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REVIEW AND OUTLOOK

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Alternatives to Compressor Cooling in California Climates
Review and Outlook

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Alternatives to Compressor Cooling in California Climates
Review and Outlook

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Abstract

This review and discussion has been prepared for the California Institute for Energy Efficiency (CIEE) to examine research on alternatives to compressor cooling. The report focuses on strategies for eliminating compressors in California's transition climates — moderately warm areas located between the cool coastal regions and the hot central regions. Many of these strategies could also help reduce compressor use in hotter climates. Compressor-driven cooling of residences in California's transition climate regions is an undesirable load for California's electric utilities because load factor is poor and usage is typically high during periods of system peak demand. We review a number of alternatives to compressors, including low-energy strategies: evaporative cooling, natural and induced ventilation, reflective coatings, shading with vegetation and improved glazing, thermal storage, and radiative cooling. Also included are two energy-intensive strategies: absorption cooling and desiccant cooling. Our literature survey leads us to conclude that many of these strategies, used either singly or in combination, are technically and economically feasible alternatives to compressor-driven cooling.

1. Introduction

California's electricity use for cooling residential buildings in 1987 was about 4200 GWh, contributing about 5.8 GW to peak utility demands [1]. These figures indicate that residential air conditioning has a very poor load factor (about 0.08). As a very rough estimate, residential air conditioning requires an investment of about $6 billion in generation, transmission, and distribution capacity while generating only about $400 million in sales. It is an unprofitable load; if an allowance of $160 million is made for operating costs, the return is about 4 percent.

Most energy used in air conditioning is for operating compressors. This paper examines research on alternatives to compressor cooling in residences. Our emphasis is on eliminating compressors in California's transition climates, but many of the strategies that are examined can also reduce energy demand in hotter regions of the state. Transition climates are the focus because the load factor for residential air conditioning is probably lower in these climates than the statewide average for this end use and because non-compressor cooling is technically easier in these climates. Also, in addition to reducing

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electrical peaks, non-compressor cooling alternatives reduce the need for CFCs, and most of these alternatives reduce the production of CO_2.

Eliminating compressors for cooling in transition climates appears to be technically and economically feasible. Even today, many houses in transition climates are not equipped with compressor-driven coolers. In addition, a variety of technical strategies for cooling or reducing cooling load do not use compressors and appear sufficient to maintain comfortable conditions in residences in transition climates. Among these technologies are: evaporative cooling, natural and induced ventilation, reflective coatings, shading with vegetation and improved glazing, thermal storage, radiative cooling, and absorption cooling.

Despite these alternatives, compressor-driven cooling consumes a large and growing share of peak power in California's transition climates. This paper addresses ways to reverse this situation. We begin with a review of non-compressor cooling strategies, which briefly describes each technology, discusses the availability of algorithms for simulating its performance, describes its potential range of application, and tries to identify problems that may be preventing its wider use. Based on our review, we identify research priorities, and we focus on integrating different technical approaches to develop optimal combinations for the variety of micro-climates in California's transition climate regions.

2. Definition of Transition Climates in California

In California, transition climates, as we define them, are found between the cool coastal regions and the hot central regions and also in the Sierra foothills. Examples are the cities of Burbank and Livermore. Transition climates are moderately warm in the summer (e.g., mean summer temperatures in Burbank and Livermore are 74.5°F and 70.4°F respectively) and have rather large diurnal temperature swings (e.g., the mean high in Burbank is 88.6°F and while the mean low is 60.4°F; the mean high in Livermore is 88.7°F and the mean low is 52.2°F). These mean temperatures are for the July through September 1951-80 [2]; current mean temperatures are probably somewhat higher because of the heat island effect.

Estimates of electricity consumption for California's transition climates can be obtained from the forecasting models of the California Energy Commission (CEC). The CEC estimates air-conditioning consumption by climate zone as shown in Figure 1 [3]. For reference reasons, the climate zones used for Title 24 are shown in Figure 2 [4].

Transition climates are mostly located in climate zones 4, 8, 9, 12, and 13, shown in Figure 1. The boundaries of the CEC's climate zones typically follow county lines because the models require data that are often only available by county.

