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Thermal Energy Storage (TES) Methods

3.1 Introduction

Energy demands in the commercial, industrial, and utility sectors vary on daily, weekly, and seasonal bases. These demands can be matched with the help of thermal energy storage (TES) systems that operate synergistically. The use of TES for thermal applications such as space and water heating, cooling, air-conditioning, and so on has recently received much attention. A variety of TES techniques have developed over the past four or five decades as industrial countries have become highly electrified. Such TES systems have an enormous potential to make the use of thermal energy equipment more effective and for facilitating large-scale energy substitutions from an economic perspective. In general, a coordinated set of actions in several sectors of the energy system is needed if the potential benefits of thermal storage are to be fully realized.

Many types of energy storage play an important role in energy conservation. In processes which yield waste energy that can be recovered, energy storage can result in savings of premium fuels.

Energy may be stored in many ways, as pointed out in Chapter 2, but since in much of the economy in many countries, energy is produced and transferred as heat, the potential for thermal energy storage warrants study in detail.

Chemically charged batteries became common in the mid-19th century to provide power for telegraphs, signal lighting, and other electrical devices. By the 1890s, central stations were providing both heating and lighting, and many did both. Electric systems were almost all direct current (dc); so, incorporating batteries was relatively easy. In 1896, Toledo inventor Homer T. Yaryan installed a thermal storage tank at one of his low-temperature hot-water district-heating plants in that city to permit the capture of excess heat when electric demand was high. Other plants used steam storage tanks, which were generally not as successful. Other forms of TES were used to power street cars in the 1890s, including compressed air and high-temperature water that was flashed into steam to drive a steam engine. Electric cars and trucks were quite common prior to World War I, after which gasoline-powered internal combustion engines became prevalent.

TES deals with the storage of energy by cooling, heating, melting, solidifying, or vaporizing a material; the thermal energy becomes available when the process is reversed.

Storage by causing a material to rise or lower in temperature is called *sensible heat storage*; its effectiveness depends on the specific heat of the storage material and, if volume is important, on its density. Storage by phase change (the transition from solid to liquid or from liquid to vapor with no change in temperature) is a mode of TES known as *latent heat storage*. Sensible storage systems commonly use rocks, ground, or water as the storage medium, and the thermal energy is stored by increasing the storage-medium temperature. Latent heat storage systems store energy in

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phase change materials (PCMs), with the thermal energy stored when the material changes phase, usually from a solid to a liquid. The specific heat of solidification/fusion or vaporization and the temperature at which the phase change occurs are of design importance. Both sensible and latent TES also may occur in the same storage material. In this chapter, TES is considered to include the storage of heat through the reversible scission or reforming of chemical bonds.

PCMs are either packaged in specialized containers such as tubes, shallow panels, plastic bags, and so on, or contained in conventional building elements (e.g., wall board and ceiling) or encapsulated as self-contained elements.

The oldest form of TES probably involves harvesting ice from lakes and rivers and storing it in well-insulated warehouses for use throughout the year for almost all tasks that mechanical refrigeration satisfies today, including preserving food, cooling drinks, and air-conditioning. The Hungarian parliament building in Budapest is still air-conditioned, with ice harvested from Lake Balaton in the winter.

TES has always been closely associated with solar installations, including both solar heating and photovoltaic applications. Today, compressed-air storage, batteries, chilled and hot water storage, ice storage, and flywheels are used, all designed to meet one or more of the purposes listed above. Many utilities provide direct incentives for energy storage applications, while time-of-day rates and high demand charges indirectly entice customers to consider these opportunities.

TES generally involves a temporary storage of high- or low-temperature thermal energy for later use. Examples of TES are storage of solar energy for overnight heating, of summer heat for winter use, of winter ice for space cooling in summer, and of heat or coolness generated electrically during off-peak hours for use during subsequent peak demand hours. Solar energy, unlike energy from fossil fuels, is not available all the time. Cooling loads, which nearly coincide with maximum levels of solar radiation, are often present after sunset. This phenomenon is largely due to the time lag between when objects are heated by solar energy and when they release the heat to the surrounding air. TES can help offset this mismatch of availability and demand.

Energy plays a major role in the economic prosperity and the technological competitiveness of a nation. Because predicting future availability, demand, and price of energy forms is at best approximate and often imprecise, it is important to have a broad array of technologies available to meet the energy needs of the future. Furthermore, the technologies developed should be those that ensure energy security, efficiency, and environmental quality for a nation. TES is one such technology, and it is being promoted because it can substantially reduce total energy consumption, thereby conserving indigenous fossil fuels and reducing costly oil imports. As technical and economic problems and risks are reduced through proven performance, TES is expected to be accepted as an attractive option in the industrial and commercial sectors that will lead to, among other benefits, increased energy efficiency and environmental benefits. TES has been identified as a method for substantially reducing peak electrical demands, thereby helping to ameliorate predicted peak-power shortages in the future. TES provides a potentially economic means of using waste heat and climatic energy resources to meet a significant portion of our growing needs for heating and cooling, especially for industrial facilities and commercial buildings. Environmental benefits also accompany the use of TES in many applications.

TES technology has been used in various forms and applications. Some of the more common applications include the use of sensible TES (oils, molten salts) or latent TES (ice, phase change material) for refrigeration and/or space heating and cooling needs. Research activities on TES are continuing at various national laboratories, universities, and research centers throughout the world, as well as at industrial facilities.

3.2 Thermal Energy

Thermal energy quantities differ in temperature. As the temperature of a substance increases, the energy content also increases. The energy required E to heat a volume V of a substance from a temperature T_1 to a temperature T_2 is given by

$$E = mC(T_2 - T_1) = \rho VC(T_2 - T_1)$$

where C is the specific heat of the substance. A given amount of energy may heat the same weight or volume of other substances, and increase the temperature to a value greater or lower than T_2. The value of C may vary from about 1 kcal/kg °C for water to 0.0001 kcal/kg °C for some materials at very low temperatures. Further information on such materials is available in Section 3.6.

The energy released by a material as its temperature is reduced, or absorbed by a material as its temperature is increased, is called the *sensible heat*.

Latent heat is associated with the changes of state or phase change of a material. For example, energy is required to convert ice to water, to change water to steam, and to melt paraffin wax. The energy required to cause these changes is called the *heat of fusion* at the melting point and the *heat of vaporization* at the boiling point. To illustrate, let us consider water, and suppose that we wish to evaporate 1 kg of ice by converting it to liquid and then heating it until it boils. In this case, 80 kcal is required to melt the ice at 0 °C to water at 0 °C; then, about 100 kcal is needed to raise the temperature of the water to 100 °C; finally, 540 kcal is needed to boil the water, giving a total energy need of 720 kcal. The sensible heat for a given temperature change varies from one material to another. The latent heat also varies significantly between different substances for a given type of phase change.

It is relatively straightforward to determine the value of the sensible heat for solids and liquids, but the situation is more complicated for gases. If a gas restricted to a certain volume is heated, both the temperature and the pressure increases. The specific heat observed in this case is called the *specific heat at constant volume*, C_v. If, instead the volume is allowed to vary and the pressure is fixed, the specific heat at constant pressure, C_p, is obtained. The ratio C_p/C_v and the fraction of the heat produced during compression can be saved, significantly affecting the storage efficiency.

3.3 Thermal Energy Storage

As an *advanced energy technology*, TES has attracted increasing interest for thermal applications such as space heating, hot water, cooling, and air-conditioning. TES systems have the potential for increasing the effective use of thermal energy equipment and for facilitating large-scale fuel switching. Of most significance, TES is useful for addressing the mismatch between the supply and demand of energy.

There are mainly two types of TES systems, sensible (e.g., water and rock) and latent (e.g., water/ice and salt hydrates). The selection of a TES system mainly depends on the storage period required, for example, diurnal or seasonal, economic viability, operating conditions, and so on. Many research and development activities on energy have concentrated on efficient energy use and energy conservation, and TES appears to be one of the more attractive thermal technologies that has been developed.

TES is basically the temporary "holding" of energy for later use. The temperature at which the energy is held in part determines the potential application. Examples of TES systems are storage of solar energy for night and weekend use, of summer heat for winter space heating, and of ice from winter for space cooling in summer. In addition, the heat or cool generated electrically during off-peak hours can be used during subsequent peak demand hours. Solar energy, unlike energy from fossil, nuclear, and some other fuels, is not available at all times. Even cooling loads, which coincide somewhat with maximum levels of solar radiation but lag by a time period, are often present after sunset. TES can provide an important mechanism to offset this mismatch between times of energy availability and demand.

Increasing societal energy demands, shortages of fossil fuels, and concerns over environmental impact are providing impetus to the development of renewable energy sources such as solar, biomass, and wind energies. Because of their intermittent nature, effective utilization of these and other energy sources is in part dependent on the availability of efficient and effective energy storage systems.

TES involves the storage of energy by heating (or cooling) or melting or vaporizing (or solidifying or liquefying) a material, or through thermochemical reactions. The energy is recovered as heat or cool when the process is reversed. Storage by causing a temperature rise is known as *sensible TES*, and by causing a phase change as *latent TES*. Thermochemical thermal storage, in which a chemical reaction that can be reversed absorbs energy, is described in detail in Chapter 2.

TES has a wide variety of applications, the majority of which relate to heating and cooling. TES provides a link and buffer between a heat source and a heat user. A common example of a TES is the solar hot water storage system. The energy source is solar radiation and the heat user is the person demanding hot water. In this situation, storage is required because the energy supply rate is small compared with the instantaneous demand, and because solar radiation is not always available when hot water is demanded.

As an example of the cost savings and increased efficiency achievable through the use of TES, consider the following case. In some climates, it is necessary to provide heating in winter and cooling in summer. Typically, these services are provided by using energy to drive heaters and air-conditioners. With TES, it is possible to store heat from the warm summer months for use in winter, while the cold ambient temperatures of winter can charge a cool store and subsequently provide cooling in summer. This is an example of seasonal storage, which can be used to help meet the energy needs caused by seasonal fluctuations in temperature. Obviously, such a scheme requires a great deal of storage capacity because of the large storage timescales. The same principle can be applied on a smaller scale to smooth out daily temperature variations. For instance, solar energy can be used to heat tiles on a floor during the day. At night, as the ambient temperature falls, the tiles release their stored heat to slow the temperature drop in the room. Another example of a TES application is the use of thermal storage to take advantage of off-peak electricity tariffs. Chiller units can be run at night when the cost of electricity is relatively low. These units are used to cool a thermal storage, which then provides cooling for air-conditioning throughout the day. Not only are electricity costs reduced, but the efficiency of the chiller is increased because of the lower night-time ambient temperatures, and the peak electricity demand is reduced for electrical-supply utilities.

3.3.1 Basic Principle of TES

The basic principle is the same in all TES applications. Energy is supplied to a storage system for removal and use at a later time. What mainly varies is the scale of the storage and the storage method used. Seasonal storage requires immense storage capacity. One seasonal TES method involves storing heat in underground aquifers. Another suggested method is circulating warmed air into underground caverns packed with solids to store sensible heat. The domestic version of this concept is storing heat in hot rocks in a cellar. At the opposite end of the storage-duration spectrum is the storage of heat on an hourly or daily basis. The previously mentioned use of tiles to store solar radiation is a typical example, which is often applied in passive solar design.

TES Processes

A complete storage process involves at least three steps: charging, storing, and discharging. A simple storage cycle can be illustrated as in Figure 3.1, in which the three steps are shown as distinct. In practical systems, some of the steps may occur simultaneously (e.g., charging and storing), and each step may occur more than once in each storage cycle.

In terms of storage media, a wide variety of choices exists depending on the temperature range and application. For sensible heat storage, water is a common choice because, among its other positive attributes, it has one of the highest specific heats of any liquid at ambient temperatures.

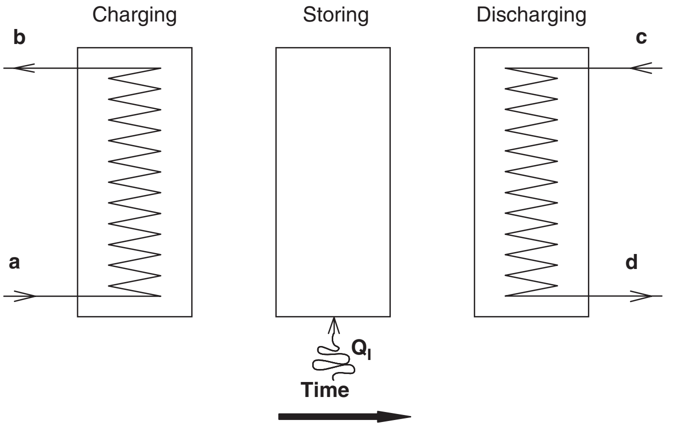


Figure 3.1 The three processes in a general TES system: charging (left), storing (middle), and discharging (right). Here the heat Q_l is infiltrating and is positive in value for a cold thermal storage. If it is released, it will be toward the surroundings and Q_l will be negative. The heat flow is illustrated for the storing process, but can occur in all three processes

While the specific heat of water is not as high as that for many solids, it has the advantage of being a liquid that can easily be pumped to transport thermal energy. Being a liquid, water also allows good heat-transfer rates. Solids have the advantage of higher specific heat capacities, which allow for more compact storage units. When higher temperatures are involved, such as for preheating furnace air supplies, solids become the preferred sensible heat stores. Usually refractories are then used as the storage material. If the storage medium needs to be pumped, liquid metals are often used.

TES using latent heat changes has received a great deal of attention. The most common example of latent heat storage is the conversion of water to ice. Cooling systems incorporating ice storage have a distinct size advantage over equivalent-capacity chilled-water units because of the relatively large amount of energy that is stored through the phase change. Size is the major advantage of latent heat thermal storage. NASA has considered using lithium fluoride salts to store heat in the zero-gravity environment of the space shuttle. Another interesting development is the use of PSMs in wall paneling. These panels incorporate compounds that undergo solid-to-solid structural phase changes. With the appropriate choice of material, phase change occurs at ambient temperature. Then, these materials, when incorporated into the panels, act as high-density heat sinks/sources that resist changes in ambient room temperature.

The other category of storing heat is through the use of reversible endothermic chemical reactions, and in some literature this method is considered TES. However, we include it in Chapter 2 separately as chemical heat storage technology. In this method, the reactions involve the breaking and forming of chemical bonds; so, a great deal of energy can be stored per unit mass of storage material. Although not currently viable, a variety of reactions are being explored. These include catalytic reactions such as the steam reforming reaction with methane and the decomposition of sulfur trioxide, and thermal dissociation reactions involving metal oxides and metal hydrides. These reactions are expected to be useful in high-temperature nuclear cycles and solar-energy systems, and as topping cycles for industrial boilers. At present, lower temperature reactions ($<300\,^\circ$C) have not proven promising. TES can be an effective way of reducing costs and increasing efficiency. While effective thermochemical storage is still some way off, latent and sensible heat storage are already well established. In these cases, TES has the potential to produce significant benefits, particularly for low-temperature heating and cooling applications. These benefits should allow TES to gain wider acceptance.

Topics of Investigation

TES systems combined with heating, cooling, and air-conditioning applications have attracted much interest in recent years. Many related studies have been carried out in a variety of countries, particularly in the United States, Europe, and Japan. These studies address technical issues arising from new TES concepts and the improvements required in the performance of existing TES systems. Studies have also investigated the design of compact TES systems and the use of TES in solar applications. TES research and development has been broad based and productive, and directed toward both the resolution of specific TES issues and the potential for new TES systems and storage materials. The following discussions summarize many investigations and indicate the scope of TES studies.

During the past few decades, many articles have appeared in the literature reporting investigations of TES systems and their applications (especially with solar energy), field performance characteristics and evaluations, design fundamentals, transient behavior and thermal analyses, and system and process optimization. In addition, theoretical, experimental, and numerical studies have been undertaken on the thermophysical properties of new TES materials, TES selection criteria, the integration of TES systems into solar power plants, and the economics and environmental effects of TES. Some details on these studies are given below:

- For sensible heat storage, the performance and thermal characteristics of packed-bed storage systems, the use of different storage materials, and uses for aquifer TES, water TES, and solar ponds have been investigated, as have operating conditions, effectivenesses, economics, and so on, for these systems.
- Thermal analyses of PCMs and their use for energy conservation in buildings have been carried out. Experimental and theoretical investigations and performance evaluations of the PCMs in latent heat storage applications have also been undertaken.
- Aspects of TES systems and materials during operation have been studied, including heat and mass transfer, and transient behavior, and second-law optimization and performance.
- Many practical applications of solar heating using TES have also been reported.
- Numerous investigations have considered specific TES systems and applications, as well as the general objectives of TES and the energy conservation, and related benefits of different TES methods.

There is a growing interest in the use of diurnal, or daily, TES for electrical load management in both new and existing buildings. TES technologies allow electricity consumption costs to be reduced by shifting electrical heating and cooling demands to periods when electricity prices are lower, usually during the night. Load shifting can also reduce demand charges, which can represent a significant proportion of total electricity costs for commercial buildings.

Many TES studies aim to inform professionals concerned with heating and cooling systems in buildings about the characteristics of TES, and to examine the development of relevant technologies and assess their application in the field using data from case studies in different countries. Other studies also consider factors influencing technology adoption.

Space heating using electric TES has been used extensively in Europe and North America. The storage media can include ceramic brick, crushed rock, water, and building mass, and systems can be either room or centrally based. Many improvements have been introduced in such systems in the past few years, including the development of new PSMs for latent heat storage, which have recently become available commercially.

Cool storage using ice, water, or eutectic salts as the storage media arewidely applied in the United States, where summertime cooling requirements are high. This technology is also used in Europe, often in combination with heat recovery and hot water storage, and in Australia, Canada, Korea, Japan, Taiwan, and South Africa.

TES systems can be installed in both residential and commercial buildings, and can be cost effective. Results from many of the monitored projects demonstrate payback periods of less than three years. If time-of-use tariffs exist, electricity costs to the consumer can be reduced by shifting the main electrical loads to periods when electricity prices are lower. If demand charges are implemented, a shifting or spreading of the load can reduce these significantly. To be effective, each storage system must be sized and controlled to minimize electricity costs and other system costs.

District heating and cooling systems often also incorporate TES and can benefit from its careful integration into the overall system.

Benefits from TES also accrue to the electricity utilities. The shifting of loads to off-peak periods not only spreads the demand over the generating period, but may also enable electricity output from the more expensive generating stations to be reduced. Worldwide, electrical utility incentive programs promoting the use of storage technologies exist, many of them within demand-side management programs. Such programs can greatly influence the economic feasibility of installing thermal storage by offering financial rebates, information, or special electricity rates for consumers.

Research and development programs for TES are needed in a number of areas, including the following related to utility-based TES applications:

- Establishing quantitative models for ascertaining the effects and benefits of changes in storage-capacity levels on service reliabilities, optimum generation mixes, and reserve margins. These models need to incorporate detailed demand projections for the future that reflect probable changes in utility load characteristics.
- Establishing the benefits of dispersed storage as a function of the geographic land use and demand characteristics of utilities. The work should be carried out on a regional basis where possible, and on an average national basis where necessary.
- Establishing the possible interactions between storage and load control for areas of differing load characteristics.
- Relating dispersed storage to dispersed generation, particularly in the context of total energy systems.

In parallel with such studies, there is a need for research and development support of promising storage concepts in order to ensure their timely availability and that they include a wide range of operating characteristics.

3.3.2 Benefits of TES

Although TES is used in a wide variety of applications, all are designed to operate on a cyclical basis (usually daily, occasionally, seasonally). The systems achieve benefits by fulfilling one or more of the following purposes:

- **Increase generation capacity.** Demand for heating, cooling, or power is seldom constant over time, and the excess generation available during low-demand periods can be used to charge a TES in order to increase the effective generation capacity during high-demand periods. This process allows a smaller production unit to be installed (or to add capacity without purchasing additional units), and results in a higher load factor for the units.
- **Enable better operation of cogeneration plants.** Combined heat and power, or cogeneration, plants are generally operated to meet the demands of the connected thermal load, which often results in excess electrical generation during periods of low electricity use. By incorporating TES, the plant need not be operated to follow a load. Rather, it can be dispatched in more advantageous ways (within some constraints).
- **Shift energy purchases to low-cost periods.** This measure constitutes the demand-side application of the first purpose listed, and allows energy consumers subject to time-of-day pricing to shift energy purchases from high- to low-cost periods.

- **Increase system reliability.** Any form of energy storage, from the uninterruptable power supply of a small personal computer to a large pumped storage project, normally increases system reliability.
- **Integration with other functions.** In applications where on-site water storage is needed for fire protection, it may be feasible to incorporate thermal storage into a common storage tank. Likewise, equipment designed to solve power-quality problems may be adaptable to energy-storage purposes.

One may ask: what is the most significant benefit of a TES system? A common answer is reducing electric bills by using off-peak electricity to produce and store energy for daytime cooling. Indeed, TES is successfully operating in offices, hospitals, schools, universities, airports, and other facilities in many countries, shifting energy consumption from periods of peak electricity rates to periods of lower rates. This benefit is accompanied by the additional advantage of lower demand charges.

3.3.3 Criteria for TES Evaluation

There are numerous criteria to evaluate TES systems and applications such as technical, environmental, economic, energetic, sizing, feasibility, integration, and storage duration. Each of these criteria should be considered carefully to ensure successful TES implementation.

Technical Criteria for TES

Independent technical criteria for storage systems are difficult to establish, since they are usually case specific and are closely related to and generally affected by the economics of the resultant systems. Nevertheless, certain technical criteria are desirable, although appropriate trade-offs must be made with such other criteria as

- storage capacity,
- lifetime,
- size,
- cost,
- resources use,
- efficiency,
- commercial viability,
- safety,
- installation, and
- environmental standards.

Before proceeding with a project, a TES designer should possess or obtain technical information on TES such as the types of storage appropriate for the application, the amount of storage required, the effect of storage on system performance, reliability and cost, and the storage systems or designs available.

TES is difficult to employ at sites that have severe space restrictions. Also, TES tanks often have significant first capital costs. Financial analysis for TES-based projects can be complex, although most consulting energy engineers are now capable of performing financial calculations and evaluating TES benefits.

Environmental Criteria for TES

The basic design, materials, and operational practices that are used for TES should preferably not overly impair public health or the natural ecology and environment. Materials should not be used that are toxic or dangerous if released, or that could adversely affect the environment during the manufacture, distribution, installation, or operation of the storage system.

Economic Criteria for TES

The economic justification for storage systems normally requires that the annualized capital and operating costs for TES be less than those required for primary generating equipment supplying the same service loads and periods. In general, TES systems accrue fuel cost savings relative to primary generating equipment, but often at the expense of higher initial capital costs.

The key performance characteristics involved in the evaluation of the cost effectiveness of TES include

- hourly thermal loads for the peak day;
- the electrical load profile of the base-case system against which TES is being compared; and
- the size of the storage system and the control methods used.

Economic information that is needed includes

- electricity demand charges and time-of-use costs;
- the costs of the storage; and
- financial incentives available.

Economic evaluation and comparison parameters often determined include the simple payback period. Other methods are also used to compare the annualized investment cost of a TES with annual electricity cost savings.

Energy Savings Criteria for TES

The past few years have seen a significant shift in understanding about the economics and environmental impact of TES. Today, well-designed TES systems can in some cases reduce the first costs on some projects. Moreover, they can reduce the amount of electricity that a facility uses, not just the amount it pays. Many project engineers now find that TES technology can significantly reduce energy use and demand, which translates into lower operating costs.

In addition, TES provides environmental advantages by using electricity produced at night, when utilities are generally operating their most efficient plants. As a result, significant savings of "source energy" (coal, natural gas, oil, or nuclear fuel) accrue to electric utilities and reduce pollutant emissions.

Air-conditioning typically accounts for a large portion of a building's energy use. One or more chillers are usually used to match the cooling load, which rises during the day and peaks in mid-afternoon. With TES, peak electric use can be reduced, so that smaller chillers can handle the load. In addition, air-cooled equipment can take advantage of lower night-time ambient temperatures to increase operating efficiency. Also, since water from TES systems may be colder than conventional chilled water, smaller pipes, pumps, and air handlers may be integrated into the building design.

Stored cooling capacity can be used alone to meet the entire cooling load (so chillers remain off during the day) or to supplement chillers by satisfying part of the load.

Perhaps the greatest shift in thinking about the potential uses of TES comes from the growing use of cold-air distribution. Cold-air distribution typically requires 30% less cold air than conventional cooling systems for a similar load, resulting in smaller fans, ducts, and risers. The related cost savings often offset the first-cost premium of TES.

The ability of cool storage to shift large amounts of peak electric demand to off-peak periods usually leads to the greatest interest in TES. When combined with cold-air distribution, TES systems can yield significant cost savings and improve a building's energy efficiency and comfort level. Yet, building owners often hesitate to use TES, erroneously believing that installing it is expensive. TES paired with cold-air distribution offers a more efficient, and often more cost-effective, cooling option, which is competitive with conventional technology and which offers promising payback periods. By integrating TES with cold-air distribution during the design and construction of office and other buildings, building owners add floor space for useful purposes or rental. This space becomes available because such systems require smaller air-handling units and often do not need a mechanical room.

Careful designing of a TES often yields first-cost savings by permitting the use of

- smaller air-handling units,
- smaller ducts, and
- smaller variable air volume (VAV) boxes.

Cold-air distribution can increase the capacity of existing air-conditioning systems or be used to replace older chillers. In general, existing fans and ductwork can be used, although in some cases more duct insulation and upgraded diffusers or mixing boxes may be needed.

Fan energy usage in cold-air distribution is typically reduced by 30–40%. Actual long-term energy-cost savings can often be even greater because compressor energy consumption is shifted to less expensive, off-peak hours. Research by the Electric Power Research Institute (EPRI) in the United States indicates that overall heating, ventilating and air conditioning (HVAC) operating costs can be lowered by 20–60% by combining TES with cold-air distribution. In such combined systems, conditioned spaces are maintained at 35–45% relative humidity, as compared to the 50–60% relative humidity often found with conventional systems. At lower humidity, occupants perceive improved air quality. In humid climates, the cooling energy requirement may increase slightly, but this is often offset by the inherent efficiencies of cold-air distribution.

Sizing Criteria for TES

A need exists for improved TES-sizing techniques as analyses of projects reveal both undersized and oversized systems. Undersizing can result in poor levels of indoor comfort, while oversizing results not only in higher than necessary initial costs, but also in the potential wasting of electricity if more energy is stored than is required. Another requirement for successful TES that affects sizing is proper installation and control. Using state-of-the-art equipment, properly designed and controlled storage systems often do not use more energy than conventional heating and cooling equipments.

Performance data describing the use of TES for heating and cooling by shifting peak loads to off-peak periods are limited, although the potential for such technologies is substantial. The initial costs of such systems can be lower than those for other systems. To yield the benefits, new construction techniques are required together with the use of more sophisticated thermal-design calculations that are, as yet, unfamiliar to many designers.

The costs of TES systems for heating range from US$ 20 to US$ 60/kWh in Canada. A major development over the last decade or so has been improved controls. Modern storage systems can shift nearly all of the space-heating energy use to off-peak hours, whereas, with conventional systems, only about 50% of the energy for heating is consumed during off-peak periods. Off-peak periods typically last for more than 7 h (CADDET, 1997).

Energy use for conventional heating systems tends to be less than that for storage heaters for rooms but greater than that for central brick- and water-storage systems. Base-case heating systems vary greatly and include direct electric-resistance baseboard heating, heat pumps, and electric central furnaces. Detailed comparisons of energy use for TES and base-case systems are often complicated by variations in other parameters such as the age and thermal integrity of buildings and homes.

The use of off-peak storage for heating in commercial buildings is growing as manufacturers produce more sophisticated storage equipment that is suited to larger buildings. Sizing of systems can, however, be difficult because of the more complex energy considerations and variable occupancy patterns for such buildings. Developments in energy control systems are enabling building operators to control HVAC and lighting systems more effectively. These improvements, in turn, allow better integration of thermal energy storage with other energy systems. The payback periods for such systems often range from one to ten years, depending on the capacity and application.

TES systems for cooling capacity have been most successful in larger buildings, although research is underway on the development of smaller units. Unlike heat storage, part of the cost of cold storage can be paid for through savings derived from the installation of a smaller chiller than would be required for a conventional cooling system. Costs for cold TES often range from about US$ 15 to US$ 50/kWh, and many designers claim that initial costs for cold storage systems are below those for conventional cooling (CADDET, 1997). Cold TES systems for most buildings use ice or chilled-water on floor mass as the storage medium. The systems may include full, partial, and demand-side storage. Payback periods for some systems, based on measured data and/or estimates, vary from less than one year to 15 years.

Feasibility Criteria for TES

A variety of factors are known to dramatically influence the selection, implementation, and operation of a TES system. Therefore, it is necessary to carry out a comprehensive feasibility assessment that takes into consideration all parameters that impact on the cost and the benefits of the TES systems considered. However, it is not always possible to follow all steps in a feasibility study for an application and, in such instances, as many items should be considered and studied as possible. In such TES feasibility studies, a checklist can be helpful in ensuring that significant issues related to the project are addressed and details regarding the evaluation, selection, implementation, and operation of the system are assessed correctly. Figure 3.2 provides a checklist that can be beneficial to the TES industry and analysts involved in TES projects. A checklist completed in the preliminary stages of the project guides the technical staff.

Integration Criteria for TES

When considering the integration of TES into an existing thermal facility, an additional checklist (Figure 3.3) can assist in conducting the feasibility study for the TES system and its incorporation into the facility. For a facility under design, the information required is generally the same as in Figure 3.3, except that the database must be developed or estimated since there is lack of actual operating data.

Storage Duration Criteria for TES

In practice, it is useful to characterize different types of TES depending on the storage duration: short-, medium- or long-term.

Short-term storage is used to address peak power loads lasting a few hours to a day in order to reduce the sizing of systems and/or to take advantage of energy-tariff daily structures. Short-term is often called *diurnal storage*.

Medium- or long-term storage is recommended when waste heat or seasonal energy loads can be transferred with a delay of a few weeks to several months. Long-term storages that take advantage of seasonal climatic variations are often referred to as *annual or seasonal storage*.

TES can be separated into high- and low-temperature systems, where low-temperature TES is the storage where heat enters and leaves at temperatures below approximately 120 °C. The storage of cold or cooling capacity is also considered within this category. Low-temperature storage often permits efficient utilization of heat that otherwise would have been partially or entirely wasted. Low-temperature TES also permits the storage of heat obtained from solar radiation from day to night or from summer to winter, and permits the storage of heat from central power plants, from times of low-demand to hours of high-demand on both diurnal and seasonal bases.

TES also permits the storage of cold for air-conditioning purposes, from night to day and from winter to summer. On a diurnal basis, the storage energy efficiency can exceed 90%, while on a

Checklist for evaluating a general TES project

Please tick (√) items which are available or known.

( ) 1. Management objectives
( ) 2. Economic objectives
( ) 3. Financial parameters of the project
( ) 4. Available utility incentives
( ) 5. Status of TES system (a) New ( ) (b) Existing ( )
( ) 6. Net heating or cooling storage capacity
( ) 7. Utility rates and associated energy charges
( ) 8. Loading type of TES system (a) Full ( ) (b) Partial ( )
( ) 9. Best possible TES system options
( ) 10. Anticipated operating strategies for each TES system option
( ) 11. Space availability for TES system (e.g. tank)
( ) 12. Type of TES system (a) Open ( ) (b) Closed ( )
( ) 13. General implementation logistics of TES system under consideration
( ) 13.1. Status of TES system
( ) 13.2. TES system location
( ) 13.3. Structural impact
( ) 13.4. Heat exchanger requirements
( ) 13.5. Piping arrangement
( ) 13.6. Automatic control requirements
( ) 13.7. New electrical service requirements
( ) 13.8. Others

Signature:

Project Leader:

Date:

Project Title and Number:

Figure 3.2 Checklist for evaluating a TES project

seasonal basis it usually is not much above 70%. Low-temperature TES has wide applicability in domestic hot-water systems.

Another kind of diurnal TES is the use of electric heaters that produce heat at night using low-cost electricity and store the thermal energy in the mass of bricks.

Table 3.1 provides information on diurnal and seasonal TES techniques for small- and large-scale applications. Diurnal storage equipment often reduces HVAC costs or avoids the need for backup heating or cooling equipment. Diurnal storage is increasingly used as a demand-side management technology (especially with cold storage in air-conditioned buildings). Wider use of air-conditioning in buildings combined with a need to reduce peak energy demands is motivating TES development.

Nonenergy regulations are rather neutral toward TES, although large-scale seasonal storage is subject to a large number of codes and standards that may conflict with plans of building managers. For short-term storage, safety (e.g., related to PCM handling), or hygiene regulations may to a

Checklist for integrating TES into an existing thermal facility

Please tick (√) items which are available or known.

Database

( ) 1. Utility's maximum incentive

( ) 2. Facility occupancy hours

( ) 3. Facility operating requirements

( ) 4. Existing physical constraints

( ) 5. Facility peak-day load and monthly average requirements

( ) 6. Historic energy consumption rates

Analysis

( ) 1. Best possible TES system options

( ) 2. General implementation logistics of each TES system under consideration

( ) 3. Plant's yearly energy consumption with or without a TES system

( ) 4. Size utilization factor for TES

( ) 5. Projected operating cost reduction for each TES system under consideration

Conclusion

( ) 1. Financial analysis

( ) 2. System implementation recommendation

( ) 3. Others

Signature:

Project Leader:

Date:

Project Title and Number:

Figure 3.3 Checklist for integrating TES into an existing thermal facility

Table 3.1 Storage durations for small- and large-scale applications

	Small-scale/decentralized storage		Large-scale/centralized storage	
	New	Existing	New	Existing
Diurnal latent TES (e.g., salt hydrates)	++	++	–	–
Diurnal sensible TES	++	+	–	++
Seasonal latent TES	–	–	–	–
Seasonal sensible TES (e.g., aquifers, rocks)	+++	–	+++	+

+++, high probability; ++, medium probability; +, low probability.

certain extent hinder the development of TES markets. Insurance companies are often reluctant to support the incorporation of products or equipments that have not received appropriate certification, as is often the case with innovative devices.

3.3.4 TES Market Considerations

Since TES is an energy efficiency option that complements other energy conservation strategies, government support could enhance the development of such technologies. At present, TES products or equipments do not contribute significantly to international trade. A good level of knowledge of TES exists in developed countries. The main area where trade could grow is ice storage, which is already widely marketed in the United States.

Widespread implementation of large seasonal storage appears unlikely in the near future. In France and other southern European countries, large-scale TES applications will likely remain limited in part, because there are few district-heating (or cooling) networks. TES can be a valuable complement to such networks. Table 3.2 compares TES application potential in France and the United States. In practice, large-scale TES will face implementation challenges similar to those for district heating, due to its complementary nature. Another challenge for TES technology is the absence of an industry support group that can extol the benefits of TES, promote its use, and provide information. Such support groups are common and important in other sectors.

Barriers to TES Adoption

Although TES technology is proven and economically viable, it is sometimes not readily accepted. Barriers to TES adoption can be categorized into several types:

- lack of proper information;
- lack of commercial options;
- high initial cost; and
- infrastructure constraints.

The first of these barriers can be overcome with appropriate information dissemination and related activities (on-site visits, publication of independent monitoring results, etc.). High initial costs as a barrier can only be overcome by establishing reimbursable funds dedicated to large-project investments. In the near term, TES developments are not likely to significantly reduce TES initial costs. For example, the European community could arrange with banks a third-party financing scheme for TES investment. Infrastructure constraints, such as the types of buildings and energy infrastructures largely in place, seem to be the most difficult to overcome, because they are linked to wider policy considerations, especially in the case of large-scale TES. For short-term TES, support of renewable energy technologies in the building sector and of passive solar design can help overcome this barrier.

Table 3.2 Comparison of potential TES implementation in France and the United States

Country	Market area	Predicted maximum potential deployment by 2010	Units in which deployment is measured
France	Seasonal storage	25–30	Number of sites
	Diurnal storage	500,000	Number of dwellings
United States	Diurnal storage	50	GW

Source: (Anon, 1990; Piette, 1990).

Other barriers that hinder greater use of TES can be summarized as follows:

- decision makers often do not think about using TES, with the possible exception of ice storage in air-conditioned buildings;
- long-term (seasonal) TES is perceived to be high risk;
- demonstration of economic long-term TES systems of local interest is lacking (e.g., in the immediate future emphasis is likely to be on aquifer and borehole storage);
- short-term TES using PCMs is not fully developed, and safety and hygiene concerns exist for PCMs; and
- insurance companies are not enthusiastic about systems using innovative products like TES that have not yet received certification, and obtaining certification is expensive.

To overcome these barriers, priority should be given to the following:

- developing appropriate information packages on commercially developed TES systems aimed at those with no previous knowledge of storage systems;
- carrying out technical development to improve performance and reduce costs;
- focusing in the short term on technologies for which local experience has been gained and keeping systems as simple as possible;
- providing training on these systems for designers, operators, and builders;
- providing risk capital for construction of systems close to commercialization; and
- carrying out research and development on financially promising TES systems, including PCMs suitable for use in the building industry, and innovative systems suitable for solar applications.

Maturity of TES

A large amount of TES technology has reached a level of maturity and begun to establish markets. PCMs are still undergoing research and development, but they, nevertheless, have been demonstrated and are commercially available. Thus, TES is mature and its lack of dissemination mostly relates to barriers other than technical (e.g., financial). For large-scale seasonal storage, cost reductions can likely be obtained (e.g., by improving excavating techniques and large-store construction methods). Demonstrations are needed of the use of PCMs in diurnal applications, especially by integrating them into building components (ceiling, tiles, wallboards, shutters, etc.). A comparison of TES system characteristics for diurnal applications is given in Table 3.3.

Market Position of TES

TES applications are at various states of development, depending on the country considered. Diurnal heat storage has not taken on a large market share in any country, with the exception of cold storage in air-conditioned buildings for demand-side management purposes (mostly in the United States, Canada, and Japan, and in some commercial premises in Europe and pilot-project “zero energy” houses in Finland). Diurnal cool storage in the United States has allowed about 15 GW of cooling power to be shifted to off-peak periods. Seasonal storage has been investigated and tested in the 1980s, and the main sites are located in northern European countries (especially Sweden) and are associated with district-heating networks. Seasonal storage in aquifers is well developed in China.

Large-seasonal TES facilities have been installed either to complement solar collection systems in large-scale building projects or in association with district-heating plants. Long-term seasonal TES development is thus linked to the market status of these technologies.

Individual houses or commercial (including office) buildings can use diurnal TES for either heating or cooling applications. Demonstration projects and information dissemination are, nevertheless, needed to increase building managers’ awareness of these options. The needs of passive, hybrid,

Table 3.3 Thermal and technical data for selected TES techniques

Thermal and technical data	Concrete or steel tank	Basin with total insulation	Basin with top insulation	Rock cavern	Aquifer	Earth bed	Vertical tubes in clay	Drilled wells
Specific thermal capacity (kWh/m^3K)	1.16	1.16	1.16	1.16	0.75	0.70	0.80	0.63
Reference ΔT (°C)	55	55	55	55	55	55	15	55
Typical storage efficiency	0.90	0.85	0.70	0.80	0.75	0.60	0.70	0.70
Conversion factor (kWh/m^3)	57	54	45	51	31	23	8	24
Size range (m^3)	0–100,000	0–75,000	0–50,000	50,000–300,000	50,000–500,000	0–100,000	50,000–300,000	50,000–400,000
Investment cost (ECU^a/m^3)	150–250	120–220	40–60	80–120	20	50–100	5–8	30–40
Cost of energy supplied by TES (ECU/kWh)	0.2–0.4	0.15–0.25	0.05–0.1	0.12–0.20	<0.05	0.16–0.40	0.05	0.09–0.12

[a] 1 ECU was approximately 0.85 US$ in 1990.
Source: (Anon, (1990); Piette, 1990).

and other low-energy cooling techniques for some type of short-term cold TES should foster the development of this kind of TES.

