## MEASURE 2.11.1 Install cooling thermal storage.

**RATINGS**

| New Facilities | Retrofit | O&M |
|---|---|---|
| C | C | |

This Measure helps facility owners to decide whether to acquire cooling storage, provides an outline for the designer of a cooling storage system, and guides facility staffs in operating cooling storage systems.

Deciding whether to install cooling storage is complex. Stated most generally, cooling storage is desirable in applications where the opportunities and benefits outweigh the disadvantages. Both the benefits and the disadvantages are explained below. Following that is a sequence of steps that lead you from the initial decision to consider cooling storage to successful operation of the installed system. This is followed by a comparative review of all contemporary types of cooling storage equipment. At the end is an introduction to the major engineering issues.

**SUMMARY**

Currently popular as means of purchasing electricity at lower rates. Sometimes used in new plants to reduce chiller cost. Bulky, expensive, and complex. Reliability has been poor, but performance will probably improve with time. Will not operate properly without continuous monitoring. Ice storage, the most common method, seriously reduces chiller efficiency. Economic feasibility depends largely on long-term considerations that are not under the user's control.

**SELECTION SCORECARD**

| | |
|---|---|
| Savings Potential | $ $ $ (faded: $) |
| Rate of Return, New Facilities | % (faded: % %) |
| Rate of Return, Retrofit | % (faded: %) |
| Reliability | ✓ (faded: ✓) |
| Ease of Retrofit | ☺ (faded: ☺) |

## Overview

A cooling thermal storage system is like a conventional chiller system, with the addition of a large container that stores cooling in ice, chilled water, or some other material. A cooling storage system is analogous to the electrical system of an automobile. The chiller is like the automobile's generator, and the cooling storage unit is like the automobile's battery. At different times, the cooling load of the facility may be served by the chiller directly, by the cooling storage unit, or by both. (Not all systems can operate in all three of these modes.)

Cooling storage has two main advantages over a system without storage. One is that cooling can be available on any desired schedule, independently of the operation of the chillers (within limits). The other is that the cooling storage unit may be able to deliver cooling at a higher rate than the chillers, or to supplement the chillers.

Cooling thermal storage is not an energy conservation measure in the strict sense. On the contrary, all forms of thermal storage involve losses, and they require additional energy for the operation of the system. Some forms of cooling storage make the chillers operate less efficiently. Thermal storage exists primarily for the benefit of the electric utility. It allows the utility to generate more of its electricity with its most efficient generators. It may also allow the utility to generate electricity with fuels that are less scarce or less critical.

From the standpoint of the facility owner, thermal storage is a means of purchasing electricity at lower rates. The electric utility rewards the facility owner who uses cooling storage by offering lower electricity rates. All parties should understand that this is a business arrangement, not a matter of engineering. The electric utility attempts to persuade the facility owner to use cooling storage for its own purposes. In turn, the facility owner must have enough savvy to negotiate the best rates with the utility.

Less frequently, the facility owner may use cooling storage as a way of reducing the chiller capacity that is needed for a new facility. By itself, this yields an economic benefit for the owner only if the cooling load is concentrated in short time periods. In many applications, cooling storage can provide both types of benefit.

At the present time, cooling storage is partly a fad among facility owners who fail to understand the underlying purposes of the technology, and the business motives behind it. Be especially cautious that cooling storage will serve your purposes in the long term. Cooling storage requires the facility owner to understand the motives and needs of the electricity utility company, to understand the theory of electricity pricing, and to be able to negotiate effectively with the electric utility.

Cooling storage has long been used successfully in a variety of specialized cooling applications. It cannot yet be considered a success in air conditioning applications, where it has experienced a large number of failures. These have been caused by deficient design, installation flaws, neglected maintenance, and failure to understand the logic of the systems' operation.

Cooling storage will undoubtedly become more successful, both technically and economically, as experience accumulates. Even so, cooling storage will always be risky. Long-term success depends largely on future conditions that cannot be predicted reliably and that the user does not control.

## Benefits of Cooling Storage

The following are the benefits provided by cooling storage. The first two are the main reasons that cooling storage is usually installed. The remaining benefits are ancillary. They may improve the economics of cooling storage, but they generally do not justify it by themselves.

### ■ Reduced Electricity Cost

At the present time, most cooling storage is installed to reduce electricity costs. Review Reference Note 21, Electricity Pricing, for an understanding of the electricity pricing issues that are involved. In brief, the price of electricity is related to the time period when the electricity is purchased. Electrically powered chillers typically account for a large fraction of a facility's energy consumption, and cooling storage allows the operation of the chillers to be shifted to time periods when electricity is cheaper.

The key issue in reducing electricity costs is the "demand" charge, which varies with the time of day, the day of the week, and the season. Make sure that you are comfortable with this concept before studying the following examples. In brief, the demand charge is a charge based on the maximum *rate* of energy consumption (measured in kilowatts), not for the *amount* of electricity consumption (measured in kilowatt-hours). In the following examples, the objective of cooling storage is the minimize the demand charge.

Figure 1 shows how cooling storage can reduce electricity cost in a facility where the non-cooling load (lights, air handling units, computers, etc.) are essentially constant during the period of high demand charges. For example, this is typical of office buildings and retail stores. In this example, cooling is provided by storage, rather than by chiller operation, during the periods of higher demand charges. There are three demand charge periods during the day, and the objective is to operate the chillers only during the period of lowest rates.

The cooling load to be avoided during periods of higher demand charges is marked "A." The cooling storage unit can be charged at any time during the off-peak rate period, but preferably during the coolest hours of the night (to maximize chiller efficiency). This cooling load is marked as "B." During off-peak periods, the chillers can also serve the cooling load directly, if a cooling load exists then. Direct cooling is more efficient than cooling with storage, as we shall see, so we try to use direct cooling as much as possible during the off-peak period. In our example, this direct cooling load is marked "C."

Figure 2 shows how cooling storage can reduce electricity demand charges in a facility where the non-cooling load fluctuates widely during the demand charge period. For example, this is typical of colleges and manufacturing facilities. In this example, cooling storage is controlled so that it satisfies the portion of the cooling load marked "A." The purpose of this is to limit the maximum electric load during the peak demand charge period. The cooling storage unit is charged during off-peak hours. As in the previous example, this load is marked "B." Again, direct cooling is used during off-peak hours to the maximum extent possible. The off-peak direct cooling load is marked "C."

Unlike the example in Figure 1, direct cooling is used for a portion of the cooling load during the period of higher electricity rates. This is because the demand charge during this period is determined by the highest value of the non-cooling electrical load, which occurs at 6 PM in this example. This method of using cooling storage is called "peak shaving." In this case, the cooling unit can be charged at any time, provided that the cooling load never increases the demand above that determined by the non-cooling loads.

Demand charges typically are established on a monthly or seasonal basis. In Figure 2, the non-cooling demand that is shown represents the highest demand during the measurement period, not the highest daily demand, which may be much lower.

Don't blindly follow the example of Figure 2 when you are considering cooling storage for peak shaving. The electricity rates that you pay may have an important additional complication. Some utilities penalize high demand not only by a demand charge, but also by increasing the kilowatt-hour charge during periods of higher demand rates. This makes it desirable to shift as much of the cooling load as possible to the off-peak rate period, regardless of the demand profile of the non-cooling loads.

Reducing demand benefits the electric utility, so many utilities presently offer incentives for the owner to install cooling storage equipment. These incentives typically take the form of partial rebates of the cost of installing cooling storage. Where such rebates are offered, they may be a major factor in the overall economics. Unfortunately, such rebates tend to dazzle facility owners, making them careless in assessing the overall cost of the project or the long-term operating liabilities. It is foolish to burden a facility with inappropriate equipment for the sake of a rebate.

### ■ Ability to Reduce Chiller Capacity in New Plants

If you are building a new chiller plant, you can use cooling storage to reduce the chiller capacity, saving overall chiller plant cost. The price of storage equipment is only about 10% to 20% of the price of conventional chiller equipment, per unit of cooling capacity. Therefore, storage may reduce equipment costs. However, the cooling load in your application must occur during predictable intervals that leave ample time for charging the storage unit. For example, cooling storage has been used to reduce the size of air conditioning equipment in churches, which need a large cooling capacity for only a few hours per week. Similarly, cooling storage has long been used in dairy operations, where rapid cooling of a large volume of milk is required for a few hours each day.

Figure 3 shows how cooling storage can be used to reduce chiller capacity. Here, the cooling load pattern is typical of an office building. In this example, the chiller is controlled on weekdays so that it operates at full output until the cooling storage unit is fully charged, at which time the chiller throttles back to handle the current cooling load. This method of control avoids the possibility of running out of cooling capacity during weekdays, although it may keep more energy in storage than necessary. During the weekend, the chiller does not store cooling until late on Sunday. This minimizes losses from the cooling unit. (Other possible control approaches are covered below.)

In applications where cooling storage can reduce chiller capacity, storage is likely to reduce electricity costs as well. Design the system to get the greatest combined benefit. In the previous example, you might wish to increase the size of the chillers and increase the storage capacity so that the chillers can be turned off during periods of higher electricity rates.

### ■ Ability to Exploit Lower Condensing Temperatures

Cooling storage operation usually shifts the operation of chillers into the night, when the outside air is considerably cooler. If the chillers are able to reduce their condensing temperatures to follow the night air temperature, their average COP improves considerably. (Many chillers cannot exploit reduced condensing temperature. See Measure 2.2.2 for the reasons.)

This is a major bonus that tends to be overlooked. With chilled water storage, the chillers may actually be able to operate with higher net COP than in conventional daytime cooling. With ice storage, the reduced condensing temperature may substantially reduce the COP penalty caused by the low evaporating temperatures needed for freezing.

### ■ Reserve Capacity in the Event of Chiller Failure

Cooling storage buys time for the repair of a failed chiller, provided that the chiller fails when the storage unit has a substantial remaining charge. However, this bonus is offset by the fact that the storage system itself increases the probability that a failure will occur in the chiller system.

### ■ Smaller Water and Air Distribution Components

In attempting to make a virtue of the lower evaporator temperatures required for ice storage, systems are being developed that exploit the lower chilled water temperatures. The main advantage of these systems is smaller size for chilled water and air distribution equipment. These systems are a mixed blessing. They are discussed below.

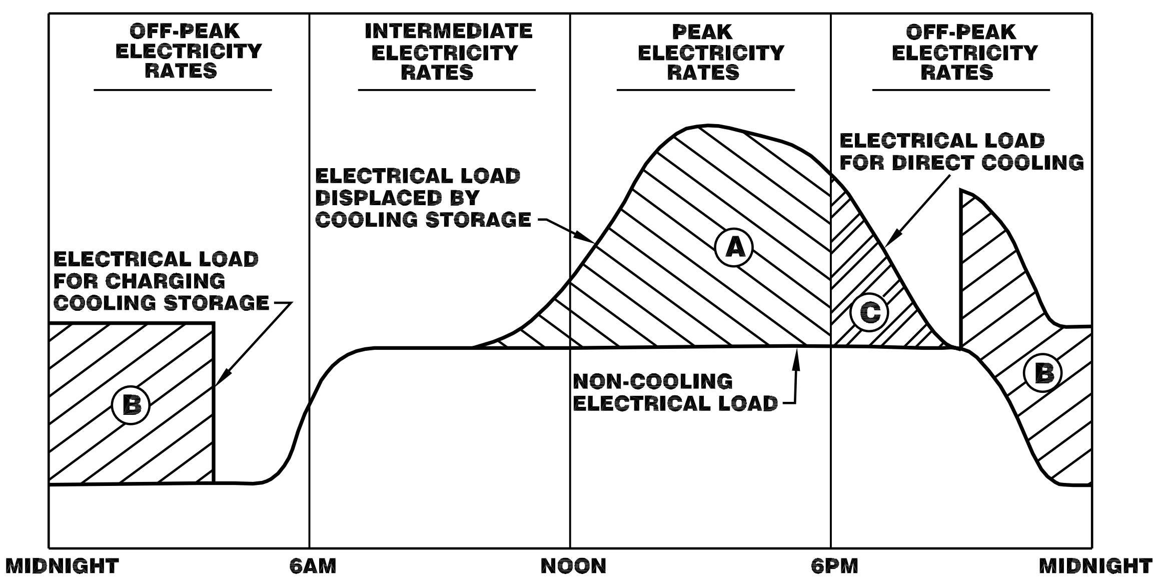


**Fig. 1 Using cooling storage to minimize electricity cost (case 1): the electrical loads other than cooling are fairly constant during the period of high demand charges** The load profiles are typical of an office building. This situation favors providing enough storage capacity so that all chiller operation occurs during off-peak hours. This method of control is simple and reliable.

### ■ Compensating for Capacity Loss with Replacement Refrigerants

Some common refrigerants used in the past must be replaced to satisfy environmental concerns. (See Reference Note 34, Refrigerants, for details.) Converting existing chillers to use new refrigerants has a capacity penalty, typically 10% or less. Most chiller plants have enough reserve capacity to make up for the lost capacity. If not, you can use cooling storage to make up for the loss. However, before you do this, look for energy conservation measures to make up the difference. (You should exploit most of your other energy conservation opportunities before getting involved with cooling storage.)

### ■ Increasing Heat Recovery

Cooling storage may improve the potential for recovering condenser heat from chillers. This is because cooling storage causes the chillers to operate at steady loads for longer, predictable periods of time. On the other hand, cooling storage may make heat recovery more expensive by eliminating chiller operation during periods of time when recovered heat is needed. Refer to Subsection 2.10 for details of chiller heat recovery.

Ice storage reduces chiller COP by lowering the evaporator temperature. Similarly, if you increase the condensing temperature to enhance heat recovery, this also reduces the COP. Therefore, you usually don't want to do both at the same time. On the other hand, a chiller that is designed for ice storage may also be effective for heat recovery at elevated temperatures when it is used for direct cooling of chilled water.

Under some conditions, you can increase chiller heat recovery by installing a heat storage unit. See Measure 2.10.5 for details. In some of these cases, which are discussed below, you can use the same storage unit for both heating storage and cooling storage.

## Disadvantages of Cooling Storage

Cooling storage illustrates the maxim that engineering is compromise. Cooling storage systems can be designed in many ways, each with its own advantages and disadvantages. The following are the main disadvantages of cooling storage, which vary in importance among the different types.

