energydesignresources

design brief

AIR CONDITIONING & VENTILATION

Summary

Air-conditioning and ventilation systems have a large impact on building profitability. Not only do they consume about one-fourth of an office building's electricity, but they have a large influence on worker productivity. Nonetheless, considerable evidence indicates that air-conditioning systems receive less attention than they deserve. Opportunities to cost-effectively improve the energy efficiency of these systems frequently go overlooked, and surveys of office workers have shown that one-third to one-half of those questioned find their offices too hot or too cold.

This state of affairs is both unnecessary and uneconomical. Using the whole-systems approach, designers around the world have succeeded at crafting highly efficient air-conditioning systems that also provide excellent workspace comfort. They begin by minimizing unwanted heat gains to reduce cooling loads. Next, they design air-distribution systems and cooling plants to meet those reduced cooling loads, taking advantage of both capital and operating cost savings. Finally, they specify highly efficient cooling plants.

In one exemplary building that benefitted from this approach, worker productivity improved by 16 percent, while electricity consumption went down by 40 percent. Another building's clever design made it possible to maintain thermal comfort in a hot climate without any electrically powered air-conditioning and ventilation system. Designers need not feel pressured, however, to produce such extraordinary results. Virtually any air-conditioning and ventilation design can be incrementally improved through the use of the whole-systems problem-solving approach.

Using the whole-systems approach to building design, designers around the world have succeeded at creating highly efficient air-conditioning systems that provide excellent workspace comfort.

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Introduction

Air-conditioning and ventilation systems have a tough assignment. Although they work tirelessly to make buildings comfortable and healthy, they are rarely noticed unless they aren't working well. That's a shame, because these systems have a huge impact on the bottom line for building owners and operators. For example, air-conditioning and ventilation systems consume nearly one-fourth of the electricity used in commercial buildings in the five-state Pacific region that includes California.[1] Although the minimum efficiency of these systems is prescribed by local and national codes and standards—such as the California Energy Commission's Title 24—there are often many economically justifiable opportunities for reducing air-conditioning energy costs that go overlooked.

Air-conditioning and ventilation systems consume nearly one-fourth of the electricity used in commercial buildings in the five-state Pacific region that includes California.

The impact that air-conditioning systems have on worker productivity is also frequently overlooked by owners and operators. As **Figure 1** shows, in a single year, office-worker salaries equal about $130 per square foot. That is about one-and-one-half times the cost of constructing the building, nearly 100 times the annual electric bill, and about 160 times the operating cost of the building's space cooling and air-handling system.[2]

Is it worthwhile to spend more money on a high-quality air-conditioning and ventilation design that yields a more comfortable building and improved worker productivity? Judging from studies showing that one-third to one-half of the office workers questioned find their offices to be too hot or too cold, the answer would appear to be yes.[3] Productivity gains need not be large to quickly pay for the additional design and construction costs of improving these systems. For example, assuming that a new commercial air-conditioning system costs about $10 per square foot to design and install, if a 10 percent increase in the cost of that system resulted in only a one percent increase in productivity, the additional cost would be paid for sometime during the first year of operation.

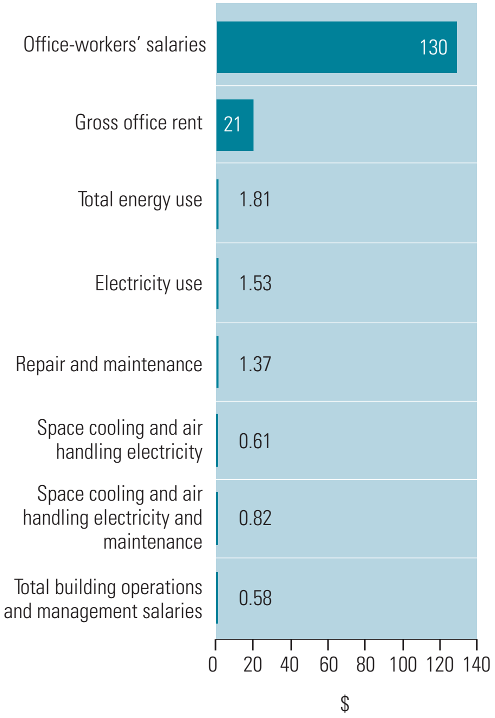
Because productivity improvements have the potential to produce far greater returns than energy efficiency improvements, we also need to ask whether it might make sense to improve productivity at the cost of increased energy consumption. If one had to choose between these two attributes, the obvious choice would be productivity. Fortunately, building designers do not have to settle for that kind of trade-off. It is possible to design highly efficient air-conditioning systems that also provide excellent workspace comfort, yielding lifetime economic benefits for owners and well-modulated temperatures for occupants.

If forced to choose between improving productivity or energy efficiency, the obvious bottom-line choice would be productivity. Fortunately, designers don’t have to settle for that kind of trade-off.

For example, when the West Bend Mutual Insurance Company built its new 150,000-square-foot headquarters in West Bend, Wisconsin, several years ago, the building design incorporated many energy efficient features, such as upgrades to lighting and window systems. The finished, all-electric building uses 40 percent less electricity than West Bend’s old building, which was gas-heated.[4]

Figure 1: Annual operating costs per square foot for a medium-size office building

In a medium-size office building, one year’s worth of office-worker salaries is roughly equivalent to one-and-a-half times the entire cost of constructing the building.