Market demands for TES are linked to general energy policy. For example, increased support for and use of renewable energy would lead to large efforts to inform designers of active solar technologies and others of the possibilities offered by TES.

Relatively high risks are perceived as existing for seasonal TES (especially when used with an aquifer). Possible technical difficulties with pumps and exhaust water systems (clogged pump strainers, choked filters) can lead to performance and safety problems, which in turn can induce higher initial costs.

Ice storage is an exception to these concerns as many systems have been implemented and have demonstrated a high cost effectiveness. When economic evaluations of TES are based on current energy-price structures, risks are associated with modified price structures. Widely disseminated information on successful operations can help reduce the perceived risks. Transfer and exchange of knowledge internationally through detailed specifications can limit the risks of projects that have been encountered in the past, and thus foster the development of TES.

Environmental legislation that directly controls the development of TES does not exist, but growing concern for the water quality in aquifers and the use of various PCMs has caused some TES technologies to be scrutinized and hindered decision makers from adopting them. Governments are also concerned about ensuring that appropriate regulations are in place to ensure that TES implementations do not cause environmental problems.

Financial factors affect TES marketability. For example, access to funds or the ability to raise funds at reasonable interest rates may hinder potential investors. Access to funds does not constitute a major barrier for TES technology, but the projected payback periods are often not appealing to many decision makers in the building sector. Sometimes, a financial consortium is needed for large TES facilities. Such consortia may include local authorities, which may or may not have access to funds, and energy utilities, which can usually obtain necessary funding.

Long-term TES systems with large storage capacities (>1000 MWh) have been in use since the 1980s. The storage medium is generally water or rocks, and the "container" is often aquifers, rock caverns, and underground boreholes. The main markets for long-term (seasonal) TES have been located in northern European countries, particularly Sweden, where it is used in association with large-scale district-heating schemes.

Short-term cool storage for air-conditioning has been found to be cost effective in applications in the United States and Canada; Japan and Europe have also used these systems. PCMs are not yet fully developed for the building sector, although they have been used for certain industrial applications.

In the future, TES appears to be able to help reduce the amount of heating and cooling systems by 50–70%, which in turn can yield energy savings because of better efficiency of systems working near to reference values. But TES losses can curtail some of the savings potential, lowering the energy conservation potential of TES to approximately 5–10%.

3.3.5 TES Heating and Cooling Applications

The use of TES systems for thermal applications such as heating and cooling has recently received much attention. In various energy sectors, the potential benefits of TES for heating and cooling applications have been fully realized. In the following two subsections, we describe heating TES and cooling TES in detail.

Heating TES

Electricity, natural gas, propane, or fuel oils can produce space heating. Heating TES using electricity operates resistance heaters at night when electricity rates are low to produce heating capacity for use during the day. Electric-resistance efficiencies (near 100% on an energy basis) combined with lower off-peak electric rates can produce heating at a fraction of the cost of conventional systems. Heat produced by electrical resistance heaters at night is stored in such storage media as earth materials or ceramic bricks in insulated containers. The production of heat at night takes advantage of electric off-peak rates, which are generally 33–75% less expensive than peak rates. When heat demand rises (e.g., for space heating), heat is recovered from the storage unit and transferred into the room.

The use of earth as a TES medium is usually restricted to new construction, since the application requires that electric resistance grids be placed 0.5 to 1 m in the ground, beneath a structure. The need to place the grids under a building makes retrofit work extremely difficult for any facility without a basement or crawlspace. For new construction applications, approximately 2 m of earth directly below the structure is used for storage of heat produced by the grid. A rigid and waterproof insulating material is placed vertically around the perimeter of the building and extends approximately four feet below the earth grade level. The insulation ensures that heat stored in the ground is radiated mainly into the structure and not into the surrounding earth. The electric resistance grid is covered with about two inches of sand and earth materials.

Ceramic bricks provide an excellent heat storage medium for retrofit as well as new construction applications because of their modular sizes, ease of installation, and high heat-retention abilities. These units are normally manufactured in various sizes and transported to building sites. The construction of this type of TES normally consists of an insulated box, about the size of a conventional radiant hot water or steam heating unit, filled with ceramic bricks. The number of bricks in a module depends on the heat storage requirement. The unit also includes a small fan. The ceramic bricks contain electric resistance strip heaters in their holes. During charging, the strip heating units produce heat, which is absorbed by the ceramic bricks. The insulation surrounding the bricks restricts heat losses from them. During the day, a conventional thermostat is used to control the fractional horsepower fan that circulates air from the room across the ceramic bricks to recover the stored heat and transports it into the room. The thermostat controller shuts the circulating fan when the room temperature is acceptable.

Heating TES systems can be justified economically for most facilities which have significant space heating needs and are billed under time-of-use electric rate schedules that have large differentials between peak and off-peak electric consumption.

Cooling TES

Cooling TES can reduce cooling energy costs while maintaining a comfortable environment. Summer air-conditioning bills have two components: an electric demand charge and an electric usage charge. The usage and demand charges are often further divided into peak and off-peak periods. The peak operating period of electric air-conditioning systems normally occurs during the high-cost demand and usage periods (i.e., the summer afternoon). TES systems are designed to shift the peak operating period of electric air-conditioning systems to the less expensive night periods.

Air-conditioning systems cool by removing heat via a chilled-water network or directly from an air stream. Most air-conditioning systems produce a cooling effect precisely when cooling is needed in a building or room. Cool TES-based air-conditioning systems operate similarly, but remove heat from an intermediate substance when the building does not need cooling, producing a cool reservoir that is stored until there is a need for cooling. The intermediate substance is normally water, ice, or eutectic salt solutions.

The most popular thermal storage medium is ice. The conversion of 1 kg of water to ice at 0 °C requires the removal of 152 kJ of heat. Similarly, adding 152 kJ of heat to the ice causes water at 0 °C to be formed. Ice TES operates in this fashion. At night, heat is removed from water to produce ice (i.e., charging of the storage occurs). During the day when the building requires cooling, heat is removed from the building and added to the ice (i.e., discharge occurs). The melted ice is reused during the next charging period. The advantage of this cooling scheme is that the main electrically driven device in cooling systems, namely, the compressor motor, is operated during low-electrical cost periods.

The previous example illustrates one design possibility. In another common design, the compression system operates for the whole day to provide stored cooling at night and to partially meet the cooling load during the day. This design usually requires the least investment.

Many cooling TES systems use chilled-water systems to transfer the cooling capacity from the storage to the building air-distribution system. Although chilled-water distribution systems are usually confined to large buildings with conventional air-conditioning, chilled water distribution systems with TES are now being designed for smaller buildings.

Cooling TES systems are generally advantageous for a new facility that has large daytime cooling loads and little or no cooling load at night. For retrofit situations, cooling TES is usually difficult to justify unless the cooling system is being replaced because of old age or inadequate capacity.

TES can be a beneficial component of the refrigeration-based cooling technologies. TES can significantly reduce the size of a refrigeration system and its electrical use during peak demand periods. TES is typically employed at power plants that mainly meet peak loads or that have significantly differing revenue structures for off-peak versus peak power.

For example, if a peaking gas turbine operates only 4 h per day, it usually does not make much sense to build a refrigeration plant that also operates at full load for only 4 h per day. This is because cooling capacity, unlike electricity, can be easily stored. It is usually more sensible to size the refrigeration system to meet about 20% of the peak cooling load and, slowly, to make and store cooling capacity during other periods so that it can be discharged during peak conditions.

TES and Gas Cooling

An alternative to cold TES is the use of gas engine-driven chillers or gas-fired absorption chillers for peak cooling loads. The higher first cost of these refrigeration systems is comparable to the high capital costs of TES tanks and infrastructure. The high-electrical load of a standard vapor-compression refrigeration system is displaced by either of these gas-cooling alternatives. A gas-engine chiller is often advantageous for a site that has limited operating hours per day per year. A gas-fired absorption chiller can make sense for sites that have longer operating hours.

An additional benefit of TES and gas-cooling technologies is that they permit changes to a site's electrical infrastructure to be minimized. One challenge to back-fitting electric vapor-compression systems to most sites is the placement and connection of a large transformer for the new electrical loads. With TES and gas-cooling technologies, the electrical load of the new equipment is significantly reduced, and there may be sufficient capacity in the plant's existing control centers for the smaller loads.

During the past decade there has been increasing interest in gas cooling with TES in power generation industries, and cold TES and gas-cooling technologies are both expected to take more prominent roles in advanced cooling projects in the future.

A combustion-turbine inlet-air cooling system, with and without storage, is shown in Figure 3.4. The main components are the chiller, the cooling tower, the air coil, and interconnecting piping. Cold fluid from the chiller is pumped through the air coil, where the coolant is heated and returned to the chiller, while the inlet air is cooled prior to entering the compressor. The cooling tower provides cooling water to the chiller condenser. Alternatively, an evaporative condenser can be used with some types of chillers. Including storage and its associated piping loop increases the number of system components, but allows the chiller and cooling tower components to be downsized, assuming that cooling is not conducted for the whole day. Storage also significantly reduces peak power consumption for electrically driven chiller systems.

The fundamental benefit of inlet-air cooling is that it can increase the efficiency of the gas turbine system (see Figure 3.4). However, the technique entails additional costs. The main cost is for the purchase and periodic maintenance of the inlet-air cooling system hardware. The energy used to drive the chiller also results in a significant expense, although the cost varies significantly

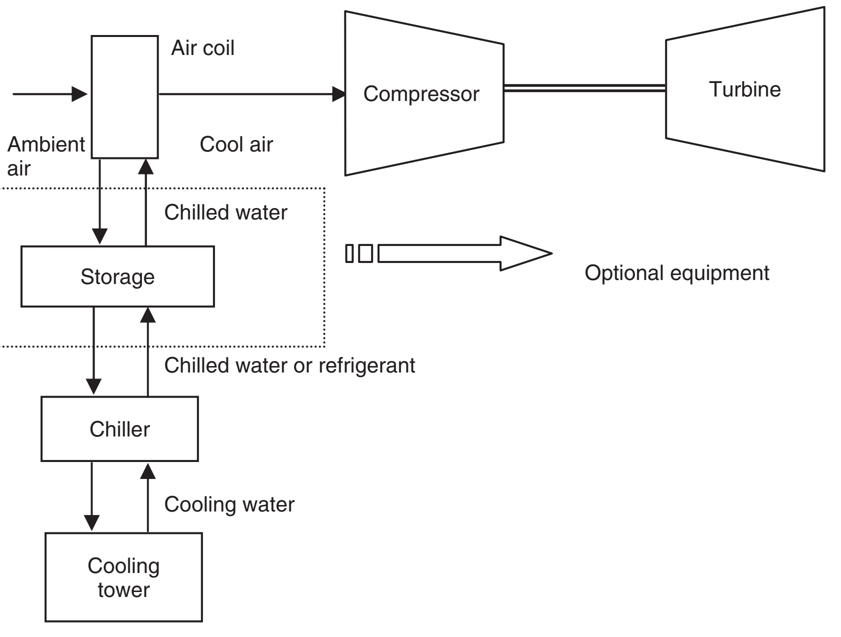


Figure 3.4 Generic inlet-air cooling system. (The cold storage inside the dotted line is optional.) (*Adopted from Brown et al*., 1996)

depending on whether the chiller is thermally or electrically driven and the source of the thermal or electric energy. Inclusion of an air-cooling coil within the inlet duct to the compressor causes an additional pressure loss, with negative consequences to gas-turbine power output and efficiency, but the impacts are generally less than 0.5% (Brown *et al*., 1996).

A common alternative to the inlet-air cooling system in Figure 3.4 is evaporative cooling. Direct-contact evaporative cooling, accomplished by passing the inlet air through a wet media can be particularly effective in drier climates. Analyses of inlet-air cooling normally consider evaporative cooling as an option. Note that evaporative and refrigeration-based approaches should be considered independently. Direct evaporative cooling followed by refrigerative cooling does not reduce the refrigeration cooling load. Rather, it substitutes latent load for sensible load.

Incorporating storage into an inlet-air cooling system is desirable for downsizing the chiller and heat-rejection components and significantly reducing peak electricity consumption for electrically driven systems. The chiller is usually the most expensive component of such systems; so, reducing its size and cost at the expense of adding storage and related piping can be cost effective. Reducing peak electricity consumption is important because increasing peak power output is usually the primary objective of combustion-turbine inlet-air cooling. Chilled water and ice are the preferred storage media for inlet-air cooling systems. Both are applicable to diurnal storage, and ice storage is also applicable to weekly storage cycles. Seasonal storage of ice via engineered ice or snow ponds or of chilled water in naturally occurring aquifers is also possible for inlet-air cooling, but these concepts suffer from site-specific limitations, and have had only limited successful applications. Eutectic salts are another storage medium possibility, but the salts are more expensive than water, suffer availability losses on charge and discharge, and also suffer from limited application experience. Steel or concrete cylindrical tanks can be used for water or ice storage. External insulation is usually sufficiently thick to avoid condensation. Chilled water is normally added and removed from the bottom of water storage tanks, while warm water is added or removed from the top, so as to form a thermally stratified tank. The preferred ice-making method uses a harvesting approach that periodically passes hot refrigerant from the compressor through the evaporator to release ice from the evaporator surface. The ice falls from the evaporator and makes a pile within the tank. Several evaporators are used to aid in distributing the ice. An alternative approach is to build up logs of ice around evaporator coils that run back and forth throughout the tank. Although its defrost cycle increases the effective cooling load by about 15%, the ice harvester is less costly to build because it requires much less evaporator surface and refrigerant inventory.

Selection of the storage media for inlet-air cooling depends partly on the chiller type. Lithium-bromide absorption chillers can only use water storage. Either water or ice storage is possible for vapor-compression chillers. The principal advantage of ice is its greater cold storage density, and the advantage of water is the mechanical simplicity of the storage system. Ice storage generally allows the inlet air to be cooled to a lower temperature than that of water storage, but ice generation requires a lower chiller evaporator temperature, which results in poorer chiller efficiency and higher chiller cost.

3.3.6 TES Operating Characteristics

A major factor in determining the feasibility of TES is the shape of the daily electrical load curve for a utility and its impact on the availability of energy for charging a TES. For example, an urban utility with a summer peak demand may have a peak of moderate duration during the day and a much reduced load for a short duration at night. Thus, the storage device may be required to supply energy for 10 h during the day, while significant charging capacity is only available for 6 h at night. Such a storage device would either have to be charged at a faster rate than it is discharged, or operate on a weekly cycle with part of the charge taking place over the weekend.

The diverse operating conditions for different utilities cause substantial variations in the duty cycles of TES systems. Table 3.4 summarizes the typical range of cycle characteristics for different applications. The values assume a storage efficiency of 75%.

Diurnal versus Seasonal TES

The primary characteristic of a seasonal storage system is the very large capacity that is required (in the order of a hundred times the capacity of a daily storage). Thermal losses become very important for such long-term storage. More care is, therefore, taken to prevent thermal losses in a seasonal system than in a system for daily storage. While diurnal systems can generally be installed within a building, seasonal storage requires such large storage volumes that separate, or requires frequent additional locations.

Table 3.4 Sample TES cycle characteristics

Duty-cycle characteristic	Type of operation			
	Peaking duty		Regular duty	
	Daily cycle	Weekly cycle	Daily cycle	Weekly cycle
Discharge time (h/day)	2–8	2–8	9–14	9–14
Charge time (h/day)				
Weekday	5–9	5–9	5–9	5–9
Weekend	–	14–34	–	14 – 34
Charge/discharge ratio	0.8–2.1	0.1–2.1	1.3–3.7	0.8–2.4
Storage period (h)	2–8	4–26	9–14	17–47
Annual operating time (h) (discharge time)	350–1600	350–1600	2300–3600	2300–3600

Source: Dinter *et al*. (1991).

The capital costs associated with the size and insulation necessary for seasonal storage systems have generally kept them from becoming economical. New technologies, increased energy costs, and the general desire to conserve scarce energy sources may warrant a review of seasonal storage systems. However, diurnal and other short-term storage will probably find broader application, and in many instances will have greater impact in a country at any given time.

Individual versus Aggregate TES Systems

A size relationship similar to that for diurnal/seasonal applications results from the consideration of individual versus aggregate use of TES systems. When individual units are aggregated into a system large enough for buildings, the total storage volume becomes the sum of the volumes of the individual units. With a larger volume, the lower surface–volume ratio of the aggregate unit reduces the thermal losses for identical storage periods.

Lower unit-storage costs also generally result as size is increased by the aggregation of individual systems. Depending on building and load density, however, thermal transmission costs and losses can eliminate any savings arising from aggregation. Control can be more difficult when a single aggregate storage system is used for several buildings. If individual accounts are maintained, cost billings can be difficult as allocation of energy costs in an aggregated situation requires a fair and inexpensive way of prorating thermal energy consumption.

Preferences for individual or aggregate systems depend on the circumstances of each particular case. For applications characterized by small loads, building ownership, and a wide diversity in consumption patterns, such as single family residences, aggregate systems are unlikely to be favored.

3.3.7 ASHRAE TES Standards

The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) provides testing standards for TES systems. ASHRAE TES standard 943 is called the "Method of Testing Active Sensible TES Devices Based on Thermal Performance." This sensible TES standard (ASHRAE, 2000) is the second half of a revision of ASHRAE's first TES standard, 94-77, "Methods of Testing Thermal Storage Devices Based on Thermal Performance." The first half was issued as ANSI/ASHRAE 94.1-1985, "Method of Testing Active Latent Heat Storage Devices Based on Thermal Performance." Sensible TES usually applies to heat storage in water or rocks or cool storage in chilled water. This standard was prepared by a group of volunteers representing users, design engineers, manufacturers, scientists, and the US federal government. Research sponsored by the US Department of Energy and the Electric Power Research Institute in solar and off-peak energy programs at government laboratories and universities has assisted TES standards development. The major change in the new standards is to provide wider freedom to the supplier of the test device in the choice of cycling time, capacity, maximum flow rate, and temperature range. Another important revision is in making the stand-by heat loss test more practical and accurate.

Since storage is usually part of a system, total performance depends on more than just the performance of the storage component. However, the results of this test procedure are intended to provide stand-alone specification of the storage-components' performance. The Standards Project Committee that developed these TES standards hopes they will be used by manufacturers and others.

3.4 Solar Energy and TES

Solar energy is an important alternative energy source that will more likely be utilized in the future. One main factor that limits the application of solar energy is that it is a cyclic, time-dependent energy resource. Therefore, solar energy systems require energy storage to provide energy during the night and overcast periods. Although the need for TES also exists for many other thermal applications, it is particularly notable for solar applications.

3.4.1 TES Challenges for Solar Applications

TES is important to the success of many intermittent energy sources in meeting demand. This problem is especially severe for solar energy, because it is usually needed most when solar availability is lowest, namely, in winter. TES complicates solar energy systems in two main ways. First, a TES subsystem must be large enough to permit the system to operate over periods of inadequate sunshine. The alternative is to have a backup energy supply, which adds a capital cost and provides a unit that remains idle. In the short run, solar energy can and probably needs to be integrated into systems that also use conventional energy sources, such as fossil fuels. In the long run, however, stand-alone solar energy systems may be desired.

The second major complication imposed by TES is that the primary collecting system must be sufficiently large to build the supply of stored energy during periods of adequate insolation. Thus, additional collecting area (and its additional capital cost) is needed. Examinations of typical sunshine records show that even in the desert, the periods of cloudy and clear weather are about equally spaced, a few days of one followed by a few days of the other. Partly cloudy days can greatly affect performance and make the difference between practical and impractical energy storage. If the total energy of a partly cloudy day can be collected, then the periods requiring energy storage are greatly reduced.

Concentrating solar systems must cope with the intermittent nature of direct sunlight on a cloudy day. Consequently, absorbers and boilers must be designed with care to avoid burn-out problems when the sun suddenly returns with full brilliance. Non-concentrating systems face the fundamental problem of trying to provide sufficiently high efficiency at medium temperatures to yield energy output at a reasonable cost. Thus, TES costs must be reasonable.

3.4.2 TES Types and Solar Energy Systems

In solar energy applications, TES can provide savings in systems involving either simultaneous heating and cooling, or heating and cooling at different times of the year. Most TES applications involve a diurnal storage cycle; however, weekly and seasonal storage is also used. Solar energy applications require storage of thermal energy for periods ranging from very short durations (e.g., buffer storage of minutes for solar thermal power plants) to annual cycle timescales. Most solar energy systems use diurnal storage, where energy is stored for at most a day or two. Diurnal storage offers a number of advantages, such as

- capital investments for storage and energy loss are usually low;
- devices are smaller and can easily be manufactured offsite; and
- sizing of daily storage for an application is not as critical as sizing for larger annual storages.

Seasonal storages do, nevertheless, have some advantages. Larger storages have lower heat losses because of their lower surfacetovolume ratios. The need for backup systems can be eliminated, since periods of adverse weather have little effect on the long-term thermal energy availability. Collector areas can consequently be reduced. Also, annual TES systems complement welldesigned energy management systems in which excess heat or coolness from the environment or adjacent structures is saved for later use.

A TES designed primarily for the storage of solar energy is not necessarily restricted to that source. It may be used to store surplus energy from the power plants, usually in the form of waste water, waste energy from air-conditioners or industrial processes, and so on. Such storage use may not be applicable for small houses, but could be useful for largescale central heating systems.

A variety of active and passive systems for storage have been developed for the effective utilization of solar energy. Passive systems, which do not need pumps are often suitable for smallscale domestic applications, and are widely used throughout Europe and the United States. The five main types of such passive systems are:

- direct heat gain,
- heat collection and storage,
- sun space,
- roof-top heat storage,
- thermosyphon.

Effective use of solar energy relies to such an extent on TES that solar systems without TES facilities are probably only utilizable in the most rudimentary applications. Some examples of solar thermal applications that do not need storage include solar grain driers, solar distillers, and solar kilns. In these systems the solar heat is used immediately as it becomes available. However, in solar space-heating applications the situation is different, because the solar system normally provides more heat than demanded by the building during the collection period. Storage is required to make such solar energy systems viable and attractive, in the long- or short-term.

3.4.3 Storage Durations and Solar Applications

Annual solar energy TES systems are designed to collect solar energy during the summer months and retain the heat in storage for use during the following winter. Although the technology exists to construct annual storage systems, and some have been demonstrated, it is challenging to make these systems cost effective. The main impediment is the lack of a cost-effective means to contain heat for long periods (e.g., three months). Ground-based TES has successfully been used in some jurisdictions. Economic breakthroughs in TES are of course possible, possibly via annual storage on a community-wide scale, which could reduce costs and dramatically improve the reliability of solar heating.

Short-term solar energy TES systems are designed to store heat for up to a few days. Although solar energy systems utilizing annual storage can contribute close to 100% of building heating needs, short-term TES systems rarely contribute in excess of 60%. Nevertheless, short-term solar energy TES systems can operate on a competitive basis with conventional fuels (Dincer *et al*., 1997a, b).

Any solar energy system has some degree of TES, either deliberately provided as a device in which to store energy, or through the thermal inertia of the extensive system of collectors and heat-transfer fluid. TES is considered cost effective only for short periods (hours to days), which is generally not enough to carry a system through much winter weather. Making TES capacity large enough is normally economically prohibitive. One exception is the special case of saline solar ponds, which act as both solar collectors and TESs having weeks of storage capacity.

TES is often thought of in conjunction with solar energy, because the latter is often associated only with technologies that translate sunlight directly into thermal energy or electricity. Solar technology today includes a broad spectrum of concepts that differ greatly in their requirements for storage. Plant matter, or biomass, is ideally storable for long periods. Wind power is another form of indirectly derived solar energy that, even though is intermittent, is available more continuously through the day and night than direct sunlight in many regions. TES is often important for solar water heating, heating of buildings, and industrial heating processes.

A factor that may facilitate storage applications and the resolving of challenges is the movement of the energy economy toward greater coordination of energy supplies and demands. Although many people will not readily give up energy choices, the flexibility of use that occurred in the eras of inexpensive energy may be changing. Time-of-day electric pricing, already introduced in some areas, is one example. The use of computer systems that automatically manage the energy load in large office buildings is another. Such changes occur gradually and tend to create a social climate in which solar energy is more acceptable.

Solar energy may also develop without storage in the future as there exist some configurations in which solar power sources can be integrated with energy systems, particularly electric systems, without bulk storage. Nevertheless, even with optimistic rates of growth, solar energy's contribution will remain relatively small in the near future. Thus, traditional energy systems can be used to compensate for the fluctuations in solar energy supply. Solar energy can also be used to match the fluctuating energy demand, particularly for electricity, without endangering the stability of electrical networks. Since large quantities of electric power are routinely transmitted through long distances, the electric network is particularly well-suited for smoothing and balancing solar-source power fluctuations. If solar-derived energy grows to too large a fraction of the total, the overall stability of an electric network might be adversely affected, but many studies indicate that this limitation is unlikely to be a problem until solar power penetration reaches 15–20%.

3.4.4 Building Applications of TES and Solar Energy

The ability to store thermal energy is important for effective use of solar energy in buildings. Today, much interest is focused on passive systems for space heating and active systems for water heating. For building heating, conventional passive TES materials include water, rocks, masonry, and concrete. To perform well, these storage materials must be massive because their allowable temperature swings are limited by comfort conditions that must be maintained inside the building.

With lightweight-building construction practices commonplace in the United States, a lightweight latent TES system which is easily installed in a building could be beneficial. One problem is the effective and economic containment of a PCM in its liquid phase. Tubes, rods, bottles, and canisters containing PCMs that melt in the room-temperature range have been studied with varying degrees of success; most have proved uneconomical. A more interesting approach is a wallboard containing a PCM. With the wallboard providing PCM containment as well as serving an architectural function, the economics are improved. Further, the large heat-transfer area of the wallboard supports large heat fluxes driven by small temperature differences.

Seasonal storage has been pilot-tested and used in a number of countries to store solar energy for providing winter space heating, in conjunction with district-heating systems. Sweden has implemented many such systems. A TES system examined by the University of Massachusetts at Amherst (Tomlinson and Kannberg, 1990) started using a long-term seasonal thermal storage of solar heat in a subsurface clay formation for heating a local athletic center. Use of seasonal storage can substantially reduce the cost of providing solar energy systems that can supply 100% of energy needs because of the reduced collector area required. In high latitudes, storage is virtually essential to provide a large percentage of heating from solar energy. The economics of scale favors relatively large systems.

Commercial buildings are now becoming more complex. Not only are architectural features such as atriums and skylights common, but sophisticated controls on HVAC equipment are being used in an attempt to provide superior comfort and lower energy costs. These situations make it difficult to determine the economic feasibility of TES systems and require computer simulation programs to model the complex systems, controls, and economic parameters of commercial buildings.

The storage system is the heart of a solar heating and cooling system. Storage evens out the extremes of temperature caused by the daily cycle of solar availability, permitting indoor temperatures to remain comfortable during the day while providing heat at night. The storage component of a solar energy system significantly affects the design and construction and therefore cost. The storage medium and the "reliability" required of a system determine the size of the storage and, to some degree, its location. Most storage systems are not sized to provide 100% of heating needs when sunshine is not available. Since solar unavailability and availability are difficult to predict

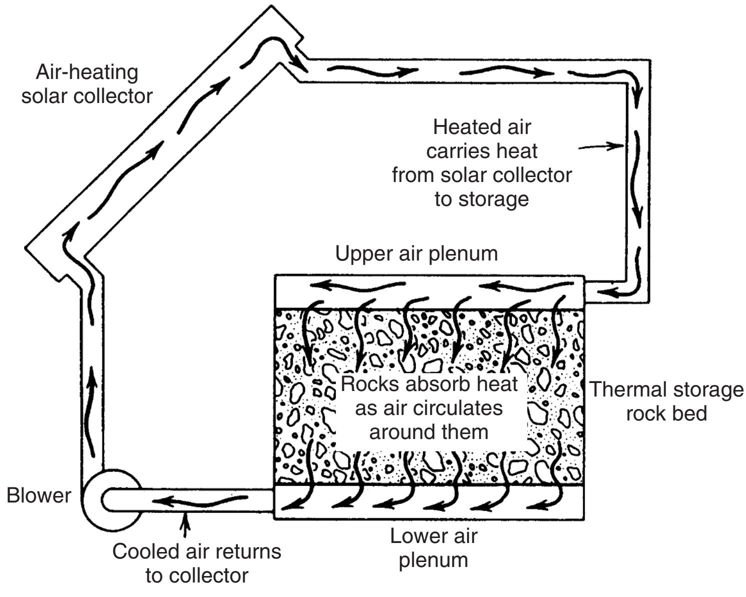


Figure 3.5 A solar rock-bed TES system (Harris *et al.*, 1985)

in most cases, 100% storage systems would be very large, but most of the capacity would remain unused most of the time. Being willing to tolerate some daily temperature swings can reduce the size of such TES.

All substances have a thermal capacity and ability to hold a certain amount of heat. Water can store large amounts of heat. Rock has about one-fifth the thermal capacity of water, but like brick and concrete, it is more dense. Rock, when used as a storage medium, is usually placed in an insulated bed under or attached to a building. Figure 3.5 illustrates a solar rock-bed TES system with air-heating collectors. As can be seen from the figure, the air from the collectors carries the absorbed solar heat to the rocks. As the heated air flows around the rocks, they absorb the heat, and the cooled air returns to the solar collectors to be heated again.

3.4.5 Design Considerations for Solar Energy-Based TES

The energy from solar collectors tends to be at low temperatures and requires a large storage mass when stored as sensible heat. Although the energy efficiency of solar collectors increases (and the collector cost probably decreases) as the temperature of the collector output reduces toward the space-conditioning comfort range of 20–25 °C, the overall mass and volume of the storage device increase further. For most locations, however, a space-conditioning system using solar energy needs to be supplemented by an electric- or fuel-powered auxiliary energy source. Thus, optimal and synergistic use of both energy sources via TES is important in designing building structures and TES systems.

A major question in the design of solar TES systems involves the quantity of solar energy to be stored. The storage system must be adequate to supply heat not only during the night, but also for several consecutive cloudy days if complete independence from external energy sources is desired. In many regions, winter periods without sunshine are so long that complete independence is not feasible. Furthermore, the solar-collector system, to achieve independence, must be sufficiently large to heat the structure even while storing more heat for the next sunless period. Days can span less than 8 h during northern winters, and under such conditions, the costs of the combined collector and storage system may effectively limit the extent to which the solar system can economically supply the needed energy. If an alternate heating system with another energy source is needed as a backup for extended sunless periods, then solar energy use may be even further limited. However, if a storage system is economically justified, perhaps because it takes advantage of low off-peak electricity prices, then storage of solar energy in addition may enhance that benefit.

The energy from solar collectors need not be used directly in space-conditioning systems. One alternative and promising application is to use it as a heat source for a heat pump in a solar-augmented heat-pump system. For such uses, the solar-collector outlet temperatures can be lower than those achieved with direct heating, thereby increasing energy efficiency and probably reducing cost. In addition, having higher source temperatures available for the heat pump increases its coefficient of performance (COP) and reduces its electricity consumption. How the solar-augmented heat-pump system operates depends, in part, on the energy storage provisions. With minimum or no storage, the solar collector only improves the heat-pump efficiency during hours of sunlight. With greater storage, the solar input also provides a reservoir of higher source temperatures for heat-pump operations during sunless periods. If the overall system is designed to limit the heat-pump operation to off-peak hours, then a dual storage system is necessary (one system for the solar input storage and a second to store the heat-pump output energy for round-the-clock use in space conditioning).

3.5 TES Methods

TES can aid in the efficient use and provision of thermal energy whenever there is a mismatch between energy generation and use. Various subsets of TES processes have been investigated and developed for building heating and cooling, industrial applications, and utility and space power systems. The period of storage is an important factor. Diurnal storage systems have certain advantages: capital investment and energy losses are usually low, and units are smaller and can easily be manufactured offsite. The sizing of daily storage for each application is not nearly as critical as it is for larger annual storage. Annual storage, however, may become economic only in multidwelling or industrial park designs, and often requires expensive energy distribution systems and novel institutional arrangements related to ownership and financing. In solar TES applications, the optimum energy storage duration is usually the one which offers the final delivered energy at minimum cost when integrated with the collector field and backup into a final application.

Some of the media available for sensible and the latent TESs are classified in Table 3.5.

3.6 Sensible TES

In sensible TES, energy is stored by changing the temperature of a storage medium such as water, air, oil, rock beds, bricks, sand, or soil. The amount of energy input to TES by a sensible heat device

Table 3.5 Available media for sensible and latent TES systems

Sensible Short term	Long term (annual)	Latent Short term
Rock beds	Rock beds	Inorganic materials
Earth beds	Earth beds	Organic materials
Water tanks	Large water tanks	Fatty acids
–	Aquifers	Aromatics
–	Solar ponds	–

is proportional to the difference between the storage final and initial temperatures, the mass of the storage medium, and its heat capacity. Each medium has its own advantages and disadvantages. For example, water has approximately twice the specific heat of rock and soil. The high heat capacity of water (~4.2 kJ/kg °C) often makes water tanks a logical choice for TES systems that operate in a temperature range needed for building heating or cooling. The relatively low heat capacity of rocks and ceramics (~0.84 kJ/kg °C) is somewhat offset by the large temperature changes possible with these materials, and their relatively high densities (Tomlinson and Kannberg, 1990).

Sensible TES consists of a storage medium, a container, and input/output devices. Containers must both retain the storage material and prevent losses of thermal energy. Thermal stratification, the existence of a thermal gradient across storage, is desirable. Maintaining stratification is much simpler in solid storage media than in fluids.

Sensible TES materials undergo no change in phase over the temperature range encountered in the storage process. The amount of heat stored in a mass of material can be expressed as

$$Q = mc_p \Delta T = \rho c_p V \Delta T$$

where c_p is the specific heat of the storage material, ΔT is the temperature change, V is the volume of storage material, and ρ is the density of the material.

The ability to store sensible heat for a given material strongly depends on the value of the quantity ρc_p. Water has a high value and is inexpensive but, being liquid, must be contained in a better quality container than a solid.

Some common TES materials and their properties are presented in Table 3.6. To be useful in TES applications, the material normally must be inexpensive and have a good thermal capacity. Another important parameter in sensible TES is the rate at which heat can be released and extracted. This characteristic is a function of thermal diffusivity. For this reason, iron shot is an excellent thermal storage medium, having both high heat capacity and high thermal conductance.

For high-temperature sensible TES (i.e., up to several hundred degrees Celsius), iron and iron oxide have thermal properties that are comparable to those of water per unit volume of storage. The cost is moderate for either pellets of the oxide or metal balls. Since iron and its oxide have similar thermal characteristics, the slow oxidization of the metal in a high-temperature liquid or air system would not degrade its performance.

Table 3.6 Thermal capacities at 20 °C of some common TES materials

Material	Density (kg/m^3)	Specific heat (J/kg K)	Volumetric thermal capacity (10^6 J/m^3 K)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravelly earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

Source: Norton (1992).

Rock is a good sensible TES material from the standpoint of cost, but its volumetric thermal capacity is only half that of water. Past studies have shown that rock storage bins are practical, their main advantage being that they can easily be used for heat storage at above 100 °C.

3.6.1 Thermally Stratified TES Tanks

TES tanks for use in heating, air-conditioning, and other applications have, in general, received increasing attention in recent years. Thermally stratified storage tanks, which have gradually seen more widespread use recently, are now described.

Figure 3.6 shows, for a thermally stratified storage tank, the positions of the inlet and outlet for well and poorly designed cases. Also shown is the thermally effective quantity of water that results from these positions. Since the tank stores thermal energy for periods of at least several hours, heat loss/gain occurs from the tank. The thermal-retaining performance of a tank is an important factor in its design.

Types and Features of Various Stratified TES Tanks

The TES system most commonly employed at present is sensible TES utilizing water as the storage medium. The term "thermal" storage is used instead of "heat" storage because the former implies storage of heat or cold and the latter just heat. An effective TES tank utilizing water as the storage medium satisfies the following three general requirements:

- The tank should be stratified, that is, it should hold separate volumes of water at different temperatures. Mixing of the volumes should be minimal, even during charging and discharging periods.
- The effective storage capacity should minimize the amount of dead water volume in the tank (see Figure 3.6).
- The heat loss/gain from the tank should be minimized.

Many types of TES tanks have been developed to satisfy these requirements, the principal ones being listed in Table 3.7.

A thermally naturally stratified storage tank has no inside partitions and has the following principle of operation. Warm water has low density and floats to the top of the tank, while cooler water

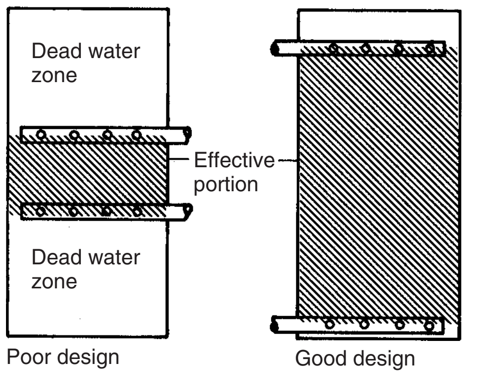
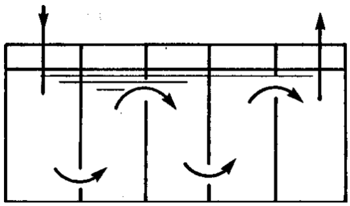
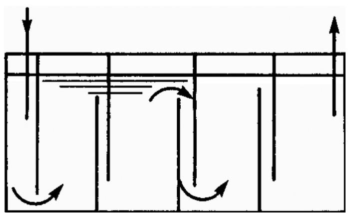
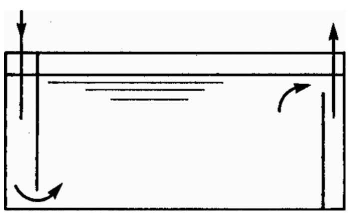
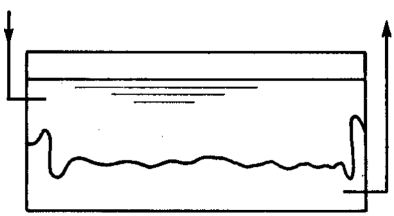
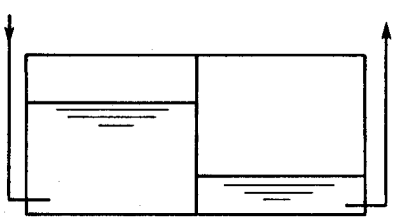


Figure 3.6 Position of inlet and outlet, and effective quantity of water (hatched regions), for a thermally stratified TES (Shimizu and Fujita, 1985)

Table 3.7 Types and features of various stratified TES tanks

Type	Schematic representation of cross section	Efficiency	Remarks
Continuous multitank type		Medium	Underground beam space can be used effectively. Insulation is difficult to install.
Improved dipped weir type		Medium ~ High	Construction is difficult
Thermally stratified type		High	Best suited for large-size tank built aboveground
Movable diaphragm type		High	Diaphragm material is problematical. Not easily adapted to tanks with internal pillars and beams
Multitank water renewing type		High	Underground beam space can be utilized to some extent. Heat loss is large

Shimizu and Fujita (1985).

with higher density sinks to the bottom. The storage volume with this type of system is reduced relative to other systems, because the dead water volume is relatively low and the energy efficiency relatively high.