### ■ Energy Losses

Cooling storage is not an energy conservation measure. Storage systems consume more energy at the facility than conventional cooling. In the least favorable applications, the increase in electricity consumption would negate the advantage of lower electricity prices. These are the main energy losses:

- ***reduced chiller efficiency,*** especially with ice storage. Ice storage pays a high energy efficiency penalty because the chillers need to operate at low evaporating temperature in order to freeze the ice. This lowers the chiller COP from 30% to 50%, compared to water chilling, for a given condensing

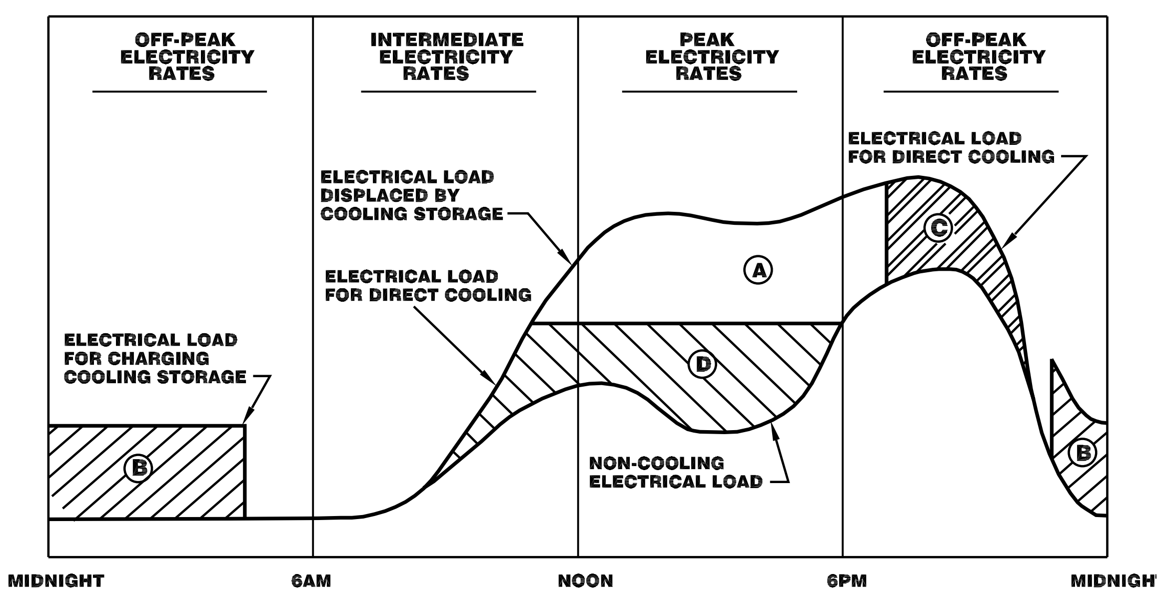


**Fig. 2 Using cooling storage to minimize electricity cost (case 2): the electrical loads other than cooling vary widely during the period of high demand charges** The load profiles are typical of a college campus. In this situation, there is no cost penalty if the chillers operate during the hours of high demand charges, but only up to a maximum total demand that is determined by the non-cooling electrical loads. (This part of the cooling load is marked "D.") This method of control allows the cooling storage unit to be smaller, and it exploits the fact that direct cooling is more efficient than storage cooling. However, you have to guess what the non-cooling loads will be. The chiller loading decision becomes more complicated if the kilowatt-hour charge (commodity charge) for electricity changes with the time of day.

temperature. Even storing chilled water as a liquid requires lower evaporator temperature.

A new chiller that is designed for both cooling storage and direct cooling of chilled water has reduced efficiency in both applications. Existing chillers may be especially inefficient if they are converted to ice storage, or they may not work at all.

The loss of chiller efficiency is partially compensated by the fact that the chiller spends more time operating at night, when the condensing temperature can be lower.

- ***conduction loss.*** All thermal storage loses energy by conduction from the storage unit. Storage systems for larger commercial applications typically lose several percent of their energy charge per day. The relative energy loss decreases as the storage vessel becomes larger. This is an important factor that weighs heavily against smaller storage systems.
- ***loss of residual stored energy.*** Energy that is left over in the storage unit at the end of an operating cycle suffers higher storage losses. Most types of ice storage require the storage unit to melt all ice completely at the end of the storage cycle. This energy is lost if it cannot be used during the off-peak period.
- ***auxiliary equipment energy consumption.*** Cooling storage also requires additional energy to put the cooling energy into storage and take it back out. This usually takes the form of energy needed to operate additional pumps. Depending on the type and design of the storage system, the additional pump load may be minor, or it may be several times greater than conventional chilled water pumping.

From a global perspective, the energy efficiency picture becomes more favorable when you consider the reasons why electric utilities promote cooling storage. Utilities promote this technology primarily to delay expensive and troublesome power plant construction, and to generate electricity with energy sources that are less expensive and less critical. It also allows utilities to minimize the operation of less-efficient generators, especially gas turbines, to handle peak loads.

Delaying power plant construction also delays the large expenditure of energy that occurs in construction. However, this advantage is lost after several generations of plant construction, because later plants must be increased in size to provide the additional energy used by the early generations of storage systems.

### ■ Space Requirements

A large amount of space is needed by the storage container and its accessories. The volume of the storage container is roughly proportional to the volume of the space being cooled. Chilled water storage requires about 20 to 30 cubic feet per ton-hour, ice storage requires about 3 to 4 cubic feet per ton-hour, and eutectic salts require a storage volume intermediate between the other two types.

For example, a typical office building with a floor area of 100,000 square feet, operating on a daily storage cycle, requires a minimum of about 3,000 cubic feet of ice storage, or about 100,000 gallons of chilled water storage.

### ■ Operation and Maintenance Burden

Cooling storage technology burdens the operating staff with additional complexity. The storage equipment is not particularly mysterious, but the control needed to optimize the operation of the system is somewhat subtle. Even if cooling storage technology were mature, many facilities would be unable to maintain and operate it reliably.

Another problem is continuity of operation. Unless you negotiate special terms with the utility, you will

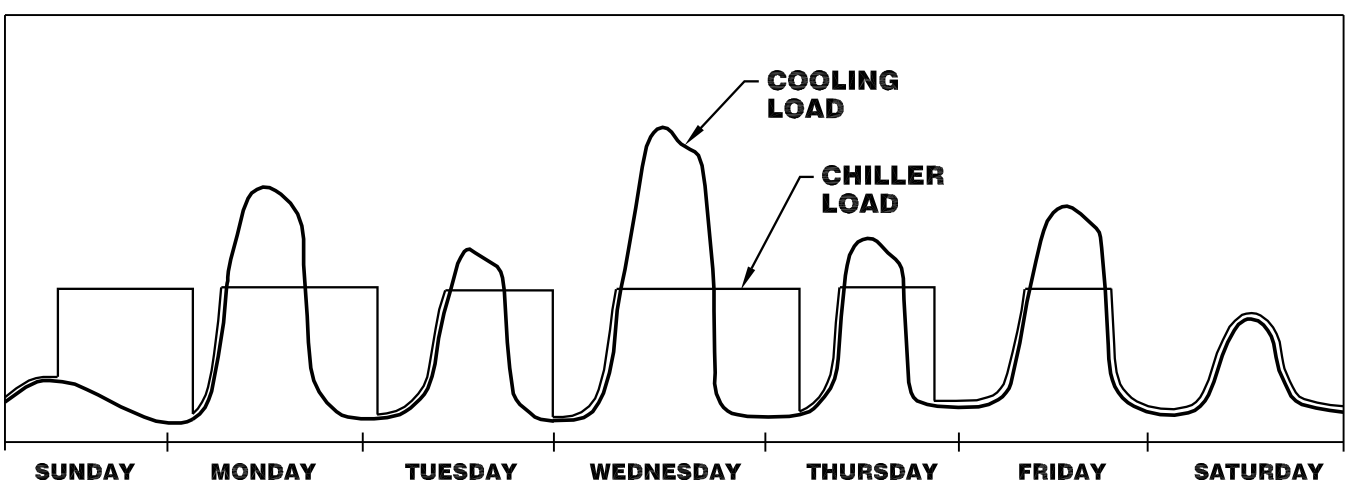


**Fig. 3 Using cooling storage to reduce chiller size** The load profile is typical of an office building. During weekdays, the chiller always operates at full load, long enough to keep the storage unit at full charge. On weekends, the chiller does not charge the storage unit until Sunday afternoon, to minimize storage losses. During months when the cooling load is lower, the chiller could be operated at lower output to reduce demand charges.

forfeit all or most of your savings in electricity prices if the plant fails even once during the high-demand period. Skilled staff must occupy the plant continuously during the months when peak demand occurs, and they must be able to immediately correct any failure of the storage system.

As a rule, do not install cooling storage in a facility where the system cannot be monitored continuously and repaired immediately. You may be able to relax this requirement somewhat if you can negotiate certain arrangements with the electric utility that are described below.

#### ■ Economic Risk

Any saving in electricity cost that is provided by cooling storage is based entirely on the pricing policy of the electric utility. The willingness of the utility to continue providing favorable pricing will depend on the benefit that cooling storage provides to the utility. Both will change with time, depending on the factors explained in Reference Note 21, Electricity Pricing.

Several growing issues presently place the commitment of utilities to thermal storage in greater doubt. One is utility deregulation, which eliminates the marriage of individual customers to a particular utility. This may kill utility support for thermal storage, except for the incentive provided by current rate schedules. Another issue is the renewed interest in electric vehicles. If electric vehicles become widespread, they will charge their batteries mostly during off-peak periods, eliminating the need for thermal storage to level the load.

To reduce the economic risk to reasonable proportions, you need to negotiate a long-term rate contract, as outlined below. If the utility will not agree to an acceptable contract, it would be economic folly to invest much money in cooling storage.

## HOW TO APPROACH STORAGE COOLING

Although the concept of cooling storage is simple, success requires the proper execution of many steps, each of which may involve a great deal of detail and special expertise. The following are the main steps in the development of a cooling storage system, from conception to birth.

### Step 1: Clarify Your Motives

Many cooling storage plants have been installed as a fad, or to reap utility incentives. Plants built for such reasons alone are likely to fail. Before investing substantial effort or expense, consider all the potential benefits and disadvantages discussed previously. Decide whether the potential economic saving is worth the long-term operational commitment.

Cooling storage systems are expensive. Decide whether the initial investment and the long-term operating cost might better be invested in other cost saving measures, or in improving your product, or in the stock market. Don't get preoccupied with cooling storage until you have exploited all the possibilities for reducing your energy costs that are less expensive and more reliable.

### Step 2: Consider the Facility's Ability to Operate Cooling Storage

A properly designed cooling storage plant does not require a great deal of extra labor to operate. However, it does require an operating staff with a high level of specialized skill and the ability to monitor the storage system continuously. If the plant fails for even a short time during the peak demand period, the utility rate advantage may be lost for a month, a cooling season, or an entire year.

### Step 3: Develop the Facility's Cooling Load Profiles

The potential saving in electricity costs is determined by the peak cooling load that occurs during the utility's high billing periods. The capacity of the cooling storage system is determined by the duration of the peak cooling periods. High cooling loads of short duration provide the greatest saving in relation to cost, whereas high cooling loads that last all day require larger storage capacities to gain the same benefit.

In new construction, you need a sophisticated computer program to estimate future load profiles, as well as for analyzing the performance of candidate storage systems. See Reference Note 17, Energy Analysis Computer Programs, for details.

In existing facilities, get the detailed load profiles for several past years and study them. You will need to contact the electric utility for this information, unless you have an in-house energy monitoring system that provides sufficient detail. Even the electric utility may not have the historical load information you need. In that case, either set up your own metering, or use a computer simulation program.

The load profiles help you to gauge the likelihood that the utility will maintain a long-term commitment to cooling storage. If only a few days of heavy cooling load occur each year, as in Minnesota, for example, it is cheaper for the utility to operate peaking generators to cover these loads than to maintain support for cooling storage. In such locales, a utility's interest in promoting cooling storage may be transient, making future operation of storage plants uneconomical. On the other hand, in a location such as Florida, where high cooling loads occur for many days each year, the utility is more likely to continue its interest in cooling storage.

If you are installing a new chiller plant, the simulated load profiles will tell you how much you can reduce your chiller capacity by using cooling storage. The greatest savings in chiller capacity are provided by cooling loads that are sharply peaked.

### Step 4: Estimate the Long-Term Saving in Electricity Cost

Estimate the potential saving in electricity cost from the cooling load profiles and from the utility's rate schedules. See Reference Note 21 for guidance in understanding rate schedules. The Big Question is whether the lower electricity rates for cooling storage will outweigh the increased consumption caused by reduced chiller efficiency. The Big Challenge is to estimate how these rates will change over the life of the cooling storage system.

It is foolhardy to assume that present electricity prices will continue, or even that they will change gradually. To convince yourself of this, review the pattern of electricity prices over the past twenty or fifty years. You can guess future rates intelligently only by assessing the utility company's future. This requires a crystal ball. The utility industry itself, with staffs of experts, has proven to be wildly wrong in predicting future conditions, even over time periods as short as a decade.

Furthermore, in the United States and some other countries, the structure of the utility industry is changing from a regulated environment to an environment in which some parts of the industry are regulated and others are not. There will be a period of chaos in which the long-term economic benefit of cooling storage is even more unpredictable.

To establish the range of possibilities, calculate for a best case and a worst case. If cooling storage looks potentially attractive, this exercise will help you to prepare for the rate contract negotiations recommended below. If cooling storage looks unrewarding or too risky at this point, forget about it and spend your money on reliable energy conservation measures. Unfortunately, the uncertainties of predicting the future are such that the best case is likely to make cooling storage look advantageous, while the worst case is likely to make cooling storage look unfeasible.

### Step 5: Investigate Utility Ownership and Operation of the Cooling Plant

Most cooling storage is installed for the ultimate benefit of the electric utility, so consider a deal in which the utility operates the storage chiller plant. The cleanest arrangement is for the utility to build and operate the cooling storage plant at its own expense. It is also conceivable that the utility could own the plant while the facility operates it, or vice versa. However, splitting responsibilities invites poor performance and eventual litigation.

At present, this is not a common arrangement, but there is precedent for such arrangements. Cogeneration plants were installed and operated at customer sites by natural gas utilities during the 1960's and early 1970's. Unfortunately, this precedent does provide a model for success, because most of those plants were abandoned before they were able to repay their costs. In that episode, the utility companies could not operate the satellite plants any better than their customers. However, the customer was not saddled with the full financial loss.

### Step 6: Negotiate a Long-Term Rate Contract with the Electric Utility

By this point, it should be apparent that cooling storage is an unacceptable gamble unless you are assured of favorable electricity prices for the life of the storage plant. Electricity prices change. It is a fundamental mistake to assume that present electricity prices provide sufficient incentive for cooling storage, even if subsidies are also provided by the utility to offset the cost of construction. A storage system will cease to be profitable unless it continues to provide an electricity price advantage that compensates for the energy losses of the system, the additional operating costs, and amortization of the original investment.

Therefore, early in the development of a cooling storage project, negotiate a long-term rate contract with the utility. This is not an activity for the naive. To do it right, you need to understand rate structures. You need to tactfully investigate the utility's present motivations and to assess its future conditions. You need to assess the future of utility regulation in your jurisdiction. You need negotiating skill, along with the authority to negotiate. The negotiation should be headed by a senior facility manager who has studied the issues in depth.

Take the initiative to prepare a contract offer that protects your investment. After all, you will be the party taking the risk of owning and operating the system, or at least providing the space for it. Furthermore, even though utilities are primary sponsors of cooling storage, many are naive about the economic and technical aspects of operating these systems. Both for negotiating purposes, and to ensure the success of your system, you need to know more about cooling storage than the utility. The utility is more likely to respond favorably to a reasonable proposal than to originate an arrangement that is satisfactory to you.

Your contract proposal should cover these four critical issues:

- the specific rates
- the duration of the rates
- exemptions for demand peaks caused by occasional equipment failure
- which metered loads will be subject to the cooling storage rate.

#### ■ The Rates

The structure of electricity rates is explained in Reference Note 21. Review this material to understand how a utility is compensated for the electricity that it produces, and how cooling storage reduces some components of the utility's costs.

The starting point for the customer is calculating the electricity price differential that is needed to make cooling storage attractive. This may require the utility to offer a more favorable price or a more favorable rate structure than it presently offers.

Remember how the utility views cooling storage. It is not a revenue producer like other electrical sales, but a means to solve a utility problem. When talking to the utility, focus on the aspects of cooling storage that help the utility. You will not get a favorable electricity rate unless your system helps the utility to satisfy its objectives. Don't be surprised if the utility itself is not clear about its objectives, especially in the long term.

