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Alternatives to Compressor Cooling in Residences

Helmut Feustel*, Anibal de Almeida†, Carl Blumstein‡

Abstract

Alternatives to compressor-driven air conditioners for cooling residences are reviewed. Methods reviewed include direct and indirect evaporative cooling, desiccant cooling, absorption cooling, natural and induced ventilation, radiative cooling, shading with vegetation, architectural shading, improved glazing, reflective coatings, radiant barriers, sensible and latent heat storage, and earth cooling. Emphasis is given to recent research results, methods for simulating performance, and problems that need to be addressed in future research. A concluding section examines the reasons for the current dominance of compressor technology and identifies research and development needed to make alternative cooling methods more competitive.

Introduction

Today, compressors are so completely dominant in residential cooling applications in the US that it is hard to realize that air conditioners that use compressors are a relatively recent development. Significant penetration of this technology in residential markets did not occur until after 1950 [1,2] §. This technological success has not been without costs. It has increased the energy intensity of the American lifestyle, it has become a key driving factor for the addition of new electric generation, transmission, and distribution capacity, and it has increased the use of chlorofluorocarbons (CFCs). These costs are only partially borne by the beneficiaries of compressor-driven air conditioners; utility capacity costs are borne by all utility rate payers and the adverse impacts of increased energy and CFC use extend to all of the inhabitants of the planet.

Concern with the social costs of compressor-driven cooling has spurred persistent efforts by a number of researchers to find acceptable alternatives. While these efforts have been hampered by weak financial support, they have produced some promising results. These results suggest that alternative cooling methods could provide indoor conditions very similar to those provided by compressors in many, possibly all, US climates. Even for circumstances in which compressors cannot be eliminated, alternative cooling methods appear to offer good means for both downsizing compressors and reducing their

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§According to estimates published in the *Statistical Abstract of the United States*, manufactures shipped 11,000 room air conditioners in 1940. Shipments increased to 201,000 by 1950 and then quickly rose to more than 1,000,000 in the early fifties. In 1954 about 2,000,000 households (about 5 percent) had room air conditioners. By 1987 about 63 percent of households had some type of compressor- driven air conditioner— 26,000,000 households had room air conditioners and 30,700,000 had central air conditioners.

operating times. This paper reviews these research results and discusses research strategies that might lead to further progress.

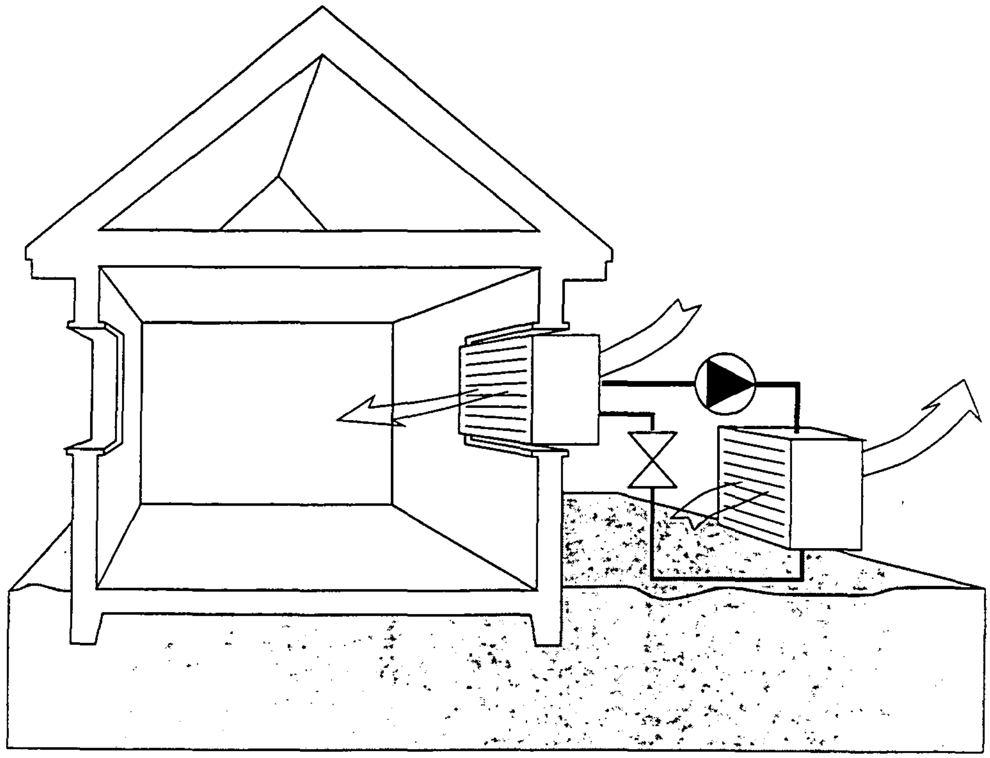

Figure 1: *Schematic of Compressor Cooling*

We have organized our review of alternative cooling methods into four categories based on the physical principles employed: *refrigerant evaporation, heat transport, insulation,* and *storage*. The first category is for processes that use the evaporation of a refrigerant (i.e., the conversion of sensible heat to latent heat). Most of the processes that we consider use water as the refrigerant and are "open cycle" (i.e., the refrigerant escapes to the atmosphere). Direct and indirect evaporative cooling, desiccant cooling, and absorption cooling have been included in this category. The heat transport category is for processes that transport heat away from a building. Natural and induced ventilation and radiative cooling have been included in this category. The insulation category is for measures that prevent the entry of heat into a building. The measures we review in this category are primarily for reducing heat gain from radiation; they include shading with vegetation, architectural shading, improved glazing, reflective coatings, and radiant barriers. The storage category is for methods of accommodating delay between when cooling resources are available and when cooling is needed. In this category we have included sensible and latent heat storage within buildings and earth cooling, which relies on storage in the earth beneath or around buildings.

In the bulk of the paper, we discuss the different alternative cooling methods in isolation from each other. We describe each method briefly, giving special attention to recent research, computer models for performance simulation, and problems that need to be addressed in future research. Our focus on performance simulation derives in part from the fact that most alternative cooling methods are climate dependent and must be tuned to the location where they are to be deployed. Simulation is needed for good design.

While it is easier to describe the alternative methods in isolation, it seems likely that the strategies that will be most successful in displacing compressors will involve combinations of these alternative technologies. In a concluding section on research issues we give attention to the problem of integrating different technical approaches to develop optimal combinations for a variety of micro-climates. This is a second reason for our focus on simulation—we are persuaded that simulation is the only practical means of assessing the many possible combinations of alternative methods.

The concluding section also addresses the reasons for the dominance of compressor technology. We point out that compressor-driven air conditioners have many desirable features including ease of design, relatively low first cost, reliability, and ease of control. These features make the displacement of compressors a more formidable challenge than is sometimes appreciated by proponents of alternative methods. We identify some of the areas where research and development are needed to meet this challenge. We argue that it is important to gain a better understanding of how people use their cooling systems and what people expect from these systems. This understanding is needed to guide technology development efforts. We find that there are many opportunities for technology development and observe that, while alternative cooling methods are sometimes thought to represent a return to the simplicity of the past, the success of these methods may depend on very sophisticated technical developments such as microprocessors, computer aided design, and advanced materials.

Refrigerant Evaporation

This section discusses methods that use the evaporation of a refrigerant for cooling. Most of these methods use water as the refrigerant and are "open cycle." That is, the refrigerant escapes to the atmosphere. Refrigerant evaporation is, of course, also the process used (in a closed cycle) for cooling in compressor-driven equipment. The technologies described here, evaporative cooling, desiccant-based cooling, and absorption cooling, more or less mimic the performance of the compressor-driven equipment. Evaporative cooling only performs well in dry climates, desiccant-based cooling is primarily of interest in humid climates, and absorption cooling has applications in both dry and humid climates.

Evaporative Cooling

Evaporative cooling is one of the oldest cooling methods available. Egyptian frescoes from about 2500 B.C. show the use of evaporation to produce cooling and pre-modern examples of the use of evaporative cooling can be found throughout the Near East [3], [4]. Modern evaporative coolers are mechanical devices that cool supply air either directly by evaporating water into the air or indirectly by bringing the air in contact with a surface that has been cooled evaporatively. In addition to cooling supply air, evaporative cooling can be used to remove heat gain from a building's opaque envelope by inducing evaporation and convection on the exterior surfaces, for example by roof spraying [5]. Evaporative cooling works best in climates where the humidity is low such as in California and the southwestern US. However, because drought is a serious problem in some of these areas, water requirements must be considered as well. We discuss here three types of evaporative cooling: direct, indirect, and roof spraying systems.

Direct evaporative cooling places supply air in direct contact with water (e.g., by passing it through a moistened pad). The supply air's sensible heat is transferred to the water and becomes latent heat by evaporating some of the water. This is an adiabatic process (no heat is gained or lost), but the air temperature falls as its sensible heat is converted into latent heat. In theory, the process can continue until the supply air is saturated with water vapor and its temperature falls to the wet-bulb temperature. For practical reasons, commercial apparatus does not produce completely saturated air. Most new commercial direct evaporative coolers have a saturating efficiency* of about 80 percent [3].

Direct evaporative cooling may be thought of as a means of precooling ventilation air. In normal operation, supply air for a building is drawn through a cooler and into the building by the cooler's fan. It flows through the building, mixing with the indoor air and absorbing sensible heat. Then it is exhausted freely through windows or other apertures. During this process the temperature of the supply air rises (usually 3 to 6 °C) and its relative humidity decreases. Comfortable indoor temperature and humidity conditions can be achieved in this way in many warm climates. However, when outside air is humid, the cooling effect is decreased—excessive supply-air flows may be required, or satisfactory indoor conditions may be impossible to achieve.

In indirect evaporative cooling, supply air does not come into direct contact with water, as it does in the direct method. Therefore, with indirect evaporative cooling, the air's moisture content is not increased. Many different systems have been developed to indirectly cool supply air using heat transfer between two fluid streams [3]. For example, supply air (the primary air) may be passed through the inside of an array of tubes. The outside of the tubes is lined with fabric and moistened by a continuous spray or drip. Secondary air is blown over the tubes, cooling them by evaporation [6].

*The saturating efficiency $E_s = (T_1 - T_2)/(T_1 - T_3)$ where T_1 is the entering dry bulb temperature, T_2 is the leaving dry bulb temperature, and T_3 is the entering wet bulb temperature.