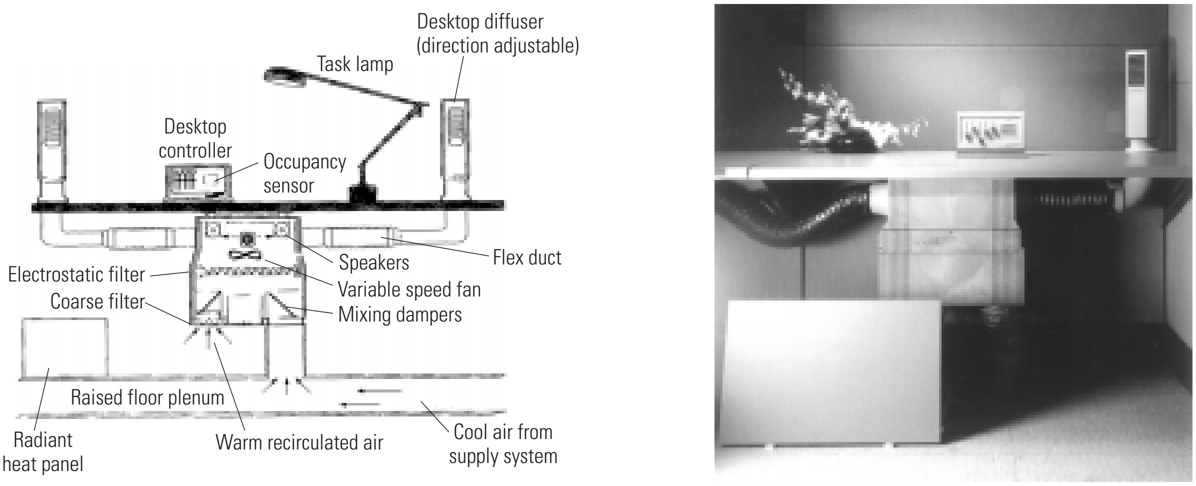
Source: E SOURCE

But the savings didn't end there. The advanced air-conditioning system designed for the building also included "personal environment modules" for 430 of West Bend's 500 employees. The modules feature adjustable desktop diffusers that allow employees to control both the airflow and the temperature right at their desktop (**Figure 2**). Before and after the move, researchers monitored the performance of West Bend's workers. Overall productivity improved by 16 percent after workers moved into the new building. To determine what portion of that improvement was due to the personal environment modules, researchers turned off some of the modules at random and continued monitoring. The results indicated that the personal environment modules were responsible for a 2.8 percent gain in productivity, worth about $364,000 a year to West Bend—enough to pay for the modules in just 18 months.

Building designers can achieve high levels of comfort and energy efficiency with or without such modular environments, but to get the best results, they must be willing to start with the objective—in this case, a comfortable and efficient workspace—and

Figure 2: A personal environment module

Johnson Controls' Personal Environment Module allows users to adjust desktop air temperature and air flow by way of a fan-powered mixing box located beneath the desk. The box draws chilled air from the floor plenum or from a vertical chase and passes it through an optional electrostatic filter to adjustable desktop diffusers. An optional electric radiant panel provides heating when needed, and an infrared occupancy sensor mounted on the desktop controller turns off the module's task lighting and other functions after the space has been unoccupied for 10 minutes.



Source: Johnson Controls

then move upstream through the possible systems, selecting the best technologies for reaching that goal. For example, a designer might first reduce cooling loads by minimizing unwanted heat gains. Next, the efficiency of air-distribution systems might be improved, and last, the designer might specify highly efficient cooling plants—or achieve even greater savings by replacing refrigerative cooling with evaporative cooling.

Although this whole-systems approach is a departure from business-as-usual, it is not so complicated; any designer could benefit from approaching problem-solving in this way. Once mastered, the whole-systems approach gives designers an edge that will clearly distinguish them from more conventional competitors who seek only to meet minimum standards and who follow conventional rules-of-thumb.

Reducing Cooling Loads

The least expensive way to cool a building may be not introducing unwanted heat into it in the first place. In many commercial buildings, during the cooling season most of the electricity used to power lights generates heat that must ultimately be carried away by the air-conditioning and ventilation system. If ordinary lighting systems are replaced with more efficient ones, less electricity is needed to power the lighting system, and therefore less heat is given off, lightening the load for the cooling system.

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Once cooling loads have been reduced, an air-conditioning designer may be able to specify a smaller, less-expensive cooling system, reducing operating costs even further. Such a system would feature a smaller cooling plant, but often the designer can also specify smaller pipes, fans, and pumps. These savings may, in turn, offset any additional costs associated with installing the technologies that lightened the cooling load.

In some buildings scattered around the world, designers have created extraordinary examples of what can happen when cool-

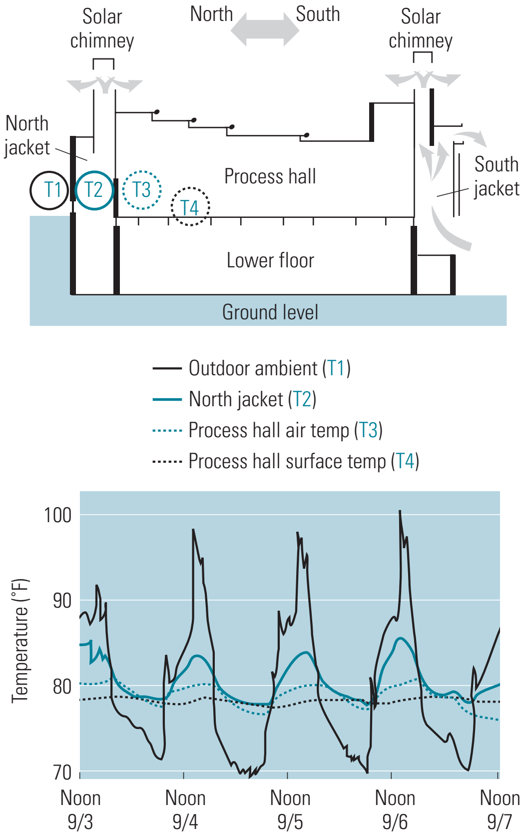
Some buildings located in hot climates around the world have been so cleverly designed that they maintain thermal comfort without any electrically powered air-conditioning or ventilation system.

ing loads are cost-effectively reduced and air-conditioning systems are designed to meet those reduced loads. Their clever designs allow thermal comfort to be maintained without any electrically powered air-conditioning and ventilation system at all (**Figure 3**). Certainly, such results will not always be appropriate or even feasible, but these remarkable buildings show what can be accomplished through the use of this innovative design philosophy.

In addition to improving the efficiency of lighting systems, other strategies that might be employed to reduce cooling loads include (see **Figure 4**):

Figure 3: Passively ventilated and cooled building in a hot climate

This brewery, on the island nation of Malta, uses thermal mass, layered construction, and convective ventilation to maintain comfortable core temperatures in a hot climate without an electrically powered air-conditioning and ventilation system. The temperature traces show three days of operation—interior air temperatures vary only by about 2°F, and interior surface temperatures change even less.