#### ■ The Duration of the Rates

As a minimum, the contract should guarantee that favorable rates will continue long enough to pay off the system and to compensate for the effort, investment, and risk involved in installing it. If the utility is unwilling to negotiate such a contract, you have no rational basis to install cooling storage. Without a long-term rate contract, all it takes is the future decision of a utility executive to turn your cooling storage plant into a white elephant.

Electricity prices depend on many factors that vary in unpredictable ways, as explained in Reference Note 21. Do not expect the utility to commit to specific prices for a long term in the face of these uncertainties. Such an agreement would be a pure gamble for both parties. Perhaps the best way to deal with this uncertainty is to negotiate long-term rates that are expressed in terms of a discount from any future non-storage rates.

For example, agree that electricity for the chiller plant, purchased during off-peak hours, will be priced at a fixed percentage of the lowest non-storage rate offered by the utility to any customer.

#### ■ Forgiveness Clause for Occasional System Failures

There is an economic hazard for the owner of a cooling storage plant that is not yet adequately recognized. The hazard is that a brief failure of storage could wipe out the saving in electricity costs for a long period of time. This is because demand charges are based on measurements that are made throughout a specified time period.

If the cooling storage systems fails for only one day during the peak period, the demand that occurs on that day becomes the basis for the demand charge for the entire demand billing period. The demand billing period may be a month, the entire cooling season, or the entire year. While demand peaks are almost always measured on a monthly basis, "ratchet" provisions in the rate schedule may extend a demand charge that is determined during one month into the months that follow.

For example, one utility bases its yearly demand charges on the highest demand that occurs during the months of July, August, or September. If the cooling storage system fails on a hot afternoon in July, the demand registered during that period becomes the basis of demand charges for the entire year. A failure that lasts one hour can wipe out most of savings that the storage system is supposed to provide for that entire year.

To avoid this risk, negotiate a forgiveness clause in your long-term rate contract. This clause exempts demand charges resulting from occasional failures of the cooling storage system. For example, the contract might stipulate that no demand charges will be levied for the three days of highest facility demand during the cooling season, provided that none of these days is coincident with the three highest days of the utility's demand. Thus, if the storage plant suffers a failure that requires two days to repair, the facility probably will not lose its savings in electricity cost.

At first glance, it might appear that this defeats the utility's purpose in having demand charges. This is not true. From the standpoint of the electric utility, rare failures of cooling storage by individual customers are not important. This is because a utility has many customers using storage or other demand-reduction techniques. Statistically, the utility can expect that only a few storage failures, at worst, will occur during a utility load peak.

This concept is novel, so be prepared to explain and persuade. Another problem is that the utility will probably have to modify the way it calculates demand. Be prepared to argue that most large utilities now calculate demand from a central computer, which can be programmed with modest effort to accommodate different rate arrangements.

#### ■ Electricity Metering Configuration

The distribution of metering may have a profound effect on electricity cost. The chiller plant may be served by the same meter as the entire facility, or the chiller plant may have separate meter, or the chiller plant may be combined with selected other loads. Each of these arrangements produces a different total electricity cost.

For example, if storage is used for "peak shaving," the chillers should be served by the same meter that serves the variable non-cooling loads. On the other hand, if the rates include excess-consumption charges, it may be better to have a separate meter for the chiller plant.

You will have to negotiate a change in metering with the utility. If you think that rearranging the metering would produce lower electricity costs, be careful to consider the net effect on electricity cost for all the metered areas. Be clear about which meters are covered by your negotiations, and which continue to be governed by the utility's existing rate schedules, and their successors.

### Step 7: Assess the Potential for Heat Recovery from the Storage Chillers

As discussed previously, cooling storage may increase the opportunity for recovering the heat rejected by the chiller plant. On the other hand, heat recovery may reduce the efficiency of cooling operation. If the facility presents an opportunity for heat recovery, refer to Subsection 2.10 for the factors to consider.

### Step 8: Select the Control Strategy for Minimizing Electricity and Equipment Cost

Controlling a cooling storage installation may be tricky. How you control storage depends on the purposes you hope to achieve. In turn, the control strategy largely determines the storage capacity that you need to install. Select the control strategy to satisfy these primary objectives:

- scheduling the chiller load to minimize electricity cost
- minimizing the amount of excess stored cooling that remains at the end of each discharge cycle
- minimizing total equipment cost. In new construction, you can reduce the cost of the chillers, and perhaps the cost of other facility cooling equipment.

You will have to compromise between these objectives.

A simple example is a typical large office building in which the non-cooling electrical loads are essentially constant throughout the working day. This example is illustrated in Figure 1. If the electric utility's demand period is from 0800 to 1800, then the chiller is controlled so that it does not run during these hours. At the end of each day, the control system estimates the amount of cooling that is needed for the next day. The chiller is operated during the coolest hours of the night to put this amount of cooling into storage, plus a reserve to cover the uncertainty in predicting the next day's cooling load.

A more complex case is one in which the electrical demand of non-cooling equipment varies widely throughout the day, as shown in Figure 2. In such cases, the chillers may operate during the demand period, but their output is limited to keep the overall demand of the facility within a set limit. Thus, chiller output declines as other electrical loads increase. Operating the chiller during the demand period allows you to reduce the storage capacity. If the demand charge changes from one month to another (which is typical), then the optimum amount of chiller operation during the demand period will vary from month to month. This particular control strategy is called "demand limiting," although all modes of chiller control should attempt to limit demand.

If the purpose of cooling storage is to minimize chiller capacity, then chillers operate as close to the usage period as possible, but still during periods of lowest electricity prices. For example, a dairy operation may have two milking cycles per day, both of which occur during the utility's demand period. The chiller operates at night to provide enough stored cooling for both of the cooling cycles. If the utility does not have a demand charge on weekends, the chiller may operate during the day on Saturday and Sunday to store cooling only for the evening cycle.

Controls are covered in greater detail at the end of this Measure.

### Step 9: Estimate the Cooling Storage Capacity

The cooling storage capacity that you need is determined by the purposes of the system and by the facility's cooling load profile. For example, an office building in a mid-latitude climate typically has an afternoon cooling peak lasting only a few hours. This profile requires less storage capacity for a given demand reduction than a hotel located in a warm, humid climate, where the cooling load may remain high all day.

It may not be economical to displace all chiller operation from the period of high electricity prices. For example, if a heavy cooling load occurs only for a few weeks a year, a storage system designed for those loads will have a large amount of idle capacity for the rest of the year. If the utility has no ratchet charges, the excess capacity provides little benefit.

The actual storage capacity needs to be somewhat greater than the amount of cooling load that is displaced. As with most equipment, provide some reserve for loads greater than expected, and for equipment performance poorer than expected.

With all cooling storage methods, the chilled water temperature rises as the storage unit discharges. This reduces cooling capacity at the end of the discharge cycle. If the cooling load remains high at the end of the discharge period, you may need additional storage capacity to account for this effect. On the other hand, you may be able avoid this problem by installing multiple storage units, and discharging them in sequence.

In ice storage units, the rise in chilled water temperature toward the end of the discharge cycle may be severe, and the effect increases with discharge rate. This may not be a problem in an ice storage system that distributes chilled water at normal temperatures, because ice storage produces water that is much colder than normal chilled water.

On the other hand, if the system uses low-temperature chilled water distribution, and the cooling load remains high near the end of the storage cycle, the rise in chilled water temperature may be unacceptable. The problem is least severe with ice shedders and ice slurry systems. Internal-melt systems and ice capsules suffer a large rise in temperature, unless the discharge rate is low. (Individual types of storage units are described in greater detail below.)

If you compensate by increasing the capacity of the storage unit, this will increase that amount of cooling energy that remains in the storage unit at the end of the cooling storage period. Much of this energy is wasted. For example, if cooling storage is not needed over the weekend, some of the residual cooling left in storage at the end of Friday is lost by conduction over the weekend. Even worse, some ice storage units require all the ice to be melted at the end of each discharge cycle, whether the cooling is needed or not.

### Step 10: Estimate the Heat Recovery Storage Capacity, If Used

If you want to recover heat from the chillers, installing a heat storage may substantially increase the amount of heat that you can recover. The heat storage capacity is determined largely by the chiller operating strategy. Refer to Measure 2.10.5 for details of heat recovery storage.

### Step 11: Estimate the Cooling Storage Chiller Capacity

The chiller capacity is determined by the control strategy and the storage capacity. If you rely entirely on storage cooling during the peak electricity price period, the chillers must be large enough to charge the storage unit during the period when electricity prices are lowest. If the chillers serve the cooling load in parallel with the storage unit, then the chiller capacity is determined by the storage load or the direct cooling load, whichever is larger.

When you select the chiller size for charging the storage unit, recall that the chiller's charging capacity is less than its capacity for direct cooling. This is because the chiller must operate at lower evaporator temperature when charging. In ice storage systems, chiller capacity is reduced by about 40% compared to direct cooling, for the same condensing temperature. This effect is compensated somewhat by lower nighttime condensing temperatures, provided that the chiller is able to exploit lower condensing temperatures.

In new construction, if storage is being used to reduce chiller capacity, consider future changes in the cooling of the facility. Leave space for more chiller capacity if the cooling load increases. For example, an office building in a warm climate may presently be cooled only eight hours per day, but it is conceivable that future conditions will require much longer periods of cooling.

### Step 12: Select the Cooling Storage Technology

The various types of cooling storage are described below. Your selection of the type of storage unit has major effects on system size, cost, complexity, and efficiency.

The first selection step is deciding whether to use ice, chilled water, or eutectic storage. Under present conditions, ice appears to be preferable for most applications. Chilled water is rarely used unless there is an existing water tank of adequate capacity. Eutectic storage probably is not the best choice unless there has been a significant improvement in the technology by the time you read this. If you select ice storage, you have another major decision in selecting the type of ice maker.

A major part of this decision is figuring out where to put the storage vessel. The vessels used with the different types of storage vary considerably in volume, height requirements, and accessibility requirements. For example, underground tanks are acceptable for some applications and storage methods, but not for others.

### Step 13: Select the Type of Cooling Storage Chiller

See Reference Note 32, Compression Cooling, and Reference Note 33, Absorption Cooling, for details of chiller selection factors. As in all chiller plants, high COP should be a dominant criterion.

You face additional selection issues if the chiller makes both ice (for storage) and chilling water (for direct cooling). This requires the chiller to operate at two different pressure differentials. These issues are similar to the ones related to selecting chillers for heat recovery at elevated temperatures. See Measure 2.10.3 for details. In brief, screw compressors and reciprocating compressors are favored in this case because of their ability to adapt to different pressure differentials.

Be sure to select chillers that can exploit low ambient condensing temperatures, for the reasons explained previously.

### Step 14: Select the Evaporator Configuration

The method of controlling refrigerant flow to the evaporator has a major effect on system COP. Storage systems have been built with each of the three major evaporator types: liquid overfeed, flooded evaporators, and expansion valve. These types are explained in Reference Note 32, Compression Cooling. Expansion valve evaporators are inherently less efficient than the other two types.

In ice storage systems, expansion valve evaporators require additional complications to allow them to switch efficiently between making ice and chilling water directly. One way of doing this is to install an expansion valve that maintains a fixed superheat, regardless of the evaporator temperature. Such expansion valves have been available for a number of years. Another approach is to use two expansion valves, one for making ice and one for chilling water. Solenoid valves control which expansion valve is used, based on signals from the system controls.

### Step 15: Design the Connections between the Chiller Plant, the Storage Unit, and the Facility Equipment

The type of storage unit dictates major aspects of the design. These include isolating the storage unit from the pressure of the chilled water system, reconciling the supply and return water temperatures, and switching from charging to direct cooling. These topics are covered at the end of this Measure. In general, keep the overall configuration as simple and reliable as possible, while providing for efficiency in all the modes of operation.

### Step 16: Design the Controls and Alarms

Control is the trickiest aspect of the design, installation, and operation of a cooling storage system. Cooling storage may require a large number of control functions because a system changes its connections, running time, and chiller loading for different operating conditions. A peculiar difficulty of cooling storage is that the control system must predict load conditions from several hours to several days in advance. Details are given below.

### Step 17: Design the Physical Layout

From the standpoint of long-term performance, the most important aspect of the physical layout is easy access for maintenance. Design the layout so that any component in the system can be replaced easily. *Make it easy to maintain the system for the life of the facility.* Don't design for the short lifetimes used in economic analysis. You don't want a system to be unrepairable just because it is paid off.

Many cooling storage systems are being installed today in a manner that makes it virtually impossible to repair them economically. Burying systems underground not only makes them inaccessible, but invites deterioration by ground water. Equally bad is stacking modular units inside a building in a way that makes it impossible to remove an individual unit or to replace the components in a unit. No system on the market is sufficiently well proven to justify these practices.

### Step 18: Install the System

Installing cooling storage is similar to installing other complex HVAC equipment. Effective communication between the designer and the contractor is important. Selecting packaged equipment reduces installation cost, and it lessens the opportunities for installation problems.

### Step 19: Train and Preserve a Skilled Staff

Among the many failures of cooling storage systems, failure to operate the systems properly looms large as a primary cause. Operating a cooling storage plant requires a high level of skill, unconventional knowledge, and continuous monitoring. The staff must receive special training to operate the system. There can be no lapses in staff continuity as long as the system is operating.

This is a major management challenge. Staff turnover requires continual retraining. Furthermore, talented operating personnel tend to be diverted to tasks outside the chiller plant.

## COOLING STORAGE EQUIPMENT

The various types of cooling storage differ markedly in size, efficiency, reliability, and other significant characteristics. Early cooling storage for HVAC applications focussed on liquid water as the storage medium. Within a few years, growing awareness of the huge volume required by water storage, along with its economic and practical problems, forced designers to switch their preference to ice storage. In turn, ice storage has posed a whole new set of challenges. The design compromises required in ice storage are stimulating development of a variety of storage vessels and system types. The following is an introduction to the types of cooling storage that are presently available, with emphasis on their comparative characteristics.

#### ■ Common Considerations for Ice Storage Units

Using ice for thermal storage has two major advantages over using chilled water storage. One is that much more energy can be stored in a given volume. The heat required to melt ice is about 144 BTU's per pound, while liquid water can absorb less than 20 BTU's per pound in typical cooling storage applications. As a result, a typical ice storage unit requires only about one fifth the volume of a chilled water tank.

The other major advantage of ice storage is that ice always melts at a fixed temperature, regardless of the state of charge of the storage unit. This keeps the chilled water supply temperature fairly constant as long as ice remains, regardless of the return water temperature. Therefore, the cooling system served by the storage unit can be entirely conventional.

This advantage is lost in air conditioning systems that are designed to exploit the low chilled water temperature available with ice storage. This is covered in greater detail below.

The main disadvantage of ice storage is low energy efficiency. The evaporator temperature needed to freeze ice is about 12°F to 30°F (7°C to 17°C) colder than is needed to chill water in conventional applications. This imposes a severe reduction of chiller COP, typically in the range of 20% to 40%. Some types of ice storage require substantially lower evaporator temperatures than others.

A fundamental problem in ice storage design is that ice expands when it freezes. Freezing of water is one of nature's most destructive forces. Given sufficient time, it destroys mountains. In much less time, it destroys man-made constructions, such as roads and thermal storage systems. Ice also exerts force by its buoyancy. Some types of ice storage accommodate these forces with a greater margin of safety than others. With types that require coils in the tank for freezing, use well proven packaged units, rather than run the risk of repeating past mistakes with a custom design.