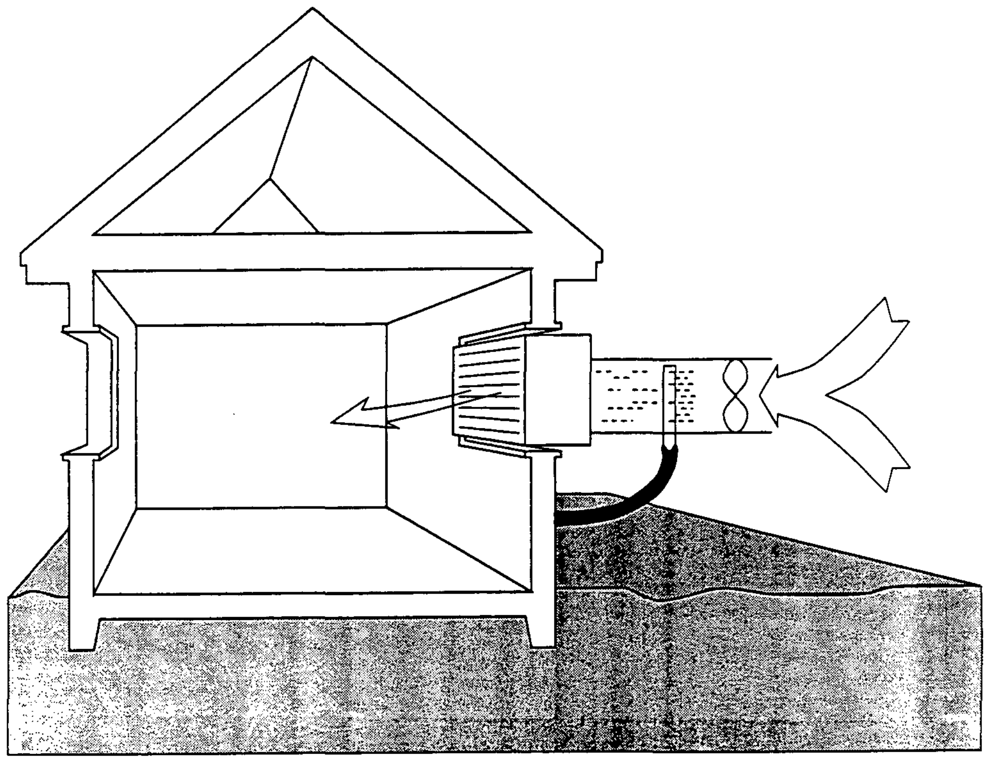

Figure 2: *Schematic of Direct Evaporative Cooling*

Since the moisture content is not increased by indirect evaporative cooling, the once-through ventilation required with direct evaporative cooling is not necessary; air cooled by an indirect evaporative cooler can be recirculated in the same manner that air is recirculated with compressor-driven systems. Regenerative indirect evaporative coolers split the primary air flow, diverting some of it to the wet side of the heat exchanger. This is essentially a method for precooling secondary air. Temperatures below the wet-bulb temperature can be achieved in this way [7]. Temperatures below wet bulb can also be achieved by coupling direct and indirect coolers. A common arrangement is a two-stage unit, in which incoming air is first cooled in an indirect unit and then further cooled in a direct unit before entering the building. This arrangement increases the moisture content of supply air and thus its application does require once-through ventilation.

Evaporative roof spraying cooling systems have been used successfully in industrial buildings and a few commercial buildings to decrease the solar heat gain. Water is distributed to the roof by a network of pipes and low-volume sprayheads; each sprayhead typically covers 10 m^2. The water used can come from a water utility; it is preferable, however, to use well or waste water. Water temperature is not critical because most cooling is provided by the latent heat of evaporation. An installed roof spray cooling system costs about $3/m^{2}d [8].

The spraying system is normally activated by a programmable controller, distributing a thin, uniform film of water on the roof. A dry roof is a large solar heat absorption panel, but a sprayed roof operates at or below ambient temperature. During at least part of the day, the roof can act as a heat sink for the building. Reduction of building cooling load is a function of roof insulation and the roof-to-floor ratio. Poorly insulated and single-floor buildings benefit most from roof spray cooling. Roof spraying can reduce an unairconditioned building's interior temperature by up to 3.3°C. In buildings with mechanical air conditioning, cooling loads are typically reduced by 20-25 percent. The lifetime of roof materials is normally extended by roof spraying because thermal cycling stress on the materials is reduced. To avoid wasting water, microprocessor-based controls coupled to temperature and humidity sensors can feed the exact amount of water that will be evaporated.

There is little experience with roof spraying of residential buildings. A recent demonstration project in Davis, California couples roof spraying with a roof solar pond covered by a floating insulated cover [9]. This system is expected to reduce cooling energy demand by 54 percent.

Huang, et al. [10] have reported the development of models for both direct and indirect evaporative cooling that are linked with the building energy simulation program DOE-2. The model for direct evaporative cooling uses a curve fit of data from field measurements performed at Arizona State University. Pad thickness and air flow velocity are used to estimate the saturation effectiveness. For indirect evaporative cooling, Huang et al. developed models for plate- and tube-type equipment calibrated against manufacturers' data. For two-stage configurations, both models for direct evaporative cooling and indirect evaporative cooling are combined.

Huang, et al.'s numerical models were used to estimate energy savings resulting from replacement of compressor driven cooling with evaporative cooling equipment in California residences. The simulation runs show good results for a prototypical residential building equipped with direct evaporative cooling in moderate climates. In Pasadena, California, for example, direct evaporative cooling would be sufficient to cool the house for all but six hours per year, reducing the electrical energy consumption by 87 percent. Results for two-stage indirect/direct evaporative cooling indicate that this technology can replace compressor-driven cooling in most California climates, apparently without comfort penalties [10].

Turner and Chen [11] have reviewed the literature and surveyed researchers and industry representatives to identify research needs in the area of evaporative cooling. They found the high cost of indirect evaporative coolers to be a key barrier to the acceptance of this technology in the residential sector and one of their recommendations is for research aimed at the development of low-cost heat exchangers for this equipment. Other recommendations address life cycle cost studies, maintenance, controls, public acceptance, health issues, and standardized measures of equipment performance.

Water requirements for evaporative cooling are a major concern in the dry regions where the technology can be most effective. Wu [12] reports water consumption of 327 l per hot day to cool a single-family house in Arizona with a two-stage evaporative cooler. A compressor-driven cooler would use 41.3 kWh for the same house, 28.7 kWh more than the two-stage evaporative cooler. Some anecdotal reports suggest that the water consumed by evaporative coolers is less than would have been used in power plant cooling towers to produce the saved energy. However, in view of the importance of this issue for the regions involved, more work is needed to evaluate the effects of large scale use of evaporative cooling on water supply.

Desiccant-Based Cooling

Desiccant materials absorb water or water vapor from other materials [13], [14]. A material commonly used for this purpose is silica gel, normally found in packages of electronic and optical equipment to remove the moisture. Desiccant materials have traditionally been used in industrial applications that require very low humidity levels and for which conventional compressor dehumidification is not efficient.

After a desiccant is saturated with moisture, the moisture must be removed so that the desiccant can be reused. This is usually done by heating the desiccant material, an energy-intensive process. Some desiccant materials on the market can withstand thousands of cycles without degradation. Some of these materials also perform well with low temperature heat (80°C) such as that provided by solar heating or waste heat systems. The use of solar heat is the reason for much recent interest in desiccant systems.

Residential systems using desiccant materials can provide cooling as well as dehumidification. This unit uses evaporative coolers and desiccant materials. Incoming air is dried by the desiccant material to a very low humidity level; the air is then blown on the wet pads of the evaporative cooler to decrease its temperature. This unit was designed to provide 10 kW of cooling capacity and 10 air changes per hour (ach). The desiccant is contained in a slowly rotating wheel and is regenerated by heat from hot water provided by a solar or a gas heater.

Desiccant-based cooling systems seem most appropriate for hot, humid climates where dehumidification is necessary for comfort. Many of the most densely populated regions in the world have hot, humid climates and most of these regions are in developing countries. Development of solar-driven desiccant systems is therefore of considerable interest to those concerned with the energy problems of these countries.

Absorption Cooling

Absorption cooling was developed in by Carl Munters and Baltzer Von Platen during the 1920's, in Sweden. Absorption cooling uses a closed cycle shown schematically in Figure 3. A generator contains a mixture of two fluids (such as NH_3/H_2O or $LiBr/H_2O$), one of the fluids acts as a refrigerant and the other as an absorbent [15].

When heat is applied to the generator, the refrigerant is distilled from the absorbent, migrating to the condenser, where it converts to liquid and releases heat to the air or to a water heat exchanger. The liquid refrigerant then goes through an expansion valve into the evaporator where the heat of the medium being cooled evaporates the refrigerant, creating a cooling effect. The refrigerant vapor then migrates to the absorber, and is absorbed by the the mixture of the two fluids, releasing heat to the outside. A forced circulation loop carries weak absorbent solution (i.e., solution with a high concentration of refrigerant) to the generator and returns strong absorbent (low concentration of refrigerant) to the absorber. The heat applied to the generator can come from several sources, including natural gas or solar [16].

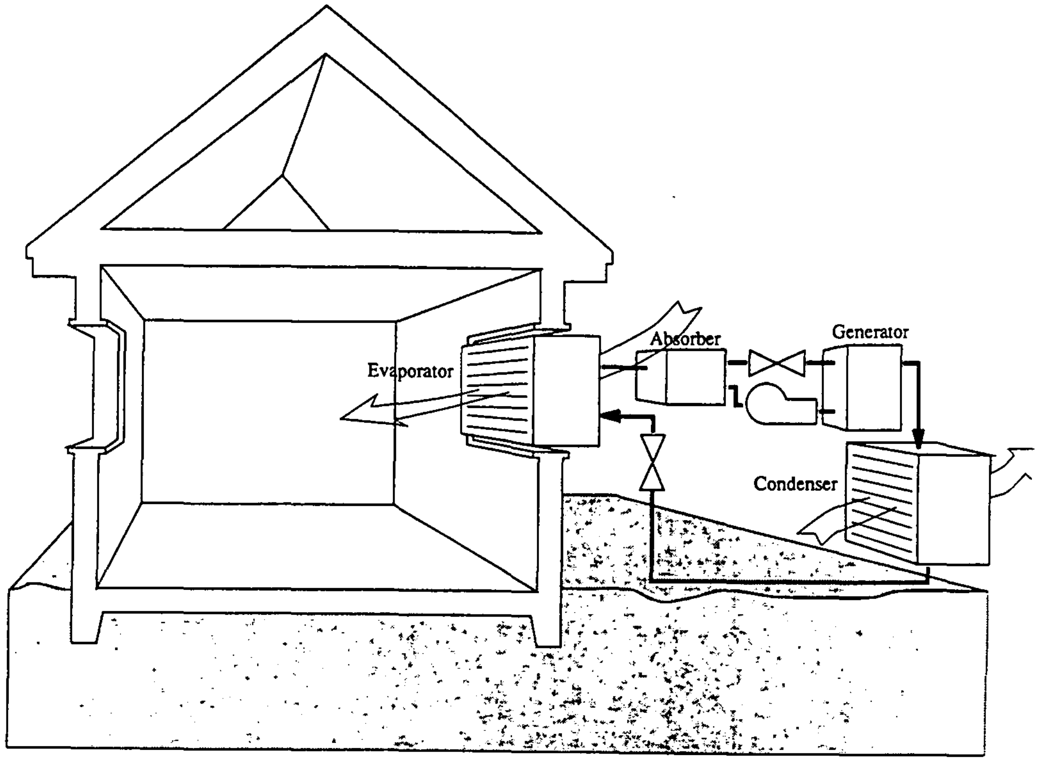

Figure 3: *Schematic of Absorption Cooling*

The fluids used in absorption cooling equipment do not pose the same environmental hazards (depletion of the ozone layer and contribution to global warming) as the CFC compounds used in compressor coolers. Because the use of CFCs is being phased out during the 1990's, research on absorption cooling may increase.

The absorption cooling unit described above has low efficiency; the maximum COP value achievable in practice is about 0.7. Residential absorption units on the market feature a modest COP of 0.5. Double-effect and triple-effect units can present higher COPs. Batelle-Columbus Division has developed a prototype, residential, double-effect, absorption heat pump that features a ten kW cooling capacity and heating and cooling COPs of 1.8 and 0.94 respectively [17]. Similar advanced units have been developed by leading air conditioner companies. Oak Ridge National Laboratory has developed triple-effect absorption chillers that have the potential to reach a COP of 1.5 in the near future.

Existing residential absorption cooling equipment, costs about $150-170 more per kW cooling capacity than electric compressor cooling equipment, and has a cost of conserved peak kW of $400-500. This is projected to remain true for the prototypes mentioned above. The difference in the running costs between absorption and electric compressor equipment will depend on the relative COPs and the prices of gas and electricity. If gas units with a COP close to 1 become available and if time of use rates are introduced for residential customers, absorption units may become serious competitors in the residential cooling market. Absorption chillers are already being successfully used in large commercial buildings where demand and rates are both high [18]. Absorption heat pumps are particularly attractive in areas with both cooling and substantial heating seasons.