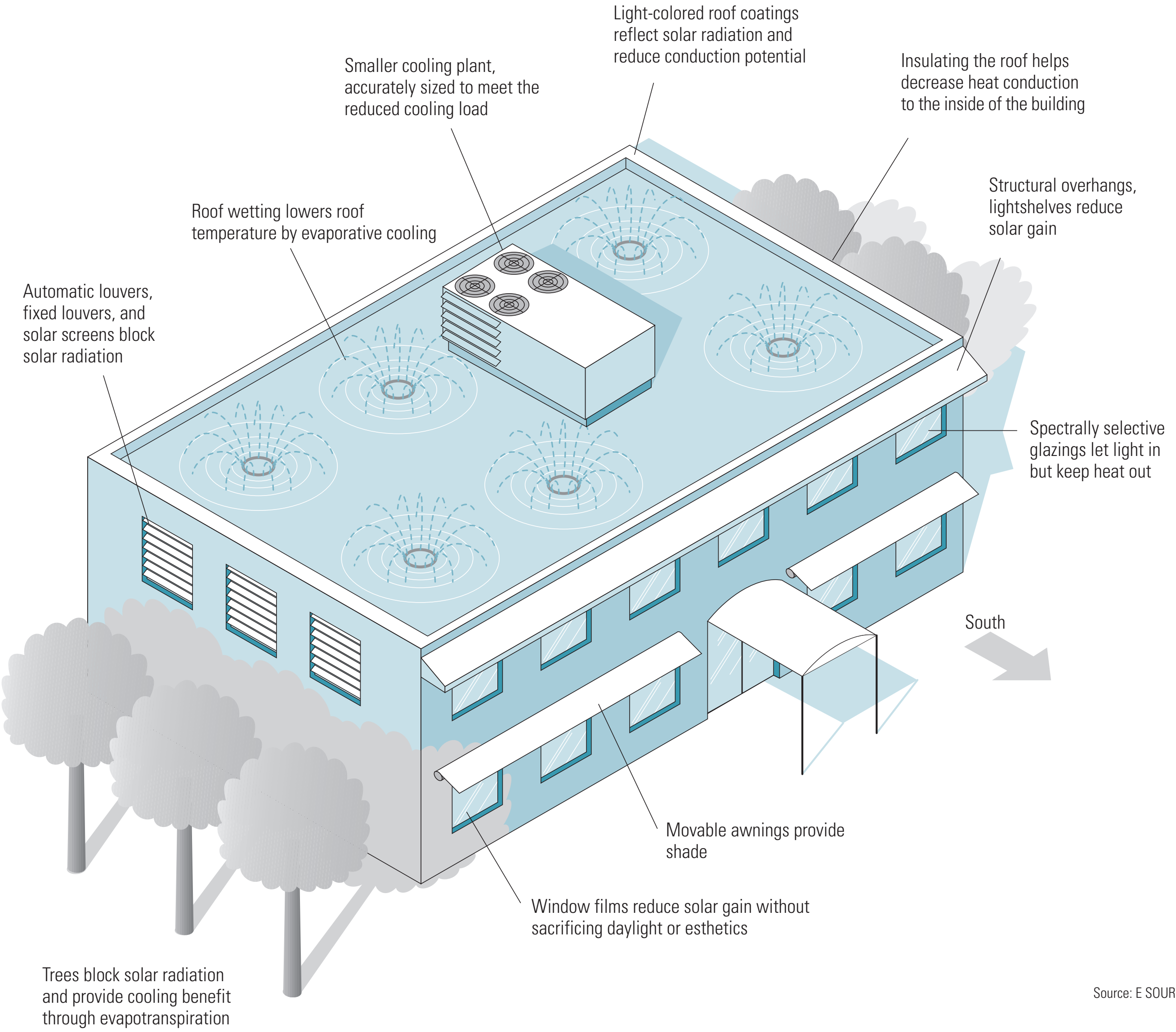
Source: Peake Short & Partners

- Carefully designing the building's form and orientation to maximize daylighting and natural ventilation, while minimizing unwanted solar gain and reducing the use of electric lighting.

- Selecting heat-reflecting envelope materials, including window shading, advanced solar-control glazings, insulation, venting, louvers, and light-colored facades and roofs.

Figure 4: Strategies for reducing cooling loads

This representative commercial building displays a variety of techniques for reducing cooling loads, including roof-wetting to lower temperatures through evaporative cooling.



Source: E SOURCE

- Planting trees and other vegetation to block unwanted sunlight.

To gain the full benefits from these strategies, designers must accurately size the cooling systems in any building where these strategies are to be implemented.

How much impact can reducing cooling loads and accurately sizing air-conditioning systems have? At one office building in Los Angeles, it was possible to downsize the cooling plant by more than 50 percent as part of a comprehensive renovation. In 1993, most of the magnetic-ballasted fluorescent lighting fixtures in this 110,000-square-foot building were replaced with electronic-ballasted units, incandescent lamps were replaced with compact fluorescent lamps, and reflective films were applied to window glazings. Afterwards, the two original 200-ton chillers were removed and replaced with a single 195-ton chiller. Of the 205 tons of capacity that were eliminated, about 100 tons were attributed to the cooling-load-reducing technologies and the remaining 105 tons were attributed to the excess capacity of the original system.

Improving the Efficiency of Air-Distribution Systems

Air-distribution systems bring in fresh outside air to disperse contaminants, to provide free cooling, to transport heat generated or removed by space-conditioning equipment, and to create air movement in the space being conditioned. About one-fourth of the energy consumed by air-conditioning systems is used to power the fans that drive air distribution.[5] In California, Title 24 sets maximum limits for the amount of power that can be consumed by air-distribution fans, but it is entirely possible to design systems that consume far less power. Again, a designer following the whole-system approach would begin downstream and work through the system, in the following sequence:

In California, Title 24 sets maximum limits for the amount of power that can be consumed by air-distribution fans, but it is entirely possible to design systems that consume far less power.

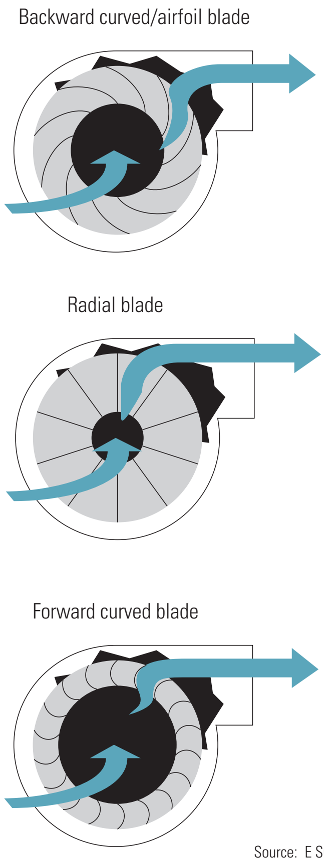
1. *Minimize air flows.* Accurately determine cooling and outside air requirements, and specify variable-air-volume controls that continuously adjust the volume of supply air to building loads.

