ENERGY
MANAGEMENT
SERIES

19

FOR INDUSTRY
COMMERCE
AND INSTITUTIONS

Thermal Storage

Energy, Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

Canada

PREFACE

Much has been learned about the art and science of managing energy during the past decade. Today, energy management is a seriously applied discipline within the management process of most successful companies.

Initially, in the early 1970's, energy conservation programs were established to alleviate threatened shortages and Canada's dependency on off-shore oil supplies. However, dramatic price increases quickly added a new meaning to the term "energy conservation" — reduce energy costs!

Many industrial, commercial and institutional organizations met the challenge and reduced energy costs by up to 50%. Improved energy use efficiency was achieved by such steps as employee awareness programs, improved maintenance procedures, by simply eliminating waste, as well as by undertaking projects to upgrade or improve facilities and equipment.

In order to obtain additional energy savings at this juncture a greater knowledge and understanding of technical theory and its application is required in addition to energy efficiency equipment itself.

At the request of the Canadian Industry Program for Energy Conservation, the Commercial and Institutional Task Force Program and related trade associations, the Industrial Energy Division of the Department of Energy, Mines and Resources Canada, has prepared a series of energy management and technical manuals.

The purpose of these manuals is to help managers and operating personnel recognize energy management opportunities within their organizations. They provide the practitioner with mathematical equations, general information on proven techniques and technology, together with examples on how to save energy.

For further information concerning the manuals listed below or regarding material used at seminars/workshops including actual case studies, please write to:

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INTRODUCTION

Thermal storage is the collection of heating or cooling energy available for use at a later time. For example, excess heat generated in a building during the day might be stored for heating at night when the heating load is usually greater. This module will examine the factors influencing the use of thermal storage in Industrial, Commercial and Institutional facilities, and assist owners and operators in the analysis of potential opportunities to conserve energy or reduce energy costs.

Purpose

The purpose of this module is summarized by the following items.

- Identify the principal benefits of thermal storage.
- Discuss potential sources of low cost thermal energy and the techniques and equipment used to store this energy.
- Present basic equations to assist in the preliminary assessment of thermal storage potential.
- Identify general parameters required for successful thermal storage applications.
- Provide, with the aid of worksheets and examples, methods of evaluating thermal storage potential.

Contents

This module is subdivided into the following sections.

- *Fundamentals* describes the principal parameters and opportunities for thermal storage and presents basic equations to assist in sizing equipment.
- *Equipment/Systems* reviews the basic components used in thermal storage systems and introduces a number of typical systems.
- *Energy Management Opportunities* lists a series of opportunities for thermal storage systems. A number of worked examples are presented with sample worksheets to assist in assessing the potential for a given facility.
- *Appendices* include a glossary of terms, conversion factors, tables and worksheets.

FUNDAMENTALS

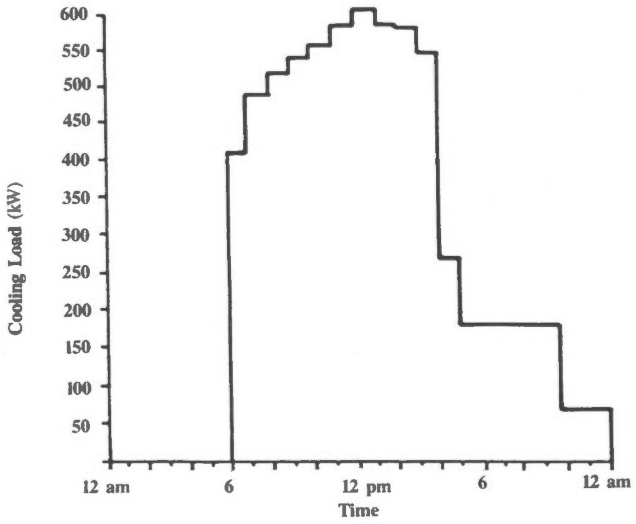
The most familiar application of thermal storage is the domestic hot water tank. Cold water in the tank is heated at a slow rate and then maintained at the desired temperature until required. Hot water is often drawn from the tank at a faster rate than it was generated, partially depleting the tank of stored hot water.

- The water in the tank is called the *thermal storage medium*. It is the substance that actually stores or contains the thermal or heat energy. The tank itself does not store thermal energy in any significant amount, it stores only the water.
- When heat is added to the water and the temperature of the water in the tank increases, the thermal storage is being *charged*, and conversely, when hot water is being removed and replaced with cold water, it is being *discharged*.
- *Thermal energy (heat)* is generated by the conversion of another form of energy, such as electricity, into heat. Other common sources of energy that can be converted into thermal energy are natural gas, propane, oil, wood, and coal.
- The amount of hot water required is the *thermal load*, and depends directly on the user's requirements, regardless of whether the water is heated slowly or quickly. Small heaters will heat water at a slower rate than large heaters, even though the total amount of heat used is the same.
- Once the tank is fully charged, only a small amount of energy is required to maintain the temperature of the water. The energy added balances the heat lost through the shell of the tank.
- The tank's *thermal capacity* becomes greater as the size increases and as the temperature of the hot water is raised.

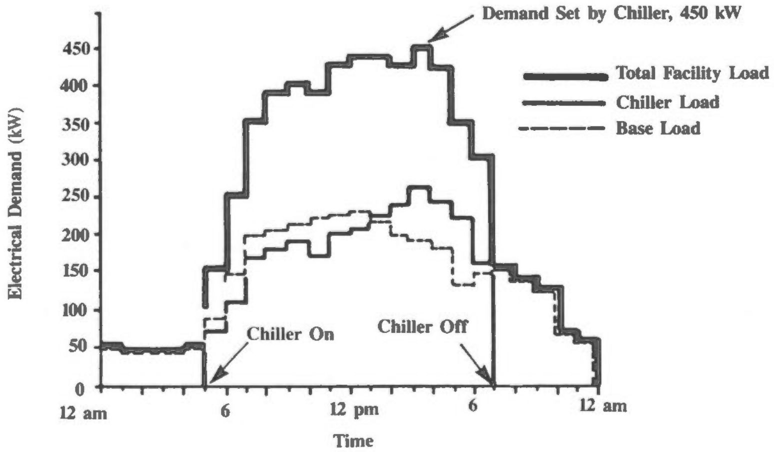
Before reviewing the details of thermal storage systems and operating strategies, the knowledge of a few terms and definitions is useful.

Terms and Definitions

- *Electric Consumption and Demand Charges* – Utilities usually charge for electricity on the basis of *consumption* and *demand*. Consumption is the amount of energy used in a given period and is charged on the basis of dollars per kilowatt hour ($/kWh). Demand is the maximum rate of energy consumption over a short period of time. The demand charge is based on dollars per kilowatt ($/kW), where the kW is the highest demand reached in a given month. For example, if the maximum demand in a one month billing period is 150 kW, and the utility charges $3 per kW, the demand charges for the month will be $450. Demand charges are usually calculated each month based on the highest demand occurring in the month and can be the larger portion of an electricity bill. Refer to Electrical, Module 3.
- *Load Shedding* — Load shedding is a technique whereby, as electrical demand loads approach a predetermined level, some electric equipment is shut down on a priority basis, either manually or automatically, to reduce the facility's peak electrical demand. For additional details refer to Electrical, Module 3.
- *Load Profiles* — A chart or graph, where the load is plotted against time, is a useful tool for reviewing thermal storage potential. Figure 1 is a typical *thermal cooling load profile* showing the cooling requirements at various times of the day. Additional profiles can be prepared to show the requirements for heating, electricity, gas, or other fuels against time. These profiles can correspond to the load of a single system or piece of equipment, or to a number of systems with loads superimposed. Figure 2 shows a facility's electrical base and chiller loads; the sum of the two corresponding to the total load profile. Variations in the profiles are caused by changes to the occupant load, switching of lights and other electrical devices, and the effect of the outside conditions.



Typical Thermal Cooling Load Profile
Figure 1



Electrical Load Profile, Conventional System
Figure 2

Objectives of Thermal Storage

The main objective of thermal storage is to save dollars. These savings can be achieved in several ways.

- Purchased energy "consumption" can be reduced by storing waste or surplus thermal energy available at certain times for use at other times. An example is the storing of "free" solar energy collected during the day for heating at night.
- Purchased electrical energy "demand" can be reduced by storing electrically produced thermal energy during off-peak periods to meet the thermal loads that occur during high demand periods. An example is using an electric chiller to charge a chilled water storage system at night, thereby reducing the electrical demand peaks usually experienced during the day.
- Defer the purchase of additional equipment for heating or cooling and reduce equipment sizing in new facilities. Operate equipment when thermal loads are low to charge thermal storage systems. Withdraw energy from storage to help meet the maximum thermal loads that exceed equipment capacity.

Using Waste or Surplus Energy

Where thermal energy, in any form, is being rejected, consider reclaiming the heat for either immediate or future use. The temperature of the waste energy stream will affect the economic benefit of recovering the heat energy. For example, warm water drained to a sewer may be useful for preheating process make-up water, but be inadequate for space heating.

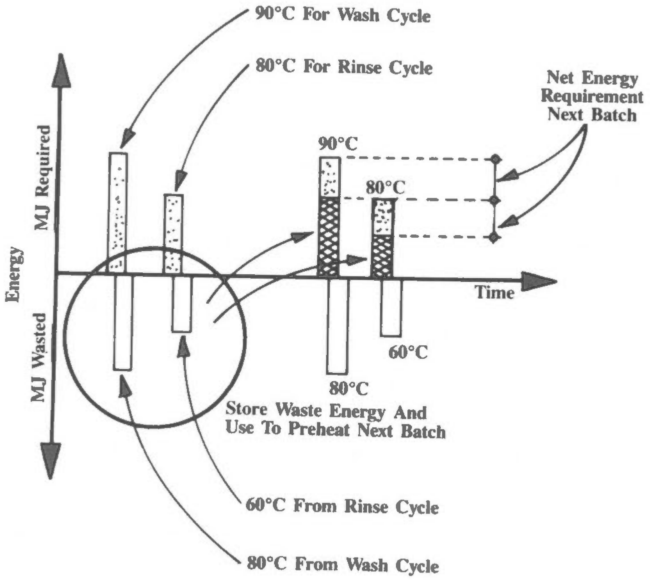
Useful energy is available from many sources.

- Hot or cold water drained to a sewer.
- Hot flue gases.
- Exhaust air streams.
- Hot (or cold) product or waste product.
- Heat collected from solar panels.
- Ground source thermal energy.
- Superheat and condenser heat rejected from refrigeration equipment. See Refrigeration and Heat Pumps, Module 11. Water cooled condensers often provide attractive opportunities to save heating energy dollars.
- Refrigeration (cooling) effect from the evaporator of a heat pump system. A heat pump operating in the heating mode extracts heat at the evaporator. The resulting cooling effect can be stored for process or building cooling.

The waste energy in *continuous* processes can be used directly to heat or cool products or processes. However, in *batch* processes, thermal storage systems are necessary to save the excess or waste thermal energy until it can be used effectively. If necessary, this energy can be upgraded by the use of heat pumps.

An example of this application may occur in a textile plant. Hot water, used in the washing and rinsing process, is drained to the sewer after each cycle (Figure 3). Energy dollars can be saved by providing a separate storage tank to hold the waste hot water from the wash and rinse cycles until it can be re-used directly in the process or for preheating the make-up water for the next cycle. Energy costs are reduced because less energy is purchased to heat the wash and rinse water. This principle applies to many *heat recovery* applications.

