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design brief

CHILLER PLANT EFFICIENCY

Though more costly to install and more complicated to operate, a chiller plant offers a number of benefits over simple packaged cooling units, including greater energy efficiency, better controllability, and longer life.

Summary

Chilled water-based cooling systems are frequently used to air-condition large office buildings or campuses that encompass multiple buildings. They represent a large investment from the perspective of first cost, physical space they require within the building, as well as energy and maintenance cost. Yet despite these fiscal and spatial impacts, many chiller plants do not reach their potential from the standpoint of energy efficiency. In the past, California's Title 24 Energy Efficiency Standards for Non-Residential Buildings did not have particularly aggressive efficiency standards for chillers, but this has changed with the 2001 revision of the code. In some cases, the 2001 Standards have increased efficiency requirements by as much as 25 percent. Chiller plants that easily complied with older Title 24 Standards might not be efficient enough to meet the 2001 Standards.

The strategies discussed in this design brief can provide the basis for designing chilled water cooling systems that can beat the more aggressive 2001 Title 24 Energy Efficiency Standards by 30 percent or more.

Introduction

All air conditioning systems require a means for generating the cooling effect that offsets building heat gain due to external loads (sun, wind, outdoor temperature) and internal loads (heat and moisture from people, lights, and equipment). In smaller buildings and residential applications, this is usually

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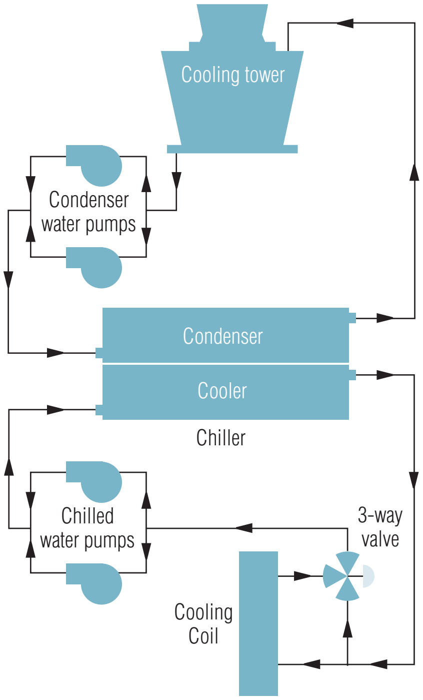
Figure 1: Typical chilled water plant

A typical chilled water cooling plant is comprised of one or more chiller(s), chilled water circulation pump(s), condenser water pump(s), and cooling tower(s), plus piping to interconnect these components. One or more cooling coils are used to transfer heat out of the supply air stream and into the chilled water.



accomplished with an air-based system that ducts cold air from the point of generation (usually on the roof) to each space in the building that requires cooling.

Larger buildings and multiple building campuses usually use a chiller plant to provide cooling. In such systems, chilled water is centrally generated and then piped throughout the building to air handling units serving individual tenant spaces, single floors, or several floors. Ductwork then runs from each air handler to the zones that are served. Chilled water-based systems result in far less ductwork than all-air systems because chilled water piping is used to convey thermal energy from the point of generation to each point of use.

Whereas the all-air systems used to cool smaller buildings usually contain all of their components packaged within a single cabinet (ergo the term “packaged cooling unit”), a chiller plant is a collection of individual components that have been selected to work together as a system (**Figure 1**). Though more costly to install and more complicated to operate, a chiller plant offers a number of benefits over simple packaged cooling units, including greater energy efficiency, better controllability, and longer life. Additionally, a chiller-based system can be much more efficient in terms of space utilization within the building because components need not be located within the same space.

Chiller plants are usually used to cool large buildings because their components require much less space within the building than all-air systems. One reason that less space is needed is that the size of pipes that convey chilled water throughout the building is much smaller than the size of air ducts that would deliver cold air to provide the same cooling effect. Water is a more space-efficient heat transfer medium than air, and therefore works well in space-constrained applications such as high-rise buildings. One pound of water can store about four times as much thermal energy as the same mass of air, and—because water is much denser than air—a pound of water has a much smaller volume than the pound of air. The combination of increased thermal capacity and higher density makes water an ideal medium for space-efficient heat transfer. This difference in heat transfer capacity is exemplified by the fact that cooling ducts are typically sized to provide 400 cubic feet per minute (cfm) of supply air per ton of cooling required, whereas a chilled water system requires only 1 to 2.5 gallons per minute (gpm) per ton (or about 0.13 to 0.33 cfm of fluid). Clearly, the chilled water pipes will be far smaller than the ducts to deliver the same rate of cooling. The benefit to the building owner is that less space will be required for mechanical systems within the building, which increases the amount of space that can be leased or put to other good use.

One pound of water can store about four times as much thermal energy as the same mass of air.

Another reason for the use of chiller plants is that a much higher level of efficiency can be achieved than with packaged, all-air systems—especially during the partial load conditions that prevail 99 percent of the time that air conditioning is needed in a typical building. Whereas a typical packaged cooling unit has an efficiency of 1.1 to 1.4 kW/ton, a chiller-based system can have a full load efficiency that is far lower—values of 0.8 to 1.0 kW/ton for the entire chiller plant are typical. The real advantage of a chiller system comes into play not necessarily under full load conditions but during partial load conditions when the outdoor temperature is warm enough to warrant air conditioning but far from the worst-case conditions the air conditioning system was designed to accommodate. Under partial load conditions, the efficiency of a packaged unit does not improve substantially, whereas a properly designed and operated chiller plant becomes far more efficient.

Typically, a chiller plant can be designed with a lower total cooling capacity than a packaged unit system designed for the same building. Because not all spaces in a building require full cooling simultaneously (e.g., west- and east-facing spaces can each have large cooling loads due to the rising and setting of the sun, but these events do not occur simultaneously), the coincident load typically is much smaller than the sum of the peak loads for each space. A chiller plant can be sized to meet that smaller coincident load, resulting in an overall reduction in cooling capacity without sacrificing comfort. On the other hand, a package unit system with individual cooling units serving each zone would typically be designed to accommodate the “sum of the peaks” for all zones, resulting in a larger cooling system.