As a consequence, climates vary considerably within the zones. However, because zones 4, 8, 9, 12, and 13 do not include many hot regions and air conditioning use is infrequent in the coastal regions, these can be considered transition zones. They provide a rough but reasonable estimate of residential air conditioning consumption in transition climates.
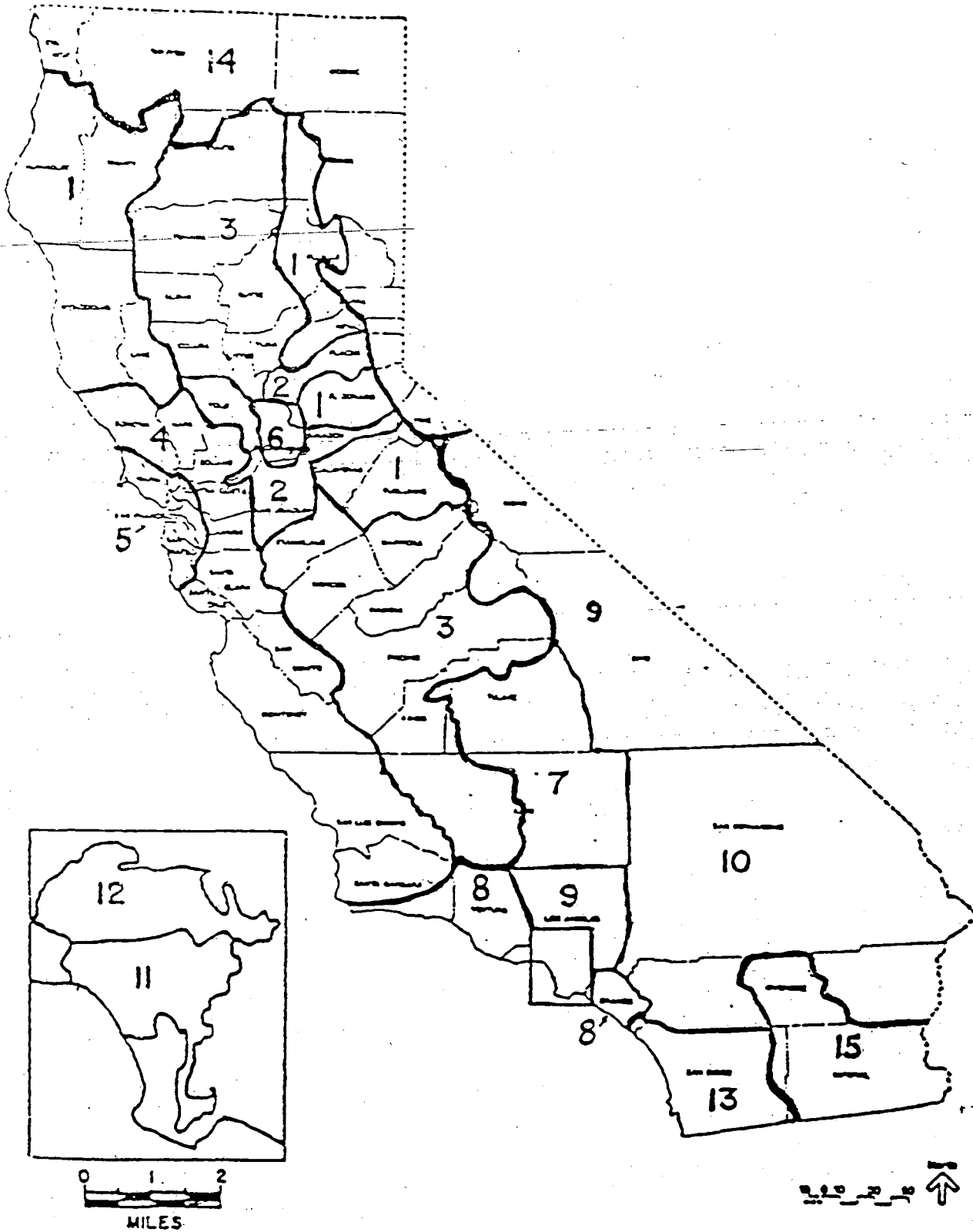
Figure 1: *Climate Zones used in Forecasting Residential Electricity Sales in California [3]*

Climate Zones

Figure 2: *Climate Zones used for Compliance Testing [4]*

According to CEC estimates, in 1990 the electricity consumed by residential air conditioners in climate zones 4, 8, 9, 12, and 13 was about 1,500 GWh. This is expected to increase to about 2,200 GWh in the year 2009 [5].

3. Strategies

3.1 Evaporative Cooling

Reviewing literature on non-compressor cooling technologies, we found most papers were on evaporative cooling. This technology is probably one of the oldest cooling strategies available; frescoes from ancient Egyptians show the use of evaporation to produce cooling [6].

Modern evaporative coolers are either direct or indirect devices. In addition to evaporative cooling devices which cool the supply air, passive evaporative cooling removes heat gain from a building's opaque envelope by inducing evaporation and convection on the exterior surfaces [7]. As California climates are low in humidity, evaporative cooling would probably work well in most locations. However, because drought is a serious problem in California, water use for cooling must be addressed in future research.

3.1.1 Direct Evaporative Cooling

In direct evaporative cooling, supply air is placed in direct contact with water (e.g., by being passed through a moistened pad). The nonsaturated air's sensible heat is transferred to the water and becomes latent heat by evaporating some of the water. In this adiabatic process, no heat is gained or lost (the enthalpy of the air remains the same), but the air temperature falls as its sensible heat is converted into latent heat [6]. During the process of cooling, the air becomes more humid, theoretically approaching its wet-bulb temperature. For practical reasons, the air's saturation point will not be reached in a commercial apparatus.

For direct evaporative cooling, cool humid air is supplied to absorb sensible heat. Therefore, exhaust air is usually 5 to 10 degrees warmer than the supply air. During the process of absorbing heat from a building, the supply air's relative humidity is decreased, which provides comfortable temperature and humidity levels in the buildings 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.

3.1.2 Indirect Evaporative Cooling

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. For example,

supply 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 (see Figure 3) [8]. Experiments with indirect evaporative coolers in the U.S. date back to the 1920's, when evaporative cooling was studied in Arizona and California [6].
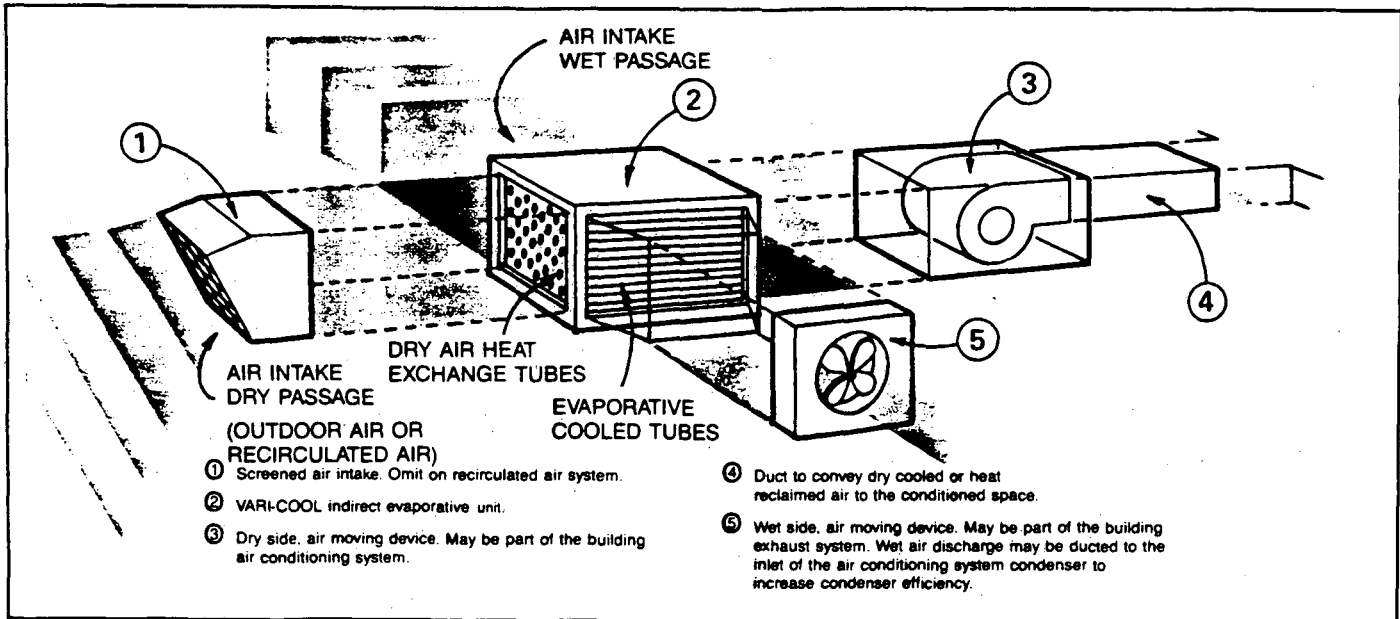