Design Considerations for Stratified TES Tanks

When designing a thermally stratified thermal storage tank, the following criteria can guide the design process:

- **Geometrical considerations.** A deep water-storage container is desirable to improve thermal stratification. The water inlet and outlet should be installed in a manner that produces a uniform flow of water to avoid mixing. To minimize dead water volume, the outlet and inlet connections should be located as close as possible to the top and bottom of the storage volume, respectively. The surface area in contact with the storage water should be minimized.
- **Operating considerations.** The temperature difference between the upper and lower parts of the tank should be large, at least 5–10 °C. Controls can be used to maintain fixed water temperatures in the upper and lower parts of the tank if desired. The velocity of the water flowing into and out of the tank should be low.
- **Other considerations.** The insulating and water-proofing characteristics of the tank should be designed to meet appropriate specifications.

Stratified TES Tank Configurations

Several possible stratified storage concepts are depicted in Figure 3.7. The advantage of the single-medium storage systems, in which the heat-transfer fluid is also the storage medium, is that no internal heat exchange between the transfer fluid and the storage medium is necessary, thus avoiding the consequential temperature losses. If the liquid has low thermal conductivity and permits good thermal stratification (e.g., for water or thermal oil), the one tank thermocline concept requires

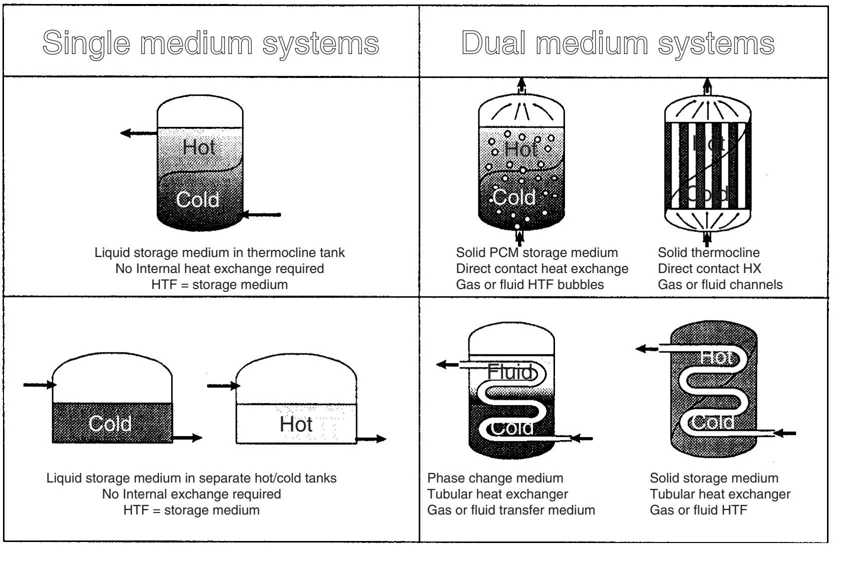


Figure 3.7 Schematics of various tank configurations (HX: heat exchanger; HF: heat-transfer fluid) (Dinter *et al.*, 1991)

the least tank volume, since the hot and cold media are contained in a single vessel. When the storage-medium thermal conductivity is higher, as in molten salts or sodium, rapid equilibration of hot and cold temperature regions occurs, making separate hot and cold tanks necessary. Since in that case, twice as much tank volume as fluid content is required, a three-tank system in which there is only 1.5 times as much tank volume as fluid content is often recommended. However, such systems are difficult to control, involve extensive piping, and are subject to increased heat losses from higher surface-to-volume ratios. Dual-medium concepts employ different transfer and storage media often, because the storage medium (usually solid) is less expensive than the transfer fluid. The transfer medium exchanges heat through direct or indirect contact with the storage medium, forming a thermocline. Apart from the temperature drop between charging and discharging due to the intermediate heat exchange, the dual-medium concept has another operational drawback relative to single-medium hot/cold tank systems. While the latter keeps constant outlet temperatures at charging and discharging until the tank is empty, in a dual medium storage system, the outlet temperature of the heat-transfer medium increases the more it is charged and decreases the more it is discharged, leading to unusable storage capacities (Dinter *et al.*, 1991).

3.6.2 Concrete TES

Concrete is sometimes chosen because of its low cost, availability throughout the world, and easy processing. Inexpensive aggregates to the concrete are widely available. Concrete has the following characteristics as a storage medium:

- high specific heat;
- good mechanical properties (e.g., compressive strength);
- a thermal expansion coefficient near that of steel (pipe material); and
- high mechanical resistance to cyclic thermal loading.

When concrete is heated, a number of transformations and reactions take place which influence its strength and other physical properties. When concrete is heated to about 100 °C, water is expelled (up to 130 kg of water per m^3 of concrete). The remaining water (50 to 60 kg of water per m^3 concrete), either physically bound in smaller pores or held by chemisorption, is expelled as temperatures rise from 120 to 600 °C. Most dehydration occurs between 30 and 300 °C. This water loss reduces the weight of concrete by 2–4%. The specific heat decreases in the temperature range between 20 and 120 °C, and the thermal conductivity decreases between 20 and 280 °C. The mechanical properties are also slightly influenced by the loss of water; compressive strength decreases by about 20% at 400 °C compared to that at ambient temperature. Resistance to thermal cycling depends on the thermal expansion coefficients of the materials used in the concrete. To minimize such problems, a basalt concrete is sometimes used. Steel needles and reinforcement are sometimes added to the concrete to impede cracking. By doing so, the thermal conductivity is increased by about 15% at 100 °C and 10% at 250 °C (Dinter *et al.*, 1991).

Such concrete storage can be supplied as prefabricated plates. Alternatively, the concrete may be poured on-site into large blocks, leading to easier and more economic construction. Whether prefabricated plates or on-site pouring is advantageous depends on local conditions.

3.6.3 Rock and Water/Rock TES

Rock is an inexpensive TES material from the standpoint of cost, but its volumetric thermal capacity is much less than that of water. Rock storage bins in home air-heating systems are practical (Dincer, 1999). The advantage of rock over water is that it can easily be used for TES above 100 °C. Rock-bed and water storage types can both be utilized in many ways. For example,

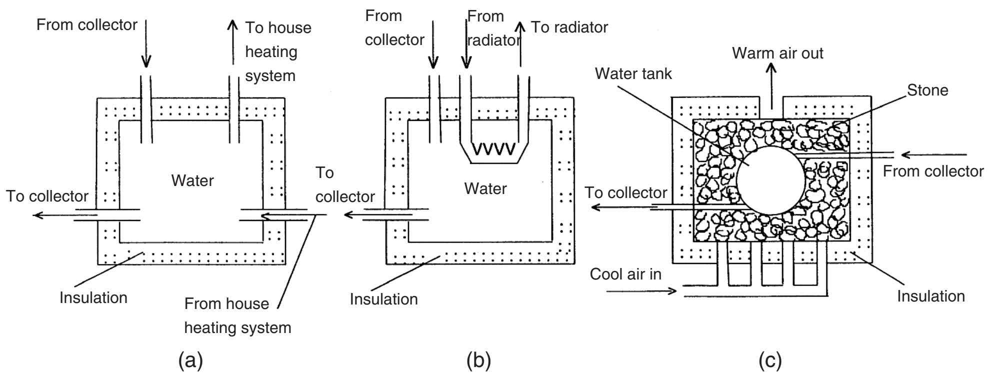


Figure 3.8 Solar storage tanks: (a) heat storage tank directly tied to both the collector and the house heating system, (b) sensible TES system using a heat exchanger to extract solar heat from a storage tank, and (c) Harry Thomason's technique using both water and stone as storage media

they may be used in conjunction with heat pumps to improve the efficiency of heat recovery, or with more elaborate heat exchangers, or with each other.

Eldighidy (1991) conducted extensive theoretical and experimental investigations on solar storage tanks with TES and indicated that water, rock beds, and PCMs are the most suitable storage media. Three different configurations of storage tanks (Figure 3.8) for TES applications were examined. The most common TES system has a water-filled container in direct contact with both the solar collector and the house heating system (Figure 3.8a). Cool water from the bottom of the tank is circulated to the collector for solar heating and then returned to the top of the tank. Warm water from the top of the tank is circulated directly through baseboard radiators or radiant heating panels inside the rooms. Figure 3.8(b) shows another system which consists of a copper coiled finned tube immersed in the tank of solar heated water. Rocks are the most widely used storage medium for air collectors.

One attractive storage method that uses both water and rocks as storage media is known as *Harry Thomason's method* (Figure 3.8c). In this system, heated water from the solar collector enters a water tank at the top, sinks as it cools, and finally leaves at the tank bottom as it is recirculated to the collectors. The water tank is surrounded by river rock through which air is circulated to carry the heat into the house; the entire rock and water tank assembly is contained within insulated walls. The advantage of this system is the high heat capacity of the water, and the extensive area of the rock's container leads to efficient transfer of heat to the air.

Rocks are sometimes the preferred storage medium over water for solar energy systems situated in northern latitudes. However, air/rock solar systems can, and in some instances do, make provision for partial heat storage in water for domestic hot water use. Storage of heat in rocks requires approximately three times as much space as an equivalent amount of heat in water. This disadvantage is often overcome by cost advantages. Water containment in a TES or a swimming pool is expensive. Combined with the higher capital and maintenance costs of a liquid collector, the economics quickly favor the use of air collectors with rock storage for domestic heating applications. Liquid solar energy systems were chosen during the early stages of solar energy development because of the superior heat-transfer characteristics of liquid over air. Initial solar energy collection systems were able to capture slightly more than 50% of the incident solar radiation with liquid collectors but barely 30% with air type collectors. Present air collectors, which incorporate developments in selective coatings, are beginning to match the energy efficiency of liquid collectors while retaining simplicity, minimal maintenance, and low costs. The volume occupied by a rock store is equal to approximately 1.6 m^3 per m^2 of collector. The average collector array for a typical residence occupies an area of 30.4 m^2. A rock store for a collector of this size occupies a volume equal to $4.6\,m^3$ (e.g., rectangle of dimensions $1.5\,m \times 1.5\,m \times 2\,m$). Such a size usually does not present a significant design problem with respect to interior living spaces.

Design Considerations for TES in Rocks

The rule of thumb for determining the size of a storage rock bed specifies that a collector area of $1\,m^2$ is needed for an amount of rock of $1.6\,m^3$. This rule assumes a home insulated to high standards and situated in regions experiencing average levels of solar radiation. Regions experiencing significantly higher levels of radiation may benefit from increasing store size if there is no corresponding decrease in ambient temperature. An increase in store size in proportion to an increase in solar radiation enables the system to store more heat for use during nonsolar periods of little or no solar insolation. However, if the increase in solar radiation is accompanied by colder weather, such as that experienced in mountainous terrain, there is probably no advantage in increasing the size of the store. This is because the additional heat gain as a result of the increased radiation is dissipated faster because of the accelerated heat loss caused by the lower ambient temperatures.

Storage configurations that are nearly cubic or slightly rectangular generally perform well. This type of geometry allows for a high ratio of volume to surface area of containment. In heat stores, an increase in surface area produces a corresponding increase in heat loss. Thus, heat retention can be enhanced by keeping the surface area of the store to a minimum. A way of further reducing surface area is to utilize cylindrical containment.

Washed gravel is preferable to crushed stone as a storage medium, because the resistance to air flow of crushed stone is up to three times greater than that of washed gravel. The major constraint associated with rock beds is that the rock should be uniform in size, which requires some sort of screening. The recommended particle diameter is 2.5 cm.

The air flow through a vertical heat store should be from top to bottom while charging and from bottom to top while recuperating heat. By reversing the flow in this manner, we are able to stratify the store. Stratification can provide a warmer air supply for the home and a cooler air supply to a solar collector or other heat source. With this arrangement, efficiency is increased.

The pressure drop through a rock store should be significantly higher (minimum five times) than that in the plenums leading to the store, so as to assure a good flow distribution through the bed. One rock bed installation, for example, is designed for a $21.2\,m^2$ single glazed, selective coated, back-pass collector array. The air stream is designed for two stages with a maximum air flow rate of $4.65\,m^3/s$. A store for this configuration with 2.5-cm diameter would have a pressure drop of 5.84 mm of water. Additional facts pertaining to pressure drop that are worth noting are as follows (Dincer and Dost, 1996):

- Pressure drop through a rock bed is directly proportional to air speed.
- Pressure drop through a rock bed is inversely proportional to the area of cross section.
- A 0.028-m^3 store containing 2.5-cm-diameter rock has approximately $0.82\,m^2$ of surface area.
- A $0.093\,m^2$ store containing 7.6 cm diameter rock has about $1.3\,m^2$ of surface area.

Pressure drop and heat-transfer coefficients can be altered by adjusting these parameters.

Water–Rock Beds

One study (Moschatos, 1993) discussed in detail a type of TES that combines rock-bed and water storage. The configuration consists of a water storage surrounded by a rock-bed storage instead of insulation, as shown in Figure 3.9. The basic concept is that, for a house heated by solar collectors, heat losses could be offset by the thermal energy of water storage, or by auxiliary energy. Part of the ventilation thermal losses can be recovered by passing fresh air through the bed storage.

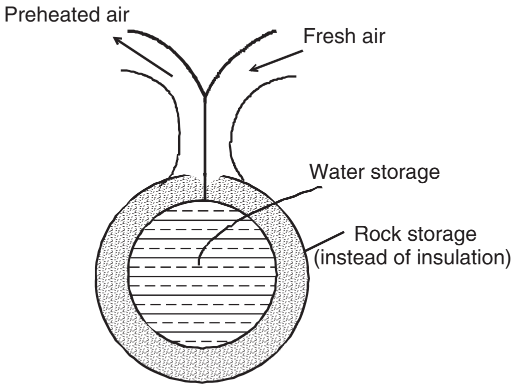


Figure 3.9 Schematic of a cylindrical combined water-rock storage (Moschatos, 1993)

The general idea of combined storage was developed for a number of houses by Thomason (1960). The differences between the storage combination of Thomason (see Figure 3.8c) and that in Figure 3.9 are

- Thomason utilizes both water and rock storage to hold solar energy, with the thermal load of the house mainly met by rock storage. The main solar TES is the water storage, which is covered by a rock bed instead of insulation. In this way, water-storage thermal losses preheat the cold fresh air for ventilation.
- Thomason's bed storage has no specific geometrical shape.

With the combined storage, (a) fresh air is preheated, (b) low-temperature thermal energy contained in the bed storage is utilized, and (c) water storage thermal losses are partially recovered.

Combining water with air/rock storage systems is becoming common for solar energy applications. Such systems aim to provide a portion of the energy needs for domestic hot water without a significant reduction in the solar energy supply for space heating needs. Conventional air–rock solar systems for space heating are pressed into service during the heating season only. Consequently, the amortization period is lengthened, because the solar energy system is inoperative for approximately six months of the year. Adding domestic hot water capability to the basic air/rock system increases the capital costs by a small fraction. So, for a relatively small additional investment, the solar energy system can provide 100% of the domestic hot water during summer and less during other seasons. The configuration for heating domestic hot water with an air/rock solar energy system can be as simple as placing a steel tank in the rock store. For such systems, tanks with glass linings, which are readily available at low prices since they are mass produced for conventional hot water heating, are often used. The glass-lined water storage tank is preferred for its long life expectancy, often greater than 20 years in solar applications.

There is relatively little thermal shock on storages associated with solar use. In conventional use, the sudden application of high-grade heat to a water store can harm the tank over time, depending on the mineral content of the water and other related factors. Compared to oil, gas, or electric heated water, which is at a very high temperature for a short period of time, solar heated water is at a low temperature for a long period of time. The actual firing or heat supply temperatures are approximately 60 °C for solar energy and over 800 °C for conventional systems.

It is advisable to provide access for visual monitoring and replacement of storage. The latter may never be needed but, if it is, it is easier to gain access through a panel than to have to destroy the storage.

In certain instances, solar collection efficiency can be improved by placing a second water reservoir in the cold end of the store. This option is sometimes considered when the water supply to the home is at a fairly low temperature (5 °C). The effect is to preheat the water entering the tank situated in the hot end of the store, and to keep the cold end of the store below the average temperature. This increases the solar heat gain and the efficiency of the collector. An additional benefit of the second water tank is an increase in thermosyphoning (natural convection) within the store, which transfers heat from the rocks to the water reservoir during periods when the solar house fan is inoperative.

There are two potential disadvantages to using this type of system. First, it may prove difficult to provide access to a water tank located under a pile of rocks. Second, the air from the house returning to the store during the heating season may nullify all or part of the preheating effect. Consequently, the addition of the secondary water reservoir should be considered for select applications only.

Storage bins may be constructed utilizing containers of water as a replacement for rocks. The containers have to be small, 1 gal or less, in order to have effective heat transfer between the air stream and the contained water. Also, the container must be of a type that withstands thermal degradation.

The most important advantage of a hybrid heating system with a water-to-air heat exchanger and storage unit is its multiple applications, including water heating, drying, space heating, and space cooling (by letting cold water flow through the system) during different times of the year. A rock-bed heat exchanger and storage unit has been successfully used for heat transfer (from water to air) and heat storage in the Thomason residential heating systems. Such systems can operate for several years, but few design investigations and parametric studies have been conducted. In one work, Choudhury and Garg (1995) conducted a performance evaluation of the system with optimized design parameters, both with and without a domestic hot water load on the system. The load is the standard hot water demand of a four person (two adults and two children) residential building in India. The system has been evaluated under both continuous and intermittent air circulation conditions (i.e., air flow rate becomes zero, when the room temperature exceeds 27 °C, which is taken to the upper limit of the comfortable range for residential buildings). No auxiliary energy is used to satisfy the space heating and the hot water demand.

3.6.4 Aquifer Thermal Energy Storage (ATES)

An aquifer is a groundwater reservoir. The word aquifer derives from the Latin words “aqua” meaning water and “ferre” meaning to carry. The material in an aquifer is highly permeable to water, and the boundary layer consists of more impermeable materials such as clay or rock. Aquifers are found throughout the world. For example, two types of aquifers are found in Sweden. The most common type consists of sand and gravel deposits left by retreating ice from the Ice Age. The second type consists of sandstone or limestone, and can be found mainly in the southern part of Sweden. Water from precipitation continuously seeps down to an aquifer and flows slowly through it until finally reaching a lake or the sea. Aquifers are often used as fresh water sources.

Aquifers often have large volumes, often exceeding millions of cubic meters, and as they consist of about 25% water they have a high TES capacity. When heat extraction and charging performances are good, high heating and cooling powers can be achieved. The amount of energy that can be stored in an aquifer depends on local conditions, such as

- allowable temperature change;
- thermal conductivity; and
- natural groundwater flows.

ATES is a concept that has been known for several decades. Aquifer systems have received worldwide attention because of their potential for large-scale and long-term TES. In its most common form, the technique involves storing excess heat in an aquifer and recovering it later during periods of heat demand. With growing concerns about global warming, the concept is receiving renewed attention as a viable means of conserving energy and reducing fossil fuel use. This increasing interest is reflected in accelerated research activities in northern European countries and Canada. In developing ATES systems, the physical processes governing the behavior of thermal energy transport in groundwater must be well understood. Numerical simulation models serve a key role in contributing to this understanding, and are thus indispensable in the design of efficient ATES facilities.

The injection of heated water into an aquifer may also be necessary for reasons other than energy conservation. For example, where water rights issues or concerns about land or water quality arise, water extracted for cooling purposes may be reinjected into the aquifer. In these situations, it is important to understand the effect of heat on the groundwater system, and to be able to predict consequences such as the accelerated precipitation of dissolved substances, or changes in the biological regime.

Research into ATES has been ongoing for several decades in North America and in Europe. Work in Denmark, for example, shows a high level of development. In the United States, pioneering research has been done at Auburn University and at the General Electric Center for Advanced Studies at Santa Barbara, California. Research into ATES is also being conducted in many other European countries, including Sweden, Germany, Denmark, and France.

Figure 3.10 illustrates the operating principle of simple ATES systems. Both heating and cooling cycles for a building are considered. Wells have been drilled to transport water to underground aquifers (underground areas of water-bearing rock, sand, or gravel). Well spacing, depth, and size are functions of the aquifer.

An aquifer storage system can be used for storage periods ranging from long to short, including daily, weekly, seasonal, or mixed cycles. To avoid undesired permanent changes of the temperature level in the aquifer, the input and output of heat must be of the same magnitude at least after a number of cycles. The system should be designed to be adjustable in case the long-term energy flows do not balance. The TES capacity should be appropriate to the heating/cooling loads.

Extensive investigations and test runs are usually needed to predict the performance of an ATES before the design of the energy system. Such preparatory work can in some cases be relatively costly.

Aquifers with groundwater, or the ground itself (soil, rock), can be used as a storage medium in ATES systems. Aquifer stores are most suited to high capacity systems. The existing capacities range in size from less than 50 to over 10,000 kW.

Utilization of ATES

ATES or groundwater energy systems utilize groundwater, and do not necessarily deplete nonrenewable resources. In some systems, external thermal energy is stored in an ATES. In others, the

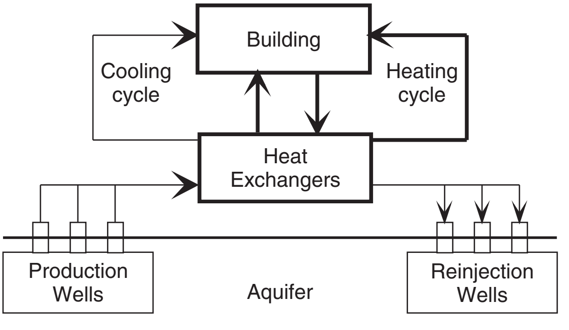


Figure 3.10 Schematic of the operation of an ATES system

natural groundwater temperatures are used. In the latter case, the system requires production wells to supply groundwater to a series of heat exchangers. In winter, heat from underground is used to preheat outside building air. In summer, direct cooling is achieved by transferring heat from buildings to the groundwater using the same principle in reverse. In both cases, the groundwater is returned to the subsurface aquifer through reinjection wells without having been exposed to any form of contamination. Over time, a thermal balance is maintained in the aquifer.

These groundwater systems can be applied to new and existing heating and cooling systems in such facilities as government buildings, business parks, residential complexes, educational institutions, hospitals, and industrial complexes. In addition, groundwater systems can be integrated into industrial process plants such as paper and textile mills, and pharmaceutical manufacturing, mining, and food processing facilities.

Groundwater energy systems provide an efficient and reliable supply of low-cost energy that can complement conventional heating and cooling systems. Furthermore, the groundwater systems are environmentally benign technology and can reduce stack emissions (e.g., carbon dioxide) and the use of chlorofluorocarbon CFCs, and can reduce electrical usage during peak demand periods.

ATES has been used successfully around the world for the seasonal storage of heat and cold energy for the purpose of heating and cooling buildings. Domestic and large-scale ATES systems are used quite widely in some countries, for example, Canada and Germany.

When heat storage is needed to match thermal demand and supply, the ground has proven to be a useful storage medium, especially for large quantities of heat and long storage durations, like seasons. Many plants use ATES to store summer solar heat for use in winter heating, and ATES for waste heat is now emerging. The efficiency of heat storage depends upon the temperature level achieved and upon the quantity of thermal losses. While heat storage in ATES in the range of 10–40 °C has been demonstrated successfully, storage at higher temperatures (e.g., up to about 150 °C) was shown to cause many problems in experimental and pilot plants in the 1980s.

Deep Confined Aquifers

Traditionally, deep confined aquifers have been preferred for ATES facilities. Some suggest that such aquifers are advantageous because (i) regional groundwater flow usually being negligible, the injected hot water is not displaced, (ii) the thickness of overburden is such that the storage is not disturbed by seasonal surface temperature variations, and (iii) the initial temperature is higher (due to the natural geothermal gradient), thus significantly reducing heat losses to confining layers. Nonetheless, unconfined aquifers are being used for ATES systems in Sweden, France, and the United States. Shallow, unconfined aquifers are easier to delineate. They are more common in many regions, and can be inexpensive when it comes to well installation and monitoring. Therefore, the use of unconfined aquifers for ATES can be advantageous, provided the energy recovery efficiency is adequate.

The aquifers used in ATES are permeable, water-bearing rock formations. Where aquifers are unavailable, a network of plastic tubing inserted into boreholes drilled into the earth can be used as underground storage, usually with water. With an aquifer system, two well fields are often tapped: one for cold storage and the other for heat. These wells, which are usually around 200 m deep, are capable of maintaining storage temperatures between 4 and 90 °C.

During the summer months, cool groundwater is extracted from one aquifer and circulated through building systems to lower the air temperature. The water, which is heated during the process, is then returned to the other aquifer for eventual use in heating in winter – a cyclic process that can be repeated indefinitely. An ATES system typically reduces cooling costs by 80% and heating costs by 40% or more, while significantly reducing emissions of greenhouse gases and ozone-depleting substances.

Environment Canada (1999) in the Atlantic region of Canada has developed a variety of tools and procedures for implementing this energy-efficient technology – including tests to determine the thermal properties of boreholes, water-treatment technologies for high-temperature applications, and environmental screening techniques – and plays an active role in the transfer of ATES technologies, both nationally and internationally.

In the mid-1990s, Environment Canada teamed up with the New Brunswick Department of the Environment, New Brunswick Power, the Canadian Electricity Association, the Panel of Energy Research and Development, and the local community to launch an aquifer-based ATES demonstration project at the Sussex Hospital in New Brunswick. The first hospital in Canada and the second in North America to adopt such a system, it has saved nearly $50,000 annually in energy consumption costs since the project began, and reduced carbon dioxide emissions by 720,000 kg annually. These savings were accomplished after the hospital had already cut its energy consumption in half by installing an energy management system. During an emergency, only small auxiliary generators are required to operate the water pumps used in heating and cooling using the ATES system.

ATES is commonly used in China and parts of Western Europe – particularly the Netherlands and Sweden, where its use is growing by 25% a year. Although office buildings remain the primary market for the technology, it is gaining ground in industrial and agricultural applications, and a new market is developing in the de-icing and cooling of roads and bridges.

The environmental benefits of ATES are illustrated in Figure 3.11, focusing on important global problems. The sizes of the circles represent the relative impact of the use of ATES technology on the emissions indicated.

The success of the Sussex Hospital ATES and other ATES projects in Canada, such as those at Saskatoon Airport and Carleton University in Ottawa, has spurred the development of several new initiatives in Ontario, Nova Scotia, and British Columbia. Other situations exist where a system of this kind can yield considerable long-term environmental benefits and reduced use of fossil fuels for heating and electricity.

Annual ATES systems use aquifers which are found near the Earth's surface. These water-bearing rocks are large geological formations that can be tapped by wells. Although some technical

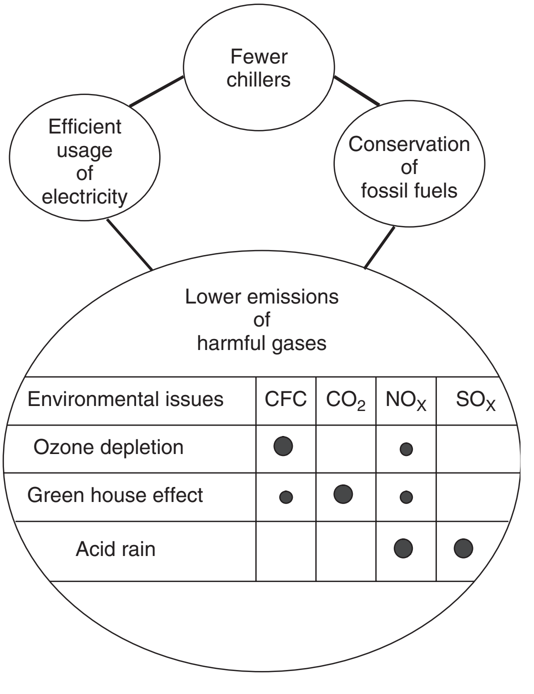


Figure 3.11 Some environmental benefits of ATES (Environment Canada, 1999)

challenges (e.g., biofouling and clogging of pipes and wells) remain to be solved, aquifers potentially offer low-cost storage for large-scale systems. The main cost is associated with access wells. However, relatively low cyclic ATES efficiencies (~70%), depending on the storage duration, may limit their use to the storage of such low-cost energy supplies as industrial waste heat.

Performance of ATES

The viability and cost effectiveness of an ATES system depend on the mechanical design and thermodynamic efficiency of the aboveground installation, as well as on the physical, chemical, and biological processes within the aquifer. The spatial and temporal variations of temperature, as well as total energy, have been found to be critical factors in determining ATES performance.

Physical processes affecting heat transport within a storage aquifer include advection, dispersion, and diffusion. The diffusion of heat depends on the thermal conductivity and heat capacity of the aquifer. In a composite medium such as an aquifer, the properties of both the fluid phase and the solid phase play important roles in heat transport, and ultimately control the recovery efficiency of stored energy. In addition, heat transfer from the aquifer system to adjacent aquitards or through the unsaturated zone to the atmosphere can be a significant process for removing heat from the ATES system. An aquitard is a zone within the earth adjacent to an aquifer that has low permeability and thus restricts the flow of groundwater from one aquifer to another. An aquitard may serve as a storage unit for groundwater.

Chemical reactions resulting from changes in temperature and from mixing of the injection water with the resident groundwater can change the porosity and permeability of the aquifer, decrease well efficiency, and increase the cost of operation and maintenance of the heat exchangers. Temperature changes can also affect the activity of subsurface microorganisms, which can lead to a decrease in permeability and increased maintenance costs.

Expansion of ATES Applications

Possible heat sources and heat users for ATES applications are listed in Table 3.8. The heat sources for many promising systems can be divided into two main groups:

- **Renewable energy sources.** Solar heat can be used with ATES to supply heat to district-heating networks, along with backup auxiliary heating systems. Solar heat can also be used with heat pumps, avoiding the need for auxiliary heating. Another ATES use may be for geothermal heating, allowing storage of excess production in summertime and to cover peaks in winter, or for storing waste heat from geothermal power plants.
- **Waste or excess heat.** The storage of waste heat from cogeneration or industrial processes (Table 3.8) may be needed on a seasonal or other cycle. ATES can also be applied as a backup for processes that use industrial waste heat, to cover heat load during periods when the industrial process is stopped (for production breaks, repairs, etc.). Similarly, ATES can be used for load leveling in a district-heating system, where the store is always charged at times of low heat demand and unloaded during peak heating periods.

The IEA study mentioned in the previous subsection shows that technical problems related to higher temperatures in ATES system may be overcome (IEA, 1990). A remaining issue is the changes in water chemistry with the drastically changing temperatures in ATES systems, resulting in clogging, scaling, corrosion, and leaching. It is possible to design and build reliable ATES plants today, but caution is necessary when working with groundwater. In the future, a range of suitable methods for various hydrogeological/hydrochemical situations and system requirements are desirable. Many opportunities exist, for promising ATES system concepts yield energy savings and reduced emissions.

Table 3.8 Some possible heat sources and heat users for ATES

Possible heat sources	Possible heat users
Renewable energy • Solar thermal (solar collectors, but also road surfaces, etc.) • Geothermal (hydrogeothermal, but also waste heat from geothermal power plants, e.g., hot dry rock) • Others (e.g., biomass combustion)	Space heating • District heating • Large buildings (houses, offices, hospitals, hotels, airports, etc.)
Waste heat • Heat and power cogeneration (likely only with high electrical efficiency) • Industrial process heat (e.g., from paper mills, steel works, etc.) • Waste incineration • Others	Industrial heat • Batch or seasonal processes such as those in sugar refineries • Drying in the food industry • Miscellaneous heat needs in many industries
Load leveling • In district-heating systems (for short- to medium-term periods)	Agriculture • Greenhouse heating • Food drying applications • Aquaculture
	De-icing and snow-melting • On roads, sport centers, airports, runways, etc.

ATES Using Heat Pumps

The concept of TES in an aquifer combined with a heat pump is relatively simple (see Figure 3.12). During the summer, cold water is extracted from a cold well and warmed by cooling a building, and then returned to a warm well in the aquifer. A heat pump can be used to chill the cold water further, if necessary. The warmed water diffuses out from the warm well, gradually raising the temperature of the aquifer. During the winter the process is reversed, with heat drawn from the warm well and the temperature boosted with the heat pump, if necessary.

The basic operational scheme of a ground-coupled heat pump with seasonal cold storage is shown in Figure 3.13 (Sanner and Chant, 1992). During heating, the ground or groundwater is cooled, while heat is supplied to the building. At the end of the heating season, enough cold is stored to run a

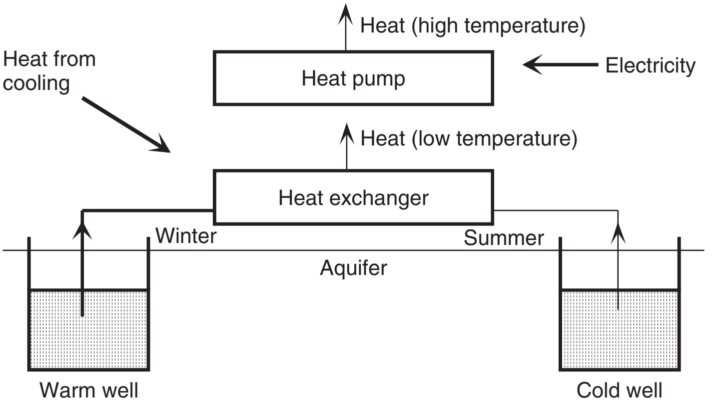


Figure 3.12 An ATES system combined with a heat pump

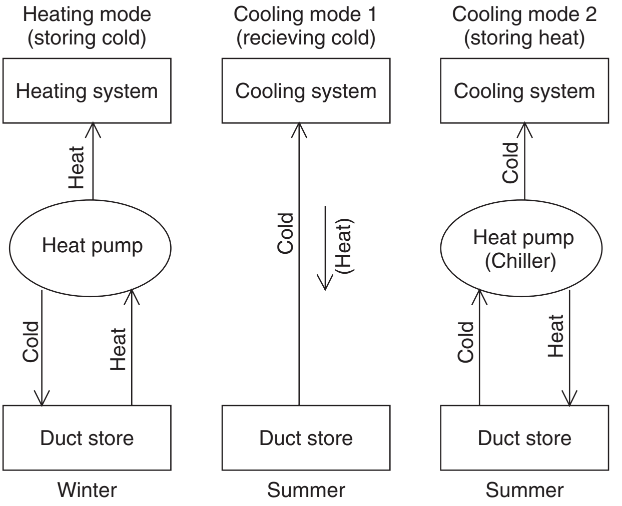


Figure 3.13 Operational principles for ATES systems using heat pumps

cooling system directly (mode 1), with cold groundwater from the injection well or cold brine from earth heat exchangers. For peak cooling loads, a backup system using the heat pump in reversed mode can be operated (mode 2). After continuously running the heat pump for space cooling for more than a few hours, temperatures in the ground may be too high for mode 1 cooling. The system should then be operated only as a conventional heat pump plant, storing heat in the ground until the beginning of the next heating season. The most cost-effective and efficient energy performance can usually be obtained by running the system in heating mode and cooling mode 1 only.

The cost effectiveness of seasonal storage depends significantly on the thermal and seasonal characteristics of the load. Storage for cooling is more cost effective for cooling systems with relatively high operating temperatures (up to 15 °C) than with more conventional temperatures (6–8 °C). By operating at higher temperatures, storage for cooling experiences reduced thermal losses, increased loading availability in winter, and reduced climatic influences on performance.

3.6.5 Solar Ponds

A salinity-gradient solar pond is an integral collection and storage device of solar energy. By virtue of having built-in TES, it can be used irrespective of time and season. In an ordinary pond or lake, when the sun's rays heat up the water, this heated water, being lighter, rises to the surface and loses its heat to the atmosphere. The net result is that the pond water remains at nearly atmospheric temperature. The solar pond technology inhibits this phenomenon by dissolving salt into the bottom layer of this pond, making it too heavy to rise to the surface, even when hot. The salt concentration increases with depth, thereby forming a salinity gradient. The sunlight which reaches the bottom of the pond remains entrapped there. The useful thermal energy is then withdrawn from the solar pond in the form of hot brine. The pre-requisites for establishing solar ponds are a large tract of land (it could be barren), a lot of sunshine, and cheaply available salt (e.g., NaCl) or bittern.

Salt-gradient solar ponds may be economically attractive in climates with less snow and in areas where land is readily available. In addition, sensible cooling storage can be added to existing facilities by creating a small pond or lake on the site. In some installations, this can be done as part of property landscaping. Cooling takes place by surface evaporation and the rate of cooling can be increased with a water spray or fountain. Ponds can be used as an outside TES system or as a means of rejecting surplus heat from refrigeration or process equipment.

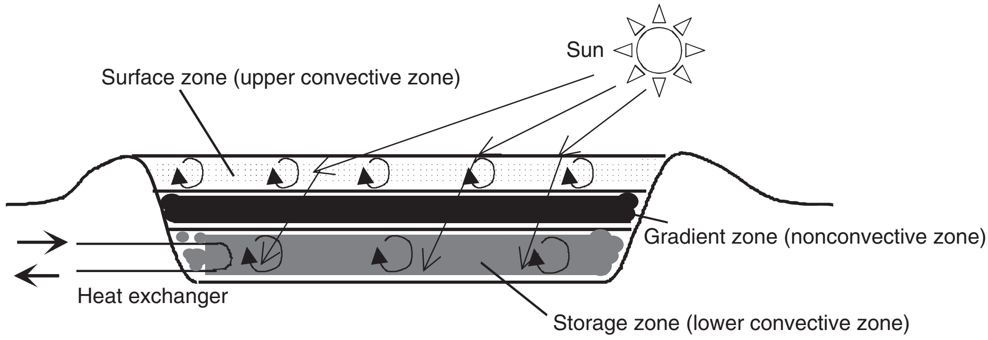


Figure 3.14 A cross-section representation of a typical salinity-gradient solar pond

Being large, deep bodies of water, solar ponds are usually sized to provide community heating. Solar ponds differ in several ways from natural ponds. Solar ponds are filled with clear water to ensure maximum penetration of sunlight. The bottom is darkened to absorb more solar radiation. Salt is added to make the water denser at the bottom and to inhibit natural convection. The cooler water on top acts as insulation and prevents evaporation. Salt water can be heated to high temperatures, even above the boiling point of fresh water.

Figure 3.14 represents a cross-section view of a typical salinity-gradient solar pond which has three regions. The top region is called the *surface zone, or upper convective zone*. The middle region is called the *gradient zone, or nonconvective zone*. The lower region is called the *storage zone or lower convective zone*. The lower zone is a homogeneous, concentrated salt solution that can be either convecting or temperature stratified. Above it, the nonconvective gradient zone constitutes a thermally insulating layer that contains a salinity gradient. This means that the water closer to the surface is always less concentrated than the water below it. The surface zone is a homogeneous layer of low-salinity brine or fresh water. If the salinity gradient is large enough, there is no convection in the gradient zone even when heat is absorbed in the lower zone, because the hotter, saltier water at the bottom of the gradient remains denser than the colder, less salty water above it. Because water is transparent to visible light but opaque to infrared radiation, the energy in the form of sunlight that reaches the lower zone and is absorbed there can escape only via conduction. The thermal conductivity of water is moderately low, and if the gradient zone has substantial thickness, heat escapes upward from the lower zone very slowly. This makes the solar pond both a thermal collector and a long-term storage device.