Revisions to Title 24 that take effect in October 2001 substantially tighten the efficiency requirements for many types of chillers.

Another benefit of a chiller-based system vs. a packaged system is longer equipment life. The components of a chiller plant are typically industrial-grade machines and are designed to last more than 20 years. Most packaged cooling systems are designed to last about 15 years.[1] This issue is particularly important in the case of high-rise buildings where HVAC equipment may be located deep in the basement or in a mechanical penthouse on the 30th floor. The longer the equipment lasts, the less frequently invasive replacement projects will need to be undertaken.

What Level of Efficiency Is Achievable Today?

The chiller efficiency requirements mandated in previous editions of California’s Title 24 Energy Efficiency Standards for Non-Residential Buildings were not particularly aggressive in light of the efficiency of most chillers sold at the time. However, revisions to Title 24 that take effect in 2001 substantially tighten the efficiency requirements for many types of chillers (**Table 1**). For example, the minimum full load efficiency for a 500-ton centrifugal chiller was 0.75 kW/ton in the 1998 edition of Title 24.[2] But in the 2001 revision of the energy efficiency code, that same chiller must meet an efficiency requirement of 0.58 kW/ton —an efficiency increase of about 25 percent. And although many may think that it will be challenging to merely meet—much less beat—the more stringent 2001 Standards, good design and efficient components can produce a chiller plant that is 30 to 50 percent more efficient on an annual basis than required by the new 2001 Standards (**Figure 2**, page 6).

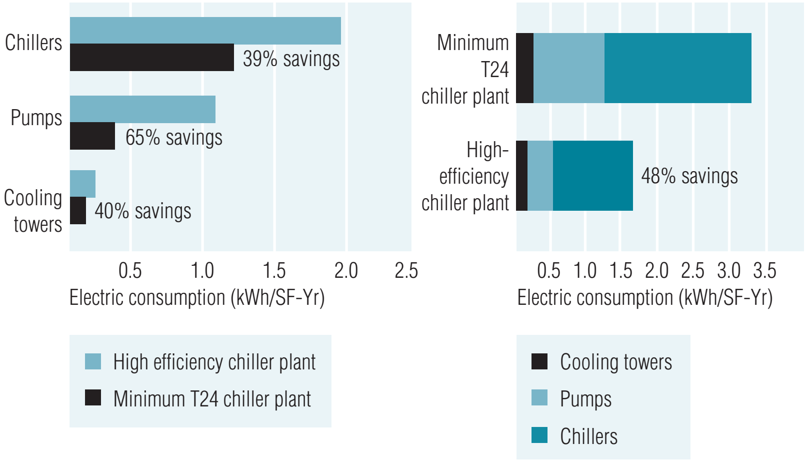
Table 1: California's 2001 Title 24 chiller efficiency requirements

California's 2001 Title 24 Energy Efficiency Standards require higher chiller efficiency than the previous Standards. In the case of centrifugal chillers greater than 300 tons, the efficiency requirement has been increased by about 25 percent (4.7 COP vs. 6.1 COP).

Equipment Type	Size Category	Efficiency Prior to 10/29/2001	Efficiency as of 10/29/2001	Test Procedure
Air-Cooled, With Condenser, Electrically Operated	< 150 Tons	2.70 COP 2.80 IPLV	2.80 COP 2.80 IPLV	ARI 550 or ARI 590 as appropriate
	≥ 150 Tons	2.50 COP 2.50 IPLV		
Air-Cooled, Without Condenser, Electrically Operated	All Capacities	3.10 COP 3.20 IPLV	3.10 COP 3.10 IPLV	
Water-Cooled, Electrically Operated, Positive Displacement (Reciprocating)	All Capacities	3.80 COP 3.90 IPLV	4.20 COP 4.65 IPLV	ARI 590
Water-Cooled, Electrically Operated, Positive Displacement (Rotary Screw & Scroll)	< 150 Tons	3.80 COP 3.90 IPLV	4.45 COP 4.50 IPLV	ARI 550 or ARI 590 as appropriate
	≥ 150 Tons & < 300 Tons	4.20 COP 4.50 IPLV	4.90 COP 4.95 IPLV	
	≥ 300 Tons	5.20 COP 5.30 IPLV	5.50 COP 5.60 IPLV	
Water-Cooled, Electrically Operated, Centrifugal	< 150 Tons	3.80 COP 3.90 IPLV	5.00 COP 5.00 IPLV	ARI 550
	≥ 150 Tons & < 300 Tons	4.20 COP 4.50 IPLV	5.55 COP 5.55 IPLV	
	≥ 300 Tons	5.20 COP 5.30 IPLV	6.10 COP 6.10 IPLV	
Air-Cooled Absorption Single Effect	All Capacities	N/A	0.60 COP	ARI 560
Water-Cooled Absorption Single Effect	All Capacities	N/A	0.70 COP	
Absorption Double Effect, Indirect-Fired	All Capacities	N/A N/A	1.00 COP 1.05 IPLV	
Absorption Double Effect, Direct-Fired	All Capacities	N/A N/A	1.00 COP 1.00 IPLV	

Figure 2: How efficient can a chiller plant be?

By applying an efficient design concept, selecting efficient components and controls, and commissioning the system, it is possible to produce a chiller plant that uses 30 to 50 percent less energy than a system designed to minimally meet 2001 Title 24 Standards.



Characteristics of an Efficient Chiller Plant

There are three key characteristics of an efficient chiller plant. Severe shortcomings in any one of these areas cannot necessarily be overcome by excellence in the others:

Good design and efficient components can produce a chiller plant that is 30–50 percent more efficient on an annual basis than required by the new 2001 Standards.

- *An efficient design concept.* Selecting an appropriate design concept that is responsive to the anticipated operating conditions is essential to achieving efficiency. Examples include using a variable-flow pumping system for large campus applications, and selecting the quantity, type, and configuration of chillers based upon the expected load profile.
- *Efficient components.* Chillers, pumps, fans, and motors should all be selected for stand-alone as well as systemic efficiency. Examples include premium efficiency motors, pumps that have high efficiency at the anticipated operating conditions, chillers that are efficient at both full and partial loads, and induced-draft cooling towers.
- *Proper installation, commissioning, and operation.* A chiller plant that meets the first two criteria can still waste a lot of energy—and provide poor comfort to building

occupants—if it is not installed or operated properly. For this reason, following a formal commissioning process that functionally tests the plant under all modes of operation can provide some assurance that the potential efficiency of the system will be realized.