AIR INTAKE
WET PASSAGE

DRY AIR HEAT
EXCHANGE TUBES
AIR INTAKE
DRY PASSAGE
EVAPORATIVE
COOLED TUBES
(OUTDOOR AIR OR
RECIRCULATED AIR)

① Screened air intake. Omit on recirculated air system.

② VARI-COOL indirect evaporative unit.

③ Dry side, air moving device. May be part of the building air conditioning system.

④ Duct to convey dry cooled or heat reclaimed air to the conditioned space.

⑤ Wet side, air moving device. May be part of the building exhaust system. Wet air discharge may be ducted to the inlet of the air conditioning system condenser to increase condenser efficiency.

Figure 3: *Indirect Evaporative Cooler Unit [8]*

One of the many indirect evaporative cooling applications is cooling with radiant cooling panels. In order to avoid condensation, the panels have to be kept above the dew point, which requires an elaborate control with refrigerated equipment. With evaporative cooling, however, the evaporative process already controls the water temperature as cooling towers cannot approach the dew point.

Indirect evaporative coolers may be used in winter as air-to-air heat exchangers for ventilation systems. This might be especially useful for overcoming indoor air quality problems in new, airtight homes. In this system, return air becomes secondary air, which preheats the incoming outside air.

Direct and indirect evaporative coolers can be coupled to achieve improved cooling characteristics. 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.

3.1.3 Roof Spraying Cooling Systems

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 100 square feet. 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 $.30/sq ft [9].

The spraying system is normally activated by a programmable controller, distributing a thin, uniform film of water on the roof. Instead being a large solar heat absorption panel, the 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 10°F. 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 [10]. This system is expected to reduce cooling energy demand by 54 percent.

3.1.4 Algorithm

The latest building simulation model algorithms developed for both direct and indirect evaporative cooling have been published by an international team of researchers from Lawrence Berkeley Laboratory, Arizona State University, and Tongji University (Shanghai, China) [11]. The mathematical models developed are installed in 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.

3.1.5 Application

The numerical models described above 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 CEC-prototype residential building equipped with direct evaporative cooling in transition climates [11]. In Pasadena, for example, direct evaporative cooling would be sufficient to cool the house in all but six hours per year, reducing the electrical energy consumption by 87 percent.

Two-stage evaporative cooling can replace compressor-driven cooling in most California climates, apparently without comfort penalties, which means a significant potential for energy savings. Evaporative cooling can also be used to cool condenser coils for compressor-driven air conditioning units.

Simulation runs performed by McClellan [12] show that evaporative cooling can reduce supply air temperatures to a point that allows cooling with "washed" air only or at least reduces energy consumption by hybrid systems in more severe climates than California's transition climates.

Although air quality is not part of this investigation, we would like to point out that use of outside air for cooling increases indoor air quality in most locations.

3.1.6 Problems

Due to small temperature differences between cooled supply air and room air, large air volumes are necessary to cool a building. This produces the comfort sensation of much colder air [13]. However, that can cause uncomfortable conditions (draft) and uses extra fan power.

Turner and Chen [14] identify four problems with evaporative cooling in contrast to compressor cooling for residential use:

- initial cost is high (indirect and double-stage units)
- reliability is uncertain
- the air handling unit requires more space
- ducts are larger

Manufacturers contacted by Turner and Chen do not plan to target the residential market because of the high cost of evaporative coolers. Turner and Chen recommend future R&D areas, including possible health effects of fungus growth in evaporative cooling systems.

The literature contained very little information about water requirements for evaporative cooling. Wu [15] reports water consumption of 86.5 gallon per hot day to cool a single-family house in Arizona with a two-stage evaporative cooler. (A compressor cooled unit 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 cooling towers to produce the saved energy.)

3.2 Natural and Induced Ventilation

3.2.1 General Information

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 90°F) and that have small (less than 20°F) diurnal temperature swings. For example, it appears to work well in Hawaii. Thermal storage ventilation 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 is blown through the building's attic, cooling this, which is usually much hotter than the rest of the building, and thus reducing heat transfer through the ceiling. Disadvantages of induced ventilation include noise and power consumption of the fan and, usually, higher initial cost [16].