Solar ponds were pioneered in Israel in the early 1960s, and are simple in principle and operation. They are long-lived and require little maintenance. Heat collection and storage are accomplished in the same unit, as in passive solar structures, and the pumps and piping used to maintain the salt gradient are relatively simple. The ponds need cleaning, like a swimming pool, to keep the water transparent to light. A major advantage of solar ponds is the independence of the system. No backup is needed, because the pond's high heat capacity and enormous thermal mass can usually buffer a drop in solar supply that would force a single-dwelling unit to resort to backup heat.

3.6.6 Evacuated Solar Collector TES

Selection of a storage medium is often based on availability, durability, and cost, and tends to favor solar TES using water or rocks. One of the most promising applications of sensible TES is for solar heated residential and commercial buildings.

As mentioned earlier, in some cases rocks are preferred to water for solar energy systems. However, air/rock solar systems can allow for partial heat storage in water for domestic hot water use. Heat stored in rocks, compared with an equivalent amount of heat stored in water, occupies approximately three times as much volume. However, liquid containment systems have higher initial and maintenance costs. Economics usually favor the use of air collectors with rock storage for domestic heating applications. Water and air/rock systems are often combined for solar energy applications (Dincer *et al.*, 1997a), so as to provide a portion of energy needs for domestic hot water and space heating. Conventional air/rock solar systems for space heating are used only during the heating season, which usually lasts no more than half of the year. Hybrid hot water and air/rock systems have slightly increased the capital costs, but operate round the year by providing domestic hot water during summer.

Active solar energy systems with standard flat-plate solar heat collectors for domestic and commercial applications have some technical and operational problems. Evacuated-tube solar collectors have some advantages, and since 1980, several million tubes have been installed in over thirty countries. In 1991, the Thermomax Mazdon evacuated solar collector (Figure 3.15a) was developed. Its manifold configuration is particularly suited to North American conditions and plumbing practices. These collectors avoid many of the thermal and operational problems that occur in the flat-plate collectors and have better efficiencies (up to 80%), mainly because of their thermophysical properties (e.g., their heat-transfer rate is thousands of times greater than that of the best solid heat conductors of the same size). Some of the features of these solar collectors are as follows:

- high efficiency;
- low heat capacity and high heat-transfer rate;
- control of maximum temperature;
- high durability;
- a wide range of availability for thermal applications ranging from hot water to industrial process heat;
- free of corrosion, maintenance, and cold weather/frost problems;
- easy installation.

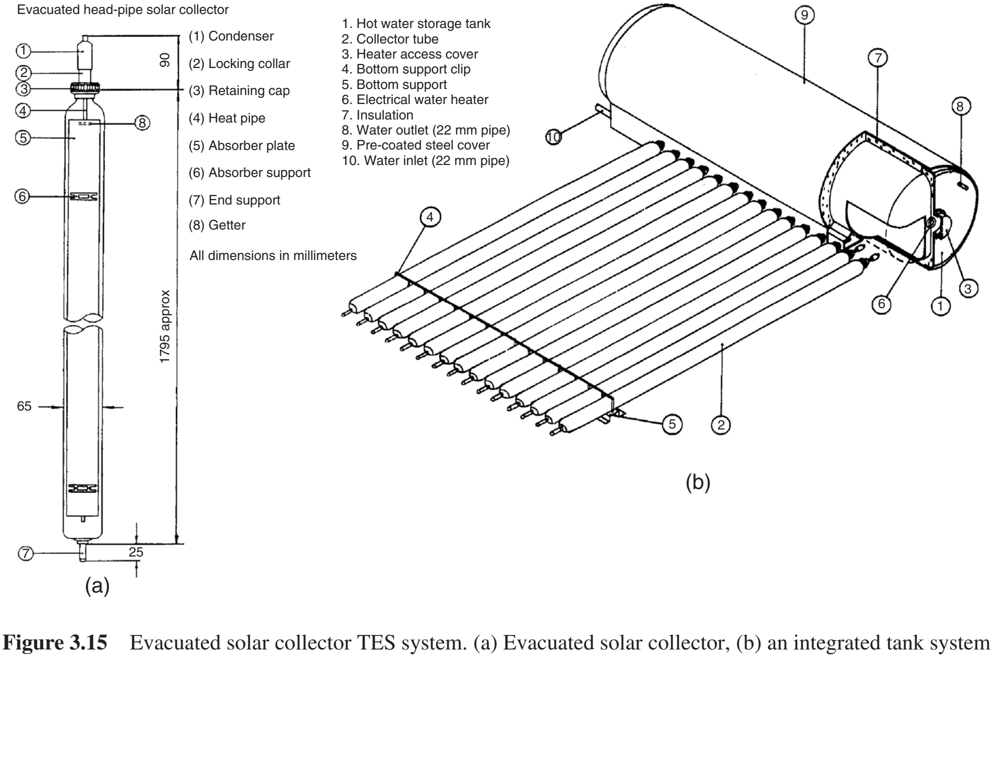


Figure 3.15 Evacuated solar collector TES system. (a) Evacuated solar collector, (b) an integrated tank system

Figure 3.15(b) shows an integrated tank system, consisting of 15 evacuated solar collector tubes and a 170-L hot water storage tank. The tank is made from a high-grade stainless steel, having at least 2.5% molybdenum content, sealed in a weather-resistant metal cover. There is a thick polyurethane foam insulation jacket that lies between the tank and the steel cover. This solar energy system produces high water temperatures, eliminating the need for large and cumbersome water storage tanks. A large volume of warm water can be obtained by mixing cold water with the hot water from the unit. During the operation, the maximum chloride concentration of the water in the tank should not exceed 40 ppm in order to avoid corrosive effects.

3.7 Latent TES

Effective utilization of time-dependent energy resources requires appropriate TES methods to reduce the time and rate mismatch between energy supply and demand. TES provides a high degree of flexibility since it can be integrated with a variety of energy technologies, for example, solar collectors, biofuel combustors, heat pumps, and off-peak electricity generators.

The heat transfer which occurs when a substance changes from one phase to another is called the *latent heat*. The latent heat change is usually much higher than the sensible heat change for a given medium, which is related to its specific heat. When water turns to steam, the latent heat change is of the order of 2 MJ/kg.

Most practical systems using phase-change energy storage involve solutions of salts in water. Several problems are associated with such systems, which includes the following:

- Supercooling of the PCM may take place, rather than crystallization with heat release. This problem can be avoided partially by adding small crystals as nucleating agents.
- It is difficult to build a heat exchanger capable of dealing with the agglomeration of varying sizes of crystals that float in the liquid.
- The system operation cannot be completely reversed.

Any latent heat TES system must possess at least the following three components (Abhat, 1983):

- A heat storage substance that undergoes a phase transition within the desired operating temperature range, and wherein the bulk of the heat added is stored as latent heat.
- A containment for the storage substance.
- A heat-exchange surface for transferring heat from the heat source to the storage substance and from the latter to the heat sink, for example, from a solar collector to the latent TES substance to the load loop.

Some systems use either $Na_2SO_4 \cdot 10 \cdot H_2O$ or $CaCl_2 \cdot 6H_2O$ crystals as their storage media, and employ a heat-exchange oil. The oil is pumped in at the bottom of the storage and rises in globules through the fluid without mixing. Other promising latent TES reactions are those of intercrystalline changes. Many of these take place at relatively high temperatures.

Solar energy applications require large TES capacities in order to cover a minimum of 1–2 days of thermal demand. This capacity is commonly achieved by sensible heat storage in large water tanks. An alternative is offered by latent heat storage systems, where thermal energy is stored as latent heat in substances undergoing a phase transition, for example, the heat of fusion in the solid–liquid transition. The main advantages of latent TES systems are high TES capacities per unit mass compared to those of sensible heat systems, and a small temperature range of operation since the heat interaction occurs at constant temperature. There is no gradual decline in temperature as heat is removed from the PCM.

Salt compounds that absorb a large amount of heat during melting are useful for energy storage. Eutectic salts and salt hydrates are widely used. Glauber's salt (sodium sulfate decahydrate) is a leading PCM, because it has a high heat-storage capacity (280 kJ/kg) and a phase-change temperature that is compatible with solar energy systems (31.5 °C).

PCM can be contained in rods or plastic envelopes to facilitate the freeze–thaw cycle. These small modules, and the small number of modules required for storage, make phase-change storage especially suitable for use in conventional design and for retrofitting.

In the Mattapoisett house in Massachusetts, which is 60% heated by passive solar gain, 8.5 m^3 of Glauber's salt is located in the ceiling. The phase-change storage has been demonstrated to lower the peak indoor temperatures. Table salt (NaCl) can be added to the PCM, lowering the melting point to about 22.7 °C. Because heat is then absorbed at a lower temperature, the house only reaches about 26.6 °C on a clear winter's day instead of the 29.4 °C or as often seen in passive solar structures (Lane, 1988).

The three most favored storage media for solar energy systems, water, rock, and Glauber's salt, vary considerably in price and required volume. For 9 m^2 of collector area (assuming a 20 °C temperature swing), the storage cost for water is $54 and for Glauber's salt it is $146. However, only 0.18 m^3 of Glauber's salt is required, which is one-quarter of the necessary 0.72 m^3 of water. Rock storage for the same collector would cost $217 at $8/t for the required 2.46 m^3. This option would seem the least appealing, but it is nonetheless established and widely used. For example, the Lof home in Denver has been heated by a rock storage system for several decades (Tomlinson and Kannberg, 1990).

Latent TES is a promising storage technique, since it provides a high energy storage density, second only to chemical energy storage, and can store and release heat at a constant temperature corresponding to the phase transition temperature of the heat-storage medium.

Another important material category capable of storing energy through phase change is paraffin waxes. These have the advantage of very high stability over repeated cycles of latent TES operation without degradation. Several types of heat exchangers have been used to retrieve the energy from this storage medium: a cylindrical pipe, a single radial-finned pipe, and a multiple radial-finned pipe. Experimental tests have been performed for each of the different configurations, and the relative merits of each discussed in terms of heat-exchange properties and total energy exchanged.

3.7.1 Operational Aspects of Latent TES

At present, problems concerning the inability to completely reverse the storing process limit the practical applications of chemical storage media. On the other hand, storage media that undergo physical processes can usually have the storage process totally reversed, but involve less TES per unit weight of the device than chemical storage. Latent TES systems thus have the advantage of compactness in comparison with sensible TES devices (as well as the operational advantage of a nearly constant storage-cycle temperature).

Among the thermodynamic phase changes at a constant temperature with the absorption or release of latent heat, the most suitable ones for TES are the solid–liquid and solid–solid transitions. Solid–gas transitions, even though they often involve the largest heat interactions per unit weight, present the disadvantage of very large volume changes.

The most important criteria to be met by the storage material for a latent TES in which the material undergoes a solid–liquid or a solid–solid phase transition are as follows:

- high transition enthalpy per unit mass;
- ability to fully reverse the transition;
- adequate transition temperature;
- chemical stability and compatibility with the container (if present);
- limited volume change with the transition;
- nontoxicity;
- low cost, in relation to the foreseen application.

3.7.2 Phase Change Materials (PCMs)

When a material melts or vaporizes, it absorbs heat; when it changes to a solid (crystallizes) or to a liquid (condenses), it releases this heat. This phase change is used for storing heat in PCMs. Typical PCMs are water/ice, salt hydrates, and certain polymers. Since energy densities for latent TES exceed those for sensible TES, smaller and lighter storage devices and lower storage losses normally result.

Like ice and water, eutectic salts have been used as storage media for many decades. Perhaps the oldest application of a PCM for TES was the use of seat warmers for British railroad cars in the late 1800s. During cold winter days, a PCM, sodium thiosulfate pentahydrate, that melts and freezes at 44.4 °C was used. The PCM was filled into metal or rubber bags.

Other early applications of PCMs included "eutectic plates" used for cold storage in trucking and railroad transportation applications. Another important application of PCMs was in association with space technology, with NASA sponsoring a project on PCM applications for thermal control of electronic packages.

The first experimental application of PCMs for cool storage occurred in the early 1970s at the University of Delaware. The University's Institute of Energy Conversion undertook the design and construction of a solar energy laboratory that became known as Solar One, located on the Newark, Delaware, campus. Dr. Maria Telkes, a leader in the research and development of eutectic salts, was selected to direct the institute's Thermal Energy Applications program. The design of the Solar One building incorporated several hydrate-based storage systems. One material was used in association with solar collectors for heat storage. In the same sheet metal bin were placed containers of a Glauber's salt mixture that melts and freezes at 12.7 °C.

During the late 1970s and 1980s, several organizations offered phase change products for solar heat storage. For instance, Dow Chemical provided a technically successful product that melts and freezes at 27.2 °C, whose market presence declined in the 1980s with the solar industry in general.

In 1982, Transphase Systems Inc. installed the first eutectic salt storage system for cool storage to serve a commercial or industrial building (Ames, 1989).

Like chilled-water storage systems, the 8.3 °C eutectic phase change temperature requires conventional chilled-water temperatures (5.5 °C) to charge the TES system. These temperatures allow new or existing centrifugal, screw, or reciprocating chillers to be used to charge the TES system, and make eutectics particular1y appropriate for retrofit applications. The 5.5 °C charging temperature also enables the chiller to operate at high suction temperatures and compressor efficiencies as low as 0.55 kW/t.

Advantageous use of a PCM's latent heat of fusion allows a TES to be moderate in size (about $0.155\,m^3$ per ton for the entire TES system, which includes piping headers and water in the tank). The storage capacity is based upon the amount of PCM frozen, and is not a temperature difference across the cooling coils.

The PCM is often contained in rugged, self-stacking, water-impermeable containers made of a high-density polyethylene. In Ames (1989), the containers measure $0.6\,m \times 0.2\,m \times 0.045\,m$, and are hermetically and redundantly sealed. The containers are designed with a surface-to-volume ratio of $24\,m^{-1}$ for maximum heat transfer; and provide 0.00635 m of space for water to pass between the containers in a meandering flow pattern. The eutectic salt does not expand or contract when it freezes and melts; so, there is no fatigue on the plastic container. The eutectic salt-filled containers are placed in a tank, typically in a below-grade concrete or gunite structure. The containers occupy about two-thirds of the tank's volume, so that one-third of the tank is occupied by the water used as the heat-transfer medium. No glycol or other water-freezing-point depressant is used. The eutectic salt density is about 1.5 times that of water, so that the containers do not float or expand when the PCM freezes and the heat transfer/container spacing arrangement is maintained throughout the melt/freeze cycle. The top of the tank is designed for heavy truck traffic, and used as a parking lot. Thus, the tank does not use or alter above-grade space and may be placed away from the chiller plant.

Longevity, or the repeated use of a containerized PCM over 20 or more years and thousands of freeze/thaw cycles is one of eutectic salt's greatest strengths as a thermal storage medium. Because it is a passive system with no mechanical parts, the storage system is maintenance-free (apart from water treatment).

For the PCM with the 8.3 °C phase change temperature, the eutectic has been cycled in the field for 6.5 years with complete retention of thermal storage capacity. Also, the PCM has been subjected to accelerated life cycling equivalent to 12 years of performance with no loss of capacity. With the physical equilibrium of the PCM established after the first few cycles, the phase change appears to be stable and the TES capacity constant indefinitely, or at least as long as the life of chiller equipment used to freeze the PCM.

Paraffins

A large number of organic compounds suitable to be storage media for solar heating have been investigated in recent decades. The most promising candidates seem to be the normal paraffins. Their solid–liquid transitions (fusions) satisfactorily meet seven important criteria for PCMs. For example, the heat of fusion has a mean value of 35–40 kcal/kg, there are no problems in reversing the phase change, and the transition points vary considerably with the number of carbon atoms in the chains. Also, the normal paraffins are chemically inert, nontoxic, and available at reasonably low cost. The change of volume with the transition, which is in the order of 10%, could represent a minor problem.

Zeolites

The zeolites are naturally occurring minerals. Their high heat of adsorption and ability to hydrate and dehydrate, while maintaining structural stability have been found to be useful in various thermal storage and solar refrigeration systems. This hygroscopic property coupled with the rapid exothermic reaction that occurs when zeolites are taken from a dehydrated to a hydrated form (when the heat of adsorption is released) makes natural zeolites an effective storage material for solar and waste heat energy.

Low energy density and time of availability have been key problems in the use of solar energy and waste heat. Commercial TES systems have been developed incorporating GSA (2000) zeolites to overcome these problems. These systems are capable of utilizing solar heat, industrial waste heat, and heat from other sources, thereby converting underutilized resources into useful energy. A typical means of using zeolites as a heat storage medium is illustrated in Figure 3.16. The capacity of natural zeolites to store thermal energy and adsorb the water vapor used in that energy interaction comes from their honeycomb structure and resultant high internal surface area.

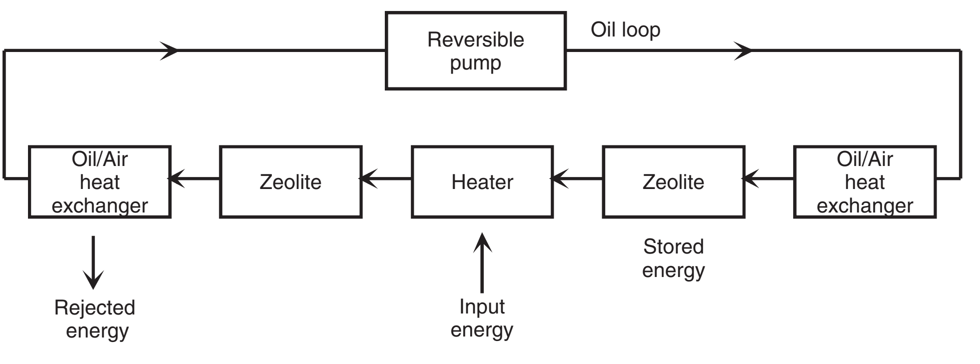


Figure 3.16 A process for using GSA zeolites as a heat storage media (GSA, 2000)

When charged, GSA zeolites can store energy as latent heat indefinitely if maintained in a controlled environment and not exposed to water vapor. This stored energy can be liberated as needed simply through the addition of controlled amounts of water vapor, which initiates the exothermic reaction. Most other storage media do not possess this property. TES units using natural zeolites can reduce the dependence on secondary/backup heating systems, and allow for efficient and safe use of waste heat.

Requirements of PCMs

Latent TES in the temperature range 0–120 °C is of interest for a variety of low-temperature applications, such as space heating, domestic hot water production, heat-pump-assisted space heating, greenhouse heating, solar cooling, and so on. The development of dependable TES systems for these and other applications requires a good understanding of heat-of-fusion storage materials and heat exchangers.

Knowledge of the melting and freezing characteristics of PCMs, their ability to undergo thermal cycling, and their compatibility with construction materials is essential for assessing the short- and long-term performance of a latent TES. Using two different measurement techniques (e.g., differential scanning calorimetry and thermal analysis), the melting and freezing behavior of PCMs can be determined. Commercial paraffins are characterized by two phase transitions (solid–liquid and solid–solid) that occur over a large temperature range, depending on the paraffin concerned. *n*-paraffins are usually preferred in comparison to their iso-counterparts, as the desired solid-to-liquid phase transition is generally restricted to a narrow temperature range. Fatty acids are organic materials with excellent melting and freezing characteristics and may have a good future potential, if their costs can be reduced. Inorganic salt hydrates, on the other hand, must be carefully examined for congruent, “semi-congruent,” or incongruent melting substances with the aid of phase diagrams. Incongruent melting in a salt hydrate may be “modified” to overcome decomposition by adding suspension media, or extra water, or other substances that shift the peritectic point. The use of salt hydrates in hermetically sealed containers is normally recommended. Also, the use of metallic surfaces to promote heterogeneous nucleation in a salt hydrate is seen to reduce the supercooling of most salt hydrates to a considerable extent. Thermal cycling and corrosion behavior are also of importance in the appropriate choice of materials as they affect the life of a latent heat store.

Characterization of PCMs

Many characteristics are desired of a PCM. Since no material can satisfy all of the desires, the choice of a PCM for a given application requires careful examination of the properties of the various candidates, weighing of their relative merits and shortcomings, and, in some cases, a certain degree of compromise. The properties of many PCMs were investigated and reported earlier (Lane, 1988). It should be noted, however, that properties of industrial-grade products, which are used in practical applications, may deviate broadly from reported values because of the presence of impurities, composition variations (mixtures, distillation cuts), and chain-length distribution (in the case of polymers). Dilution by additives, such as the stabilizing agents required by salt hydrates, also modify thermal properties and, in particular, TES capacity. Selections should be based on assayed values of fully formulated products, whenever feasible.

Difficulties with PCMs

Although significant advances have been made, some major hurdles still remain in the development of reliable and practical storage systems utilizing salt hydrates and similar inorganic substances:

- Difficulties in obtaining an optimal match between transition zone and operating range, because of the small number of materials available in the temperature range of interest.

- Uncertainties concerning the long-term thermal behavior, despite testing over a number of cycles generally much below the number of cycles that can be expected during the useful life of a storage system.
- Increased costs and reduced effective storage capacities because of the diluting effect of stabilizing additives.
- The potential for slow loss from water for encapsulated hydrates, and a resulting drift in thermal behavior.

During the last decades, attention was focused on a new class of materials: low-volatility, anhydrous organic substances such as polyethylene glycol, fatty acids and their derivatives, and paraffins. Those materials were not viewed as high-potential candidates in early studies, because they were costlier than common salt hydrates, they have somewhat lower heat storage capacities per unit volume, and, possibly, because of a bias against petroleum derivatives. Recent studies have shown that some of these materials have advantages that outweigh these shortcomings. The advantages include physical and chemical stability, good thermal behavior, and an adjustable transition zone. Paraffins appear particularly well suited for applications related to energy conservation in buildings and solar energy.

Expectations of PCMs

Numerous organic and inorganic PCMs melt with a high heat of fusion in the temperature range 0–120 °C. However, for their employment as heat storage materials in TES systems, PCMs must also possess certain desirable thermodynamic, kinetic, chemical, technical, and economic characteristics. Some of the criteria considered in evaluating PCMs follow (Abhat, (1983); Dincer *et al.*, 1997b):

Thermodynamic criteria:

- a melting point at the desired operating temperature;
- a high latent heat of fusion per unit mass, so that less amount of material stores a given amount of energy;
- a high density, so that less volume is occupied by the material;
- a high specific heat, so that significant sensible TES can also occur;
- a high thermal conductivity, so that small temperature differences are needed for charging and discharging the storage;
- congruent melting, that is, the material should melt completely, so that the liquid and solid phases are homogeneous (this avoids the difference in densities between solid and liquid that causes segregation, resulting in changes in the chemical composition of the material); and
- small volume changes during phase transition, so that a simple containment and heat exchanger can be used.

Kinetic criterion:

- little or no supercooling during freezing, that is, the melt should crystallize at its freezing point. This criterion can be achieved through a high rate of nucleation and growth rate of the crystals. Supercooling may be suppressed by introducing a nucleating agent or a cold trigger into the storage material.

Chemical criteria:

- chemical stability;
- no susceptibility to chemical decomposition, so that a long operation life is possible;

- noncorrosive behavior to construction materials; and
- nontoxic, nonflammable, and nonexplosive characteristics.

Technical criteria:

- simplicity,
- applicability,
- effectiveness,
- compactness,
- compatibility,
- viability, and
- reliability.

Economic criteria:

- commercial availability, and
- low cost.

Applications of PCMs

There are many different methods of using PCM storage systems for heating or cooling buildings, as demonstrated by the following concepts (Lane, 1988):

- A PCM melting at 5–15 °C could be used for cool TES. The PCM is frozen by operating a chiller at night, when electricity demand and prices are low, and melted during the day to cool the building.
- A PCM melting near room temperature, for example, $CaCl_2 \cdot 6H_2O$, which has a melting point (m.p.) of 27 °C, could be incorporated into a building structure to temper diurnal swings in ambient temperature.
- A building could be heated and cooled using heat pumps that are connected to circulating water tempered by a PCM melting at 20–35 °C, for example, $CaCl_2 \cdot 6H_2O$ (m.p. = 27 °C).
- A solar hot-air heating system could use a PCM melting at 25–30 °C, for example, $CaCl_2 \cdot 6H_2O$, to provide night-time heating and as a preheat for daytime heating.
- A solar hot-air heating system could use a PCM melting at 40–60 °C, for example, $Mg(NO_3)_2 \cdot 6H_2O{-}MgCl_2 \cdot 6H_2O$ eutectic (m.p. = 58 °C), for day and night heating.
- Domestic hot water could be preheated in a tank filled with an encapsulated PCM melting at 55–70 °C, for example, $Mg(NO_3)_2 \cdot 6H_2O{-}MgCl_2 \cdot 6H_2O$ eutectic.
- A solar hot-water baseboard system could employ a PCM melting at 60–95 °C, for example, $Mg(NO_3)_2 \cdot 6H_2O$ (m.p. = 89 °C).
- Off-peak electricity could be used to melt a PCM (with m.p. above 25 °C) to heat a building during later periods.
- Concentrated solar energy could be used with a PCM melting at 100–175 °C, for example, $Mg(NO_3)_2 \cdot 6H_2O$ (m.p. = 117 °C), to drive an absorption air-conditioner.

Evaluation of PCMs

In the evaluation and selection of a PCM, a good understanding of various aspects, including freezing or solidification, supercooling, nucleation, thermal cycling, encapsulation, and compatibility is needed.

- **Freezing or solidification.** Many materials are not suitable as PCMs because of their freezing or solidification behavior. Some have incongruent freezing behavior. Others crystallize exceedingly slowly, form viscous mixtures, or are not stable over the range of temperatures. Some materials have near-congruent freezing behavior and so may be suitable as PCMs. To overcome the solidification problem, the nucleation rate can be increased by two methods: homogeneous nucleation and heterogeneous nucleation.

- **Supercooling.** A major problem associated with salt hydrates as PCMs is the fact that they tend to supercool considerably. This behavior is of major importance, and has not always received sufficient attention from workers in the field. The reason for the high degree of supercooling is the fact that either the rate of nucleation (of crystals from the melt) or the rate of growth of these nuclei (or both) is very slow. Therefore, as the melt is cooled, it does not solidify at the thermodynamic melting point. Thus, the advantage of the material for heat storage is reduced. The reason for the strong tendency to supercool is well understood. Some empirical evidence connects the tendency to supercool with the viscosity of the melt at the melting point. Materials with high viscosity in the liquid state have low diffusion coefficients for their constituent atoms (or ions), and these may be unable to rearrange themselves to form a solid; instead the liquid supercools. Supercooling occurs when, in attempting to freeze the material, the temperature drops well below the melting point before freezing initiates. Once the freezing process begins, the temperature rises to the melting point where it remains until the material is entirely frozen. Supercooling behavior is undesirable in heat storage systems. If excessive, it can prevent the withdrawal of stored heat from the PCM.
- **Nucleation.** Supercooling can often be mitigated by adding nucleating materials. Some success has been attained by using additives with a crystal structure similar to that of the PCM. Often this fails. Usually nucleating additives are discovered by trial and error. Using these approaches, effective nucleating additives have been discovered for zinc nitrate hexahydrate, calcium chloride hexahydrate, magnesium chloride hexahydrate, magnesium nitrate hexahydrate and its eutectics with magnesium chloride hexahydrate or ammonium nitrate. In homogeneous nucleation, the rate of nucleation of crystals from the melt is increased without adding any foreign materials. One way in which this can be done is to use ultrasonic waves in which we stir the liquid, and thus increase the diffusion of ions in the melt; they also create cavities that act as nucleation centers and, finally, they break up the forming crystals and distribute them through the melt, creating new nucleation centers. Many crystals, such as sodium thiosulfate and potassium alums, have been nucleated from more dilute solutions. Also, other classes of materials, such as metals and organic crystals, have been nucleated by ultrasonic waves. In heterogeneous nucleation, the walls of the container, or some impurity present within the melt, act as a catalyst for nucleation by providing a substrate on which the nuclei can form. In order for an impurity to be an effective nucleating agent, it should satisfy the following criteria:
  - have a melting point higher than the highest temperature reached by the energy storage material in the storage cycle;
  - be insoluble in water at all temperatures;
  - not form solid solutions with the salt hydrate;
  - have a crystal structure similar to that of the salt hydrate;
  - have unit cell dimensions that do not vary by more than 10% from those of the salt hydrate; and
  - not chemically react with the hydrate.
- **Thermal cycling.** Practical heat storage PCMs must be able to undergo repetitive cycles of freezing and thawing. Some unsuitable materials exhibit changes within a relatively short time. Some experimental results demonstrate this. After 21 cycles from 95 to 20 °C, palmitic acid, normally white, takes on a yellowish color, and the melting point diminishes by 2 °C. The eutectic of 25.1% propionamide and 74.9% palmitic acid progressively discolors from white to yellow, orange, and then black, although little change occurs in the freezing curve (Lane, 1988).
- **Encapsulation.** Successful utilization of a PCM requires a means of containment. For active solar systems with a liquid heat-transfer medium, tanks with coil-type heat exchangers are appropriate. For passive or air-cooled active solar systems, much effort has centered on the packaging of a mass of PCM in a sealed container, which itself serves as the heat exchange surface.

Potential containers include steel cans, plastic bottles, polyethylene, and polypropylene bottles, high-density polyethylene pipe, flexible plastic film packages, and plastic tubes. The choice of the construction material for the container of a PCM is important. Appropriate tests that are realistic and representative of usage conditions are needed in any product development. The container material should be an effective barrier that prevents loss of material or water or, when the PCM is hygroscopic, gain water. Oxygen penetration and subsequent oxidization may also be detrimental. The encapsulating material should also be a good heat conductor, so that it facilitates effective heat transfer, and be mechanically resistant to damage from handling, processing, and transport. Systems based on salt hydrates may sometimes have encapsulation problems, particularly in early designs, because of corrosion and fatigue for metals, or water loss through plastics.

- **Compatibility.** To determine the suitability of encapsulant materials, PCMs are subject to compatibility tests with packaging materials. For example, a plastic–aluminum foil laminate is not suitable for use with organic PCMs, because the heat-sealed seam is attacked by the organic material, and it is unsuitable for temperatures above 70 °C. Paraffins are compatible with most metals and alloys, but they can impregnate and soften some plastics.

Characteristics and Thermophysical Properties of PCMs

The precise determination of the transition zone at fusion and at solidification is essential for the optimal design of a latent TES unit, since the transition zone of the PCM must match, sometimes exactly, the intended operating temperature span of the latent TES unit. Pure substances have exact melting and freezing points, but they are affected by impurities even in small amounts. Polymers and mixtures have a more complex behavior, with a true, and sometimes very broad, transition zone over which fusion or solidification is progressive. Salt hydrates, when pure, behave as pure substances and afford little design flexibility. Design options based on salt hydrates are rather limited in the range 15–65 °C, because their fusion–solidification behavior cannot be easily modified. Thermophysical properties of paraffins generally change monotonously as a function of chain length (e.g., melting temperature). An important advantage of paraffins is that neighboring homologs are totally compatible and that stable, homogeneous mixtures can be readily prepared. It is thus possible to design paraffin-based PCMs meeting a wide variety of transition-zone specifications (Paris *et al*., 1993). Formulating a compound PCM for a given transition range is a key task in which composition, thermophysical properties, and most other characteristics are fixed. However, properties of mixtures cannot be calculated from simple interpolation of properties of pure components, and therefore experimental characterization is required.

The heat storage capacity of a latent TES is primarily a function of the heat of fusion of the PCM. The heat of fusion of paraffins increases with chain length until 24 and is generally higher than that of salt hydrates. The heat of fusion of salt hydrates increases with the degree of hydration, but higher hydration often comes with incongruent or semicongruent fusion (Lane, 1988).

The specific heats of solid and liquid PCMs are not critical factors in the performance of a system unless the operating span of the storage unit far exceeds the transition zone of the PCM. Then, the mode of operation tends toward sensible heat storage and the relative contribution of latent heat to its performance diminishes. Since a PCM changes temperature during operation, heat transfer over a charge (or discharge) cycle includes sensible heat. Paraffins generally have higher specific heats in both the solid and liquid states than salt hydrates.

Heat transfer to and from a storage unit strongly depends on the thermal conductivities of the solid and liquid PCM. The higher the conductivities, the more efficient the heat transfer for a given design. However, the heat-transfer phenomena during fusion or solidification of a PCM are very complex because of the moving solid–liquid interface, the density and conductivity differences between the two phases, and the induced movements in the liquid phase. Salt hydrates have higher thermal conductivities than those of paraffins.

The density of a PCM is important, because it affects its storage effectiveness per unit volume. Salt hydrates are generally more dense than paraffins, but are slightly more effective on a per volume basis, despite a slightly lower heat of fusion. The rate of crystallization of a salt hydrate can be low, and can become the limiting factor in the rate of heat storage and restitution. Crystallization is generally more rapid for paraffins, and heat-transfer mechanisms are then the limiting factors. In addition, paraffins exhibit little or no supercooling, which is frequent and often significant in magnitude with salt hydrates.

Paraffins have very low vapor pressures, which leads to low long-term loss of material and flammability. Salt hydrates have significantly higher vapor pressures, which induce water loss and progressive changes of thermal behavior. The vapor pressure of salt hydrates increases with the degree of hydration, and salt hydrates exhibit variable chemical stability and can be subject to long-term degradation by oxidization, hydrolysis, thermal decomposition, and other reactions. Some salt hydrates are very corrosive in the presence of water. Paraffins are very stable and unreactive, but slow oxidization may occur when they are exposed to air at elevated temperatures over extended periods. Paraffins are not corrosive.

Salt hydrates are neither toxic nor flammable. They can be irritants, and contact with skin and eyes should be avoided. Paraffins are innocuous, being neither toxic nor irritants. Although paraffins are flammable in the presence of oxygen and at elevated temperatures, because of their low vapor pressure they are considered low fire hazards. Compliance with safety codes for products containing paraffin-based PCMs should not present particular difficulties if this point is properly addressed in the design stage.

Table 3.9 presents experimental data on melting temperature, heat of fusion, thermal conductivity and density data for several organic and inorganic compounds, aromatics, and fatty acids.

Latent TES using PCMs provides an effective way to store thermal energy from a range of sources, high storage capacity, and heat recovery at almost constant temperatures. The relatively constant temperature of storage can maximize solar collector efficiency, where relevant.

Performance of Latent TES with PCMs

To improve the performance of latent TES with PCMs, nucleating agents and thickeners have been used to prevent supercooling and phase separation. Also, extended heat-transfer surfaces can be used to enhance the heat transfer from PCM to the heat-transfer tubes. While many studies on the latent TES systems have been performed at relatively low temperatures (below 100 °C) for TES in home heating and cooling units, few studies have been undertaken for higher temperature heat (above 200 °C), as is applicable for some solar energy systems and intermediate-temperature latent TES. Magnesium chloride hexahydrate ($MgCl_2{\cdot}6H_2O$), with a melting temperature of 116.7 °C, is an attractive high-temperature PCM in terms of cost, material compatibility, and thermophysical properties (a specific latent heat of 168.8 kJ/kg, a specific heat of 2.25 kJ/kgK in the solid state and 2.61 kJ/kgK in the liquid state, a thermal conductivity of 0.704 W/mK in the solid state and 0.570 W/mK in the liquid state, and a density of 1570 kg/m^3 in the solid state and 1450 kg/m^3 in the liquid state) (Choi and Kim, 1995).

Sharma *et al*. (1992) showed that the acetamide–sodium bromide eutectic is a promising latent TES material that could find use in such applications as commercial and laundry water heating, process heating, domestic water and air heating, crop drying, and food warming. Vaccarino *et al*. (1985) conducted an experimental study on the low-temperature latent TES and found that two mixtures containing $Ca(NO_3)_2{\cdot}4H_2O$ and KNO_3 or $Mg(NO_3)_2{\cdot}6H_2O$ are suitable PCMs for passive heating of such facilities as buildings and greenhouses in the temperature range 15–35 °C, and for domestic hot water production and active space heating in the range 25–55 °C.

Although PCMs must usually be placed in capsules or other vessels to prevent them from mixing with heat carriers after melting, concepts have recently been developed that permit PCMs to come into direct contact with heat carriers, thereby providing good heat exchange without the usual heat exchangers or capsules. In such a system, an immiscible fluid is bubbled into the storage bottom

Table 3.9 Measured thermophysical data of some PCMs

Compound	Melting temp. (°C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/mK)	Density (kg/m^3)
Inorganics				
$MgCl_2 \cdot 6H_2O$	117	168.6	0.570 (liquid, 120 °C)	1450 (liquid, 120 °C)
			0.694 (solid, 90 °C)	1569 (solid, 20 °C)
$Mg(NO_3)_2 \cdot 6H_2O$	89	162.8	0.490 (liquid, 95 °C)	1550 (liquid, 94 °C)
			0.611 (solid, 37 °C)	1636 (solid, 25 °C)
$Ba(OH)_2 \cdot 8H_2O$	78	265.7	0.653 (liquid, 85.7 °C)	1937 (liquid, 84 °C)
			1.255 (solid, 23 °C)	2070 (solid, 24 °C)
$Zn(NO_3)_2 \cdot 6H_2O$	36			1828 (liquid, 36 °C)
		146.9	0.464 (liquid, 39.9 °C)	1937 (liquid, 84 °C)
$CaBr_2 \cdot 6H_2O$	34		–	1956 (liquid, 35 °C)
		115.5	–	2194 (solid, 24 °C)
$CaCl_2 \cdot 6H_2O$	29		–	1562 (liquid, 32 °C)
		190.8	0.540 (liquid, 38.7 °C)	1802 (solid, 24 °C)
			1.088 (solid, 23 °C)	
Organics				
Paraffin wax	64	173.6	0.167 (liquid, 63.5 °C)	790 (liquid, 65 °C)
			0.346 (solid, 33.6 °C)	916 (solid, 24 °C)
Polyglycol E400	8	99.6	0.187 (liquid, 38.6 °C)	1125 (liquid, 25 °C)
			–	1228 (solid, 3 °C)
Polyglycol E600	22	127.2	0.187 (liquid, 38.6 °C)	1126 (liquid, 25 °C)
			–	1232 (solid, 4 °C)
Polyglycol E6000	66	190.0	–	1085 (liquid, 70 °C)
			–	1212 (solid, 25 °C)
Fatty acids				
Stearic acid	69	202.5	–	848 (liquid, 70 °C)
				965 (solid, 24 °C)
Palmitic acid	64	185.4	0.162 (liquid, 68.4 °C)	850 (liquid, 65 °C)
			–	989 (solid, 24 °C)
Capric acid	32	152.7	0.153 (liquid, 38.5 °C)	878 (liquid, 45 °C)
			–	1004 (solid, 24 °C)
Caprylic acid	16	148.5	0.149 (liquid, 38.6 °C)	901 (liquid, 30 °C)
			–	981 (solid, 13 °C)
Aromatics				
Biphenyl	71	119.2	–	991 (liquid, 73 °C)
			–	991 (liquid, 73 °C)
Naphthalene	80	147.7	0.132 (liquid, 83.8 °C)	976 (liquid, 84 °C)
			0.341 (solid, 49.9 °C)	1145 (solid, 20 °C)

Source: Lane (1980).

of the fused PCM and heat is transferred as the droplets rise. Here, the immiscible fluid agitates the PCM so that the disadvantage of supercooling is minimized (Sokolov and Keizman, 1991).

Over 20,000 compounds and/or mixtures have been considered as PCMs, including single-component systems, congruent mixtures, eutectics, and peritectics. Criteria being investigated include melting point, phase-diagram characteristics, toxicity, stability, corrosivity, flammability, safety, availability, and cost. Over 200 compositions, organic and inorganic compounds, eutectics, and other mixtures have been considered as promising (Lane, 1988).