How to Minimize the Cost of an Efficient Chiller Plant

A valid concern when designing a highly efficient chiller plant is that it be cost-effective and not prohibitively more expensive on a first-cost basis than standard practice. One of the most effective ways to minimize the possible extra cost of an efficient plant is to apply the concept of *integrated energy design* (see the Energy Design Resources design brief on this topic for more information). The least expensive ton of air conditioning is the one you don't have to purchase, and following an integrated design approach is one way to ensure that HVAC systems are "right-sized" instead of "super-sized." Specifying high-efficiency lighting, good glass, and appropriate insulation materials reduces the cooling load for the building, which can translate into a smaller-capacity, less expensive chiller plant that still provides excellent comfort. It is often the case that a properly sized, highly efficient chiller plant has a lower initial cost than an oversized plant designed to minimum Title 24 requirements. However, to achieve such cost savings, when performing cooling load calculations the mechanical engineer must use the actual design information for these more efficient building systems. The mechanical engineer should not use the conservative estimates that are often initially used but not always updated. Because large HVAC systems can cost $2,000 or more per ton (air and water-side), there is ample motivation to properly size the HVAC system.

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An example of a recent project that benefited from an integrated design process is the Santa Monica Public Safety Facility. The peak cooling load for this 100,000+ square-foot facility was initially calculated to be about 240 tons, but application of a number of load reduction measures reduced the peak to only

180 tons. Due to smaller equipment sizes, this resulted in savings of both construction cost and space. This reduction in equipment size became critical later in the design process when architects and engineers faced the challenge of fitting ductwork into some especially constrained spaces. Fortunately, the mechanical engineer on the project updated the load calculations to reflect the reduced loads, and as a result they were able to "right-size" the systems with confidence.

Five Design Strategies for Efficient Chiller Plants

Though there are a vast number of details associated with designing an efficient chiller plant, stakeholders in new construction projects will benefit if the following key design strategies are addressed:

- *Design Strategy 1:* Focus on Chiller Part Load Efficiency
- *Design Strategy 2:* Design Efficient Pumping Systems
- *Design Strategy 3:* Properly Select the Cooling Tower
- *Design Strategy 4:* Integrate Chiller Controls with Building EMS
- *Design Strategy 5:* Commission the System

Design Strategy 1: Focus on Chiller Part Load Efficiency

To achieve the impressive levels of energy efficiency shown in **Figure 2**, page 6, it is necessary to change the way one thinks about chiller plant efficiency. In most facilities, efficient operation under average conditions is more important than how the chiller operates under extreme but rare weather conditions.

Chillers are usually selected based on their efficiency when providing 100 percent of their cooling capability, but most rarely operate at this condition (**Figure 3**). There are a number of ways to express the efficiency of a chiller (see **Sidebar**, "How Is Chiller Efficiency Measured?"), but probably the most common metric is kiloWatts of electrical input (kW) per ton (12,000 Btu/hr) of cooling produced, abbreviated as "kW/ton". Though advertisements

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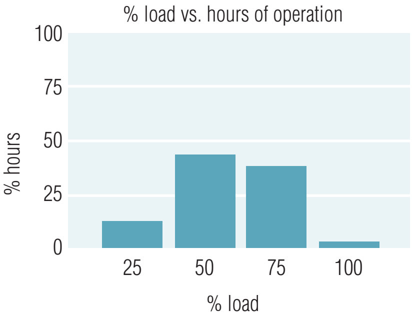
in trade magazines often tout “0.55 kW/ton” chiller efficiency (or better) at full load, hoping that this implies efficiency under all conditions, it is more significant in most cases to know the efficiency across the spectrum of loads from 10 to 100 percent. An analogy would be purchasing a car based upon its handling at top speed instead of at normal driving speeds. On a few invigorating occasions, perhaps that high-speed performance will be useful, but the performance during average driving conditions will probably be of greater utility over the life of the vehicle.

Figure 3: Typical office building cooling load profile

Peak cooling capacity is needed for only a few hours per year. The rest of the year, light to medium loads dominate a chiller plant’s operating landscape.



Three methods for improving chiller plant load efficiency are: specify a chiller that can operate with reduced condenser water temperatures, specify a variable speed drive (VSD) for the compressor motor, and select the number and size of chillers based on anticipated operating conditions.

Specifying a chiller that can operate with reduced condenser water temperatures provides the opportunity to significantly improve efficiency. The condenser water loop on a chiller plant (**Figure 1**, page 2) is typically designed to cool condenser water leaving the chiller at 95°F to 85°F degrees before it reenters the chiller (this is referred to as a 10° “split” or “delta T” on the condenser). As the entering condenser water temperature drops below 85°F, though, the efficiency and capacity of the chiller improve by about 1 to 2 percent per degree of reduction.[3] Thus, if a chiller can operate with 65°F entering condenser water temperature, it will be 20 to 40 percent more efficient than when it receives the warmer 85°F water. The balancing act that takes place means that it is more difficult to design a chiller that operates at the lower condenser water temperatures without encountering operational problems, such as tripping a low oil pressure alarm.

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From the standpoint of the chiller manufacturing community, there are certain companies whose chillers excel in this area—and this capability is promoted extensively in their product literature. Other manufacturers do not recommend operating their chillers at significantly reduced condenser water temperature. While each manufacturer probably leads the pack in at least one facet of chiller performance, it pays to ask each company sales engineer about their ability to operate at reduced condensing water temperatures. This feature gives the building operator substantial energy benefits and is worth the inquiry.