2. *Minimize the friction of distribution system components.* Mechanically delivered air must cover a lot of territory before it reaches a building occupant, winding its way through filters, cooling coils, silencers, ducts, dampers, and diffusers. Select components that offer low pressure drop wherever it will be cost-effective. For example, doubling the diameter of a duct reduces its friction by a factor of 2 to the fifth power, or one-32nd of its original value.

3. *Specify high-efficiency fans.* With total efficiency ratings of 70 to 85 percent, the most efficient fans are well-designed axial units and backward-curved centrifugal models. Although widely used, forward-curved fans are much less efficient (**Figure 5**).

Figure 5: Centrifugal fan impeller blades

Backward-curved airfoil impellers provide the highest efficiencies for centrifugal fans.



Backward curved/airfoil blade

Radial blade

Forward curved blade

Source: E SOURCE

Much of the energy consumed to drive fans turns into heat that must ultimately be removed from the building by the cooling system. When an air-distribution system is made more efficient, the fan will consume less energy and the cooling load will also be reduced. This compounding of savings may add as much as 23 percent to the direct fan savings.[6]

When the Sacramento Municipal Utility District (SMUD) began designing a new 175,000-square-foot customer service center in the mid-1990s, they applied the whole-systems approach. The designers selected an underfloor air-distribution system, which uses a 12-inch gap below raised flooring throughout the office space as the supply-air plenum (**Figure 6**). Underfloor systems offer six major benefits:

1. *Reduced fan power.* Although more air flows through underfloor systems, the floor plenum presents far less resistance than ductwork, so the fan doesn't have to work as hard.

2. *Higher chiller efficiency.* Underfloor systems use warmer supply air (about 60° to 65°F), allowing for a warmer evaporator temperature, which boosts chiller efficiency.

3. *Extended economizer range.* Using warmer supply air significantly extends conditions for free cooling (using outside air directly for cooling, with no chiller operation), especially in mild climates.

4. *Better heat removal.* Since underfloor systems provide floor-to-ceiling air flow, most of the heat from ceiling-mounted lights is carried away before it can enter conditioned space. This reduces the effective cooling load in the conditioned space, allowing warmer air to condition the area.

5. *More effective pollutant removal.* The vertical air flow eliminates lateral air mixing. Pollutants are drawn up in a vertical plume to the ceiling rather than being swirled around with room air.

6. *Flexible space arrangements.* The raised floor, with its modular panels, makes it easy to relocate diffusers, wiring, and even plumbing to accommodate changes in occupancy.

Figure 6: Raised flooring

Raised floors look conventional from above, but there is plenty of space for cabling and air flow beneath the 2-foot by 2-foot structural squares.

Source: E SOURCE

Given these benefits, one might expect underfloor systems to be considerably more expensive than conventional air-distribution systems, but evidence suggests they are not. A comparison of floor and duct costs from four projects shows construction costs for the two types of systems to be nearly equal. In general, the costs of the raised floor cancel out the savings from not having to build a duct system.[7]

The underfloor system at the SMUD Customer Service Center has cut the building's cooling energy requirements by about 9.6

percent and fan energy requirements by about 4.6 percent—yielding savings of nearly $4,800 a year in energy costs.[8] Although the underfloor system at the Customer Service Center did have higher first costs than a conventional overhead system, because of its flexibility, the project engineer expects that the marginal cost will be recouped after the first reconfiguration of office space within the building.

Choosing High-Efficiency Unitary Equipment

Take a peek at the equipment that cools nearly any commercial building, and you are likely to see unitary equipment. Available as single packages or as split systems (**Figure 7**), unitary equipment cools two-thirds of all the air-conditioned commercial buildings in the U.S.[9]

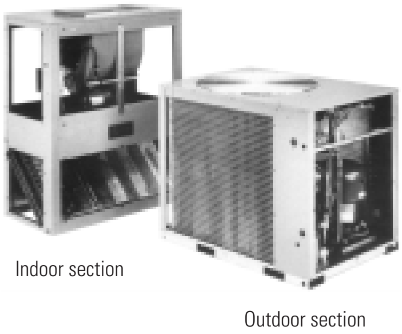
The cooling efficiencies of both single-package and split-system unitary air conditioners under 250,000 Btu per hour are certified according to standards published by the Air Conditioning and Refrigeration Institute (ARI). ARI standards also apply to units of 250,000 Btu per hour and over, but ARI has no certification program and does not publish efficiency data for this size range.

The three cooling-efficiency measurements defined in the ARI standards are EER, the energy efficiency ratio; SEER, the seasonal energy efficiency ratio; and IPLV, the integrated part-load value. EER is a ratio of the rate of cooling (Btu per hour) to the power input (W) at full-load conditions. The power input includes all inputs to compressors, fan motors, and controls. SEER and IPLV are estimated or calculated ratios of annual cooling (Btu) to the annual energy consumption (watt-hours). SEER is a seasonally adjusted rating based on representative residential loads that applies only to units with a cooling capacity of less than 65,000 Btu per hour. IPLV, a seasonal efficiency rating method based on representative commercial loads, applies to units with cooling capacities at or greater than 65,000 Btu per hour. EER is the rating of choice when determining which unit will operate most efficiently during full-load conditions. SEER

Figure 7: Split and single-package unitary equipment systems

Split systems are made up of an indoor unit (containing a fan and an evaporator) and an outdoor unit (containing a condenser, a condenser fan, and a compressor). Single-package systems include all functions in one outdoor package.

Split system



Single package

Source: The Trane Company

and IPLV are better than EER for determining which unit will use less energy over the course of an entire cooling season.

Standards for the minimum efficiency of unitary equipment have been established by the California Energy Commission via Title 20, “Appliance Efficiency Regulations,” and Title 24, “Energy Efficiency Standards for Residential and Nonresidential Buildings.” **Table 1** summarizes these minimum efficiencies, which are nearly identical to the requirements stipulated in national standards.

When trying to minimize operating costs, the design challenge is to specify the most efficient unit that will fit within a client’s cost-effectiveness limits. There is a lot of choice—manufacturers offer units with a wide range of efficiencies that exceed the minimum efficiency ratings across the different sizes of cooling plants (see **Figure 8**).