Solar heating systems require thermal storage to accumulate “free” solar energy, in the form of heat, until the energy is needed.



Example of Batch Process
Figure 3

Reducing Demand Charges

The primary goal of most thermal storage systems is to lower electrical demand and thus reduce the electrical demand charges. Reductions in demand charges are accomplished by shutting off or limiting electrical input (load shedding) to electrically operated heating or cooling devices during the electrical peaks of a facility. The devices are operated before the peak occurs (e.g., overnight) to charge the thermal storage systems. During the peak demand period the heating and cooling equipment is off, and the thermal loads are met with the heating or cooling energy taken from storage. Control of the use of other electrical equipment should also be considered for demand limiting even though it is not applicable to thermal storage (eg. lighting).

A facility that has an electrical load profile with major peaks in demand is a good candidate for thermal storage. The normal thermal and electrical load profiles should be plotted to assist with the evaluation of reducing electrical demand charges. In Figure 2, the peak electrical demand for the facility occurred when the chiller output reached its maximum in the late afternoon. If the chiller could operate as shown in Figure 4, the electrical peak would be reduced by 125 kW. The chiller thermal load profiles in Figure 5 show the strategy of storing thermal energy during nonoccupied hours to satisfy the thermal loads during occupied hours. The figures also show that the chiller can operate during occupied hours. Operation in this manner can still result in a lower overall facility electrical peak, depending on the actual facility load profiles.

The electrical source that powers the heating or cooling equipment can be shut off, or have power limiters installed, to reduce electrical demand during peak periods. Many types of equipment can be energized and de-energized in accordance with thermal storage operating strategies.

- Building heating and cooling.
- Domestic water heating.
- Process heating and cooling.
- Refrigeration.
- Snow melting.
- Drying.
- Icemaking.

Low demand charges and flat consumption rates are typical in most areas of Canada and are not as supportive to thermal storage when compared to areas of higher cost electricity. Several Canadian utilities are studying the feasibility of various time-of-day rate structures. Under such a system, consumption or demand charges, or both, could vary depending on the time of day. Electric power would be more expensive during the *utility's peak period* and less expensive during the night or on weekends. Should any of these time-of-day schemes be implemented, opportunities for thermal storage will increase. Negotiations with the local utility may result in a lower rate structure for users of off-peak power.

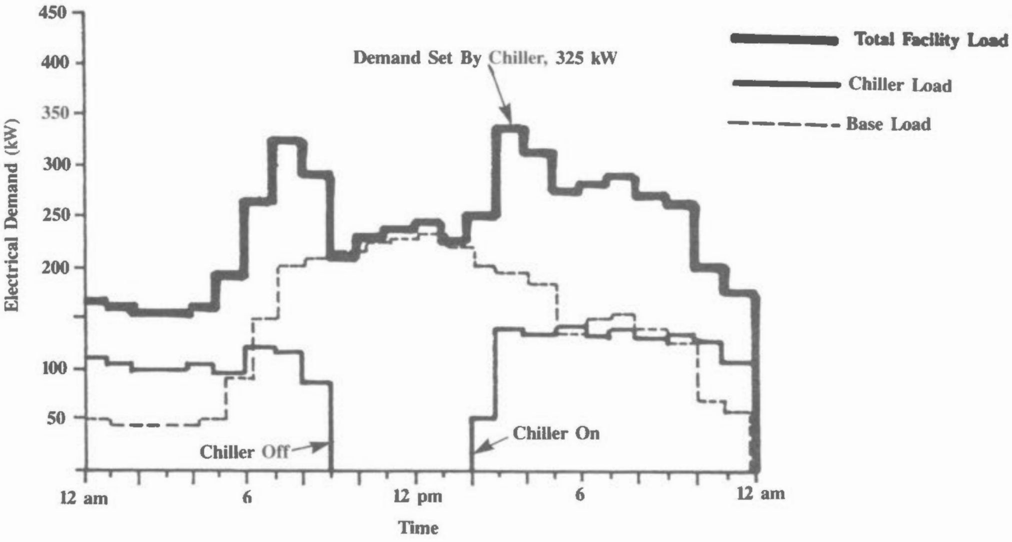
Deferring Equipment Purchases

The capacity of heating and cooling equipment is normally selected to match the "design day" load, when the requirements for heating or cooling are near maximum. These design loads occur only for short periods of time resulting in excess capacity on average days. The difference between the peak and average thermal loads, combined with thermal storage, provides an opportunity to defer equipment purchases in a retrofit application or reduce the equipment size in a new installation.

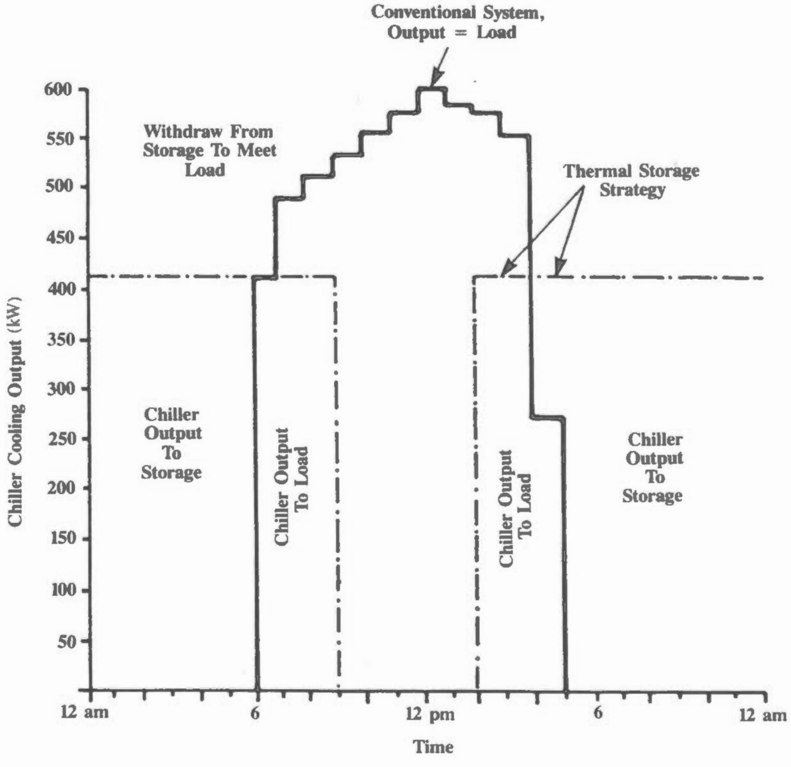
For example, consider a building with an average cooling load of 500 kW and a peak cooling load of 650 kW. The capacity of the existing chiller is 750 kW. A proposed expansion will increase the average cooling load to 700 kW and the peak to 850 kW. The new average load could be satisfied with the existing equipment, but not the peak. A new chiller with a capacity of 100 kW is required using a conventional approach.

Rather than provide a new chiller, a thermal storage system could satisfy the peak cooling load. During off-peak hours, when the thermal load is less than the capacity of the existing chiller, the chiller would operate to maintain the desired building or process conditions, and excess capacity would be used to charge a chilled water storage system. When the cooling load exceeded the chiller capacity, chilled water would be drawn from storage. Benefits include capital savings and reduced operating costs. The reduced operating costs result from limiting peak electrical loads to that required to provide only 750 kW of cooling instead of 850 kW and from having less equipment to maintain. The annual electrical consumption for cooling would increase and be proportional to the new cooling loads.

This technique is also used in new facilities, where the capacity of the thermal equipment is selected closer to the average condition rather than the peak condition.



Revised Chiller Operation
Figure 4



Thermal Load Profile (Chiller Output)
Figure 5

Understanding Sensible and Latent Heat

When thermal energy is added to, or removed from a substance, the temperature of the substance will change or the substance will change *state*.

Thermal energy associated with a change in temperature is called *sensible heat*. The amount of energy is dependent upon the temperature change, the amount of material and the *specific heat* of the material expressed in kJ/(kg·°C).

The thermal energy associated with a change of state (or phase) is called *latent heat*. When the change of state is from gas to liquid (eg., steam to water) the *latent heat of condensation* is removed. The latent heat of condensation is generally dependent on material properties, temperature and pressure. When the change of state is from liquid to solid (eg., water to ice) the *latent heat of fusion* is dissipated. The heat of fusion is dependent on material properties and temperature, and for practical purposes is independent of pressure. Units for both are kJ/kg. In most storage systems, thermal energy is stored in the form of *sensible heat* or *latent heat of fusion*.

Sensible heat storage is accomplished by raising (or lowering) the temperature of the storage medium. A hot water bottle is a simple example. The water, heated to a higher temperature, will store more thermal energy than if heated to a lower temperature.

An ice pack is an example of thermal storage based on a phase change. Heat is removed from the water until freezing occurs. Later, as the ice pack melts, heat is absorbed from the surroundings causing a cooling effect.

Phase change thermal storage systems are more compact than sensible heat storage systems and generally store about 10 times more energy per unit volume. For example, freezing one kilogram of water will store about 334 kJ of cooling in the form of ice at 0°C. Melting the ice will remove the 334 kJ from the surroundings. About 10 kg of water would have to be cooled through 5°C to store the same amount of thermal energy.

Basic Calculations

Calculations are necessary to make a preliminary assessment of thermal storage opportunities in a given facility.

Calculations for Sensible Heat Storage

The amount of heat that can be stored in a liquid or solid by raising the temperature is given by the following equation.

$$E = \frac{M \text{ x } cp \text{ x } DT}{1000}$$

Where, E = Thermal energy stored, (MJ)

M = Mass of storage medium, (kg)

cp = Specific heat at the mean temperature, [kJ/(kg·°C)]

DT = Temperature change of the storage medium, (°C)

1000 = Conversion of KJ to MJ

The volume of storage medium required to hold a given amount of thermal energy can be calculated.

$$V = \frac{M}{d}$$

Where, V = Volume, (m^3)

d = Density, (kg/m^3)

Volume can also be expressed by the following equation.

$$V = \frac{E}{d \text{ x } cp \text{ x } DT}$$

The specific heat and density of a number of common substances are listed in Table 1.

The volume of a storage medium required for a given amount of thermal storage can also be calculated using data from Table 2.

The potential storage effect for any building is best determined by experimentation. As a guide, the amount of energy that can be stored in a typical industrial space going through a 3°C temperature change is about 0.370 MJ/m^2. For a typical office space undergoing a 2°C temperature change, about 0.250 MJ/m^2 can be stored.

The equation E = M x cp x DT for sensible heat storage can be rewritten.

$$E = 0.370 \times A \text{ (typical industrial space), or}$$

$$= 0.250 \times A \text{ (typical office space)}$$

Where, E = Thermal energy stored, (kJ)

= Area of building or floor, (m^2)

Note that only the surface layer of a concrete slab will actively exchange or store heat when operating on a daily cycle. Time cycles are too short to get more storage effect even with thick slabs.

Calculations for Phase Change Storage

When considering phase change materials for storing energy, the volume of storage media required can be approximated from Table 2 or calculated.

$$E = M \times (\text{Latent heat of fusion})$$

$$\text{or,} \quad M = \frac{E}{\text{Latent heat of fusion}}$$

Where, E = Thermal energy stored, (kJ)

M = Mass of phase change medium, (kg)

Latent heat of fusion = amount of heat required to melt or freeze the substance, (kJ/kg)

Other Considerations

The assessment of thermal storage in a facility requires an appreciation of other criteria.