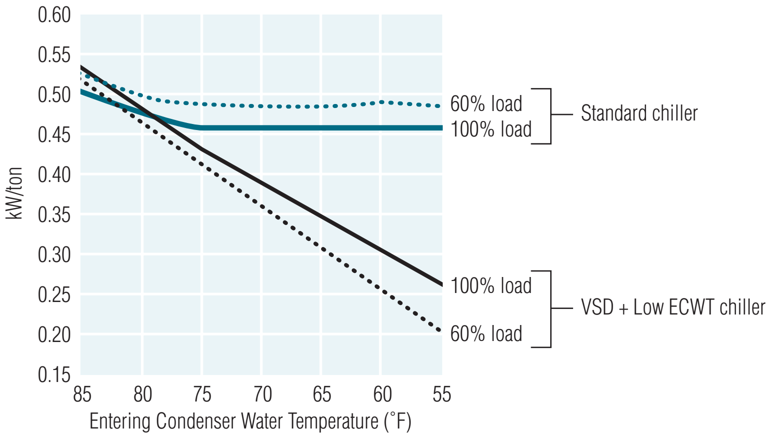
For centrifugal chillers, the second factor to consider is inclusion of a variable speed drive (VSD) to modulate compressor capacity. This option is available from all major chiller manufacturers (though, once again, certain manufacturers have greater expertise with this approach than others), and it can dramatically improve chiller part load efficiency—especially at low loads.[4]

From a practical standpoint, centrifugal chillers are usually available in capacities of 200 tons or more, and VSDs are not often used with other compressor types (reciprocating, scroll, or screw compressors). Thus, the benefits of a variable-speed chiller will not be available for every project. For projects that will use centrifugal chillers, though, a VSD is best considered when a new chiller is ordered from the factory. It is more complicated and costly to install a VSD on a retrofit basis because careful engineering is required to make centrifugal compressors operate properly at slower speeds, and compressor motors and accessories must be selected to provide reliable operation under variable speed. If you've missed the opportunity to order the chiller with a VSD and a retrofit is desired, it is important to have the installation performed by factory-trained technicians for your particular brand of chiller. This is because they will have the detailed compressor performance data necessary to make the VSD operate synergistically with the rest of the system, as well as support of the factory to make sure the retrofit operates as intended.

Centrifugal chillers featuring a VSD and the ability to operate at reduced condenser water temperature can have impressive energy performance (**Figure 4**). According to one source, the

Figure 4: Reduced condensing water temperature and variable speed operation greatly improve part load efficiency

This centrifugal chiller, which includes a variable speed drive (VSD) as well as the ability to use low entering condenser water temperature, is substantially more efficient than a standard chiller under most load conditions.



combination of low entering condenser water temperature (ECWT) capability and a VSD-driven compressor can provide an average of 30 percent annual energy savings and up to 75 percent savings under light load conditions, compared to a fixed-speed, fixed-condensing water temperature chiller.

Regardless of whether the chillers specified for a particular project have the features mentioned above, it makes sense to select both the quantity and the capacity of individual chillers based on the anticipated operating conditions. For example, if a 20-story office building will primarily house “9-to-5” tenants but one floor will be devoted to a 24-hour call center, it makes sense to install a smaller-capacity, “pony” chiller to serve that relatively small but constant cooling load. By operating the pony chiller overnight when all but one floor of the building is largely vacant, operation of a much larger chiller, along with its associated chilled water pump, condenser water pump, and cooling tower, can be avoided. In addition to improved energy efficiency, this strategy will reduce short cycling of the larger chiller compressor, which can extend its useful life.

In cases when the usage habits of the eventual building tenants are not well understood (such as in a speculative office building), it can be effective to specify multiple unequally sized chillers. One proven approach for a two-chiller system is to install one chiller sized to meet one-third of the cooling load and a second one to meet two-thirds of the load. In this way the capacity of the plant can be staged in increments of 33 percent so there will seldom be occasions when any chiller operates at extremely light loads. A downside of this approach vs. the conventional approach of installing two equally sized chillers is that some flexibility is lost with respect to taking a chiller off-line for preventative maintenance. If the larger chiller requires service, only one-third of the design capacity will be available to meet building cooling loads.

How is Chiller Efficiency Measured?

- **Coefficient of Performance (COP)** $[W_{\text{cooling output}}/W_{\text{power input}}]$—the ratio of the rate of heat removal to the rate of energy input to the compressor. Higher values correspond to improved efficiency.
- **Full Load Efficiency** [kW/ton]—the ratio of the rate of power input (kW) to the rate of heat removal, in tons (1 ton = 12,000 Btu/hr). Lower values correspond to improved efficiency.
- **Integrated Part Load Value (IPLV)** [kW/ton]—the weighted average cooling efficiency at part load capacities related to a typical season rather than a single rated condition (see **Sidebar**, page 14), at rating conditions specified by ARI Standard 550 or 590, depending on chiller type.[5]
- **Applied Part Load Value (APLV)** [kW/ton]—calculated the same way as IPLV, but using actual chilled and condenser water temperatures rather than those specified by ARI standard rating conditions.
- **Non-Standard Part Load Value (NPLV)** [kW/ton]—a revision of APLV that provides a more realistic model of off-design performance.

When the occupancy of a facility is well understood, it is often helpful to use computer-based simulation tools, such as DOE-2, to predict daily cooling load profiles and then determine the most logical sizing increments for the chillers. When properly applied, building simulation can provide useful design input on sizing, as well as the quantified energy savings information for a variety of energy efficiency upgrades (see the Energy Design Resources Design Brief entitled "Building Simulation" for more information).

Design Strategy 2: Design Efficient Pumping Systems

Energy use of chilled and condenser water circulating systems is often overlooked, but it can be substantial. In extreme cases, the collective energy use of these systems can eclipse that of the chillers. Nevertheless, Title 24 doesn't say much about the efficient design of such systems.

A common cause of energy waste is that many chilled and condenser water circulation systems are significantly oversized and then "throttled" to produce the desired performance. In such systems, pumps are selected to provide a certain amount of fluid flow while overcoming frictional resistance as the fluid moves through pipes, coils, valves, and other piping system components. Often, pumps are oversized, meaning that they are capable of overcoming a higher level of pressure than will actually be experienced in operation. Because of the way in which a centrifugal pump operates, it circulates more fluid when working against lower pressure than when working against higher pressure, and this is not usually desirable in HVAC applications.