Two main sources of information are available to help designers identify units that exceed the minimum efficiency ratings: ARI and the California Energy Commission. The most widely used references are directories maintained by ARI, which

Table 1: California’s minimum efficiency requirements for unitary cooling equipment

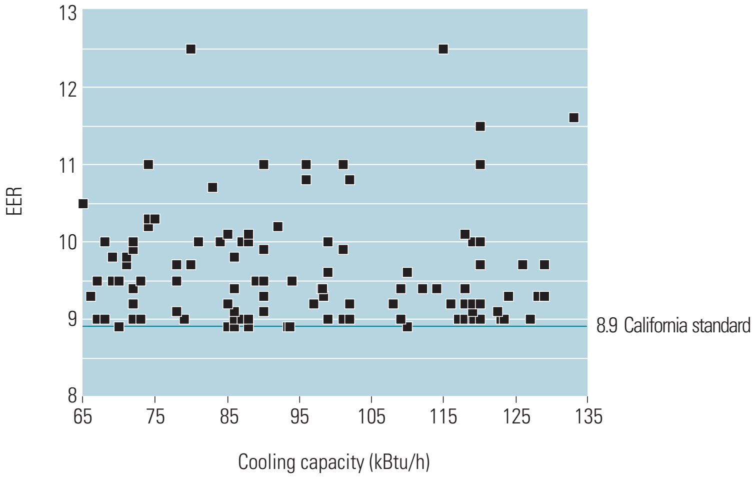
Unitary equipment in California with a cooling capacity of less than 135,000 Btu per hour must meet the minimum efficiency requirements of the California Energy Commission’s Title 20, “Appliance Efficiency Regulations.” Equipment with a capacity greater than 135,000 Btu per hour must meet the minimum efficiency requirements of Title 24, “Energy Efficiency Standards for Residential and Nonresidential Buildings.”

Equipment size (Btu/h)	California minimum standards
Under 65,000	
Split systems	10.0 SEER
Single package	9.9 SEER
65,000 to 134,000	8.9 EER and 8.3 IPLV
135,000 to 760,000	8.5 EER and 7.5 IPLV
760,000 and larger	8.2 EER and 7.5 IPLV

Source: California Energy Commission

Figure 8: Efficiency ratings for unitary air conditioners

Unitary cooling equipment is available in a wide range of efficiency ratings. The air-cooled units plotted here have capacities that range from 65,000 to 134,999 Btu per hour.



Source: California Energy Commission (3/31/97) include products from all ARI member-manufacturers. These directories are available in both print and electronic formats. Although ARI and the California Energy Commission also maintain databases on their Web sites, only units with up to 65,000 Btu per hour cooling capacity are listed there.

To calculate the potential savings that might be realized with a unit that exceeds minimum efficiency, the designer starts by determining the demand savings that would occur during a peak cooling moment, using the following equation:

$kW_{savings} = tons \times (12/EER_{minimum} - 12/EER_{improved})$

where:

$kW_{savings}$ = demand savings

tons = capacity (tons) (12,000 Btu/h = 1 ton)

$EER_{minimum}$ = rating of minimum-efficiency unit (Btu/hW)

$EER_{improved}$ = rating of improved-efficiency units (Btu/hW)

There is a lot of choice—cooling equipment manufacturers offer products with a wide range of efficiencies.

To estimate annual electric energy savings, you will need an estimate of the "annual equivalent full-load cooling hours" (AEFLCH). That's the number of hours an air-conditioner would run at full load to consume the same amount of electric energy it consumes on average over the course of an entire year. Annual equivalent full-load hours are listed in a variety of engineering manuals, including those published by ASHRAE (the American Society of Heating, Refrigerating, and Air Conditioning Engineers).[10] In Southern California, the AEFLCH generally range from about 1,000 to 1,500 hours per year. With an estimate of AEFLCH in hand, annual savings may then be calculated as follows:

$kWh_{savings} = kW_{savings} \times AEFLCH$

where:

$kWh_{savings}$ = annual electric energy savings (kWh)

AEFLCH = annual equivalent full-load cooling hours (hours)

The costs and efficiency ratings of individual unitary air conditioners vary so widely that the economics of purchasing a high-efficiency unit must be analyzed on a case-by-case basis. Take, for example, a choice between a 10-ton rooftop unit rated at 8.9 EER and another rated at 10.3 EER. Let's say that the high-efficiency unit costs about $1,050 more than the minimum efficiency unit. During peak cooling conditions, the high-efficiency unit would draw 1.8 kW less power, and assuming 1,500 annual equivalent full-load cooling hours, it would save about 2,750 kilowatt-hours (kWh). At an average electricity cost of 9.4¢ per kWh, annual savings would be, on average, about $260 per year, yielding an simple annual payback period of four years.

Designing High-Efficiency Chilled Water Systems

Chilled water systems feature separate central chillers and air handlers, with a network of pipes and pumps to connect them. These systems are mainly found in large buildings. Although only 19 percent of all commercial building floor space in U.S. buildings is cooled, at least in part, by chillers, about half of all buildings larger than 100,000 square feet contain chilled water systems.[11]

By their nature, chilled water systems are complex, so it is not surprising that they present a cornucopia of efficiency opportunities.

By their nature, chilled water systems are complex (**Figure 9**), so it is not surprising that they present a cornucopia of efficiency opportunities. Designers who think their way upstream through these systems, starting at the cooling coil and ending at the cooling tower fan, are likely to find opportunities to improve efficiency while taking advantage of capital cost savings for upstream components. For example, by reducing resistance within the piping system, a designer might be able to reduce capital costs by specifying a smaller pump and a smaller chiller. The following list presents efficiency opportunities for chilled water systems in downstream-to-upstream order:

- Select cooling coils for low air-side and water-side flow resistance, for low cooling-water flow rates, and for operation at warmer water temperatures.

- Increase pipe diameters and specify low-friction valves to reduce flow resistance for the chilled water.

- Specify highly efficient pumps with highly efficient motors.

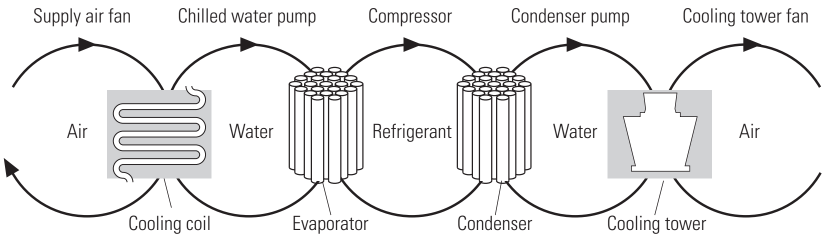
- Control chilled water pumps with adjustable-speed drives. (But do take precautions to ensure that flow rates through chillers are maintained at safe levels.)