Another challenge in the design of ice storage units is the relatively poor thermal conductivity of ice, which is about the same as for granite, and about 0.5% the conductivity of copper pipe. Lower evaporator temperatures are needed to freeze greater thicknesses of ice, so the storage unit should minimize the thickness. Some types do this better than others.

Another problem is non-uniform flow of the chilled water or heat transfer fluid as it flows through the melting ice. Where water flows freely in a tank, it tends to melt channels through the ice, reducing heat transfer during the discharge cycle. Some types of ice storage are very vulnerable to this problem, while at least one type is immune to it.

## Ice Shedders

A simple method of cooling storage is making ice, dropping it into a tank, and circulating water through the ice. The ice making machines are similar to the ones that make the ice cubes for your drinks. These storage systems are called "ice harvesters," or "ice shedders," because the ice maker is usually mounted above the ice storage tank, where it drops the ice into the tank below. Figure 4 shows the equipment layout.

Ice shedder systems are popular because they offer several significant advantages, and they are free of some of the problems of other types of ice storage. A primary advantage is the simplicity of the system connections. Ice shedders average about the same overall efficiency as other ice storage systems.

A major advantage of ice shedder systems is that they are less vulnerable to flaws in the design of the site installation. The ice making machine is usually purchased as a complete package, ready to be installed on top of the tank. If the machine is derived from well proven standard equipment, it is less likely to have crippling flaws that appear the day after the warranty expires.

The ice maker itself is relatively expensive, although its cost per unit of capacity drops radically with increasing size. Therefore, ice shedders are favored for applications that require a large storage volume in relation to chiller capacity. The storage tank is relatively inexpensive because it is simple. Commonly used materials for the tank and tank circuit include plastic, fiber-reinforced plastic (fiberglass), and concrete.

Ice shedder systems may be several stories tall, because the ice maker is mounted on top of the tank. Figure 5 shows a typical installation. The height can be reduced by using a conveyor to move the ice to the tank, but this sacrifices some of the elegant simplicity of the system.

### ■ Evaporator Features

Ice is formed on the evaporator from water that is circulated from the storage tank. Many contemporary units use flat plate evaporators, from which the ice sheds in the form of sheets or large flakes. The flat sheet form is favored because it shortens the path of heat through the freezing ice, allowing higher evaporator temperatures, and hence higher COP. However, ice can be made in many shapes. Figure 6 shows a typical unit in operation.

Ice tends to stick to the evaporator as it freezes, so the method of releasing the ice from the evaporator is a major issue with ice shedders. At present, the most popular method is similar to a defrost cycle, which operates about 5% of the time. The ice is released by periodically bleeding hot gas into the evaporator while the compressor is turned off. The hot gas typically comes from a compressor discharge manifold that links several compressors. Figure 7 is a diagram of the cycle.

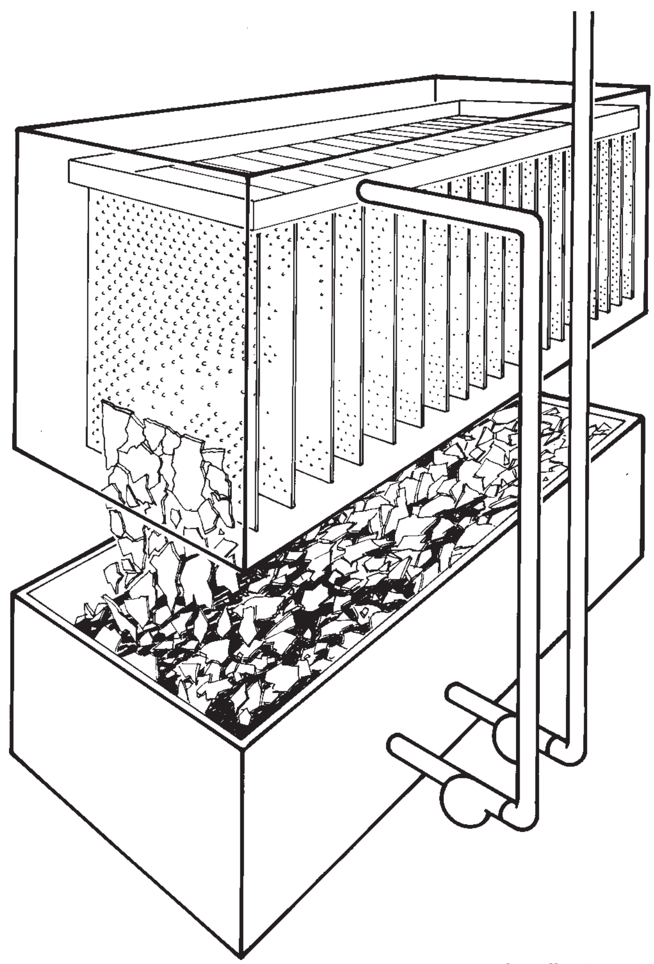

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**Fig. 4 The basic components of an ice shedder system**
An ice maker dumps ice into a tank, and chilled water is circulated through the ice.

Defrosting wastes a certain amount of energy, so manufacturers search for more efficient methods of releasing the ice from the evaporator. One method is scrapers, which come in various designs. Another involves freezing the water as it is carried by a carrier liquid that acts as a release agent. The latter type are called slurry systems. Two versions of slurry systems are described below.

Some models of ice shedders are incapable of cooling chilled water directly. Such units have expansion valve evaporators that are set to operate at only one temperature for freezing.

Other models have liquid overfeed evaporators, which can vary their evaporator temperature. These units cool chilled water by pumping it over the evaporator in the same manner as for ice making.

### ■ Storage Tank Features

Ice shedders avoid the trickiest problems of designing ice storage units, which is dealing with the expansion of water as it freezes. The ice tank is simply a bin. The equipment inside the bin is not exposed to expansion or buoyancy forces. The return chilled water distributors may be kept above the ice, and the headers that extract water from the bottom of the tank may easily be designed to resist damage. Although the tanks are simple, tank shape and control of water level are important to keep large voids from forming in the ice. Voids can be eliminated by stirring the ice pile mechanically, but it is best to avoid the complication.

The chilled water is cooled by direct contact with ice in the form of small pieces, providing a large surface area. As a result, ice shedder system have a high peak cooling rate. By the same token, if the water flow through the tank is well designed, the water discharge temperature is kept low until most of the ice has melted.

Short-circuiting of water flow poses somewhat less of a problem than with other methods of ice storage. Minimize it by careful design of tank shape and header configuration, by control of the water level in the tank, and perhaps by using mechanical agitators to redistribute the ice. Short-circuiting is more difficult to control if the ice is stored for long periods, because the ice pieces may fuse together, channeling water flow.

The independence of the storage bin from the ice maker allows you to select the size and shape of the bin to fit available space and to meet the owner's stylistic preferences. This flexibility is not unlimited. The ice falling from the ice maker forms a conical pile, which leaves some void space. If you need to minimize the

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**Fig. 5 Ice shedder system for a military club in Florida** The compressor and evaporator unit, surrounded by the railing, sits atop a rectangular concrete ice tank. The cooling tower for the unit is at upper left.

volume of the tank, make the tank round and tall. This shape also improves heat transfer and reduces heat loss.

### Possible Need for Heat Exchanger

Ice shedders heavily aerate the water in the tank by virtue of pumping it continuously over the evaporator. The resulting high oxygen content makes the water especially corrosive to steel components. As a result, these systems commonly use a heat exchanger to isolate the tank water from the steel piping of the chilled water system.

## Ice Freezing on Coil, External Melt

At first glance, the simplest way to make ice for cooling storage is to put a refrigerant coil in a tank of water and freeze the water around the coils. Cooling is recovered by circulating water around the frozen coils. This technique has been named "external melt" ice storage, to distinguish it from another method in which the ice is melted by the coil. Figure 8 shows a cutaway of an external-melt ice storage unit.

The large ice surface area gives external-melt units a high discharge rate, if needed. Another virtue of external-melt systems is that their system connections are simpler than with some other types. Figure 9 shows the basic layout. This reduces the uncertainties of engineering and makes it easier for the facility staff to understand the operation of the system.

External-melt systems tend to have lower overall efficiency than other types of cooling storage systems. An inherent problem is the thickness of ice on the coils, which typically grows to several inches with reasonable coil spacing. This forces the chiller to operate at progressively lower evaporator temperatures as the ice accumulates. The average efficiency of the system is further reduced by inability to predict the exact cooling

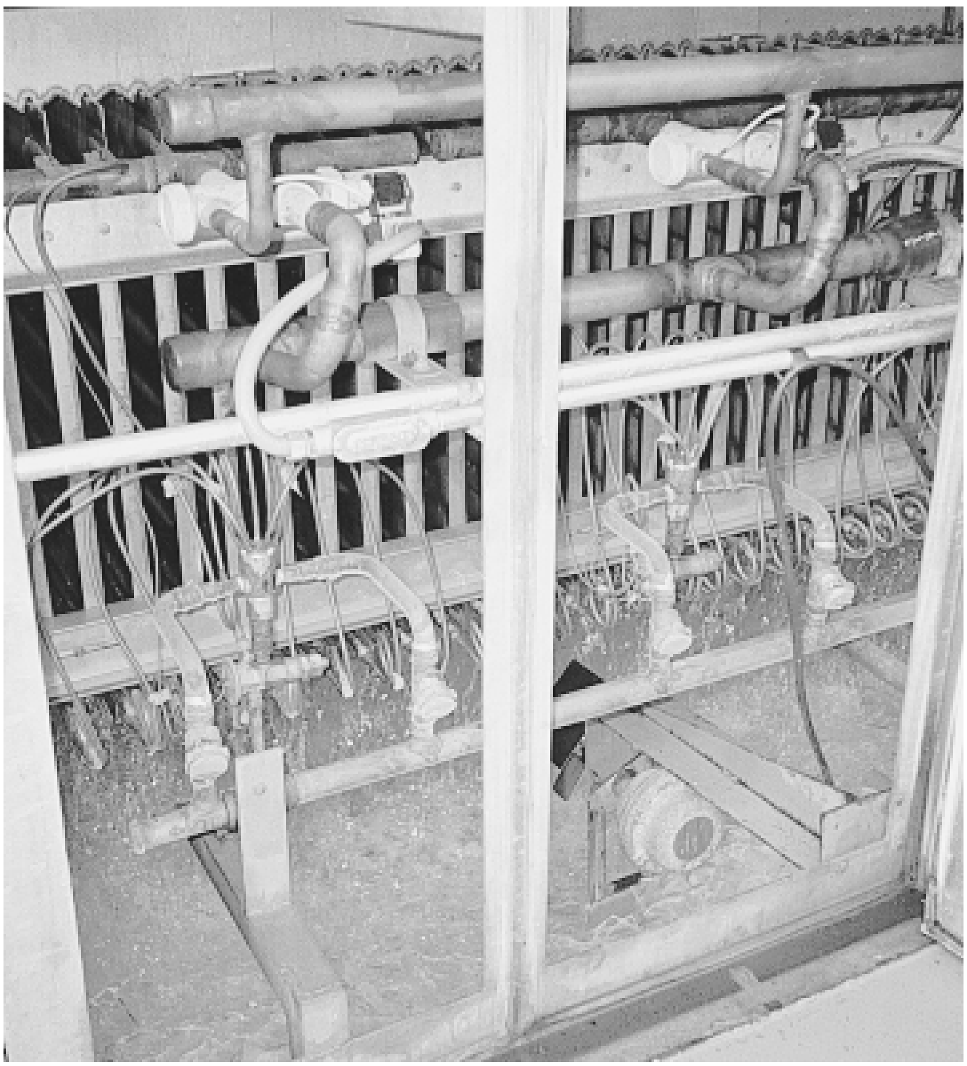

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**Fig. 6 Ice shedder in operation** Ice is being released from the vertical evaporator plates into the ice bin below, which is almost full. The thin tubes feed refrigerant to the evaporator plates from the horizontal header at the bottom. The horizontal header at the top feeds hot gas to the evaporator plates in sequence to release the ice. At lower right is the ice level sensor that tells when the ice bin is full.

load during the next cycle, the irregularity of ice formation, and other storage inefficiencies. The cost of the storage units is relatively high, because they are packed with coils, attachments, and accessories.

The simplicity of the concept made this method the first to be tried on a large scale. However, serious problems in the first generation of equipment almost led to the extinction of this method. Most of the problems have now been brought under reasonable control, and this type of ice storage has climbed back to a prominent position. External-melt storage units are now used in systems of all sizes. Figure 10 shows one module of a large system being installed.

A major failing of early external-melt storage units was that they failed to account for the enormous expansion force of freezing ice, which destroyed coils and tanks. Also, the buoyant force of the ice tore the coil assemblies loose from their attachments. These problems are now avoided by using packaged ice storage units that are carefully designed and heavily built. It would be folly to repeat the mistakes of the past by attempting to design external-melt storage units on a custom basis, unless the designer is very skilled and the customer has a large budget.

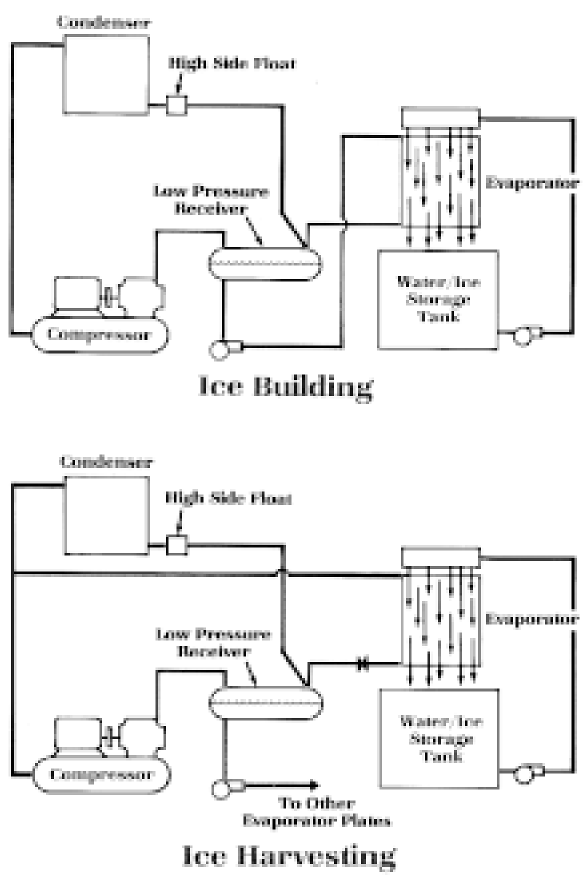


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**Fig. 7 Ice making and release cycle of an ice shedder** Ice forms on the cold evaporator plates. To release the ice, it is partially melted by feeding hot gas from the compressor into the evaporator. This process involves some energy loss.

## ■ Direct-Expansion Storage Units

Ice can be formed on direct-expansion coils as well as on coils that are cooled indirectly by an antifreeze solution. Direct-expansion coils avoid heat transfer losses, but system design is more complex, mostly in the feeding of refrigerant to the coils. Coils have been made from various plastics, copper alloys, and steel. The strength of steel is probably needed for larger units. Steel coils make it possible to cool directly with ammonia, which is an excellent refrigerant for large ice storage units. (Ammonia attacks components containing copper.) Figure 11 shows a direct-expansion external-melt system that serves a small professional building.

## ■ Ice Bridging

Another fundamental problem of external-melt systems is ice bridging from one coil to adjacent coils. Bridging impedes the flow of chilled water in some parts of the storage unit, forcing short-circuiting through other parts. In order to minimize storage volume and cost, the coils are packed as close as possible. As a result, bridging will occur if the nominal ice capacity of the unit is exceeded.