In order to adjust the flow to what is actually required, a valve is installed on the discharge side of the pump and partially closed in order to choke or throttle the flow of fluid leaving the pump. By adjusting this false pressure drop, it is possible to achieve the desired flow. While a throttling valve is useful for making minor adjustments to fluid flow and balancing the system, it is common for pumps to be selected in exceedingly conservative fashion with the knowledge that adjusting this valve after the system is installed will atone for any design flaws. Engineers rarely get in trouble for selecting a pump that is too large, but an undersized pump can lead to all sorts of issues.

There are two significant problems with oversizing pumps. First, this practice increases construction cost due to the larger pump, pump motor, and electrical system serving it. Second (and more significant), an oversized pump can waste a lot of energy because of the extra work required to overcome pressure drop through the throttling valve. An analogy would be stepping on the gas pedal and the brake simultaneously in order to drive a car slowly. This approach penalizes the building owner every hour the pump is in operation, year after year.

Energy use in pumping systems may be reduced by sizing pumps based upon the actual pressure drop through each component in the system as well as the actual peak chilled water flow requirements, accurately itemizing the pressure losses through the system, and then applying a realistic safety factor to the total.

The idea is not to design systems that are undersized, inflexible and ill-prepared for unforeseen changes to system operation, but rather to balance uncertainty about how a system will be used

What is Integrated Part Load Value (IPLV)?

Chillers rarely operate at their full rated cooling capacity. In fact, most chillers operate at full load for less than one percent of their total operating hours. Thus, it follows that selecting a chiller based solely on its full load efficiency might not lead to the most efficient selection on a year-round basis. Integrated Part Load Value (IPLV) is a metric that is often used to express average chiller efficiency over the range of loads encountered by most chillers. IPLV is the weighted average cooling efficiency at part load capacities related to a typical season rather than a single rated condition, based upon a representative load profile that assumes the chiller operates as follows:

- 100% load: 1% of operating hours
- 75% load: 42% of operating hours
- 50% load: 45% of operating hours
- 25% load: 12% of operating hours

When the chiller energy efficiency is expressed in kW/ton, IPLV is calculated according to the following equation[8]:

$$\text{IPLV} = \frac{1}{\frac{0.01}{A} + \frac{0.42}{B} + \frac{0.45}{C} + \frac{0.12}{D}}$$

Where: A = kW/ton at 100% capacity
B = kW/ton at 75% capacity
C = kW/ton at 50% capacity
D = kW/ton at 25% capacity

now and in the future with the resultant energy waste from oversizing.

In addition to following a reality-based approach to sizing the pumps, the following design strategies and tips can further reduce energy use of pumping systems.

- *Keep the fluid velocity down.* Friction increases as the square of fluid velocity, so keeping velocities low can substantially reduce pressure loss as fluid flows through the piping system. To keep frictional losses low, size pipes for a fluid velocity that does not exceed four feet per second and, depending on the pipe sizes involved, consider selecting the next larger (instead of the next smaller) pipe diameter that will result in acceptable pipe velocities.[6] The longer the lengths of pipe involved with a project, the greater the savings potential will be for this strategy.

- *Keep the temperature differential up.* A chilled water system that is designed based upon a 10° F temperature rise through the cooling coils must circulate about 2.4 gpm/ton, whereas a system with a 20° F difference circulates only about 1.2 gpm/ton, resulting in a nominal savings of 50 percent of pumping energy.[7] Selecting chilled water coils that provide a larger temperature difference will reduce the size of piping, pumps, motors, and piping accessories, which can offset some or all of the added cost of the coils.

- *Keep the piping system simple.* Spaghetti is great on a plate, but not in a mechanical room. Avoid arranging piping in exceedingly complicated configurations that use numerous changes of direction to get around beams, electrical conduit, or other obstacles. Better communication during construction among the architects, engineers, and installation contractors can minimize interference between these components, allowing more direct piping paths to be taken. Shorter piping paths mean less piping, less welding, and reduced pressure loss.

- *Don’t litter the system with hidden “pressure wasters.”* Minimize the use of unnecessary valves, flow control devices, turns, transitions, and other “pressure wasters.” Though these devices all have their place in good piping design, most systems are littered with an excessive quantity of them, resulting in additional pumping energy. Also, newer technology can eliminate the need for some pressure-wasting devices that are de rigueur in yesterday’s system designs, such as automatic flow control valves. For example, pressure-independent control valves can eliminate the need for flow control devices that waste pumping energy while still ensuring that flow is balanced to each coil in the system.

  Another loss that is frequently overlooked is pressure drop through the evaporator and condenser barrels. This can be mitigated by selecting a chiller that balances heat transfer efficiency with pressure loss.

Avoid arranging piping in exceedingly complicated configurations that use numerous changes of direction to get around beams, electrical conduit, or other obstacles.

- *Use variable flow configuration and controls.* Pump horsepower varies as the cube of fluid flow, so cutting flow by one-half can reduce horsepower by seven-eighths (e.g., one-eighth of its original value) if the system is properly controlled. An effective way to do this is to install variable speed drives (VSDs) on the pumps. Consider variable flow for the chilled water loop when long pipe runs are present (and therefore piping frictional losses represent a large percentage of the total loss in the distribution system). For smaller, simpler systems, it may be more cost-effective to use a constant flow strategy but design an efficient distribution system, specify efficient components, and consider a higher design chilled water supply temperature.

  In instances where a system must be designed to accommodate future load growth (e.g., the pumps have been intentionally oversized), VSDs can be used to make such systems operate properly today without using the

Pump horsepower varies as the cube of fluid flow, so cutting flow by one-half can reduce horsepower by seven-eighths.

previously discussed throttling approach. By operating the pumps at reduced speed instead of throttling the discharge, it is possible to achieve the desired flow and save energy at the same time.