3.2.2 Algorithm

Thermal building simulation models used for compliance testing with Title 24 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.
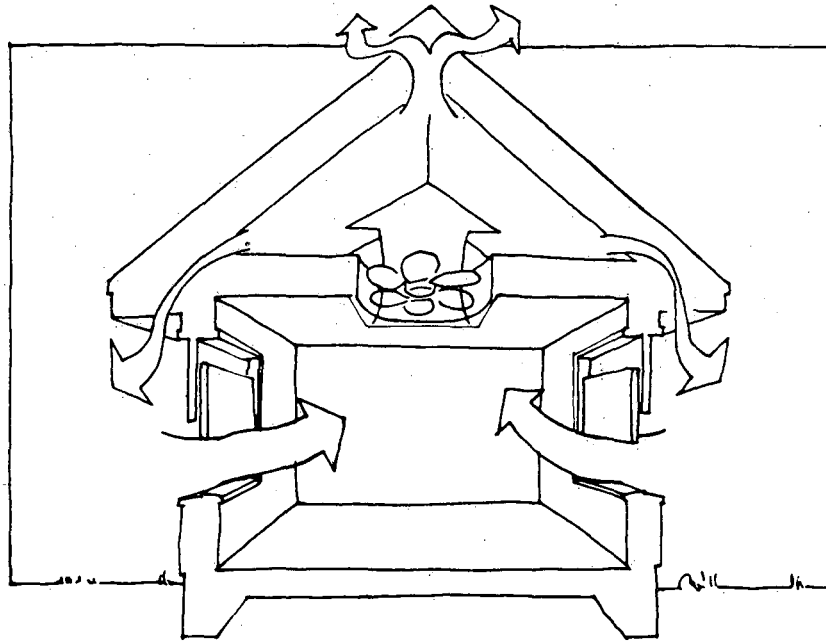
Figure 4: *Whole-House Fan Installation [16]*

An algorithm for natural ventilation for cooling purposes was developed by the Florida Solar Energy Center (FSEC) [17] and implemented in TARP, a building simulation program developed by the National Bureau of Standards. Byrne [18] shows 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.

Predicting indoor air motion for occupant cooling is being researched at University of California Berkeley [19]. The study 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 [20] 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 [21] to predict thermal behavior of a building cooled by whole-house fan ventilation.

3.2.3 Applications

Convective cooling by natural ventilation is one of the most cost-effective measures to offset or replace compressor-driven cooling. It can be used together with a whole-house fan if the swing of the inside temperature is out of phase with the outdoor temperature, and outside temperatures are beyond the comfort limits. Although electrical energy is used to operate the fan, friction is relatively small in a well-designed installation and fans operate at a low pressure drop. Therefore, power consumption based on air flow is moderate.

Whole-house fans should be sized to provide between 30 and 60 air changes per hour (ach), which is significantly higher than the ventilation provided by open windows [16].

Cooling with outside air works best for well-insulated buildings with thermal storage in climates where there are large changes in outdoor temperature. Ventilation must be kept to minimum level during the daytime to reduce the heat transfer resulting from air flow.

Direct cooling of occupants is a tradition in some warm humid climates. In the U.S., Hawaii is a perfect place for this type of natural cooling. However, together with vegetation, this cooling strategy could probably be used in transition climates, too.

3.2.4 Problems

How well convective heat transfer is simulated in thermal building simulation models is unclear. From Chandra and Kerestecioglu [22] as well as Clark [23], we learn that simulation models usually work with convection coefficients based on an air flow velocity of zero. Givoni [24] states this explicitly for DOE-2. In parametric studies using the simulation program BLAST, Akbari et al. [25,26] show that the effect 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.

Future research has to focus 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.

For ventilation to increase internal air velocities, comfort criteria have to be studied very carefully. Full-scale measurements are needed to evaluate models used for predicting air velocities.

3.3 Reflective Coating

3.3.1 General Information

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 [27]. The energy balance of a building depends on the net solar radiation at its surface. Simulations for a residential building in Sacramento indicate that whitewashing the buildings can reduce significantly the amount of electricity used for cooling and also reduce the utility's peak demand [28]. The same study shows that reflective surfaces have the greatest effect on interior temperature in buildings with little insulation because high external surface temperatures cause heat transfer through the walls.

3.3.2 Algorithm

The effects of reflective coating can be simulated by using URBMET for ground surface energy together with a thermal building simulation program. URBMET is a planetary boundary layer model which simulates ground surface energy and moisture budget. The model solves energy and moisture equations based on temperature profiles, moisture content, wind speed, etc., for both soil and air. Thermal building simulation models can use URBMET's information about reflective coating (e.g., as albedo) to calculate its effect on the cooling load. There seems to be no need for further development of simulation models.

3.3.3 Application

Light-colored building envelopes are most beneficial for buildings with a low insulation level. Reduced surface temperatures reduce the heat transfer through the wall and produce lower inside surface temperatures. In contrast, large amounts of insulation reduce the dependence of internal surface temperatures on outside conditions significantly, which reduces the effect of reflective coating on cooling load.

Figure 5 shows the effect of color on the surface temperature for a building in Washington, D.C. on the design day in July [29].