Bridging also occurs if the ice is not completely melted between cooling cycles. Ice grows in a somewhat irregular manner, so bridging becomes probable after several cycles of incomplete ice melting. Therefore, the controls must ensure that the coils are melted completely at the end of every operating cycle, or perhaps after several operating cycles. This takes no special action if the cooling load continues into hours of low electricity prices. This allows the storage unit to operate until all the ice has melted. However, if cooling occurs mostly during hours of peak electricity cost, some ice may remain until the next charging cycle. In this case, energy may have to be expended to melt the remaining ice prior to charging.

## ■ Achieving Uniform Melting

External-melt systems have difficulty maintaining low chilled water temperature as the ice melts, especially toward the end of the discharge cycle. There is a strong tendency toward short-circuiting, and this problem has not been solved entirely. If one path through the ice enlarges faster than others, the increased water flow will further hasten the enlargement, to the point that one part of the storage unit may melt completely while the rest of the unit still has considerable ice.

Various methods are used to encourage uniform melting, including careful coil design, baffles, and headers. One major manufacturer even uses an air bubbling system to keep ice melting uniform. A disadvantage of this method is that it aerates the chilled water, making it corrosive. This requires major corrosion protection features for the storage unit, and usually, a heat exchanger to isolate the aerated water from the chilled water system.

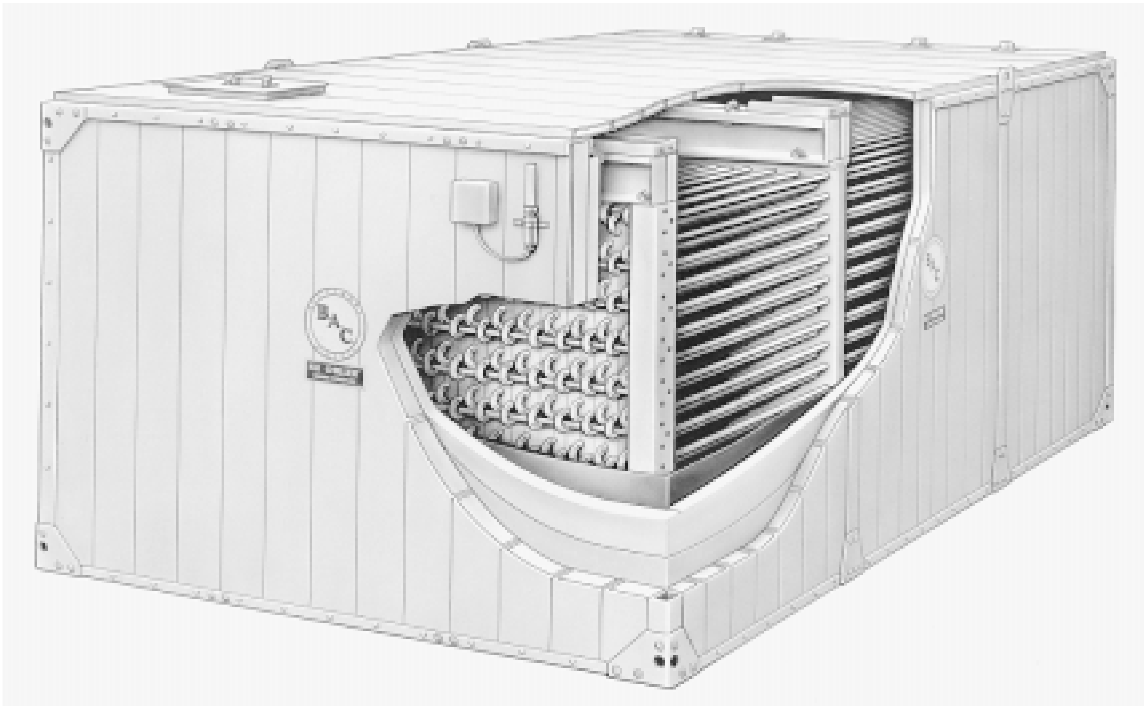

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**Fig. 8 External-melt ice storage unit** This is a tank full of water that is filled with freezing coils. The coils may be cooled by glycol from a chiller, or they may be cooled by direct expansion. Avoiding ice bridging between the coils and maintaining uniform water circulation are important challenges with this type of unit.

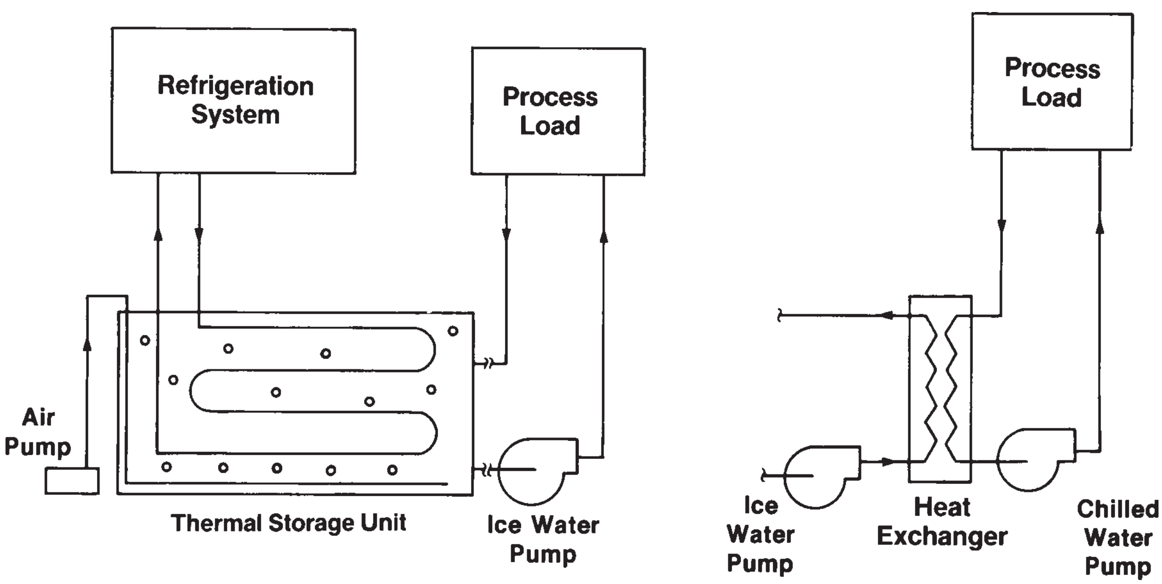


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**Fig. 9 System connections with external-melt systems** The chilled water can be pumped directly from the tank, or a heat exchanger can be used. A heat exchanger is needed to isolate the tank from pressure if portions of the chilled water system are located above it. This system includes an air bubbler to promote uniform water circulation. The bubbler saturates the water with oxygen, making it corrosive to steel. This is another reason to use a heat exchanger.

■ **Alternating Use for Heat Storage**

An interesting possibility is using the storage unit to heat and store hot water during the off-peak season. To do this, the evaporator coil connection is switched so that the coil becomes a second condenser bundle. This has been done in some small packaged systems.

## Ice Freezing on Coil, Coil Melt

Another type of ice storage also freezes ice on coils, but the method of melting the ice is entirely different. Instead of melting the ice from the outside of the ice layer, the ice is melted by the same coil that freezes it. This system uses a heat transfer fluid, typically glycol, inside the coils. During the charging cycle, the glycol flows through the chiller to freeze the ice. During the discharge cycle, the ice is melted by circulating the heat transfer fluid with the chiller turned off. Figure 12 shows the system operating modes.

■ **Advantages**

Coil-melt systems avoid the most vexing problems of external-melt ice storage. Ice bridging is not a problem because the entire mass of water surrounding the coils can be frozen solid. This also increases the compactness of the storage unit. The water in the storage tank does not circulate, so there is no need for headers, baffles, or other complications.

It is easy to protect the storage equipment from corrosion because the water that freezes in the storage unit does not circulate, and it is not aerated. There is no corrosion problem in the chilled water system, because it is a closed system.

■ **Charging and Discharging Characteristics**

The performance characteristics of coil-melt systems vary during the freezing and thawing cycle to a greater extent than with other ice storage methods. The charging efficiency and charging rate are greatest at the beginning of the charge cycle because ice was cleared from the coils by the previous discharge.

The temperature rises considerably throughout the discharge cycle, for a constant charge rate. This is due to the thermal resistance of the growing water layer that forms around the tubes as the ice melts. Liquid water has about four times the thermal resistance of ice when stationary, but convection currents in the water layer probably reduce the resistance considerably. This effect is not a major worry in chilled water systems that operate at conventional temperatures. However, it may disqualify this method of ice storage if you want to exploit low-temperature chilled water distribution.

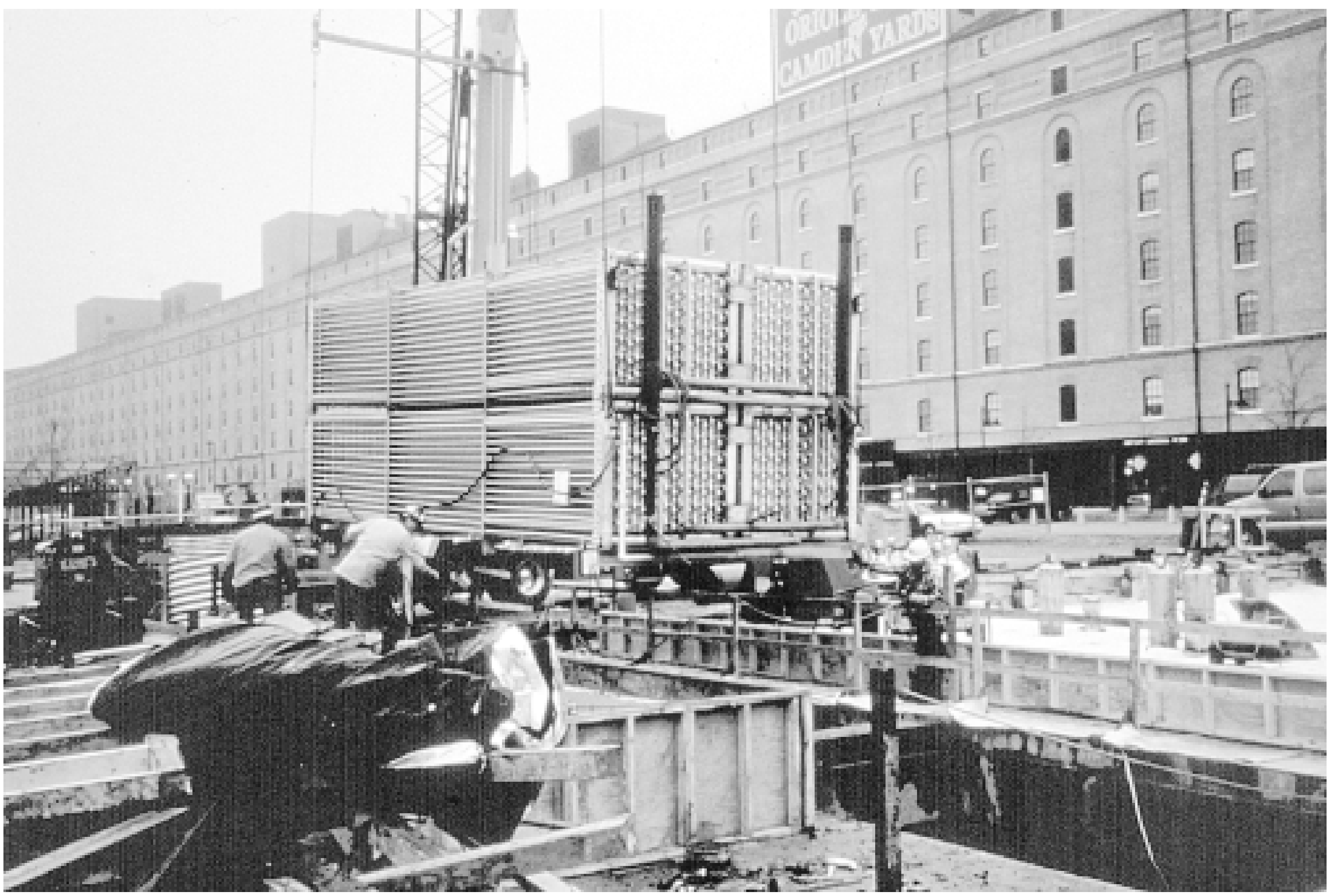


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**Fig. 10 An external-melt storage module for a district cooling system** A large number of these modules are installed underneath a parking lot. The system serves a portion of downtown Baltimore.

By the same token, the maximum discharge rate also declines as the ice melts. This may be a problem if the cooling load remains high near the end of the discharge cycle.

### ■ Storage Unit Design

Packaged coil-melt storage units are available in a variety of sizes and shapes. The storage unit can freeze solid from one side to the other, so the tank must be designed to resist bursting or progressive leakage. (As an alternative, the system can be controlled to prevent complete freezing of the tank, but this method is less reliable.) Plastic pipe is typically used in smaller units, and steel pipe in larger units. Figure 13 shows a cutaway of a typical packaged storage unit.

Large storage systems can be assembled easily from any number of modular units. Figure 14 shows an example. Another approach is to use prefabricated coil arrays that are available for installation in large site-built tanks.

### ■ Connections to the Chilled Water System

The chiller and the ice storage unit can serve the cooling load individually or simultaneously, and the chiller can charge the storage unit while it serves the cooling load. It is challenging to design a system configuration that optimizes operating efficiency under all possible operating modes.

Some designs compromise by simply connecting the chiller and storage unit in series. This is fairly satisfactory, but sacrifices some efficiency or capacity, depending on whether the chiller is upstream or downstream of the storage unit.

Small systems may use the heat transfer solution directly in the chilled water system. This approach reduces heat transfer in the end-use equipment because glycol and other heat transfer fluids have worse heat transfer characteristics than water. An alternative is using a heat exchanger, which allows pure water to be used in chilled water circuit. This approach incurs a temperature rise in the heat exchanger. In larger systems, a heat exchanger becomes more desirable to reduce the quantity of glycol that is needed.

The heat exchanger, if one is used, needs freeze protection. This is because the glycol solution may be well below freezing temperature while the chilled water is unprotected. One method is to bypass the glycol around the heat exchanger when the glycol is below freezing temperature. Reliability requires multiple bypass valves and safety controls that stop glycol flow if the heat exchanger gets too cold.

## Ice Capsules

In ice capsule storage systems, a tank is filled with sealed containers, or capsules, of water. The capsules are frozen by circulating a heat transfer fluid (generally glycol) through the tank. The storage unit is discharged simply by turning off the chiller and continuing to circulate the glycol through the tank, thawing the capsules.

