LOW-ENERGY COOLING

A Guide to the Practical Application of Passive Cooling and Cooling Energy Conservation Measures

DONALD W. ABRAMS, P.E.

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Let us cross over the river and rest under the shade of the trees.
General T. J. "Stonewall" Jackson

For my Dad, William F. Abrams, Jr.

PREFACE

Most of us are inevitably more concerned with heating our homes and the small commercial buildings we operate than with cooling them. Heating represents the greater energy load in most buildings, and certainly on a national scale it is a more significant economic concern than cooling. More basically, cold weather poses a very real threat to human survival; we simply could not live without heated shelters. We can survive quite easily, however, if not comfortably, without mechanical cooling. Needless to say, simple survival is not the issue; the concern here is on a higher level in the hierarchy of needs. Modern comfort standards, social practices, and design practices have made mechanical cooling an essential requirement in all but a few buildings.

The cooling problem that confronts us encompasses both a human comfort component and an energy consumption/economics component. High temperature and humidity combine to make the problem most severe in the sunbelt states, but other areas of the country are not exempt. Modern large commercial buildings simply cannot operate without air conditioning, regardless of location. High summer temperatures strike almost all of the country each summer. For instance, the extreme design dry-bulb temperatures for Philadelphia, Newark, Kansas City, New York City (Central Park), and Bismarck, North Dakota are equal to or higher than the design temperature for New Orleans. As a result, about three-fourths of the new homes built in the United States this year will incorporate central air-conditioning systems.

Humidity adds another element to the comfort issue—and to the possibility of passive or natural solutions. Evaporative and radiative cooling have real potential only in the arid Southwest and parts of the Rockies. In the balance of the country—again, not just in the South—humidity levels preclude the use of these and other natural cooling alternatives. For all practical purposes, there simply are no passive means for providing positive control of comfort conditions to hold them to present standards. Conventional air conditioning systems are required. Only in the extreme North, arid areas, and at higher elevations can air conditioning be altogether avoided. Even there a comfort problem will still exist to a lesser degree. Of course, natural cooling methods can be relied upon in any location so long as a compromise in comfort standards is understood.

Low-Energy Cooling looks for practical solutions to the problem of providing comfort in residences and small commercial buildings. It deals in realistic methods for making people comfortable in the nonarid regions—that is, most of the United States. It does not indulge in the wishful notion that some magic passive or natural solution will provide an endless supply of cooling in violation of common sense and thermodynamics. Instead, the book examines the problems and opportunities that arise in each aspect of the cooling and comfort problem and the building design and operation process. A comprehensive approach is suggested:

- Understand cooling loads and comfort so as to be able to provide comfort by means other than strict temperature control.
- Reduce heat gain to the building in question to improve comfort and reduce air-conditioning loads.
- Use ventilation as a substitute for, as well as a supplement to, air conditioning.
- Provide an efficient cooling system and operate it efficiently.

Specific chapters address each of these concerns. In addition, other chapters explore alternative cooling methods, including evaporative cooling, radiative cooling, earth cooling, and various innovative concepts. In an effort to respond to the level of interest shown in such interesting, but largely unworkable, alternatives as solar chimneys and earth cooling tubes, detailed discussions of these devices are included.

The fundamental intent of *Low-Energy Cooling* is to provide readers with the means for selecting the best solution to their individual situation and needs. Comfort and minimum construction and operating costs are the objective. Three general strategies are recognized: (1) comfort at any cost, (2) minimum cost with necessary comfort compromises, and (3) reasonable comfort and reasonable cost. The third strategy is encouraged. Specific measures and alternatives are dealt with realistically, with both their opportunities and limitations identified. This treatment allows the users of the book to make informed judgments and compose a specific solution to their own cooling problem.

Donald W. Abrams, P.E.

CONTENTS

1

INTRODUCTION

One of the finest examples of a naturally, or passively, cooled residence is the Hay House in Macon, Georgia (Fig. 1.1). Designed by Thomas and Griffith Thomas, the grand, 23,000-ft^2 house was completed in 1859. Like other Thomas designs, it was an example of 19th-century "high tech," incorporating many quite innovative features. A spring routed through the property drove a ram pump to provide hot and cold running water and operate hydraulic elevators and flush toilets. A voice tube intercom system was included to communicate with the staff of 12.