- Specify high-efficiency water-cooled chillers. Although Title 24 sets minimums for chillers, a lot of equipment is available with higher efficiency ratings. For example, the Title 24 minimum for water-cooled chillers 300 tons or greater is 0.75 kW/ton at standard full-load conditions, but some of the centrifugal chillers now available operate at less than 0.5 kW/ton. The cost of higher chiller efficiency averages $6 to $7 per ton for each improvement of 0.01 kW per ton, but for a very large chiller, it can run as low as $3 per ton for each 0.01 kW per ton improvement. Given that annual energy

Figure 9: Conceptual view of a chilled-water air-conditioning system

In this figure, thermal energy moves from left to right as it is extracted from the space and expelled into the outdoors through five loops of heat transfer:

• **Indoor air loop.** In the leftmost loop, indoor air is driven by the supply air fan through a cooling coil, where it transfers its heat to chilled water. The cool air then cools the building space.
• **Chilled water loop.** Driven by the chilled water pump, water returns from the cooling coil to the chiller's evaporator to be re-cooled.
• **Refrigerant loop.** Using a phase-change refrigerant, the chiller's compressor pumps heat from the chilled water to the condenser water.
• **Condenser water loop.** Water absorbs heat from the chiller's condenser, and the condenser water pump sends it to the cooling tower.
• **Cooling tower loop.** The cooling tower's fan drives air across an open flow of the hot condenser water, transferring the heat to the outdoors.



Source: E SOURCE

costs for a chiller may amount to as much as a third of its purchase price, even a modest improvement in efficiency can yield substantial energy savings and attractive paybacks. For example, paying an extra $6 per ton for each 0.01 kW per ton improvement to raise the efficiency of a 500-ton chiller from 0.6 kW/ton to 0.56 kW/ton would increase that machine's first cost by $12,000. But that change would reduce operating costs by $3,000 per year, yielding a four-year simple payback.[12]

Designers need to determine what the actual operating conditions are likely to be and then evaluate the efficiency with which different chillers are likely to operate under those conditions.

- Select a chiller that will be most efficient under the conditions it is likely to experience. Even though chiller performance can vary dramatically depending on loading and other conditions, designers frequently select chillers based on full-load, standard-condition efficiency. However, chillers spend most hours at 40 to 70 percent load, under conditions that are often considerably different from standard conditions. To select the chiller that will have the lowest operating costs, designers need to determine what the actual operating conditions are likely to be and then evaluate the efficiency with which candidate chillers are likely to operate under those conditions.

- Select unequally sized machines for multiple chiller installations. Chillers operate more efficiently when they are loaded close to their full rating than when they are only lightly loaded. If one chiller in a two-machine installation is smaller than the other, under most operating conditions, one or the other of the two chillers should be able to run close to full load. This will result in more efficient operation than if one or two same-sized chillers were operating at a lighter load.

- Install a variable-speed drive (VSD) on the chiller compressor. The VSD will allow the compressor to run at lower speed under part-load conditions, thereby yielding a lower compressor kW/ton rating under those conditions than is typically achieved by ordinary centrifugal chillers that control part-load operation with inlet vanes.

- Specify an induced-draft cooling tower. Although it requires more space than a forced-draft tower, the induced-draft tower is more efficient.
- Oversize the cooling tower so that it returns condenser water to the chiller closer to wetbulb temperature.
- Install VSDs to control cooling-tower fans on chilled water systems with multiple manifolded towers or multicell towers.
- Install heat exchangers and controls to allow cooling towers to produce chilled water when weather conditions permit.

There are a pair of serious challenges inherent in this design approach. First, it is difficult to generalize about the cost-effectiveness of these opportunities. Selecting the most cost-effective chiller for a particular building often requires a designer to take into account energy and demand prices, building load characteristics, local climate, building construction, operating schedules, and the part-load operating characteristics of the available chillers. Accounting for all these variables can be a daunting task, especially since some of them change on an hourly basis.

Although it is tempting to improve the efficiency of chilled water systems by minimizing the energy consumption of each individual component, that approach will not necessarily produce the most efficient system.

Second, although it is tempting to improve the efficiency of chilled water systems by minimizing the energy consumption of each individual component, that approach does not necessarily lead to the most efficient system. The pieces of a chilled water system interact in complex ways that make such general prescriptions difficult. For example, the efficiency of a chiller can be improved by increasing chilled water flow. However, that will necessitate more pumping power, which may exceed the saved chiller power, resulting in a net loss of system efficiency.

To illustrate these challenges, consider the case of a designer who switched a chiller condenser-tube bundle from two-pass flow to four-pass flow in order to improve chiller efficiency. That change improved chiller efficiency from 0.62 kW per ton to 0.60 kW per ton, but it also added 28 feet of pressure drop to the chilled water flowstream and increased the required pumping power by 8.6 kW. At full load, the new tube bundle reduced chiller power by 8.8 kW, but when the increased pumping power was added, overall system power was cut by 0.2 kW. At 75 percent load, which was typical in this building, the new tube bundle reduced chiller power by 6.6 kW, but since this particular building featured a constant-flow system, the pumping power increase of 8.6 kW led to an overall system power-demand increase of 2 kW. The net effect was even worse at lower loads. Although this designer had intended to reduce energy consumption by improving chiller efficiency, he wound up increasing overall building energy consumption.

In the face of such complexity, how can building designers determine the combination of strategies that will produce an optimal chilled water system? One of the best options is to turn to a building energy performance simulation package.

In the face of such complexity, how can building designers determine the combination of strategies that will produce an optimal chilled water system? One of the best options is to turn to a building energy performance simulation package. These computer programs carry out the numerous and complex equations needed to evaluate how buildings use energy. The most sophisticated programs are capable of calculating building energy consumption hour by hour for an entire year. That allows designers to see how modifications to any of the building's systems—including the chilled water system—will affect the building's annual energy consumption. Furthermore, these packages account for interactions between building components. As a result, building designers can experiment with a variety of combinations of efficiency strategies and determine which ones produce the most cost-effective building.