Sokolov and Keizman (1991) developed an attractive PCM application for hot water heating. The system contains a solar pipe consisting of two concentric pipes with the space between them filled with PCM (Figure 3.17). Solar radiation is directly absorbed on the outer surface and then

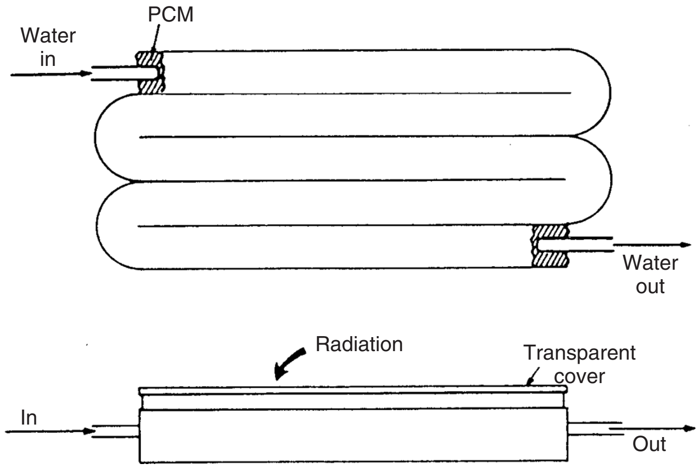


Figure 3.17 A solar TES pipe using a PCM (Sokolov and Keizman, 1991)

transmitted to the PCM, where it is stored as sensible and latent heat. During energy release, heat is exchanged between a water flow through the inner tube and the PCM storage, and hot water is delivered at the discharge of the solar pipe.

In this system, direct solar radiation absorption onto the PCM container and direct heating of water eliminate the need for energy transport media. Some advantages of the system include

- simple construction;
- efficient and compact latent heat storage;
- elimination of expensive components such as a water tank, pump, and control devices;
- suitability of the system for modular construction and installation;
- protection against freezing.

Solar TES as latent heat has an enormous potential. With latent heat, the temperature of the phase change medium stays fixed. The most common PCM for solar applications is Glauber's salt ($Na_2SO_4{\cdot}10H_2O$).

Two approaches are under development to improve the performance of phase change storage. One approach is to increase the temperature at which PCMs such as salts change phase, and the other is to employ the use of a heat pump. The heat pump raises the temperature of the heat extracted from the phase change storage to a temperature high enough to satisfy the thermal needs.

A further advantage of using a PCM is its capability to store up to nine times more energy for the same volume of containment occupied by rocks. This characteristic is particularly advantageous for retrofits (e.g., adding a solar energy system to an existing dwelling). One of the prime difficulties in solar retrofits is locating and charging the store. The volume and mass of sensible TES in rocks or water limit applications. On the other hand, the relatively low mass and volume of PCM often makes it a good choice for retrofits. These characteristics permit latent TES to be located in attic spaces, closets, or even sandwiched between floors and ceilings.

Selection of PCMs for Latent TES

No material has all the optimal characteristics for a PCM, and the selection of a PCM for a given application requires careful consideration of the properties of various substances. Among PCMs, sodium acetate trihydrate deserves special attention for its large latent heat of fusion–crystallization

(264–289 kJ/kg) and its melting temperature of 58–58.4 °C. However, this substance exhibits significant subcooling, preventing most practical large-scale applications, even though attempts have been made to find ways of suppressing or reducing this phenomenon.

Energy balance simulations of a PCM wall as a TES in a passive direct gain solar house suggest that the PCM melting temperature should be adjusted from the climate-specific optimum temperature to achieve maximum performance of the storage. A nonoptimal melting temperature significantly reduces the latent heat storage capacity, for example, a 3 °C nonoptimality temperature causes a 50% loss (Dincer and Dost, 1996).

Of practical importance in the selection of PCMs for solar and other thermal applications are thermophysical properties such as

- heat of fusion,
- heat capacity of solid and liquid,
- thermal conductivity of solid and liquid, and
- density of solid and liquid.

Another important factor in PCM selection is supercooling and nucleation. Several PCMs exhibit supercooling, that is, on attempting to freeze the material the temperature drops well below the melting point before freezing initiates. Although the temperature rises to the melting point once freezing begins, supercooling is nevertheless undesirable in latent TES because it can prevent the withdrawal of stored heat. For this reason, nucleative materials are sometimes used.

The STL system

Peak cooling loads for buildings are often at a level two or more times higher than the average daily load. Some industrial processes also have load peaks that are much greater than the average load. Since many electric utilities impose demand charges based on a customer's highest power demand during on-peak hours and/or during the entire billing cycle, TES can be beneficial. The STL (*le stockage latent* in French, or latent heat storage) latent TES can be an efficient solution for these applications. The STL is composed of a tank filled with spherical nodules. The tank has upper manholes to allow the filling with nodules. A lower manhole allows emptying. Inside the tank two diffusers (inlet and outlet) spread the heat-transfer fluid along the tank. The pressure drop through the tank is 2.5 mWG. The inlet in charge mode must be via the lower diffuser in order to ensure the natural stratification.

The tanks are manufactured with black steel (test pressure between 4.5 to 10 bar), are delivered empty and positioned on site or, if access to the site is impossible, constructed on site. The nodules are spherical with a diameter of 77 mm, 78 mm, or 98 mm (depending on the nodule type).

The nodules (Figure 3.18a) contain the PCM. The mechanical and chemical characteristics of the nodule shell (manufactured with polyolefin) are well adapted to the conditions encountered in

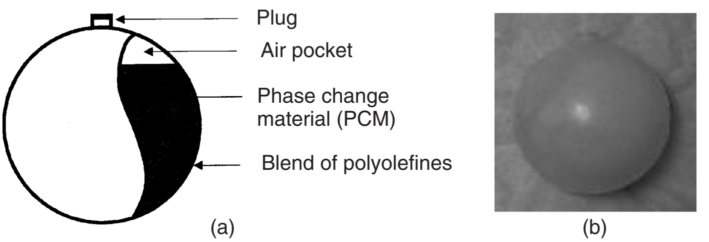


Figure 3.18 (a) The nodule for STL system (*Courtesy of Cristopia Energy Systems*), and (b) a capsule for the new STL latent TES (*Courtesy of Mitsubishi Chemical Co.*)

air-conditioning or refrigeration systems. Once filled with PCM, the nodule plugs are sealed by ultrasonics to ensure perfect water tightness. The nodules are delivered in 22-kg bags. Tanks are filled on site. The filling is regular and homogeneous. Filling procedures are described elsewhere (for details, see Cristopia, 2000).

The shape of the tank is usually cylindrical in order to withstand service pressure higher than 3 bar. The test pressure varies between 4.5 and 10 bar. The spherical shape also allows an easy filling. The nodule diameter has been calculated to meet economical and technical requirements. The size allows high exchanges until the end of the cycle.

The use of modern technologies permits quality control. The materials used are completely neutral to the PCMs and heat-transfer fluid. This product development work has led to a very high reliability of the STL. The temperature range offered is -33 to $+27\,^{\circ}$C.

It is important to mention that in the STL system the quantity of energy stored for each type of nodule is proportional to the storage volume. The number of nodules in a system determines the heat exchange rate between the nodules and the heat-transfer fluid.

In the terminology, an STL is determined by the phase change temperature and the volume (i.e., the storage capacity and the heat exchange rate). There are three types of nodules characterized by their diameter: AC (98 mm), IC, and IN (78 mm) (Cristopia, 2000), such as

- **STL-AC.OO-15.** Where AC: 98_mm diameter nodules, 00: phase change temperature in OC, and 15: tank volume in m^3.
- **STL-IN.15-50.** Where IN: 78-mm diameter nodules for negative temperature, 15: the phase change temperature (melting) is $-15\,^{\circ}$C, and 50: tank volume in m^3.
- **STL-IC.27-100.** Where IC: 78-mm diameter nodules, 27: the phase change temperature (melting) is $+27\,^{\circ}$C, and 100: tank volume in m^3.

The features and characteristics of the nodules can be summarized as follows (Cristopia, 2000):

- material is a blend of polyolefins;
- chemically neutral toward eutectics and heat-transfer fluid;
- thickness is 1.0 mm; there is no migration of the heat-transfer fluid;
- sphere is obtained by blow moulding and there is no leakage;
- sealing of the cap is by ultrasonic welding;
- exterior diameter is 98 mm for air-conditioning and 78 or 77 mm for industrial cooling or backup;
- exchange surface diameter is 78 or 77 mm for 1.0 m^2/kWh stored and the diameter is 98 mm for 0.6 m^2/kWh stored;
- air pocket for expansion; no stress on the nodule shell;
- useful number of nodules per m^3; diameter is 77 mm for 2548 nodules per m^3, 78 mm for 2444 nodules per m^3, and 98 mm for 1222 nodules per m^3.

The characteristics of the STL tanks can be summarized as follows (Cristopia, 2000):

- black steel,
- horizontal or vertical,
- outside, inside, buried, built on-site,
- rustproof exterior paint,
- insulation on-site,
- efficient diffuser system,
- high service pressure,
- pressure drop of 2.5 mWG,
- made to measure according to site requirements.

The Energy Research Group in Japan in collaboration with Mitsubishi Chemical Co. is investigating the performance of the STL system in combination with storage tanks developed for solar energy utilization. The STL system consists of salts and hydrates contained in plastic capsules (Figure 3.18b), where the thermal energy is stored during hydration of the thermally dehydrated salt. Different PSMs that operate at a wide range of storage temperatures are suitable for various applications such as domestic hot water, space heating, and cooling.

Traditional refrigeration systems are designed to satisfy the peak cooling demand, which occurs only a few hours per year, and thus spend most of their operational lives working at reduced capacity and lower efficiency. The STL system, which is suitable for any air-conditioning system or refrigeration plant, allows installed chiller capacity (and the size of other components) to be significantly reduced – typically between 40 and 60%. The STL system provides the shortfall of the energy when demand exceeds chiller capacity. Thus, chiller operation is continuous and at maximum efficiency. The result is reduced operating costs for refrigeration and building air-conditioning by taking advantage of lower cost off-peak electricity and reducing demand charges. The STL system allows real management of the cooling energy according to the demand. In addition, the STL allows the consumption of night-time electricity produced with a higher efficiency (2300 kcal/kWh compared to 3500–4000 kcal/kWh at peak hours), resulting in a reduction in CO_2 emissions and energy consumption. The reduction in the chiller size also reduces the quantity of refrigerant used, which is important with increasingly strict laws on refrigerants.

Heat Pump Latent TES

A heat pump was integrated with latent TES to enable quick room temperature increases and defrosting. This inverter-aided room air-conditioner/heat pump was put on the market by Daikin Industries Ltd. in Japan in 1989. The latent TES consists of the PCM, polyethylene glycol, which surrounds a rotary compressor, as shown in Figure 3.19. Heat released from the compressor is transferred to the TES through a finned-tube heat exchanger. The TES is used during start-up and during defrosting. During start-up, the TES reduces the time required to reach a 45 °C discharge air temperature by 50%. During defrosting, a heating capacity of 3.5 kW is made available by the TES, which avoids a drop in room temperature. Integrating the system improved heat capacity by about 10% and COP by 5%. The characteristics of the system were also improved with TES. The installation space required is the same as that for a conventional heat pump/air-conditioner.

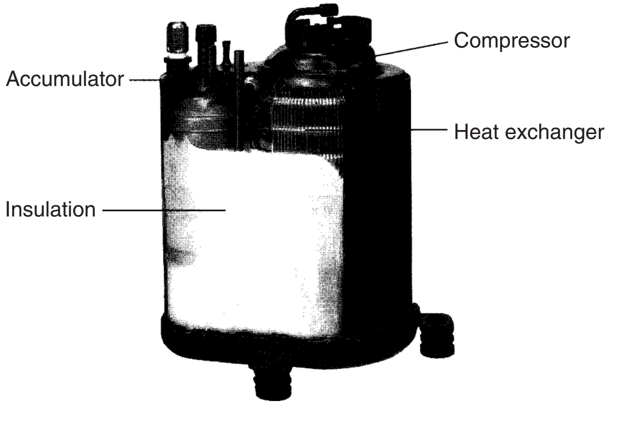


Figure 3.19 A latent TES integrated with a heat pump (IEA, 1990)

3.8 Cold Thermal Energy Storage (CTES)

Cooling capacity can be stored either by chilling or freezing water (or such other materials as glycol and eutectic salts). Water is the storage material of choice for a variety of practical and thermodynamic reasons, including its ready availability, relative harmlessness, and its compatibility with a wide availability of equipments for its storage and handling. The choice of whether the water should be used in sensible or latent types, which equipment should be used, if eutectic salts should be applied to raise freezing temperatures, and so on, is often not simple. Options are numerous, and answers are not clear-cut. Ultimately, the CTES method selected must meet the particular needs and constraints of the specific facility in which it is installed.

CTES is an innovative way of storing night-time off-peak energy for daytime peak use. In many locations, demand for electrical power peaks during summer. Air-conditioning is the main reason, in some areas accounting for as much as half of the power demand during the hot mid-day hours when electricity is most expensive. Since, at night, utilities have spare electrical generating capacity, electricity generated during this “off-peak” is much less expensive.

In essence, one can air-condition during the day using electricity produced at night. CTES has become one of the primary means of addressing the electrical power imbalance between high daytime demand and high night-time abundance. If properly designed, installed, operated, and maintained, CTES systems can be used to shift peak cooling loads to off-peak periods, thereby evenly distributing the demand for electricity and avoiding shortages usually encountered during peak periods.

Although the phrase “cool TES” may appear to be contradictory, it is not. The phrase TES is widely used to describe storage of both heating and cooling energy. TES for heating capacity usually involves using heat at above environment temperatures from a variety of sources to heat a storage medium for later use. In contrast, cold TES uses off-peak power to provide cooling capacity by extracting heat from a storage medium, such as ice, chilled water, or PCMs. Typically, a CTES system uses refrigeration equipment at night to create a reservoir of cold material, which is tapped during the day to provide cooling capacity. In this book, the abbreviation CTES represents both cool and cold TES.

CTES has many advantages. Lower night-time temperatures allow refrigeration equipment to operate more efficiently than during the day, reducing energy consumption. Lower chiller capacity is required, which leads to lower equipment costs. Also, using off-peak electricity to store energy for use during peak demand hours, daytime peaks of power demand are reduced, sometimes deferring the need to build new power plants.

CTES systems are presently operational in many commercial and industrial buildings in various countries. Some are not achieving expected design performance, often because TES design engineers and construction companies in the past lacked experience. Now, package-type TES systems are available and are commonly used, which involve more straightforward design and installation for conventional air-conditioning systems. Therefore, the economic and other benefits of TES operating performance at design conditions for system owners are more likely to be attained.

3.8.1 Working Principle

CTES systems, which have the potential to provide substantial operating cost savings, are most likely to be cost effective in situations where

- a facility’s maximum cooling load is much greater than the average load;
- the utility rate structure has higher demand charges for peak demand periods;
- an existing cooling system is being expanded;
- an existing tank is available;
- limited on-site electric power is available;
- backup cooling capacity is desirable;
- cold air distribution is desirable or advantageous.

It is difficult to generalize about when cool storage systems will be cost effective, but if one or more of the above criteria are satisfied, a detailed analysis may prove worthwhile.

Some CTES systems generate ice during off-peak hours and store it for use in daytime cooling. Until recently, decreasing electricity costs and an abundance of reliable cooling equipment had slowed the development of this technology, which has existed for more than half a century. Today, increases in maximum power demands, major changes in electric rate structures, and the emergence of utility-sponsored incentive programs have inspired a renewed interest in CTES. For instance, utility companies often experience peak electrical demands for 4 to 6 h on hot summer afternoons, when air-conditioning loads also peak, and apply time-of-use rates to discourage energy consumption during these peak demand periods. One objective is for the air chiller to be shut down during peak-load hours and to have a TES system that provides cooling for the facility at those times.

An ice-ball system uses chillers to build ice at night. The ice balls float in a glycol solution that runs through chillers in the evening. These chillers, which are set at −7.5 to −6.5 °C, freeze the ice balls in the storage tanks, and the glycol circulates around the ice balls. Chilled glycol is pumped into the bottom of the tank to freeze the ice balls, and warms as it rises and extracts heat from the ice balls. Later, the cycle is reversed and the glycol is pumped into the top of the tank and past the ice balls. The cold glycol solution then passes through heat exchangers and is connected to the building's chilled-water system, which interfaces with the air handler. Cooling is thus obtained while only operating the fans on the air handlers, but cooling is the same if chillers are operated with the air-handling units.

3.8.2 Operational Loading of CTES

Several strategies are available for charging and discharging a storage to meet cooling demand during peak hours. The main strategies are full storage and partial storage.

Full-Storage CTES

A full-storage strategy shifts the entire peak cooling load to off-peak hours (Figure 3.20a). The system is typically designed to operate on the hottest anticipated days at full capacity during all nonpeak hours in order to charge the storage. This strategy is most attractive when peak demand charges are high or the peak period is short.

Full-storage (load-shifting) designs are those that use storage to fully decouple the operation of the heating or cooling generating equipment from the peak heating or cooling load. The peak heating

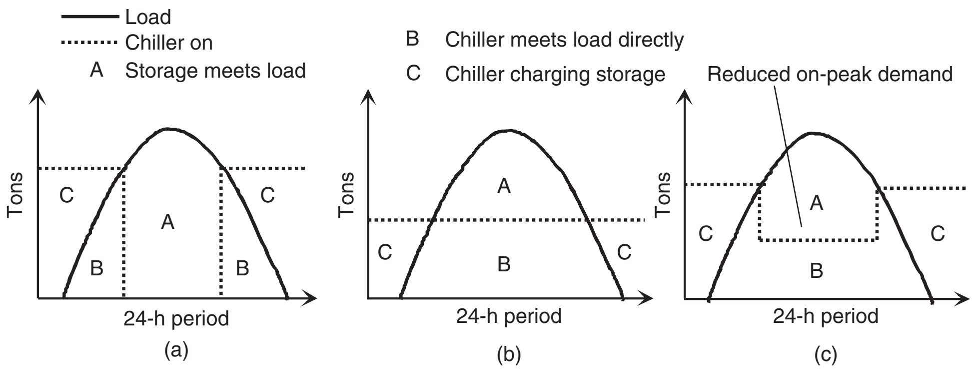


Figure 3.20 Operating strategies: (a) full-storage, (b) partial-storage load leveling, and (c) partial-storage demand limiting

or cooling load is met through the use (i.e., discharging) of the storage while the heating or cooling generating equipment is idle. Full-storage systems are likely to be economically advantageous only under one or more of the following conditions:

- spikes in the peak load curve are of short duration;
- time-of-use energy rates are based on short-duration peak periods;
- there are short overlaps between peak loads and peak energy periods;
- large cash incentives are offered for using TES;
- high peak-demand charges apply.

For example, a school or business whose electrical demand drops dramatically after 5 p.m. in an electric utility territory where peak energy and demand charges apply between 1 p.m. and 9 p.m. can usually economically apply a full CTES. Cooling during the 4-h period between 1 p.m. and 5 p.m. can be fully shifted, that is, can be met with a relatively small and cost-effective CTES system and without oversizing the chiller equipment.

Partial-Storage CTES

In a partial-storage method, the chiller operates to meet part of the peak-period cooling load, and the rest is met by drawing from storage. The chiller is sized at a smaller capacity than the design load. Partial-storage systems may operate as load-leveling or demand-limiting operations. In a load-leveling system (Figure 3.20b), the chiller is sized to run at its full capacity for 24 h on the hottest days. The strategy is most effective where the peak cooling load is much higher than the average load. In a demand-limiting system, the chiller runs at reduced capacity during peak hours, and is often controlled to limit the facility's peak demand charge (Figure 3.20c). Demand savings and equipment costs are higher than they would be for a load-leveling system, and lower than those for a full-storage system.

Partial storage is more often the most economic option, and therefore represents the majority of thermal storage installations. Although partial storage does not shift as much load (on a design day) as a full-storage system, partial-storage systems can have lower initial costs, particularly if the design incorporates smaller equipment by using low-temperature water and cold-air distribution systems.

For many applications, a form of partial storage known as *load leveling* can be used with minimum capital cost. A load-leveling system is designed with the heating or cooling equipment sized to operate continuously at or near its full capacity to meet design-day loads. Thus, equipment having minimum capacity (and cost) can be used. During operation at less than peak design loads, partial-storage designs can function as full-storage systems. For example, a system designed as a load-leveling partial storage for space heating at winter design temperatures may function as a full storage (with a full demand shift) on mild spring or autumn days.

3.8.3 Design Considerations

CTES can take many forms to suit a variety of applications. This section addresses several groups of CTES applications: off-peak air-conditioning, industrial/process cooling, off-peak heating, and other applications.

Selecting a storage system and its characteristics usually requires a detailed feasibility study. An analysis is involved, and is best accomplished following an established procedure. Data needed for feasibility analysis can include (i) an hour-by-hour 24-h building-load profile for the design day, and (ii) a description of a baseline non-storage system, including chiller capacity, operating conditions, and efficiency. The description of a CTES often stipulates the following:

- the sizing basis (full storage, or load leveling, or demand limiting);

- sizing calculations showing chiller capacity and storage capacity, and considering the required supply temperature;
- the design operating profile, showing load, chiller output, and amount of heat added to or taken from storage for each hour of the design day;
- chiller operating conditions while charging the storage, and, if applicable, when meeting the load directly;
- the chiller efficiency under each operating condition;
- a description of the system control strategy, for the design-day and part-load operation.

An operating-cost analysis includes

- an evaluation of demand savings;
- a determination of changes in energy consumption and cost;
- a description and justification of the assumptions used for annual energy demand and use estimates.

Storage equipment manufacturers often provide simulations of storage performance for a given load profile and chiller temperature to assist design efforts.

Although applications and technologies vary significantly, certain characteristics and design options are common to all TES systems. Whether for heat or cool storage, and whether for storing sensible or latent heat, storage designs follow one of two control strategies: full storage or partial storage (Figure 3.21).

The following steps should be considered for all ice TES refrigeration systems:

- **Design for part-load operation.** Refrigerant flow rates, pressure drops, and velocities are reduced during part-load operation. Components and piping must be designed so that, at all load conditions, control of the system can be maintained and the working fluid can be returned to the compressors.
- **Design for pull-down load.** Because ice-making equipment is designed to operate at water temperatures approaching 0 °C, a higher load is imposed on the refrigeration system during the initial start-up, when the inlet water is warmest. The components must be sized to handle this higher load.

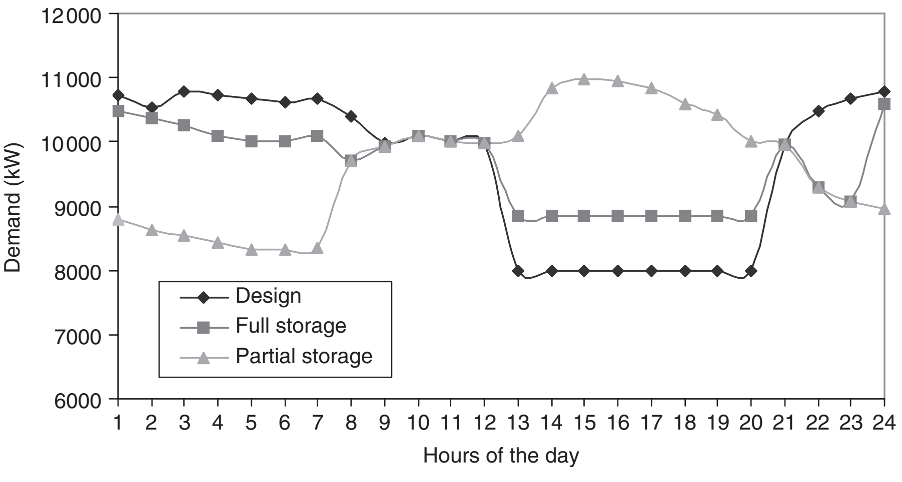


Figure 3.21 Sample demand profiles for the design, full-storage and partial-storage systems

- **Plan for chilling versus ice making.** Most ice-making equipment has a much higher instantaneous chilling capacity than ice-making capacity. This higher chilling capacity can be used advantageously if the refrigeration equipment and interconnecting piping are properly sized to accommodate alternative modes of operation.
- **Protect compressors from liquid slugging.** Ice producers and ice harvesters tend to contain more refrigerant than chillers of similar capacity used for nonstorage systems. The opportunity, therefore, exists for compressor liquid slugging. Care should be taken to oversize suction accumulators and equip them with high-level compressor cutouts and suction heat exchangers to evaporate any remaining liquid.
- **Oversize the receivers.** The system should be made easy to maintain and service. Maintenance flexibility may be provided in a liquid overfeed system by oversizing the low-pressure receiver and in a direct-expansion system by oversizing the high-pressure receiver.
- **Prevent oil trapping.** Refrigerant lines should be arranged to prevent the trapping of large amounts of oil anywhere in the system, and to ensure its return to compressors under all operating conditions, especially during periods of low compressor loads. All suction lines should slope toward the suction line accumulators, and all discharge lines should pitch toward the oil separators. Oil tends to collect in the evaporator because that is the location at the lowest temperature and pressure. Because refrigerant accumulators trap oil as well as liquid refrigerant, the larger accumulators needed for ice storage systems require special provisions to ensure adequate oil return to the compressors.

It is important to fully analyze design trade-offs; comparisons of CTES to other available cost- and energy-saving opportunities should be fair. For example, if energy-efficient motors are assumed for a CTES design, they should be assumed for the nonstorage system being compared. Current designs should be considered in comparisons, whether based on hydrochlorofluorocarbons (HCFCs), hydrofluorocarbon (HFCs), or ammonia refrigerants, or on any of the proven refrigeration techniques (e.g., direct expansion, flooded, liquid overfeed).

Means are often sought to reduce electrical costs. One way to do this is to lower electrical consumption at peak times of the day. Conventional air-conditioning systems often contribute a large percentage to this peak load, because they typically run during peak hours. Shifting air-conditioning loads to off-peak times when demand costs are lower cuts demand costs significantly. CTES can help shift air-conditioning loads in this way.

CTES is a proven and workable technology. Over 10,000 CTES systems currently operate in the USA. TES relies on an inexpensive storage medium using high specific or latent heat to store cooling. The most common types of storage units use chilled water or ice. Because of the difference in energy density of the storage, ice storage units are smaller.

3.8.4 CTES Sizing Strategies

The decision of which sizing strategy to use for a CTES is generally an economic rather than a technical one. There are three basic storage-sizing strategies:

- full storage,
- load-leveling partial storage, and
- demand-limiting partial storage.

The full-storage strategy supplies all of a facility's peak cooling needs using a storage unit by shifting all of the electrical demand caused by cooling to off-peak hours. Calculating the design-day cooling requirement (tons per hour) during peak times and dividing that by the tank's efficiency factor determines the size of storage tank needed. Initial costs are usually expected to be high.

The load-leveling partial-storage strategy supplies only part of a building's cooling load during peak hours. This method levels the building's electrical demand caused by cooling over the design day. Compared to the other two strategies, this method minimizes the size of storage and refrigeration equipment needed to cool a building, resulting in lower equipment costs. However, this strategy does not create as great operating savings as the others.

Demand-limited partial storage requires less storage capacity than full storage, but more than load-leveling strategies, and lowers a building's peak electrical demand to a predetermined level. This level is normally equal to the peak demand imposed by noncooling loads. To effectively keep the total electric demand below the predetermined level, real-time controllers are required to monitor the building's non-cooling loads and control the ratio of storage- and chiller-supplied cooling.

Reduced operating costs are the primary benefit derived from using CTES. Energy cost can be reduced for cooling a facility by as much as 70%. Typical payback periods using CTES usually range from 2 to 6 years. Prediction of cost savings from using CTES requires the following building-specific information:

- hour-by-hour power usage;
- performance of the proposed cool storage system;
- the local electrical utility's rate structure.

Particularly in the United States, utility companies sometimes offer incentive programs, reduced rates, or free feasibility studies related to saving energy. Incentive payments for installing a functional TES unit can be in the form of cash subsidies or rebates to the customer. Retrofits are usually eligible for higher incentives than new construction. Feasibility studies are an indirect inducement that may be offered free or at a reduced rate by the utility.

3.8.5 Load Control and Monitoring in CTES

Two key control issues unique to CTES systems are monitoring and regulating the water or ice temperature and controlling tank-water level (Maust, 1993). Temperature sensors inside chilled-water storage tanks provide data which the control system uses to evaluate the tank's cooling capacity. Temperature monitoring also gives the operator information to make load-management and chiller-operation decisions. For instance, encapsulated ice systems evaluate cooling capacity by monitoring tank liquid level and the amount of ice that remains. By trend-logging the cooling demand and the rate at which stored cold is used, an operator can operate a chiller plant and the storage system to achieve the desired objectives.

It is also important to monitor the tank water level, because it can indicate faulty operation. Large volumes of water are often involved, and a leak or break in the treated-water system could lead to large and expensive losses. Sensors monitoring tank level, performance of the makeup water system and pressure regulating components provide important diagnostic information.

Small ice CTES systems have built-in control systems. For large ice storage systems, such as the encapsulated systems, control systems are integrated into the building automation system that controls chillers, pumps, and air-handling units. These control systems are normally custom designed and constructed on site. Systems typically consist of a set of microprocessors connected to a high-speed, local-area network and an operator's workstation. Network control systems usually require minimal operator training. Software continuously monitors building load, storage capacity, and outdoor conditions and compares them with historical data. The program determines the best use of chillers and stored cool water. A control system also can provide troubleshooting capabilities.

Monitoring and control of CTES systems are generally straightforward. For example, consider two basic modes of operation such as near-full storage and partial storage. In near-full storage, chillers are permitted to operate as little as possible during peak hours. In partial storage, chillers are allowed to operate up to a pre-determined load limit during peak hours, with storage making up the remainder of a daily load.

3.8.6 CTES Storage Media Selection and Characteristics

The storage medium determines how large the storage tank will be and the size and configuration of the HVAC system and components. The main options include chilled water, ice, and eutectic salts. Ice systems offer the densest storage capacity, but have the most complex charge and discharge equipment. Water systems offer the lowest storage density, and are the least complex. Eutectic salts have intermediate characteristics. Some details on each storage medium are as follows:

- **Chilled water.** Chilled-water systems require the largest storage tanks, but can easily interface with existing chiller systems. Chilled-water CTES systems use the sensible heat capacity of water to store cooling capacity. They operate at temperature ranges (3.3–5.5 °C) compatible with standard chiller systems and are most economical for systems greater than 2000 ton-hours in capacity.
- **Ice.** Ice systems use smaller tanks and offer the potential for the use of low-temperature air systems, but require more complex chiller systems. Ice CTES systems use the latent heat of fusion of water (335 kJ/kg) to store cooling capacity. Storage of energy at the temperature of ice requires refrigeration equipment that provides charging fluids at temperatures below the normal operating range of conventional air-conditioning equipment. Special ice-making equipment or standard chillers modified for low-temperature service are used. The low chilled-water-supply temperatures available from ice storage allow the use of cool-air distribution, the benefits of which include the ability to use smaller fans and ducts and the introduction of less humid air into occupied spaces. With ice as the storage medium, there are several technologies available for charging and discharging the storage: ice harvesting systems feature an evaporator surface on which ice is formed and periodically released into a storage tank that is partially filled with water. External melt ice-on-coil systems use submerged pipes through which a refrigerant or secondary coolant is circulated. Ice accumulates on the outside of the pipes. The storage is discharged by circulating the warm return water over the pipes, melting the ice from the outside. Internal melt ice-on-coil systems also feature submerged pipes on which ice is formed. The storage is discharged by circulating warm coolant through the pipes, melting the ice from the inside. The cold coolant is then pumped through the building cooling system or used to cool a secondary coolant that circulates through the building's cooling system. Encapsulated ice systems use water inside submerged plastic containers that freeze and thaw as cold or warm coolant is circulated through the storage tank holding the containers. Ice slurry systems store water or water/glycol solutions in a slurry state (a partially frozen mixture of liquid and ice crystals that looks like slush). To meet a cooling demand, the slurry may be directly pumped to the load or to a heat exchanger cooling a secondary fluid that circulates through the building's chilled-water system. Internal melt ice-on-coil systems are the most commonly used type of ice storage technology in commercial applications. External melt and ice-harvesting systems are more common in industrial applications, although they can also be applied in commercial buildings and district-cooling systems. Encapsulated ice systems are also suitable for many commercial applications. Ice slurry systems have not been widely used in commercial applications.
- **Eutectic salts.** Eutectic salts can use existing chillers but usually operate at warmer temperatures than ice or chilled-water systems. Eutectic salts use a combination of inorganic salts, water, and other elements to create a mixture that freezes at a desired temperature. The material is encapsulated in plastic containers that are stacked in a storage tank through which water is circulated. The most commonly used mixture for thermal storage freezes at 8.3 °C, which allows the use of standard chilling equipment to charge storage, but leads to higher discharge temperatures. These temperatures, in turn, limit the operating strategies that may be applied. For example, eutectic salts may only be used in full-storage operation if dehumidification requirements are low.

Water versus Ice CTES

To increase compactness, CTES systems have been developed that utilize the latent heat of in-phase changes (usually solid–liquid) of substances. Presently in practice, latent storage utilizing water and ice is employed most widely.

Figure 3.22 shows that the cooling capacity of an ice CTES system under total freezing is 18 times as high as that of a water CTES operating between 12 and 7 °C. Consequently, the thermal storage volume can be substantially reduced. However, because of practical difficulties in melting ice, it is often not advantageous to turn all the water into ice. Figure 3.23 shows how the ice packing factor (IPF) affects the tank volume for ice CTES in comparison to water CTES. As shown, if 10% of the water is converted to ice, the tank volume is 32% of that for a water storage tank.

Currently, buildings in Japan have a cooling load to heating load ratio of approximately 2 : 1 to 3 : 1 due to the heating load of office equipment. If a TES tank is used as a hot water tank in winter, the same tank can be used with an IPF of about 10% for balanced service in winter. As a result of the reduced tank volume, it is possible to install it on the roof. A further advantage of the reduced volume of ice storage is lower surface area, which leads to lower heat losses relative to a water CTES.

Conventional water CTES systems utilize sensible heat and thus need large tanks. These are often located under a building. In many cases, however, it is difficult to secure such a large tank space, and the use of conventional systems is thus restricted. The design and development of more compact thermal storage tanks has therefore become important.

A major drawback of ice thermal storage is that, since ice must be produced, the chiller evaporator temperature must be lower than that for a water CTES, so chiller capacity and COP are decreased. For water CTES, the evaporation temperature of an ordinary chiller is in the vicinity of 0 °C. For ice CTES, however, evaporator temperatures are often below −10 °C so that the capacity and COP are reduced to about 56 and 71%, respectively, of those of a water CTES system. A capacity drop leads to an increase in the size and cost of the chiller, while a COP reduction leads to an increase in energy costs. To control both of these costs, it is desirable to store the minimum of ice required by the available space.

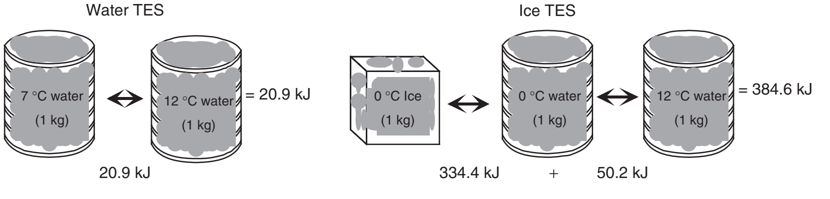


Figure 3.22 The capacity of an ice CTES is 18 times as high as that of water CTES (Kuroda, 1993)

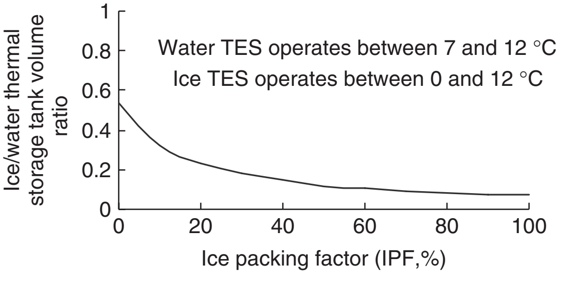


Figure 3.23 Variation in tank volume (expressed as the ratio between ice and water thermal storage tank volume) with ice packing factor (Kuroda, 1993)

Two basic types of commercial ice storage exist: static (ice building) and dynamic (ice shucking) systems. In the static system, ice is formed on the cooling coils within the storage tank itself (ice-on-coil). Such systems are normally manufactured in packaged units and connected to the building's chilled-water system. Dynamic systems, which are becoming popular, make ice in chunks or crushed (so-called *ice harvesting*) form and deliver it for storage in large pits similar to those used in chilledwater systems. Dynamic systems may also include the formation of ice glycol slurry, which can be stored in a tank. Static ice storage systems are designed to form ice on the surface of evaporator tubes, and to store it until chilled water is needed for cooling. The ice is melted by the warm return water, thereby re-cooling the water before it is pumped back to the coils in the building. Other static systems use brine that circulates through tubes in an ice block or around containers filled with frozen water. These systems have the advantage of being closed and not open to the atmosphere. An examination of the relative costs of ice CTES systems versus comparable water storage systems sometimes indicates that the ice CTES system costs less, mainly because of the considerably reduced storage volume requirements. Ice CTES has the disadvantage of lower evaporator temperatures and higher electrical energy requirements to achieve the necessary freezing of the water.

On the basis of years of experience, many companies believe that chilled water and encapsulated ice are the most practical storage methods. Chilled CTES requires a large vertical tank with a capacity of approximately $0.283\,m^3$ per ton-hour of storage. Encapsulated ice requires a much smaller storage capacity, approximately $0.071\,m^3$ per ton-hour stored.

Both systems have advantages that are site specific. In general, chilled-water storage becomes practical in capacities exceeding 25,000 ton-hours. In addition, companies note the following:

- Encapsulated ice CTES systems produce much colder water, so pumps, piping, heat exchangers, and cooling coils can be smaller. Chiller compressors must be of the positive displacement type, such as rotary screws or reciprocating. Centrifugal compressors are not practical for this application.
- Chilled CTES systems may use any type of system as long as there is a 20 °C difference during the discharge cycle between supply and return water. Each cooling coil should be equipped with a dedicated pump and a direct digital control (DDC) system.

PCMs (Eutectic Salts) for CTES

PCMs have recently received significant attention for CTES, although they have been considered for heating since the early 1980s. PCMs suitable for CTES are eutectic salts that undergo liquid/solid phase changes at temperatures as high as 8.3 °C, and absorb and release large amounts of energy during the phase change. Stored in hermetically sealed plastic containers, PCMs change to solids as they release heat to water, or to another fluid that flows around them. At these temperatures (up to 8.3 °C), chillers can operate more efficiently than at the low temperatures required by ice CTES systems. PCMs also have about three times the storage capacity of a typical chilled-water CTES system. The choice of ice, chilled water, or PCMs depends on the services needed. If low temperatures are needed, ice is likely preferable. If more conventional temperatures are needed and space is available, chilled-water CTES can be installed. If space is limited, but low temperatures are not required and a passive, easy-to-maintain system is desired, PCM may be a good choice.

Ice CTES is one example of using the latent heat characteristic of a storage medium. The significance of latent heat is that far more energy may be added or removed from a storage material as it undergoes a change of phase than can be added or removed from a material that remains in a single liquid phase, such as water, or a single solid phase, such as rock or brick.