The capsules are made of thin-walled plastic, typically polyethylene. They are shaped to survive the expansion of ice inside them. Some are dimpled spheres, typically a few inches in diameter. Others are shaped like large rectangular hot water bottles. These shapes

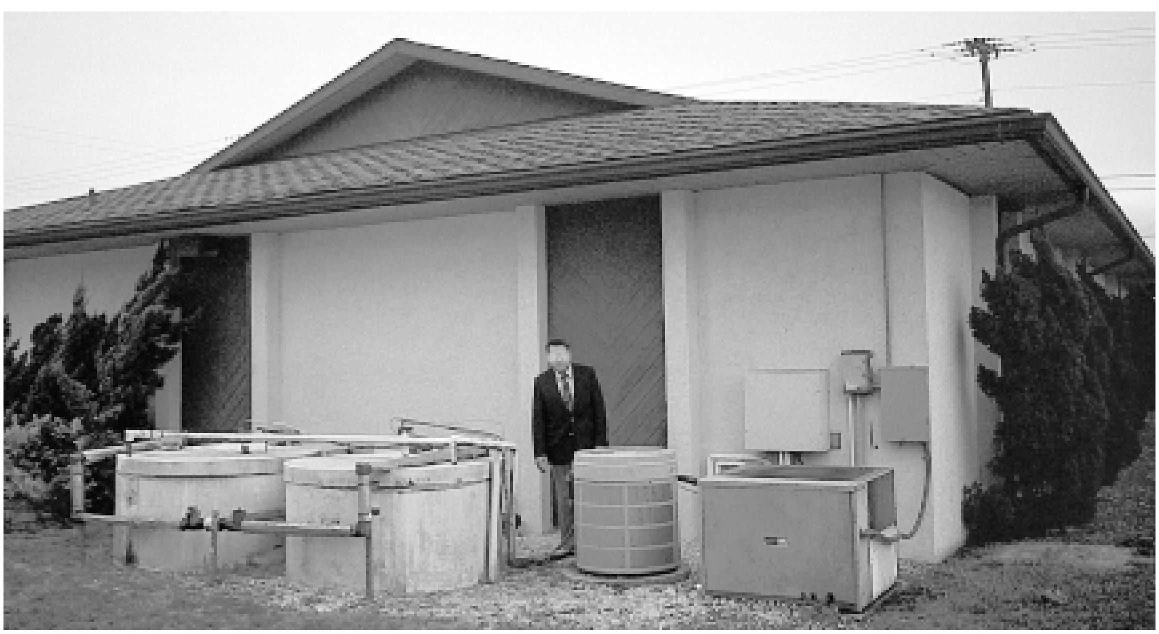

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**Fig. 11 External-melt cooling storage system using direct-expansion coils** The partially buried, round tanks are filled with spiral copper evaporator tubing. The compressor and condenser units are on the right . This system serves a small professional building.

allow the glycol to flow between the capsules. Some shapes, especially spheres, may be held in place only by dense packing. Other shapes require an external framework, or they may be held apart by spacers that are molded into the capsules.

Ice capsules are the simplest form of ice storage. The tank can be of any type that has the appropriate volume and shape. Common materials are concrete, steel, and fiberglass. Tank design is fairly simple, because the ice capsules float freely in the tank, requiring no supporting structures.

Ice capsule systems are immune to overcharging problems. They are relatively foolproof, simple to install and control, and relatively inexpensive. Their particular failure modes, ruptured capsules and leaking tanks, are non-catastrophic and fairly easy to repair. Ice capsule systems have not received as much attention as they deserve, perhaps because their price is too low to finance advertising and technical support.

The storage unit is completely independent of the chiller. This makes it simple to operate the chiller separately from the ice storage unit, at normal chilled water temperatures. The chiller can also operate in parallel with the ice storage unit. The chillers are conventional, except that the evaporator temperature is selected for efficient freezing.

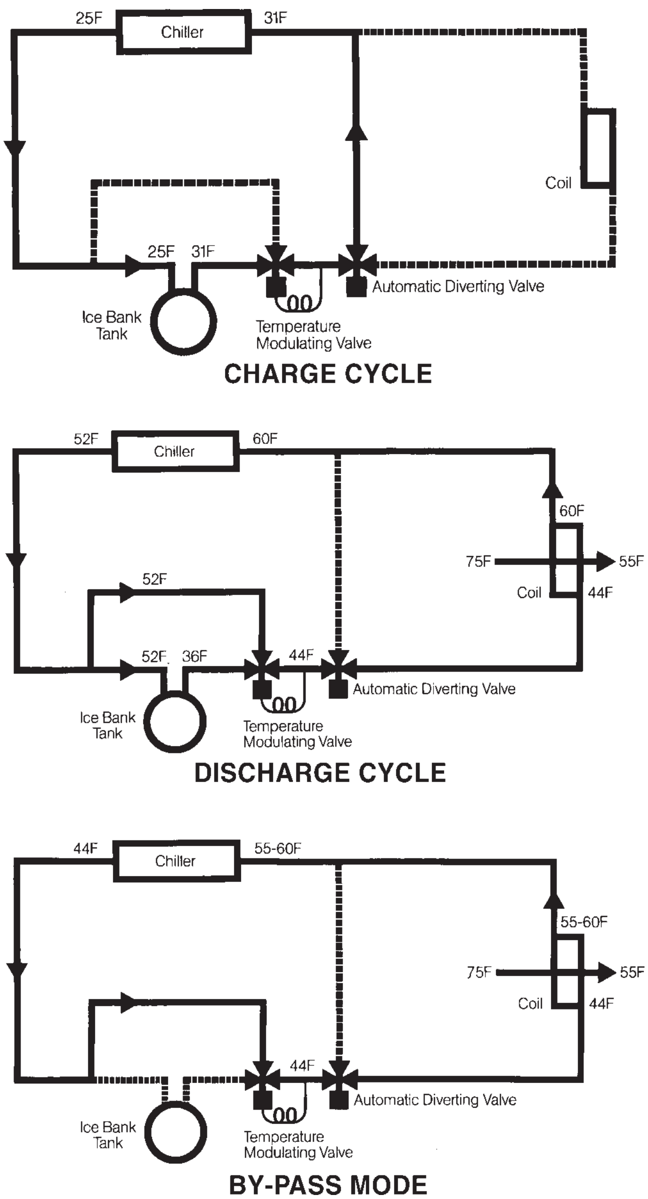


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**Fig. 12 Coil-melt cooling storage system operating modes**

### ■ Discharge Characteristics

The surface temperature of each ice capsule remains near freezing until the ice melts completely, because the small volume of water inside each capsule stays in equilibrium with the remaining ice. As a result, the discharge temperature remains almost constant until some of the capsules thaw completely. Beyond that point, the discharge temperature rises rapidly.

To preserve full cooling capacity at the end of the discharge cycle, design the flow of glycol in the tank so that all the ice capsules melt evenly. During the discharge cycle, the first capsules to encounter the warm entering glycol are melted most rapidly. One solution is to install a pipe network that distributes entering glycol over all the ice capsules evenly. This requires a lot of pipe, takes up space, and complicates installation. Another solution is to oversize the storage tank for the load. Such steps may be unnecessary if chilled water is used by the facility at normal temperatures, and if the cooling load tapers off at the end of the cooling period.

### ■ Freezing Problems Inside the Capsules

Ice capsules have an odd problem that occurs at the beginning of the freezing cycle. If water is kept still and cooled slowly, it will cool to well below 32°F (0°C) before it starts to freeze. These conditions occur inside the sealed ice capsules. Therefore, the capsules must be cooled to about 25°F (-4°C) to be sure of freezing. Once freezing starts, the first ice triggers freezing of the rest of the water at normal freezing temperature.

Any residual ice inside a capsule prevents subcooling. However, this effect is not helpful. If some capsules are completely thawed at the beginning of the next charging cycle, and some are not, this only aggravates the problem of unequal freezing.

Ice capsules that are purchased with the water permanently sealed should contain an agent that stimulates freezing. If capsules are filled on site, add an appropriate agent for this purpose.

If the glycol temperature distribution in the tank is irregular, some of the capsules may never be cooled enough to freeze. To get a full cooling charge, you may have to operate the chiller at below-normal for a short time at the end of the charging cycle.

## Stored Ice Slurry Systems

The stored ice slurry system is one of the newest entries in the cooling storage market. Figure 15 shows a diagram of this type of system. It has several unusual features

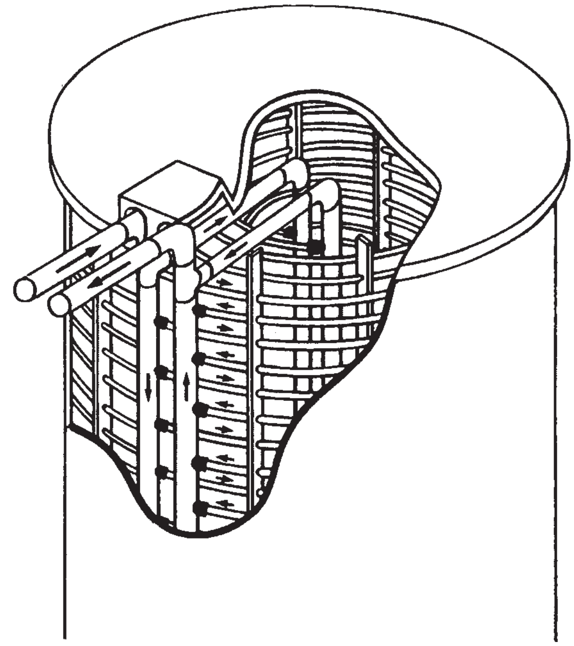
One distinguishing feature of the system is a special evaporator that allows water to be frozen while combined with a carrier liquid. The carrier liquid is usually propylene glycol. The solution of water and glycol flows by gravity down a tall evaporator surface. The surface is agitated aggressively by a mechanical scraper, so that the water freezes in the form of microscopic crystals, forming a slurry with the glycol.

In one version of the system, the slurry is pumped to an insulated storage tank. The ice-bearing slurry floats to the top of the tank, leaving a solution of glycol and water at the bottom of the tank. Usually, the solution at the bottom of the tank is pumped to the application. The returning warmed liquid is sprayed over the slurry at the tope of the tank.

Another version of the system pumps the slurry itself to the application. This can be a very efficient method of transporting cooling, because the ice crystals in the slurry have a high cooling energy content in the form of latent heat of freezing.

The stored slurry system should offer a high discharge rate because the ice crystals have a large surface area.

The system usually employs a heat exchanger. This isolates the glycol mixture, which has a poor heat



*Calmac Manufacturing Corporation*

**Fig. 13 Coil-melt cooling storage unit** The tank is full of water, which does not circulate. The water is frozen by circulating glycol from a chiller to coils within the tank. Stored cooling is extracted from the ice by the same glycol, which is now connected to the chilled water system.

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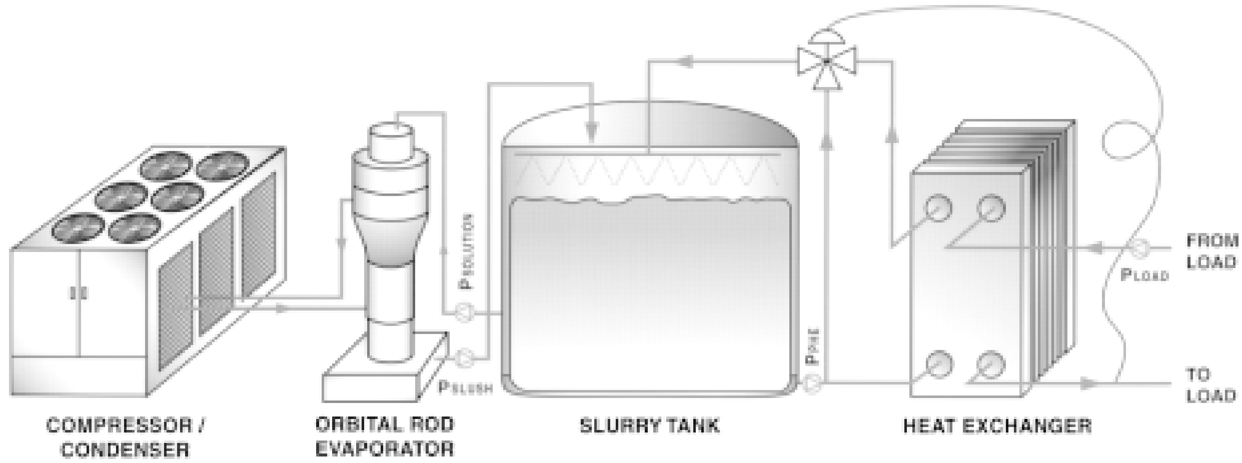
**Fig. 14 A large modular coil-melt cooling storage system** The storage units are installed on grade, outside the low mechanical equipment building. The system serves the large domed building in the rear.




*Paul Mueller Company*

**Fig. 15 Stored ice slurry system** A slurry of ice in glycol is formed in the evaporator. The slurry is pumped to the storage tank. In this version of the system, a mixture of glycol and water settles out of the bottom of the slurry. This liquid is pumped to a heat exchanger to cool the chilled water system. The return liquid is sprayed over the slurry to cool it. In a different version of the system, the slurry itself is pumped to the cooling application.

transfer characteristics, from the pure water of the chilled water system. However, there are applications that do not need a heat exchanger.

The chiller, the evaporator, and the storage tank are independent of each other, except for pipe connections. This provides a great deal of flexibility in physical layout. The tank can be any shape or size, within broad limits, but it does require specialized design. The warm returning solution is sprayed uniformly over the top of the slurry mass in the tank. This is necessary to prevent channeling of flow.

Freezing the water on the surface of the evaporator avoids the heat transfer loss that occurs in ice storage systems that freeze water with glycol. However, mixing of the water with the carrier liquid reduces the freezing temperature. Also, the various circulation pumps require energy.

The big question about stored slurry systems is their actual performance. They have only recently arrived on the market. As with any equipment that is supposed to last for decades, performance can be judged fairly only after years of operation in actual applications.

## Separated Ice Slurry Systems

An older type of ice slurry system freezes ice in large flakes. Water that is mixed with a carrier liquid flows by gravity down a tall plate evaporator. Ice freezes out of the stream, but does not stick to the evaporator because it is carried along in the other liquid. The ice forms a slurry with the water, which is pumped to a

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**Fig. 16 Separated ice slurry cooling storage system** The system provides air conditioning for an elementary school. The storage equipment is surrounded by the brick enclosure in the foreground.

collecting bin. In the bin, the glycol falls free of the ice, which forms in a mass similar to a pile of snow. The separated glycol is then mixed with melt water to repeat the freezing process.

(Because water is combined with another liquid for freezing, slurry systems are sometimes called "binary" systems.)

The evaporator in a separated slurry system is much taller than the evaporator in a stored slurry system. The evaporator plate and ice collector is typically several stories high. This is necessary to allow the large flakes of ice to form. The ice bin also tends to be tall, because this is an efficient configuration for storing the ice, separating the glycol, and circulating chilled water through the ice.

Separated slurry systems are the most complex type of cooling storage, in terms of the number of large components and the complexity of piping. Figures 16, 17, and 18 show an ice slurry system used for air conditioning an elementary school in Florida.

The efficiency of a separated slurry system is probably better than the average for ice storage systems. Heat transfer on the evaporator is good, but mixing of the water with the carrier liquid reduces the freezing temperature. Distributing the chilled water efficiently with the ice mass is a challenge. Also, the additional pumps and conveyors require energy.

The system may not need a heat exchanger. If there is no heat exchanger, a certain amount of the carrier liquid will be carried along into the cooling distribution system.

The complexity of ice slurry systems outweighs their advantages in most applications. Initial cost is high. Slurry systems were never popular, and it seems that their niche in cooling storage is becoming narrower. Consider them for larger applications where the cost of custom fabrication is less of an economic penalty.

The original motivation for slurry systems was to freeze ice in such a way that it can be separated from the evaporator without a defrost cycle. In this regard, separated ice slurry systems can be considered a variation on ice shedder systems.

## Liquid Chilled Water Storage

When electric utilities first started promoting commercial-scale cooling storage during the early 1980's, most designers envisioned storing the chilled water itself in large tanks. This method is conceptually simple. It also has a fundamental efficiency advantage over ice storage, namely, it does not require the chillers to operate at the low evaporator temperatures needed to freeze ice.

The storage tank is independent of the chillers, making it possible for the two to operate in parallel or separately. The connections between the chiller, the storage units, and the chilled water system are relatively simple.