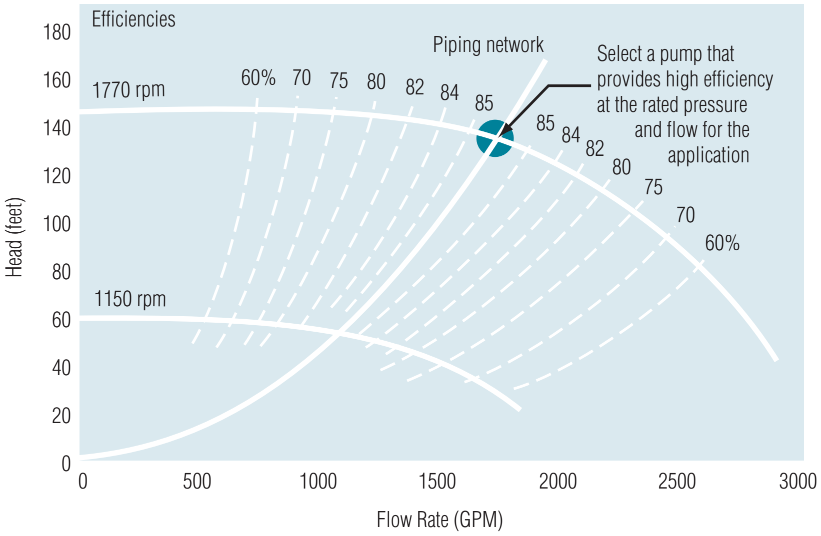
- *Evaluate variable flow piping options.* More and more new chiller plants are defying the long-held design wisdom that flow rates through the chiller should not vary. Such plants use variable speed drives to control the primary chilled water pumps so that flow through the chillers and out to the coils varies with the demand for chilled water, instead of the traditional "primary/secondary" approach method by which only flow to the coils is varied. If properly implemented, the variable flow piping approach uses less physical space, requires fewer components, and is intuitive to many building engineers.

Most motors use many times their initial cost in energy over their life.

- *Specify efficient pumps and premium efficiency motors.* Once an efficient system concept is established, the next step is to select pumps that are efficient under the anticipated operating conditions. When referring to manufacturers' pump performance curves, select a pump where the design pressure and flow are as close to the point of highest efficiency as possible (**Figure 5**). This will minimize the brake horsepower requirements, and therefore the size of the motor required to drive the pump. For specifying the pump motor, go beyond Energy Policy Act of 1992 (EPACT) standards for motor efficiency and choose a premium efficiency motor (see the Energy Design Resources Design Brief entitled "Drivepower" for more information).[9] Premium efficiency motors can often be a couple of percentage points higher on the efficiency scale than motors that meet the "energy-efficient" rating requirements encompassed by Title 24. In new construction, it is almost always cost-effective to spend a bit extra when purchasing the motor, because most motors use many times their initial cost in energy over their life.

Figure 5: Pump performance curves and efficiency

To minimize pumping energy, select a pump for high efficiency under anticipated pressure and flow conditions.



Design Strategy 3: Properly Select the Cooling Tower

The cooling tower is responsible for rejecting unwanted heat from the condenser water loop to the air outside of the building. Proper sizing and control of cooling towers is essential to efficient chiller operation. Cooling towers are often insufficiently sized for the task; however, this undersizing may result from the following two issues:

- *Cooling towers are large and heavy.* They usually dominate the roof of the buildings they serve and are heavy because they are full of water. Additionally, they must be screened so they are not readily visible from outside the building. As a result, cooling towers are not popular with some members of the design team, and there is often motivation to reduce the size of the cooling tower in order to ameliorate other design problems.

- *Cooling tower sizing is not well understood.* Though it is common to refer to cooling tower capacity in terms of the "tons" of heat rejection provided, this is really not the most accurate metric. In reality, a cooling tower is rated

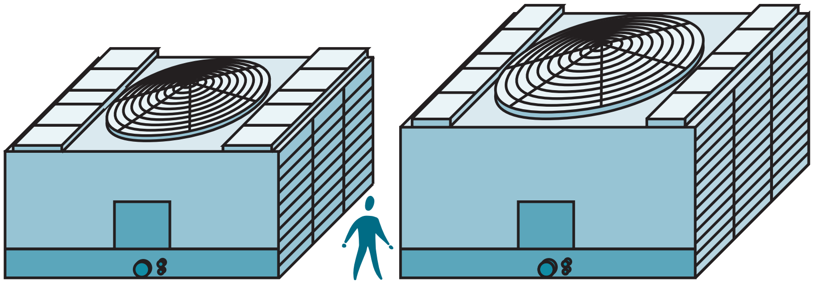
A tower rated at 500 tons at a 71° F wetbulb might provide only about 340 tons of cooling if the wetbulb is 78° F.

Reducing the entering condensing water temperature is one of the most effective ways to improve chiller efficiency.

according to its ability to cool a certain flow rate of water from one temperature to another under specific wetbulb conditions. For example, a tower may be rated to cool 3,000 gpm of water from 95° to 85° F when the ambient wetbulb temperature is 78° F. Wetbulb temperature is an indicator of the energy content of ambient air and has a profound impact on cooling tower sizing. The higher the design wetbulb temperature used for rating a particular tower, the more heat transfer surface that will be required (and, hence, the larger the tower will have to be) to provide the required amount of heat rejection. A tower rated at 500 tons at a 71°F wetbulb might provide only about 340 tons of cooling if the wetbulb is 78°F (**Figure 6**). Obviously, the wetbulb conditions that are prevalent in a region must be well understood in order to properly size the tower. Yet, in many instances, "optimistic" (e.g., unrealistically low) wetbulb conditions are assumed, leading to selection of a tower that cannot provide the necessary heat rejection under actual wetbulb conditions. However, from a technical standpoint, it can be said that the tower is sized for "X" tons of heat rejection, so the size is not questioned.

Figure 6: A 500-ton tower ... but at what wetbulb temperature?

These two cooling towers could both be properly described as providing 500 tons of heat rejection, because this capacity depends on the wetbulb temperature used for rating each tower. When rated under identical conditions (78°F wetbulb temperature), the tower on the left provides only about 340 tons of heat rejection.



Properly sizing a cooling tower is critical to attaining overall chiller plant efficiency. As previously stated under Design Strategy 1, reducing the entering condensing water temperature is one of the most effective ways to improve chiller efficiency. An undersized cooling tower makes this difficult to achieve, however, because the tower cannot produce sufficiently cold condenser water during much of the time that cooling is required. In fact, facilities that have undersized cooling towers often experience this effect: on hot, humid days, their tower is not capable of providing to the chiller the 85° F water that is needed to produce that chiller's rated capacity. This results in reduced chiller capacity and plummeting chiller efficiency. Incidentally, this performance penalty usually occurs during hot summer afternoons when tenants are at their crankiest and electricity is at premium prices.