The heating and cooling systems were also state-of-the art and rather luxurious by standards prevailing then. The design emphasized cooling to provide comfort in the hot, humid central-Georgia climate. Of necessity, the cooling system relied solely on natural, or, as we call them today, passive, measures. Ventilation was the key. The design provided for both horizontal and vertical air flow through the house, using wind-induced ventilation and stack-effect ventilation.

Large windows, as tall as 15 ft were used liberally. Numerous smaller windows high above the gallery floor in a "lantern" were opened and closed by the staff as required. Another of the first-floor rooms incorporated vertical air flow through openings cleverly concealed in the decorative ceiling. The central stair in the house provided another vertical flow path. The house's 21 fireplaces could be used as ventilation shafts during the summer, in conjunction with a network of ventilation chases opening onto each of the several levels of the house (Fig. 1.2).

The design also included earth cooling features in the form of extensive underground chambers beneath the house. Ventilation air could be drawn through these chambers and through the wine cellar to cool it before it entered the living areas. Air inlets around the perimeter of the first level allowed air to be drawn in from above ground at the coolest locations. Movable solid panels and grilles in doors allowed air circulation while still providing security and privacy.

The design incorporated other common sense measures to reduce undesirable heat gain during the hot summers. The summer kitchen was housed in a separate

Figure 1.1. Hay House, front elevation.

building adjacent to the main house. Shutters and heavy drapes helped block solar gains. The massive exterior walls were finished with white stucco to reflect solar heat. High ceilings, typically 17 ft but rising as high as 40 ft, kept hot interior air far away from the occupants below.

Economics and imagination were certainly no limitations in the design of the house. The original owner, William Butler Johnson, was quite wealthy and something of a technological innovator. He owned the local ice house and the first gas works in the city. The architects were some of the most knowledgeable of the time. Every effort was made to create a comfortable interior environment in a severe summer climate. Compared with other houses of the time, the Hay house was a great success. Even in modern times, the house has never had a mechanical cooling system. The members of the group who now care for the house report that it is remarkably comfortable in summer. Interior temperatures remain reasonable even when the outdoor temperature climbs to 100°F. High humidity is a problem, however.

In the 125 years since the Hay house was completed, we have added few additional passive techniques to our repertoire for coping with hot, humid climates. The most significant advantages we have today are greatly improved insulating materials and a variety of specialized glazing materials to block and reflect the sun. Should a similar project be undertaken today without the aid of

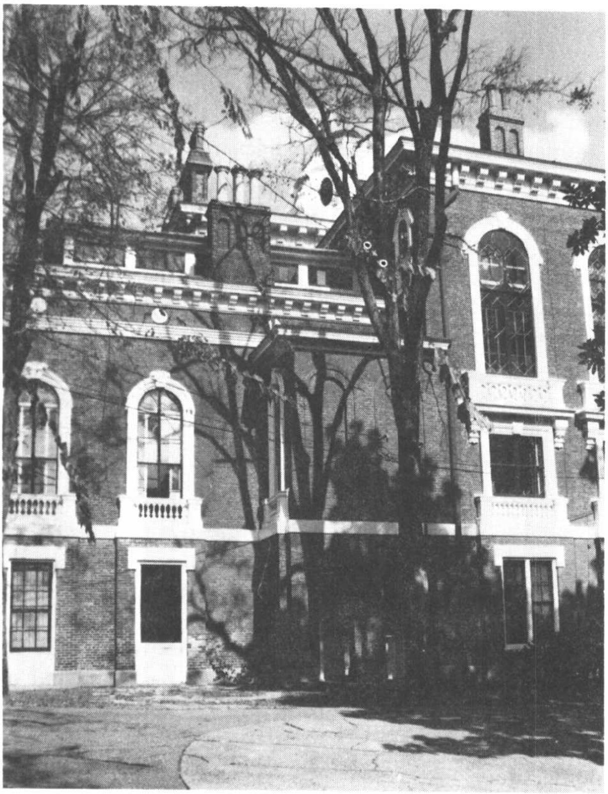

Figure 1.2. Hay House, rear elevation.

mechanical cooling, little more could be done. Although much of the discomfort associated with summer heat could be ameliorated, humidity would remain a problem. In all but the more arid and cool areas of the country, natural, or passive, cooling simply cannot provide the controlled interior conditions offered by air conditioning. If we demand temperatures no higher than 78°F and protection from high humidity, passive cooling does not work.