Heat Transport

This section discusses methods for transporting heat away from a building via ventilation or radiation.

Natural and Induced Ventilation

Ventilation is often used for cooling in warm climates. We distinguish between two methods: a) direct cooling ventilation—ventilation air is supplied when cooling is desired, and b) thermal storage ventilation—ventilation air is supplied primarily during non-cooling periods to reduce the temperature of the thermal mass of the building. Direct cooling ventilation works by removing internal heat gains (i.e., by keeping the indoor temperature from rising much above the outdoor temperature). In residences, solar heat gain is typically the largest source of heat gain. The cooling effect of direct ventilation is enhanced because people feel cooler when air is moving over them. This is in part a result of air motion increasing the rate of evaporation from the skin. The direct method is used typically in climates that are not extreme (outdoor temperatures below 32°C) and that have small (less than 10°C) diurnal temperature swings. For example, it appears to work well in Hawaii. Thermal storage ventilation (discussed further in the section on "Storage") only works in climates with large diurnal temperature swings. Air is supplied to the building during cool periods, both cooling the indoor air and storing "coolth" in the structure. Ventilation is stopped when the outdoor temperature rises. The indoor temperature rises more slowly than the outdoor temperature because the cool structure absorbs heat from the indoor air.

Both methods of ventilation cooling may be either natural (i.e., wind and/or thermal gradient driven) or induced (i.e., fan driven). Induced ventilation must be used when the natural driving forces are inadequate or when the large openings in the building envelope that are required for natural ventilation would create an unacceptable security problem. Induced ventilation is also easier to control automatically. A further advantage of induced ventilation is that exhaust air can be blown through the building's attic, cooling this space, which is usually much hotter than the rest of the building, and thus reducing heat transfer through the ceiling. Disadvantages of induced ventilation as compared to natural ventilation include noise and power consumption of the fan and, usually, higher initial cost [19].

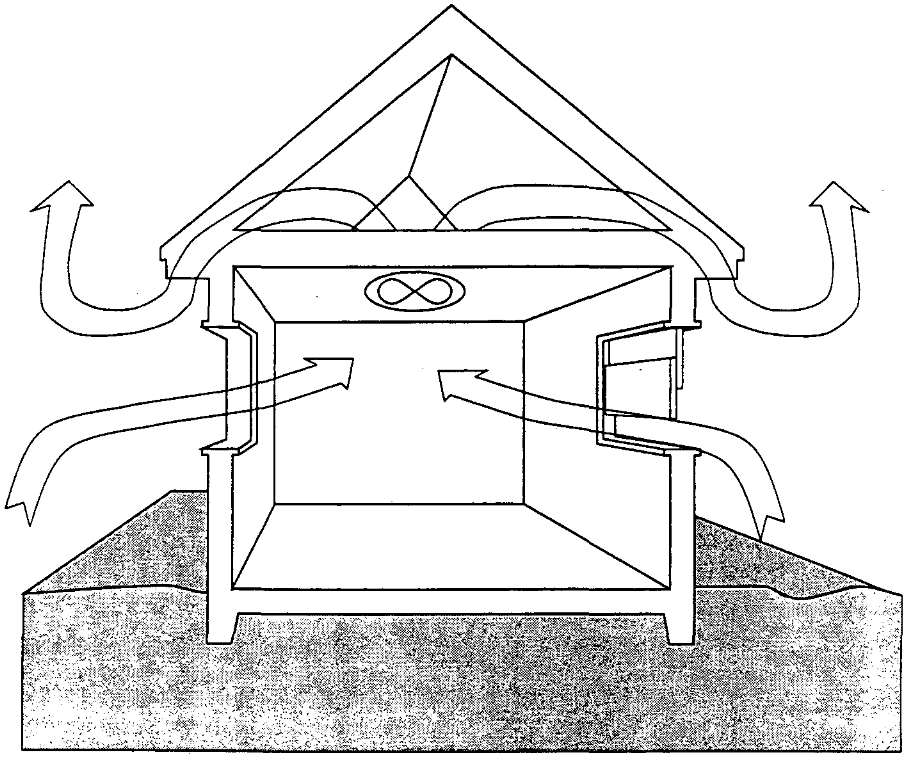

Figure 4: *Whole-House Fan Installation*

Most thermal building simulation models do not calculate the indoor air-flow distribution resulting from wind, thermal buoyancy or HVAC systems in buildings. The overall infiltration/ventilation flow rate for a single-zone building, however, can be calculated using the simplified LBL-model incorporated into the building simulation model DOE-2. Models are available to calculate air flows and distribution in multizone structures, but these have not been linked with building simulation models. DOE-2 in its standard configuration cannot simulate changes in air flows based on temperature criteria using either manual control of window opening or whole-house fans. However, the latest version of DOE-2 allows development of functions; this feature might be used to create control strategies for whole-house fans.

An algorithm for natural ventilation for cooling purposes was developed by the Florida Solar Energy Center (FSEC) [20] and implemented in TARP, a building simulation program developed by the National Bureau of Standards. Byrne et al. [21] show the impact of wind induced ventilation on residential cooling load and human comfort for different climates, providing a design tool for buildings in hot climates.

Research on the prediction of indoor air motion for occupant cooling is being conducted at the University of California at Berkeley [22]. This work takes wind characteristics, wind pressure distribution, interior room partitions and geometries and the size of the opening area as well as, its geometry, and distribution, into account. Simplified correlations have been developed that allow prediction of air motion based on wind pressure distribution obtained in wind tunnel tests.

The BLAST building load simulation model was used by Ford [23] to model whole-house fan performance. The whole-house fan has been described as a mechanical ventilation system. When there is no additional cooling source, manual interventions and interactions are necessary to control the whole-house fan operation. Ford mentions a graphical method, developed by Baer [24] to predict thermal behavior of a building cooled by whole-house fan ventilation.

There are several problems with existing performance simulation methods for ventilation. The performance of thermal storage ventilation depends in part on the rate of heat transfer between the ventilating air and the structure. The dominant heat transfer mechanism is convection and the convection coefficients depend on the velocity of air moving over the surfaces of the structure. However, from Chandra and Kerestecioglu [25] as well as Clark [26], we learn that simulation models usually use convection coefficients based on an air flow velocity of zero. Givoni [27] states this explicitly for DOE-2. In parametric studies using the simulation program BLAST, Akbari et al. [28,29] show that variation in convection coefficients has significant effect on thermal energy storage in interior partition and exterior walls. Under these circumstances, the cooling effect from natural ventilation as calculated by thermal building simulation models is very questionable. Additional research is needed on estimation of air flow rates and the effect these rates have on convective heat transfer. The effect can only be studied with simplified models because the three-dimensional air flow models necessary to calculate accurately the heat transfer coefficients resulting from air movement are too time-consuming for this task.

While it is well established that the increased air velocities that result from ventilation can extend the range of comfortable temperatures, there is uncertainty about how to quantify this effect. Field studies of occupant comfort in ventilated environments and studies of the effects of air turbulence on comfort in warm environments are needed to help define acceptability criteria.

Radiative Cooling

Radiation always takes place between objects facing each other directly; geometry, area, distance, emittance of radiant object, and the temperature difference between the two objects have an effect on the radiant heat transfer. Cooling occurs for the object that has a negative net energy exchange. The cooled object might be a rooftop or a specially designed radiator. The second "object" is usually the clear sky, which provides a potential heat sink [19], [30].

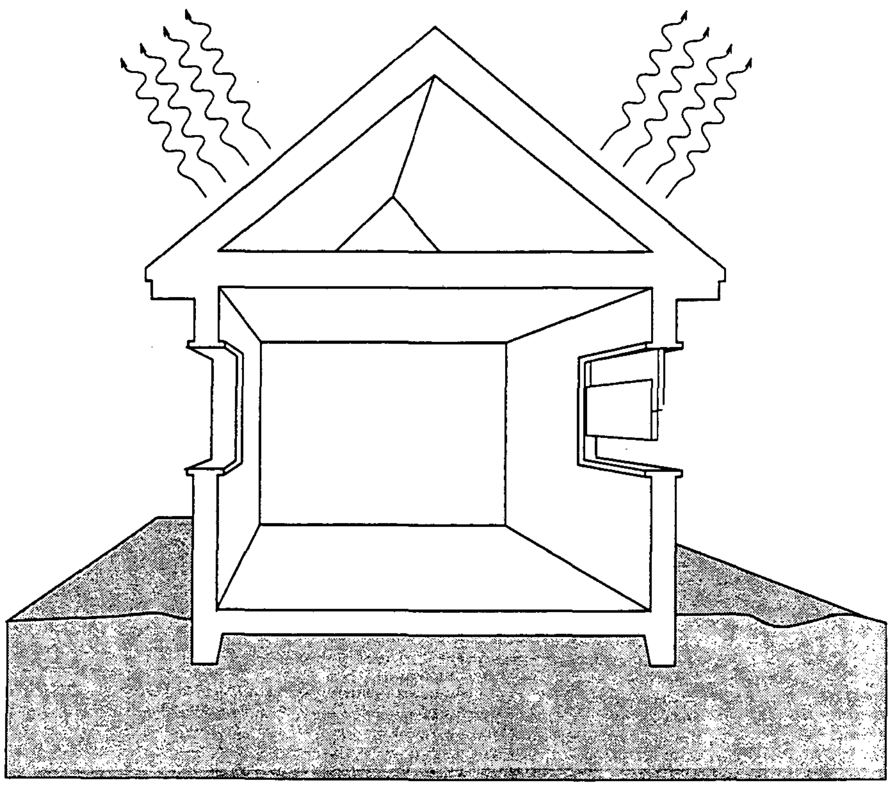

Figure 5: *Radiative Cooling*

Sky temperature determines the effect of radiant cooling; in hot, humid climates sky temperature is often determined by cloud temperature, which is usually much higher than the temperature of a clear sky. In dry climates, sky temperatures are much lower. For example, except for foggy coastal areas, California's summer sky temperature averages more than 10°C cooler than the ambient temperature [31]. The emissivity of most non-metallic roofing materials is for practical purposes independent of surface color or texture [32]; color is not important in radiative cooling.

Key requirements for radiative cooling are: 1) because sky temperatures are lowest when cooling needs are also low, some form of storage is needed, 2) the radiator must be protected from solar heat gains during the day, and 3) the radiator must be protected from convective heat gains at all times. A variety of solutions to these problems have been investigated [30]. The approach that has received the most attention is the roof pond.

The roof pond system uses water (usually enclosed in plastic bags) as both radiator and storage medium. Movable insulation covers the pond during the day, blocking solar radiation and reducing convective heat gain. Experiments indicate that the wind speed just above the boundary layer (typically several inches thick) of a roof pond residence in an urban area is typically only one tenth of the meteorological wind speed. Cooling of the interior space is by radiation and convection to the ceiling. Roof ponds have been demonstrated at a number of sites and researchers have concluded that these systems can provide comfortable conditions in a wide range of climates provided that they are combined with ceiling fans and, in humid regions, with some type of dehumidification [26]. The biggest drawback of roof ponds is that they involve construction that is very different from conventional practice. Although they have been available for two decades they have not found acceptance in the market.

Radiative cooling can be described by the basic equation for radiant heat transfer. Several algorithms have been developed to simulate the performance of integrated systems (e.g., Ito and Miura [33], Givoni [34]), but they have not been incorporated into basic simulation models. A model calculating the performance of a radiative cooling system including its stagnation temperature has been developed by Ingersoll and Givoni [35].

Insulation

While the word "insulation" usually calls to mind fiber-glass batts or other materials for reducing conductive heat transfer, these materials are not the subject matter of this section. Here we are concerned with reducing heat gains from radiation; several strategies with this objective are reviewed.