- Energy for heating, refrigeration and heat pump equipment.
- Storage size limitations.
- Thermal load profiles.
- Optimizing conventional systems.

Energy for Heating, Refrigeration and Heat Pump Equipment

Electricity can be converted to thermal energy by electric resistance elements or by mechanical means. In resistance heating systems, each kWh of electricity is converted to one kWh (3.60 MJ) of heat, and conversion efficiency is 100 per cent. Typical examples are electric baseboard heaters, electric water heaters and slab heating systems.

Where refrigeration and/or heat pump systems are used to produce heating and/or cooling, the conversion efficiency or Coefficient of Performance (COP) is greater than 100 per cent. However, a waste heat stream is required to achieve this result. (Refer to Refrigeration and Heat Pumps, Module 11.) In typical systems the COP is approximately 3.5 where each kWh of electrical input to the equipment produces approximately 3.5 kWh of heating or cooling output. A refrigeration system producing heating or cooling at a rate of 350 kW will have a power requirement of 100 kW, which is calculated by dividing 350 by the COP value of 3.5. This fact is important when storage systems, whose principal goal is demand reduction, are being considered. If the waste heat stream has a high heat content and heating is required elsewhere, heat exchangers can be used to transfer the heat, thereby increasing the system COP and reducing energy dollars.

When existing systems are being considered for conversion to thermal storage arrangements, actual equipment COPs should be obtained from the manufacturers. When this information is not available, heat pump and refrigeration system energy requirements can be approximated using a COP of 3.5. Systems with a COP in the range of 10 to 20 exist, but are not common.

Refrigeration system energy consumption per unit of capacity increases as the cold side (evaporator) temperature is reduced and as the hot side (condenser) temperature increases. Producing ice at 0°C, therefore, requires more energy than producing chilled water at 4°C. Conversely, it takes more refrigeration power to produce hot water at 50°C than at 35°C. As the results usually vary less than 3 per cent, when the COP is near 3.5, these effects are ignored in this module.

Storage Size Limitations

Thermal storage systems have been considered in a range of capacities from only a few hours to long term storage. An example of long term storage is the collection of solar energy available during the summer, to be used for winter heating. A number of practical limitations restrict most thermal storage schemes from storage cycles of a few hours to a maximum of a few days. The principal limitations of thermal storage are space requirements and capital costs.

For example, consider a building or process requiring 1000 kW of chilling capacity for 900 hours of full load operation. The minimum annual cooling energy that must be stored is 900 x 1000 = 900 000 kWh. If ice is used as the storage medium, Table 2 indicates that about 3 litres of ice (about 3 kg) is required to store one megajoule of cooling.

$$\text{Ice required} = 3\ \text{L/MJ} \times 900\ 000\ \text{kWh} \times 3.6\ \text{MJ/kWh}$$

$$= 9\ 720\ 000\ \text{litres}$$

$$\text{or} = \frac{9.72 \times 10^6\ \text{L}}{1000\ \text{L/m}^3}$$

$$= 9720\ \text{m}^3$$

Assuming "perfect tanks" with no *standby heat losses* and no "safety margin", a tank two metres deep would cover an area the size of a football field. A water storage system would be at least ten times larger. Costs for such large systems are prohibitive. Because of energy losses, the inability to use all the thermal energy stored, and the necessity to provide some margin of safety, the minimum storage system size may be 25 per cent larger than the volumes estimated from Table 2.

Thermal Load Profiles

When thermal loads fluctuate, a potential exists for storing thermal energy to meet later thermal requirements.

Many buildings and facilities have load profiles conducive to thermal storage. Office buildings with low cooling requirements overnight and during the morning, and high cooling demands in the late afternoon, show the optimum profile for thermal storage. Often, the air-conditioning systems of these buildings are shut off at night. The combination of daytime part loads and nighttime shutdown provides the equivalent of 15 to 20 hours per day in which a chilled water storage system could be recharged to meet the demand period.

Hotels, hospitals and industrial plants that operate "around the clock" are less likely candidates for full building storage systems as the load profile is flatter. Less time is available for recharging the storage between the long peak cooling periods. However, these facilities are often suited to partial thermal storage and peak shaving systems. For example, the base thermal load may be provided by a chiller, with peaks reduced using a combination of chiller and storage. In this case, the chiller would contribute to the electrical demand, but by a lower amount. The return on capital investment can be maximized with careful sizing and using the compressor heat for preheating domestic or process hot water.

Weather affects the thermal load profile of a building and is also a major factor in determining the feasibility of thermal storage. For cooling storage, the summer weather profile should include a limited number of peak days and, if possible, large temperature variations during a given 24 hour period. Where storage for heating is being considered, a minimum of 2200 *degree days below 18°C* are usually required to make the project viable. Most Canadian locations meet these general criteria.

Optimizing Conventional Systems

Existing heating and cooling systems should be upgraded and properly maintained to reduce energy inefficiencies before implementing any active storage system. When reviewing conventional systems, be alert to the possibility of heat reclaim to recover energy from exhaust streams such as boiler flue gases.

Consider changing from batch to continuous processes so that direct heat reclaim, without intermediate thermal storage, can be used. This results in more effective heat reclaim, no standby losses, and reduced capital expenditures.

Energy Audit Methods

A number of Energy Management Opportunities using the concepts of thermal storage exist in Industrial, Commercial and Institutional facilities and many are recognizable during a *walk through* audit of a facility. This audit is usually more meaningful if a "fresh pair of eyes‘, generally familiar with energy management, is involved. However, such an audit would likely generate a list of opportunities related to the condition and operation of existing, conventional heating and cooling systems. A detailed analysis is required to establish whether or not real opportunities exist for thermal storage systems.

The following questions might be asked, and require analysis as part of any assessment of thermal storage.

- What are the electrical demand and consumption charges?
- Are there peaks in the electrical demand profile?
- Is the demand charge portion of the electrical charges the major portion of the electric bill?
- Is electric heating or cooling equipment operating at the time of the peak, and can this equipment be shut off?
- Is thermal energy being wasted?
- Do some processes or products require cooling while others require heating at different times?

This information is used to perform a *diagnostic audit* to mathematically determine existing operating conditions, potential energy reductions and cost savings. Once capital costs are determined, simple payback calculations can establish the financial viability of the opportunity.

The implementation of Energy Management Opportunities can be divided into three categories.

- *Housekeeping*, refers to an energy management action that is *repeated on a regular basis and never less than once a year.* Repair of leaks, and preventive maintenance programs to prevent deterioration in existing systems are examples.
- *Low cost*, refers to an energy management action that is *done once and for which the cost is not considered great.* Examples of low cost items are revising operating schedules, using existing storage tanks for thermal storage, modifying controls to permit preheating or precooling followed by load shedding, and installing tanks for reclaiming waste hot water.
- *Retrofit*, refers to an energy management action that is *done once and for which the cost is significant*. Examples of retrofit items include the installation of ice makers and storage bins for storage of cooling energy, or hot/chilled water storage systems working with a heat reclaim chiller.

It must be noted that the division between low cost and retrofit is normally a function of the size, type, and financial policy of the organization.

Summary

Substantial energy and dollar savings can be realized by taking advantage of thermal storage when the following techniques can be implemented.

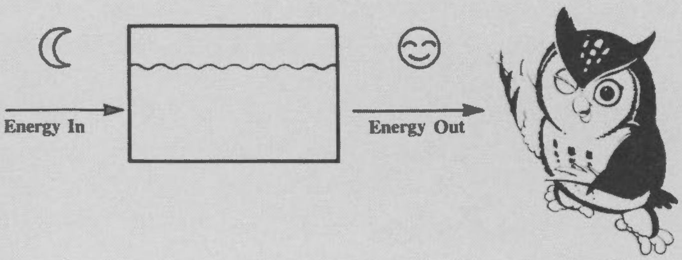
- *Use surplus heat or waste energy* by storing thermal energy which is not immediately useful. Later, when thermal energy for heating or cooling is required, draw the heat energy out of storage, thereby reducing the facility's energy requirements.
- *Reduce electrical demand charges* by operating selected electrical equipment at off peak times to charge a thermal storage system. Thermal energy is then withdrawn from storage during peak electrical periods so that peak electrical demand can be reduced.
- *Avoid heating or cooling equipment purchases* by drawing from storage the extra heating or cooling energy required to satisfy the peak building or process thermal loads. The existing heating or cooling plant is used to charge storage during off-peak times.

Several parameters influence the viability of any thermal storage proposal.

- 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.
- Building type and occupancy.

For energy consumers contemplating some of the more complex schemes discussed further in this module, thermal storage opportunities should be evaluated by a specialist.

EQUIPMENT SYSTEMS



Common components of thermal storage systems, such as pumps, piping, control valves and chillers, are discussed in other modules of this series. Storage media, tanks and equipment specific to thermal storage systems are briefly described in this module. A limited number of systems typical of larger thermal storage facilities are also presented.

Thermal Storage Media

The basic theory of sensible and latent heat of fusion types of thermal storage media was reviewed in Fundamentals. Tables 1 and 2 list the key characteristics of construction materials and storage media in use today.

Selection of media type is dependent on a number of features.

- *Volume* – How much space will be required for the storage medium?
- *Temperature* – In what temperature range will the system operate? Will it be used for heating, cooling or both?
- *Life* – Will the storage medium effectiveness diminish through repeated use or contamination?
- *Temperature degradation* – Is the storage medium prone to degradation of the stored energy because of the properties of the material?

Water, which can be used for both heating and cooling, is the most practical sensible heat storage media because of low cost, high thermal storage capacity, nontoxicity, long life and ease of handling.

Water, when used as a phase change material, is ideal for the same reasons. Ice systems use latent heat as the principal thermal storage technique, with sensible heat storage in the solid and liquid phases accounting for only a fraction of the total capacity.

Other phase change materials are available, but toxicity, cost, heat storage capacity and media degradation must be carefully examined. For example, Glauber's salt will deteriorate with age and lose the ability to store heat.

Solid storage media using sensible heat storage are common. A simple example is the preheating or precooling of a building or product by using its thermal mass to store sensible heat for a short period of time in order to shut off electrical equipment and reduce the electrical demand. Another example is using the floor slab of a greenhouse or solarium for storing solar heat during the day for use at night.

Sensible Heat Storage

Liquid and solid media can be used in sensible heat storage systems.

Liquid Media

Liquid media used for sensible heat storage must be contained in tanks. A number of options are available, and, provided that proper care is taken, conventional tank construction may be used. The most common materials are steel, concrete and fiberglass.

Tank selection and design is based on several factors.

- *Location and size* – Is the tank system to be located on grade, below grade, in a basement or parking garage, or on the top floor of a building? Size and pumping requirements are major factors in these decisions.
- *Existing or new facilities* – If the tanks are to be installed in existing facilities, can tanks be prefabricated or must they be assembled on-site?
- *Thermal expansion* – Allowances must be made for the expansion and contraction of the storage medium and the tank over the range of operating temperatures.
- *Piping connections* – If there are a large number of piping connections to be made below the fluid level, how difficult is it to make and maintain leakproof connections?
- *Corrosion* – Steel tanks and other components corrode or deteriorate if proper care is not taken. Liners, coatings, chemical treatment or other means of corrosion protection must be maintained.