We have often misused mechanical cooling systems. Building designers and occupants frequently ignore thermal design considerations and sensible operations and simply overpower their mistakes with air conditioners. While we were blessed with low energy costs we became spoiled; we developed expensive tastes for rigidly controlled conditions. Today most of us are unwilling to compromise those standards; many of us consider air conditioning a necessity. We have grown accustomed to buildings and lifestyles that leave no alternative but to rely on air conditioning.

What then can natural, or passive, cooling do for us? If we are willing to accept reduced levels of comfort, natural cooling can allow us to eliminate air conditioning systems from many buildings. Perhaps more importantly natural cooling can work effectively in conjunction with modern construction and design practices and mechanical systems to reduce the cost of meeting more rigid comfort requirements. We can use rational design and natural cooling to reduce the load on air conditioners. We can supplant the use of energy-consuming systems during the milder portions of the cooling season. We can provide comfort by alternative methods that reduce energy consumption.

This book does not suggest that natural, or passive, measures can provide a one-for-one replacement for air conditioning. To idealistically pretend that they can is foolish. Instead, a more pragmatic and realistic approach is taken. This book seeks to describe methods for designing, building, and operating residential buildings to reduce the adverse thermal load during the cooling season and to improve comfort conditions. The central objective is to reduce the cost of staying cool in our homes. Regardless of your individual orientation—avoiding air conditioning or avoiding discomfort—the principles discussed here are valuable.

COOLING—A THERMAL SYSTEM VIEWPOINT

Cooling involves manipulating thermal systems—networks of interrelated heat flows and heat storage. As designers, builders, operators, and occupants of buildings, we commonly deal with four major thermal systems:

1. the building site
2. the building
3. the mechanical system and
4. the human body

Each of these thermal systems exchanges heat with its environment, generates heat internally, and stores heat. Each demands specific internal temperatures for efficient operation and proper function. It is the job of building and mechanical system designers to use the first three systems as tools to reduce the stress on the human thermal system and provide comfort.

All thermal systems obey basic laws that describe the relationship between heat and energy flows. The first law of thermodynamics states that the sum of all the energy flows in a system must be zero. The heat gained is equal to the heat lost plus the heat stored. Every British thermal unit (Btu) of heat must be accounted for; energy is neither created nor destroyed. The second law dictates that heat will always flow from high-temperature to low-temperature regions, unless additional energy is added to the process. These principles are frequently overlooked in examining natural cooling systems, resulting in hopeful designs

HEAT GAIN = HEAT LOSS + HEAT STORAGE

Figure 1.3. First Law of Thermodynamics—heat balance.

that do little but remind the owners of the inviolate nature of the laws of thermodynamics (Fig. 1.3).

A convenient parallel can be drawn between the two thermal systems of most interest—the human body and the building. Both behave similarly as thermal systems, generating, storing, gaining, and losing heat. A building exchanges heat with the surrounding air by conduction through the walls, roof, and floor; the body does the same. Whenever the surrounding air is warmer than the building surface or the body's skin surface, heat flows into the building or the body. The difference in temperature between the air and the surface provides the potential, or driving force, for the flow of heat. The greater the temperature difference, the greater the rate of heat transfer. Similarly, heat loss—cooling—occurs when the temperature of the surrounding air falls below the temperature of the building or body surface.

Air motion may also be responsible for heat flow in both systems. Air leakage or ventilation through a building and the body's respiration process have similar effects. Both the building and the human body are also subject to radiant heat gains and losses, solar heat gain, for example.

Internal heat generation also occurs in both the body and buildings. In a building, lights, machinery and equipment, and people are sources of interior heat; in the human body the metabolic process provides a parallel. Thermal storage can be particularly significant in buildings where mass has been added for passive solar systems. However, because the human body demands a relatively stable interior temperature, heat storage in the body is less significant.

In searching for cooling strategies and techniques to reduce energy consumption and costs, each of the four major thermal systems should be examined. The site, the building, the mechanical system, and the human body all present opportunities. The challenge is to use those mechanisms to produce human comfort with minimum use of purchased energy. Energy-consuming, mechanical cooling systems are usually a requirement for buildings, but they should be operated only when other alternatives have been exhausted. And when they are used, they must be used efficiently.

Human-Scale Cooling

The ultimate objective of space-cooling systems for homes and most commercial buildings is to provide comfortable conditions for the human occupants. Prior to the advent of mechanical cooling systems, the focus was on actually cooling the *people* in the buildings. Open windows permitted breezes to reach the occupants. High ceilings allowed heat to rise away from occupied zones.