Shading with Vegetation

Buildings' thermal performance can be significantly affected by vegetation. There are at least three ways of using vegetation to reduce the cooling load for a building: 1) vegetation attached to the building (e.g., ivy), 2) vegetation around the building, which reduces ambient temperatures through evaporation and radiation, and 3) vegetation that shades the building during sunshine hours.

Planting trees, shrubs, and ivy around buildings is a familiar strategy to limit solar gains and to create a comfortable indoor environment [36]. The value of landscaping in reducing cooling loads has not been well documented. However, the few attempts that have been made to measure the effect have shown consistently large savings. Meier [37] concludes that the available measurements "... suggest that the careful application of shrubs, trees, and vines could reduce cooling electricity use by 25-50 percent."

Shading is only one of several processes by which trees and vegetation influence cooling loads. Other effects that reduce cooling load are: 1) reduction of longwave heat gain because surface temperatures are lower than impermeable surfaces such as asphalt and concrete, 2) reduction of conductive and convective heat gain because outside air temperature is reduced by plant evapotranspiration, and 3) reduction of heat gains from infiltration because windspeed is lowered. Effects that increase cooling load are: 1) reduction of net outgoing longwave radiation because the night sky is obscured, 2) increase in latent cooling load because of plant evapotranspiration, and 3) reduction in natural ventilation potential and convective heat loss because of reduced wind speed [38], [39].

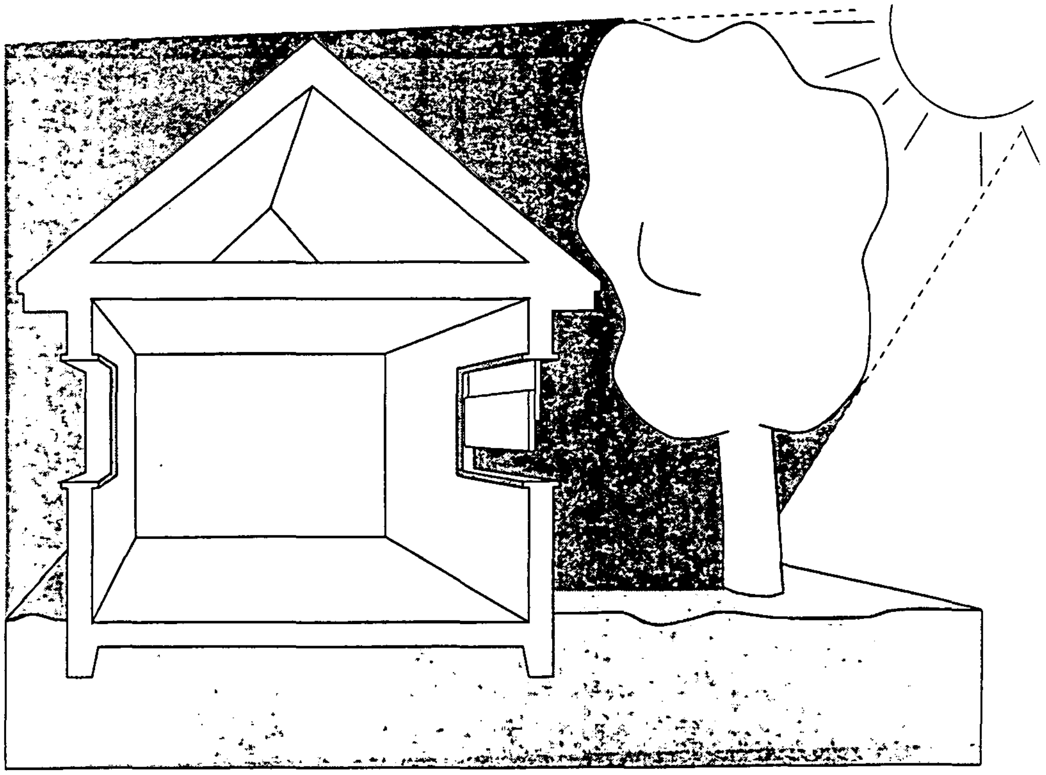

Figure 6: *Shading with Vegetation*

Water requirements for vegetation are a matter of concern in dry climates. Evapotranspiration from a tree can consume up to 380 l of water a day [38]. (Note that this is about the water requirement for an evaporative cooler on a hot day.) If sub-surface waters cannot meet the needs of vegetation, the costs of water can be significant. In some cases, savings produced by vegetation from reducing mechanical cooling may be more than offset by increased irrigation water costs [40].

Precise prediction of the effect of landscaping on cooling energy use is very difficult because the heterogeneous optical characteristics of the plants, the exchange of long-wave radiation between the building and its cultivated surroundings, the established microclimate, and wind shielding are difficult (or impossible) to describe mathematically [37]. However, fairly good approximations are possible and several models are available. They range from simple approaches (e.g., simulating vegetation by a screen with limited transmittance [41]) to more sophisticated models used by Holm, by McPherson et al., and by Huang et al.

Holm uses the dynamic computer model DEROB (dynamic energy response of buildings) to simulate the thermal effect of deciduous and evergreen vegetation cover on exterior walls. DEROB was begun by Arumi-Noe at the Numerical Simulation Laboratory of the University of Texas in 1972-73 and was further developed by Higgs and others into DEROB-IUA (International Users Association) [42]. The model is for passive solar design. McPherson et al. used MICROPAS and SPS to test the effect of irradiance and wind reductions on the energy performance of residences in four U.S. cities—Madison, WI, Salt Lake City, Tucson, and Miami. MICROPAS is a microcomputer-based building energy simulation program that provides hour-by-hour estimation of building energy use based on specific weather data and a building's thermal characteristics and occupant behavior [39]. Irradiance reductions from vegetation have been modeled using SPS, which simulates shade cast by plants onto buildings. SPS was developed to calculate hourly shading coefficients for each building surface, which overcomes a limitation of MICROPAS (MICROPAS only simulates shading for glazed surfaces). To calculate shading coefficients, SPS uses the geometrical relations among the sun, plants, and the building, as well as plant shape and plant canopy density [43]. Huang et al. [38], [44] used DOE-2 in their modeling efforts. Shading effects were approximated by treating trees as exterior building shades. Wind-shielding calculations used an empirical correlation between wind-speed reduction and tree canopy density derived from data obtained by Heisler [45]. Huang et al. are the only group to attempt to model the effect of evapotranspiration. Their results suggest that this process is quite important, with a cooling effect in dry climates that may be larger than the effect of shading.

The effect of evapotranspiration on cooling load needs further examination. While the work of Huang et al. suggests that the effect may be quite important, improvements in their model and verification of their data on evapotranpiration rates are needed before the magnitude of the effect can be assessed with confidence. The model assumes that evaporatively cooled air is well mixed in a volume that is bounded above by the average mixing height (a height on the order of 1 km); localized effects of evapotranspiration are not captured in this formulation. Huang et al. used potential evapotranspiration rates (a measure of the theoretical amount of evapotranspiration possible assuming an ample supply of water) obtained in an agricultural study. They note that actual rates for urban trees may be very different from the potential rates for crops.

Plants take time to grow, they may require considerable maintenance, they are often vulnerable to extremes of temperature, and they are subject to depredations from disease and insect pests. These are serious inconveniences from the cooling system designer's perspective but they are usually more than compensated for by the other values that landscaping brings to a residential setting.

Glazing and Architectural Shading

The high intensity of direct solar radiation makes it by far the most significant external source of cooling loads [46], [47]. Direct solar radiation that contributes to cooling loads is transmitted through windows and is absorbed by the building walls and roof and then conducted and convected to the interior. Although windows typically cover a relatively small fraction of a buildings surface, heat gain through them can be very significant because conventional windows offer very little resistance to radiant heat transfer [48]. However, daylight admitted through windows can be advantageous as it contributes to interior illumination, and reduces the need for electric lighting. This not only saves lighting energy but can reduce cooling requirements if excessive light is not admitted because the daylight distribution can provide an overall better efficacy, i.e., lumens/watt, than an electric lighting system.

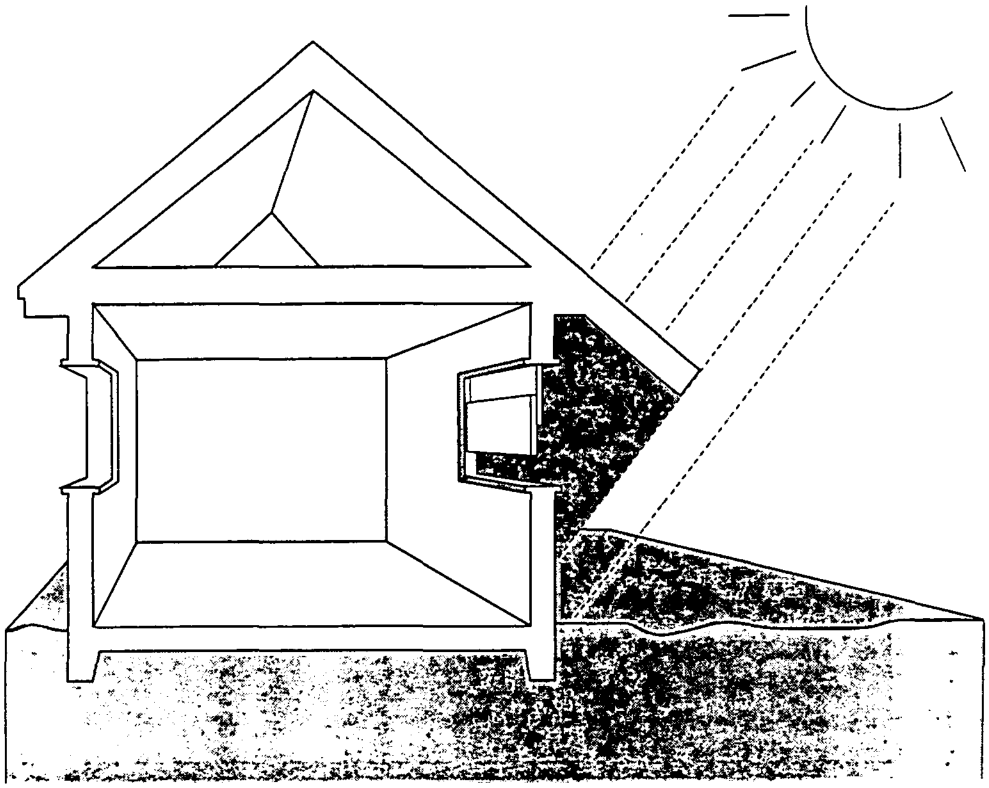

Figure 7: *Architectural Shading*

Strategies for reducing cooling-season heat gains through windows must address the interactions among summer gains, daylighting, winter gains and losses, and aesthetics. The starting point is proper placement and sizing of windows. Design can be challenging, especially when an aesthetic value, such as a west view, is a constraint [49]. New glazing technologies, better shading techniques, and improved design tools can offer designers more options for enhancing aesthetic values and reducing energy consumption.

Glazing technologies to reduce cooling loads mainly try to decrease solar transmittance and then solar absorptance. However, because transmission of the visible part of the solar spectrum may be desirable for daylight utilization, the latest glazing technologies involve media that transmit and reflect selectively. These developments started as modified versions of low-emissivity (low-e) glazings. Low-e glazings are nearly opaque to far-infrared radiation, which is important for reducing heat gains by radiation from the surroundings (e.g., adjacent buildings) but has little effect on gains from direct sunlight, where the energy is concentrated in the visible and near-infrared regions. Products now available include some reformulated green and blue tinted glazings that are nearly opaque to near-infrared radiation. Once fully developed, these coatings will offer designers aesthetic options with solar gain reductions of 30 to 50 percent.

The latest research in glazing technologies is on glazing systems with controllable solar-optical properties that can be adjusted according to solar dynamics and desired indoor conditions. Although research and development in switchable glazing technology is promising, it will not be commercially available for more than five years.

