diminish the sustainable qualities of the material. The locations of these natural resources and its thermal characteristics make slate an unattractive choice for the hot-humid climates. Other roofing materials with similar features as slate but with lower cost are the tile types of roofing.

Tiles

Tiles are another early form of roof materials that have been in use world wide for thousands of years. There is archeological evidence dating roof tile use as far back as 3rd millennium BC in the Early Helladic House of the tiles in Lerna, Greece.[22] Tiles can be made either on site or at a separate manufacturing plant and shipped to the site. Tile roofs are very durable and often will be re-roofed with the same tiles originally installed because normally the underlayment or flashing fails before the roof tiles. It is common for tile roofs to last more than 100 years. The most common materials for roof tiles are clay and concrete although mud is also used in limited applications.

Figure 41: *This shows a typical concrete tile roof on a residential structure. (http://www.bayferrox.com/photo_tour/images/concrete_roofing_tile1.jpg)*

Figure 42: *These are Mission or Spanish tiles made of clay and have the same profile alternating facing up and down channeling the water off the roof. (http://www.digitalapoptosis.com/archives/HR/tile_roof.jpg)*

Tiles come in a variety of shapes or profiles including the Pantile which are S shaped in profile, the Mission or Spanish style which are C shaped in profile, the Imbrex and Tegula or Roman style which are a combination of flat and curved shapes in profile, and the Flat or Shingle style which as the name implies are flat in profile. The availability of raw materials for tiles also reflects in the costs for each type of tile. Since clay is a harder to acquire material than concrete, the cost for clay tile is higher.

Tile roofs work best on steeper sloped roofs (minimum 4:12 and preferably 6:12) and historically, the steeper the slope the longer the life span for a tile roof. Tiles are installed similarly to a slate roof which is sometimes referred to as a "slate tile roof" with holes being bored in the upper part of the tile where a fastener is used to attach the tile to the roof system. The head lap (distance the tiles are overlapped) of common roof tiles are a minimum of 3" and the exposure (distance of tile exposed) can be increased as the roof slope increases. Since tiles are hard and rigid they also chip and break easily. Special care must be taken when walking on tile roofs or locating tile roofs under trees or other obstacles that could drop branches or other items causing breakage and eventual failure. Tile roofs also are considered heavy roofs and the roof and wall structures will need to be designed and built to support this increased loading. Tile roofs are installed over a roof deck that has roof sheathing and underlayment of a minimum two layers of 30-45lbs felt or similar material. Although, in some rare cases, tile roofs have been installed without the use of roof sheathing or underlayment and have still achieved water tightness but, this is usually with very steep roofs and only moderate rainfall.

Clay Tiles

The quality of any clay tile depends on the initial ingredients. Although fireclay is the main ingredient, the geographical source of this clay is important to the clay's overall quality. Historically, clay tiles were made by rolling clay out in sheets that were cut to the desired size and formed by pressing over a person's thigh before baking in a stone oven. Today, clay is extracted from the ground and mixed with shale and water. This semi-liquid material is extruded through a die and the tiles are cut to desired lengths. Glazing is applied for glazed tiles or they are left blank for a natural look. The tiles are then stacked in a kiln with temperatures exceeding 1000°F. to be baked for a length of time depending of the type of tile or glazing applied. After the tiles have cooled they are ready for transport and installation.

Figure 43: *The Mediterranean style homes usually are covered with the terra-cotta tiles.*

Clay tiles react to temperature extremes and one of the biggest problems is the freeze-thaw cycles which can cause color change and severe cracking. Clay tiles have been classified into different grades with Grade 1 tiles resistant to freeze-thaw cycles and Grade 3 which cannot resist freeze-thaw cycles. The grades also take into account the amount of water absorption for each with Grade 1 with an average of 6% maximum water-absorption, Grade 2 with an average of 11%

maximum water-absorption, and Grade 3 with an average of 13% maximum water-absorption.23 Clay tiles are also categorized into three types of styles; Type 1 High profile, Type 2 Low profile, and Type 3 All others. Clay tiles are fragile and due to their long service life clay tiles are best installed by a professional clay tile installer who is familiar with the type of tile, flashing system and underlayment specified for the project.

Figure 44: *These are glazed "S" clay tiles during installation. The wood mounting strips are visible and the underlayment to prevent any leakage. The brackets on the top of the tiles are snow clips to prevent snow from sliding off the roof . (http://www.rooftilemanagement.com/Images-Products/Tile/TerraCotta/Large/Glazed_Clay_Tile_3.jpg)*

Figure 45: *This is an example of colored glazed clay tiles. (http://www1.istockphoto.com/file_thumbview_approve/369554/2/istockphoto_369554_blue_tile.jpg)*

Clay Tile Advantages:

- Beautiful aesthetic quality and a full range of colors and shapes
- High resistance to water absorption
- Certain tiles have resistance to the freeze-thaw cycles
- Glazed clay tiles have excellent colorfastness. The clay tiles at the Forbidden City in China are a good example.
- Hold both the accuracy of size and of weight
- Class A fire rating.
- Long life-span saving precious landfill space
- Made using natural materials
- Can be used in water catchment systems provided the tiles were not produced with lead glazing or other potentially harmful chemicals that could leach it to the water

Clay Tile Disadvantages:

- One of the most expensive of all roofing options
- Heavy and require a stronger system which explains why clay tile roofs are not normally used as a re-roofing option
- Need special care in installation and repairs
- Fragile and should not be walked on (causing problems for inspecting roof)
- Can be damaged by falling limbs or flying debris leading to costly repairs

Concrete Tiles

In the middle of the 19th century, in Bavaria, a mixture of cement, sand and water was first used to form roof tiles out of concrete. Many structures covered with these first concrete roofing tiles still remain proving their durability. In the early 1900s, coloring pigments were added to concrete roofing tiles in Europe to simulate the appearance of clay. While these early concrete tiles were handmade or made with semi-automated machines, innovation over the past century has automated production, making concrete tile more economical than other roofing products on a life cycle basis.[24]

Figure 46: *This image shows a typical concrete tile roof. (http://www.hgroofing.com/images/concrete1.jpg)*

Concrete tiles, are normally shaped into Flat tile, Single S tile, and Double roll tile. To add color to the concrete tiles glazing is sometimes applied, but normally a slurry coat will be applied with different colors of pigmentation. Concrete tile are also kiln dried at lower temperatures than that of clay tile. In the United Stated concrete tiles are common in Florida and the southwestern areas such as New Mexico and California. Concrete tiles, like clay tiles, are also affected by the freeze-thaw cycles and can be adversely affected by high winds if not properly installed with hurricane clips. Moisture under the concrete tiles can also degrade the wood structure and battens if the wood is not properly treated for decay.

Concrete tiles are applied to a roof similarly to the application of clay tiles. Concrete tiles are normally used on more utilitarian and common structures such as residences and commercial buildings. Concrete roof tiles will normally last the lifetime of a house or similar structure and commonly come with a limited life-time warranty. Even though concrete tiles are heavier than some other roofing options, they are usually lighter than clay tiles. Some manufactures are adding different additives to the concrete to lighten the tiles and increase specific thermal characteristics.

Figure 47: *This is a concrete tile roof being installed. (http://www.concretethinker.com/Content/ImageLib/pcano5079.jpg)*

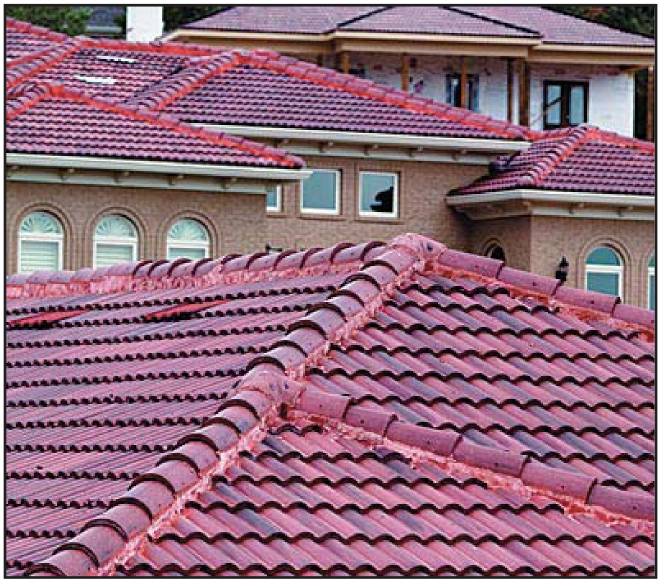


Figure 48 *This image shows how a concrete roof can mimic the look of a clay tile roof. The concrete roofs are also less expensive than the clay tile roofs. (http://www.homeimprovementmag.com/Articles/Images/2006/Mar_roof_concrete.jpg)*

Concrete Tile Advantages:

- A long life-span saving precious landfill space
- Class A fire rating
- Resistant to hail and high winds (if installed properly) and typically achieve a minimum of a Class 3 hail resistance rating
- Exceed current seismic load requirements for building materials
- Less expensive than other roofing options based on life-cycle basis
- Provide similar aesthetic qualities for clay tiles, wood shake, and slate
- Offer a wide range of thermal characteristics for different climates
- Can be used in water catchment systems except if there are potentially harmful additives or petroleum that could leach out or if tiles were made with asbestos

Concrete Tile Disadvantages:

- Initial high expense limiting their use
- Heavier roofing option requiring a stronger structural system (newer lightweight options gaining popularity)
- Not recommended in freeze-thaw areas
- Generally are not used in re-roofing due to weight and structural inadequacies
- Can be damaged if walked on or impacted with flying debris
- Do not hold their colorfastness as well as clay tiles.

Tile Overall

Both clay and concrete tile roofs are considered the top-of-the-line of water-shedding roof types. The aesthetic beauty is hard to beat and that fact that they are both made from natural resources make them very attractive in the sustainable arena. Although the amount of extra materials used in the roof structure to support the increased load from the weight of these materials and the fact that, once broken a tile is not considered recyclable may diminish the "greenness" of the tile.

The thermal characteristics of tile roofs seem suited better for a hot-arid climate with a larger day to night temperature difference due to the thermal massing associated with stone type materials. The moisture in the hot-humid climates also seems to be an issue for tile roofs as the wood below the tiles can decay and the unglazed tiles will tend to absorb the moisture as well. There are principles that should be noticed such as degree roof slopes, overlapping distances, lipped edges (to prevent water movement), and attachment details which make this roof type a highly successful water shedder.

The last type of roofing material is metal and it can be a water shedder or a water barrier and can be used as shingles, strips or panels.

Metal Roofs

Using different types of metal for waterproofing roofs date back to the Roman Empire, when both lead and copper were used for roofing and plumbing. The reason these metals were used was because lead and copper both form self-protecting oxide layers which enable them to last for more than 50+ years. Lead roofing is most prevalent in Europe, and is still used there today as is copper roofing. In the past the use of metal roofs in America was mostly reserved for industrial, agricultural and commercial roofing applications. This trend is now changing with increased usage of metal roofs residential projects.