The best-known hourly simulation software is DOE-2 (developed by the Simulation Research Group at Lawrence Berkeley National Laboratory), but there are several other packages available on the market, a few of which are produced by HVAC equipment manufacturers. It does takes some practice to become adept at using these building energy performance simulations, and running a variety of scenarios can be quite time-consuming. Therefore, some designers may prefer to hire consultants who specialize in performing these evaluations. Either way, designers and their clients may seek to amortize the cost of simulating building performance by using simulations after the building is occupied in order to verify savings, optimize HVAC system control, and identify malfunctions in building systems.

Replacing Refrigerative Cooling with Evaporative Cooling

All cooling systems currently produced for commercial buildings are based on the principle of evaporation. As molecules are energized from the liquid to gas state, they carry away from the liquid the heat of vaporization. In most cooling systems, a refrigerant evaporates within a sealed heat exchanger. In another, albeit less popular technology, water simply evaporates into air to produce a cooling effect. Known by the moniker, "evaporative cooling," these water-based systems typically use less than one-fourth the energy of refrigerative air-conditioning systems. The reason evaporative systems use less energy is that unlike refrigerative systems, they do not have to compress vapor and condense it back into liquid to repeat the cooling cycle. Instead, evaporative coolers continually introduce fresh supplies of air and water.

Water-based evaporative cooling systems typically use less than one-fourth the energy of refrigerative air-conditioning systems.

Despite such favorable energy-consumption characteristics, evaporative coolers are rarely found in commercial buildings. In fact, less than five percent of all commercial building floorspace in the U.S. is cooled, at least in part, by this technology. Why is that so? It may be because evaporative cooling applications are limited by local climate, many HVAC designers are unfamiliar with evaporative technologies, and evaporative cooling systems typically have a higher first cost than refrigerative cooling systems. However, in Southern California, evaporative cooling is feasible in most inland locations; the technology is rapidly becoming more popular, in part, thanks to demonstration sites such as the Southern California Gas Company's Energy Resource Center; and any additional first costs are usually returned quickly in the form of energy savings.

There are four types of evaporative cooling systems, and they are listed here in order of complexity and cost:

1. *Direct:* Long used to cool homes and small commercial buildings in the arid American west, direct evaporative coolers (also known as “swamp coolers) use a fan to blow hot, relatively dry outside air across a wetted pad (**Figure 10**). The water evaporates directly into the incoming air stream. To keep the process going, an equal quantity of air must constantly be exhausted from the building to offset the in-flow. The chief drawback to direct coolers, at least in moist climates, is that they increase the humidity of the conditioned space.

2. *Indirect:* These coolers feature an impermeable heat-exchange surface such as a thin plastic plate or tube. A direct evaporative process cools air or water on one side of the exchanger so that air passing by the other side of the exchange surface is cooled without any moisture being added (**Figure 11**). Indirect coolers are occasionally used to cool outside-air ventilation intake flows. Water-side economizers are another form of indirect evaporative coolers.

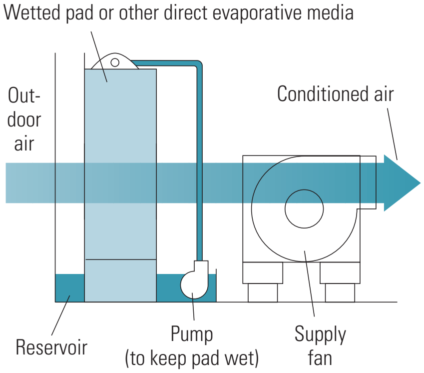
3. *Two stage*: By placing an indirect cooler upstream from a direct cooler, lower-temperature air can be supplied than is possible with either of these technologies alone (**Figure 12**). Two-stage systems are capable of providing cooling that is equivalent to, or even superior to refrigerative air-conditioners.

4. *Hybrid:* These systems combine evaporative and vapor-compression technology. They use evaporative cooling whenever possible, but provide vapor-compression refrigeration for additional cooling or humidity control.

To determine whether a two-stage system is capable of meeting peak cooling loads for a particular location, designers need to begin by determining the local summer design wetbulb temperature. Wetbulb temperature is measured by a thermometer that

Figure 10: Direct evaporative cooler

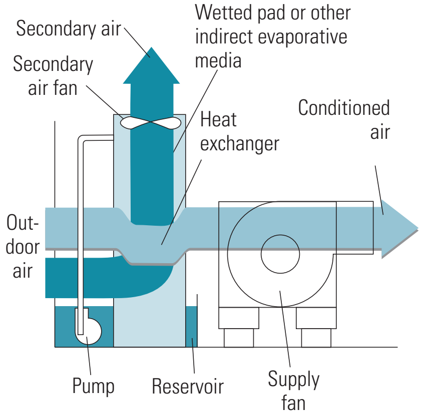
Wet-surface direct evaporative coolers typically use pumped recirculating water systems to keep the media wet, and a fan that blows air through the media, thereby cooling it and increasing its humidity.



Source: E SOURCE

Figure 11: Air-to-air indirect evaporative cooler

In a typical indirect evaporative air cooler, the essential element is a heat exchanger in which dry air contacts heat exchange surfaces whose other sides are cooled evaporatively.



Source: E SOURCE

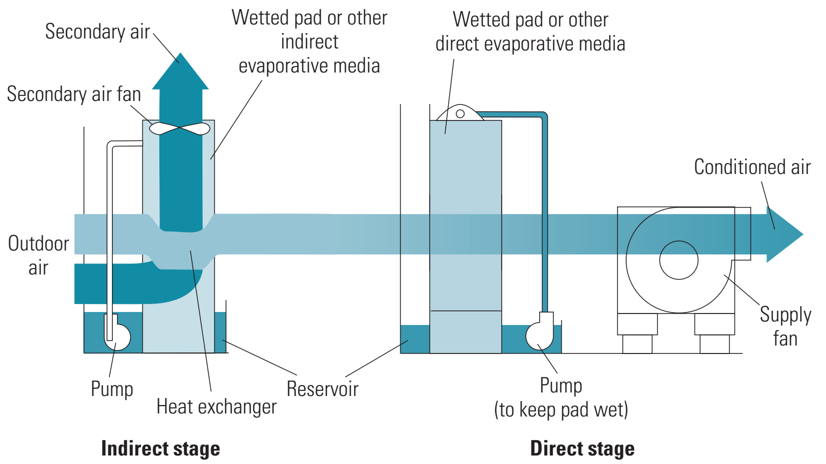
has a wetted sock stretched over the bulb. Air is allowed to flow over the sock at a specified velocity. The drier the air that passes over the sock, the lower the wetbulb temperature will be. The California Energy Commission publishes summer design wetbulb temperatures for hundreds of locations throughout California.[13] Wherever the summer design wetbulb temperature is below 70°F, a two-stage system is likely to work well, nearly all the time. Before making a commitment to such a system, however, designers should also check local weather records to ensure that the location does not experience extended periods of high wetbulb temperatures combined with high drybulb temperatures. A hybrid system may well be the most cost-effective option for locations that experience conditions that exceed the capabilities of two-stage coolers.