Shading devices reduce direct solar transmittance to zero. The heat-trapping properties of glass, which cause the familiar greenhouse effect, mean that external rather than internal shading devices are preferable for reducing cooling energy consumption. Shading devices may be fixed or adjustable, manual or automatic. The selection of a shading device for a particular application is based on sun positions relative to the window during the course of the year, especially during the period of cooling loads. The sun's relative position is a function of the orientation of the window and the sun's paths, which depend on the local latitude.

In addition to simple vertical architectural elements, integral or add-on parts of window systems are available for shading. These are usually classified as awnings, external blinds and louvers, shutters, shades, and screens [50]. A small number of double- or triple-glazing systems are equipped with blinds between the glass panes. Finally, a large number of internal shading devices are available in the form of blinds and louvers, shutters, shades, drapes, and screens.

Various algorithms, simplified and sophisticated, have been developed to estimate heat transfer through a building's envelope [51]. As the cost of computational power decreases, the accuracy and modeling capabilities of the algorithms increase, especially for the purpose of determining solar heat gain and indoor daylight illuminance levels. The latest version of the DOE-2 energy analysis program [52,53], currently under development, includes the WINDOW heat transfer program [54,55] that computes the solar-optical properties of any glazing system based on first physics principles [56]. Moreover, a future version of the WINDOW computer program will account for the combined effects of shading devices, and the new version of the DOE energy analysis program, DOE-2.1E, will even model electrochromic, photochromic, and thermochromic glazings.

In addition to computer-based techniques, manual procedures involving the projection of the sun's path on to "shading masks" have been used to determine the shading performance of shading devices [46]. However, these manual techniques provide very limited, if any, quantitative information on actual loads. As computers are used more in the building design industry, manual techniques are being replaced with software models that provide more detailed and accurate data.

Exterior shading devices are more effective at cooling a building than interior ones are. However, because they are exposed to weather elements, they require more durable materials and better construction and maintenance than interior devices. Operable shading systems are usually more effective than fixed ones, if they are operated properly. This is often not the case when operation is left to building occupants, who may be motivated more by convenience than by energy concerns. Automatic controls are thus increasingly common.

Accurate modeling of dynamic heat transfer through window systems that incorporate complex shading devices, e.g., Venetian blinds, is not yet widely available. Accurate modeling is especially rare for operable shading systems where the operation strategy may significantly affect performance. However, modeling methods combining both analytical and experimental procedures are being developed [57]. Such sophisticated methods require detailed, angle-dependent, solar-optical properties of window components and systems that are not yet widely available [58].

Solar radiation availability data are not detailed and accurate enough to satisfy the detailed input requirements of the more sophisticated models. Such data need to be generated for the radiance distribution of the sky. Moreover, algorithms to account for the radiation exchange among exterior surfaces to determine their radiance distribution need to be integrated with available solar heat gain and daylighting models.

Reflective Coatings

Light-colored surfaces are effective and inexpensive measures to reduce buildings' surface temperature and thus summer cooling energy needs. Light colors decrease surface absorption of short-wave radiation, thereby reducing surface temperatures and convective heating of air near the surface [59], [60]. Figure 9 shows a simulation of the effect of color on the surface temperature for a building in Washington, D.C. on the design day in July [61]. Simulations of a residential building in Sacramento, California suggest that increasing the albedo (i.e., the ratio reflected to incident radiation over all wavelenghts of solar radiation) of a well insulated house from 0.30 to 0.90 will decrease the cooling load by about 20 percent [60].

Light-colored building envelopes are most beneficial for buildings with a low insulation level [60]. Reduced surface temperatures reduce conductive heat transfer through the walls and ceiling and thus produce lower inside surface temperatures. Insulation also reduces conductive heat transfer and thus decreases the benefit of the lower surface temperatures that result from reflective coatings.

The effect of surface temperature on conductive heat gain is well understood and is a routine feature of building simulation models. In contrast, little is known about the effect of the interaction between surface temperature and the air immediately surrounding buildings. It is possible, for example, that when the surface temperature is high, air infiltrating into a building is heated significantly by contact with the building's exterior surfaces. This would lead to higher heat gains from infiltration than would be predicted by the usual assumption that the temperature of infiltrating air is the outdoor ambient temperature. But this effect has not been measured or modeled.

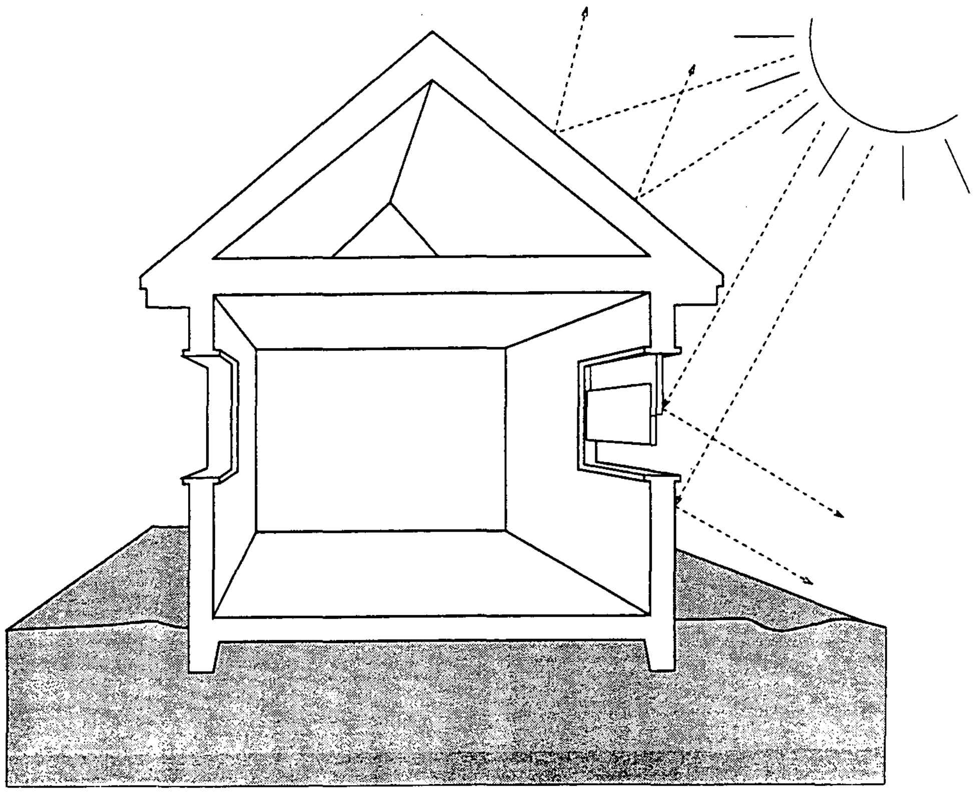

Figure 8: *Reflective Surfaces*

Recent work suggests that reflective coatings can have a significant effect on cooling load by altering climate on a meso scale. Akbari et al. [59], [60] examined the effect of increasing the albedo of a city by increasing the reflectivity of both structures and other surfaces such as streets and parking lots. In climate simulations for the city of Sacramento, they obtained a drop in temperature of about 1-4°C, depending on time, by increasing the albedo from 0.25 to 0.40. From simulations of a residential building, they concluded that these reduced temperatures could reduce the cooling load by more than 40 percent.

Radiant Barriers

The use of radiant barriers in attics in order to reduce cooling loads has generated widespread controversy, which might be the result of exaggerated performance claims by manufacturers and limited field experience with this technology [62]. Radiant barriers are installed in attics to reflect back long-wave radiation received from the roof, so there is no significant temperature rise in the barriers. Their impact depends on attic ventilation and ceiling insulation.

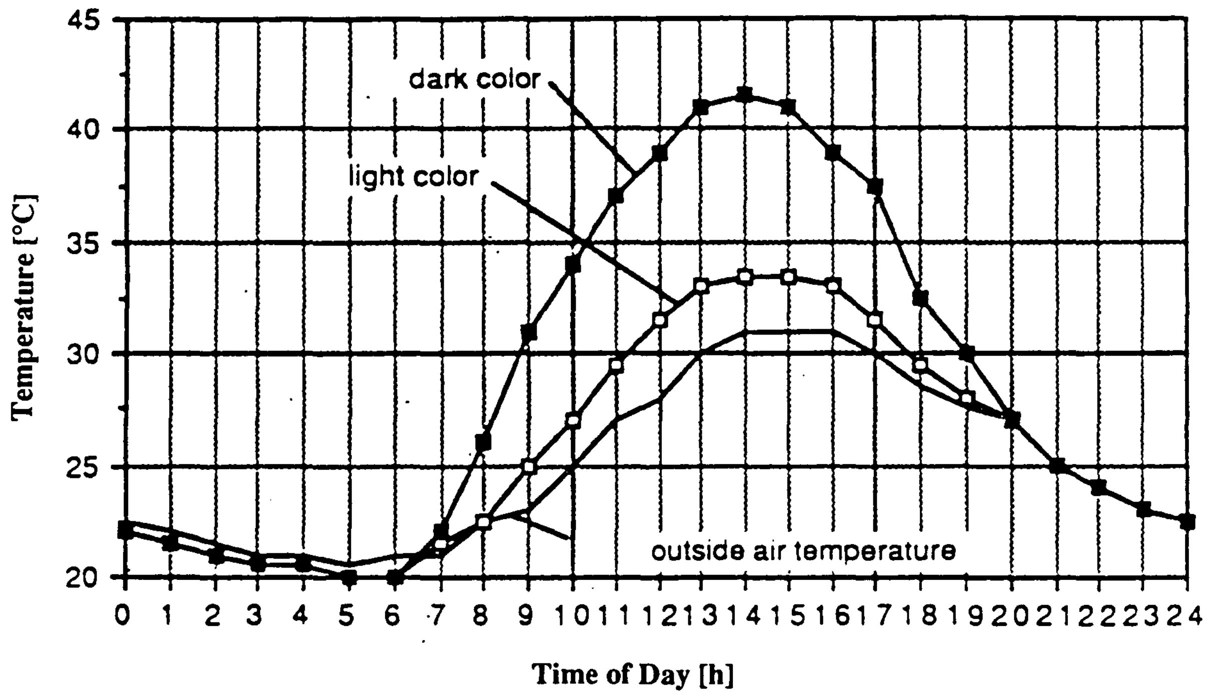

Figure 9: *Exterior Surface Temperature depending on the Color of the Surface [61]*

Several problems are related to this technology, including: 1) deterioration of long-term performance of radiant barriers, for example, as a result of dust build-up in a horizontal installation, 2) danger of condensation on barriers, and 3) overheating of and possible damage to exterior roofing if reflected heat cannot be removed from the attic.

A routine that simulates the impact of radiant barriers on heat transfer from roofs to ceilings has been developed by the Davis Energy Group. With MICROPAS, this routine has been used to demonstrate the potential effectiveness of radiant barriers [63,64]. Unfortunately, it appears that insufficient data are available to evaluate the model for all climates. Data obtained by Wu [65] covers only horizontal installations, which are not suggested by the Reflective Insulation Manufacturers Association because of dust buildup. Fairey [66] reports on the performance of aluminum foil that was glued to bottom surface of the roof decking. Wilkes [67] introduced a model developed at Oak Ridge National Laboratory that is based on the Stefan Boltzmann law. The model has been tested using data obtained in a number of laboratory and field tests with clean horizontal radiant barriers. Comparison with test data shows that the model predicts the heat flows to within 10% of their measured values.

Storage

Thermal energy storage is a means of accommodating delay between the availability of cooling resources and the need for cooling. This section reviews methods for thermal energy storage within buildings and for earth cooling, which relies on storage in the earth beneath or around buildings.