An undersized cooling tower is a difficult system deficiency to correct because of the high "hassle factor" associated with replacing the tower, as well as the limited options to improve the performance of an existing tower. Because space is generally at a premium adjacent to the tower and because the tower may be on the roof of a high-rise building, it is usually not feasible or cost-effective to replace an existing undersized tower. Given the challenges associated with overcoming an improperly sized tower—as well as the energy and comfort implications—the importance of properly selecting this component should be clear.

To appropriately select an efficient cooling tower, the following factors should be considered:

Since cooling towers are relatively inexpensive compared to chillers, it makes sense to invest a little more in a tower that allows the chiller to deliver its full rated capacity.

- *Use realistic wetbulb sizing criteria.* Consider more than just the ASHRAE data for the nearest weather station. Are there microclimate conditions that may cause higher humidity levels (lakes, rivers, agriculture, industry)? Be mindful of the fact that chiller capacity will suffer if the tower cannot meet its heat rejection requirements. Since cooling towers are relatively inexpensive (about $100/ton) compared to chillers ($300–600/ton), it makes sense to invest a little more in a tower that allows the chiller to deliver its full rated capacity.

- *Specify an induced draft tower when space permits.* Though physically larger than a forced draft tower design, induced draft towers usually require only about half of the fan horsepower to provide the same amount of heat rejection. An

Given the challenges associated with overcoming an improperly sized tower—as well as the energy and comfort implications—the importance of properly selecting this component should be clear.

Table 2: California's 2001 Title 24 efficiency requirements for heat rejection equipment

California's 2001 Title 24 Energy Efficiency Standards introduce efficiency requirements for both air- and water-cooled condensers.

Equipment Type	Total System Heat Rejection Capacity at Rated Conditions	Subcategory or Rating Condition	Performance Required as of 10/29/2001[a,b]	Test Procedure
Propeller or Axial Fan Cooling Towers	All	95˚F Entering Water 85˚F Leaving Water 78˚F Wetbulb Outdoor Air	≥38.2 GPM/hp	CTI ATC-105 and CTI STD-201
Centrifugal Fan Cooling Towers	All	95˚F Entering Water 85˚F Leaving Water 78˚F Wetbulb Outdoor Air	≥20.0 GPM/hp	CTI ATC-105 and CTI STD-201
Air-Cooled Condensers	All	125˚F Condensing Temperature R22 Test Fluid 190˚F Entering Gas Temperature 15˚F Subcooling 95˚F Entering Drybulb	≥176,000 Btu/h-hp	ARI 460

[a] For purposes of this table, cooling tower performance is defined as the maximum flow rating of the tower divided by the fan nameplate rated motor power.

[b] For purposes of this table, air-cooled condenser performance is defined as the heat rejected from the refrigerant divided by the fan nameplate rated motor power.

induced draft tower (using a propeller or axial fan) uses a fan located at the top of the tower that "pulls" the air in (**Table 2**).

- *Apply intelligent controls.* Like a chiller, the load on a cooling tower varies throughout the year, and there are many hours when it operates at partial load. To meet part loads efficiently, specify variable speed drives to control cooling tower fans. When comparing the cost of VSDs with that of other approaches such as two-speed fan motors, keep in mind that the VSD allows you to purchase a less expensive single-speed motor, eliminates the more expensive two-speed starter, and gives more precise control of condenser water temperature. A VSD will normally reduce the wear and tear on the fan belt when compared to one- or two-speed fan motors.

  Along with the VSD, it is beneficial to specify control sequences that reset the condenser water temperature setpoint based on ambient conditions. This will allow a balance of improved chiller performance with cooling tower fan energy savings. Note also that the minimum condenser water temperature should be determined in close cooperation with the chiller manufacturer to ensure reliable operation.

- *Develop sequences of operation that minimize overall energy use.* Do not fall into the trap of optimizing performance of one chiller plant component at the expense of others. For example, running the tower fans at minimum speed may save lots of fan energy, but this savings may be overshadowed by chiller efficiency penalties. Measure and record the energy use of each plant component so that an overall system efficiency can be determined, and develop sequences that optimize this number.

Don't fall into the trap of optimizing performance of one chiller plant component at the expense of others.

Design Strategy 4:
Integrate Chiller Controls with Building EMS

Most new chillers are microprocessor-controlled, but for some reason their local "brain" is not usually networked with the computer-based Energy Management System (EMS) that controls other HVAC system components. This is usually because the chiller and the EMS follow different communication protocols and therefore cannot communicate directly without additional hardware or software.

Modern chiller control panels pull together a wealth of detailed operating data for the chiller, but these data can be used only if intelligent decisions are made about how to operate the rest of the system. For example, raising the chilled water temperature setpoint improves chiller efficiency and capacity, but may increase the amount of water that is circulated to the cooling coils or the amount of air delivered to the building. This leads to a net increase in energy use. Networking the chiller controls together with the rest of the EMS—and installing sensors on all plant components to measure instantaneous and ongoing energy use—is the only way to get a handle on the overall HVAC system efficiency.

Four strategies for integrating chiller controls with building EMS are: specify an "open" communications protocol, use a hardware gateway, measure the power of ancillary equipment, and analyze the resultant data.

- *Specify an "open" communications protocol.* If all HVAC control components are specified to comply with an established "open" protocol (BacNET, LonWorks), then achieving networked operation and data sharing should be as simple as connecting the devices together on a common network.

- *Use a hardware gateway.* All is not lost when the chiller control panel follows a different protocol than the house EMS. A hardware device called a "gateway" can be installed that serves as a translator between the two languages, allowing most data to be shared between the foreign devices.

- *Measure the power of ancillary equipment.* If it is not measured and recorded, it can be difficult to get a handle on how much energy is used by pumps and fans in the chiller plant—and if this information can't be measured, then it is difficult to manage it effectively. To make these data available, specify that kW transmitters be installed on chilled and condenser water pump motors as well as cooling tower fan motors. Rather than installing simple current transformers that may not be accurate when used to measure power drawn by inductive loads such as motors, specify that true RMS-reading kW sensors be installed. Many of these devices are available in a standard signal output configuration in which a 4-20 mA signal corresponds to kW, but some are now available in a network-enabled version that makes far more data (power, plus volts, Amps, power factor) available to the house EMS.