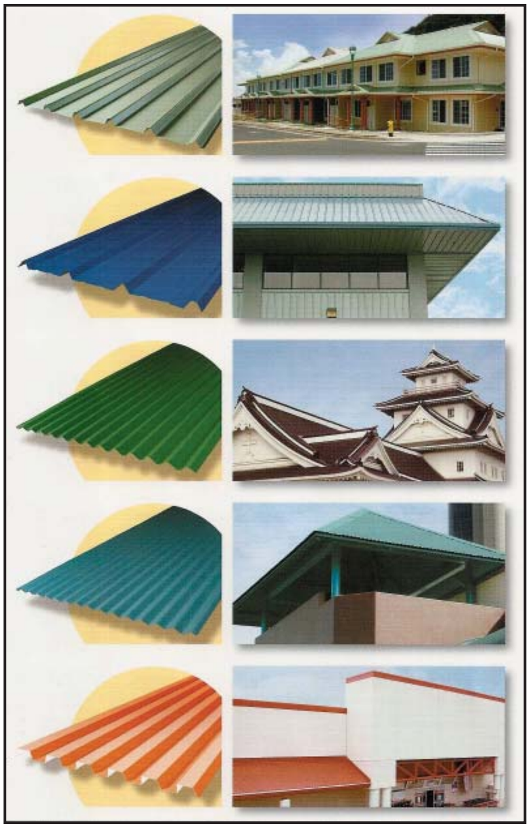


Figure 49: *The different profiles and different colors offered by a certain manufacturer. These are all structural metal roof panels which do not need roof decking or underlayments.*

Over time the metal roofing industry has evolved and now metal roofs are made out of a variety of different metals including aluminum, copper, steel, tin, and zinc. The metals are commonly coated to prevent the corrosion or in some cases to preserve the physical appearance of the material. These metals are formed into either structural roofs in which no roof decking or sheathing is used or architectural roofs where roof decking or sheathing is used. Structural metal roofs come in a variety of shapes and sizes including structural standing seam, lock-seam, R-panel, and corrugated panels. Architectural metal roofs come in a variety of shapes and sizes including shingles, flat seam, standing seam, batten seam, and lock seam.

The metal structural roof panels must be watertight since no waterproofing underlayment is used and these panels are commonly attached to purlins spanning 5 feet. The structural panels are normally made with heavier gauge steel. The more bends and breaks the structural panel has, the longer they can span unsupported. Structural metal roof panels are overlapped and attached to the roof structure (purlins) using mechanical fasteners fitted with gaskets or seals. The largest difference between metal roofing and metal roof decking is that metal roof decking has the ability to provide lateral load resistance to a building and metal roofing does not.

Architectural metal roofing is installed in smaller sheets than that of structural roof panels using ingenious systems of joining and fastening to maintain water tightness at the seams.25 The visual patterns caused by the seams are often utilized by architects and designers to accent certain roof configurations. Architectural metal roofing is applied over roof decking or sheathing covered with a waterproof underlayment and rosin paper to prevent bonding between

Figure 50: *This is a typical example of a standing seam roof. The strips of metal are crimped together with a machine on-site to seal them. (http://www.olympicsteelwa.com/images/105_0521_frame)*

Figure 51: *Metal roof are commonly used with water catchment systems, This is due to smooth surface that resists mold, mildew, and fungal growth. (http://www.rainwaterconnection.com/products/roofs/metal%20roof.jpg)*

the felt and the metal roofing. The seams of architectural metal roofs traditionally are sealed with tar, caulk, or adhesive sealing tape. The seams of architectural metal roofing do not always remain watertight due to the increased movement caused by expansion and contraction of the metal. The effects of expansion and contraction are also amplified by increasing the size of the metal pieces used. Thus metal shingles are affected less than the longer runs of metal used in standing seam roofs.

Figure 53: *This is a metal roof even though it looks like a shingle or shake style roof. (http://www.olympicsteelwa.com/images/105_0521_frame)*

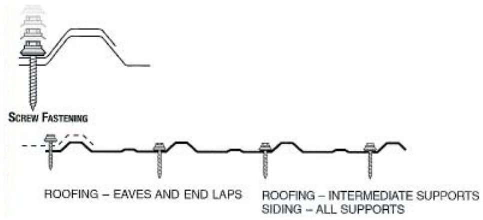


Figure 52: *One problem with many structural metal roof systems is that the fastening hardware is punched through the roof surface. This is one of the first places for leaks. The constant expanding and contracting of the metal loosens the fasteners and water is able to wick into the interior space.*

As metal roof designs advance there seems to be a blending between the structural roof panels and the architectural roof panels. Today some structural roof panels appear more architectural with well defined lines, concealed fasteners, and a greater variety of colors. Similarly, some architectural roof panels require no roof decking or sheathing which also eliminates the use of a waterproofing underlayment. The terminologies of metal roofs are also beginning to change from structural and architectural to structural and nonstructural.

Metal Advantages:

- Longer life-span than asphalt roofing products
- Extremely fire resistant with a Class A rating
- Light-weight roofing system minimizing structural components
- Resistant to rot and insect damage
- Can reflect the sun's radiant heat reducing cooling costs
- Do not have a large thermal mass causing them to cool quicker than other roofing materials
- Very wind resistant and can withstand winds of up to 140mph
- Resistant to mold, mildew, and fungal growth
- Aesthetically pleasing and can be made to resemble many other roofing systems
- Easier and quicker to install than most other roofing options
- Highly recommended for water catchment systems (depending on coating)
- Can be recycled after their useful life is over

Metal Disadvantages:

- Increased initial cost than that of asphalt shingles (although this cost is lessened if compared with life-cycle costs)
- Can be dented and marred
- Difficult to patch or repair
- Noisier compared to other roofing options
- Problems with interior condensation in some areas

Metal Roofs Overall

Although, the initial costs are higher than other roofing options the longevity of this material offsets the costs and can actually make them cheaper in the long run. The aesthetics of metal roofs range from shingles that resemble tiles to standing seam that creates a visual accent to the roof configuration. Metal roofs are environmentally friendly due to their recyclability and, if using structural roof panels, to the minimizing of structural material needed. The inherent properties of metal roofs do not require additional chemicals to be added to prevent decay, fire, or insect damage. The thermal characteristics (high thermal reflectivity and low thermal mass) of metal roofs (if used properly) make for a very attractive roofing material in hot-humid climates.

The following gives a comparision of the above mentioned roofing types.

Roof Material Comparisions

The materials chosen for the roof covering may help in the reduction of interior temperatures by choosing materials with high emissivity, low thermal mass, and low thermal absorption. The impacts of these materials on the environment must also be addressed to provide a holistic approach to responsible roofing design. These environmental issues include resource efficiency, toxicity, rapid renewability, and the embodied energy of the chosen material.

Selecting the correct roof covering materials can have a major impact on interior comfort levels since; the roof has the greatest exposure to the sun. Great heat is generated during the day. The problem is one of reducing the penetration of heat to the interior and dispensing any accumulation of day heat to prevent further radiation on the sleeping quarters at night.[26] This directly relates to the thickness of roof surface since the thicker a roof is, the more heat the roof can store. Then there is also the interval or "lag" between the upper and lower temperatures which corresponds to the thicknesses of the material and the material's properties. The thicker and denser a material, the longer the interval is for heat traveling from one side to the other. A thicker denser roof material is beneficial for a climate with large diurnal temperature differences but, it has a negative effect in the hot-humid climates.

For the proposed design, metal roofing material has been selected due to its thermal and sustainable qualities. This type of material leaves less impact on the planet than the most commonly used asphalt shingles. The low cost of metal roofing also makes it a viable option for the lower income areas in the hot-humid climates. The issue of corrosion will need to be addressed to increase the life expectancy of this material in this harsh environment.

Since each roof covering has its own unique attributes the matrix found in Table 1 can be used for comparison of the different types with additional information not covered above. Table 1 covers common roof materials for steep roofs (slope > 3:12 or 25%).27

Common Roofing Material Charateristics

ROOFING TYPES	Structural-Architectural Metal	Steel Shingle	Asphalt Shingle	Wood Shingle	Wood Shake	Slate	Clay Tile	Concrete Tile
Weight	50-200 lbs. per sq.	50-100 lbs. per sq.	205-380 lbs. per sq.	600-800 lbs. per sq.	250-300 per sq.	800-3600 lbs. per sq.	800-1000 lbs. per sq.	900-1200 lbs. per sq.
Sheathing	Solid and Spaced	Solid	Solid	Solid/ Spaced	Solid/ Spaced	Solid/ Spaced	Solid/ Spaced	Solid
Underlayment	optional	15 lbs. asphalt felt	15 lbs. asphalt felt	35-40 lbs. asphalt felt	35-40 lbs. asphalt felt	30 lbs. asphalt felt	35-40 lbs. asphalt felt	30-45 lbs. asphalt felt
Recyclable	Yes	Yes	Limited	Yes	Yes	Limited	Yes	Yes
Life Span	20-50+ years	50+ years	15-30 years	25+ years	25+ years	50+ years	50+ years	50+ years
Cost	$150-600 per sq.	$100-600 per sq.	$50-100 per sq.	$100-600 per sq.	$100-600 per sq.	$500-1000 per sq.	$200-500 per sq.	$200-500 per sq.
Fire Rating	Class A	Class A	Class A, B, C depending on type	Class B & C	Class B & C	Class A	Class A	Class A
Absorptance	33-41%	33-41%	79-95%	N/A	N/A	N/A	67%	75%
Albedo	33-41%	33-41%	3.4-26.1%	22%	22%	N/A	33%	25%
Emissivity	0.25-0.87	0.25-0.87	0.91	0.9	0.9	N/A	0.9	0.91

Table 1: *Roof Material Comparisions*

PASSIVE VENTILATION

Passive ventilation systems rely on naturally occurring properties (physics) to cool the occupants and to move air. For passively ventilated systems to increase human comfort, the outside air must be cooler than the inside air. Passive ventilation can be seperated into two types: passive cooling ventilation and solar-induced ventilation. There are two major types of passive cooling ventilation systems: the cross ventilation and the stack ventilation. Solar-induced ventilation uses the solar radiation to increase air velocities. There are two major types of solar-induced ventilation systems: the solar roof and solar chimneys. There are also many common roof ventilators that use both passive and mechanical means to move air through the attic spaces.

Roof Ventilators

Roof ventilators come in a wide variety of shapes and sizes. Some roof ventilators are just the form and shape of the roof itself which naturally (passively) ventilate the interior. Others are either active or passive systems or a combination of the two. The active systems include attic fans powered by either electricity or solar power (small photovoltaics located on the fan housing) which push or pull the air out of the interior space to the exterior.

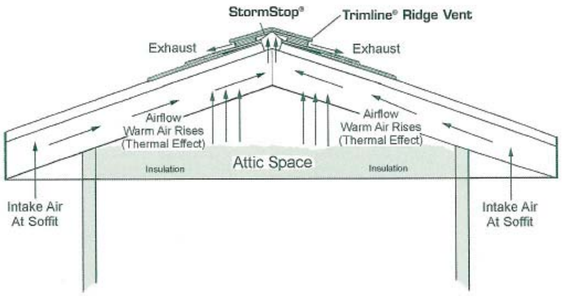


Figure 54: *This is a detail of a typical ridge ventilator. The air is drawn in through the soffit vents and expelled out of the ridge vent. This ventilates the attic space and not the interior spaces. It is only minimally effecive in cooling the occupants in a hot-humid climate.*

Most roof ventilators are concerned with removing warm air from attic spaces and keeping air movement on the underside of the roof to eliminate condensation problems. Roof ventilationors rarely address the issues of ventilating the interior occupied spaces. There are some "attic fans" which mechanically ventilate interior air to the attic using a large fan. Commonly, the problem with this system is that the roof ventilators are not sized appropriately to move this extra amount of air resulting in a hot air backup and less efficiency.