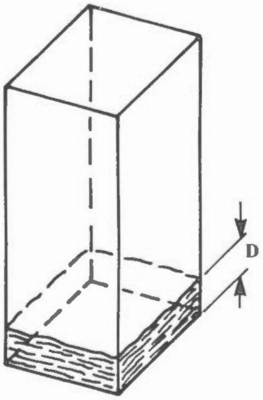
- *Sealing against leaks* – Some materials such as concrete are porous and suitable methods of sealing must be employed. Liners or coatings must be compatible with other materials in the system.
- *Operating temperatures* – Liner materials, sealants and other components have certain temperature limitations. While most products are adequate for normal chilled and heating water applications, care must be taken in selecting materials subjected to extreme heat or cold.
- *Tank shape* – The tank shape will affect the cost and performance of a thermal storage system. "Cubical" tanks are generally less expensive than "rectangular" tanks, but taller rectangular tanks may be more effective for storage (Figure 6). Standard tanks are always less expensive than custom designed ones.
- *Used tank availability* — Purchase used tanks, or use surplus in-house tanks. Tanks must be cleaned to avoid contamination of the thermal storage medium.

- Lowest Cost
- Lowest Standby Losses
- Acceptable Unusable Volume

(A)

- Cost Similar To (B)
- Highest Standby Losses
- Highest Unusable Volume

(C)



- Cost Similar To (C)
- Standby Losses
  Higher Than (A)
- Lowest Unusable Volume

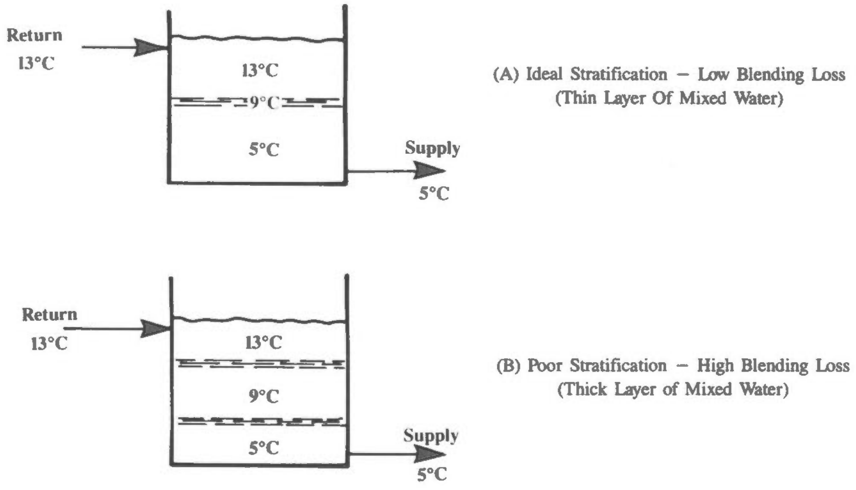
(B)

Note: Unusable depth (D) is equal in all tanks

Tank Shapes
Figure 6

Blending and Thermal Losses in Liquid Media

The thermal storage capacity of a tank can be improved by incorporating features which prevent mixing of the return flow with the stored fluid. If mixing occurs, the resultant storage media temperature may not be usable for the intended purpose. For example, consider a chilled water storage tank filled with equal parts of 5°C supply water and 13°C return water from the cooling system (Figure 7). If the supply and return water were allowed to mix, the resultant 9°C water would probably be too high for air-conditioning purposes.



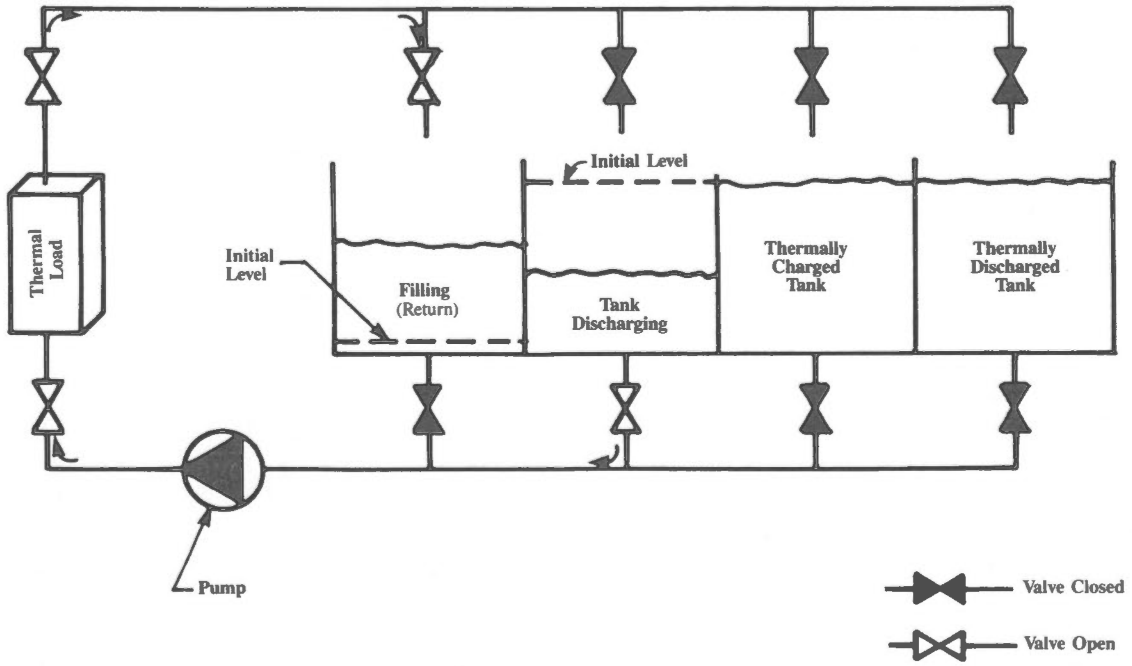
(A) Ideal Stratification – Low Blending Loss
(Thin Layer Of Mixed Water)

(B) Poor Stratification – High Blending Loss
(Thick Layer of Mixed Water)

Stratification In Thermal Storage Tanks
Figure 7

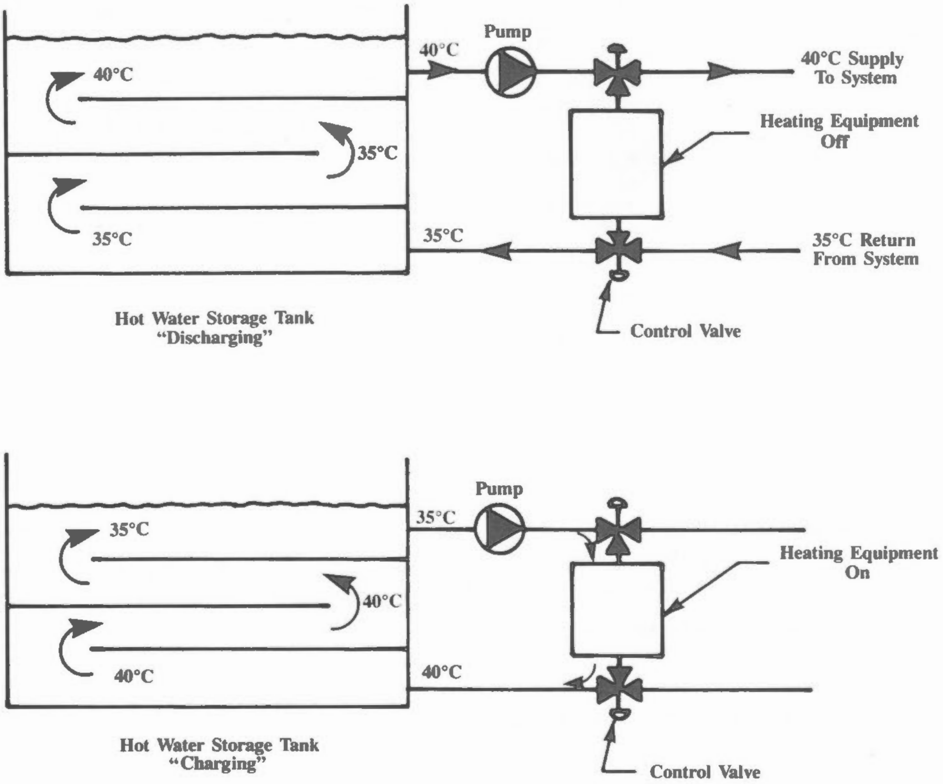
A variety of techniques can be used to prevent blending.

Multiple tanks are used to physically separate the supply water from the return water (Figure 8). After the water is pumped out of storage and used in the heat transfer application, it is returned to an empty tank to prevent mixing. This common method is simple and dependable, but losses occur because some water must be left at the bottom of each tank to ensure that the pump suction is submerged. This volume of water can be reduced by providing taller and thinner tanks, or sumps at the bottom of each tank. The total volume contained within the tanks must also increase accordingly to allow for one empty tank.



Multiple Tank Concept
(Storage Being Discharged)
Figure 8

Fixed baffles within a tank direct the water flow through a maze of channels (Figure 9). Interfaces between supply and return water are minimized as the channels make the tank behave in a manner similar to a long pipe. This figure also shows how a heating water storage tank with baffles is charged and discharged. In the discharging mode, 35°C water returning from the system enters the bottom of the tank and displaces the 40°C water that is pumped into the system. In the charging mode, the 35°C water is taken from the top of the tank, passed through a heating device to increase the water temperature to the required 40°C and returned to the tank. This operation continues until the tank is totally charged with 40°C water.

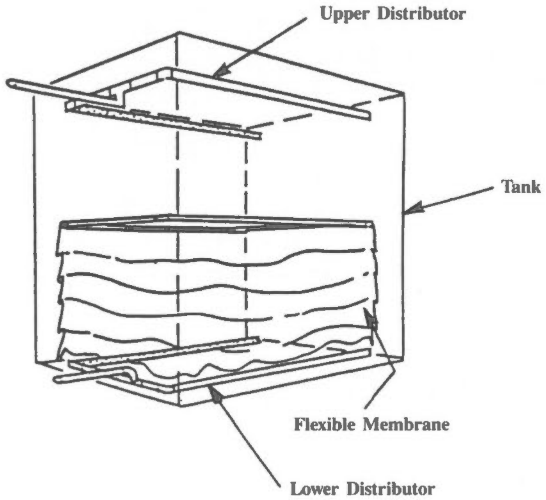


Storage Tank With Baffles To
Separate Supply And Return Flows
Figure 9

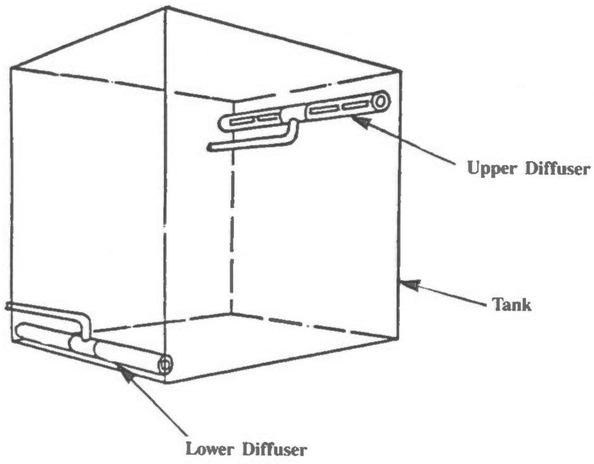
A *flexible membrane* within a tank separates the supply water from the return water. The membrane moves up or down in the tank as the proportion of return water changes (Figure 10). Heat loss is minimal across the membrane and mixing is eliminated. Care must be taken to ensure that the membrane does not collapse into the pump suction, tearing the membrane and perhaps damaging the pump. To prevent this occurrence, some water must be left in the bottom of the tank, wasting a portion of the stored energy.