- *Analyze the resultant data.* Collecting scads of data from the chiller plant is of no benefit unless this information is analyzed and ultimately used to draw useful conclusions about how to improve chiller plant operation. Though it is not the ongoing responsibility of the design team, it is worthwhile to specify that the eventual operators of the chiller plant receive training in the use of EMS so that they can take advantage of it. This is most often tied in with specification language related to commissioning, addressed in the next section.

Though it is not the ongoing responsibility of the design team, it is worthwhile to specify that the eventual operators of the chiller plant receive training in the use of EMS so that they can take advantage of it.

Design Strategy 5: Commission the System

Most chiller plants (even those designed to minimum Title 24 Standards) have the potential to operate reasonably efficiently, but many never reach this potential due to installation problems, poor control system programming, or lack of coordination between the design team and the contractor. In

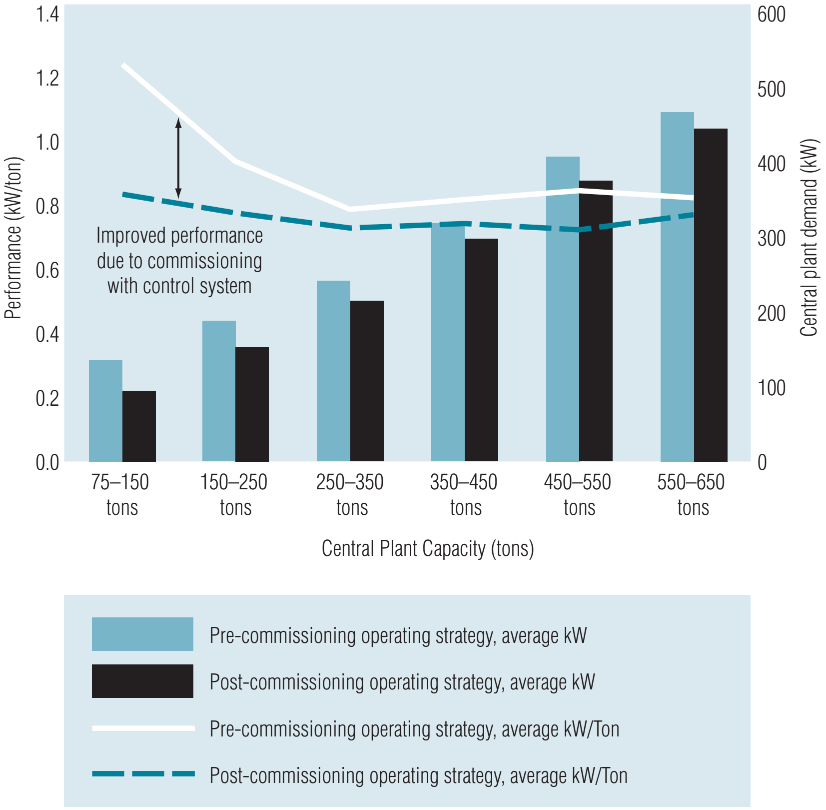
Ideally, commissioning starts early in the design process and is performed by an independent third party.

particular, the advanced control systems that now pervade most building systems can be problematic if their programming is not carefully implemented.

Commissioning a chiller system—that is, functionally testing it under all anticipated operating modes to ensure that it performs as intended—can improve efficiency and reliability and ensure that the owner's are getting the level of efficiency they paid for. Ideally, commissioning starts early in the design process and is performed by an independent third party (that is, an entity who is not part of the design or construction team). For more detailed information, please refer to the Energy Design Resources Design Brief entitled "Building Commissioning."

Figure 7: Abbreviated chiller plant commissioning provides improved efficiency

A commissioning effort spanning just a few days for this chiller plant at the campus of a large university in Southern California improved the plant's efficiency by as much as 30 percent under certain load conditions.



Source: USC

Ultimately, a combination of good design practice, efficient components, and proper installation and commissioning is the key to efficient, reliable chiller plant performance.

Even when a full commissioning process cannot be implemented, some focused commissioning of specific building systems can still reap substantial dividends. This was the case for a new chiller plant installed on the campus of a large university in Southern California, where a two-day commissioning effort identified improvements to the sequences of plant operation that improved chiller efficiency by as much as 30 percent under certain operating conditions (**Figure 7**).

Conclusion

Even though California's 2001 Title 24 Standards require a higher level of efficiency from chiller plants, it is still possible to improve upon these standards by a significant margin—and to do so cost-effectively. Designers who are interested in energy efficiency should consider the Title 24 Standards as the starting point for efficiency and not the final destination. Ultimately, a combination of good design practice, efficient components, and proper installation and commissioning is the key to efficient, reliable chiller plant performance.

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Notes

1 1999 ASHRAE Applications Handbook, Chapter 35, states that the useful service life is 15 years for packaged units and 23 years for centrifugal chillers.

2 For chillers with CFC refrigerants with ozone depletion factors less than those for R-22.

3 This is a rule of thumb. Consult the manufacturer of your specific chiller for a comprehensive chiller performance selection for more accurate data.

4 Sales literature, York Millennium Centrifugal Chillers, published by York International, P.O. Box 1592, York, PA 17405-1592, Form 160.00-SG1 (1999).

5 44° F chilled water supply temperature, 54° F chilled water return temperature, 85° F condenser water supply temperature, 95° F condenser return temperature.

6 This is a rule of thumb. Ideally, an economic evaluation should be performed that compares piping costs with energy impacts associated with pipe diameter.

7 Assuming that pipes and other system components were sized for the same velocity in each case. If the same pipe diameters were used with the higher temperature differential, the savings would be greater.

8 The equipment COP is derived for 100%, 75%, 50%, and 25% loads, with consideration for condenser water relief. Condenser water relief assumes that the temperature of the water decreases from 85°F by 4°F for every 10% reduction in load.

9 EPACT is an abbreviation for the Energy Policy Act of 1992, which specified (among other things) higher efficiency levels for most general-purpose electric motors.

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This design brief was prepared for Energy Design Resources by Architectural Energy Corporation, Boulder, CO.