There are four major types of venting systems used for attic/plenum spaces:

- Soffit venting
- Roof louver venting
- Gable-end venting
- Ridge venting[28]

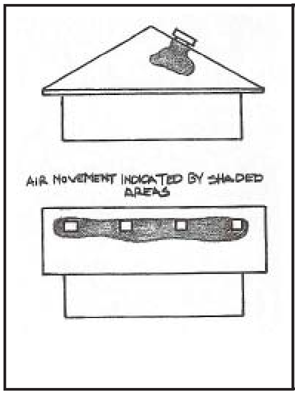


Figure 55: *Demonstrates how roof louver vents move air in the attic. (Hardy, Steve 1997, 162)*

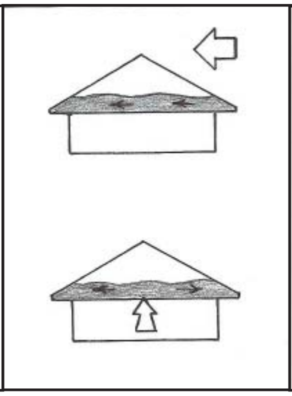


Figure 56: *Demonstrates how soffit venting moves air in the attic. (Hardy, Steve 1997, 162)*

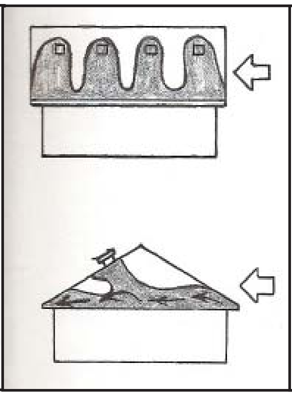


Figure 57: *Demonstrates how soffit and louver venting moves air in the attic. (Hardy, Steve 1997, 162)*

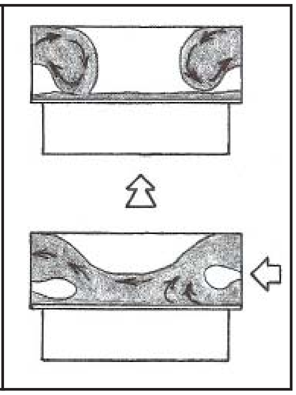


Figure 58: *Demonstrates how gable and soffit venting moves air in the attic. (Hardy, Steve 1997, 162)*

It is shown that using only one type of venting system is very ineffective in removing heat and moving enough air to make a difference. By incorporating two or more systems more adequate ventilation of attic spaces may occur. The sizing of the ventilators must be calculated for the system to work properly and most efficiently. The following images demonstrate how many common roof ventilators move air.

The common formula used for the volume of air which flows through a vent is:[29]

$Q = EAV$

Where: Q = air flow, ft3/min (cfm)

A = net area of vent opening, ft2

V = wind velocity, ft/min

E = effectiveness factor of vent

The efficiency of the vent components dictates how well the total vent system will function. The effective cfm of flow through vents is calculated by the formula:

$EC = D/T$

Where: EC = effective cfm

D = volume of attic, ft3

T = time of replacement of all attic air, min.

These formulas could also be used in calculating the air movements of interior spaces if the ceiling were omitted.

The major problem of roof ventilator systems is that they are meant to be used in ventilating attic spaces. The notion of an attic in hot-humid climates needs to be re-evaluated. Do buildings in hot-humid climates benefit from attics? Are drop ceilings in passively cooled buildings beneficial in hot-humid climates? The early designs for shelters in hot-humid climates were void of drop ceilings and attic spaces. By eliminating the attic and the drop ceiling the air flow could be increased and the warmer air could be raised further away from the occupants increasing the comfort level. Investigation of other passive and solar-induced ventilation systems reveals the following information.

Cross Ventilation

The most widely used of all the passive ventilation systems is cross ventilation. Cross ventilation utilizes pressure differences to move the air through the interior spaces. By having windows, doors, or other openings on opposite sides of a space, wind currents can flow through the space. Proper sizing to increase efficiency requires the leeward openings (outlet) to be 25% larger than the windward openings (inlet). Calm or light winds result in loss of cross ventilation. Calm or light winds allow little or no air flow thought the structure. The following images show drawbacks of cross ventilation in certain instances.

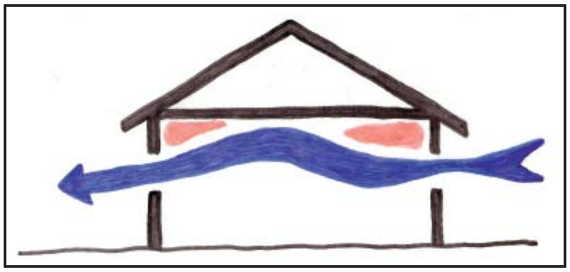


Figure 59: Cross ventilation with drop ceiling. Warm air pockets trapped in corners.

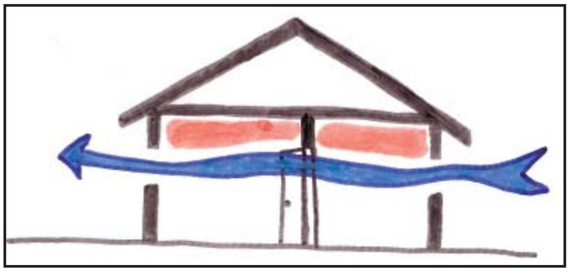


Figure 60: *Cross ventilation with drop ceiling and partition wall with door open. More warm air trapped lower.*

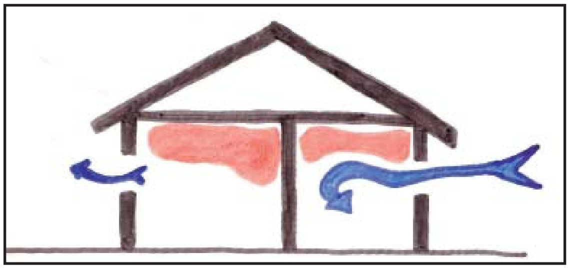


Figure 61: *Cross ventilation with drop ceiling and partition wall with door closed warm air trapped inside.*

Figure 62: *Cross ventilation without drop ceiling. Notice warm air rises away from occupants although still trapped inside.*

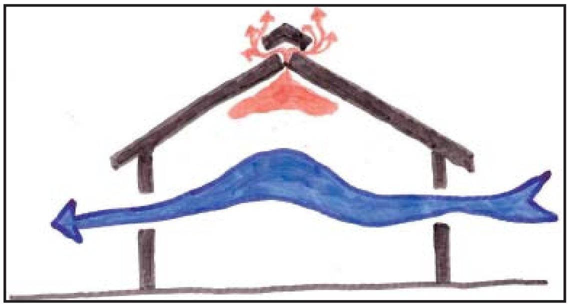


Figure 63: *Cross ventilation without drop ceiling and ridge vent. Notice warm air rises further away from occupants.*

Figure 64: *Cross ventilation without drop ceiling and partition wall. Notice elimination of cross ventilation and amount of trapped warm air.*

Stack Ventilation

The stack ventilation method incorporates the elimination of a drop ceiling with a higher exhaust stack that vents the warm air out of the structure. The form of the roof in a stack ventilation system relies on convective air flow to draw cooler air into the lower occupied spaces while releasing the hot air vertically. The incorporation of both a stack and cross ventilation system might aid in increasing the air flow enough to increase the comfort level in hot-humid climates.

Solar Roof

The solar roof in this context refers to a type of double roof system that uses solar radiation to create convective air flows. Most solar roofs are constructed with the roof plane orientated horizontally. This type of roof is common in the tropics in countries such as Malaysia and Indonesia. The warm air from the interior is drawn into the air cavity and out to the exterior through the roof plane. Solar roof systems have yet to provide enough air flow to create a noticeable difference in the human comfort levels

Solar Chimney

The solar chimney utilizes a tall chimney heated by solar radiation, in turn heating the air inside the air cavity. This aides in the buoyancy effect which draws air out of the interior spaces. The taller the chimney the more the air velocity increases, thus enabling a larger amount of air to be moved. These are commonly tall elements attached to the sides of structures. Occasionally solar chimneys are used to block thermal gains from transferring through the sides of structure into the interior space.

There are currently many ventilation options for the roof, but these are mainly used to ventilate the attic spaces and not the interior spaces. By ventilating the attic spaces the interior cools slightly due to the reduction of heat transmitted from the attic through the ceiling into the interior space. In the best case scenario, the temperature of the interior space can only be lowered to the equivalent of the exterior temperature. In hot-humid climates this temperature is still very high and the relative humidity is one of the main factors creating discomfort. To create a more comfortable space in hot-humid climates, it takes the combination of decreasing the temperature and increasing the air flow to properly cool humans. The question remains: Can a passive roof design cool the interior space below the outside ambient temperature?

METHODOLOGY

The methodology for this project is divided into three sections: Combination of Passive Ventilation Strategies, Design, and Testing. The first section, Combination of Passive Ventilation Strategies, draws principles gained from the research and knowledge of passive and solar induced ventilation strategies including; cross ventilation, stack effect, solar roof, and solar chimney designs. The second section, Design, explains the new proposed design which incorporates the above mentioned principles into a unique roof system. The third section, Testing, explains the testing location, procedures, and equipment used to test the new design against a typical roof system with physical data collection. This section also introduces computational simulation used to test temperatures and air velocities. These methodologies were selected from existing literary sources and discussions with the committee members and adapted to fit within the parameters of this research and are described further in this chapter.

COMBINATION of PASSIVE VENTILATION STRATEGIES

In hot-humid climates normal passive ventilation techniques typically do not produce high enough air velocity to induce the proper cooling effects on the human body. By incorporating common passive with solar-induced ventilating techniques in one system, the heat (energy) from solar radiation attempts to increase the convective air flow to increase the interior air velocity. The passive ventilation principles used in this design are borrowed from cross ventilation and stack effect strategies and the solar-induced ventilation principles are borrowed from solar roof, and solar chimney strategies. The following explains different principles borrowed for the proposed design.

Cross Ventilation

By using the cross-ventilation principle of a 25% larger opening on the leeward side than on the windward side, the design will incorporate an outlet vent 25% larger than the inlet vent. The vent openings will be located to aid in directing the air flow across the occupants. To promote even air distribution at least one inlet vent will be located on the opposite side of the outlet vent.

Stack Effect

The stack effect principle where the differences in air temperatures create buoyancy causing a convective air current will be utilized. This principle relies on a minimum difference of 3˚F in temperature between the air cavity and the interior air to promote effective air movement. Additionally, the location and cross sectional areas of the inlet and outlet vents are important for the increased efficiency of this stack effect principle. The lower locations for the inlet vents and the upper locations for the outlet vents will increase the temperature differences to promote the stack effect.

Solar Roof

By introducing the double-skin roof design from the solar roof the heat transfer to the occupied spaces can potentially be reduced. By changing the configuration of the common solar roof from a horizontal orientation to an angled orientation the roof would use the buoyancy principle to move more air and increase the effectiveness. This angled orientation will also incorporate the sun angles to gain the maximum amount of solar radiation (energy) available. The rule of thumb for proper sun orientation in the northern hemisphere is to face south at plus or minus 15° of the latitude where the building is located. The outlet vent openings should be located near the ridge of the roof enabling the pressure difference to draw warm air out during windy conditions.