However, after a few years of analysis and experience, including some successful installations, it became clear that the enormous volume required to store water as a liquid is a serious economic disadvantage and a physical obstacle. The minimum temperature of liquid water is 32°F (0°C), and avoiding freezing in heat transfer forces the minimum temperature to be a few degrees warmer than this. In most HVAC applications, the chilled water is warmed to a temperature no higher than about 50°F (10°C). As a result, the cooling storage capacity of water is limited to about 15 BTU's per pound. This translates to about 100 gallons per ton-hour, an enormous amount of weight and volume that is difficult or impossible to accommodate in the layout of most facilities. Furthermore, the large surface area increases conduction losses.

In general, chilled water storage is not the best method of cooling storage unless storage is cheap or the storage volume is very large. Proponents of chilled water storage often pin their hopes on the availability of a large fire protection storage tank. Figure 19 shows

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**Fig. 17 Separated ice slurry system equipment** The tall tower in the center is the evaporator. The ice storage tank is on the right. The chiller condensing unit is on the left.

a chilled water storage tank that also serves as a storage tank for fire protection.

Economy of scale benefits chilled water storage more than it benefits ice storage (except for ice capsule systems, which also have large economy of scale). The main reason is that tanks comprise most of the extra cost of chilled water storage, and the cost of the tanks per unit volume drops sharply with size. Also, relative heat loss drops substantially with larger tanks. Thus, chilled water storage may emerge as the best choice in very large applications.

### ■ Compatibility with the Chilled Water System

To achieve maximum storage capacity, the chilled water in the storage tanks is kept at the lowest possible temperature. This is lower than the usual chilled water supply temperature for HVAC applications, which is 42°F (6°C) or higher. Solving this problem is easy. Supply water from the storage tank is mixed with return water to produce the desired supply temperature.

A more critical problem is maintaining the highest possible chilled water return temperature. If the chilled water returns while it is still relatively cool, its remaining cooling energy will probably be unavailable for the remainder of the cooling cycle. This is because the water will be too warm to satisfy the cooling load if it is sent back through the chilled water system. If chilled water is wasted in this way, storage may be depleted before the end of the cooling cycle.

Keeping the return water temperature as high as possible requires special design of the user systems. The application equipment, typically cooling coils, should have throttling control valves, rather than bypass valves. The coils or other devices should be designed to maximize the temperature rise of the chilled water. Expect to use variable-flow chilled water distribution. This adds cost, but it also improves pumping efficiency, a valuable energy conservation measure in itself. (See Measure 2.5.2 for details.)

To keep the supply chilled water as cold as possible until the end of the storage cycle, the storage unit must keep the return water from mixing with the supply water. Any mixing dilutes the chilled water in the tank and poisons the ability of the storage unit to provide full cooling capacity. The need to separate the return chilled water somewhat increases the already huge volume requirement, and complicates the storage design. There are several methods of storing chilled water in a way that separates the return and supply water. Each of these methods, which are described next, has significant drawbacks.

### ■ Storage Using Multiple Tanks

One way of keep the supply water separate from the return water is to use a number of separate tanks. For example, use four tanks of equal size, three of which hold the initial charge of chilled water, while the fourth is empty. As chilled water is drawn from the first tank, return water is drained into the fourth tank. When the first tank is emptied, it becomes the return tank for the second tank, and so forth.

This method provides absolute segregation of supply and return water, which is especially valuable if chilled

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**Fig. 18 Separated slurry system ice storage tank** The returning chilled water is sprayed into the ice tank for cooling. The irregularity of the ice pile suggests that water distribution is less than ideal.

water is stored for longer periods, say, longer than one daily cycle. On the other hand, this method has several drawbacks. It requires extra volume. It increases tank cost per unit volume. The tanks have more surface for conductive heat loss. And, the piping and valve arrangements are somewhat complex.

### ■ Storage Tanks with Siphon Baffles

To avoid the disadvantages of multiple tanks, a single large tank may be divided into a labyrinth by partitions that form a series of siphon loops. Water is taken out of one end of the tank and is returned at the other end. At the point where the head of the return water stream contacts the tail of the chilled water stream, the area of contact is reduced by the baffles. Mixing is resisted by the difference in density of the supply and return water, especially in the downward flowing legs of the siphon loops.

Unfortunately, labyrinth tanks do not work as well in practice as it seems they should. The return water tends to overrun the chilled water, especially in the upward legs of the siphon loops. Also, the uninsulated steel baffles conduct heat from the return water to the chilled water. Experience teaches that a labyrinth tank should not be used unless its exact configuration has been tested and proven satisfactory.

### ■ Storage Tanks Using Stratification

"Stratification" is another method of keeping return water separate from the supply water. It allows water to be stored in a single large tank by exploiting the density differences of water at different temperatures. Water that is less dense floats on top of water that is denser. Cold water at supply temperature enters or leaves from the bottom of the tank, while return water enters or leaves from the top of the tank.

Water must enter and leave the tank gently, because the tendency to stratify is weak. The density difference between water at 39°F (4°C) and 50°F (10°C) is only about 0.03 percent. Therefore, the tank needs extensive diffuser trees in the top and bottom to reduce velocity and to control the flow direction.

The major disadvantage of stratified storage is its inability to separate supply and return water as the temperature approaches the point of maximum water density. The density of water is greatest at 39.2°F (4.0°C). If water is either warmer or cooler than this, it becomes lighter. If water colder than 39°F is pumped into the tank, it will float upward to mix with the water warmer than 39°F, destroying the stratification. Since a stratified tank cannot store chilled water below about 40°F, it needs more volume to compensate for the unusable temperature band.

There is much misunderstanding of this behavior, including a superstition that chilled water cannot be stored below 39°F. This is true only of tanks using stratification to separate the return and supply water. The other storage methods allow water to be stored at any temperature down to freezing.

Stratified storage has the advantage that the chillers operate at higher evaporator temperature, which increases COP. Also, using a single large tank has the advantage of minimizing the surface area for conductive heat loss.

An important efficiency drawback is that heat flows between the supply and return water by conduction within the tank. Any stratified tank has a region where the return water and supply water are of mixed temperature. This region, called the "thermocline," is typically several feet thick, regardless of tank shape. It

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**Fig. 19 Chilled water storage** This system provides air conditioning for a Florida prison. The huge tank was originally designed to hold water for fire protection. It functions well in both roles.

represents wasted cooling by the chiller, and it requires even more storage volume. You can minimize the thermocline problem by selecting a tank that is tall in relation to its diameter. For a system of any size, such a tank will be very tall.

You can achieve positive separation of the supply and return water within a single tank by using a moving diaphragm inside the tank. At the beginning of the discharge cycle, all the water is on one side of the diaphragm. As water returns, it enters on the other side of the diaphragm. The diaphragm itself adds some complexity, but it also eliminates the need for elaborate diffusers at each end of the tank. So far, this method has not become popular, perhaps because present diaphragm designs lack long-term reliability. Also, present diaphragm designs conduct heat from the return water to the supply water.

With stratified storage, the chillers operate at about the same temperature as they do when generating chilled water directly. Therefore, it is not necessary to make substantial efficiency compromises when selecting the chiller. For the same reason, stratified storage is usually compatible with existing chillers, except perhaps absorption units. With other types of chilled water storage, existing centrifugal chillers may seriously lose efficiency and capacity if chilled water is produced near freezing temperature. However, if charging is always done at night, the lower condensing temperature may avoid this problem.

#### ■ How to Measure the Charge

With any of the previous types of storage, you can measure the amount of chilled water remaining in the tank fairly accurately. The usual method is installing a series of temperature sensors along the path of water flow in the storage unit. Systems with multiple tanks also need level sensors in each tank.

#### ■ Combining Thermal Storage with Chiller Heat Recovery Storage

Chilled water storage offers the possibility of using the same tanks, at different times, for both chilled water storage and for storage of heat recovered from air conditioning condensers. This possibility becomes more attractive if the system has several storage tanks. For example, consider a system with four tanks. During hot weather, all four could be used for cooling storage. During cold weather, all four could be used for heating storage. During spring and fall, one or two of the tanks could be used for one purpose, and the rest used for the other purpose. See Measure 2.10.5 for storage of heat recovered from chillers.

### Eutectic Storage Media

Eutectic cooling storage seeks to combine the efficiency advantage of chilled water storage with the compactness of ice storage. The main efficiency disadvantage of ice storage is that ice freezes at a temperature that is lower than necessary for most cooling applications, forcing ice storage chillers to operate at low evaporating temperatures. The desire to overcome this limitation has led to a search for materials that change in phase at a more desirable temperature. Such materials are called "eutectic." (This word is based on Greek words that mean, approximately, "good freezing.")

Ironically, the present eutectic alternatives to ice have phase change temperatures that are too high for optimum system performance.

#### ■ Eutectic Materials to Date

Up to now, the best results for cooling storage have been obtained with hydrated salts, in which heat is absorbed in separating water molecules from salt molecules, a reaction that occurs at a fairly distinct temperature. (This is not a "phase change," strictly speaking, but the term is used.) The material has a phase change temperature averaging about 47°F (8°C).

Formulations of salts with other melting temperatures are being tried. Unfortunately, the phase change in hydrated salts involves substantially less heat than the melting of ice. Commercial eutectic salt storage units require somewhat more than twice the volume of ice units. This is somewhat less than half the volume of chilled water storage.

Changes in the structure of organic polymers, especially the melting of waxes, have also been investigated, but these have relatively low heat storage potential. These materials also suffer from loss of storage capacity with cycling. The melting temperature may be different from the freezing temperature.

Other exotic materials have been investigated, such as clathrates, where the heat is given off when molecules of one type enter voids in the crystal lattice of a different type of material.

Eutectics are an evolving area. Newer materials may someday improve upon the shortcomings of the present materials. A phase change temperature in the range of 38°F to 42°F (3°C to 5°C) would be ideal. Even with this property, eutectic materials would need to increase their volumetric heat capacity by at least a factor of two to make them superior to ice in most applications.

#### ■ Tank Configuration

Storage units using eutectic salt solutions are similar to those using ice capsules. Sealed containers of the eutectic material are stacked in a tank, and water is circulated through the tank. One major advantage is that glycol is not necessary, since water can be circulated through the tank without freezing.

The design of the storage unit is simplified by the fact that eutectic materials are heavier than water, so they do not tend to move around the tank by flotation. Also, eutectic materials do not change volume appreciably with the phase change, so there is no stress on the containers.

The lack of volume change makes it impossible to measure the charge by measuring the system water volume. So far, nobody has developed a reliable method of directly measuring the cooling charge in a eutectic system.

### ■ Dealing with the High Phase Change Temperature

The freezing temperature of present eutectic systems is too high to provide chilled water at normal temperatures. In addition, present eutectic materials do not maintain their low temperature throughout the discharge cycle, so the chilled water temperature may exceed 50°F (10°C) toward the end of the discharge cycle. Chilled water systems designed for conventional temperatures will not be able to provide full cooling capacity at these higher temperatures. If a system is designed to operate with the warmer chilled water, it may not be able to provide adequate dehumidification.

A eutectic system can be used for pre-cooling return chilled water in conventional chilled water systems, providing about half the cooling load, while the chiller further reduces the chilled water system. This may be satisfactory in some applications where only a partial reduction of the peak cooling load is required to satisfy the purposes of the system.

Present eutectic systems cannot use heat exchangers, because the temperature rise in heat transfer would worsen the problem of high chilled water temperature. Since eutectic storage cools the chilled water directly, the system does not need a heat exchanger unless there is excessive static pressure in the chilled water system. System pressure can be handled in a variety of ways that are suggested below.

### ■ Unusual Opportunities

Eutectic storage at these high temperatures offers several possibilities that are not available with other methods of cooling storage. One is operation with conventional absorption chillers. Another possibility is storing “free cooling” from the operation of cooling towers alone (see Measures 2.9.2 and 2.9.3). This can be done when the outside air temperature is below the phase change temperature.

## GENERAL DESIGN ISSUES

The previous discussion outlined the steps needed to put a storage cooling system into operation, and gave a comparative overview of the types of storage cooling technology that are available. We will now examine in greater detail several important engineering aspects of installing the system. These apply to most types of systems.

## How to Deal with Chilled Water System Pressure

The height of a chilled water system causes hydrostatic pressure. Unlike chillers, most cooling storage units are not capable of resisting this pressure. Furthermore, most storage units are vented to the atmosphere. If they were directly connected to the chilled water system, portions of the system higher than the tank would overflow the tanks when the pumps are turned off. The following are methods of dealing with the static pressure of the distribution system.

### ■ Use a Heat Exchanger

The simplest method of isolating distribution system pressure is to use a heat exchanger. This method works well with ice storage systems that are designed to provide chilled water at normal temperatures. The low storage temperature easily makes up for the temperature drop in the heat exchanger. On the other hand, if an ice storage temperature is designed for low-temperature chilled water distribution, a heat exchanger would limit the minimum distribution temperature.

Heat exchangers are undesirable with chilled water storage, because their temperature loss would seriously reduce the effective storage capacity. By the same token, heat exchangers cannot be used with contemporary eutectic storage, which stores water at temperatures that are already higher than conventional chilled water temperature.

### ■ Elevate the Storage Unit

You can avoid the need for pressure isolation in open storage units by making the water level in the storage unit as high as the top of the distribution system. However, the enormous weight of water or ice is an obstacle to installing the storage unit high in the building structure. In existing facilities, it may be impractical to add sufficient structural support. In new construction, it may be easy to modify the structural design to provide adequate support. In fact, some huge ice storage systems have been installed in buildings above the level of the chillers, at the cost of heavily reinforced structures.

The weight of a storage system can be distributed to different parts of the structure by using a number of smaller storage modules. This practice is becoming common, especially for larger systems.

Chilled water storage is four to six times heavier than ice storage, making it generally impractical to install on the building structure. An exception is using fire protection tanks as storage units. These probably will not be large enough for a full-capacity storage system, but they may serve as valuable mini-storage units to reduce chiller size and reduce peak electricity costs.

### ■ Use a Backpressure Valve and Check Valves

Another approach is to install a backpressure valve at the bottom of the chilled water return leg. The valve is set to maintain a pressure somewhat higher than the hydrostatic pressure in the system. When the chilled water distribution pump turns off, the backpressure valve closes completely, trapping the water in the return leg.

Similarly, a check valve is used at the bottom of the supply leg to prevent water from draining out of the supply leg when the pump turns off.

Both backpressure valves and check valves tend to be leaky. One solution is to add a small pump to return any leaked water from the storage unit to the chilled water system. Another is to install automatic tightly closing valves to augment the backpressure and check valves when the pump turns off.

A backpressure valve may greatly increase the energy needed for pumping chilled water. In a closed system, the hydrostatic pressure in the return leg balances the hydrostatic pressure in the supply leg, so gravity plays no role in the pump power. However, using a backpressure valve effectively adds a gravity load that is equivalent to pumping all the water in the system to a height that corresponds to the pressure setting of the backpressure valve. Then, all the pumping energy is converted to heat in the return water, increasing the chiller load. This energy penalty will be imposed whether cooling is being provided from storage or by the chillers directly. In a tall building, a backpressure valve may cause pumping to absorb a large fraction of the energy consumption of the chilled water system.

#### ■ Use a Pressurized Storage Unit

In principle, most types of cooling storage could be installed in closed tanks directly connected to the chilled water system. Expansion of ice would be accommodated by the expansion tank in the chilled water system.