3.3.4 Problems

Although whitewashing is the first of defense against solar heat gain, dust accumulating on roofs and walls gradually reduces reflectivity. Furthermore, light-colored buildings can cause glare and increased UV radiation problems. Ideally, surfaces should be self-cleaning and reflect most solar radiation (with the possible exception of UV radiation).
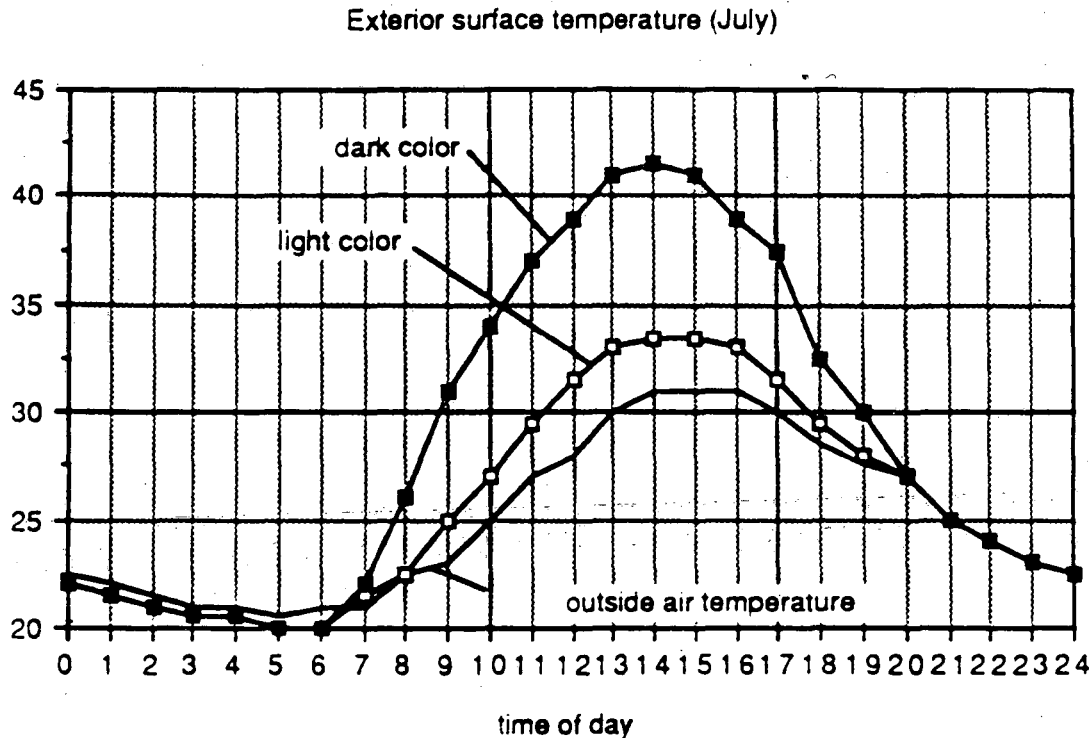
Exterior surface temperature (July)

Figure 5: *Exterior Surface Temperature depending on the Color of the Surface [29]*

3.4 Shading

3.4.1 Shading with Vegetation

3.4.1.1 General Information

Buildings' thermal performance can be significantly affected by the influence of vegetation. There are at least three ways of using vegetation to reduce the cooling load for a building:

● vegetation attached to the building (e.g., ivy),

● vegetation around the building, which reduces ambient temperatures through evaporation and radiation,

● vegetation which 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 [30]. The value of landscaping to reduce 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 [31] concludes that the available measurements "... suggest that the careful application of shrubs, trees, and vines could reduce cooling electricity use by 25-50 percent."

Vegetation on buildings also reduces wind velocity on the surface of the walls [32]. In cold climates, lower wind velocity may decrease the potential for heat removal from natural ventilation and may decrease heating loads [32],[33]. In hot climates, reduced wind speeds may save energy by decreasing infiltration of hot outside air [33].

Predicting 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 [31].

Vegetation can also reduce the cooling loads of buildings in hot arid climates by modifying air temperature, solar heat gain, longwave heat gain, and heat loss by convection. However, savings from reduced mechanical cooling may be offset by increased irrigation water costs [34].

Irradiance reductions from plants can reduce energy use for space cooling and increase energy use for space heating. Plant canopies that shade buildings move the active heat absorbing surface from the building to leaves [33].

3.4.1.2 Algorithm

Very detailed vegetation models are available, but they are usually poorly linked to building energy models [31]. Models are available to calculate the impact of vegetation on energy savings in conditioned buildings. They range from simple approaches (e.g., simulating vegetation by a screen with limited transmittance [35]) to more sophisticated models used by Holm and by McPherson. 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) [36]. The model is for passive solar design. McPherson 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 [33]. 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 sun, plants, and the building, as well as plant shape and plant canopy density [37].

The effect of landscaping on building energy use has also been simulated by Huang et al. [38] using DOE-2 and treating the shading effects of trees as exterior building shades.

3.4.1.3 Problems

Most of the models described above deal only with impacts of irradiance reduction on solar heat gain and impacts of wind reductions on infiltration and convective heat transfer [34, 36].

The most significant limitations of the models are:

- Extreme temperatures of 0°C and 50°C can be resisted by most plant covers for only limited periods of time, after which plants will die. Some models make no provision for this.

- The angle of incidence of sunlight varies widely as a result of the sun's apparent movement, wind action, leaf curvature, partial shading, and differential growth; models do not describe this variation.

- Phototropism and wilting can increase or decrease the total radiation received by an area of a leaf cover [34], and this is not accounted for in models.

- Variations in radiative properties of about 5 percent occur on an individual leaf, and the pattern changes seasonally. The radiative interaction of many leaves in nature is impossible to predict or model. The best approximation would appear to be treating the leaf cover as a selective filter [36].

- Evapotranspiration from plants near buildings may reduce air temperature. Recent findings suggest that this form of latent heat loss may be more important than previously believed [27], so models need to factor this in.

3.4.2 Glazing and Architectural Shading
3.4.2.1 General Information

An effective way to reduce cooling loads is to prevent their generation by controlling the output of heat sources and heat transfer through the building envelope. Heat sources can be either external (i.e., direct and diffuse solar radiation along with associated convective and conductive heat transfer), or internal (electric lighting, equipment, and people) [39]. The building designer can only control electric lighting output. Strategies to control generation of cooling loads from other sources concentrate on reducing heat transfer from the exterior to the interior and increasing heat transfer from the interior to the exterior.

The high intensity of direct solar radiation makes it by far the most significant external source of cooling loads [40]. 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 [41]. 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.

Strategies for reducing cooling-season heat gains through windows must address with 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 [42]. 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 can be considered the extreme case of reducing 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-window 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 [43]. 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.