Solar Chimney

By using the solar chimney's air cavity configuration as part of the roof design instead of a separate structure it may be possible to integrate the overall design without using additional tall elements. The length of the roof from exterior wall line to the ridge line will be used as the chimney (air cavity). This will enable a longer (taller) chimney while still fitting under the height limitations of many municipalities. The sizing of the solar chimney (air cavity) will be calculated to minimize the heat transfer to the interior space and to promote efficient air movement.

DESIGN

The design utilizes a structural metal roof material to generate and transfer heat from the sun's solar radiation into an air cavity located on the underside of the roof surface and above the occupied space. The air cavity has adjustable inlet vents located on its underside facing the interior space and adjustable outlet vents located at the ridge of the roof. There are adjustable inlet vents located at the lower portions of the exterior walls to enable cooler air to flow into the interior space. The heat generated in the air cavity is meant promote an increased convective air current. This current is expected to draw cooler air in through the lower inlet vents into the interior across the occupants' skin. The heated interior air will then be drawn through the air cavity vents and out the outlet vents. The air cavity increases in size and area toward the outlet vent to enable proper air flow and to prevent the bottleneck of air currents. The outlet vents at the ridge are sized 25% larger than the inlet vents of the air cavity and the inlet vents of the interior space to promote increased air flow.

The design includes the application of standard corrugated metal roofing material for the exterior roof surface. This material was chosen for the rapid transfer rate of heat from solar radiation (to increase heat in the air cavity promoting an accelerated convective air flow) and low absorptance rates which will enable the roof surface to cool rapidly after the sun goes down. The thinness of metal roofing nearly eliminates the thermal "lag" (a characteristic of many other roofing materials) aiding in the rapid cooling process. This material is light in weight as compared with other roofing materials and requires less structural materials in building the roof assembly. Metal roofing is considered a sustainable roofing option due its ease of transport and installation and due to its ability to be recycled.

Many metal roofing manufacturers are applying reflective coatings on their products to increase the reflectivity of the surface reducing the heat transferred through the material (emissivity). The need for increased heat in the air cavity of this design requires the surface of the metal roofing material to be coated with flat black paint to absorb as much potential heat (energy) as possible. The corrugated roofing material is applied with minimum obstructions of the air flow in the air cavity.

The vents for the air cavity are of a louver design enabling adjustments in the cross sectional area depending on the proposed inlet and outlet configurations. Two different louver designs will be tested, one design will use wood and the other will use radiant barrier for the louver material. A third roof module will be retrofitted with a typical asphalt roofing construction with window openings for cross ventilation to be used as a control module.

These designs were fitted into preexisting roof testing modules for physical testing. Three roof test modules were constructed. The first, shown in Figures 67 &68, incorporated the original design. The second, shown in Figure 69 & 70, was an adaptation of the original design (using radiant barrier). The third, shown in Figure 71&72, is of typical roof construction to be used as a control module. The size and shape

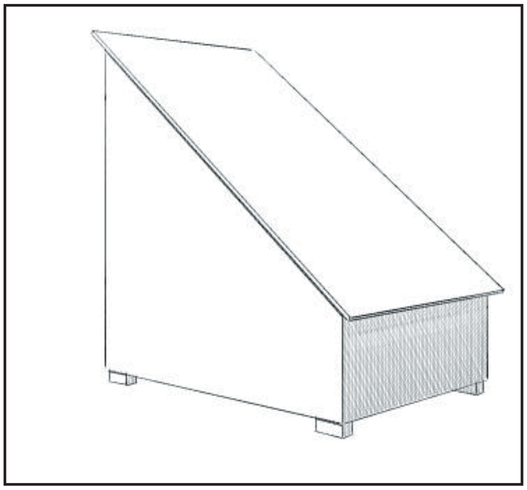


Figure 65: *This is a sketch of the roof testing module configuration. Three roof testing modules were tested and the data was compared.*

Figure 66: *All three roof testing modules located at the University of Hawaii, School of Architecture.*

of these modules were predetermined by the existing roof testing module dimensions. The dimensions are 8'-0" in height, 5'-1 ½" wide, and 7'-6" in length with a roof pitch (slope) of 9:12 or 37%.

Figure 67: *Computer rendering of Roof Module 1.*

Figure 68: *The wood louvers in Roof Module 1 before the corrugated roof was installed.*

Figure 69: *The exterior of Roof Module 2 with the access hatch visible.*

Figure 70: *The radiant barrier louvers in Roof Module 2 before the installation of the corrugated roof.*

Figure 72: *The exterior of Roof Module 3 with the opening for cross ventilation visible.*

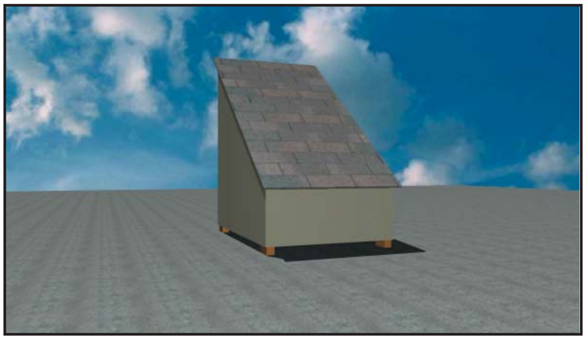


Figure 71: *Computer rendering of Roof Module 3 with asphalt shingles used for control testing.*

Roof Testing Module Descriptions

Roof Module 1 is the first prototype of the design. It uses an air cavity which is heated by the heat transfer of solar radiation on the roof surface to generate an increased convective air flow to ventilate the interior. The air cavity is separated from the interior space by a louvered vent configuration used to draw heated air out of the interior space and into the air cavity. This air cavity enlarges from the south exterior wall line to the north ridge of the roof to maximize air flow potential. This enlargement has been calculated by the using the inlet vents, louvered ceiling vents, and outlet vents cross sectional areas. To provide maximum air flow potential the outlet vent is sized 25% larger in area than the total of the inlet vents.

The inlet vent louvers on Module 1 are constructed of wood and are mounted so they can be opened and closed depending on the testing parameters. The wood louvers are 4" in width ¾" thick and span the interior space. The louvers are constructed on a movable panel that allows for the adjustment of the internal area of the air cavity. The air is drawn into the interior space through adjustable inlet vents located at the lower portions of the north and south exterior walls. The openings of these inlet vents can also be adjusted depending on the testing parameters. To vent the heated air from the interior space and the air cavity, an adjustable outlet vent has been located at the top of north exterior wall adjacent to the roof surface. All exterior venting openings have been covered with ¼" wire mesh to prevent birds or other animals from entering the modules.

The exterior walls and floor of the modules are built with typical 2X4 @ 24" on center stud construction with EPS insulation rated at an R-19 value and sheathed on the exterior with ¾" plywood. The roof is constructed out of galvanized corrugated metal roofing that has been painted flat black to absorb and transfer the maximum amount of heat to the air cavity. The roof is sealed with rubber weather stripping to prevent air infiltration. Drawings with details of Roof Module 1 can be seen on the following page in Figure 73.

Module 1 drawings fig. 73

Roof Module 2 is identical to Module 1 using the initial design with the exception of the material used and the size of the air cavity louvers. Roof Module 2 uses radiant barrier for the louver material and this material is stretched across and attached to the frame. These louvers are 8” in width as compared to the 4” in width of Module 1. Similar to Module 1 the louvers and the air cavity area are adjustable. This alteration of Module 1 was used to test if the radiant barrier could heat the air cavity to a higher temperature than the wood louvers while using fewer materials. The increased heat could possible promote a higher air flow and thus increasing human comfort. Drawings with details of Roof Module 2 can be seen on the following page in Figure 74.

Module 2 Drawings fig. 74

Module 3 is used as a control unit to test the proposed design against what is currently being used in typical residential construction. Module 3 has the same dimensions as Module 1 and 2 and is built with the same floor and wall construction techniques. The differences are in the roof construction and with added apertures in the walls. The roof uses a typical asphalt shingle construction installed over 30lb felt on ¾" plywood roof decking. The roof assembly has 4" EPS insulation equaling R-19 insulating value with a 1" air gap. There are openings for soffit and ridge vents to provide attic space air flow per the IRC regulations. The apertures (window) openings are located on the east and west walls to provide cross ventilation. These opening have been scaled down to ½ of typical size and are 1'-6" in height by 1'-0" in width. Drawings with details of Roof Module 3 can be seen on the following page in Figure 75.

Module 3 drawings fig. 75

TESTING

For this design experiment both physical models and computational models were tested. The models were created using the same materials, dimensions, and scales for the most reliable testing results. The physical models were used to test temperature variations and the computational tests were run to test the design in calm and light wind conditions to mimic the climatic conditions in hot-humid climates.

Physical

The physical models were constructed and tested at the School of Architecture on the University of Hawaii Manoa campus located in Honolulu, Hawaii. The effects of the location in relation to the existing School of Architecture building must be taken into account with the air velocity results. Even though the climatic conditions of the Hawaiian Islands do not mimic that of true hot-humid climates (increased wind velocities, lower ambient air temperatures, and decreased solar radiation levels) the testing could still show if this design might be a viable option to be explored further. The physical models were tested for temperature and air velocity levels. The testing equipment used for this experiment was Onset HOBO Pendant Temperature/Light Data Loggers and HOBOware Pro software for downloading and compiling the gathered data. The HOBO data loggers were loggers were located within the roof test modules. Physical testing limitations may include temperature, wind and solar radiation levels.

Computational

The computational models were generated using SolidWorks software and tested using CosmosFlo CFD software. The computational models enabled a stricter control of climatic variables and ease in changing design variables. The computational models were test for temperature, air velocity, and pressure differences. The recorded computational data was generated by CosmosFlo and exported into charts, graphical images, and animations. The learning curve for this software limited the testing procedures for this experiment. More tests must be preformed to provide accurate results. Computational testing limitations may include knowledge of testing software and engineering principles related to CFD.

RESULTS and ANALYSIS

Physical Testing Results

The initial testing on the physical models was carried out for three days for April 3, 2008, to April 6, 2008. During this time the sky was clear with the average high temperatures ranging from the mid to upper 80s to low temperatures in the mid to upper 60s. The winds during this period were gusty trades (north easterlies) ranging from 15-25mph. These strong winds made it difficult to test the interior wind velocities and diminished the accuracy of the velocity tests.

The testing was carried out by Onset HOBO temperature data loggers which were located in the roof testing modules at three different locations and one located outside to record the external temperature. These three locations represent strategic areas of interest in proving the possibility of increasing the air velocities and the human thermal comfort level using temperature differences. The first is located within the air cavity to measure the heat transferred by solar radiation. The second is located in the middle (3'-6" off the floor) of the interior space representing the temperatures the occupants would feel. The third is located on the lower level (4" off the floor) to measure the air temperature entering the inlet vents. The air velocity levels were taken using Solomat handheld anemometers held at the locations indicated in following figures. The following are the results and discussion of the physical modeling testing.

Module One Testing Results

The data collected from Module 1 show an approximate 9°F temperature difference between the lower temperature and the air cavity temperature readings, see Figure 77. The middle temperature demonstrates a slightly lower (1°F) than that of outside temperature during the midday heat. There is also evidence of a slight thermal lag as the middle temperature exceeds the outside temperature as evening cooling begins. The following pages contain drawings with the HOBO data logger locations and the Solomat anemometer test locations and a chart of the recorded data.