The practical limitation is tank weight and cost. The wall thickness that a tank needs to withstand a given pressure is directly proportional to the tank diameter. Cooling storage tanks are large, so designing them to withstand pressure would require extreme thicknesses. In the United States, any vessel holding 15 PSI of pressure requires ASME pressure vessel certification, which further increases cost. This amount of hydrostatic pressure is produced by a height of merely three stories. Furthermore, tanks require access for inspection and maintenance. Large access panels are difficult to create and seal in pressurized tanks.

Coil-melt ice storage systems are a significant exception. In these systems, only the interior of the coils are subjected to system pressure. The coil diameters are small, so they can easily withstand large pressures. However, this is usually a moot point. The coils in coil-melt systems are filled with glycol. To avoid the need to fill the entire distribution system with glycol, it is common to use a heat exchanger with coil-melt systems. This by itself isolates the storage unit from system pressure.

Pressurized vessels cannot be used ice shedders, slurry systems, and multi-tank chilled water systems, because these types must be open to the atmosphere.

### Chilled Water Supply and Return Temperature

Some cooling storage systems impose severe restrictions on chilled water supply and/or return temperatures. Using these types of storage systems requires you to modify the equipment that uses chilled water. Other types of storage systems impose no restrictions. The following are the major cases.

#### ■ Ice Storage with Normal Chilled Water Temperatures

The simplest situation is using an ice storage system to provide chilled water to the facility at conventional chilled water temperatures. In this case, no change to the distribution system or user equipment is needed.

Using the chilled water at storage temperature would waste energy by excessive dehumidification, and might cause control instability at low cooling loads. To avoid these problems, control the chilled water supply temperature by using a mixing valve to dilute the cold water from the ice tank with return water.

#### ■ Ice Storage with Minimum Chilled Water Temperatures

In attempting to salvage some benefit from the unnecessarily cold chilled water produced by ice storage systems, user systems are being developed that exploit the lower chilled water temperatures, especially in new construction. Colder chilled water carries more cooling energy, so pipes and pumps can be reduced in size, and the pump energy can be reduced correspondingly.

Where the low-temperature chilled water is used for air conditioning, air can be made colder. This can reduce the size of ducts, enclosures, and fans, and can reduce fan power consumption. These advantages have captured the attention of many designers. However, enthusiastic designers should be cautious of these potential problems of low-temperature air distribution:

- ***cold air dumping.*** Cold air "dumps" from overhead diffusers, causing serious localized discomfort. Overcoming this problem requires new types of diffusers that mix supply air with room air. It remains to be seen whether such diffusers will be satisfactory, especially in VAV applications. Terminal units with mixing fans may be required, adding cost, noise, and energy consumption.
- ***duct sweating,*** which may damage ducts, insulation, ceiling surfaces, and other equipment.
- ***excessive dehumidification.*** The low coil temperature increases dehumidification, which increases energy expenditure. Below normal air distribution temperature, the additional dehumidification usually does not improve comfort, and it may be an irritant.

Low-temperature air distribution is likely to provide more headaches than benefit, at least for the near future. This is a new area of comfort engineering, and it is likely that lessons will be learned at the cost of expensive mistakes.

Low-temperature distribution marries the facility systems to the low evaporator temperatures required for ice storage. This may be an unwise commitment, because the low chiller efficiency may cause storage cooling, at least on a continuous basis, to be abandoned at some time in the future.

If the facility is designed to use low-temperature chilled water distribution, the ice storage system must be able to sustain low water temperature throughout the discharge cycle. Ice shedders and external-melt units are best in this regard, while internal-melt units are worst. Ice capsules suffer a serious rise in chilled water temperature in the second half of the discharge cycle.

#### ■ Maximizing Efficiency with Liquid Chilled Water Storage

Refer to the description of liquid chilled water storage in the previous summary. The main design challenge is that you have to maximize the temperature differential between supply and return chilled water in order to preserve the cooling capacity of the storage unit. As explained previously, the way to do this is to use variable-flow chilled water pumping. In retrofit, this may require major modifications of the cooling equipment, including coils, control valves, and pumps.

#### ■ Eutectic Storage with High Chilled Water Temperatures

Present eutectic storage systems produce chilled water that is warmer than normal. If the chilled water from the storage unit is not cold enough to satisfy the cooling load, it can be cooled further by a chiller before being distributed to the facility. This method is a hybrid of direct and storage cooling.

In any event, the return water temperature must remain high enough so that melting of the eutectic material does a large fraction of the cooling. Using variable-flow chilled water pumping and 2-way throttling valves on the coils helps to maximize the return temperature.

### Keep Charging Separate from Direct Cooling

Chiller COP falls along with evaporator temperature, so operate the chillers at low evaporator temperature only for charging the storage unit. Try to operate the chiller separately, at the highest possible evaporator, for direct cooling. In other words, avoid using the same chiller for both storage charging and direct cooling simultaneously.

In principle, any kind of cooling storage system can be designed to allow the chiller to switch between charging and direct cooling. This is easier with some types of systems than with others. It is easiest with a liquid chilled water storage system. It is also fairly easy if the chiller cools a glycol solution. The glycol solution can be sent either to the cooling storage unit or to a heat exchanger for direct cooling.

Using a heat exchanger forces the chiller to operate with lower evaporator temperature. In principle, the chiller could switch between chilling glycol (for ice freezing) and chilling water (for direct cooling), but the complications would not be justified by the reduced temperature loss.

There is another solution that is less conventional, but more efficient: add a second evaporator to cool the chilling water directly. The two evaporators cannot operate at the same time, because the evaporator temperatures are different. This solution may be fairly simple if the chiller system is designed for a separate evaporator, as with a liquid overfeed system. It may be difficult to accomplish with some packaged chillers. In any event, this is a job for someone who knows how to design unconventional chiller systems.

#### ■ Separate Chillers for Storage and Direct Cooling

With any type of storage, a chiller that is optimized for one evaporator temperature is less than optimum at any other temperature. This is especially true of centrifugal chillers. Screw compressors with variable discharge ports can maximize their COP's at different evaporator temperatures. Reciprocating chillers are fairly tolerant of changes of evaporator temperature.

From the standpoint of efficiency alone, it would be desirable to install separate chillers for direct cooling and for charging the storage unit. However, this is generally not economical if it leads to duplication of equipment cost. Consider this approach if the facility has a large cooling load during the utility's off-peak periods. In this case, size one set of chillers to operate continuously during the off-peak period to charge storage, and size another set of chillers to satisfy the off-peak cooling load. For example, hospitals and hotels might benefit from this approach.

### Controls and Alarms

Cooling storage systems require specialized control. You may have to do some or all of the control design separately, even with packaged storage systems. This is because the control sequences vary with the purposes of the system, with different electricity pricing structures, and with the load characteristics of the facility. You generally need a computer or a programmable logic controller (PLC) to control cooling storage for optimum efficiency. The control functions are too complex, too variable, and too repetitive for manual operation. The following is a guide to the control and alarm functions that the system may need.

#### ■ Controlling the Amount of Storage for Each Cycle

The system controls must charge the storage unit based on the anticipated cooling requirement during the next discharge cycle. Having too little capacity will either forfeit the electricity price saving or leave the facility without cooling at the end of the day.

On the other hand, storing too much cooling wastes energy, because more energy is required to produce stored cooling than to cool the space directly. Some of the excess stored cooling is wasted between discharge cycles by conductive loss from the tank.

With some types of storage, such as ice shedders, residual ice is melted if the chiller changes to direct cooling, wasting the ice. Even if the ice storage chillers are not used for direct cooling, the storage units require periodic melting of all the ice to prevent channeling or uneven ice accumulation. Exceptions are ice capsule systems and some slurry systems.

Unfortunately, the control system cannot predict the storage load for the next cycle accurately, because of changes in weather and internal loads. If the system wastes much energy as a result of leftover cooling storage, be ready to make manual control adjustments when a weather system is approaching or other changes in the load are foreseeable. Manual adjustment is an unreliable mode of operation in the long term, so try to avoid a system design that requires it.

### ■ Time Control to Conform to Electricity Rate Schedules

Electricity prices are usually related to the time of purchase. For example, the utility may charge its highest demand rate between the hours of noon and 8 PM. There may be a lower demand rate that applies for several hours before and after these times, respectively. Design the controls to limit chiller operation to the times of lowest electricity cost.

Optimum scheduling depends on the electricity rates for each period, the existence of ratchet provisions in the rates, the cooling load, the storage capacity, etc. Operate the storage system only at times when electricity costs are low enough to offset its efficiency disadvantage. The exception is when storage capacity is needed to augment chiller capacity.

### ■ Other Control to Conform to Electricity Rate Schedules

Electricity rates may not always be based on time. For example, excess-consumption charges and "hour charges" are based on consumption. Design your controls to get the most benefit from these rates, which involves measuring the total facility load. Some rates make it difficult to achieve optimum control. Expect to use a computer that you can program to follow changes in rates and rate schedules.

### ■ Facility Demand Limiting While Cooling Directly

If the electric utility's demand charge is an important cost factor, balance direct cooling with cooling from the storage system to keep demand below a target level. If the non-cooling electrical load varies during the demand period, as illustrated in Figure 2, this load usually determines the peak demand setting. A higher demand level is necessary if the storage capacity is not large enough to carry the entire cooling load. The arrangement of electric metering is a factor to consider, because different metering arrangements result in different total demand charges, as explained previously.

If the non-cooling load is unpredictable, limit chiller operation based on a conservative estimate of the non-cooling load. If the non-cooling load rises above this level, creating a higher demand charge for the period, raise the chiller load limit accordingly. Reduce the charging of the storage unit by a corresponding amount. Start all over again at the beginning of the next demand measurement period.

### ■ Time Control to Minimize Condensing Temperature

The controls should exploit the fact that condensing temperature has a major effect on chiller efficiency. Unless a weather system is moving through the area, the outside temperature drops continuously throughout the night. Therefore, charge the storage units as late as possible without running into a period of higher electricity rates. This control feature applies only to chillers that are able to exploit low ambient condensing temperatures.

### ■ Time Control to Reduce Storage Losses

The storage tank loses heat by conduction, so recharge it as late as possible. Charging at night provides an additional bonus of lower condensing temperature. If the storage tank is well insulated, small differences in the time of charging will not make much difference.

### ■ Control of Evaporator Temperature When Charging Storage

To save energy in charging, keep the evaporator temperature as high as possible. This requires control to correlate the evaporator temperature to the percentage of charge. An easy way to achieve this is to keep the compressor load constant throughout the charging period. With most types of storage units, this slows the rate of charging as the charge increases. Exceptions are ice shedders and some ice slurry systems, in which the charging rate is constant.

Increasing the evaporator temperature during charging lengthens the charging time. Therefore, coordinate this control function with the control function that determines the starting time for charging.

### ■ Maintaining Efficient Chiller Loading During Charging

The efficiency of a chiller may vary substantially with load. Set the chiller load during charging for maximum efficiency, whenever possible. The effect of loading on efficiency for different types of chillers is covered by Reference Note 32, Compression Cooling.

Depending on the type of chiller, this control consideration may conflict with minimizing the evaporator temperature differential during charging. This is because the temperature differential increases with load.

**■ Distributing the Load Among Chillers**

See Measures 2.1.1 ff for the most efficient ways to distribute load among chillers. The storage system controls should determine which chillers serve the cooling load directly and which chillers charge the storage unit. If more than one chiller is used for charging storage, or if more than one chiller is used for direct cooling, try to use the same controller that distributes the load between the chillers, if there is one.

**■ Safety Control to Prevent Overcharging**

Install an independent override control to prevent overcharging. Overcharging may burst the tank with some types of ice storage. Also, energy is wasted in making more ice than the storage unit's design capacity. This control is a safety device, so it should be entirely independent of the operating controls. It should have a separate sensor that is triggered when the tank's ice capacity is exceeded.

**■ Alarms**

Install an alarm for each critical control function. For example, if a tank is not accumulating ice when it should be, an alarm should indicate this as early as possible, to avoid exceeding the demand limit during the next discharge cycle.

There should also be alarms for casualty conditions that are not related to controls. For example, open tanks should have high and low level alarms. The system should have all the conventional refrigeration alarms, such as high and low head pressure.

Alarms should be independent of the control system, and they should have their own sensors. Otherwise, a failure of the control system may disable the alarm. For example, the timing of chiller operation with respect to demand periods should be monitored by an independent alarm having its own clock.

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## ECONOMICS

***SAVINGS POTENTIAL:*** *Cooling storage provides cost savings, not energy savings. The savings vary widely with circumstances, depending mostly on the pricing policies of electric utilities and your ability to negotiate with the utility. The cost savings provided over the life of the system are much less predictable than with most energy conservation measures.*

***COST:*** *Coil-type thermal storage units and large chilled water storage tanks cost from $50 to $100 per ton-hour of storage, depending on size and type. This cost does not include the chillers themselves, piping connections, or controls. Heat exchangers, if needed, cost from $100 to $200 per ton of heat exchanger capacity. The evaporator assemblies of ice harvester systems cost from $500 to $700 per ton of capacity, not including the compressors, insulated storage tank, piping, and pumps. Ice slurry evaporators cost from $300 per ton in large sizes, to $800 per ton in small sizes. At the present time, many electric utilities will defray part of the system cost.*

***PAYBACK PERIOD:*** *Several years, to much longer.*

## TRAPS & TRICKS

***MOTIVES:*** *One of the reasons that cooling storage units have a poor performance record is that they are installed as toys. When the charm wears off, the toy is abandoned. Before you install one of these big, expensive systems, make sure that you are ready to live with its operating and maintenance requirements. Understand that thermal storage exists for the benefit of the utility, and that you will benefit only to the extent that the utility provides a rate subsidy or other incentive for operating the system. Utility representatives will give you an optimistic pitch about this, but probably will not offer to provide a rate guarantee for a period that is long enough to protect your investment. You must learn enough about utility issues to judge whether a thermal storage installation is likely to be profitable in the long term. In particular, consider the effect of utility deregulation. Also, monitor the development of electric vehicles, which may abolish utility interest in thermal storage.*

***DESIGN:*** *Designing an optimum thermal storage system involves a broad range of subjects, some of which are outside the realm of conventional HVAC design. A single detail that you overlook can cripple your system. Don't take the building design off on tangents to accommodate the storage system. In particular, be skeptical about low-temperature chilled water and air distribution.*

***SELECTING THE EQUIPMENT:*** *Thermal storage equipment is still evolving, and performance is spotty. Favor equipment that has been in operation long enough to demonstrate good reliability. Shop the market thoroughly. Check with other users of the equipment you are considering. Remember that the equipment has to last for 20 years or longer if it is replaceable, and for the life of the facility if it is not replaceable.*

***INSTALLATION:*** *Storage systems are heavy and require a lot of space. Make sure that structural support is adequate. Install the equipment so that it will survive. For example, avoid burying steel tanks. Provide easy access to all parts of the equipment for repair and replacement.*

***ALERTNESS:*** *Maintaining a high level of skill and attention is an inherent part of operating a thermal storage system. During peak load conditions, the system must operate with total reliability to avoid losing the* *economic benefit. The system requires continuous surveillance during the peak load period. Install alarms to reveal all likely failure modes.*

***EXPLAIN IT:*** *The logic of the system can be confusing to the operators. Put up a well designed system diagram that explains how the system works, identifies its components, and spells out operating procedures. Install placards on all parts of the system that require action or inspection.*

***MONITOR OPERATING EFFICIENCY:*** *Make a continuous record of the charge status of the storage units and the loads on the chillers. Check the record often to make sure that the amount of energy stored is not too much or too little for the facility cooling load. Schedule periodic checks of controls operation.*