Fans provided cooling in localized areas. Even with window air conditioning units, rooms were closed off and only the occupied areas were conditioned. Of course, not all the ideas suggested were widely adopted, as Fig. 1.4 illustrates. There is a major shortcoming of such natural cooling methods—the inability to cope with extremes of temperature and humidity. Except in a few locations in the United States, consistently comfortable conditions in buildings can be produced only with mechanical systems. People can survive without air conditioning, but they will be uncomfortable at times.

The power and convenience of mechanical cooling systems have brought on an unfortunate change in our building design and operation practices. The emphasis has shifted from the human system to the building system. The objective has become providing uniform, comfortable temperature and humidity throughout the *entire building*, losing sight of the basic issue of making people com-

ARM AND LEG MOVEMENT
OPERATE SERIES OF FINS

Figure 1.4. Cooling suit. Reproduced by Permission from *Principles of Air Conditioning*, Delmar Publishing, Inc., 1972.

fortable. Other means of providing comfort, such as air motion, are overlooked, and areas that require little or no conditioning, such as storage areas and entry vestibules, are wastefully heated and cooled with the occupied portions of the building. Recently interest has surged in "natural" home designs, often despite the facts that conventional comfort standards may not be met and the first costs are not justified by savings. People with six-digit incomes will spend hours cutting wood to save $300 in heating costs. Is something missing from the typical surburban house? A friend once described a visit from his grandfather, who still lived in a drafty rural house heated only by a woodstove. The old gentleman stalked around his grandson's house (heated by a heat pump) for half a day and then grumbled, "I'm not exactly cold, but I'll be damned if I can find a place to warm my hands."

Certainly fireplaces and ceiling fans are not the answer to our heating and cooling needs; they are inconvenient and often leave us uncomfortable. But they can provide a point of focus in a building, places that *feel* different, where the heating or cooling is concentrated. This contrast to "thermal boredom" may partially explain the popularity of fireplaces, woodstoves, and ceiling fans.

Mechanical systems are necessary for our current lifestyle, providing pleasant indoor conditions in any kind of weather. But they should be designed and used judiciously, conditioning only the appropriate occupied portions of a building. The central objective of making people comfortable should be kept in mind, and alternative measures for "people cooling" rather than building cooling should be considered.

There are no simple natural, or passive, methods to consistently cool a building to the comfort conditions that most Americans demand. Although there are methods that work quite well during portions of the cooling season, most of us are not willing to do without air conditioning. Consequently, this book is directed at methods of achieving comfort with the minimum expenditure of energy, making only reasonable compromises, using natural concepts and mechanical systems in sensible combination. It deals with the building, the human occupants, mechanical equipment, and the building site. Rather than focusing exclusively on removing heat from the building, it examines methods of cooling by reducing or even avoiding heat gains.

2

THE COOLING PROBLEM

There is virtually no location on earth that is too hot for man to survive. In the long, slow course of evolution man's physiology has been tailored to his environment, meeting the challenges of mild and severe climates alike. Even Death Valley, California, and Tasmania, Australia, with their 130°F temperatures support human life. For centuries, Indians and aborigines have lived in these inhospitable areas without mechanical cooling systems. These locations represent the hot extreme of the earth's climate. The areas of the world in which the majority of the population is concentrated are much milder, seldom experiencing temperatures above 100°F. Except in cases of individual illness or infirmity, our environment poses no high-temperature threat to man's survival. As a species, man has evolved to match his environment and has done so with remarkable success.

In a well-developed society, such as that of the United States, however, most people spend the majority of their lives in another environment—the building interior. A primary function of man's shelter has always been to ameliorate the daily and seasonal fluctuations in climate conditions. Examples of the clever and effective development of architectural styles to meet the requirements of local environmental conditions are numerous. With the advent of oil, gas, and electric heating and cooling, the degree to which interior conditions can be controlled has increased dramatically. Over the past three decades it has become possible to completely disregard the effects of climate forces in the design and construction of buildings and to overcome these forces with mechanical space-conditioning equipment. We commonly create interior environments that provide remarkable comfort conditions, but depend entirely upon the use of large quantities of energy. The common glass office building without operable glazing must have air conditioning. During power outages, such buildings often must be evacuated. In many cases, it is not possible for man to exist in his new environment without the use of energy-intensive mechanical systems.