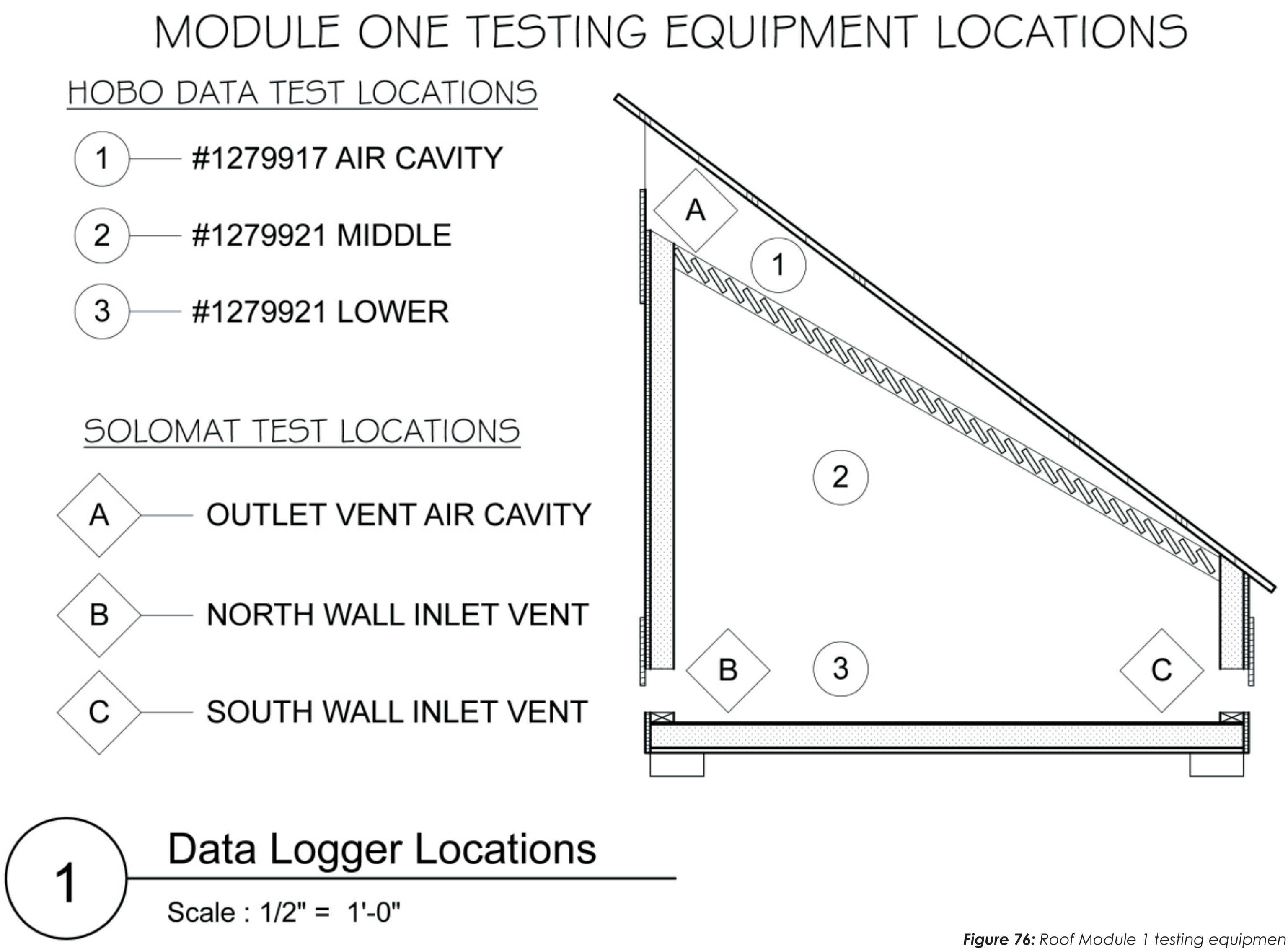
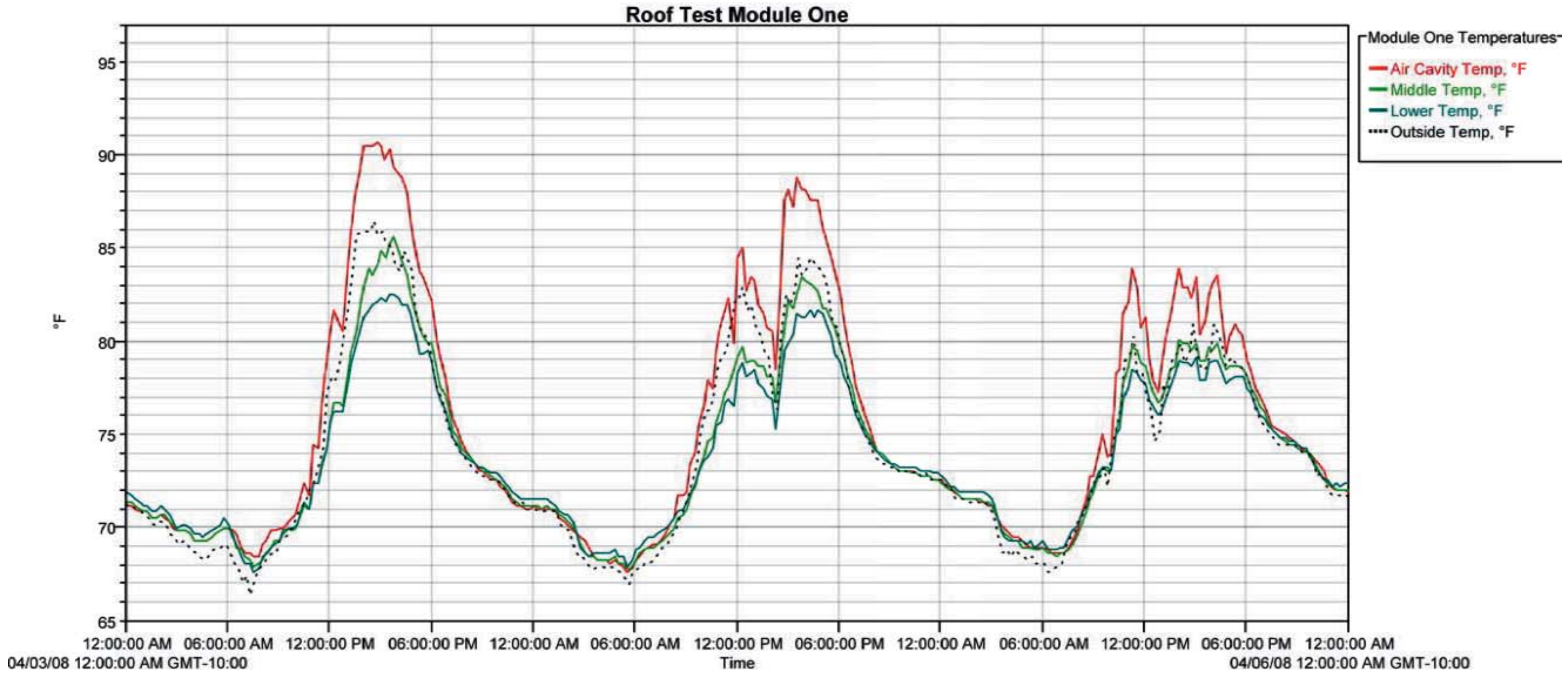


Figure 76: *Roof Module 1 testing equipment locations.*



Air velocity readings

A - 20-60ft/s

B - 15-180ft/s

C - 40-120ft/s

__Figure 77:__ Roof Module 1 temperature data and air velocity levels.

Module Two Testing Results

The data collected from Module 2 show an approximate 14°F temperature difference between the lower temperature and the air cavity temperature readings see Figure 79. The middle temperature demonstrates larger reduction of temperature (3°F) than that of the outside temperature during the midday heat. There is also a noticeable decrease in the thermal lag evident in Module 1 as evening cooling begins.