3.4.2.2 Algorithms

Various algorithms, simplified and sophisticated, have been developed to estimate heat transfer through a building's envelope [44]. 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 [45,46], currently under development, includes the WINDOW heat transfer program [47,48], which computes the solar-optical properties of any glazing system based on first physics principles [49]. 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, sun-path projections have been widely used to determine shading masks, i.e., the time-dependent shading performance of shading devices. Such techniques are easy to use but provide very limited, if any, quantitative information on actual loads. As computers are used more in the building design industry such manual techniques are being replaced with software models that provide more detailed and accurate data.

3.4.2.3 Problems

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 [50]. Such sophisticated methods require detailed, angle-dependent, solar-optical properties of window components and systems that are not yet widely available [51].

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.

3.5 Thermal Storage

3.5.1 General Information

Thermal energy storage (TES) is a means of accommodating delay between the availability of cooling resources and the need for building cooling load. 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.

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 [52].

Independent of the size, all thermal storage must have the following properties [52]:

- 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 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
- the system's cost.

3.5.2 Applications

Our literature review shows that short-term thermal energy storage systems are used commonly in building applications [52], [53], and [54]. There are two different storage modes:

- sensible heat storage
- latent heat storage

Sensible heat storage has been the most important storage for building applications. Several materials satisfy the requirements for sensible heat storage: including concrete, steel, adobe, stone, and bricks. The two most commonly used materials are rock pebbles and water [52].

For sensible heat storage the building structure [54] or a pebble bed [52] 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 [54]. For example, a pebble bed can cool incoming air to lower air temperatures inside a building [52].

Gruber and Toedtli [55] 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 and is described in [55]. Weekly storage of coolth in heavy brick and adobe walls was investigated by Bahadori and Haghighat [54]. They concluded that a wall thickness greater than 50 cm does not significantly improve a building's thermal performance.

Although latent energy storage has a high energy density and features isothermal discharge, it has not proved attractive in residential buildings for because of its cost [53]. 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 [56]. Mixtures of paraffins have high energy densities (30-60 cal/gram), phase transition temperatures in the range of 15 to 30°C, and low cost ($0.25-0.50/lb).

3.5.3 Algorithm

The problem of defining the optimal thickness of walls has been studied by numerical simulations and by experiments [57]. An explicit finite-difference time-marching solution was chosen by Maldonado and de Almeida to study a wall's, energy storage characteristics. For periodic boundary conditions, analytical solutions to the problem of the optimal storage capability have been available for quite a while [55]. The determination can be done either in the time domain by superposition of two waves (incoming and outgoing or incident and reflected [58] or in the frequency domain by means of a matrix method [59].

3.6 Radiative Cooling

3.6.1 General Information

Radiative cooling is the transfer of heat by radiation in order to reduce the surface temperature of a building. 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 second "object" is usually the clear sky, which provides a potential heat sink [16].

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, near 50°F [16]. Because sky temperatures are lowest when cooling needs are also low, radiant cooling works best with thermal storage.

3.6.2 Application

Radiative cooling could be used during most of California's dry, cloudless summers for reducing air conditioning loads and improving comfort in houses. Except for foggy coastal areas, California's summer sky temperature averages more than 20°F cooler than the ambient temperature [60]. Although radiative cooling is often used nocturnally, it can be used during daylight hours if solar radiation can be rejected efficiently.

The radiation of energy from a roof surface to a clear sky often results in roof temperatures less than ambient. The emissivity of most non-metallic roofing materials is for practical purposes independent of surface color or texture [61], so color is not important in radiative cooling, which can be integrated as a passive system (e.g., roof pond or radiation traps [62]) or active system (radiative panels).

Polyethylene films are used as windscreens to reduce convective heat gain from the ambient air to the radiant surface. In order to block solar heat gains and to prevent deterioration of the windscreens, movable insulation panels cover the installation during the day. Cooling in the building is provided by radiation, with ceilings working as cooling panels and by means of convective heat transfer.

3.6.3 Algorithm

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 [63], Givoni, [64]), 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 [65].

3.7 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 [66]. 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.

Several problems are related to this technology, including:

- deterioration of long-term performance of radiant barriers, e.g., as a result of dust build-up in a horizontal installation

- danger of condensation on barriers

- overheating of the roof if reflected heat cannot be removed from the attic. This might cause damage to the exterior roofing.

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 [67,68]. Unfortunately, it appears that for the climates we are considering insufficient data are available to evaluate the model. Data obtained by Wu [69] covers only horizontal installations, which are not suggested by the Reflective Insulation Manufacturers Association because of dust buildup. Fairey [70] reports on the performance of aluminum foil that was glued to bottom surface of the roof decking based on test data from FSEC's side-by-side attic test facility.

Wilkes [71] introduced a model developed at Oak Ridge National Laboratory which 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. The model was coupled with the thermal building simulation program DOE-2.1C via the FUNCTION command. As expected, calculated cooling load reductions from radiant barriers scale with the inverse of the attic insulation thickness; for California climates, between 500 and 600 Btu/ft^2 can be expected for attics with an R30 insulation level and a clean, horizontal radiant barrier.