Storage within Buildings

Storage within buildings requires some storage medium. The use of extra thermal mass (e.g. plaster in place of drywall) or special features such as pebble beds or a massive concrete wall is usual in residences that are designed with thermal energy storage in mind. But, such features are not essential for all thermal energy storage strategies; normal building materials and construction practices can suffice, particularly in mild climates. Both the charging and discharging of the storage medium can be either passive or active. The passive/passive case corresponds to thermal storage ventilation (cool night air removes heat from the structure and then the structure absorbs heat during the day). A passive/active combination may be used when night air is too cold for continuous night ventilation of the structure. The cold air can be directed to an isolated storage medium (e.g., a pebble bed) and then, when necessary, heat can be absorbed by the medium (e.g., by blowing air through it). Active charging of storage typically involves use of compressors.

Independent of the size, desirable properties for thermal storage materials are [68]: large heat capacity per unit mass, per unit volume, and per unit cost, complete reversibility for a great number of cycles, temperature uniformity, long life, low toxicity, and low risk of fire.

The major characteristics that determine choices of thermal energy storage systems are: the capacity, the temperature range over which a system operates, the energy transport medium properties, the temporary stratification in the storage unit, the material container associated with the storage system, the means of controlling thermal losses from the storage system, and the system's cost.

From the temporal point of view there are two types of thermal storage: short-term and long-term storage. Short-term storage provides a reservoir of energy that can adjust for small phase differences between local energy supply and local demand. Long-term storage can aid in meeting seasonal demands [68]. In building applications, short-term thermal energy storage is much more common than long-term storage [69], [70]. There are two different storage modes: sensible heat storage and latent heat storage.

Sensible heat storage is the most important storage method for building applications. All structures have some capacity for sensible heat storage. Even in light-weight structures, this capacity can be used to advantage, especially if the structure is well insulated [71]. Buildings designed to make use of thermal storage include features that increase thermal mass. These may be for storage only or they may serve both as storage and as structural elements. Several structural materials satisfy the requirements for sensible heat storage including concrete, steel, adobe, stone, and bricks. The two most commonly used materials for storage only are rock pebbles and water [68].

For sensible heat storage the building structure or a pebble bed is cooled at night—internally by circulating the night air through the building or through the pebble bed or externally by allowing the outside surfaces to lose heat to the air by convection and thermal radiation to the clear sky. During the day the cooled internal surfaces have a lower mean radiant temperature than indoor air temperature and help provide thermal comfort at higher air temperatures [70]. When a pebble bed is used, incoming air can be circulated over the bed to lower the air temperature inside a building.

The problem of defining the optimal thickness of walls has been studied by numerical simulations and by experiments. An explicit finite-difference time-marching solution was chosen by Maldonado and de Almeida to study a wall's energy storage characteristics [72]. Gruber and Toedtli [73] show that the efficiency of a homogeneous wall for sensible heat storage increases with increasing thickness and then decreases beyond some optimal thickness. The optimal thickness depends on the material used. Weekly storage of coolth in heavy brick and adobe walls was investigated by Bahadori and Haghighat [70]. They concluded that a wall thickness greater than 50 cm does not significantly improve a building's thermal performance.

Latent heat storage uses a phase-change material as the storage medium. Applications typically involve liquid/solid transitions. The phase-change material is solidified when cooling resources are available and melted when cooling is needed. Phase-change materials have two important advantages as storage media: they can offer an order-of-magnitude increase in heat capacity [74] and their discharge is isothermal. The latter advantage is most important when the discharge is passive. Passive discharge requires that the transition temperature be just slightly below the desired room temperature.

In spite of its advantages, latent storage has not proved attractive in residential buildings because of its cost [69]. However, recent developments in the use of paraffin waxes, a by-product of oil refining, suggest that these materials have significant potential for latent heat storage in residences [75]. Mixtures of paraffins have high energy densities (120-250 kJ/kg), phase transition temperatures in the range of 15 to 30°C, and low cost ($0.55-1.10/kg).

Earth Cooling Tubes

The earth's temperature below the surface is below or within comfort conditions throughout the year. The earth can therefore be used as a heat sink during the summer. Thermal coupling between a building and the earth can be accomplished by slab-on-grade foundation, by integrating the building into the earth (underground or earth-covered space), or by earth tubes [76].

Direct earth-contact cooling is uncontrollable; the rate of heat flow from a warm building to the somewhat cooler earth is determined by the temperature and the heat transfer properties of the building and those of the earth as well as the area of contact.

Controlled earth cooling involves tubes or pipes buried in the ground. This method can be used in houses and small commercial buildings. In applications using air, supply air is drawn through underground earth tubes, cooling by heat transfer along the tubes. Earth tubes and pipes can also be used as pre-coolers for air conditioners and can be designed

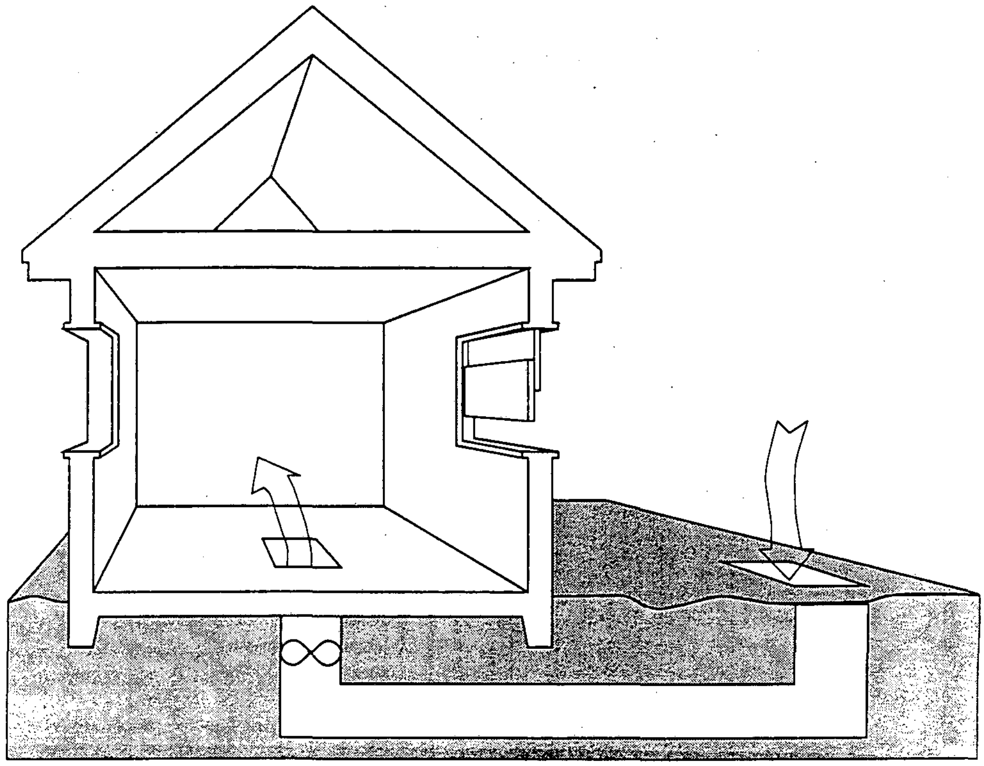

Figure 10: *Open-Loop Earth Tube Cooling*

as closed-loop or open-loop systems [19].

Although cooling with earth tubes seems very simple, it has drawbacks. Installation is expensive, and the latent cooling provided is very limited. Ground water also often penetrates the system; small amounts of water, which accumulate even in sloped systems, will add moisture to the indoor air and this can lead to biological growth and odor problems. To get reasonable and steady air flow through the tubes, a fan is needed, which adds to the building's electricity consumption [19]. Abrams says that, even with the lack of formal research on earth cooling, many systems have been built and that "in practice earth cooling tubes seldom live up to the hopes and expectations of enthusiasts." Abrams does not recommend earth cooling tubes for general use [19].

Research Issues

The problem of researching alternatives to compressor cooling is a puzzling one. Especially in mild climates, it appears that the problem is already solved; there are many alternatives to compressors that will do the job either alone or in combination. All that seems to be needed is development like that often undertaken in the private sector. But this development is not happening.

Before anyone attempts to displace compressors in residential markets, we need to understand better the reasons for their current dominance. We will speculate about this below, but this needs to be researched. Proponents of alternative technologies have devoted little attention to understanding the market for cooling technologies; it seems certain that a better understanding of this market would contribute to the development of a more effective research strategy.

Why is Compressor Technology Dominant?

What might be some reasons for the dominance of compressor technology? First, compressors are the easy way to supply cooling. Equipment, parts, and service are readily available. Matching a cooling unit to a building is simple, requiring only the use of rules of thumb. (A simple design involves a primitive cooling load calculation to estimate the capacity needed, adding some extra capacity to provide a margin for error.) The first cost of compressor cooling is relatively cheap; if a house under construction has central heating, the addition of central air conditioning will add only about $1,000 to the cost—a small fraction of the total cost of construction. Second, compressor-driven air conditioners are reliable both mechanically (they require little maintenance), and in their ability to meet cooling requirements in extreme climatic conditions. In contrast, even dry climates typically have a few humid days when evaporative cooling does not perform well; night ventilation does not perform well if the nighttime temperature does not fall sufficiently; etc. Finally, compressor technology is easy to control. Control of compressor-driven air conditioners is both simple and immediate. To maintain a nearly constant temperature, all that is required is a thermostat; reducing the temperature means simply turning the thermostat down, and the resulting change in temperature is fairly rapid. Room units can be turned on and off, also with rapid effects. The importance of these features should not be underestimated—we believe that people like to be able to control their environments.

Although we recognize that further research is needed to establish the relative importance of the factors listed above, we believe that a research program on alternatives to compressors must take these factors into account from the outset. This belief has guided us in the paragraphs below, where we present research recommendations.

Simulation and Design

The variety of strategies available for reducing cooling loads by using non-compressor-driven equipment raises the possibility that the best results might be obtained by a combination of strategies. A parametric study using a building simulation model that incorporates modules for each strategy could identify the most promising combinations, and performance of these combinations could be explored in experiments and demonstrations.

Unfortunately, all of the simulation tools needed for such a parametric study do not yet exist. Several strategies identified in our review are not yet well characterized in numerical simulation models. Also, previous work on the simulation of individual strategies may not be easy to bring together because several different models have been used (BLAST, DEROB, DOE-2, MICROPAS, and TARP). In spite of these difficulties, we believe that the development of a model that can simulate all (or most of) the alternative strategies should be a high priority because parametric studies appear to be the only affordable way to investigate the many possible combinations of strategies.

Another reason for developing simulation models is the need for design tools. Simulation models used by researchers are *not* appropriate for the design of residential cooling systems because these models are much too cumbersome to use. However, good simulation is necessary for development of good design tools. As we have noted, compressor-driven equipment has an advantage because systems are so easy to design. To help alternative cooling strategies compete with this advantage, design issues should be made an integral part of simulation efforts and the development of easy-to-use design tools should be a central (albeit long-term) objective.

Field-Performance Measurements

Simulation efforts must be coupled with performance measurement. Simulation allows us to investigate at low cost many different strategies in different climates. But experience has shown that if simulation is not grounded in actual measurements it can produce very inaccurate results. Performance measurements are much more expensive than simulation and care must be taken to keep costs under control. Existing data can be exploited, and existing sites should be used for data collection when possible.

An effort should be made to collate existing performance measurements and to compile a data base of sites where alternative cooling strategies have been employed. Although few of these sites are reported in the literature, there may be a significant number of them because of the wide publicity for passive solar design during the late 1970s and early 1980s. Some of the unreported sites could be located through contacts with designers and energy specialists. Monitoring at these sites could provide data that would be very useful for validating simulation results.