Two commercially available materials that enhance the phase change process that ordinarily occurs between water and ice are eutectic salts and gas hydrates. Eutectic salts are mixtures of inorganic salts, water, and additives. Gas hydrates are produced by mixing gas with water. Both of these materials work by raising the temperature at which water freezes. These materials have the advantage of a freezing point of 8.3 or 8.8 °C, which reduces energy requirements for freezing.

PCMs can, therefore, provide a highly desirable TES storage medium for cooling purposes. PCMs also provide most of the storage space advantages associated with ice storage systems. By freezing and melting at 8.3 or 8.8 °C, the PCMs can be easily used in conventional chilled-water systems with centrifugal or reciprocating chillers. The storage tank can be placed above or below grade. In addition, chiller power requirements are reduced when PCMs are used for TES because evaporative temperatures remain fairly constant.

Gas hydrates, still in the development stage for large, commercial installations, have some advantages over eutectic salts. Gas hydrates have high latent heat values, which lead to size and weight advantages. Gas hydrates require only one-half to one-third of the space, and are approximately one-half the weight of an equivalent eutectic salt system.

Like ice and chilled-water storage systems, hydrated salts have been in use for many decades. PCMs with various phase-change points have been developed. To date, the hydrated salt most commonly used for CTES applications changes phase at 8.3 °C, and is often encapsulated in plastic containers. The material is a mixture of inorganic salts, water, and nucleating and stabilizing agents. It has a latent heat of fusion of 95.36 kJ/kg and a density of 1489.6 kg/m^3. A CTES using the latent heat of fusion of this PCM requires a capacity of about 0.155 m^3/ton-hour for the entire tank assembly, including piping headers.

PlusICE™ PCMs The disadvantages of conventional ice CTES (low temperature chillers to build ice) and water CTES (large volume of water storage) can be overcome by utilizing the latent heat capacity of various eutectic salts, otherwise known as *PCMs*. Table 3.10 lists several types of commercially available PlusICE™ substances and their thermophysical data. For different phase change temperatures, some other types of substances are also available. PlusICE™, mixtures of nontoxic eutectic salts, have freezing and melting points higher than those of water, and the temperature range offered by this concept provides the following benefits:

- space-efficient coolness and heat recovery CTES;
- utilization of existing chiller and refrigeration equipment for new and retrofit CTESs;
- elimination of low-temperature glycol chillers;
- improvement of system efficiency due to higher evaporation temperatures and possible charging by means of free cooling (i.e., without operating the chiller).

Table 3.10 Commercially available PlusICE™ substances

PlusICEtype	Phase change temperature (°C)	Density (kg/m^3)	Heat of fusion (kJ/kg)	Latent heat (MJ/m^3)
A4	4	766	227	174
E7	7	1542	120	185
E8	8	1469	140	206
A8	8	773	220	170
E10	10	1519	140	213
E13	13	1780	140	245
E21	21	1480	150	222
A22	22	775	220	171
A28	28	789	245	193
E30	30	1304	201	262
E32	32	1460	186	272
E48	48	1670	201	336
E58	58	1280	226	289
E89	89	1550	163	253
E117	117	1450	169	245

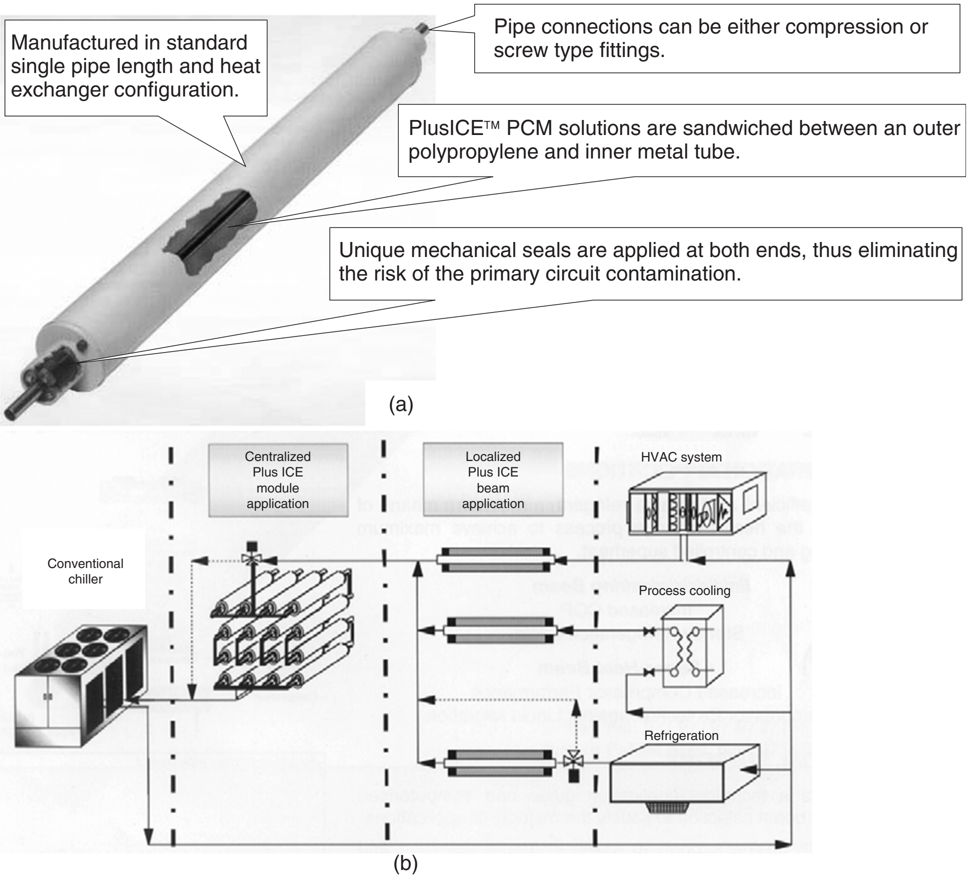


Figure 3.24 (a) PlusICE™ beam for CTES applications, (b) centralized and localized PlusICE™ applications (*Courtesy of Environmental Process Systems Limited*)

PlusICE™ beams (Figure 3.24a) provide a static CTES system, and the self-stacking modular tube concept offers flexibility for the size and location. They can be manufactured either as a single or multi-pass arrangement for the most economical capacity and duty balancing for any given new and retrofit application. Site-assembled modular self-stacking design offers flexibility and simple installation. Future capacity increases can be easily accommodated by simply adding more beams into an existing module with minimal modification. In the operation of the system, water or refrigerant is circulated within the inner tube and the excess capacity from this fluid is stored in the form of latent heat by the eutectic salts during the charging mode. This operation is reversed during the discharge mode to supplement the system load. Beams can be applied as either a totally centralized CTES, similar to a conventional storage tank, or totally localized, that is, spread over the system as part of the pipe runs, or a combination of the two (Figure 3.24b). This enables a reduction or even elimination of the central storage module.

3.8.7 Storage Tank Types for CTES

Storage tanks must have the strength to withstand the pressure of the storage medium, and be watertight and corrosion resistant. Aboveground outdoor tanks must be weather resistant. Buried tanks must withstand the weight of the soil covering and any other loads that might occur above the tank, such as the parking of cars. Tanks may also be insulated to minimize thermal losses (which are typically 1–5% per day).

The options for tank materials include the following:

- **Steel.** Large steel tanks, with capacities up to several million cubic meters, are typically cylindrical in shape and field-erected of welded plate steel. Corrosion protection, such as an epoxy coating, is usually required to protect the tank interior. Small tanks, with capacities of less than $100\,m^3$, are often rectangular in shape and typically made of galvanized sheet steel. Cylindrical pressurized tanks are generally used to hold between 10 and $200\,m^3$.
- **Concrete.** Concrete tanks may be precast or cast-in-place. Precast tanks are most economical in sizes of one million gallons or more. Cast-in-place tanks can often be integrated with building foundations to reduce costs. However, cast-in-place tanks are more sensitive to thermal shock. Large tanks are usually cylindrical in shape, while smaller tanks may be rectangular or cylindrical.
- **Plastic.** Plastic tanks are typically delivered as prefabricated modular units. Ultraviolet (UV) stabilizers or an opaque covering is required for plastic tanks used outdoors to provide protection against the UV radiation in sunlight.

Steel and concrete are the most commonly used types of tanks for chilled-water storage. Most ice harvesting systems and encapsulated ice systems use site-built concrete, while external melt systems usually use concrete or steel tanks, internal melt systems usually use plastic or steel, and concrete tanks with polyurethane liners are common for eutectic salts.

CTES tanks often use insulation. Because of the low temperatures associated with ice storage, insulation is a high priority. Ice storage tanks located above ground are normally insulated to limit standby losses. For external melt ice-on-coil systems and some internal melt ice-on-coil systems, the insulation and vapor barrier are part of the factory-supplied containers; most other storage tanks require field-applied insulation and vapor barriers. Belowground tanks used with ice harvesters sometimes do not need insulation beyond 1 m below grade. Because the tank temperature does not drop below $0\,^{\circ}C$ at any time, there is no danger of freezing and thawing groundwater. All belowground tanks using fluids below $0\,^{\circ}C$ during the charge cycle should have insulation and a vapor barrier system, generally on the exterior. Interior insulation is susceptible to damage from the ice and should be avoided.

Exposed tank surfaces should be insulated to help maintain the temperature in the tank. Insulation is especially important for smaller storage tanks, because the ratio of surface area to stored volume is relatively high. Heat transfer between the stored water and the tank contact surfaces (including divider walls) is a primary source of loss. Not only does the stored fluid lose heat to (or gain heat from) the ambient by conduction through the floor and wall, but heat also flows vertically along the tank walls from the warmer to the cooler region. Exterior insulation of the tank walls does not inhibit this heat transfer.

The cost of chemicals for water treatment may be significant, especially if the tank is filled more than once during its life. A filter system helps keep the stored water clean. Exposure of the stored water to the atmosphere may require the occasional addition of biocides. While tanks should be designed to prohibit leakage, the designer should account for the potential impact of leakage on the selection of chemical water treatment. Storage circulating pumps should be installed below the minimum operating water level to ensure flooded suction. The required net positive suction pressure must be maintained to avoid sub-atmospheric pressure conditions at the pumps.

3.8.8 Chilled-Water CTES

A chilled-water CTES system uses the sensible heat in a body of water to store energy. Given its specific heat of $4.187\,kJ/kg\,^{\circ}C$, about $0.2\,m^3$ of water is needed to absorb 12,000 kJ and provide 1 ton-hour of cooling if the coil raises the water temperature by $20\,^{\circ}C$.

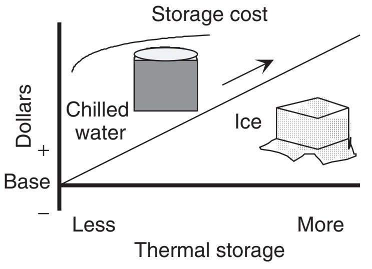


Figure 3.25 CTES cost relationship (AEP, 2001)

By contrast, the same ton-hour of cooling can be provided with just 0.042 m^3 of ice, since each kilogram of ice absorbs 152 kJ as it melts. Therefore, a CTES system that uses chilled water rather than ice requires six to seven times more installed storage volume. Figure 3.25 shows a plot of the cost of CTES components as a function of the ton-hours of cooling stored. The sizable cost penalty imposed by the significantly larger storage tank volume required for chilled water is readily apparent compared with ice storage. Note, however, that the cost of the water storage tank is mainly a function of its surface area, while the capacity of the tank is mainly a function of its volume. Therefore, as the size required of a chilled-water storage tank increases, the per-ton-hour cost of the storage tank actually decreases. Consequently, it appears that chilled water may be competitive with ice in applications that require more than 10,000 ton-hours of thermal storage.

A chilled-water storage system can be viewed as a simple variation of a decoupled chiller system. Since the same fluid water is used both to store and to transfer heat, few accessories are needed and the system is simple. As shown in Figure 3.26, a decoupled system separates the production and distribution of chilled water. The balance of flow between the constant-volume production of chilled water and its variable-volume distribution is handled with a bypass pipe commonly called a *decoupler*. The decoupler redirects surplus chilled water to storage when production exceeds distribution and withdraws storage water when distribution exceeds supply.

Chilled-water CTES systems offer a number of benefits, especially for larger systems. In addition, the large storage volume of water can be incorporated into fire safety systems, and in fact, some sprinkler systems use storage water in their design. The disadvantages of chilled-water storage, which relate to the tank design, weight, location, and space requirements, can pose challenges.

The relative installed cost of a chilled-water CTES (see Figure 3.27) shows the significance of storage tank expense. While somewhat prohibitive for most applications under 10,000 ton-hours,

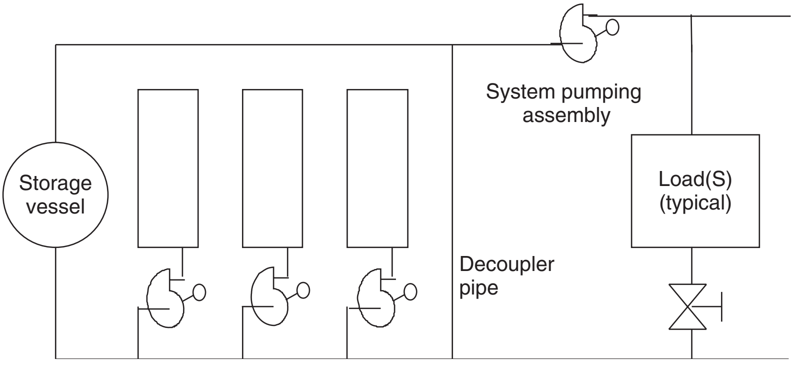


Figure 3.26 Schematic of a chilled-water production and distribution system (AEP, 2001)

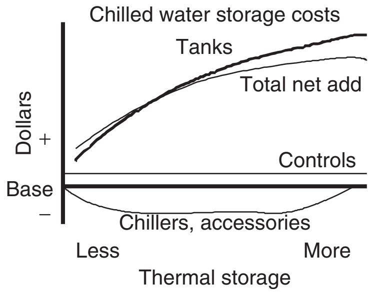


Figure 3.27 Advantages and disadvantages of tank configuration (AEP, 2001)

the decreasing unit cost of chilled-water CTES systems can be very attractive for large central plants and industrial installations.

Series Storage Tanks for Chilled-Water CTES

The simplest form of chilled-water storage places one or more tanks in series. This concept is illustrated in Figure 3.28 as a single baffled tank. When the chillers produce more chilled water than the system requires, the excess is diverted to the series tank where it displaces the warmer water already present there.. Likewise, when chilled water demand exceeds the quantity produced, chilled water is drawn from the tank by displacing it with warm return water.

A number of chilled-water CTES systems with designs similar to that in Figure 3.28 have been installed and proven to be effective in reducing peak electrical demand. However, series-tank designs can cause the water to stratify or become stagnant. Stagnation is the tendency of some water to shortcut through the tank, and renders large volumes of tank water ineffective for storage. Also, intercompartmental mixing can raise the tank-water exit temperature, reducing the tank effectiveness during its final hours of discharge.

Parallel Storage Tanks for Chilled-Water CTES

The problems of mixing and stratification can be reduced with a multiple-tank parallel design (see Figure 3.29). This arrangement replaces the bypass pipe or decoupler with a number of separate tanks piped in parallel between the 14.5 °C return water from the cooling coils and the 4.5 to 5.5 °C supply water from the chiller(s). Each of these tanks has individually controlled drain and fill valves.

In practice, one of the parallel-piped tanks is empty when the storage is changed, and that tank's drain and fill valves are closed. When the discharge cycle starts (i.e., when the system starts to use

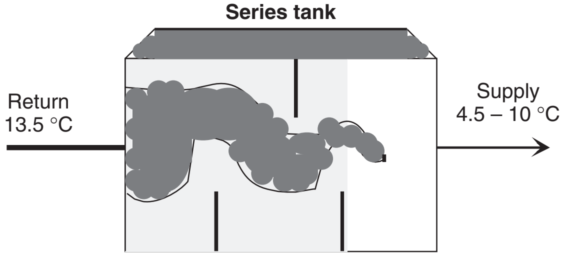


Figure 3.28 Series tank configuration for chiller-water CTES (AEP, 2001)

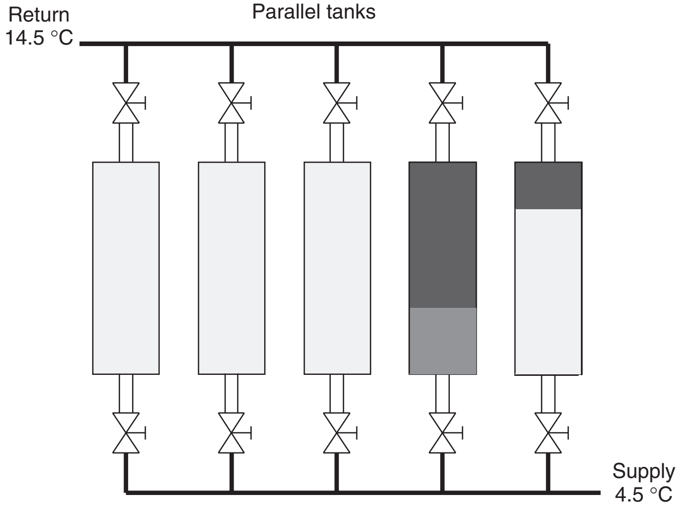


Figure 3.29 Parallel tank configuration for chilled-water CTES (AEP, 2001)

chilled water), the empty tank's fill valve opens to allow it to receive warm return water. The drain valve on any one of the tanks filled with previously chilled water opens so that, as warm return water fills the empty tank, an equal flow of cold water is drawn from the tank with the open drain valve.

Proper valve sequencing is especially important when the receiving tank is nearly full and the draining tank is almost depleted. In this valve control sequence:

1. The drain valve on a new tank previously filled with chilled water must open.
2. The drain valve on the just-emptied tank must close as its fill valve opens, allowing the tank to receive warm return water.
3. The fill valve on the once-empty tank that is now full of warm return water must close. (This tank is now ready for off-peak recharging.)

A building of automation system and an accurate method of measuring tank volume are required to facilitate this control task. Although the multiple-parallel-tank scheme eliminates many of the problems associated with mixing and tank stratification, its complexity can add to the cost of a chilled-water CTES system.

Stratified Storage Tanks for Chilled-Water CTES

Most chilled-water storage systems installed today are based on designs that exploit the tendency of warm and cold water to stratify. Cold water is then added to or drawn from the bottom of the tank, while warm water is returned to or drawn from the top. A boundary layer, or thermocline, often 0.2 to 0.4 m in height, is established between the resultant warm and cold zones (Figure 3.30). Specially engineered diffusers or any array of nozzles can ensure laminar flow within the tank. This laminar flow is necessary to avoid mixing and promote stratification, since the respective densities of the 15.5 °C return water and 4.5 to 5.5 °C supply water are almost identical.

Advantages of Chilled-Water CTES

The most important advantage of water thermal storage is the fact that water is a well understood and familiar medium. No danger is associated with handling water as a TES material. Basically,

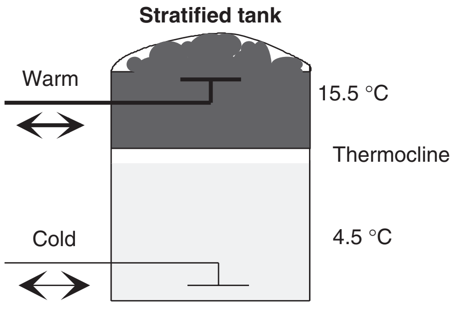


Figure 3.30 Stratified tank configuration (AEP, 2001)

heating and cooling applications require only a moderate temperature range (5 to 45 °C). Water can be used as a storage medium for both cooling and heating, allowing the same TES material to be used throughout the year. The relatively high thermal capacity of water is also attractive for TES applications. These advantages give water CTES economic advantages over other air-conditioning systems, including those using ice CTES systems.

For example, an economic comparison between water CTES and ice CTES for a model building of 10,000 m^2 situated in Tokyo indicates the following (Narita, 1993):

- The initial cost of water thermal storage is approximately 20% less than that of ice CTES. The main reason is the cost of the ice-making unit in the TES tank.
- In the ice-making mode, the COP is approximately 20% lower than that for the water cooling mode because of the lower evaporating temperature. Consequently, more electricity is consumed in ice CTES.
- The ice CTES system has little thermal storage capacity for potential use in the heating season.
- The operating cost of water thermal storage is approximately 20% less than that of ice CTES.

A major disadvantage of water CTES is volume. For the same amount of thermal capacity, a water CTES system requires approximately three times as much tank volume as ice CTES. To somewhat circumvent this problem, alternative design configurations are sometimes considered.

Heat Pumps and Chilled-Water CTES

The heat pump is an important technology for energy conservation. Combining heat pumps and water CTES has many advantages, including the economic operation of the heat pump as well as a load-leveling effect on electricity demand. Such combined systems can overcome some of the disadvantages of water CTES that have been introduced in actual plants.

In conventional air-conditioning systems using heat pumps, the heat pump must be operated during the day when cooling demand exists. This operation contributes to electricity demand during the same period. Cooling demand is often responsible for approximately one-third of the electricity demand at the peak period. In a typical water CTES system, half of the daily cooling load can be covered by night operation of the heat pumps.

The combination of a heat pump and a water CTES can provide the following benefits:

- **Load leveling of electricity demand for air-conditioning.** If 50% of the air-conditioning load is shifted to the night on the peak day, the annual dependence on night-time electricity can be as high as 70% for cooling and 90% for heating. Thus, the CTES system achieves peak shifting on the peak day and improves the annual load factor of electricity-supply facilities. At

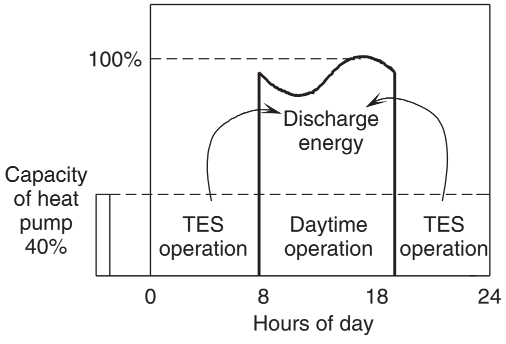


Figure 3.31 Operation of heat pump CTES

the same time, customers accrue economic advantages with a CTES system when electric power companies provide discount rates for night-time electricity.

- **Efficient operation of the heat pump unit.** Heat pumps and other such devices as chillers and boilers have a maximum efficiency point of operation. In commercial and residential applications of heat pumps, heat pump operation cannot be maintained at the most efficient point because the cooling and heating loads vary temporally. This variation reduces the seasonal efficiency of heat pumps. CTES can help to avoid this problem by allowing operation of heat pumps at the most efficient point, because heat pumps can operate independent of the cooling and heating loads of buildings.
- **Reduction of heat pump capacity.** As Figure 3.31 shows, for the same amount of air-conditioning load, the longer operating hours allow for smaller size of heat pump, which leads to a reduction in demand for electricity. Thus both initial and operating costs decrease.

3.8.9 Ice CTES

Ice CTES systems can be economically advantageous and require less space than water CTES systems. This space advantage often allows heating and cooling capacity to be enlarged within the often restricted area of existing machine rooms.

An ice CTES system with heat pump is composed of a heat pump, an ice-making system, a storage tank, and an air-conditioning system that can be a conventional central system.

Ice CTES systems are often classified as static or dynamic, according to the way ice is delivered to the storage tank. Each of these ice CTES types are discussed below.

- **Static systems.** In static systems, an ice-making pipe is installed in the storage tank where ice is formed and later melted. Ice-in-tube systems produce ice inside the ice-making coil. Ice-on-coil systems produce ice outside the coil. The ice may be melted using either an external melting system that melts ice from the outer side, or an internal melting system (for ice-on-coil only). Internal melting may be achieved by feeding the warmed brine returning from the air-conditioning equipment into the coil. Alternatively, a refrigerant subcooling system can pass high-temperature and high-pressure refrigerant from the condenser through the coil. Another type of static system is the ice-tube float system that uses a polyurethane tube filled with water.
- **Dynamic systems.** In the dynamic type of ice CTES system, ice is produced outside the storage tank and removed from the ice-making surface continuously or intermittently by various means. The ice harvest system feeds refrigerant that has passed through the expansion valve into an ice-making plate where ice is peeled off and dropped into a storage tank. The ice chip system continuously produces ice, which is scraped off as ice chips. In the liquid–ice system, fine

ice crystals are formed in an ethylene glycol solution (ice slurry) by cooling with refrigerant. Alternative systems use PCMs. The sherbet–ice system produces very fine (sherbet-like) ice by a water or brine subcooling system.

Ice-on-Pipe CTES

Ice-on-pipe CTES designs produce ice by pumping very cold liquid refrigerant (usually HCFC-22 in commercial applications or ammonia in industrial refrigeration) through an array of pipes immersed in a tank of water. A system configuration, including the chiller components, is shown in Figure 3.32. Technically, ice-on-pipe CTES resembles process refrigeration. System components, that is, the compressor and condenser(s), high- and low-pressure receivers, refrigerant pumps, evaporators, and ice tanks, are individually selected for the application and integrated to provide a reliable refrigeration system.

Unlike direct-expansion systems, which rely on additional heat-transfer surface area to separate refrigerant vapor from liquid refrigerant, ice-on-pipe systems use a low-pressure receiver and a method called liquid overfeed to accomplish this.

A liquid-overfeed system works as follows. Chilled water and/or ice is produced by pumping cold liquid refrigerant to a chiller evaporator or an ice tank at a rate 1.3–1.6 times faster than that required to evaporate it. A “two-phase” solution of refrigerant liquid and vapor results, and is returned to the low-pressure receiver. This 30–60% higher refrigerant flow rate is the reason for the system being referred to as liquid overfeed.

The refrigerant returned to the low-pressure receiver is nearly saturated (see Figure 3.33). Refrigerant liquid that does not “boil off” in the evaporator is returned for a second pass.

Note that the open or “atmospheric” design of an ice-on-pipe system dictates the use of a heat exchanger to separate ice water from the building cooling water loop. The cooling loop is normally a closed system.

On the high-pressure side of the system (Figure 3.34), the cold refrigerant vapor that collects at the top of the low-pressure receiver is drawn off by the compressor. After compression, the pressurized (and now hot) vapor passes to the condenser, where cooling tower water circulating through the shell causes the refrigerant to condense. The liquid refrigerant, still at high pressure,

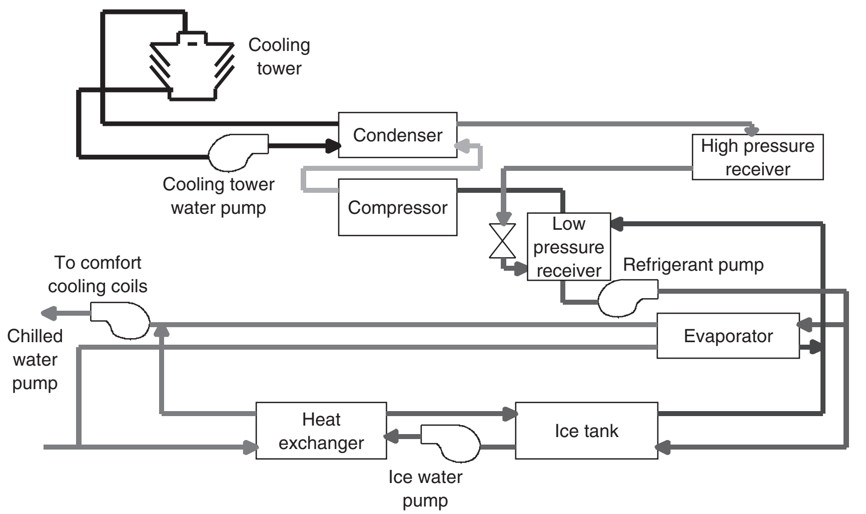


Figure 3.32 Ice-on-pipe CTES for process refrigeration (AEP, 2001)

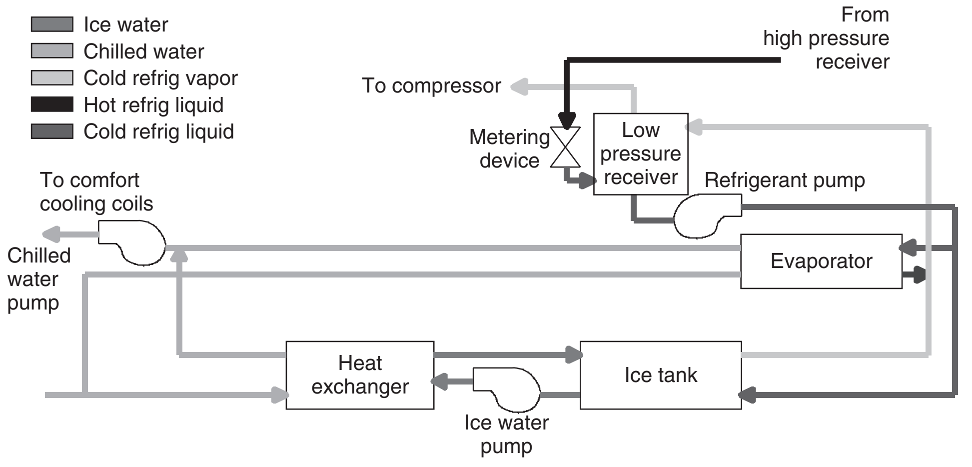


Figure 3.33 Low-pressure portion of an ice-on-pipe CTES for process refrigeration (AEP, 2001)

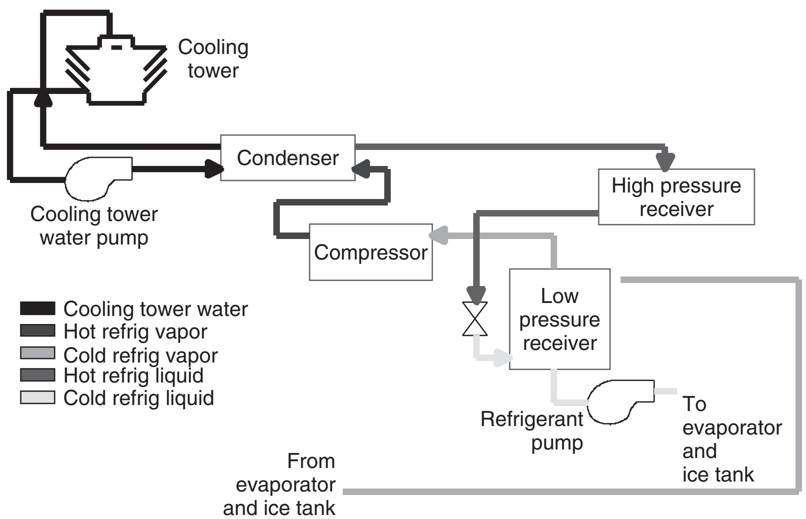


Figure 3.34 High-pressure portion of an ice-on-pipe CTES (AEP, 2001)

exits the condenser and enters a high-pressure receiver, where it is stored for later use. Refrigerant flow from the high-pressure receiver is regulated by a refrigerant metering device to ensure that a minimum liquid level is maintained in the low-pressure receiver.

The ice produced by an ice-on-pipe system forms on the exterior surfaces of an "ice coil." This coil is actually a series of steel pipes immersed in a tank of water. Cold refrigerant (usually HCFC-22) is then pumped through these pipes to freeze the water that surrounds them. Bubbles flow around the steel pipes to agitate the water in the tank, sometimes by injecting air at the bottom. The rising air bubbles promote dense, even ice formation during the freezing cycle and uniform melting when the tank is discharged.

The low-pressure receiver plays a critical role in liquid-overfeed ice-on-pipe systems: it separates the two-phase refrigerant solution returning from the ice coil (or chiller evaporator) into liquid and vapor. Gravity induces this separation, causing the liquid refrigerant and oil to settle at the bottom of the receiver while pure refrigerant vapor collects at the top. As the compressor draws this vapor from the receiver, the liquid level falls. To ensure that there is always sufficient liquid in this vessel, a liquid level control adds refrigerant from the high-pressure receiver as needed.

Liquid-overfeed systems require a separate oil return/recovery system. This is because the preferred compressor type (helical rotary/screw) expels significant amounts of oil into the discharge line. Entrained in the refrigerant, the oil makes its way through the condenser and high-pressure receiver, eventually ending up in the low-pressure receiver. There, the oil collects at the bottom of the tank (along with the liquid refrigerant) and cannot return to the compressor through the suction line. A separate oil-recovery system is needed to capture, distill, and return the oil to the compressor. This must be carefully addressed in the system design. The complexity of the liquid overfeed ice-on-pipe system translates into significant fixed costs that are independent of the quantity of ice produced and stored. The refrigerant and oil inventory control systems, refrigerant pumps and other system accessories, plus the field labor required to install them, constitute a sizable investment.

Depending on the system size, the tank can be either premanufactured to include both the ice coil and tank, or field-assembled by installing the ice coil in a field-erected concrete tank. While the latter option makes the per-ton-hour cost of the tank attractive, it only partially offsets the combined cost of field labor and accessories, even when the lower compressor cost is considered. Liquid overfeed ice-on-pipe systems are expensive because they require not only large inventories of oil and refrigerant, but refrigerant containment equipment as well. The high costs of engineering and installing liquid-overfeed ice-on-pipe systems typically limit their use to larger applications.

Ice-on-pipe systems offer a number of benefits over chilled-water storage. The storage volume required is considerably less, since each ton-hour of cooling stored can occupy as little volume as 0.085 m^3. Also, unlike their chilled-water counterparts, ice storage systems can operate at any return-water temperature.

Ice Harvesters

Ice harvesters circumvent the problems associated with liquid-overfeed ice-on-pipe systems by combining all of the components and accessories required for ice production in a single manufactured package. This device, called an ice harvester (see Figure 3.35), is installed above an open tank that stores a combination of water and flakes of ice.

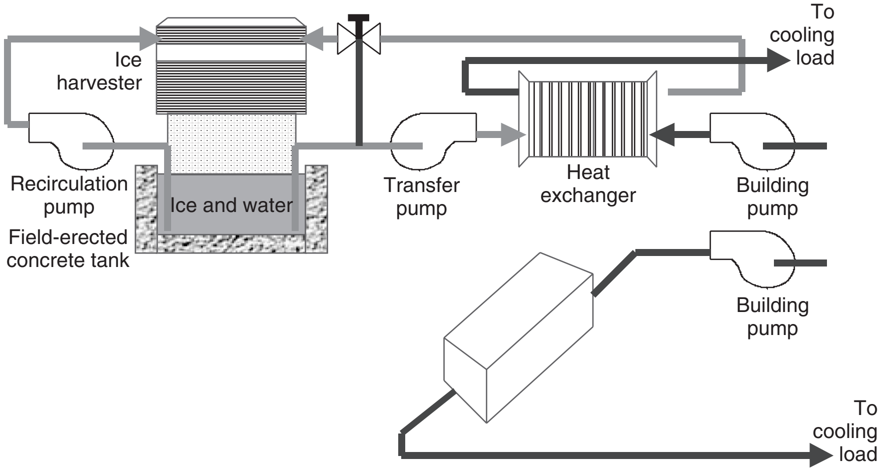


Figure 3.35 Ice harvester system (AEP, 2001)

To produce ice, 0 °C water is drawn from the storage tank and delivered to the ice harvester by a recirculation pump at a flow rate of 1.75 to 2.75 m^3/h per ton of ice-producing capacity. Once inside the ice harvester, the recirculated water flows into a drain pan positioned over a series of refrigerated plates. Each of these plates is constructed of two stainless steel sheets welded together at their circumference. A refrigeration system integral to the ice harvester maintains the plates at a temperature of −9.5 to −6.5 °C.

As the water leaves the drain pan, it flows freely over both sides of the refrigerated plates, where it freezes to a thickness of 0.3 to 1.0 cm. On reaching a given thickness (or at the initiation of a time), the ice is dislodged from the plates by a hot-gas defrost cycle, and falls into the tank below. When cooling is required, a transfer pump draws iced water from the storage tank and delivers it to a building heat exchanger.

It is possible to use the ice harvester as a water chiller by raising the suction temperature of the refrigeration system and pumping warm water from the building heat exchanger over the refrigerated plates. In fact, operating at this higher suction temperature improves the ice harvester's efficiency. Unfortunately, the ice harvester cannot produce chilled water without melting ice stored in the storage tank.

This inability to operate as a true water chiller in a chilled-water system poses a significant efficiency penalty on ice storage systems with ice harvesters. To address this inefficiency, ice harvesters are commonly used in tandem with conventional water chillers. Ice harvesting systems separate ice formation from ice storage. Ice is typically formed on both sides of a hollow flat plate, or on the outside or inside (or both) of a cylindrical evaporator surface. The evaporators are arranged in vertical banks located above the storage tank. Ice is formed to thicknesses between 0.5 and 1 cm. This ice is then harvested, often through the introduction of hot refrigerant gas into the evaporator; the gas warms the evaporator, which breaks the bond between the ice and the evaporator surface and allows the ice to drop into the storage tank below. Other types of ice harvesters use a mechanical means of separating the ice from the evaporator surface.

Ice is generated by circulating 0 °C water from the storage tank over the evaporators for a 600–1800 s build cycle. The defrost time is a function of the amount of energy required to warm the system and break the bond between the ice and the evaporator surface. Depending on the control methods, the evaporator configuration, and the discharge conditions of the compressor, defrost can usually be accomplished in 20–90 s. Typically, the evaporators are grouped in sections that are defrosted individually so that the rejected heat from the active sections provides the energy for defrost.

In load-leveling applications, ice is generated and the storage tank charged when there is no building load. When a building load is present, the return chilled water flows directly over the evaporator surface, and the ice generator functions either as a chiller or as both an ice generator and a chiller. Cooling capacity as a chiller is a function of the water velocity on the evaporator surface and the entering water temperature. The defrost cycle must be energized any time the exit water from the evaporator is within a few degrees of freezing. In chiller operation, maximum performance is obtained with minimum system-water flows and highest entering-water temperatures. In load-shifting applications, the compressors are turned off during the electric utility on-peak period.

Positive displacement compressors are usually used with ice harvesters, and saturated suction temperatures are usually between −7.5 and −5.5 °C. Condensing temperatures should be kept as low as possible to reduce energy consumption. The minimum allowable condensing temperature depends on the type of refrigeration system used and the defrost characteristics of the system. Several systems with evaporatively cooled condensers have operated with a compressor-specific power consumption of 0.9 to 1.0 kW/ton.

Ice-harvesting systems can melt stored ice quickly. Individual ice fragments are characteristically less than 15.5 × 15.5 × 0.65 cm, and provide a minimum of 1.5 m^2 of surface area per ton-hour of ice stored. When properly wetted, a 24-h charge of ice can be melted in less than 30 min for emergency cooling demands.

During the ice-generation mode of operation, the system is energized if the ice is below the high ice level. A partial-storage system is energized only when the entering water is at or above a temperature that will permit chilling during the discharge mode; otherwise, the system does not operate, and the ice tank is discharged during the peak period to meet the load. The high-ice level sensor can be mechanical, optical, or electronic. The entering-water temperature thermostat is usually electronic.

When ice is floating in a tank, the water level remains nearly constant, rendering it difficult to measure ice inventory by measuring water level. The following general methods are used to determine ice inventory:

- **Water conductivity method.** As water freezes, dissolved solids are forced out of the ice into the liquid, thus increasing their concentration in the water. Accurate ice-inventory information can thus be maintained by measuring conductivity and evaluating the ice level.
- **Heat balance method.** The cooling effect of a system may be determined by measuring the mechanical power input to, and heat of rejection from, the compressor. The cooling load on the system is determined by measuring coolant flow and temperature. The ice inventory is then determined by integrating cooling input minus load and evaluating the ice level. A variant of the heat balance method involves a heat balance on the compressor only, using performance data from the compressor manufacturer and measured load data.