3.8 Earth Cooling Tubes

3.8.1 General Information

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 [72].
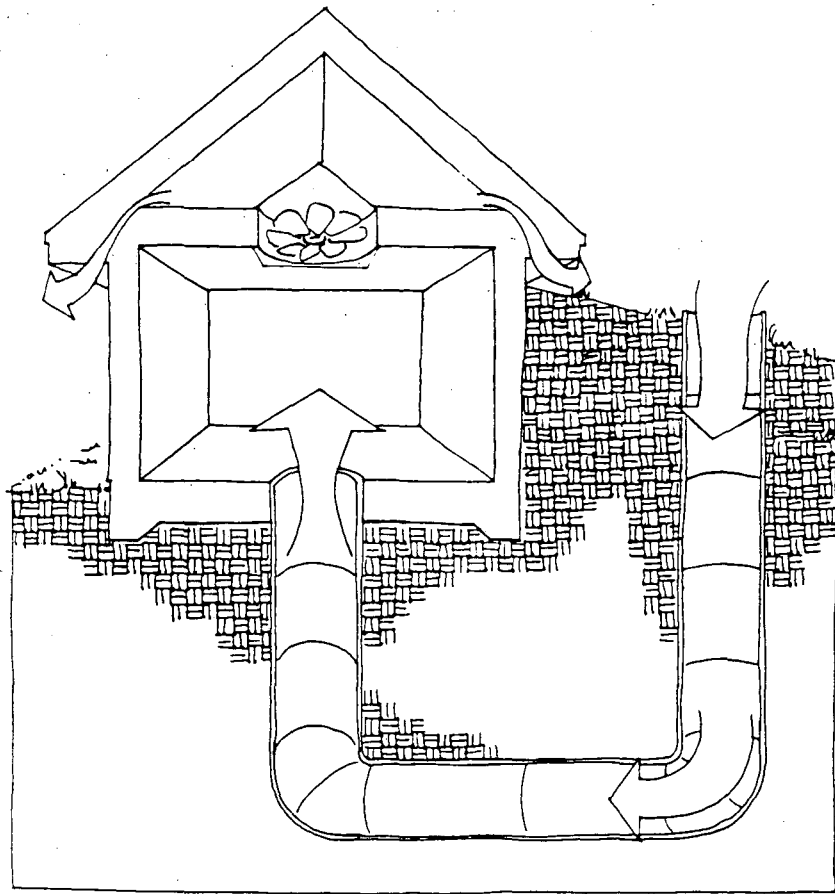
Figure 6: *Open-Loop Earth Tube Cooling [16]*

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. In applications using air, supply air is drawn through underground earth tubes and cooled by heat transfer along the tubes. Earth tubes and pipes can also be used as pre-coolers for air conditioners and can be designed as closed-loop or open-loop systems [16].

Earth cooling can be used in houses and small commercial buildings. 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 [16].

3.8.2 Problems

Although cooling with earth tubes seems very simple, it has drawbacks. Integrating the system into the ground is expensive, and the latent cooling provided is very limited. Ground water also often penetrates the system; small amounts of water accumulated even in sloped systems, will add moisture to the indoor air, which 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 [16].

3.9 Desiccant-Based Cooling

Desiccant materials absorb water or water vapor from other materials [73], [74]. 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 which require very low humidity levels and for which conventional compressor dehumidification is not efficient.
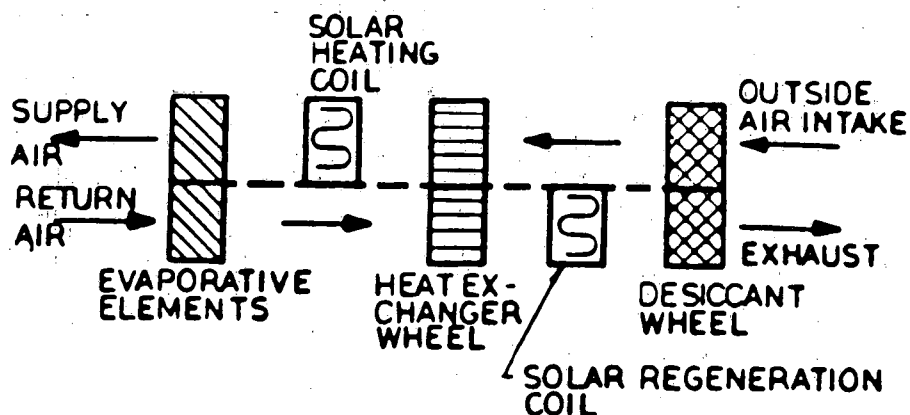
Figure 7: *Schematic of Residential Solar/Desiccant Air Conditioning System [73]*

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 (180°F) 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. A schematic of such a system is shown in Figure 7. 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 three tons of cooling capacity and 10 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 seems more appropriate for hot, humid climates (where dehumidification is necessary for comfort) than for California's relatively dry transition climates, where evaporative coolers perform satisfactorily without preliminary dehumidification of the air. The small improvement in performance resulting from preliminary dehumidification seems unlikely to justify the cost.

3.10 Absorption Cooling

Absorption cooling was developed in by Carl Munters and Baltzer Von Platen during the 1920's, in Sweden. The basic principle of absorption cooling is shown in Figure 8. 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 [75].

When heat is applied to the generator, the refrigerant is destilled from the absorbant, 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 [76].