While existing data and existing sites can provide much useful information, specially constructed demonstrations of alternative cooling strategies will also be necessary. Standard measurement protocols should be developed so that, when these demonstrations take place, results will be comparable among demonstrations and supportive of simulation work.

Controls

Ease of control is an important advantage of compressor-driven cooling systems. Control of many of the alternative systems is inherently more complex. For example, ventilation can be difficult to control manually because it should usually be off when the outdoor temperature is higher than the indoor temperature. But this condition is not always apparent to a building occupant because, if the structure is cool and the radiant temperature is lower than the air temperature, the ventilating air may appear to be cooling. Thus, automatic control of ventilation requires at least a knowledge of both the indoor and the outdoor temperatures and optimal control may require information about humidity, time of day, heat capacity of the residence, etc. The control problem is more complicated when ventilation is combined with other strategies (e.g., evaporative cooling).

Developments in microelectronics offer a technical solution to these difficulties. The advent of inexpensive microprocessors and random access memories makes it possible to store and execute very complex control strategies. But, this technical capability for control does not translate readily into controllers that are appropriate for the residential setting. Papers in this volume by Kempton et al. [77] and by Lutzenhiser [78] show that users understandings of how controls work is often at odds with the designers' understandings and intentions and that users frequently intervene manually in the control of automatic systems. What appears to be needed are better means for designers to learn how their products are likely to actually be used by buyers and, perhaps, controllers that not only work when properly set but also can "explain" to users how they should be set.

Microprocessor-based controls have potential that extends well beyond the control of cooling systems. One can envisage systems that perform various energy related functions such as the control of heating and lighting and the management of load in response to real-time pricing. These systems might also include fire detection and burglar alarms. Developments along these lines have already been initiated and can be expected to continue. This provides a context for the development of sophisticated controls for cooling systems and gives additional impetus for overcoming what engineers call "human factors" problems.

Technology Development

None of the alternative cooling strategies that we have examined can be considered to be technically mature; there are many opportunities for technology development. The topics suggested below—adjustable speed drives, heat exchangers, and phase change materials—are by no means an exhaustive list, they are intended simply to illustrate some of the many good possibilities.

Adjustable speed drives could reduce energy consumption and increase control of the fans used in evaporative coolers and in ventilation. This technology is already being employed by manufactures of premium quality heat pumps and gas furnaces. In addition to reducing energy consumption and increasing control, adjustable speed drives might increase the acceptability of alternative technologies because the drafts associated with high ventilation rates would be reduced except in extreme conditions.

Because they cool air without increasing its moisture content, indirect evaporative coolers could perform similarly to compressor-driven coolers. However, current equipment is bulky and expensive. More compact, less expensive heat exchangers for indirect evaporative coolers would help to solve this problem.

Of the latent thermal storage materials (phase-change materials) developed so far, mixtures of paraffin waxes seem to present the best combination of properties. Paraffins deserve further investigation, including: development of environmentally acceptable fire retarding procedures, study of the effects of long-term cycling, and design of optimal encapsulation. Encapsulation within building materials (e.g., drywall) is a particularly interesting possibility.

Policy, Environmental, and Behavioral Issues

In our view, alternatives to compressors are not likely to make great headway in the residential sector without significant policy interventions. From the consumer's perspective, compressor technology is convenient and relatively inexpensive—there is no strong "market pull" for alternatives. But the reason for policy interventions is clear: much of the cost of compressor-driven air conditioning is not borne by consumers. Costs of utility capacity to meet the demand for air conditioning are borne by all utility rate payers and costs of increased energy and CFC use are borne globally. Research is needed to identify and evaluate strategies for intervention.

Behavioral and environmental studies are needed both to inform policy and to guide technological research. It is well accepted that policies that ignore behavioral and environmental concerns are likely to be inept. Similarly, technology development that fails to take account of behavior and environment is less likely to succeed.

While the externalities arising from the use of compressor-driven air conditioning are well known, we are unaware of any studies that have attempted to quantify all of the social costs. Such studies are needed as a basis for policy interventions. Good measures of external costs are especially necessary if the interventions are to include internalizing these costs through such measures as taxes or time-of-use rates. A variety of other means can also be employed to encourage alternative cooling strategies including, standards, incentives, and education programs. All of these measures should be examined to learn which combination of policies might have the greatest chance of success and what information is needed to support their implementation.

The net environmental impacts of alternative cooling strategies are almost certainly positive because CFCs are eliminated and energy consumption is (usually) reduced. However, there will be some negative impacts and their significance needs to be evaluated. Typically, indoor air quality is improved by the increased ventilation associated with alternative cooling strategies, but this may not be the case in regions such as Los Angeles because the outdoor air quality is poor. Evaporative cooling uses water at the site but may reduce water use for power plant cooling. The importance of these effects in comparison with other water uses and water availability has not been determined. Structural changes to accommodate alternative cooling strategies may have adverse fire and earthquake safety consequences (e.g., roof ponds may be an earthquake hazard).

Barring draconian measures, consumer acceptance of alternatives to compressors must be a central concern of those engaged in development of the technology. As a starting point, information is needed on how people use their cooling systems and what people expect from these systems. The relative importance of such factors as ease of control, responsiveness, and reliability needs to be determined. As the papers in this volume indicate, comfort requirements and air conditioner usage patterns are quite variable. Closer study of this variation may reveal market niches where alternatives to compressors may be more readily accepted and where initial development efforts can be focussed. Efforts should be made to gain a better understanding of the extent to which people are willing to tolerate some discomfort on the few hottest days of the year in exchange for the lower operating costs and environmental benefits of alternatives to compressors. The decision making processes of designers and builders should be investigated to learn how choices are made when cooling systems are built and designed and to learn ways to influence these choices.

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References

1. *Statistical Abstract of the United States*, 76th ed., US Bur. of the Census, Washington DC, 1955

2. *Statistical Abstract of the United States*, 110th ed., US Bur. of the Census, Washington DC, 1990

3. Watt, J. R. *Evaporative Air Conditioning Handbook*, Second Edition, NY Chapman & Hall, 1986

4. Fardeheb, Fewzi "Examination and Classification of Passive Solar Cooling Strategies in Middle Eastern Vernacular Architecture," *Passive Solar J.*, 4:377-417, 1987

5. Sodha, M. S., S. Ashutosh, A. Kumar and A. Sharma "Thermal Performance of an Evaporatively Cooled Multi-Storey Building," *Building and Environment*, 21:71-79, 1986

6. "Vari-Cool, Indirect Evaporative Cooling," Bulletin VC60-4, Vari-Cool, Product Division of H&C Metal Products, Santa Rosa CA

7. Maclaine-cross, I. L. and P. J. Banks "A General Theory of Wet Surface Heat Exchangers and it Application to Regenerative Evaporative Cooling," *J. Heat Transfer*, 103:579-585, 1981

8. Smith, J. C. "Theory Vs. Practice in Evaporative Roof Spray Cooling," in *Optimizing HVAC Systems*,Thumann, A., ed. Fairmont Press, 1988.

9. "Investing in California's Energy Future—A Report to the Legislature on the Energy Technologies Advancement Program," California Energy Commission, Sacramento CA, 1990

10. Huang, Y. J., H. F. Wu, J. W. Hanford, P. L. Chen and H. M. Qin "The Energy and Comfort Performance of Evaporative Coolers for Residential Buildings in California," Preprint IN-91-11-4, *ASHRAE Trans.*, 97(2), 1991

11. Turner, R. H. and F. C. Chen "Research Requirements in the Evaporative Cooling Field," *ASHRAE Trans.*, 93(1):185-196, 1987

12. Wu, H. "Moisture Up-take and Energy Efficiencies Associated with the Use of Evaporative Coolers", Environmental Testing Laboratory, Arizona State University, May 1990

13. Banks, B. "Technology Update for Desiccant-Based Air Conditioning Systems," in *Optimizing HVAC Systems*, A. Thumann, ed., Fairmont Press, 349-363 1988

14. Penney, T.R., G.C. Groff and B.K. Parsons "Advances in Desiccant Cooling Systems for Building Space Conditioning," paper from second European Symposium on Air Conditioning and Refrigeration, available from Solar Energy Research Institute, Golden, CO 1988

15. "Absorption Cooling, Heating and Refrigeration Equipment," Chapter 13 of *The ASHRAE Handbook Equipment*, 1988

16. Grossman, G. "Solar Cooling and Air Conditioning," *Prog. Energy Combust. Sci.*, 7:185-228, 1981

17. Colander, C. B. "Advances in Thermally Activated Heat Pumps," IEA Heat Pump Centre Newsletter, 8:2, 1990

18. Krisner, W. F. "Can Absorption Chillers Beat Electric Centrifugal Chillers?" in *Optimizing HVAC Systems*, A. Thurmann, ed., Fairmont Press, 317-332, 1988

19. Abrams, D. *Low-Energy Cooling*, Van Nostrand Reinhold, NY, 1986

20. Chandra, S. "Ventilative Cooling," in J. Cook, ed., *Passive Cooling*, 42-84, MIT Press, Cambridge, MA, 1989

21. Byrne, S. J., Y. J. Huang, R. L. Ritschard and D. M. Foley "The Impact of Wind Induced Ventilation on Residential Cooling Load and Human Comfort", Lawrence Berkeley Laboratory, LBL-Report 20919, 1986

22. Ernest, D. R., F. S. Baumann and E. A. Arens "The Prediction of Indoor Air Motion for Occupant Cooling in Naturally Ventilated Buildings," *ASHRAE Trans.*, 97(1):539-552, 1991

23. Ford, J. T. "Modeling Whole-House Ventilation with Building Load Simulation Methods," Master's Thesis, Mechanical Engineering Department, University of Illinois, at Urbana-Champaign, 1984

24. Baer, S. "Cooling with Night Air," Zomeworks Corporation, Albuquerque, New Mexico, 1981

25. Chandra, S. and A. A. Kerestecioglu "Heat Transfer in Naturally Ventilated Rooms: Data from Full-Scale Measurements:", *ASHRAE Trans.*, 90(1B):221-225, 1984

26. Clark, G. "Passive Cooling Systems." in J. Cook, ed., *Passive Cooling*, 347-583, MIT Press, Cambridge, MA, 1989

27. Givoni, B. "Performance and Applicability of Passive Cooling Systems," *Energy and Buildings*, (in press), 1990

28. Akbari, H., D. Samano, A. Mertol, F. Baumann and R. Kammerud "The Effect of Variations in Convection Coefficients on Thermal Energy Storage in Buildings; Part I—Interior Partition Walls," *Energy and Buildings*, 9:195-211, 1986

29. Akbari, H., D. Samano, A. Mertol, F. Baumann and R. Kammerud: "The Effect of Variations in Convection Coefficients on Thermal Energy Storage in Buildings; Part II—Exterior Massive Walls and Simulations," *Energy and Buildings*, 10:29-47, 1987

30. Martin, M. "Radiative Cooling," in J. Cook, ed., *Passive Cooling*, 138-196, MIT Press, Cambridge, MA, 1989

31. Martin, M. and P. Berdahl "Characteristics of Infrared Radiation in the United States," *Solar Energy*, 33:321-336, 1984

32. Bekett, H. E. in Cullen, W. "Solar Heating, Radiative Cooling and Thermal Movement: Their Effects on Built-up Roofing," Washington D.C.: U.S. Dept. of Commerce, National Bureau of Standards; for Sale by the Superintendent of Documents, U.S. Govt. Print. Off., 1963, Series Title: NBS Technical Note: 231.