As the building interior environment has changed, we have made distinct changes in our lifestyles, dress, customs, and preferences. These modifications have then added to our climate-related cooling problem to further increase the need for mechanical cooling. Our clothing styles are a good example. Most people have largely abandoned traditional, practical clothing in favor of dress considered fashionable. Business suits are a standard uniform for male office workers in the United States, regardless of location or season. Long sleeves, vests, coats, and closed collars insulate the body and prevent the dissipation of heat. Consequently, lower air temperatures are required to maintain comfort conditions. Cats, dogs, and horses have the good sense to shed their winter coats in the summer. Don't we?

Standards of hygiene and appearance have also risen significantly over the past few decades, and with them the demands we place on cooling systems. Body odors and perspiration-dampened clothing are no longer acceptable. Popular magazines from the 1940s ran advertisements for absorbant pads to be placed to prevent underarm perspiration from moistening ladies' dresses. Such solutions are generally unheard of today.

On a larger scale, man's actions have changed the environment itself. Trees, shrubs, and grasses shade the ground and either reflect solar radiation or allow winds to dissipate it into the atmosphere. As cities form, buildings and man-made surfaces displace vegetation. Buildings and paved surfaces typically have high absorptance values and retain heat far into the night.

In photosynthesis, vegetation releases huge amounts of water. As liquid turns to vapor and leaves the plant, heat is absorbed. The trees on a residential building site can provide site cooling measured in millions of Btus per day. In contrast, buildings consume energy for lighting, cooling, and equipment and release the waste heat to the air. Essentially all of the energy consumed in a residence or office building leaves the building as heat.

The result of these effects is a significant increase in the air temperatures in cities, commonly 2 to 4°F above the surrounding rural areas. Differences of up to 10° occur frequently. In residences, an increase of only 3° corresponds to an increase of more than 10% in cooling loads.

A portion of our present cooling problem is an inevitable consequence of the climate and the nature of our modern society. However, a large portion of the total problem arises as a result of our indifference to the implications of our habits, lifestyles, and building practices. This indifference was a luxury permitted by the low-priced energy sources of the past. With the reality of present energy costs and the specter of future increases, the need to reassess lifestyles and design practices is clear. Fortunately, a combination of traditional common sense methods, modern materials and mechanical systems, and new knowledge are available to ease the burden. It is possible to maintain comfortable homes and workplaces without excessive energy expenditures. We have a great deal of room for improvement.

COOLING LOADS IN PERSPECTIVE

In attempting to design and operate a building for minimum energy costs, it is important to maintain a broad overall orientation toward the problem. The primary objective is to save energy and reduce costs with the least expenditure of effort and capital and the least inconvenience and compromise of comfort. The first priority should be those alternatives that match this objective best, regardless of whether they are associated with cooling, heating, lighting, equipment, water heating, or some other energy use. When the designer or operator of a building focuses solely on a single aspect of energy use, higher costs and a less than optimum solution are inevitable. Cooling must be considered within the overall perspective of energy consumption and comfort in buildings as only one of several aspects of the energy conservation program. Neither cooling nor any other part of the problem should receive disproportionate attention.

Only in relatively few locations in the United States is cooling the major energy use in residential and small commercial buildings. In the majority of the country and even in the majority of the South, heating is the dominant concern. For well-insulated and weatherized houses in locations where combined heating and cooling degree-days are less than about 4500 per year, water heating can even be the major single energy use. In commercial buildings, lighting is frequently the major load.

Too often, people form a perception of their energy-use patterns based only on the highest month's utility bill, often a summer electric bill that includes air conditioning, water heating, lighting, and miscellaneous electric consumption. While the monthly heating season bills might be lower, they occur over a greater number of months.

Before starting a design or an energy conservation program, an energy budget for the building or the proposed design should be established. At the least, the balance between annual heating and cooling loads and costs should be understood. The distinction between loads and costs must be kept in mind; electricity costs often vary from summer to winter, different energy sources are used for heating and cooling, and the efficiency of the heating and cooling equipment is usually different. Setting altruistic energy conservation goals aside, cost is the fundamental governing force.

An indication of the cooling/heating balance in typical residences is provided by the following information, which was originally developed by Andy Lau and Ted Hyatt at the Southern Solar Energy Center in Atlanta (Ref. 2.1). For 30 locations throughout the country, annual cooling and heating energy loads and costs are calculated for a 1536-ft^2 single-story house representative of the average new house being built. Three different design and insulation conditions are assumed, representing a standard house, an energy-conserving house, and a sun-tempered house that incorporates energy conservation features and basic, passive solar direct gain measures. These loads and costs for electric air con-