Uniform inlet and outlet distribution manifolds (Figure 11), located near the tank bottom and top provide stratification within the storage media. Such stratification is more effective in hot rather than chilled water storage because of a greater temperature difference between supply and return water.

Standby heat losses or heat gains reduce the amount of energy in storage. Tank heat loss is dependent on the temperature difference between the contents of the tank and the ambient temperature, insulating value of the tank walls, and time. Insulation is required on steel and fiberglass tanks to control the heat loss. Concrete tanks have lower overall heat transmission coefficients and may not require insulation. An analysis to determine the economical thickness of insulation is required in each case. Refer to Process Insulation, Module 1.



Stratified Storage Tank With Flexible Membrane
Figure 10



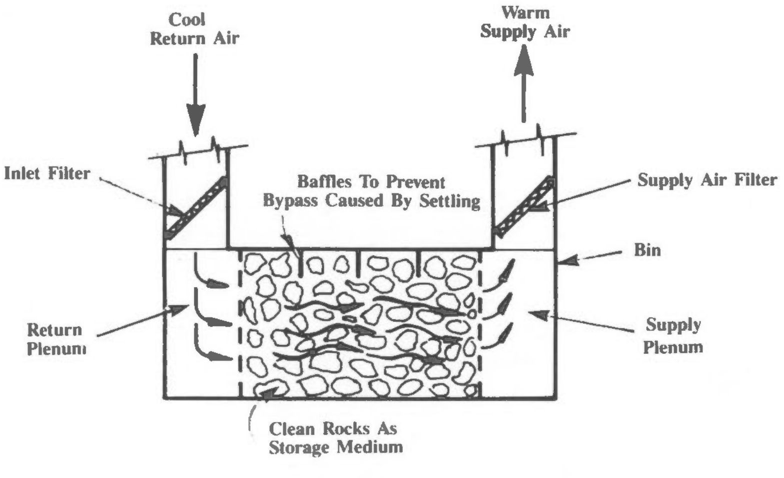
Stratified Storage Tank With Distribution Manifolds
Figure 11

Solid Storage Media

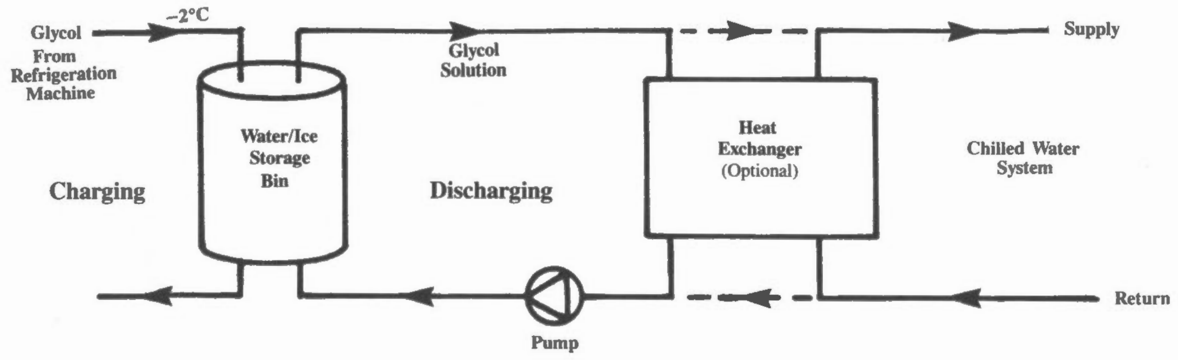
Rock beds and building structures are typical solid storage media.

Rock beds consist of large bins of clean gravel through which a heat transfer media, such as hot air from a solar heating system, would circulate, to charge the bed. Cooler building return air would circulate through the bed to take thermal energy out of storage for space heating (Figure 12).

Building structures effectively store thermal energy. Preheating or precooling a space "soaks" thermal energy into floors, walls, ceiling and other building components. During an electrical peak when equipment is shut down, or a thermal peak when equipment capacity is inadequate, the stored energy returns to the space. Building temperature is allowed to fluctuate during the charging and discharging cycle to save energy. This technique is referred to as *temperature float*. A "float" limited to 2°C in an office or commercial environment, and approximately 3°C in an industrial environment, minimizes possible complaints from the occupants. Preheating or precooling a structure may allow equipment of smaller thermal capacity to be selected to meet the system capacity requirements. This strategy reduces electrical demand and is common in theatres where peak loads normally occur for relatively short periods of time.



Rock Bed Thermal Storage (Discharging)
Figure 12



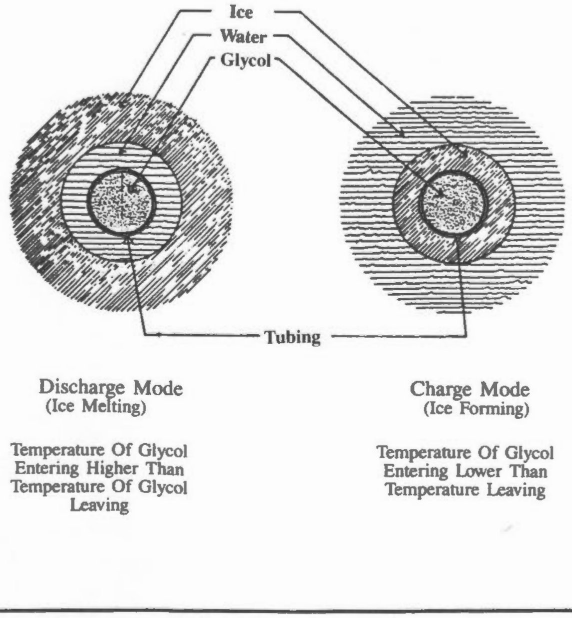
Solid Ice System
Figure 13

Phase Change Storage Media

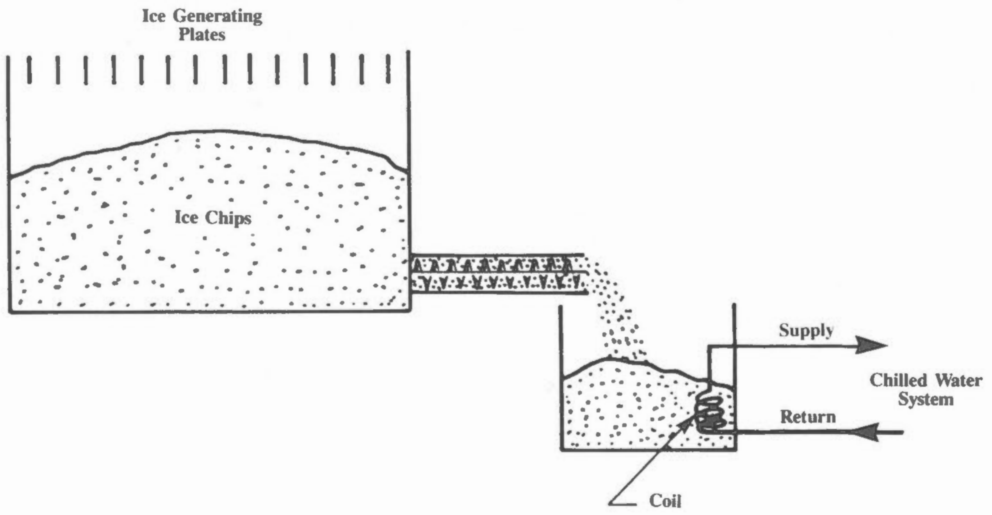
In the majority of phase change systems, water is used as the storage medium. These systems are designed in two basic forms.

- *Solid ice systems* – A water tank, referred to as a bin, contains a series of coils through which −2°C glycol from a refrigeration machine is circulated (Figure 13). Solid ice builds around the coils (Figure 14). A second glycol loop transfers low temperature glycol to a heat exchanger (optional), where the chilled water is cooled. In some systems the intermediate glycol loop is not used and the water from the chilled water system is taken from, and returned, to the ice storage tank.
- *Flake ice systems* – Ice is made in thin sheets which are broken up and stored in a bin (Figure 15) . The bin is filled with ice flakes or chips during each bin-charging cycle. Ice is removed by an auger and deposited into a smaller bin which contains a coil that is part of the chilled water system. Water, circulating through the coil, is cooled.

Ice systems are popular in retrofit applications where space may be limited since they can store approximately 10 times more cooling energy per cubic foot than chilled water.



Cross Section Through Icemaking Coils In Ice Storage System
Figure 14



Flake Ice System
Figure 15

The following items are critical to an ice storage system design.

- *Standby losses* – Phase-change media systems have higher standby losses than sensible heat storage systems because of the higher temperature differences between the storage medium and ambient conditions. Care in the application of vapor barriers and insulation is essential to prevent condensation damage.
- *Thermal expansion* – Allowances for expansion and contraction of the storage media and equipment connections to the tank must be made to prevent equipment damage and spillage.
- *Agitators* – Improved heat transfer rates and higher density ice are obtained when the solution surrounding the coils is subjected to mild agitation. An air "bubbler" is the most common method of providing agitation.
- *Refrigeration system power requirements* – Mechanical refrigeration systems are less efficient at generating the low temperatures required for ice making than for making chilled water and therefore consume more electrical energy. However, more cooling per unit volume is provided.

Ponds and Aquifer Storage

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 thermal storage system or as a means of rejecting surplus heat from refrigeration or process equipment.

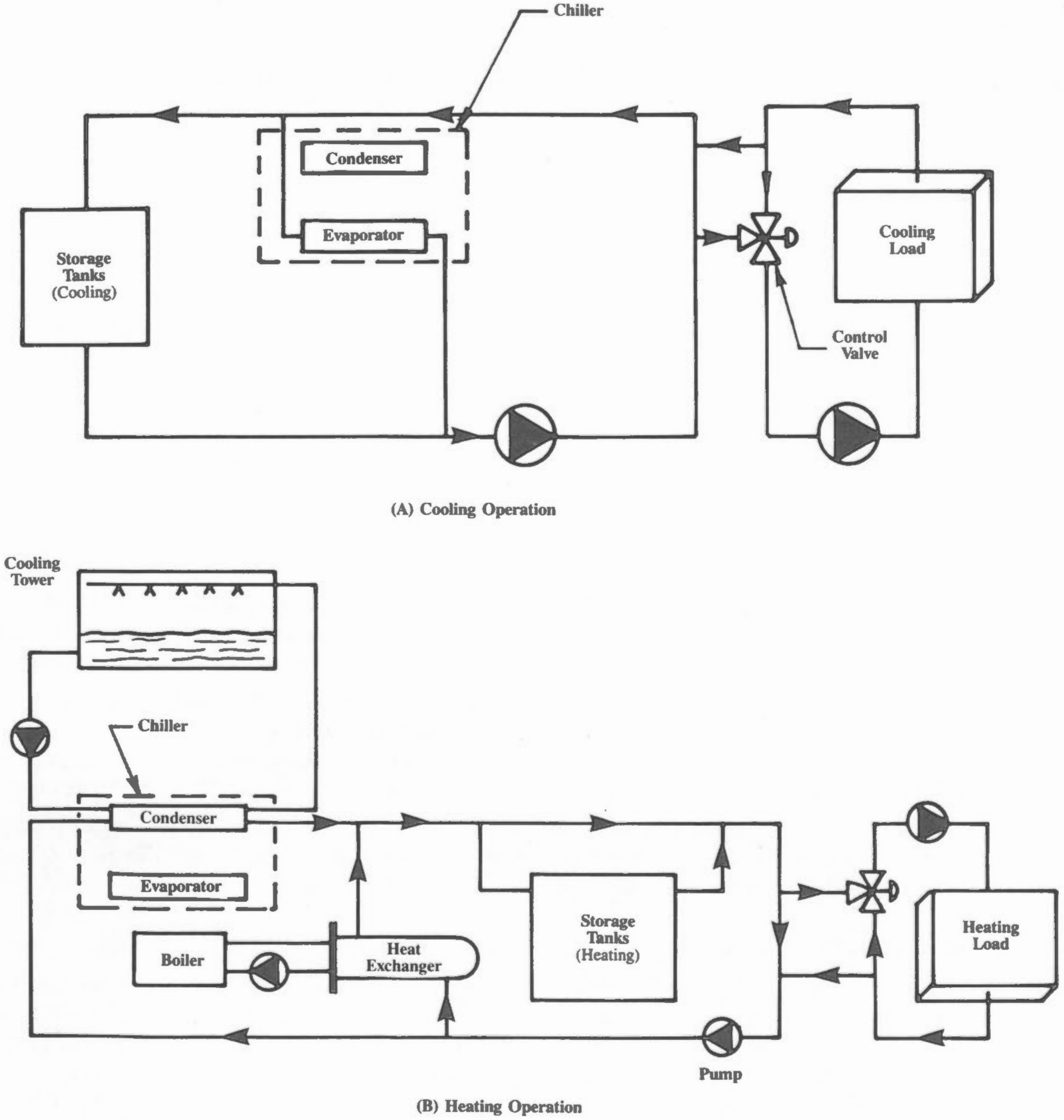
Wells have been drilled to transport water to underground aquifers (underground areas of water bearing rock, sand or gravel). Well spacing, depth and size are functions of the aquifer. Special permits are required from provincial environmental authorities to drill wells for this purpose. Buried piping systems have also been used to extract energy from the ground (usually cooling). While neither of these methods is common, a small number of sites have performed successfully.