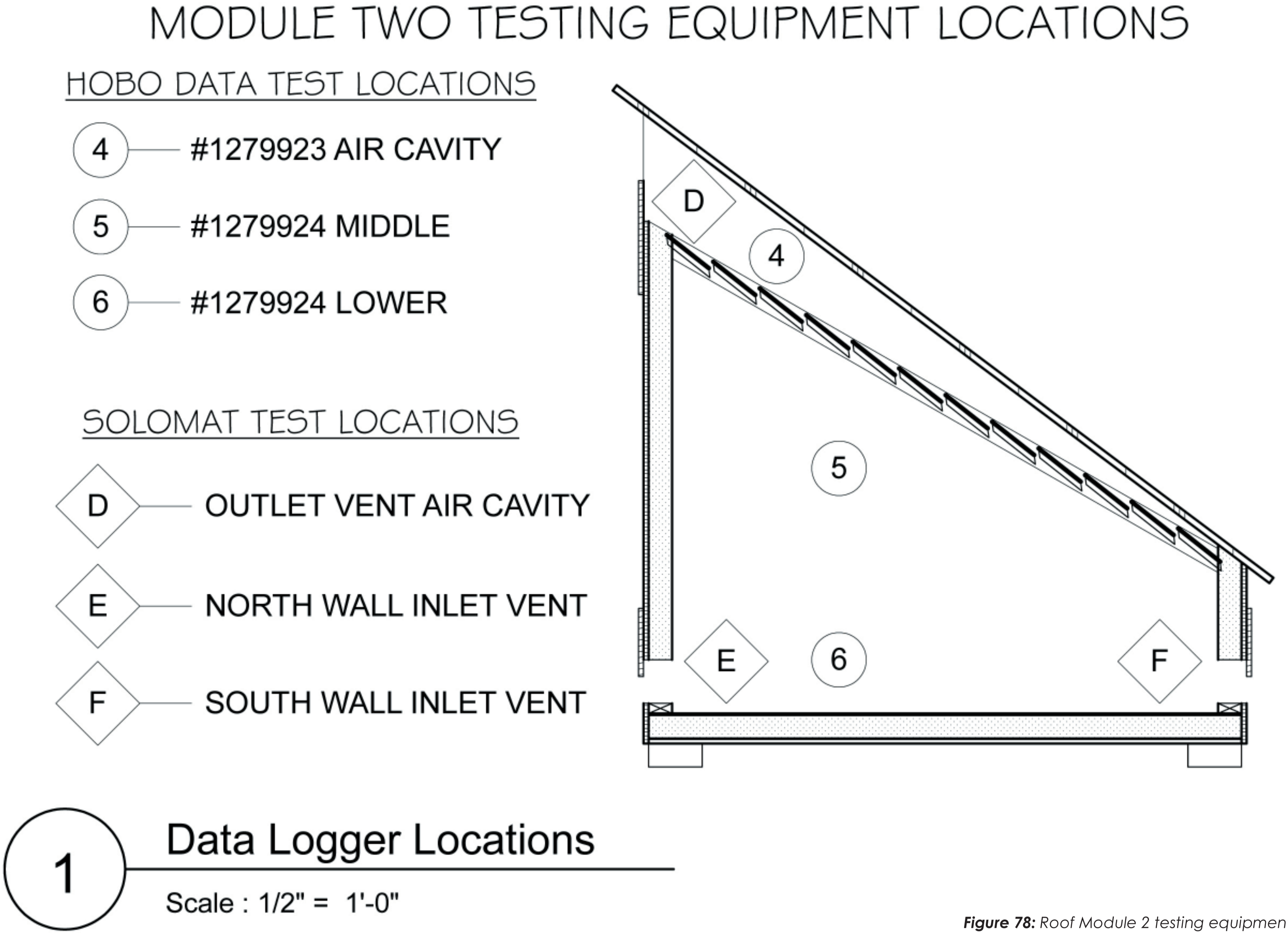
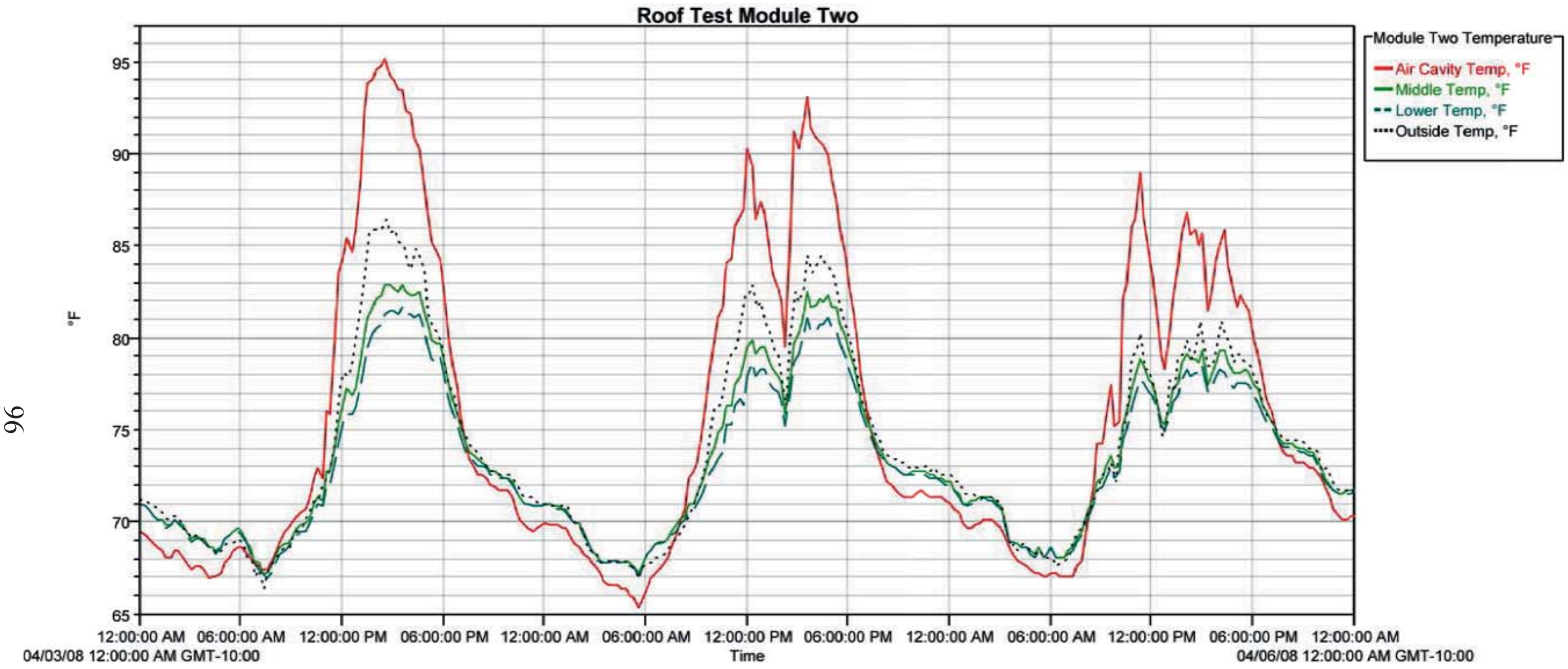


***Figure 78:** Roof Module 2 testing equipment locations.*



Air velocity readings

D - 20-37ft/s

E - 40-190ft/s

F - 19-133ft/s

Figure 79: *Roof Module 2 temperature data and air velocity levels.*

Air Cavity Results Compared

By comparing Module 1 against Module 2 in air cavity temperatures ,it is evident that Module 2 is able to heat the air in the cavity over 4° more than Module 1, see Figure 80. The data also shows Module 2 is able to cool the air cavity down to a lower temperature than Module 1. The temperature differences between the outside temperature and both Module 1 and Module 2 show potential to move air exceeding the minimal 3° temperature difference.

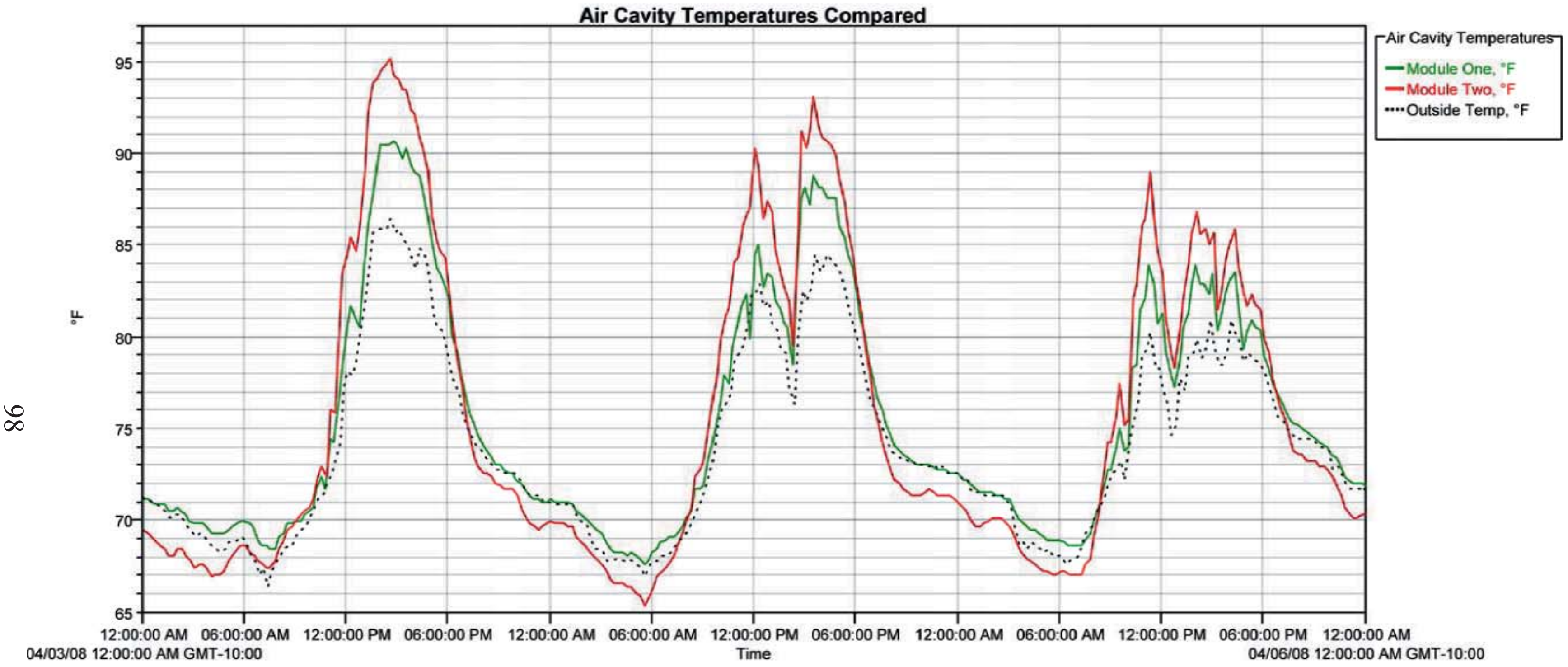


Figure 80: *Roof Module 1 and 2 air cavity temperature comparision data.*

Module Three Testing Results

The data collected from Module 3 show an even distribution of temperatures between the upper and middle temperatures and an increased lower temperature. The upper and middle temperature relate closely to the outside temperature with the increased thermal lag evident. The interior of module three heats up past the outside temperature a couple of hours past the warmest period and remains warmer until the next morning, see Figure 82. The lower temperature sensor could possibly be misreading the data and will be checked on the next test cycle.