Optimal performance of ice-harvesting systems may be achieved by recharging the ice storage tank over a maximum amount of time with minimum compressor capacity. Ice inventory measurement and the known recharge time are used to determine such specifications. Efficiency can also be increased with proper selection of multiple compressors and unloading controls.

Design of the storage tank is important to the operation of the system. The amount of ice stored in a storage tank depends on the shape of the storage, the location of the ice entrance to the tank, the angle of repose of the ice (which normally is between 15 and 30°, depending on the shape of the ice fragments), and the water level in the tank. If the water level is high, voids occur below the water surface because of the buoyancy of the ice. Ice–water slurries have been reported to have a porosity of 0.50 and typical specific storage volumes of 0.08 m^3 per ton-hour.

Cost A cost analysis of ice harvester systems indicates increasing costs for both the tank and the harvester as the quantity of ice stored increases (see Figure 3.36). Given their high dollar-per-ton cost, ice harvester systems are usually used to provide additional capacity in retrofit applications, or in large installations.

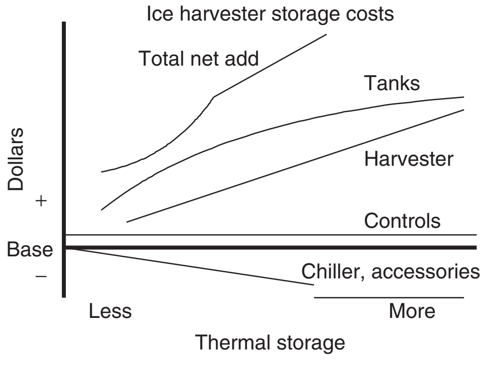


Figure 3.36 Cost relationship for ice harvesters (AEP, 2001)

Advantages Ice harvesters present the system designer with a number of benefits. As with other ice storage systems, the space requirement and cost of the volume stored are less than those for chilled-water systems. In addition, the ice harvester is a packaged device, leading to simplified installation, reduced installed costs, and, in most cases, factory-tested performance.

Disadvantages Ice harvesters have some limitations, particularly since the harvester and tank are open to the atmosphere. For example, the plates and chassis of the ice harvester are normally constructed of stainless steel, a material that adds significantly to the ice harvester's already high cost. Water treatment is also necessary because of the open nature of the tank and drain pan. The complexities of evenly distributing the ice in the bin and the prevention of piling and bridging add to the cost and operation of this system. Finally, the ice harvester's inability to produce chilled water without depleting the ice in the storage tank may be an economic deterrent.

CTES glycol systems

Glycol systems freeze water by circulating ethylene or propylene glycol through storage tanks (Figure 3.37). The glycol ice storage system is simple. Few accessories are needed, and conventional water chillers are used. Instead of water, a glycol solution (in this case, 25% ethylene glycol) is pumped through the chiller coils and ice storage tanks in the chilled-water loop. The −5.5 to −4.5 °C ethylene glycol produced by the packaged chiller freezes the water contained inside the ice storage tanks.

Glycol ice storage systems are available from all major chiller manufacturers. Though similar in concept, they may be packaged differently. Glycol ice storage systems can generally be divided into two major categories: modular and encapsulated ice storage.

Cost Glycol ice storage systems have low installed costs since the same packaged chiller that provides space cooling also doubles as the ice maker. The storage tanks themselves are the only significant additional cost in these systems. In fact, glycol ice storage systems sometimes reduce chiller costs.

Advantages Glycol ice storage systems present numerous benefits, including the ability to use a standard packaged chiller. They also offer an opportunity to reduce pump work, and require few ancillary devices. The choice of modular storage tanks or encapsulated ice systems offers not only application flexibility, but cost choices and reliable performance as well. Simple control schemes

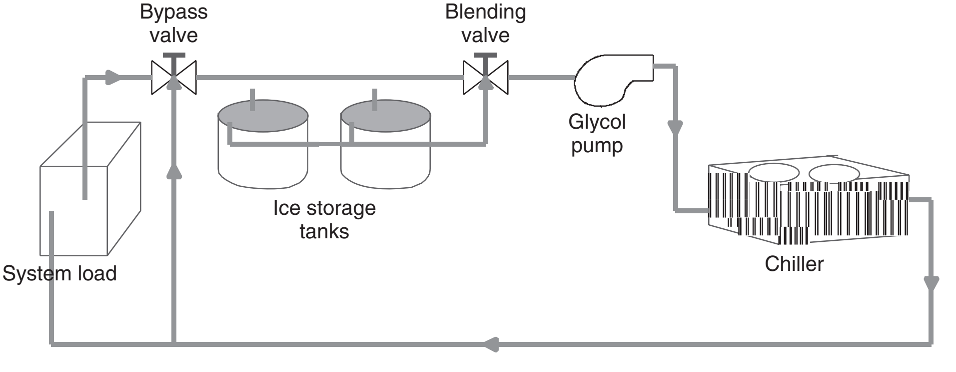


Figure 3.37 Glycol ice CTES system (AEP, 2001)

can be used and, as for all ice storage systems, volume and space requirements per ton-hour of storage are considerably lower than those for chilled-water storage.

Disadvantages Glycol ice storage systems have some problems, the most significant of which is the need for a heat-transfer system that uses ethylene (or propylene) glycol rather than water.

Types of Systems Glycol ice-storage systems presently enjoy a great deal of market popularity because of their simplicity and low installed cost. They can operate a wide variety of CTES technologies and equipment, and these are now discussed.

Modular Ice Storage for Glycol Systems Modular ice storage tanks can be constructed in many sizes or shapes. Two designs are common: a cylindrical polyethylene tank with circular polyethylene heat exchangers; and a rectangular metal tank with polypropylene heat exchangers. Some modular ice storage tanks are illustrated in Figure 3.38, along with some details of their storage capacities and key physical characteristics. In both modular ice storage designs, the heat exchanger separates the glycol solution from the water in the tank. The water is frozen by circulating -6.5 to $-4.5\,^{\circ}$C glycol through the heat exchanger. The differences in tank geometry and heat exchanger design pose different problems for the design engineer. For example, the shape of circular ice storage tanks allows heat exchangers with fewer circuits of longer length, and permits freezing or melting at lower flow rates and higher temperature differences. Low flow-rate freeze cycles enable the designer to better match the capacities of the storage tanks and chiller. Rectangular tank designs, on the other hand, incorporate high flow-rate, low pressure-drop heat exchangers that operate with a lower temperature difference during freezing. These characteristics not only place additional design constraints on chiller selection, but require individual flow balancing for each storage tank.

Both modular ice storage tank designs share the advantage of pre-engineering and factory manufacture. Factory design and testing increase the likelihood of reliable performance. Piping two or more modular tanks in parallel can increase capacity as required.

Encapsulated Ice Storage for Glycol System The other class of glycol-system storage, encapsulated ice, offers a wide degree of latitude in the design of the ice containment vessel. Various construction materials and geometries can be exploited and designed to conform to the space available and building architecture.

Encapsulated ice designs store the water to be frozen in a number of plastic containers. These containers may be thin and rectangular, spherical, or annular. Figure 3.39 illustrates some encapsulated ice storage containers, and provides information on their storage capacities and design-related characteristics. The number of containers or units required for an application depends on their

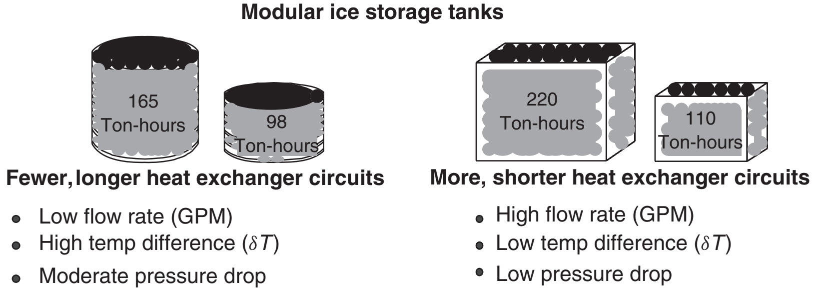


Figure 3.38 Modular ice storage tanks and some of their characteristics (AEP, 2001)

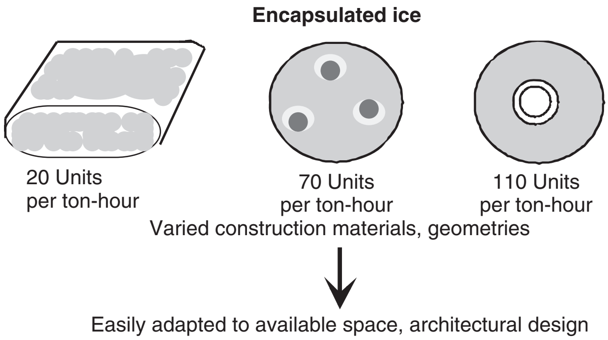


Figure 3.39 Encapsulated ice storage tanks (AEP, 2001)

individual storage capacities. For example, as seen in Figure 3.38, 1 ton-hour of storage can be provided with approximately 20 ice "trays" or by 70 of the 10-cm-diameter spheres, called *ice balls*. Some commercially available rectangular containers are approximately $3.5 \times 30.5 \times 76.5$ cm. Other designs are also available.

Perhaps the greatest advantage of this type of glycol system is the degree of application flexibility it affords the system designer. By selecting or designing a specifically adapted containment vessel, the storage system can be customized to the application. If desirable, it can even be placed below ground.

Encapsulated ice units consist of plastic containers filled with ionized water and an ice nucleating agent. These primary containers are placed in storage tanks, which may be either steel pressure vessels, open concrete tanks, or fiberglass or polyethylene tanks. In tanks with spherical containers, water usually flows vertically through the tank, and in tanks with rectangular containers, water flows horizontally. The type, size, and shape of the storage tank are limited only by the need to achieve an even flow of heat-transfer fluid between the containers.

A fluid coolant (e.g., 25% ethylene glycol or propylene glycol and 75% water) is cooled to -4.5 to $-3.5\,^{\circ}$C by a liquid chiller, and circulates through the tank and over the outside surface of the plastic containers, causing ice to form inside the containers. The chiller must be capable of operating at this reduced temperature. The plastic containers must be flexible to allow for change of shape during ice formation; the spherical type has preformed dimples in the surface, and the rectangular type is designed for direct flexure of the walls. During discharge, coolant flows directly either to the system load or to a heat exchanger, thereby removing heat from the load and melting the ice within the plastic containers. As the ice melts, the plastic containers return to their original shape.

Ice inventory is measured and controlled by an inventory/expansion tank normally located at the high point in the system and connected directly to the main storage tank. As ice forms, the flexing plastic containers force the surrounding secondary coolant into the inventory tank. The liquid level in the inventory tank may be monitored to account for the ice available at any point during the charge or discharge cycle.

Ice-Slurry CTES Systems

Ice slurry is a very versatile cooling medium. The handling characteristics, as well as the cooling capacities, can be matched to suit any application by means of simply adjusting the percentage of ice concentration. At 20–25% ice concentration, ice slurry flows like conventional chilled water while providing five times the cooling capacity. At 40–50% ice concentration, an ice-slurry flow demonstrates thick slurry characteristics, and at a 65–75% concentration, slurry ice has the consistency

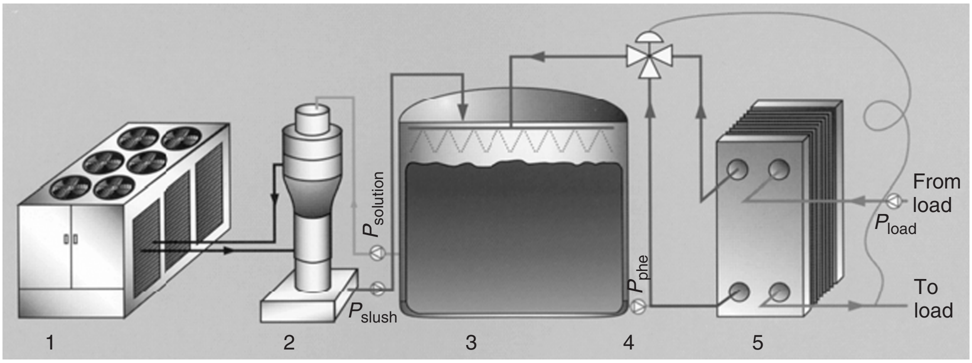


Figure 3.40 A MaximICE ice-slurry system (*Courtesy of Paul Mueller Company*)

of soft ice cream. When slurry ice is produced in dry form (i.e., 100% ice), it takes the form of nonstick pouring ice crystals, which can be directly used in various products and processes.

Ice slurry is a crystallized water-based ice solution that can be pumped, and offers a secondary cooling medium for CTES while remaining fluid enough to pump. It flows like conventional chilled water while providing five to six times higher cooling capacity. The ice-slurry system is a dynamic type of ice CTES system that offers a pumpable characteristic advantage over any other type of dynamic systems. Compact equipment design and the pumpable characteristics offer tremendous flexibility for the location of the storage tank(s) and the most economic capacity and duty balancing for any given application. The storage tank can be placed under, beside, inside, or on top of a building, and can be in any shape and size to match the building, and architectural requirements. Multiple small storage tanks can be used instead of a single large static-type ice storage tank.

Figure 3.40 shows a MaximICE ice-slurry CTES system and its components. In the operation of such a system, a compressor/condenser (1) supplies refrigerant to the evaporator. A MaximICE orbital rod evaporator (2) uses a freeze-depressant solution to produce a pumpable ice slurry. Low-temperature slurry makes MaximICE ideal for use with low-temperature air systems. An insulated ice storage tank (3) separates ice manufacturing from ice usage. The tank contains a freeze-depressant solution that is converted to an ice slurry in the MaximICE evaporator. The slurry melts as the stored ice absorbs the heat of the cooling load. A load control pump and valve (4) control the supply temperature to the load. A plate heat exchanger (5) separates the storage tank from the cooling load and prevents cross-contamination between the ice-melting loop and the cooling load. It is important to note that the solution can be supplied from the ice storage tank to the load at various temperatures to satisfy specific application needs.

Ice-slurry CTES systems offer a large number of advantages:

- **Higher energy efficiency.** These systems provide relatively high energy efficiency. Unlike static ice systems, where ice adheres to the heat-transfer surface, ice slurry produced by the ice-slurry generator does not adhere to the heat-transfer surfaces, and unlike ice harvesters, defrost is not required to harvest the ice for storage in tanks.
- **Cost-effective tank design.** Ice slurry can be pumped into storage tanks, reducing the need for extra structural support, as required for ice harvesters located above the storage tanks.
- **Compact equipment.** The systems have a small evaporator footprint, which leads to space savings in the refrigeration equipment room.
- **Lower supply temperature.** Such systems offer lower supply water temperature compared to other ice systems.

- **Flexible ice storage tank design.** Ice slurry can be stored in tanks of any shape. For example, the height of an ice storage tank can be increased, resulting in a reduction of the tank footprint that leads to often valuable floor space savings. This is difficult to achieve in static and other dynamic ice storage systems.
- **Maintenance-free ice tank design.** Unlike ice-on-coil systems, ice-slurry systems do not require extensive lengths of pipe or tubing in the storage tanks, sometimes on the order of kilometers. This characteristic eliminates the need for repairing leaking pipes or tubing inside the tank.
- **Satisfies large loads.** Large loads for short durations can be met by ice-slurry systems because of the quick melting of ice that is achieved by a large area of contact between the warm return solution and stored ice.
- **Ease of modification.** The systems can be easily adapted to changing needs, which can occur. for example, when facility expansion takes place and facility use and/or utility rates change.

CYFLIP as a new CTES system

Among the various systems to facilitate night-time power usage, the CHIYODA Corp. has developed the CYFLIP CTES system, which reduces 40% of the refrigerator duty of a normal air-conditioning system. CYFLIP is a static CTES system that makes ice in a polyethylene tube filled with water. These tubes are placed in a TES vessel where low-temperature brine is circulated. CYFLIP has a simple design and low equipment costs. The total investment can be less than that for a conventional air-conditioning system, since the capacity of the refrigerator becomes smaller. The CYFLIP system is regarded as reliable, because of its ease of operation and durability. The CYFLIP system is illustrated in Figure 3.41, where several operating parameter values are given.

Practical Example I: Performance Curves for an Ice TES

In this section, a practical design application for a school is given to point out the design and technical aspects of ice TES.

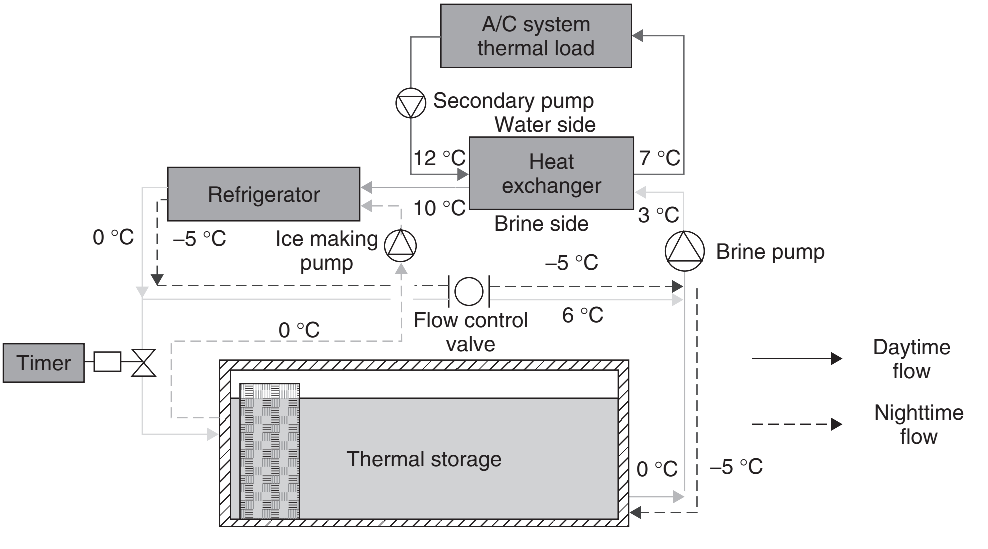


Figure 3.41 The CYFLIP ice CTES (*Courtesy of CHIYODA Corp.*)

In this project, the chiller capacity of 225 t is the capacity at ice-making conditions. At the lower temperatures required to make ice, the chiller is derated to 225 t.

The 288 t listed in the example is the chiller when operating at supplemental chiller capacity. This means that the chiller is running to supply cooling to the load directly, and not making ice. In this mode, the chiller would be running at standard conditions, at the higher normal air-conditioning temperatures. A chiller that is capable of producing 225 t at ice-making conditions would be capable of approximately 320 t at standard conditions.

Because this is a partial storage example, the chiller supplies cooling directly to the load between the hours of 6:00 am and 1:00 pm (supplemental chiller operation) The thermal storage system then takes over and supplies cooling during the peak electrical period from 1:00 to 8:00 pm (storage discharge-ice melting). Finally, during off-peak hours, the chiller operates at the reduced capacity of 225 t to replace the ice consumed during the day. The final hour of the charge is lower as the chiller unloads at the end of the cycle.

During the ice-making mode, we have modified the table to provide for a chiller running at 225 t for 7 h and at 97 t for 1 h. This provides a total ice build of 1672 ton-hours. This is the same amount of energy that is removed from the storage system during storage discharge. This is also known as the *rated capacity.*

The nominal capacity of the system is 1800 ton-hours. Therefore, following the discharge of 1672 ton-hours from storage, there is an unused capacity of 128 ton-hours still remaining. This difference between nominal and rated capacity, and the unused ice left in storage, is normal for all thermal storage systems. Indeed, it is impossible to discharge 100% of the ice in storage at useful rates, because the discharge rates fall off rapidly as we approach 100% discharge. It is normally not possible for thermal storage to melt 100% of the ice at rates that are high enough to satisfy a typical load. Unfortunately, there are still manufacturers and designers who insist that thermal storage is 100% efficient. This myth leads them to install smaller and less expensive thermal storage systems wherein the nominal and rated capacities are the same. Such systems usually run out of ice before the end of the discharge period and the discharge temperatures from storage climb prematurely (Ott, V.J. (2001). *Personal communication*, President of CRYOGEL Ice Ball Thermal Storage, San Diego.).

Figures 3.42 and 3.43 illustrate performance curves for charging (freezing) and discharging (melting) for Cryogel ice balls. The details of a CTES using Cryogel ice balls for a typical application (a sample input/output design report), along with a load profile table, follow:

Project:	Typical Elementary School	
Storage rating:		
	Rated capacity:	1,672 ton-hours
	Nominal capacity:	1,800 ton-hours
Charge-cycle specifications:		
	Entering-fluid temperature:	−5.55 °C
	Leaving-fluid temperature:	−1.66 °C
	Tank temperature difference:	−13.88 °C
	Tank LMTD:	−14.55 °C
	Chiller capacity:	225 t
	Charging period:	8 h
	Chiller shut-off temperature:	−6.66 °C
Discharge-cycle specifications:		
	Entering-fluid temperature:	12.22 °C
	Leaving-fluid temperature:	3.33 °C
	Tank temperature difference:	−8.8 °C
	Tank LMTD:	−10.94 °C
	Peak discharge rate:	288 t

Load profile:

Hour	Building Load	Supplemental Chiller	Storage		Ice Making Charge	Net Storage Inventory
			Discharge	Ton-hours		
Mid to 1	0	0	0	0	225	1,028.00
1 to 2	0	0	0	0	225	1,253.00
2 to 3	0	0	0	0	225	1,478.00
3 to 4	0	0	0	0	225	1,800.00
4 to 5	0	0	0	0	97	1,800.00
5 to 6	0	0	0	0	0	1,800.00
6 to 7	118.00	118.00	0	0	0	1,800.00
7 to 8	205.00	205.00	0	0	0	1,800.00
8 to 9	257.00	257.00	0	0	0	1,800.00
9 to 10	252.00	252.00	0	0	0	1,800.00
10 to 11	255.00	255.00	0	0	0	1,800.00
11 to 12	279.00	279.00	0	0	0	1,800.00
12 to 1	288.00	288.00	0	0	0	1,800.00
1 to 2	285.00	0	285.00	285.00	0	1,515.00
2 to 3	287.00	0	287.00	572.00	0	1,228.00
3 to 4	262.00	0	262.00	834.00	0	966.00
4 to 5	216.00	0	216.00	1,050.00	0	750.00
5 to 6	208.00	0	208.00	1,258.00	0	542.00
6 to 7	207.00	0	207.00	1,465.00	0	335.00
7 to 8	207.00	0	207.00	1,672.00	0	128.00
8 to 9	0	0	–	1,672.00	0	128.00
9 to 10	0	0	–	1,672.00	245	353.00
10 to 11	0	0	–	1,672.00	245	578.00
11 to Mid	0	0	–	1,672.00	245	803.00
TOTAL	**3,326.00**	**1,654.00**	**1,672.00**		**1,921.00**	

Note: Chiller must run fully loaded at storage entering fluid temperature as specified above. Estimated sizing may change with actual load profile. All units are tons, except the totals across the bottom and the data under the columns "storage-ton hours" and "net storage inventory" which are in ton-hours (*Courtesy of CRYOGEL Ice Ball Thermal Storage*).

The curves in Figures 3.42 and 3.43 are based on typical heat exchanger sizing methods using log mean temperature differences (LMTDs). Indeed, ice CTES systems are like large heat exchangers but the surface area of the thermal storage media changes as ice is frozen or melted. Therefore, a degradation is observed in Figures 3.42 and 3.43 in instantaneous performance as ice melts during discharge. Also observed is a reduction in instantaneous performance as ice gets thicker and impedes the heat-transfer process during charging. This behavior is typical of all ice-based CTES systems.

The LMTD is calculated using the storage tank inlet (T_i) the storage outlet (T_o) and the ice temperature (T_c) as follows:

$$\text{LMTD} = \frac{[(T_i - T_c) - (T_o - T_c)]}{\ln[(T_i - T_c)/(T_o - T_c)]}$$

Using LMTD together with the performance curves allows one to predict instantaneous capacity at any point during the discharge of the storage system. This assessment is critical to be certain that a system has sufficient ice to meet the most demanding periods of each daily cycle. In a similar manner, although less critical, one can determine proper chiller sizing to match the ability of the ice balls to release heat during the charge process. Although the CTES market is generally not interested

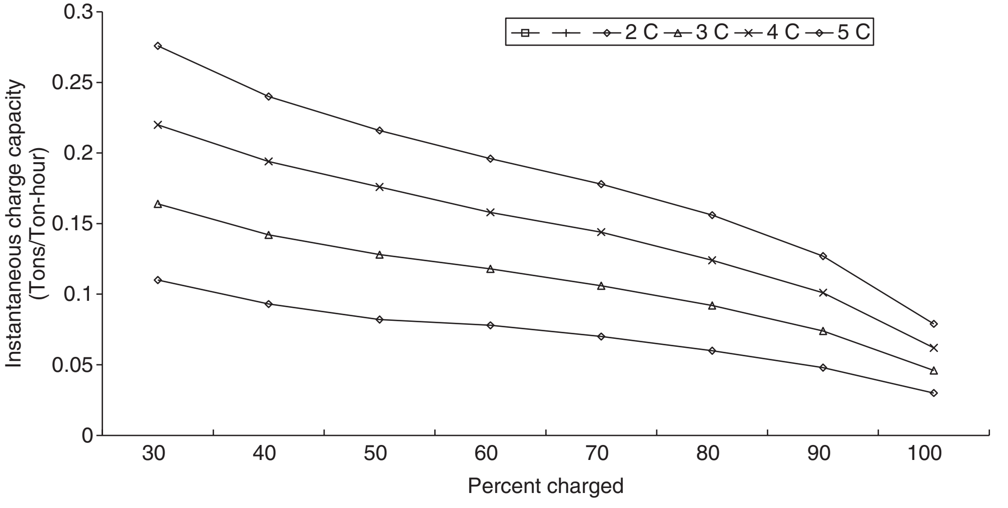


Figure 3.42 Instantaneous charge capacity of Cryogel ice balls (in tons per ton-hour of storage capacity), as a function of storage inlet and outlet LMTDs (*Courtesy of CRYOGEL Ice Ball Thermal Storage*)

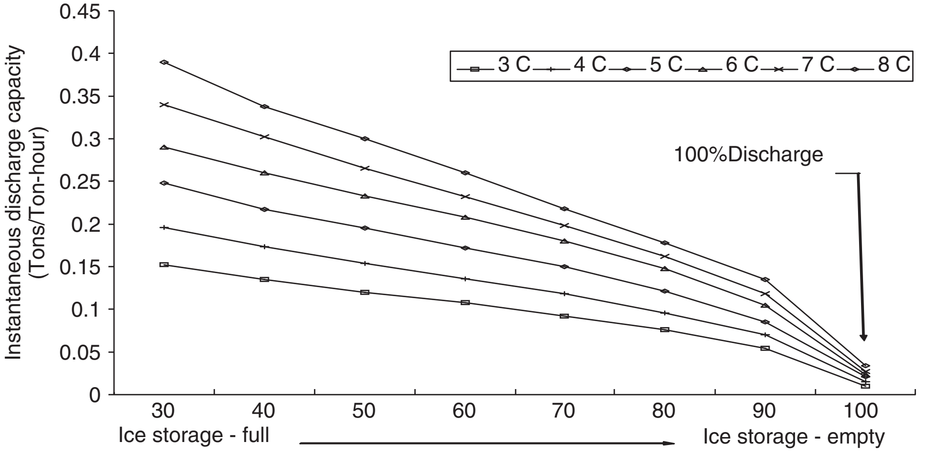


Figure 3.43 Instantaneous discharge capacity of Cryogel ice balls (in tons per ton-hour of storage capacity), as a function of storage inlet and outlet LMTDs (*Courtesy of CRYOGEL Ice Ball Thermal Storage*)

in this level of detail, and focuses on the practical output of the sizing methodology, this information helps understand some of the design details for ice CTES systems (e.g., Figures 3.44 and 3.45).

Practical Example II: Design and Operational Loads

The following design example is taken from Baltimore Aircoil Company (BAC, 1985). The analysis is performed using ice chiller Thermal Storage Unit Selection (TSU-M) software. The selected TES, substance, and chiller are

- BAC thermal storage: 1 TSU-476M 1 TSU-761M
- Glycol charge: 4776 L of 25% ethylene glycol
- Specified chiller: Model A-chiller 12 at approximately 514 kW (for details, see Table 3.11).

Before providing details, it is necessary to introduce some definitions which are important in design calculations:

- **LBT.** Chiller-leaving brine temperature.
- **EDB.** Dry-Bulb air temperature (for air-cooled chillers used in ice building).
- **CWT.** Condenser water temperature (for water-cooled chillers used in ice building).
- **Parasitic load(s).** The heat input to the thermal storage device from other devices in the TES system. Internal melt ice-on-coil systems do not have such parasitic loads. However, for external melt ice-on-coil systems, the parasitic auxiliary device is the air pump used for agitation of the storage media. In this case, the parasitic heat gain must include the heat input to the thermal storage device as the air is cooled from its source temperature to the temperature of the storage media.
- **Operational modes.** Status of the thermal devices in the cooling system in relation to meeting the required load. Modes include cooling with chillers (compressor) only, cooling with TES device plus chiller (in partial-storage systems), building ice without cooling, building ice with cooling, cooling with ice only (full-storage systems), and no chiller plus no TES (in the case of no cooling load).
- **Chiller load.** Cooling load supplied by the chiller compressor.

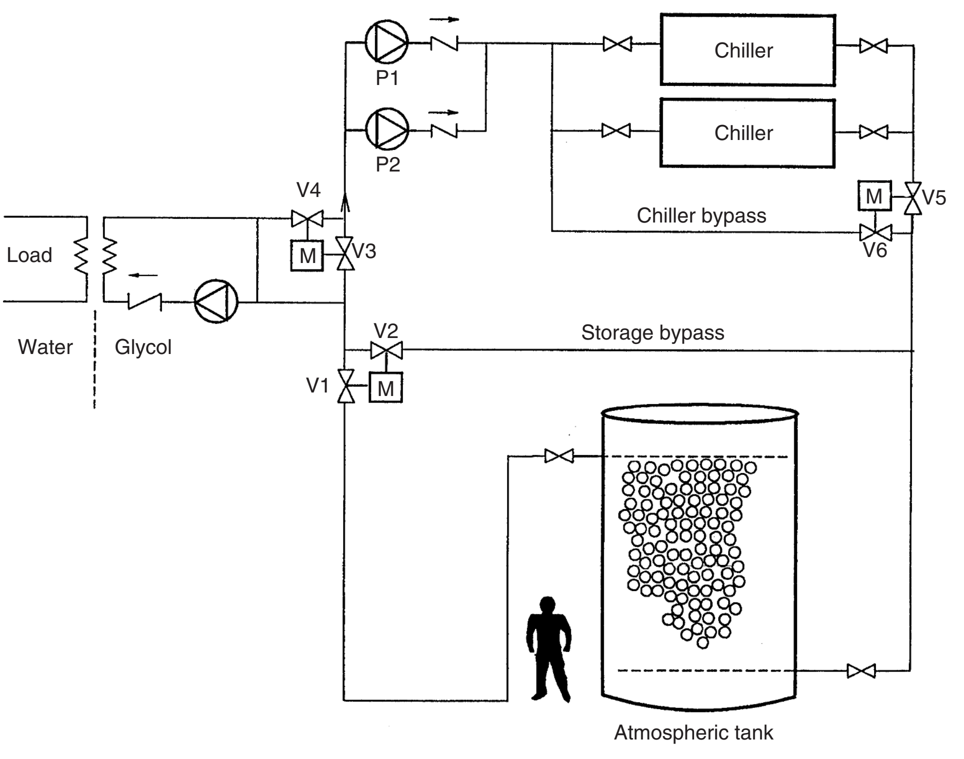


Figure 3.44 An atmospheric ice ball, single tank (series) TES system (*Courtesy of CRYOGEL Ice Ball Thermal Storage*)

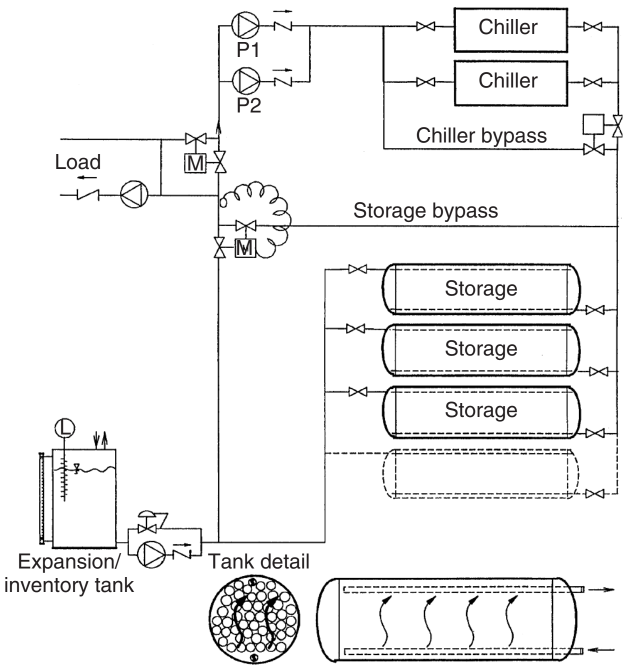


Figure 3.45 A pressurized ice ball, single tank (series) TES system (*Courtesy of CRYOGEL Ice Ball Thermal Storage*)

Table 3.11 Details for chiller A (38 L/s)

LBT (°C)	EDB (°C)	Capacity (kW)	Power (kW)	COP
−5.6	23.9	374	154	2.43
−5.6	35.0	331	166	2.00
6.7	23.9	568	180	3.15
6.7	35.0	513	199	2.57

Courtesy of Baltimore Aircoil International N.V.

- **Base load.** Load to be met completely by the chillers. Selection of base load chillers should be done so that the chillers are running at maximum efficiency.
- **Total load.** Total thermal load of the building/process to be delivered by the cooling system (chillers and ice TES system).
- **Heat rejection.** Heat dissipated by the condenser of the chiller to achieve the cooling required from the chiller.
- **Charge and discharge rates.**
  - *Charge rate*. The rate (typically expressed in tons or kW) at which energy (heat) is removed from the storage device during the charge period.
  - *Discharge rate*. The rate (typically expressed in tons or kW) at which energy (heat) is added to the storage device during the discharge period.
- **Ambient loss.** Sum of conduction, convection, and radiation heat escaping from the thermal energy storage tank to the surroundings.
- **Net storage.** Actual quantity of ice present in the ice TES tank at a particular time.
- **Flow rate.** Brine flow rate within the ice TES system.

- **Inlet temperature.**
  - *Inlet temperature for the thermal storage device*. Temperature of the brine entering the ice thermal energy storage tank.
  - *Inlet Temperature for the thermal storage system*. Temperature of the brine entering the ice thermal energy storage system (chiller and tank).
- **Exit temperature.**
  - *Exit temperature for the thermal storage device*. Temperature of the brine leaving the ice thermal energy storage tank.
  - *Exit temperature for the thermal storage system*. Temperature of the brine leaving the ice thermal energy storage system (chiller and tank).
- **Pressure drop.** Pressure loss due to brine flow through the coil of the ice thermal energy storage system.
- **Chiller peak load.** Maximum load delivered by the chiller at certain ambient and brine temperatures.
- **Chiller average load.** Average load delivered by the chiller at certain ambient and brine temperatures.
- **COP.** Coefficient of performance.

On the bases of the load profile and operating strategy, the selection will deliver a peak of 1000 kW at design conditions of 38 L/s of 25% by weight ethylene glycol from 10.2 to 3.4 °C. The maximum pressure drop across the storage unit is 79.1 and 75.3 kPa in the ice build and melt modes, respectively. Summaries for the loads, flow, temperature, and pressure parameters, and energy demand and use are presented in Tables 3.12–3.14.

3.8.10 Ice Forming

The ice-making equipment is expected to form ice and deliver it to the storage tank accordingly. Three main systems are available for forming ice:

- direct expansion, which forms ice by directly feeding refrigerant into the ice-making heat exchanger;
- the brine system, which exchanges heat between refrigerant and brine in the heat pump evaporator to produce low-temperature liquid brine that is fed to the ice-forming coil, and
- the heat pipe system, which exchanges heat between the refrigerant evaporator and water, and forms ice on the heat pipe surface.

In the United States, direct expansion is used in the majority of large-scale systems, while the brine system is mainly used for medium- and small-scale equipment. In Japan, the brine system is favored regardless of building size.

Compared to the other types, brine systems require more space and special materials, and have lower COPs because of the additional temperature difference between refrigerant and brine, and the power consumption by the brine pump. However, they do have the advantage that the tank and heat pump can be located separately. Direct expansion systems require a much larger refrigerant charge, are more expensive, and are difficult to maintain.

3.8.11 Ice Thickness Controls

The oldest type of ice storage is the refrigerant-fed ice builder, which consists of refrigerant coils inside a storage tank filled with water. The tank water freezes on the outside of the chiller evaporator coils to a thickness of up to 0.065 m. Ice is melted from the outside of the formation (hence the

Table 3.12 Design and operational loads and TES system parameters

Hour	Mode	EDB (°C)	Chiller load (kW)	Base load (kW)	Total load (kW)	Chiller load (kW)	Heat rejection rate	Charge rate (kW)	Discharge rate (kW)	Ambient loss rate (kW)	Net storage (kWh)
0:00	B	38	0	0	0	347	520	347	–	1.8	2,081
1:00	B	38	0	0	0	345	518	345	–	1.8	2,426
2:00	B	37	0	0	0	346	517	346	–	1.8	2,769
3:00	B	36	0	0	0	346	517	346	–	1.8	3,113
4:00	B	36	0	0	0	345	516	345	–	1.8	3,457
5:00	B	36	0	0	0	344	514	344	–	1.8	3,801
6:00	B	36	0	0	0	215	375	215	–	1.8	4,143
6:37	S	36	0	0	0	–	–	–	–	1.8	4,357
7:00	S	37	0	0	0	–	–	–	–	1.8	4,357
8:00	I	38	800	0	800	464	661	–	336	1.8	4,354
9:00	I	39	840	0	840	460	661	–	380	1.8	4,016
10:00	I	41	860	0	860	466	673	–	394	1.8	3,635
11:00	I	43	890	0	890	465	675	–	425	1.8	3,239
12:00	I	45	950	0	950	463	679	–	487	1.8	2,812
13:00	I	47	980	0	980	459	679	–	521	1.8	2,323
14:00	I	47	1,000	0	1,000	458	679	–	542	1.8	1,800
15:00	I	48	990	0	990	455	677	–	535	1.8	1,256
16:00	I	47	880	0	880	444	662	–	436	1.8	719
17:00	I	47	660	0	660	414	623	–	246	1.8	281
18:00	B	45	0	0	0	339	526	339	–	1.8	33
19:00	B	44	0	0	0	340	524	340	–	1.8	371
20:00	B	42	0	0	0	342	523	342	–	1.8	709
21:00	B	41	0	0	0	345	523	345	–	1.8	1,049
22:00	B	39	0	0	0	346	522	346	–	1.8	1,392
23:00	B	38	0	0	0	347	522	347	–	1.8	1,736

Since storage device(s) is passive, there are no parasitic loads.
mode, mode of operation; B, ice build; S, standby; I, cooling (ice with compressor); C, cooling (compressor only) (*Courtesy of Baltimore Aircoil International N.V*.).

term *external melt*) by circulating water through the tank, causing it to become chilled. Air bubbled through the tank agitates the water to promote uniform ice buildup and melting.