Typical Thermal Storage Systems

Each thermal storage project is unique because of different load profiles, climate, energy costs and financial considerations. However, generic models can be presented to identify some of the main characteristics. The following sections briefly describe basic storage systems.

Chiller Heating and Cooling Storage

The primary purpose of the scheme illustrated in Figure 16 is to reduce demand charges for a chiller operation. A secondary benefit is the displacement of the conventional heating load to the chiller. The operation of electrical resistance heating is usually uneconomical as compared to gas and oil heating. However, a chiller operating with a minimum COP of 3 can provide heat more economically than gas. When combined with thermal storage, this system charges the heating and cooling storage off-peak to reduce demand charges. An office/commercial complex system can be used to explain the technique.



Heating And Cooling Storage System
Figure 16

Cooling operation – During periods requiring cooling, chilled water is drawn from storage, pumped to the load (coils, process equipment, etc.) through a secondary circuit and returned to an empty tank. Once a tank is emptied of chilled water, it serves as the next return tank.

The chiller, piped in parallel with the storage tanks, can function in one of two ways. First, when full storage capacity is provided, the chiller can be shut off during the peak electrical demand period to reduce the electrical peak of the facility. However, full storage may be impractical. Second, with partial storage, the chiller operates at reduced load. The building electrical peak is reduced, but to a lesser degree than if the full cooling load was provided from storage.

The chiller plant is operated during off peak periods to recharge the chilled water storage. Care must be taken to avoid establishing new electrical peaks during the recharging process.

Heating operation – During periods requiring simultaneous heating and cooling, the cooling is provided by the chiller evaporator as previously discussed.

During low electrical demand periods the chiller, operating as a heat pump, simultaneously recharges the cooling and heating tanks. The tanks are emptied and filled on an alternate basis as each is fully charged.

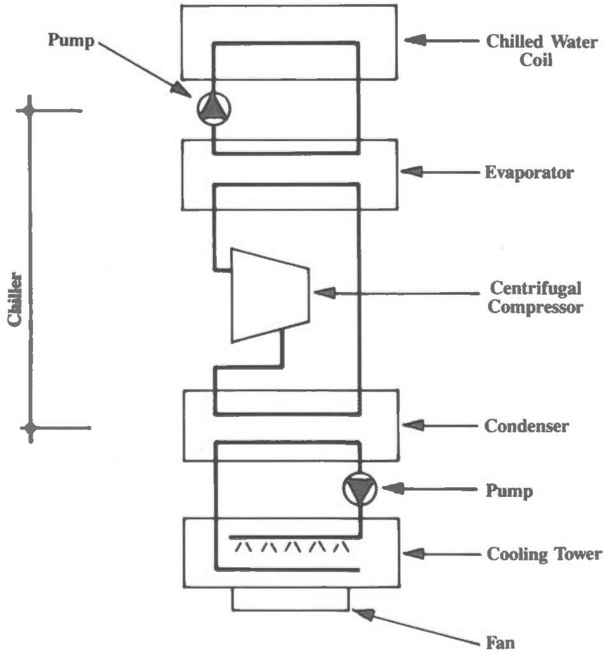
If heating is required during the hot water tank recharging, the load can be provided from storage, the condenser, or the boilers, depending on the charged condition of the storage and the selected operating strategy.

During high electrical demand periods thermal energy can be withdrawn from the tanks as required.

Benefits are obtained by off-peak operation of the chiller or heat pump to meet the cooling and heating requirements and by taking advantage of the COP. "Free" cooling using outdoor air may not be economical under these circumstances, and reduced sizes of the outdoor air ductwork and fans could lower the capital costs of new construction.

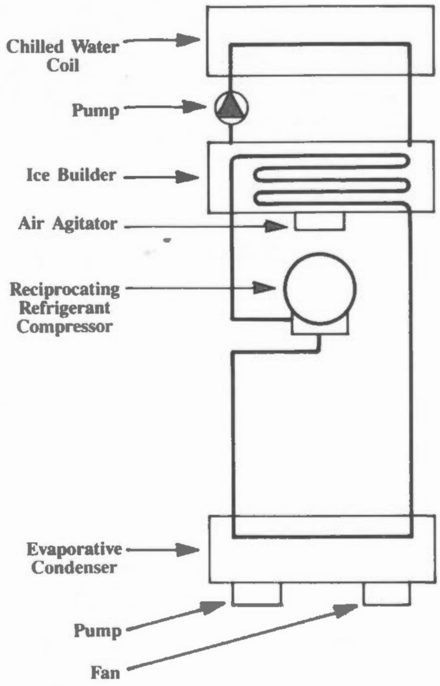
Ice Storage

Figure 1 shows a typical thermal cooling load profile for a commercial building. The electrical load profile would resemble Figure 2 if this load were satisfied with a conventional chiller system (Figure 17). For this design, the chiller electrical load would peak in the late afternoon at the same time as the cooling load.

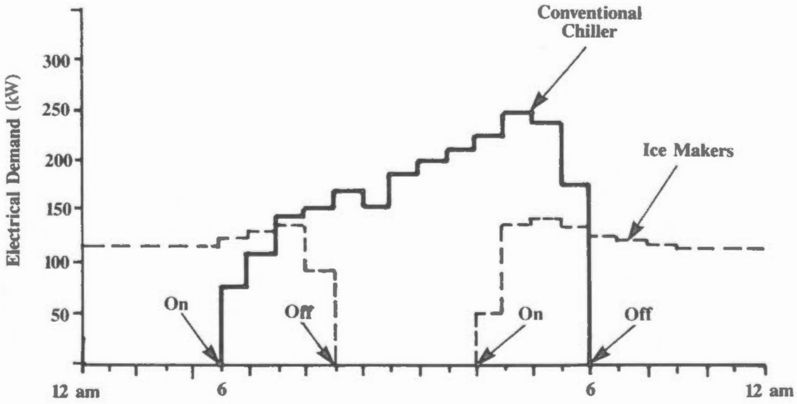


Conventional Chiller System
Figure 17

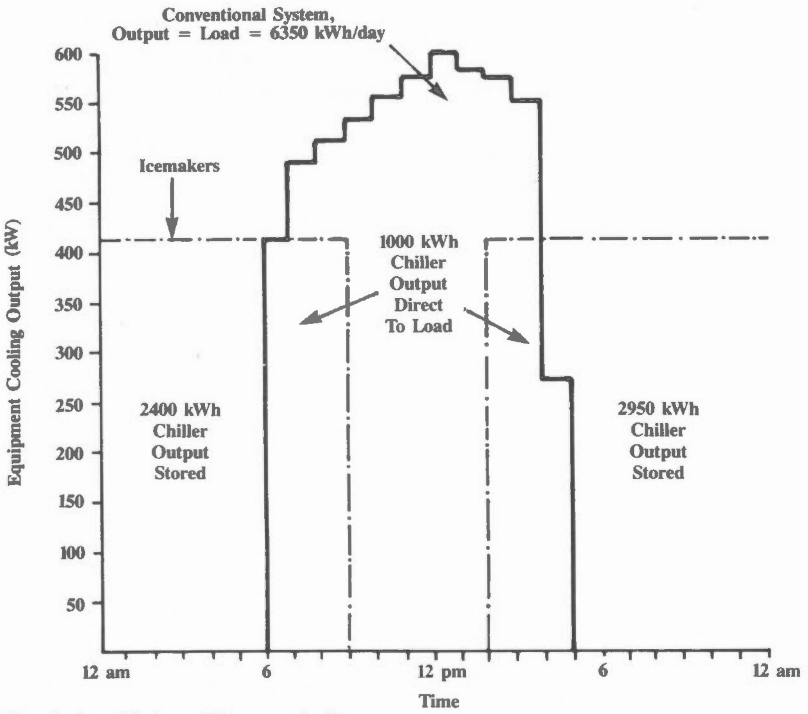
A full storage ice system (Figure 18) can be designed to meet the full cooling load requirements during the facility's peak hours, to reduce electrical demand. Ice production occurs at other than peak hours, such as on weekends and during early morning periods when the thermal and other electrical loads are lower. With the operating strategy represented by Figures 19 and 20, the chiller or ice maker is off during the electrical peak period. The rejected heat from the refrigeration equipment could be used for water heating creating an additional benefit.