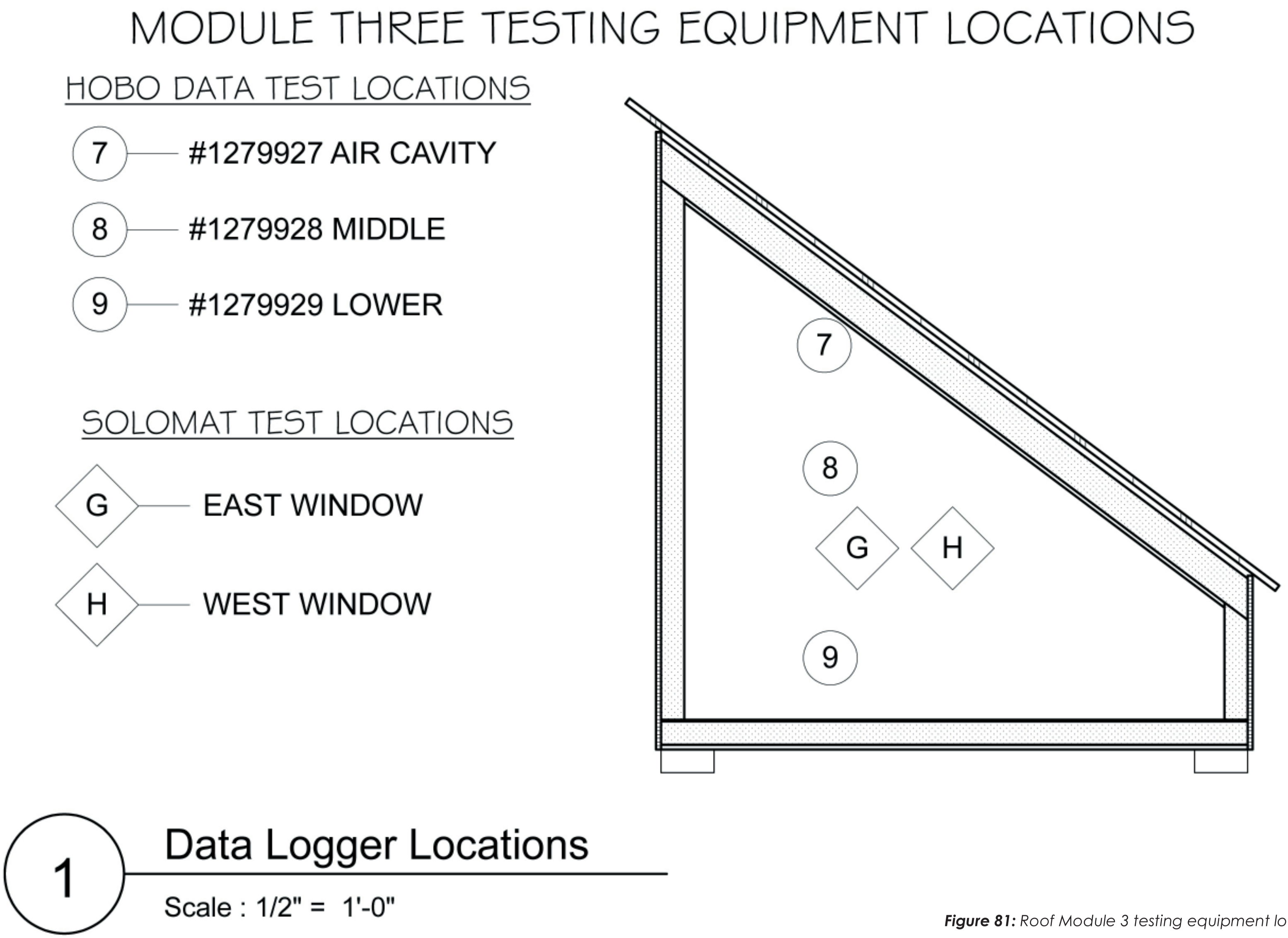
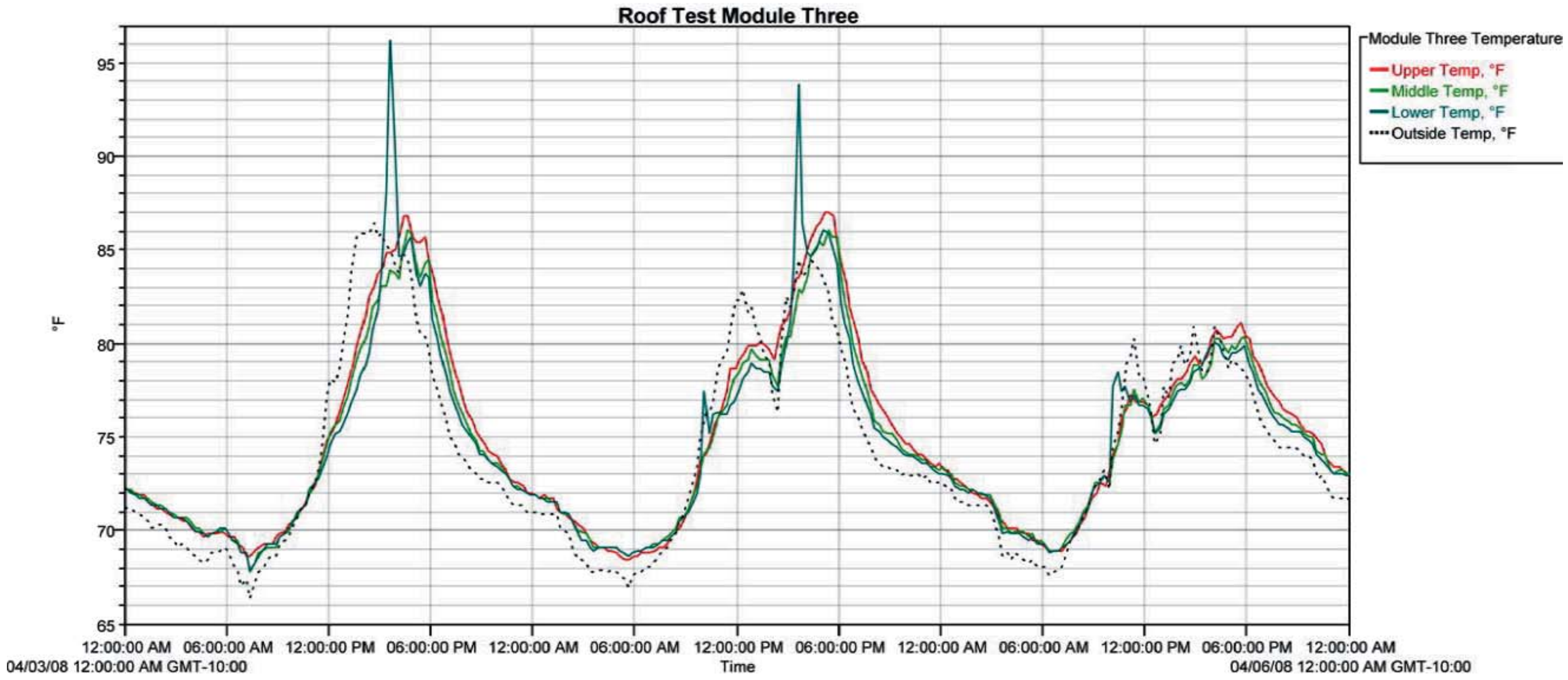


Figure 81: *Roof Module 3 testing equipment locations.*



Air velocity readings

G - 36-189ft/s

H - 40-69ft/s

Figure 82: *Roof Module 3 temperature data and air velocity levels.*

Middle Temperatures Compared

By comparing the data collected on the middle temperatures it can be shown which module would increase thermal comfort for its occupants. The data shows Module 3 having the highest temperatures of all three modules tested. The data also shows Module 3 takes longer to heat up but then holds the heat longer than the other two modules. Module 2 demonstrates the coolest temperatures of all three modules with the least amount of thermal lag.

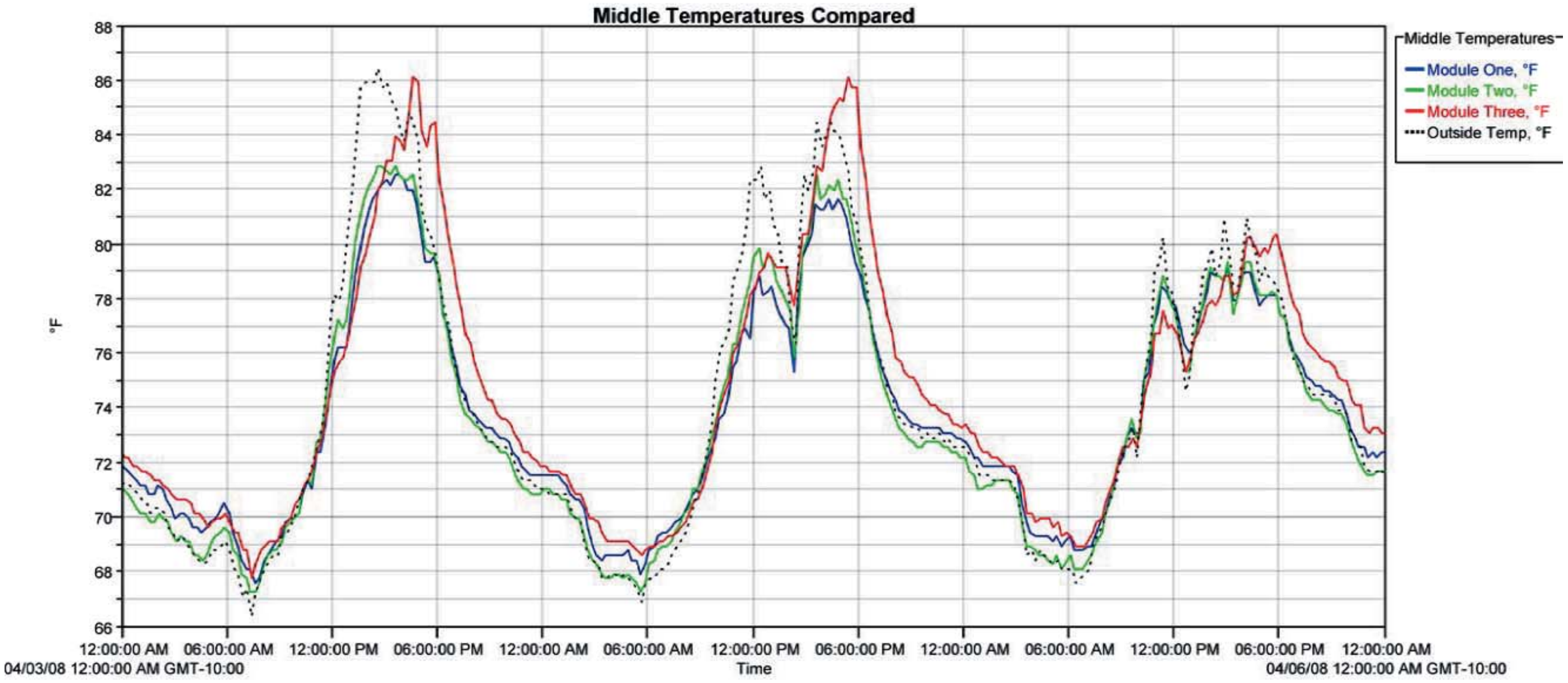


Figure 83: *Modules 1,2,and 3 interior temperature comparisions.*

Computational Testing Results

The computer software Solidworks was used to model the roof testing modules for computational testing. After measuring the physical models the data was entered into Solidworks to reproduce as accurate as possible the scale, materials, and venting configurations. These computer models were then tested for temperature and air velocity readings using the embedded CosmosFlo CFD software. The data was then extracted into graphical images and animations for analysis.

Testing was carried out following a flow chart (See Figure 84.) to check different venting configurations and climatic conditions. Due to time limitations only a few samples of the results will be included here. These results are to be used to configure the physical roof testing modules for later comparison testing.

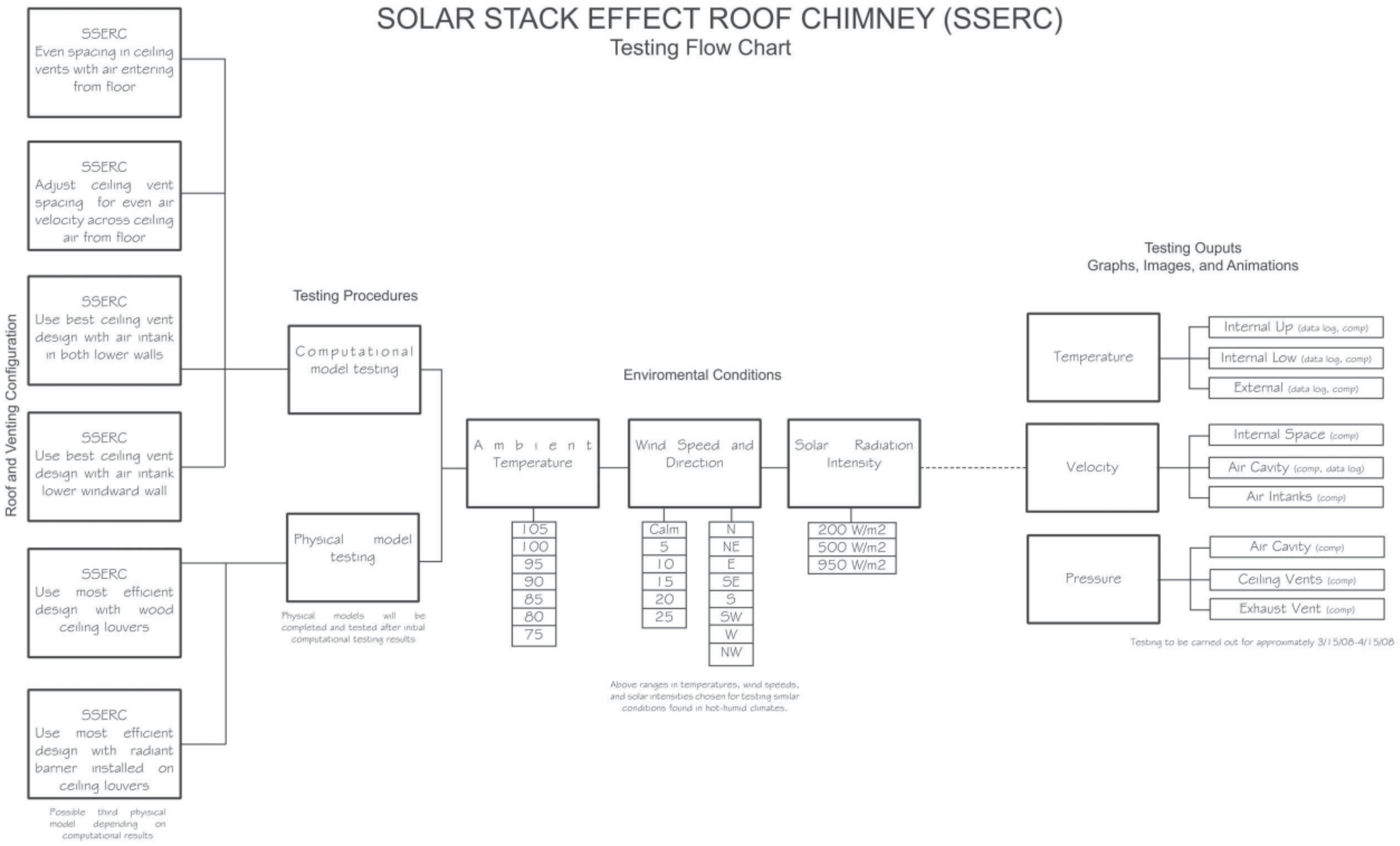


Figure 84: *Flow chart of testing parameters for computastional models.*

Computation Test One

Computational Test One was conducted using the double inlet vent configuration opened at 6.5" vertically and the outlet vent opened 16.25" vertically. All louvers were opened with an even spacing of ½" each. The wind direction selected was light south and the ambient temperature was 75 degrees. The following figures show both the temperatures levels and the air velocity levels. The temperatures show the roof design holding the extreme heat within the air cavity without transferring the heat to the interior.