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 (such as the three-ton unit by Dometic Corporation) 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 which features a three-ton cooling capacity and heating and cooling COPs of 1.8 and 0.94 respectively [77]. 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.
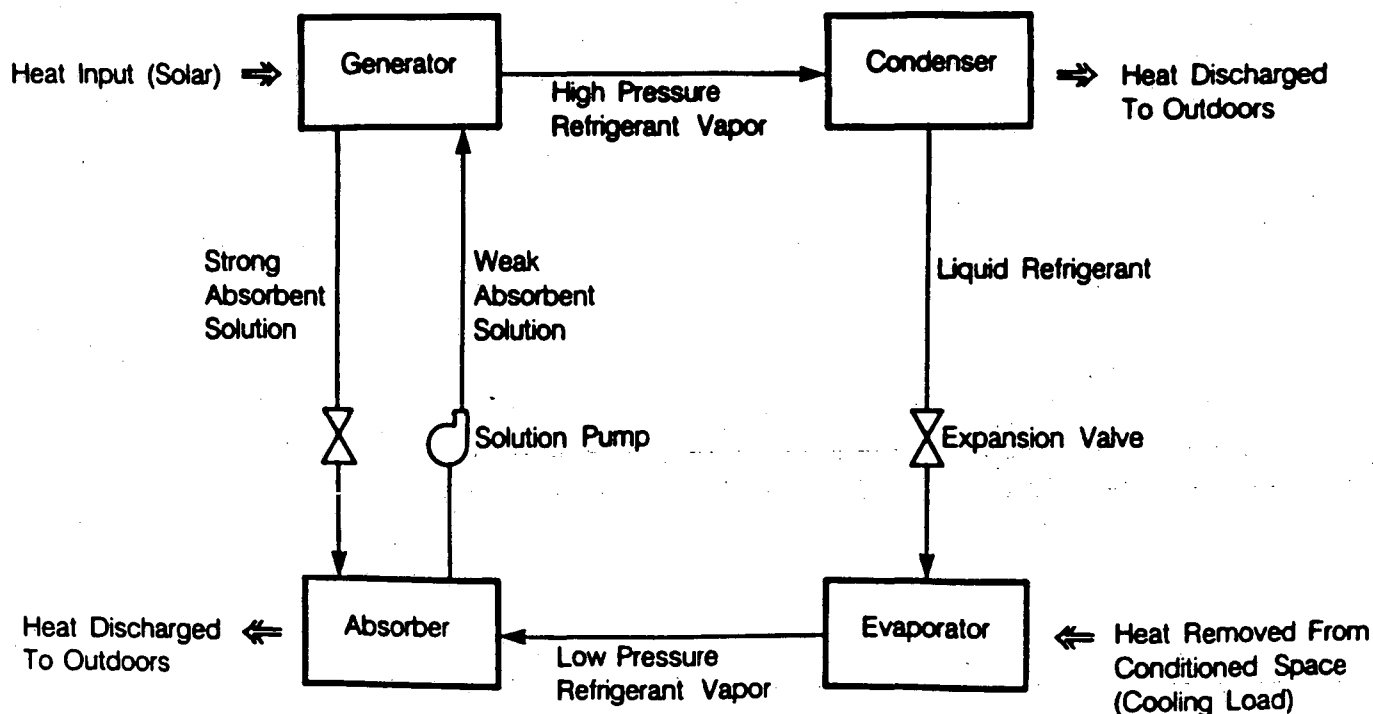
Figure 8: *Schematic of Absorption Cooling [76]*

Existing residential absorption cooling equipment, costs about $500 - 600 more per ton 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 [78]. Absorption heat pumps are particularly attractive in areas with both cooling and substantial heating seasons.

4. Research Issues

The problem of researching alternatives to compressor cooling in transition climates is a puzzling one. 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 we try to displace compressors in transition climate residential markets, we need to understand better the reasons for the dominance of this technology. 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.

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. Designing a workable system is simple, requiring only the use of rules of thumb. (A simple design involves a primitive cooling load calculation to estimate the capacity needed and the addition of some extra capacity to provide a margin for error.) 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 technology is reliable and easy to control; that is, compressor-driven air conditioners are reliable in the mechanical sense (they do not require a lot of maintenance), and they are capable of meeting cooling requirements in wide variety of climatic conditions. In contrast, evaporative cooling does not perform well when the humidity is high; night ventilation does not perform well if the nighttime temperature does not fall sufficiently, etc. 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. The importance of these features should not be underestimated—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 eliminating compressors in transition climates must take these factors into account from the outset. This belief has guided us in the paragraphs below, where we present research recommendations for CIEE.

4.1 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 for CIEE 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, CIEE should make design issues an integral part of its simulation efforts and should make the development of easy-to-use design tools a central (albeit long-term) objective.

4.2 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. Because performance measurements are much more expensive than simulation, CIEE should look at ways to reduce costs. 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. The largest number of such measurements is probably in utilities' load research programs. The data collected in these programs include measurements of compressors' performance and of temperature. These data can be used to learn more about how compressors actually perform in transition climates (the estimate of load factor given in Section 1 above is based on simulations by the CEC). In residences without compressors, temperature measurements may provide insight on ways to develop non-compressor cooling strategies. If these residences are accessible, much could be learned by comparing houses that perform well with houses that do not. Also, because these houses already have monitoring systems in place, they could be very good sites for demonstrations. CIEE is already conducting a research project using some utility load research data (PG&E's AMP data) as part of an effort to develop data for forecasting models. This connection should be expanded.

We believe that CIEE should 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.

Inevitably, a program to eliminate compressors in transition climates will require demonstrations of the alternative cooling strategies. CIEE should develop standard measurement protocols so that, when these demonstrations take place, results will be comparable among demonstrations and supportive of simulation work.

4.3 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 may offer a solution to these difficulties. The advent of inexpensive microprocessors and random access memories makes it possible to store and execute very complex control strategies. The issues that CIEE should address are: (1) the development of controllers that are "user friendly" and (2) development of controls that address the indoor climate in general rather than focusing on one specific cooling strategy. A successful program could improve the performance of both compressor-driven systems and non-compressor alternatives. Good controllers will probably have to control space heating and perhaps perform other functions (e.g., load management) as well.

4.4 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 are by no means an exhaustive list, nor do they purport to be the best ideas. They are intended to illustrate some of the many good possibilities that could be pursued by CIEE investigators.

4.4.1 Adjustable Speed Drives (ASDs)

Adjustable speed drives (ASDs) 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, ASDs might increase the acceptability of alternative technologies because the drafts associated with high ventilation rates would be reduced except in extreme conditions.

4.4.2 Heat Exchangers

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.

4.4.3 Phase-Change Materials

From 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.

4.5 Policy Issues

While CIEE does not make or implement policy, CIEE can conduct investigations that provide information and analytical tools for use by those who do make and implement policy. Research topics related to issues of concern to policymakers and program developers are discussed below.

4.5.1 Environmental Impacts

The net environmental impacts of alternative cooling strategies are probably 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 the South Coast Air Quality Management District 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).

4.5.2 Behavioral Questions

Behavioral research is needed both to improve the design of the research program and to aid in the design of programs that will encourage the use of alternative cooling strategies. CIEE should research 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. 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.

4.5.3 Program questions

A variety of means could be employed to encourage use of alternative cooling strategies, including standards, incentives, and education programs. CIEE should examine these and others measures to learn what information is needed to support their implementation. This effort could be assisted by an advisory group with experience in designing and implementing conservation programs.

5. Acknowledgements

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