Ice Storage System
Figure 18



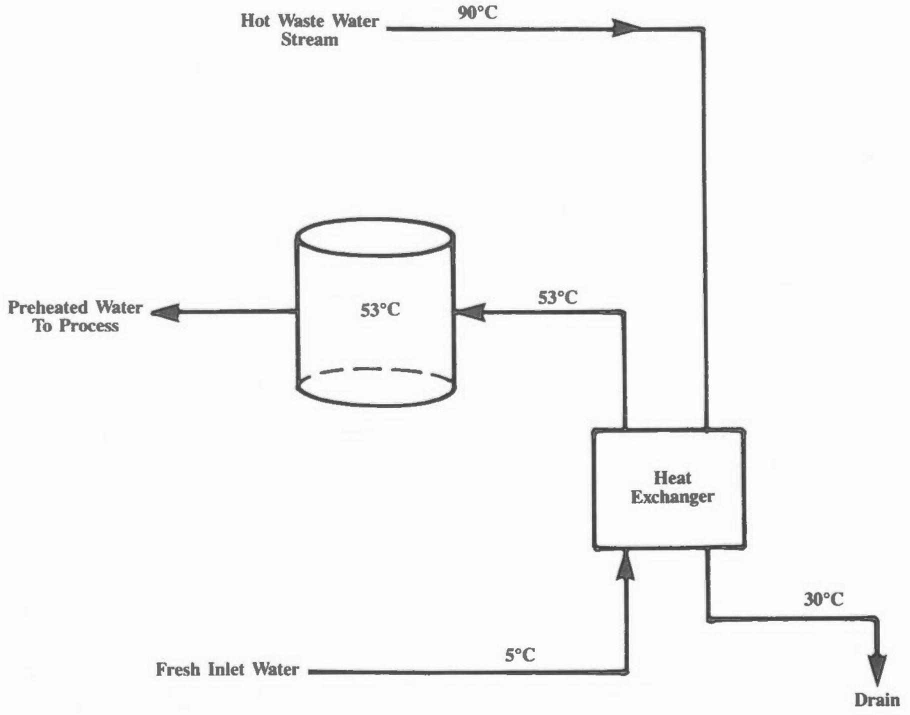
Electrical Load Profiles For Ice Storage Example
Figure 19



Thermal Storage Strategy For Ice Storage Example
Figure 20

Heat Reclaim Using Thermal Storage

A thermal storage system may act as a holding tank which permits matching make-up and waste flows to process requirements (Figure 21). While the storage of dirty or contaminated waste water is often impractical, waste water can often preheat clean make-up water by the use of a heat exchanger. The preheated water is then stored until needed. Better opportunities exist if large volumes of "high quality" heat is available as a waste source. In these cases more energy can be transferred to useful purposes because the system COP is increased. Direct use of waste heat for preheating is more efficient than providing a storage cycle. This method is possible only if make-up heating and waste heat discharge occur simultaneously.



Waste Water Storage
Figure 21

Controls

Control flexibility is the key to optimizing building thermal storage systems because exact operating modes and schedules vary continuously and are difficult to accurately predict. A system designed with manual controls, or one which uses state of the art computerized controls can be equally effective, provided the system operation can be readily adjusted to meet the actual site conditions.

Monitoring of thermal storage system operation is required to track system performance and to identify operating problems or potential areas for future improvements. Small systems can be monitored with standard meters, gauges and manual entry logs. Electronic instrumentation and control systems with automatic data logging, trend analysis and other features are generally used in larger systems. For additional control information see Measuring, Metering, and Monitoring, Module 15, and Automatic Controls, Module 16.

ENERGY MANAGEMENT OPPORTUNITIES

Energy Management Opportunities is a term that represents all the ways that energy can be used wisely to save money. A number of typical Energy Management Opportunities subdivided into Housekeeping, Low Cost, and Retrofit categories are outlined in this section. This is not a complete listing of thermal storage opportunities. However, it is intended to provide ideas for management, operating and maintenance personnel to allow them to identify opportunities that are applicable to a particular facility.

The Correct Approach to Thermal Storage

A facility owner or operator should implement conventional energy management opportunities as outlined in the other modules of this series before considering thermal storage techniques. Reducing energy waste and optimizing existing systems is generally more cost effective than providing a thermal storage system. If the facility then appears to have potential for thermal storage, further analysis can be performed to quantify potential savings.

The initial task in the evaluation of thermal storage Energy Management Opportunities usually begins with recording building electrical demand patterns through several typical operating periods. These records can be examined to identify loads which might be shifted to off-peak periods, and equipment operations which can be rescheduled to remove unnecessary peak electrical demands. Worksheet 19-1 is used to assess the potential for demand charge reductions.

Housekeeping Opportunities

Implemented housekeeping opportunities are energy management actions that are *done on a regular basis and never less than once per year.* The following are typical Energy Management Opportunities in this category.

1. Isolate storage tanks if they are not charging or discharging. Improperly isolated tanks decrease storage capacity caused by unnecessary mixing and impose unnecessary loads on the thermal equipment.
2. Repair leaks in storage tanks to avoid storage capacity losses and reduce make-up water and water treatment costs. Inadequate storage may require emergency start-up of equipment and cause a new electrical demand peak. Leaks may also cause water damage.
3. Check antifreeze (glycol) concentration in ice systems. An excessive concentration reduces heat transfer effectiveness and increases the pump power. An inadequate concentration may cause freezing and equipment damage.
4. Keep storage media clean. Ensure that strainers and filters are cleaned regularly to prevent increased pump and fan power. Ensure proper water treatment in systems to control the growth of algae. Keep rock bed filters clean to prevent dirt and lint from clogging the media and increasing fan power.
5. Review data from system operation and the related energy bills. Adjust operating strategies to optimize the system based on actual experience rather than the design projections.
6. Check for proper operation of all control components, particularly primary temperature sensing elements. Improper operation may cause equipment damage, lower system efficiency and reduced storage capacity.
7. Maintain all mechanical equipment according to the manufacturer's instructions.
8. Repair/replace damaged insulation.

Low Cost Opportunities

Implemented low cost opportunities are energy management actions that are *done once and for which the cost is not considered great*. The following are typical Energy Management Opportunities in this category.

1. Use the thermal storage capacity of a building to store heating or cooling energy to reduce electrical demand during peak periods.
2. Use the thermal storage capabilities of process equipment to reduce the operation of heating equipment during plant warm-up periods.
3. Precool chilled water loops before periods of electrical peak loads, so that chiller demand can be reduced by shutting off the chiller or limiting the load.
4. Raise domestic hot water tank temperature. Use the greater thermal capacity to keep the heating equipment off during peak electrical demand periods. Maintain supply water at the customary temperature by installing a fail-safe, three-way valve to blend heated and cold make-up water.
5. Use surplus equipment (tanks, pumps, etc.) to lower capital investment.

Low Cost Worked Examples

1. Use Storage Capacity of Building Structure

The thermal storage capacity of a building structure can be used to reduce both the electrical demand peaks of a facility and the requirement for new heating and cooling equipment. The following procedures would be necessary when storing cooling energy in a 5000 m^2 air-conditioned industrial building.

- Operate the space at 1.5°C below normal for one hour before electrical load peak times to allow cooling energy to "soak" into the building fabric.
- As electrical loads approach the peak, reduce the chiller power draw with a load limiter switch.
- Allow the space temperature to rise 1.5°C above normal during the peak electrical demand period.

The thermal capacity that can be put into storage through a 3°C temperature float can be approximated.

$$
\begin{aligned}
E &= 0.370 \text{ x } A \\
&= 0.370 \text{ x } 5000 \\
&= 1850 \text{ MJ} \\
\text{or } &= \frac{1850 \text{ MJ}}{3.6 \text{ MJ/kWh}} \\
&= 514 \text{ kWh}
\end{aligned}
$$

Reduced electrical demand charges result. A 514 kWh refrigeration load reduction will reduce chiller electrical demand during a one hour period by about 145 kW (where COP = 3.54). Such a reduction will reduce monthly demand charges by 145 x 6 = $870 based on an electrical demand charge of $6 per kW.

The same facility could also store 1850 MJ of thermal energy, during the heating season, if the temperature was allowed to float by 3°C. The temperature is allowed to increase during facility production periods and this stored heat energy is released during nonproduction periods when the area cools, thus reducing the building heating requirements. If the facility is heated by gas, the estimated fuel savings per production cycle can be estimated.

Natural gas cost	$\$0.14/m^3$
Heating system overall efficiency	68%
Heating value of natural gas (Appendix C)	37.2 MJ/m^3

$$
\begin{aligned}
\text{Gas cost per heating cycle} &= \frac{1850 \text{ MJ x } \$0.14/\text{m}^3}{37.2 \text{ MJ/m}^3 \text{ x } 0.68} \\
&= \$10.24
\end{aligned}
$$

On the basis of 5 heating cycles per week, a 16 week heating season when this stored heat can be used, and a 5 month cooling season, the annual dollar savings can be calculated.

Annual dollar savings = ($10.24 x 5 cycles/week x 16 weeks/yr) + (5 mo x $870/mo)

= $819 + $4,350 = $5,169

The capital cost to modify the controls and provide additional dampers on the exhaust and fresh air intake ducts is estimated to be $5,000.

$$\text{Simple payback} = \frac{\$5000}{\$5169}$$

= 1 year (approximately)

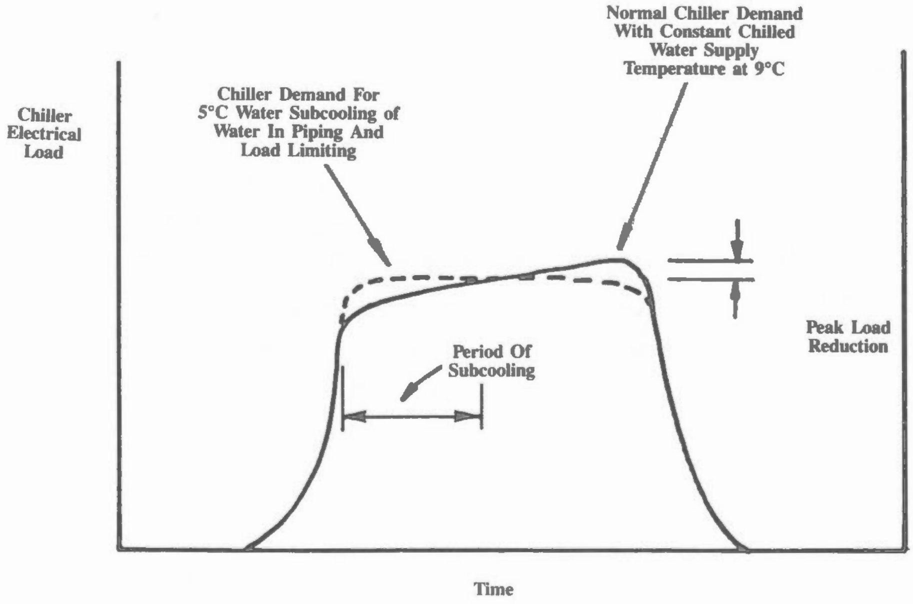
2. Thermal Storage in Equipment and Products

Industrial process equipment and products can be used in a manner similar to using the building fabric for thermal storage. For example, if the process equipment requires cooling during the normal production cycle, and the building requires heating during off-hours, consider reducing the amount of cooling at the end of shift to store heat in the equipment. Cooling would occur slowly during the off-hours, while partially offsetting the need for building heating. Simultaneous heating and cooling is reduced.

Where hot products such as hot coiled metal sheet must be cooled before further handling, consider placing the cooling areas at the building perimeter so that the heat loss from the product offsets the building heat losses.

3. Thermal Storage in Piping Systems

The *liquid contained in piping loops or tanks can be used as thermal storage media*. Consider a chilled water system that requires 9°C water to meet cooling requirements. The load causes the chiller to operate at maximum capacity thereby establishing the electrical demand charge for the month (Figure 22). Lowering the water temperature to 5°C before the expected peak cooling time puts additional thermal capacity into the chilled water enabling a load reduction at the chiller during electrical peak periods.



Chiller Subcooling Strategy
Figure 22

Consider a building chiller with a capacity of 1000 kW of refrigeration and 4000 litres of water in the chilled water piping system. The following calculation shows that lowering the water temperature by 4°C will store 18.6 kWh (67 MJ) of refrigeration capacity in the water.

$$E = V \times d \times DT \times cp$$

$$= \frac{4000 \times 1 \times 4 \times 4.1855}{3600}$$

$$= 18.6 \text{ kWh}$$

Where 3600 is conversion of kJ to kWh

Thermal storage allows 18.6 kW of refrigeration capacity to be advanced for one hour to avoid a peak period and to reduce the peak electrical demand charges. If the electrical demand charge for this facility is $6 per kW and chiller COP is 3.5, savings can be calculated.