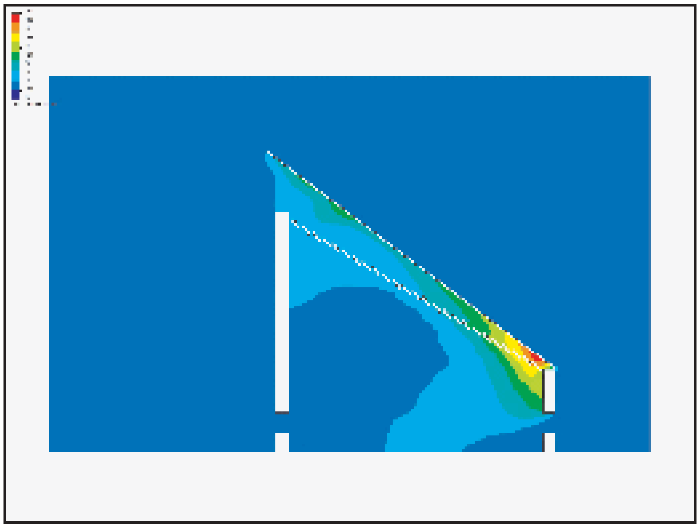


Figure 85: *Computational Test One modeling of temperature data using CosmosFlo CFD software demonstrating the heating of the air cavity to initiate the convective air flow.*

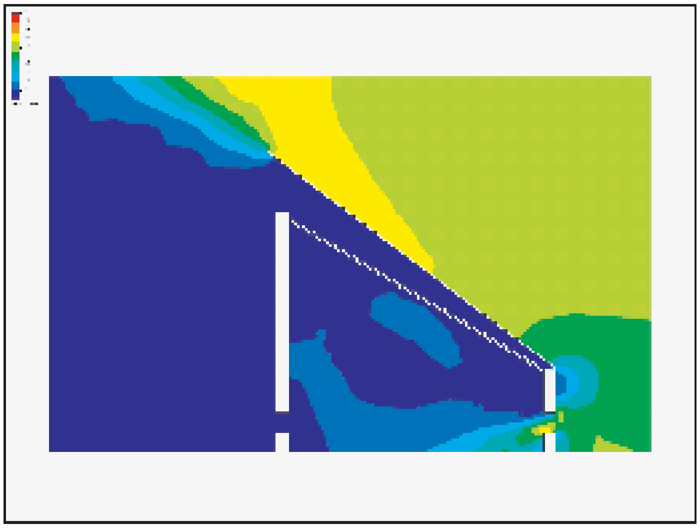
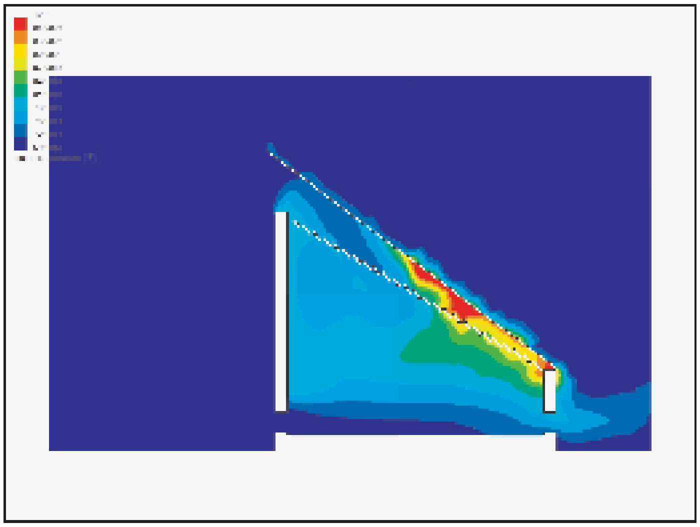


Figure 86: *Computational Test One modeling of air velocity data. This test has light south winds and does not increase the air velocity enough for increasing human comfort.*

Computational Test Two

This test was conducted using the double inlet vent configuration as used in the physical testing modules. The louvers were equally spaced at ½" each. The wind was light out of the northeast to mimic the Hawaiian trade winds. The two inlet vents were opened at an equal 6.5" vertically and the outlet vent was opened 16.5" vertically. This test shows the air path as it enters the inlet vents and exits the outlet vents. This test demonstrated how the air can be pushed into the air cavity reducing the effectiveness of the system. This test also shows how the heated air remains in the air cavity giving the potential to move the air convectively .

__Figure 87:__ Computational Test Two modeling of air temperature data. The wind blowing in the outlet vent is causing the heated air to enter the intior space.



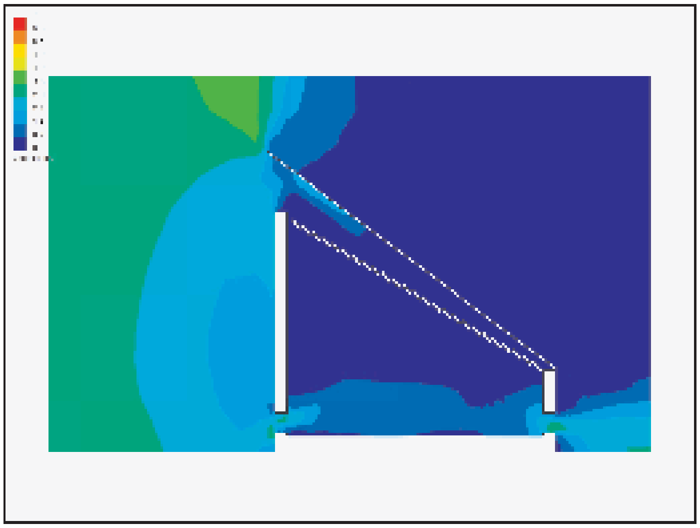


__Figure88:__ Computational Test Two modeling of air velocity data. Demonstrate air flowing through the bottom of the module due to the direction of the air currents.

SUMMARY and CONCLUSION

This section summarizes the test findings answering the reseach questions, gives considerations for future development of the design, and finishes with the conclusion.

Summary of Testing Results

These testing results demonstrate that the design can heat the air cavity to the appropriate temperatures needed to create increased air velocities.

By using the radiant barrier in Module 2 the heat transferred into the air cavity is reflected increasing the temperature. This increased temperature has the potential to create more air flow than Module 1. This increased air flow can be directed over the occupants to aid in psychological cooling in calm to low wind situations.

The design also mitigates the heat being transferred into the interior space keeping the occupied space cooler. The temperatures in Module 1 and Module 2 remain lower than those of Module 3 and the outside temperatures.

The data collected shows the design out performing the typical asphalt roofing construction techniques by reducing daytime temperatures and by reducing the thermal lag times. The new design potentially uses fewer materials than typical roofing systems and a lighter gauge structural system may be used.

Using the design in hot-humid climates show promise by the system's efficiency and lower costs than that of other roofing systems or the installation of air conditioning.

Considerations

When proposing any new designs there are many variables to be considered. The main consideration of any design should be how it can better human lives while saving energy, resources, and the environment. The design is no different and there are many aspects to be examined in more detail in the future. Some of these aspects are as follows:

- How could repositioning the inlet vents to the center of a space change the air flow?
- How will increasing the length of roof affect the air velocity levels?
- How would the ridge vent configuration of the design be different from existing ridge vents?
- How could the design be utilized in urban areas where obstructions block prevailing wind flows?
- Could the design be used economically as a retrofit on existing residential structures?
- What are the actual cost differences between typical roofing systems and the design?
- What is the proper sizing of the inlet and outlet vents to provide the most efficient air movement?
- How could the use of aerodynamic designs within the louvered system increase air velocities?
- Could the design be factory produced and assembled on site?
- How can the orientation of the design be used for other purposes (solar electric and solar thermal systems)?
- What type of new connections could be designed to prevent the inherit water leakage of current metal roofing mechanical

fasteners?

- How can the aesthetics of the system as a whole be improved?
- How can the infiltration of flying and crawling pests be minimized?
- How can theacoustical issues of the metal roofing material be addressed?
- Who might be interested in supporting further research and development?

These are a few of the considerations that begin to appear as the design begins to evolve. More considerations are sure to develop as the design changes.

Conclusions

By going back to the question, "Can Roofs Breathe?", this research has proven that there is potential to use form, materials, and methods of roof construction to generate air movement for the interior spaces without mechanical means. This air movement can draw the warmer air out of the interior replacing it with cooler air from the exterior. The air movement can cool the interior space, reducing the MRT and adding thermal comfort to the occupants. This design also lowers the interior temperatures even with the roof surface colored black. The interior space is shown to be cooler than a light-colored asphalt shingle roof. This design reduces the thermal heat gain which normally affects many solar chimney designs.

The metal material chosen for the roof surface works ideally due to its thermal qualities. This material is also easily installed, transported and recycled lessening the life cycle cost of this roofing system. Using structural metal roofing lessens the amount of materials needed to build a roof and the structure while adding performance. To increase the effectiveness of the roof surface, a transparent material might be tested to increase the temperature levels similar to the greenhouse effect which might lead into some interesting day-lighting opportunities.

After designing, building, and testing the system it is apparent that this is only the first stage. The data shows potential for this system to be a viable option for increasing human thermal comfort in the hot-humid climates. Still more computational and physical testing is needed not only to increase the systems efficiency but to definitively prove the systems worth. A more thorough physical testing setup might include a controlled climatic chamber where variables like the winds and solar intensities affecting the testing could be constrained.

The computational testing could be improved by furthering the knowledge of the CFD software and by consulting engineering professionals.

The potential for this design to be beneficial in hot-humid climates as well as in other warm climates is limitless. The design could be used where the opportunities to utilize natural wind flows might be blocked and could be beneficial where privacy issues outweigh cross ventilation options. With proper funding for additional research and development, the design could be a low maintenance, low cost, and sustainable solution for the future.

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