A hybrid system may well be the most cost-effective option for locations that experience conditions that exceed the capabilities of two-stage coolers.

Evaporative cooling systems range widely in cost, depending on the complexity of the design and the materials of construction. It is difficult to compare their costs to those of refrigerative cooling systems because the cost of evaporative systems is expressed in dollars per cubic feet per minute (cfm), rather than in dollars per ton. Another complication is that the amount of cooling an evaporative system provides can vary widely

Figure 12: Two-stage evaporative cooler

Dry air leaving the indirect stage can be further cooled in the direct stage to a temperature below the outdoor wetbulb.



Source: E SOURCE

depending on local climate. There are, however, numerous examples of systems that have been independently studied and shown to be cost-effective. Take, for example, One Utah Center, a 419,000-square-foot office tower in the Salt Lake City area. This building features a hybrid system with a two-stage evaporative cooler, oversized cooling towers, refrigerative chillers, economizer ventilation, thermal storage tanks, and variable-flow pumping. Computer models predict annual savings of about 1,700,000 kWh that can be attributed directly to the evaporative cooling system. At the local electric rate of only 3 cents per kWh, annual savings would be $51,000 against an initial added cost for the evaporative cooling system of $180,000, for a simple payback period of 3.5 years.[14] An equivalent system in a location where electricity cost 9 cents per kWh would pay for itself in just over one year.

FOR MORE INFORMATION

Air Conditioning and Refrigeration Institute (ARI)
4301 North Fairfax Drive, Suite 425
Arlington, VA 22203
tel 703-524-8800
fax 703-528-3816
web www.ari.org

ARI publishes efficiency ratings in print and on CD-ROM for all certified air-conditioners, heat-pumps, and chillers. Efficiency ratings for selected products can be searched from their Web site.

California Energy Commission
Energy Efficiency Division
1516 9th Street, MS-42
Sacramento, CA 95814-5512
tel 916-654-4080
fax 916-654-4304
web www.energy.ca.gov/efficiency/

The California Energy Commission publishes standards regulating commercial building efficiency and maintains on its Web site a list of unitary HVAC equipment with a cooling capacity of up to 65,000 Btu per hour that exceeds those standards by at least 15 percent.

E source
4755 Walnut Street
Boulder, CO 80301-2537
tel 303-440-8500
fax 303-440-8502
web www.esource.com

E source publishes the *Commercial Space Cooling and Air Handling Technology Atlas*, a comprehensive and definitive reference that combines up-to-date technical information with practical case studies and application guidelines.

Ernest Orlando Lawrence Berkeley National Laboratory
Simulation Research Group
One Cyclotron Road
Berkeley, CA 94720
tel 510-486-5711
fax 510-486-4089
web http://eande.lbl.gov/CBS/CBS.html

Lawrence Berkeley National Laboratory's Simulation Research Group is the leading national organization researching and developing simulation tools for evaluating building energy performance. The group puts out a free newsletter for simulation users and operates a DOE-2 telephone help line.

Pacific Energy Center
851 Howard Street
San Francisco, CA 94103
tel 415-973-7206
fax 415-896-1290
web www.pge.com/pec/

Although largely focused on central and northern California, the Pacific Energy Center provides a variety of services, including educational programs, design and measurement tools, technical advice, and energy information resources. They also offer several software tools for analyzing chillers and chilled water systems.

Southern California Edison
Customer Technology Applications Center (CTAC)
6090 N. Irwindale Avenue
Irwindale, CA 91702
tel 800-336-2822
web www.sce.com

At this 45,000-square-foot conference facility, visitors can learn about HVAC technologies by attending workshops, seminars, and product demonstrations.

Notes

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3 W. Kempton and L. Lutzenhiser, “Introduction,” *Energy and Buildings*, v. 18, no. 3 (1992), pp. 171–176.

4 Joseph Romm and William Browning, “Greening the Bottom Line,” Rocky Mountain Institute (1994), 1739 Snowmass Creek Road, Old Snowmass, CO 81654-9199, tel 970-927-3851, fax 303-927-4178; “Get Comfortable,” *Facility Issues* (June 15, 1994); and Johnson Controls case study X95-241.

5 U.S. DOE, Energy Information Administration [1].

6 Jay Stein, “Low-Cost/No-Cost Efficiency Retrofits for Chilled Water Systems,” E SOURCE *Tech Update TU-97-9* (September 1997), p. 5, E SOURCE, 4755 Walnut Street, Boulder, CO 80301-2537, tel 303-440-8500, fax 303-4408502, web www.esource.com.

7 Gary Cler et al. [2], p. 98.

8 Rick Wiesner, personal communication (May 21, 1997), Supervisor of New Construction Services, Sacramento Municipal Utility District, Energy Services Department, 6301 S Street, Sacramento, CA 95852-1830, tel 916-732-5398, fax 916-732-5695, e-mail rwiesne@smud.org.

9 U.S. DOE, Energy Information Administration, “Commercial Buildings Characteristics 1995,” from www.eia.doe.gov/emeu/cbecs/cb952b.html (November 17, 1997).

10 American Society of Heating, Refrigerating, and Air Conditioning Engineers, *1985 ASHRAE Handbook: Fundamentals*, Chapter 28 (1985), p. 7.

11 U.S. DOE, Energy Information Administration [9].

12 Assuming 1,500 annual equivalent full-load cooling hours and an electric rate of 10¢ per kilowatt hour.

13 "Appendix C: California Climate Descriptions," *Title 24 Energy Efficiency Standards for Residential and Nonresidential Buildings*, available from the California Energy Commission, 1516 9th Street, MS-42, Sacramento, CA 95814-5512, tel 916-654-4080, fax 916-654-4304, web www.energy.ca.gov.

14 Tom Colvin, "Office Tower Reduces Operating Costs with Two-Stage Evaporative Cooling System," *ASHRAE Journal*, v. 37, no. 3 (March 1994), pp. 23–24.

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