33. Ito, S. and N. Miura "Studies of Radiative Cooling Systems for Thermal Energy," *Journal of Solar Energy Engineering-Transactions of the ASME*, 111:3, 251-256, 1989

34. Givoni, B. "Cooling by Longwave Radiation," *Passive Solar Journal*, 1:131-150, 1982

35. Ingersoll, J. G. and B. Givoni "Modeling the Performance of Radiant Cooling," cited in Givoni, B., "Performance and Applicability of Passive Cooling Systems", *Energy and Buildings*, (in press), 1990

36. Olgyay, V. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Princeton, NJ: Princeton University Press, 1963

37. Meier, A. "Measured Cooling Savings from Landscaping," *Proc. 1990 ACEEE Summer Study on Energy Efficiency in Buildings*, 4:133-143, 1990

38. Huang, Y. J., H. Akbari, H. Taha and A. H. Rosenfeld "The Potential of Vegetation in Reducing Summer Cooling Loads in Residential Buildings," *J. Climate and Applied Meteorology*, 26:1103-1116, 1987

39. McPherson, E. G., L. P. Herrington et al. "Impacts of Vegetation on Residential Heating and Cooling," *Energy and Buildings*, 12:41-51, 1988

40. McPherson, E. G., J. R. Simpson et al. "Effects of Three Landscape Treatments on Residential Energy and Water Use in Tucson, Arizona," *Energy and Buildings*, 13:127-138, 1989

41. Nayak, J.K. et al. "The Relative Performance of Different Approaches to the Passive Cooling of Roofs," *Building and Environment*, 17:145-161, 1982

42. Holm, D. "Thermal Improvement by Means of Leaf Cover on External Walls—A Simulation Model," *Energy and Buildings*, 14:19-30, 1989

43. McPherson, E.G., R. Brown and R.A. Rowntree "Simulating Tree Shadow Pattern for Building Energy Analysis," in *Proc. Passive Solar Energy Conf.*, American Solar Energy Society, 1985 Boulder CO.

44. Huang, Y.J., H. Akbari and H. Taha "The Wind Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements," *ASHRAE Trans.*, 96(1):1403-1411, 1990

45. Heisler, G. M. "Effects of Trees on Wind and Solar Radiation in Residential Neighborhoods," Argonne National Laboratory Report, ANL-058719, Argonne IL, 1989

46. Olgyay, A. and V. Olgyay *Solar Control and Shading Devices*, Princeton University Press, Princeton, 1957

47. Danz, E. *Sun Protection - An International Architectural Survey*, Frederick A. Prager, Inc. Publishers, NY, 1976

48. Hastings, S.R. and R.W. Crenshaw "NBS Building Science Series 104 - Window Design Strategies to Conserve Energy," National Bureau of Standards, Washington, D.C., 1977

49. Benton, C., G. Cartwright, F. Moore, F. Rifki and J. Warner "How the West Was Windowed," in *1988 Energy Curriculum Project*, J. Loveland, ed., Society of Building Science Educators, (available from Center for Environmental Design Research, University of California, Berkeley CA), 88-91, 1989

50. Shurcliff, W.A. *Thermal Shutters and Shades*, Brick House Publishing Co, Andover, MA, 1980

51. Windows and Daylighting Group "Daylighting Design Tool Survey," Lawrence Berkeley Laboratory Report, DA 170, 1990

52. Building Energy Simulation Group "DOE-2 Supplement: Version 2.1," Lawrence Berkeley Laboratory, LBL-Report 8706, Rev. 4 Suppl., 1984

53. Building Energy Simulation Group "Overview of the Building Energy Analysis Program," Lawrence Berkeley Laboratory, LBL-Report 19735, UC-95d, 1984

54. Reilly, S. and D. Arasteh "WINDOW 3.1: A Computer Tool for Analyzing Window Thermal Performance," *Proc. 13th National Passive Solar Conference*, Massachusetts Institute of Technology, Boston MA, 1988

55. Windows and Daylighting Group: "WINDOW 3.1: A PC Program for Analyzing Window Thermal Performance (Program Description and Tutorial)," Lawrence Berkeley Laboratory, LBL-Report 25686, 1988

56. Arasteh, D., M.S. Reilly, and M. Rubin "A Versatile Procedure for Calculating Heat Transfer Through Windows," *ASHRAE Trans.*, 95(2), 1989

57. Papamichael, K.M. and S.E. Selkowitz "Simulating the Luminous and Thermal Performance of Fenestration Systems," *Lighting Design + Application*, 17(10):37-45, 1987

58. Papamichael, K.M., J.H. Klems, and S.E. Selkowitz "Determination and Application of Bidirectional Solar-Optical Properties of Fenestration Systems," *Proc. 13th National Passive Solar Conference*, Massachusetts Institute of Technology, Boston, MA, 1988

59. Akbari, H., A. H. Rosenfeld and H. Taha "Summer Heat Islands, Urban Trees and White Surfaces," *ASHRAE Trans.*, 96(1):1381-1388, 1990

60. Taha, H., H. Akbari, A. H. Rosenfeld and J. Huang "Residential Cooling Loads and the Urban Heat Island—the Effects of Albedo," *Building and Environment*, 23(4):271-283, 1988

61. Conner, C. "The effect of Exterior Surface Absorptivity and Emissivity on Energy Use in Residential Buildings," Unpublished Report, Lawrence Berkeley Laboratory, mentioned in Taha, H., et al. [60]

62. Henke, C. "Straight Talk about Radiant Barriers," *Home Energy*, 6(3):17-21, 1989.

63. Bourne, R.C. and M.A. Hoeschele "Climate Influence on Attic Radiant Barrier Energy and Demand Savings," in *Proc. ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, 1:5-13, American Council for an Energy-Efficient Economy, Washington, D.C., 1990

64. Eley, C. "Compliance Option Application—Attic Radiant Barrier," California Energy Commission, Draft, June 1990

65. Wu, H. "The Effect of Various Attic Venting Devices on the Performance of Radiant Barrier Systems in Hot Arid Climates," in Proceedings: Thermal Performance of Exterior Envelopes of Buildings IV, ASHRAE/DOE/BTECC/CIBSE Conference, December 4-7, 1989, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta GA, 1989

66. Fairey, P. "Seasonal Prediction of Roof-Mounted Attic Radiant Barrier System Performance from Measured Test Data," in *Proc. ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, 1:103-114, American Council for an Energy-Efficient Economy, Washington, D.C., 1990

67. Wilkes, K.E. "Analysis of Annual Savings due to Radiant Barriers," in *Proc. ACEEE 1990 Summer Study on Energy Efficiency in Buildings*, 1:235-245, American Council for an Energy-Efficient Economy, Washington, D.C., 1990

68. Hariri, A. S. and I. C. Ward "A Review of Thermal Storage Systems Used in Building Applications," *Building and Environment*, 23:1-10, 1988

69. de Almeida, A. and J. Yokoe "Residential Cool Storage: Peak Load Reduction Alternatives", *IEEE Trans. on Power Systems*, 3(3): 1988

70. Bahadori, M. N. and F. Haghighat "Weekly Storage of Coolness in Heavy Brick and Adobe Walls," *Energy and Buildings*, 8:259-270, 1985

71. Reddy, T. A., L. K. Norford and W. Kempton "Shaving Residential Air-Conditioner Electricity Peaks by Intelligent Use of the Building Thermal Mass," *Energy*, 16:1001-1010, 1991

72. Maldonado, E.A.B., and M.G. de Almeida "Effective Heat Storage in Heavy Masonary Walls," In Proc. *Third International Congress on Building Energy Management*, 4:154-161, 1987

73. Gruber, P. and L. Toedtli "On the Optimal Thermal Storage Capability of a Homogeneous Wall under Sinusoidal Excitations," *Energy and Buildings*, 13:177-186, 1989

74. McLarnon, F. R. and E. J. Cairns "Energy Storage," *Annual Review Energy*, 14:241-271, 1989

75. Salyer, I. O. and A. Sircar "Development of PCM Wallboard for Heating and Cooling of Residential Buildings," US DOE Thermal Energy Storage Research Activities Review, 1989 Proceedings, New Orleans LA March 15-17, 1989

76. Labs, K. "Earth Coupling," in J. Cook, ed., *Passive Cooling*, 197-346, MIT Press, Cambridge, MA, 1989

77. Kempton, W., D. Feuermann and A. E. McGarity "I Always Turn It on Super: User Decisions About When and How to Operate Room Air Conditioners," *Energy and Buildings*, THIS ISSUE, 1992

78. Lutzenhiser, L. "A Question of Control: Alternative Patterns of Room Air Conditioners Use," *Energy and Buildings*, THIS ISSUE, 1992

Related Literature

Cheung, F. B. and D. Y. Sohn "Numerical Study of Turbulent Natural Convection in an Innovative Air Cooling System," *Numerical Heat Transfer*, 16:467-487, 1989

Crum, D. R., J. W. Mitchell et al. "Indirect Evaporative Cooler Performance," *ASHRAE Trans.*, 93(2):1261-1275, 1987

Davies, M. G. "Transmission and Storage Characteristics of Walls Experiencing Sinusoidal Excitation," *Applied Energy*, 12:269-316, 1982

Eriksson, L., Lennart Eriksson, Tonny Masimov, Stefan Westblom; "Blocks of Flats with Controlled Natural Ventilation and Recovery of Heat," [translated by L.J. Gruber], Stockholm, Sweden: Swedish Council for Building Research: Distribution, Svensk Byggtdanst, 1986

Givoni, B. *Man, Climate and Architecture*, NY: Van Nostrand Rheinhold, 1981

Givoni, B. and M. Mostrel "Windscreens in Radiant Cooling," *Passive Solar J.*, 1:229-238, 1982

Kammerud, R., E. Ceballos, B. Curtis, W. Place and B. Andersson "Ventilation Cooling of Residential Buildings," *ASHRAE Trans.*, 90(1B):226-238, 1984

Kaushik, S. "Thermal Comfort in Buildings through a Mixed Water Mass Thermal Storage Wall," *Building and Environment*, 24:199-207, 1989

Kishore, V. V. N. "Assessment of Natural Cooling Potential for Buildings in Different Climatic Conditions," *Building and Environment*, 23:215-223, 1988

Knebel, D. "Off Peak-Cooling with Thermal Storage," *ASHRAE J.*, 32(4):40-44, 1990

Nayak, J. K., A. Srivastava, U. Singh and S. Sodha "The Relative Performance of Different Approaches to the Passive Cooling of Roofs," *Building and Environment*, 17:145-161, 1982

Sakamoto, Y. "Development of Procedure for Calculating Room Air Temperature Including Effect of Natural Ventilation," Tsukuba-gun, Japan: Building Research Institute, Ministry of Construction, Series Title: BRI Research Paper No. 102, 1983.

Shaviv, E. "Climate and Building Design—Tradition, Research and Design Tools," *Energy and Buildings*, 7:55-69, 1984

Sodha, M. S., U. Singh, A. Srivastava and G. Tiwari "Experimental Validation of Thermal Model of Open Roof Pond," *Building and Environment*, 16:93-98, 1981

Sodha, M. S., S. P. Singh and A. Kumar "Thermal Performance of a Cool-Pool System for Passive Cooling of a Non-conditioned Building," *Building and Environment*, 20:233-240, 1985

Somasundaram, S. and A. D. Carrasco "An Experimental and Numerical Modeling of a Roof-Spray Cooling System," *ASHRAE Trans.*, 94(2):1091-1107, 1988

Spethmann, H.-J. "Eine Kenngroesse zur Beurteilung des Speicherverhaltens von Bauteilen," *Gesundheitsingenieur*, 98:99-107, 1977

Srivastava, A., J. K. Nayak, G. Tiwari and S. Sodha "Design and Thermal Performance of a Passive Cooled building for Semiarid Climate of India," *Energy and Buildings*, 6:3-13, 1984

Verma, R., N. K. Bansal and H. Garg "The Comparative Performance of Different Approaches to Passive Cooling," *Building and Environment*, 21:65-69, 1986

Wu, H. "Performance Monitoring of a Two-Stage Evaporative Cooler," *ASHRAE Trans.*, 95(1):718-725, 1989

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