Instead of a refrigerant, a secondary coolant (e.g., 25% ethylene glycol and 75% water) can be pumped through the coils inside the storage tank. The coolant has the advantage of greatly decreasing the refrigerant inventory. However, a refrigerant-to-coolant heat exchanger between the refrigerant and the storage tank is required in such instances.

Some major concerns specific to the control of ice-on-coil systems are

- limiting ice thickness (and thus excess compressor energy) during the build cycle and
- minimizing the bridging of ice between individual tubes in the ice bank.

Bridging is avoided because it restricts the free circulation of water during the discharge cycle. While not being physically damaging to the tank, this blockage reduces performance, raising the water exit temperature because of reduced heat-transfer surface.

Regardless of the refrigeration method (direct-expansion or secondary coolant), the compressor is controlled by (i) a timer or controller that restricts operation to periods dictated by the utility rate structure, and (ii) an ice-thickness override control, which stops the compressor(s) at a predetermined ice thickness. At least one ice-thickness controller should be installed per ice bank. If there are multiple refrigeration circuits per ice bank, one ice-thickness control per circuit should be installed.

Table 3.13 Flow, temperature, and pressure parameters

Hour	Mode	Charge rate (kW)	Discharge rate (kW)	Flow rate (L/s)	Inlet temp. (°C)	Exit temp. (°C)	Pressure drop (kPa)	Total load (kW)	Flow rate (L/s)	Inlet temp. (°C)	Exit temp. (°C)	Net storage (kWh)
0:00	B	347	–	38.0	−3.9	−1.5	78.6	–	0	–	–	2,081
1:00	B	345	–	38.0	−4.0	−1.7	78.6	–	0	–	–	2,426
2:00	B	346	–	38.0	−4.2	−1.8	78.6	–	0	–	–	2,769
3:00	B	346	–	38.0	−4.3	−2.0	78.6	–	0	–	–	3,113
4:00	B	345	–	38.0	−4.4	−2.1	78.6	–	0	–	–	3,457
5:00	B	344	–	38.0	−4.5	−2.2	78.6	–	0	–	–	3,801
6:00	B	215	–	38.0	−4.6	−2.2	78.6	–	0	–	–	4,143
6:37	S	–	–	–	–	–	–	–	–	–	–	4,357
7:00	S	–	–	–	–	–	–	–	–	–	–	4,357
8:00	I	–	336	38.0	4.3	2.0	75.2	800	38.0	7.4	2.0	4,354
9:00	I	–	380	38.0	4.6	2.0	75.1	840	38.0	7.7	2.0	4,016
10:00	I	–	394	38.0	5.5	2.8	74.8	860	38.0	8.6	2.8	3,635
11:00	I	–	425	38.0	5.9	3.0	74.7	890	38.0	9.1	3.0	3,239
12:00	I	–	487	38.0	6.5	3.2	74.5	950	38.0	9.7	3.2	2,812
13:00	I	–	521	38.0	6.8	3.3	74.4	980	38.0	9.9	3.3	2,323
14:00	I	–	542	38.0	7.1	3.4	74.4	1,000	38.0	10.2	3.4	1,800
15:00	I	–	535	38.0	7.1	3.4	74.4	990	38.0	10.1	3.4	1,256
16:00	I	–	436	38.0	5.9	3.0	74.7	880	38.0	8.9	3.0	719
17:00	I	–	246	38.0	3.7	2.0	75.3	660	38.0	6.5	2.0	281
18:00	B	339	–	38.0	−2.3	0.0	77.6	–	0	–	–	33
19:00	B	340	–	38.0	−2.6	−0.3	77.8	–	0	–	–	371
20:00	B	342	–	38.0	−3.0	−0.6	78.0	–	0	–	–	709
21:00	B	345	–	38.0	−3.2	−0.9	78.2	–	0	–	–	1,049
22:00	B	346	–	38.0	−3.5	−1.2	78.3	–	0	–	–	1,392
23:00	B	347	–	38.0	−3.7	−1.4	78.5	–	0	–	–	1,736

Since storage device(s) is passive, there are no parasitic loads.
Mode, mode of operation; B, ice build; S, standby; I, cooling (ice with compressor); C, cooling (compressor only) (*Courtesy of Baltimore Aircoil International N.V*.).

Placement of the ice-thickness controller(s) should be determined by the ice-bank manufacturer, on the basis of circuit geometry and flow pressure drop to minimize bridging.

Ice-thickness controls are either mechanically or electrically operated. Mechanical controls typically consist of a fluid-filled probe positioned at a desired distance from the coil. As ice builds, it encapsulates the probe, causing the fluid to freeze and apply pressure. The pressure signal controls the refrigeration system via a pneumatic–electric switch. Electric controls operate by sensing difference between electrical conductivities of ice and water. Multiple probes are installed at the desired thickness, and the change in current flow between probes provides a control signal. Consistent water treatment is essential to maintaining constant conductivity and thus accurate control.

An ice logic ice quantity (ILIQ) controller (Figure 3.46) is commonly used, allowing accurate setting of the minimum and maximum ice quantity as a function of the expected cooling load. This enables maximum control, system efficiency, and operating flexibility of the cooling equipment. The setting can easily be done manually on the ILIQ controller or automatic (remote) control can be used. Ice quantities are measured and displayed, often as 0, 20, 40, 60, 80, and 100% of nominal storage capacity. The ILIQ controller has the necessary output contacts that can be connected to a building management control system to allow automatic control of the cooling system. As an option, a 4–20 mA output signal is possible. The ILIQ controller contains the necessary logic to prevent unwanted chiller cycling after the desired ice build is complete. Between the control box and the sensors, the intermediate cabling has steel reinforcement and a poly(vinyl chloride (PVC)

Table 3.14 Energy demand and usage

	Mode	Chiller used	Loading (%)	Chiller peak load (kW)	Chiller average load (kW)	Electric rate
0:00	B	A	100	173	173	1
1:00	B	A	100	173	173	1
2:00	B	A	100	172	172	1
3:00	B	A	100	171	171	1
4:00	B	A	100	170	170	1
5:00	B	A	100	170	170	1
6:00	B	A	100	170	104	1
6:37	S	–	–	–	–	–
7:00	S	–	–	–	–	–
8:00	I	A	100	197	197	1
9:00	I	A	100	201	201	1
10:00	I	A	100	206	206	1
11:00	I	A	100	210	210	1
12:00	I	A	100	216	216	1
13:00	I	A	100	220	220	1
14:00	I	A	100	221	221	1
15:00	I	A	100	222	222	1
16:00	I	A	100	218	218	1
17:00	I	A	100	209	209	1
18:00	B	A	100	186	186	1
19:00	B	A	100	184	184	1
20:00	B	A	100	181	181	1
21:00	B	A	100	178	178	1
22:00	B	A	100	176	176	1
23:00	B	A	100	174	174	1

Electric rate structure: 1, peak demand period; 2 shoulder peak demand; 3, off-peak period; mode, mode of operation (*Courtesy of Baltimore Aircoil International N.V.*).

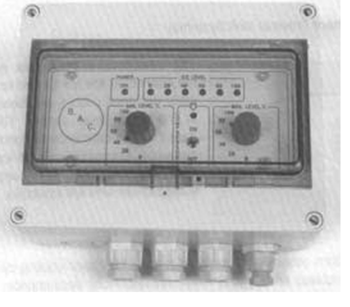
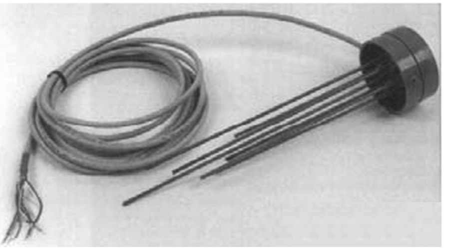


Figure 3.46 ILIQ controller for manual control (*Courtesy of Baltimore Aircoil International N.V.*)

cover. The cables possess a screening against interference. Ice TES units can be designed for two different TES system concepts: external or internal melt (the ILIQ controller is the same for both except that for each concept a specific sensor (Figure 3.47) is designed).

- **Ice thickness sensor for external melt systems.** A series of accurately positioned electrodes detect the ice thickness on the coil tube. The measurement is based on difference in electrical

(a)



(b)

Figure 3.47 (a) Ice thickness sensor for external melt systems, and (b) water level sensor for internal melt systems (*Courtesy of Baltimore Aircoil International N.V*.)

conductivity between ice and water. Combined with this sensor, the ILIQ controller limits the maximum ice thickness to the desired level.

- **Water level sensor for internal melt systems.** The water level in the sensor is proportional to the ice quantity in the ice chiller tank. A series of specially designed probes measure the water level in the water level sensor. The measurement is based on the difference of conductivity between air and water. Combined with the ILIQ controller, output signals to control the operations of the ice chiller unit are also available.

Because energy use is related to ice thickness on the coil, a partial-load ice inventory management system is often considered. This system keeps the ice inventory at the minimum level needed to supply immediate future cooling needs, rather than topping off the inventory after each discharge cycle. It also helps prevent bridging by ensuring that the tank is completely discharged at regular intervals, thereby allowing ice to build evenly.

The most common method of measuring ice inventory is based on the fact that ice has a greater volume than water. Thus, a sensed change in water level indicates a change in the amount of stored ice. Because water increases 9% in volume when it changes to ice, the water level varies directly with the amount of ice in the tank as long as all of the ice remains submerged. This water displaced by the ice must not be frozen, or it freezes above the original water level. Therefore, no heat exchange surface area can be above the original water level. The change in water level in the tank due to freezing and thawing is typically 0.153 m. This change can be measured with either a pressure gauge or a standard electrical transducer. For projects with multiple tanks, a reverse-return piping system ensures uniform flow through all the tanks; so, measuring the level in one tank is sufficient to determine the overall proportion of ice remaining.

3.8.12 Technical and Design Aspects of CTES

While conventional cooling systems operate chillers to satisfy predictable, instantaneous cooling loads, CTES systems operate chillers to produce cold during off-peak hours. Conventional chillers typically operate 8–12 h per day to meet cooling requirements, representing a large portion of a building's daytime electrical demand. Shifting electrical use through thermal energy storage reduces high peak demand charges. Utilities benefit from lower peak demand and gain off-peak load, often allowing a shift from less efficient to more efficient equipment. Thus, utilities increase plant efficiencies and delay the need for future expansion.

The selection of a specific type of CTES system is dependent on many factors. The first issue is usually whether CTES is appropriate for a facility. If so, the next question usually concerns the most appropriate type. System options often include ice or water storage, but the most appropriate choice depends on project characteristics. Some other key factors that affect system choices include building type, utility rate structure, and energy-conservation grants and incentives.

Building type, not building size, normally determines whether CTES is cost effective. A building with a fairly even load demand 24 h per day is not a good candidate. Office buildings or schools that close at night, or buildings with short, intense power demands, such as convention centers, sports facilities, and religious buildings, are often good candidates. In general, the higher the peak load, the more likely a candidate the facility is to benefit from CTES. Local energy rates also play a key role in determining CTES cost effectiveness. Most utilities charge for peak demand and have significantly higher rates for electricity used during peak, daytime hours. Therefore, careful analysis of rates and load distribution is essential when considering CTES.

Client attitudes can also affect technology choices. Although CTES systems are not entirely new, some clients may not be familiar and therefore comfortable with this technology, or may not have staff willing to take on different operating and maintenance tasks. In some applications, system redundancy is required (at least for an initial period) to overcome apprehension about CTES.

Therefore, when considering and selecting a CTES system for a client or facility, an engineer should have or obtain a thorough understanding of the following design issues (Maust, 1993):

- Is CTES economically and physically feasible?
- Is there room on-site for a chilled-water or ice or other CTES systems?
- Does the local utility have peak-demand charges, low off-peak rates or rebates for avoiding peak demand?
- Is the building-load profile flat or is there a strong peak?
- Will the client be comfortable maintaining and operating a CTES?

CTES is often best considered relatively later in the design process. While CTES must be integrated with many other aspects of building design (e.g., heating or cooling loads, mass, layout, and HVAC equipment), other efficiency measurements may level cooling loads and/or heating needs sufficiently that otherwise attractive storage schemes no longer make economic sense.

Most efficiency and many load management options cost less than CTES in retrofits, and should therefore be implemented first where appropriate. In new buildings, however, installation of an ice storage or a water tank can be synergistic with other design choices that reduce both energy consumption and peak load. Such benefits are especially achievable using fully integrated and computer-aided design.

For CTES, full storage is sometimes preferable to partial storage. Similarly, ice storage sometimes has advantages over chilled-water storage (when equally well designed). Skill and experience are needed to ensure appropriate implementation.

Significant recent progress has been made in improving the cost effectiveness and reliability of CTES equipment, especially for ice harvesters and stratified storages.

Ice storage uses more energy because of the lower temperatures needed compared to chilled-water systems and higher heat leaks through tank insulation. But ice storage uses less energy for several other reasons: the chiller always runs at its design efficiency or not at all (rather than varying continually in response to changing building loads); the ambient dry and wet bulb temperatures in contact with the condenser are lower at night; and the very cold melt water from the ice greatly reduces the energy needed for both chilled-water pumping and air handling. The net effect is usually a net decrease in electrical energy consumption with ice CTES as low as a few percent to a few tens of percent.

The economics of CTES in buildings of all types and sizes frequently hinge on two nonenergy factors: (i) the expected political and economic stability of utilities time-of-use rates; and (ii) demand charges, and the physical space available, and structural load tolerance for the storage tank.

3.8.13 Selection Aspects of CTES

Selecting a CTES for a particular application is often difficult. International standards have not yet been fully developed to provide a basis for the rating and performance testing of these systems.

In general, however, it is clear that a CTES system must cool a building in the same way as the chiller it replaces or supplements.

The selection of a CTES system should account for the load, as should its operating characteristics, that is, the discharge rate, the energy discharged at all times during the discharge cycle, and required storage inlet and outlet temperatures. Information on temperatures, energy stored, and energy discharged versus discharge cycle time describes the performance of a CTES system well. With this information, a performance data schedule should be established to fully describe the system needs (Bishop, 1992). Clearly, rating a CTES system on only energy storage capacity does not accurately describe the system needs. All aspects of the system must be such that overall the system has the capability to provide performance roughly equivalent to that for the conventional chiller supplemented or replaced. In particular, CTES must provide stored energy when the building requires it. Performance specifications that recognize this complexity can help in achieving successful CTES projects.

The selection among available system options depends upon site-specific factors. Some of the factors that can enter into this decision are as follows (Wylie, 1990):

- **Space availability.** Ice storage systems require approximately one-third to one-quarter of the space of chilled-water systems. PCMs also have similar storage advantages over chilled-water systems.
- **Efficiency.** Water chillers use less energy than ice-makers because of higher evaporating temperatures. PCMs require slightly less energy than chilled-water systems.
- **Chilled-water temperatures.** Ice storage systems can supply lower water temperatures, and systems can be designed for larger supply/return temperature differences, resulting in lower flow rates and pumping costs and smaller central plants.
- **Refrigeration compressor size.** Reciprocating compressors associated with ice storage are size limited. The use of multiple units in large plants is usually uneconomic, requiring the use of screw-type compressors instead.
- **Maintenance costs.** In general, chilled-water storage tanks have lower maintenance costs. Maintenance personnel are usually more familiar with chilled-water systems.
- **Experience of contractor and operator.** Contractors and building operation engineers are usually weakly familiar if not totally unfamiliar with the large, built-up, field-erected direct-expansion or flooded coil refrigeration systems required for ice storage.

3.8.14 Cold-Air Distribution in CTES

Reducing the temperature of the distribution air in an air-conditioning system is attractive because smaller air-handling units, ducts, pumps, and piping can be used, resulting in lower initial costs. In addition, the reduced ceiling space required for ductwork can significantly reduce building height, particularly in high-rise construction. These cost reductions can make thermal storage systems competitive with nonstorage systems on an initial cost basis.

The optimum supply air temperature is usually determined through an analysis of initial and operating costs for various design options. Depending on the load, the additional latent energy removed at the lower discharge-air temperature may be offset by the reduction in fan energy associated with the lower air flow rate.

The minimum achievable supply air temperature is determined by the chilled-water temperature and the temperature rise between the cooling plant and the terminal units. With some ice storage systems, the fluid temperature may rise during discharge; therefore the supply temperatures normally achievable with various types of ice storage plants should be carefully investigated with the equipment supplier.

A heat exchanger is sometimes required with storage tanks that operate at atmospheric pressure or between a secondary coolant and a chilled-water system. The rise in chilled-water temperature between the cooling-plant discharge and the chilled-water coil depends on the length of piping and the amount of insulation. A smaller temperature difference can be achieved with more cooling-coil rows or a larger surface area on the cooling coil, but extra heat-transfer surface is often uneconomic.

A blow-through configuration provides the lowest supply air temperature and the minimum supply air volume. The lowest temperature rise achievable with a draw-through configuration is 2–3 °C because heat from the fan is added to the air. A draw-through configuration should be used if space for flow straightening between the fan and coil is limited. A blow-through unit should not be used with a lined duct because air with high relative humidity enters the duct.

Face velocity determines the size of the coil for a given supply air volume, and the coil size determines the size of the air-handling unit. A lower face velocity generates a lower supply air temperature, whereas a higher face velocity results in smaller equipment and lower initial costs. The face velocity is limited by moisture carry-over from the coil. The face velocity for cold-air distribution systems is usually 1.5–2.5 m/s. Cold primary air can be tempered with room air or plenum return air by using fan-powered mixing boxes or induction boxes. The primary air should be tempered before it is supplied to the space. The energy use of fan-powered mixing boxes is significant, and negates the savings from downsizing central supply fans.

Diffusers designed for cold-air distribution can provide supply air directly to the space without causing drafts, thereby eliminating the need for fan-powered boxes. If the supply air flow rate to occupied spaces is expected to be below 0.02 m^3/s per m^2 of floor area, fan-powered or induction boxes should be used to boost the air circulation rate. At supply air rates of 0.02 to 0.03 m^3/s per m^2, a diffuser with a high ratio of induced room air to supply air should be used to ensure adequate dispersion of ventilation air throughout the space. A diffuser that relies on turbulent mixing rather than induction to temper the primary air may not be effective at these flow rates.

Cold-air distribution systems normally maintain space humidity between 30 and 45% as opposed to the 50–60% generally maintained by other systems. At this lower humidity level, equivalent comfort conditions are provided at higher dry-bulb temperatures. The increased dry-bulb set point generally results in decreased energy consumption.

The surfaces of any equipment that may be cooled below the ambient dew point, including air-handling units, ducts, and terminal boxes need to be insulated. Any vapor-barrier penetrations should be sealed to prevent migration of moisture into the insulation. Prefabricated, insulated round ducts are normally insulated externally at joints where internal insulation is not continuous. If ducts are internally insulated, access doors also need to be insulated.

Duct leakage is undesirable because it represents cooling capacity that is not delivered to the conditioned space. In cold-air distribution systems, leaking air can cool nearby surfaces to the point at which condensation forms. Designers should specify acceptable methods of sealing ducts and air-handling units, and establish allowable leakage rates and test procedures. These specifications must be checked through on-site supervision and inspection during construction.

A thorough commissioning process is important for the optimal operation of any large space conditioning system, particularly thermal storage and cold-air distribution systems. Reductions in initial and operating costs are the major features for cold-air distribution, but successful performance can be compromised by reducing initial costs by avoiding commissioning. In fact, comprehensive commissioning can decrease costs by reducing future system malfunctions and troubleshooting expenses, and provide increased value by ensuring optimal system operation.

Advantages of Cold-Air Distribution and TES

- **Demand reduction.** Cooling load is often the largest contributor to the peak electrical demand in a building. Since many electric utilities experience their peak electrical demands in the summer months, attributable mainly to building cooling loads, electric utilities often promote the use of CTES systems to shift the electrical demand in buildings from peak to off-peak periods. Continually increasing peak demands from customers require the utilities to either build additional generating capacity or rely on less efficient peaking plants. With higher demand charges and seemingly high “ratchet clauses” associated with electric utility rates, building owners can find CTES options attractive in retrofit situations. This advantage is especially significant when incentive or rebate programs are offered toward CTES.

- **Lower capital costs.** Thermal storage and cold-air distribution systems require considerably less volume to meet a cooling load relative to conventional systems that use 12.7 °C supply air. Thus, the mechanical system including chillers, air-handling units, pumps, fans, fan motors, and ductwork can be downsized and still satisfy the same cooling load as a conventional system. Reduced equipment size results in significant capital cost savings.
- **Lower operating costs.** The reduced size of the mechanical equipment associated with a thermal storage and cold-air distribution system leads to significant savings in the operating costs associated with running the system. Because the chillers, fans, and pumps used in the system consume less electricity than their counterparts in conventional systems, the thermal storage and cold-air distribution systems consume less energy over the operating life of the equipment, and thus provide additional operating cost savings to building owners.
- **Improved comfort.** Thermal storage and cold-air distribution systems typically provide 5.5–7.5 °C supply air into the space for comfort cooling. This low-temperature supply air improves comfort levels by lowering the relative humidity in the occupied areas. Typically, the dry bulb temperature is 5.5 °C off the coil, and results in a relative humidity of about 36% in the occupied areas, compared to about 50% for a conventional system. This reduction in relative humidity along with room conditions of 25.5 °C (typical for low-temperature primary air systems) results in a cool feeling in the occupied zone.
- **Reduced noise.** The smaller air-handling equipment and insulated ductwork associated with cold-air distribution and TES usually reduce the transmission of noise to the occupied zones, and thus reduce potential annoyances to occupants.
- **Increased usable space.** Typically, in a retrofit project, the architectural impact resulting from a modification to a conventional HVAC system is significant. The increased cooling load associated with increased occupancy loads or computer and equipment loads requires additional chiller capacity, air-handling capacity, and ductwork (or a combination of these). A low-temperature air-distribution system allows for small equipment and use of existing vertical shafts to carry low-temperature air to occupied zones, thereby reducing major architectural impacts due to modifications associated with the HVAC system. The smaller mechanical equipment frees up some existing space in the mechanical room for other systems or purposes.
- **Increased leaseability and marketability.** Reductions in the demand charges and energy costs associated with operating a thermal storage and cold-air distribution system may attract tenants, because these savings can be passed on to them through leasing-cost reductions or lower utility bills. Similarly, when the owner of a building sells the property, the CTES increases the marketability of the building.
- **Minimum disruption.** Because thermal storage and cold-air distribution systems can utilize existing ductwork in the building, this option minimizes work disruption, inconvenience to building occupants, and sometimes, the costs associated with occupant relocations.

Disadvantages of Cold-Air Distribution and TES

- **Condensation.** The main difficulty in using thermal storage and cold-air distribution is the condensation that may occur because of the low-temperature air passing through the ductwork, causing ceiling damage and mold. Properly insulated and sealed ductwork, sealed plenum spaces, and special collars at the duct connection to the VAV boxes (if used) or diffusers can prevent condensation and ensure proper operation of the cold-air distribution system.
- **Insufficient air.** The reduction in volume of air supplied to the occupied space may cause feelings of stuffiness and stagnation in those in the room. At the present time, building

owners/designers have two alternatives to address this problem. First, fan-powered VAV boxes can be used in conjunction with the low-temperature air to mix proper amounts of ceiling plenum (return) air with low-temperature supply air to produce 12.7 °C and to maintain minimum air circulation in the room. Second, low-temperature diffusers that are offered by some manufacturers can be used. These low-temperature diffusers have unique thermal characteristics that can prevent the condensation problems mentioned above, and provide high induction rates to maintain room air circulation. The noise levels produced by such high-induction unit diffusers are within acceptable limits.

- **Dumping of air.** Because of the decrease in supply air temperature and the low buoyancy of cold air jet, air from the outlets may be dumped into the occupied zone causing occupant discomfort due to concentrations of cold air. Dumping is simply the discharge of an air jet with little velocity. This problem can be addressed by using the two methods discussed earlier (fan-powered VAV boxes or high-induction diffusers).

3.8.15 Potential Benefits of CTES

During the past two decades, CTES technology has matured and is now accepted by many as a proven energy-conservation technology. However, the predicted payback period of a potential cool storage installation is often not sufficiently attractive to give it priority over other technology options. This determination often is reached because full advantage is not made of the many potential benefits of CTES, or because the CTES sizing is not optimized.

Several steps can be taken to optimize the payback period of cold TES systems. In general, cool storage should be closely integrated with the overall building and its energy systems to take full advantage of its potential benefits. These benefits depend on whether the application is for a new or existing facility.

For new facilities, the potential benefits include

- use of low-temperature chilled-water distribution to reduce pipe and pump sizes and operating costs;
- use of low-temperature air distribution to reduce duct and fan sizes and operating costs;
- use of smaller chillers and electrical systems to reduce initial costs;
- a gain in usable building space due to less space being required for the mechanical system components.

For existing facilities, the potential benefits that should be evaluated include

- the possible advantages of modifying the existing chillers to make ice versus the purchase of a new machine;
- the use of spare chiller capacity in a chilled-water CTES system;
- the use of cold storage to gain more cooling capacity in situations where the chiller and electrical service capacities are fully utilized;
- the possibility of using low-temperature air to advantage, where practical.

For both new and existing facilities, the sizing of the cool storage system should be optimized, as opposed to the typical process of considering full storage and one or two levels of partial storage versus a conventional system. A practical method to assist in determining the optimum system size should be developed. Also, the value should be accounted for of the gain in usable building space due to less space being required for mechanical system components when cool TES is used.

Most CTES systems reduce electricity demand during peak times by reducing (or eliminating) the need to run the air-conditioning compressor during the day when electricity costs are highest.

Thus, buildings can be cooled effectively during the day, while taking advantage of lower off-peak electricity rates. The chilled medium remains in storage until needed, typically during the day when the building is occupied. Then, the water or ice is used to cool the building. Cold-air distribution can be used with CTES to allow the user to take advantage of the colder temperatures supplied by some CTES systems. With cold-air distribution, the size of ductwork can be reduced, lowering construction costs.

Consequently, a CTES system can be of benefit to users in three main ways:

- **Lower electricity rates.** With CTES, chillers can operate at night to meet the daytime cooling needs, taking advantage of lower off-peak electricity consumption rates.
- **Lower demand charges.** Many commercial customers pay a monthly electrical demand charge on the basis of the largest amount of electricity used during any 30-minute period of the month. CTES reduces peak demands by shifting some of those demands to off-peak periods. Furthermore, some utilities provide a rebate for shifting electrical demand to night or other off-peak periods.
- **Lower air-conditioning system and compressor costs.** Without CTES, large compressors capable of meeting peak cooling demands are needed, whereas smaller and less expensive units are sufficient when CTES is used. Also, since water from a CTES may be colder than conventional chilled water, smaller pipes, pumps, and air handlers may be integrated into the building design to reduce costs further.

In some situations, one can reduce air-conditioning costs by up to one-half with CTES.

3.8.16 Electric Utilities and CTES

Electric utilities are placing increased emphasis on peak-load pricing strategies, such as time-of-day rates and marginal cost-based rates. These rate strategies present consumers with significant opportunities for cost control through load management in building design and operation. Consumers can take advantage of peak-load time-of-use rates, while reducing cooling and heating costs and maintaining comfort by installing a CTES system for space conditioning.

CTES systems can reduce HVAC equipment sizes, and lower air supply temperature (to as low as 8.3 °C, with 30% relative humidity). This low humidity can provide adequate comfort with a 26.6 °C ambient thermostat setting. By comparison, the supply air for conventional systems is at 12.7 °C and 50% relative humidity, which permits a 23.3 °C thermostat setting. CTES systems can also lower the first cost of equipment for energy distribution (e.g., pumps, pipes, fans, air ducts) and the operating costs for fans and pumps. The chilled-water storage media in some systems can also provide backup for fire control systems. The 30% relative humidity supply air can in some instances be passed through heat exchangers to cool incoming outdoor air from 35 to as low as 20 °C using direct evaporative cooling. Chiller condenser water (especially during ice making) can also be used in winter to reduce heating requirements.

Actual CTES systems are designed, evaluated, and approved in situations where the concerns and preferences of the electric utility are of considerable importance, since utilities often provide financial incentives to promote the inclusion of CTES in new and retrofitted air-conditioning systems. Special off-peak rate schedules are also sometimes available to larger customers for which separate metering of air-conditioning loads is practical. Rebates are normally predicated on electrical demand (in kW) shifted to off-peak periods. Substantial payments are common. Some examples from relatively recent years: southern California Edison's CTES-rebate limit was $300,000, based on $200 per kW shifted, while at Wisconsin Electric, rebates were variable, typically $350 per kW shifted and $0.08 per kWh shifted during the May to September cooling period. The combined effect of such rebates and the reduced operating costs achieved with a properly designed CTES system typically leads to simple payback periods of 2–5 years based on the CTES implementation cost.

3.9 Seasonal TES

Many heating systems, notably those using heat pumps, and including virtually all active solar space-heating systems, incorporate TES systems capable of storing heat from times when excess amounts are available to times when they are unavailable or expensive. The period of storage can vary from a few hours for diurnal storage cycles, to many months for seasonal (annual) cycles. Seasonal TES in solar heating systems is particularly favored in high-latitude locations, where

- solar energy is available more during the long summer days, when it is not needed, than during the short winter days, when heating demands must be met and
- cold ambient conditions, often below 0 °C, are available during the winter with its short days, when cooling is not needed, than during the long summer days, when space cooling demands must be met.

The potential exists for seasonal storage of heating capacity from summer until winter in the former case, while the potential exists for seasonal storage of cooling capacity from winter until summer in the latter case.

3.9.1 Seasonal TES for Heating Capacity

Water is often favored as the storage medium in seasonal TES systems because it can function as both the heat transport medium and the heat storage medium, eliminating the cost and thermodynamic losses of one heat exchange operation, and also meeting the engineering preferences for a low-cost, nontoxic, nonflammable, noncorrosive, chemically stable, nonviscous, high-specific-heat fluid with known characteristics.

Many storage containers are used for seasonal TES, including tanks, caverns, and aquifers. Seasonal storage requirements for heating capacity are often met by large, insulated-tank, hot-water systems. They are typically of substantial size, usually above 500,000 L, because the decreasing surface-to-volume ratio with increasing size reduces both the cost and the heat loss on a unit of storage capacity basis.

The optimal form for such large tanks appears to be the right circular cylinder with vertical axis. Tanks of this form have low surface-to-volume ratios. They can be built to rest on the ground surface, or to be partially or fully buried. Often the tops of the tanks in buried configurations are modified for other purposes (e.g., paved for use as a parking lot or landscaped for use as a park). All heat losses or infiltrations from buried tanks flow through the soil and ultimately reach one of the two heat sinks: the ground–air interface and the water table. It is noted for this cylindrical geometry that the condition where height and radius are approximately equal tends to minimize the overall tank heat loss, since it gives the minimum surface-to-volume ratio. The inside of the tank is often covered with a layer of insulation.

In some cases, tanks that are partially buried can have some or all of the excavated material bermed against the side walls (see Figure 3.48), to provide both physical support and a degree of insulation for the upper part of the tank wall. This configuration also provides for good surface water drainage, often has hydraulic advantages associated with the lift requirements of the system pumps, and avoids the need to haul and dispose of excavated soil from the site.

Methodologies for the analysis of the heat loss characteristics of several long-term storages have been studied (Hooper *et al*., 1980; Rosen, 1990, 1998a). In particular, the fully buried tank, with its top flush with the surface of the ground, and the on-ground tank have already received attention, and design methodologies for these cases have been developed. The thermal properties of the soil surrounding the tank are sometimes dependent on position, time, and temperature. For example, changes in soil moisture content can occur during rains or melting of snow and ice, and can significantly alter the soil's thermal properties. Some additional energy interactions that are present

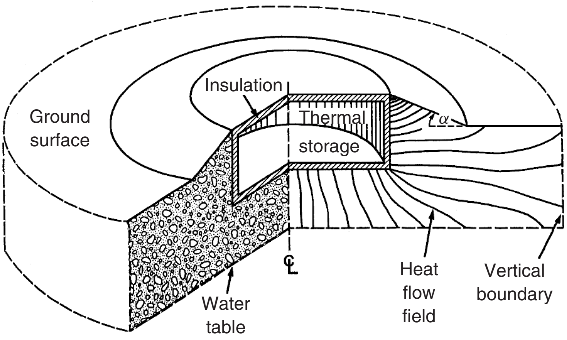


Figure 3.48 Illustration of partially buried, bermed heat storage tank. Approximate lines of heat flow outside the tank are shown

include the latent heat of fusion of soil moisture during freezing and thawing, and the latent heat of vaporization during surface drying. The structural materials of the tank walls, often reinforced concrete, sometimes have similar thermal properties as the soil regime.

3.9.2 Seasonal TES for Cooling Capacity

Several systems for seasonal storing of cold have been proposed and tested. Most of these are based on ice storage, and are applicable in climates where temperatures are below 0 °C for much of the winter.

In one system, an ice store is built up throughout the winter by spraying water into a tank that is exposed to the ambient atmosphere when conditions are suitable for freezing water. During other times, the tank, which is insulated, is closed. In the summer, when space cooling is needed, the ice is allowed to melt and the cold water is circulated as required for cooling. The tank is designed to permit enough ice to be created in the winter to meet most or all of the summer cooling needs. Such a system has been tested in Ottawa, Canada.

3.9.3 Illustration

A seasonal thermal storage for heating capacity was installed at the Aylmer Senior Citizens residence in Ontario, Canada. That storage is a cylindrical tank, with its axis vertical and with a height of 6.7 m and a radius of 7.5 m. The tank is uniformly insulated with 0.15 m of foamed polyurethane having a conductivity of 0.0346 W/m K, and is buried. The storage fluid, water, ranges in temperature from about 80 °C at the end of summer when the storage is almost fully charged, to about 30 °C at the end of winter when the storage has been for the most part discharged.

The surrounding conditions of the Aylmer area are typical of south-western Ontario. The seasonal mean temperatures of the ambient air are about 21 °C in summer, −7 °C in winter, and 7 °C in both spring and autumn. The water table is relatively constant when the temperature is about 7 °C, and the thermal conductivity of the soil is about 1.73 W/m K.

In a preliminary economic analysis of cylindrical tanks such as the one considered here (Rosen, 1998b), tanks that are buried and have soil berms applied were shown, in most instances, to be superior to other tank configurations. This analysis determined whether the initial cost savings derived from using a bermed tank, instead of an in-ground tank, are greater or less than the additional costs associated with the greater heat losses for the bermed tank over the life of the tank. The factors considered in the analysis included the increased excavation cost associated with an in-ground tank, the increased wall thickness required for an in-ground tank, the haulage of excavated soil for an in-ground tank compared to the cost of placing the soil into a berm, and the increased heat loss associated with a bermed tank.

3.10 Concluding Remarks

Although energy may be stored in many ways (e.g., in mechanical, kinetic or chemical forms), since much of the economy involves thermal energy, the storage of thermal energy warrants careful attention. TES deals with the storing of energy by cooling, heating, melting, solidifying, or vaporizing a material, the energy becoming available as heat when the process is reversed. TES is a temporary storage of high – or low – temperature energy for later use. There are mainly two types of TES systems: sensible (e.g., water and rock) and latent (e.g., ice and salt hydrates). Storage by causing a material to increase or decrease in temperature is called *sensible heat storage*. Its effectiveness depends on the specific heat of the material and, if volume is important, the density of the storage material. Storage by phase change, the transition from solid to liquid or from liquid to vapor with no change in temperature, is known as *latent heat storage*.

Short-term storage (diurnal storage) is used to manage peak power loads of a few hours to a day, in order to reduce the sizing of systems and/or to take advantage of energy tariffs. Medium- or long-term storage is more common when waste heat or seasonal energy loads can be transferred, with a delay of a few weeks to several months, to cover seasonal needs. This type of TES is called *seasonal or annual storage*.

The selection of TES systems mainly depends on the storage period required (e.g., diurnal or seasonal), economic viability, operating conditions, and so on. Some specific parameters that influence the viability of a TES include facility thermal loads, thermal and electrical load profiles, availability of waste or excess thermal energy, electrical costs and rate structures, type of thermal generating equipment, and building type and occupancy. The economic justification for TES systems usually requires that annual capital and operating costs are less than the costs for primary generating equipment supplying the same service loads and periods. Substantial energy savings can be realized by taking advantage of TES to facilitate using waste energy and surplus heat, reducing electrical demand charges, and avoiding heating, cooling, or air-conditioning equipment purchases.

Today TES is considered as an advanced energy technology. The use of TES systems has been attracting increasing interest in several thermal applications, for example, active and passive solar heating, water heating, cooling, and air-conditioning. TES is often the most economic storage technology for HVAC applications.

For solar thermal applications, the use of TES systems is essential because of fluctuations in the solar energy input. Several classes of storage may be required for a single installation, depending on the type and scale of the solar power plant, and the nature of its integration with conventional utility systems.

TES can help correct the mismatch between supply and demand of energy, and can significantly contribute to meeting society's needs for more efficient, environmentally benign energy use. TES thus plays an important role in energy conservation, and can yield significant saving of premium fuels.

TES exhibits an enormous potential to make the use of thermal energy equipment more effective, and for facilitating large-scale energy substitutions economically. A coordinated set of actions is needed in several sectors of energy systems in order to realize the maximum benefits of storage.

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Study Questions/Problems

3.1 How much energy is needed to heat a volume of $10\,m^3$ of water from 25 to 75 °C? Take the density of water as $1000\,kg/m^3$ and the specific heat as 4.2 kJ/kg °C.

3.2 List the various TES processes and explain each.

3.3 What are the benefits of TES systems?

3.4 What criteria should be considered in TES evaluation?

3.5 Modify the TES evaluation checklist to cover current environmental issues.

3.6 What are the barriers to TES adoption?

3.7 Define the storage period and the types of classifications used for them for applications.

3.8 Are there any standards available for TES? If so, identify and describe them.

3.9 What kinds of storage options are available for solar energy applications?

3.10 Discuss the types and features of various stratified TES tanks.

3.11 What are the differences between single- and dual-medium systems?

3.12 Explain how an aquifer TES works.

3.13 List the environmental benefits of TES.

3.14 Identify potential heat sources for an aquifer TES, in general, and specifically in your community.

3.15 Describe the operation of an aquifer-based heat pump.

3.16 What are the main advantages of evacuated solar collectors?

3.17 What are the main expectations of PCMs?

3.18 What is nucleation?

3.19 What is thermal cycling?

3.20 What aspects are necessary to evaluate and select a PCM?

3.21 Explain how the performance of a PCM is assessed.

3.22 What are the selection criteria for latent TES?

3.23 Explain the working principle of a cold TES.

3.24 Show the possible TES operating strategies on a chart and explain each.

3.25 What are the main design considerations for a cold TES?

3.26 Compare the storage volumes of water and ice for 1000 kJ of heat capacity.

3.27 List the classifications for ice TES and describe them.

3.28 Describe the operation and technical details of ice-on-pipe CTES system.

3.29 Describe the operation and technical details of a ice harvester system.

3.30 Describe the operation and technical details of a glycol CTES system.

3.31 Describe the operation and technical details of CTES systems with encapsulated storage media.

3.32 Describe the operation and technical details of an ice-slurry CTES system.

3.33 What are the advantages offered by ice-slurry CTES?

3.34 What are the main systems for ice formation?

3.35 What are the options to control the ice thickness?

3.36 Why is it important in many ice CTES systems that the ice buildup does not become extensive in all parts of the system?

3.37 List and explain the CTES selection factors.

3.38 What is seasonal TES? Describe how it works for cooling and heating options.