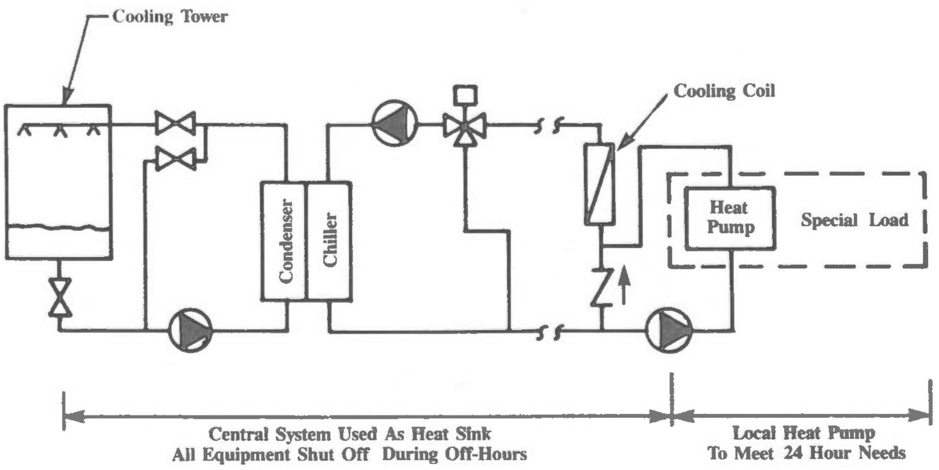
$$\text{Annual savings} = \frac{18.6 \times 6 \times 12}{3.5}$$

$$= \$383$$

An estimate of $700 for a timer and reset control allows the payback to be calculated.

$$\text{Simple payback} = \frac{\$700}{\$383} = 1.8 \text{ years}$$

A similar technique can be used to resolve local heating and cooling problems in a large facility. For example, a large office and commercial complex has a central chiller plant and piping system which transports chilled water to various areas of the building. Although the building is unoccupied during nights and weekends, the telephone switching room requires constant cooling. Part load performance of the chiller is poor. A water source heat pump, using the building's chilled water piping system as the heat sink, may permit all central systems to be shutdown, including the main pumps (Figure 23). A small pump could circulate the chilled water to satisfy the heat pump requirements. Depending on the load, the thermal storage capacity of the chilled water piping system is often sufficient to enable chiller shutdown for a full weekend. Energy savings result from shutting down the chiller, cooling tower and pumps.



Using Piping System As A Heat Sink For Special Applications
Figure 23

4. Raise Tank Temperature Settings

Hot water systems that include a storage tank can be operated to enhance thermal storage capabilities.

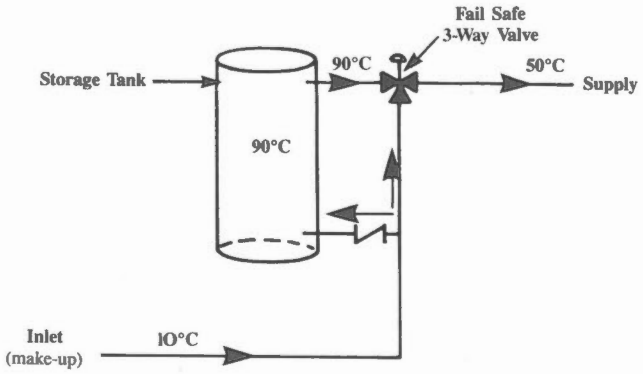
Consider a tank which maintains water at 50°C. Raising the temperature to 90°C increases the heat energy stored by the water in the tank. System water supply at 50°C is maintained by blending 90°C water from the tank with cold make-up water (Figure 24). The increased thermal storage capacity created by higher tank temperatures can reduce or eliminate the electrical domestic water heating load during peak demand periods. This approach may also remove the need for additional heating equipment when the building is expanded or loads are increased.

The proportion of supply water coming from the hot water in the tank is calculated from the following equation. (The effect of the return flow is neglected as the capacity is negligible.)

$$\text{Fraction of water from tank} = \frac{DT_1}{DT_2}$$

where DT_1 = (Supply temperature) − (Make-up temperature), (°C)

DT_2 = (Tank temperature) − (Make-up temperature), (°C)



Increased Water Storage Temperature
Figure 24

Consider the system in Figure 24 where hot water storage is 90°C, water supply is required at 50°C, and make-up water temperature is 10°C. The flow of 90°C water from the tank required to satisfy the 50°C supply temperature can be calculated.

$$\text{Fraction of water from supply tank} = \frac{(50 - 10)}{(90 - 10)}$$

$$= \frac{40}{80} = 0.50$$

The water withdrawal rate from the 90°C tank is 50 per cent of that required if the temperature of the water in the tank was maintained at 50°C. Thermal storage capacity has been increased by a factor of 2.0 (1 divided by 0.50) while permitting greater peak hot water loads to be satisfied without increasing the electrical demand for water heating.

Consider a domestic water heating system with a 5000 litre storage tank and 100 kW of electric heating capacity. During peak electrical demand periods, 60 kW of electricity was required to maintain the required water supply temperature of 50°C. The tank temperature setting was raised to 90°C using off-peak power. Operation of the electric water heaters was rescheduled to start one hour before the morning peak water use period, when the greatest capacity was needed. The heaters were automatically disconnected by a timer during the peak electrical demand periods. Altering the tank temperature in this manner, rather than holding the tank at 90°C throughout the entire day reduced the periods of high water temperature, which reduced heat loss rates and the risk of increased tank scaling and corrosion. A 60 kW demand can be eliminated from the monthly peak by automatically disconnecting the hot water heater during peak demand periods.

Annual dollar savings = Electrical demand reduction/month x mo/yr x $/kW

= 60 kW/mo x 12 mo/yr x $6/kW

= $4320/yr

The cost of the modification was estimated to be $3500.

$$\text{Simple payback} = \frac{3500}{4320} = 0.81 \text{ yr (10 months)}$$

A three-way valve is used to mix the high temperature hot water with the make-up water to effect the storage capacity increase. To avoid possible scalding to the users in the event of valve failure, the operation of the three-way valve should include fail-safe design features. Additional tank insulation may be beneficial, since raising the water storage temperature increases the rate of heat loss from the tank. Prior to raising tank operating temperatures, the tank manufacturer should be consulted to ensure that the tank temperature and pressure ratings will not be exceeded. In any open system, such as a domestic water heating system where fresh water regularly passes through the system, special precautions such as sacrificial anodes and water softeners may be necessary to control tank corrosion and scaling. Both actions increase when water temperatures are raised.

Retrofit Opportunities

Implemented retrofit opportunities are energy management actions that are *done once and for which the cost is significant*. Many of the opportunities in this category require detailed analysis by a specialist. The following are typical examples.

1. Add *pressurized water* storage tanks to heating and domestic hot water systems.
2. Provide heated or chilled water storage systems to avoid the purchase of additional heating or cooling equipment when a process is added or a building is expanded.
3. Drain waste water through a heat exchanger to transfer heat to make-up water. Add a storage tank to temporarily hold the preheated make-up water until it is needed. If necessary, consider using a heat pump to upgrade this heat.
4. Where space is at a premium, add solid *ice storage* to chilled water systems. When adequate space exists, consider flake ice storage or chilled water storage.
5. Add phase-change salt storage bins to heat pump, boiler, building heating, or solar collector systems. Where space permits, consider hot water storage tanks.

The worked examples presented identify the potential for electrical demand charge reductions and for utilizing waste heat.

Retrofit Worked Examples

1. Pressurized Water Systems

An increase in the temperature of storage tank contents will increase the thermal storage potential. Most tanks and system temperatures are limited to 90°C by the design rating of the tank. However, the water temperature can be raised with the introduction of a closed pressurized storage tank, and a heat exchanger connected to the heating system (Figure 25). This system requires a fail-safe three-way valve to ensure that high temperature water is isolated from the heating system.

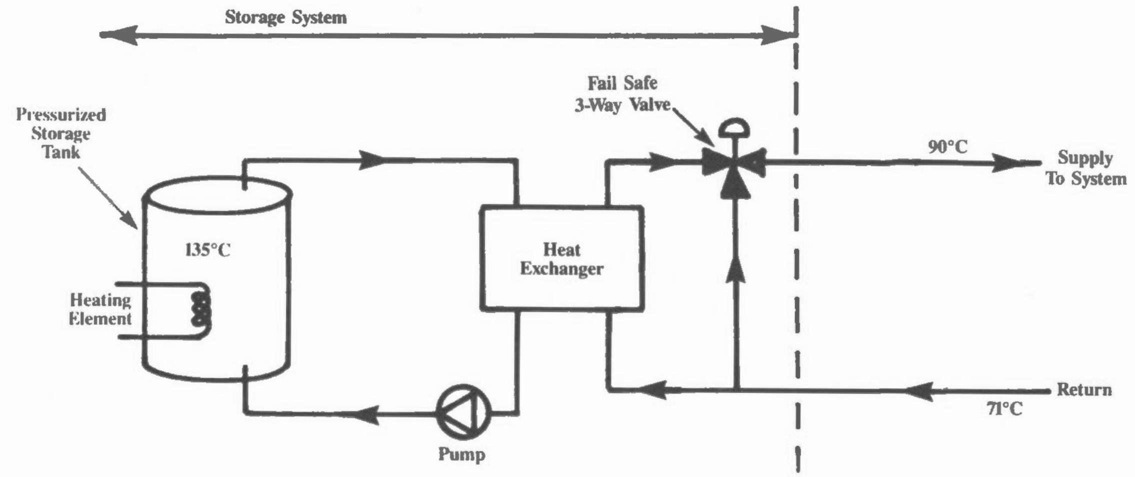
For a pressurized storage system connected to a building hot water circuit, the water in the storage tank could be heated to 135°C before the peak electrical demand occurs, and distributed at 90°C during the peak period. The additional heat storage capability of the water can be calculated.

$$E = \frac{M \times cp \times DT}{1000}$$

Note: For water, 1 kg = 1 L and cp = 4.1855 kJ/(kg·°C)

$$E = \frac{1 \times 4.1855 \times (135 - 90)}{1000}$$

$$= 0.188 \text{ MJ/kg or MJ/L}$$



Pressurized Water System
Figure 25

Consider a building having 2600 kW of electric water heating and an electrical peak period of one hour. The required hot water supply temperature is 90°C. The installation of four 9500 L pressurized storage tanks will allow the storage of 38 000 L (4 x 9500) of 135°C hot water. By heating the water to 135 °C during off-peak electrical periods the electrical demand charges will be reduced because the 90°C water is obtained from storage instead of from the electric heaters. The installation of the four storage tanks and associated piping is estimated to cost $160,000.

Stored energy (MJ) = Volume (L) x additional energy storage capacity (MJ/L)

= 4 x 9500 x 0.188

= 7144 MJ

$$\text{Electrical load reduction (kW)} = \text{Energy stored (MJ)} \times \frac{\text{hours (h)}}{3.6\ \text{MJ/kWh}}$$

$$= \frac{7144 \times 1}{3.6}$$

= 1984 kW

Electrical demand charge $6/kW

Heating season 4.5 months

Annual dollar savings = 1984 x 6 x 4.5

= $53,568/yr

$$\text{Simple payback} = \frac{\$160{,}000}{\$53{,}568}$$

= 3.0 years

2. Waste Water Storage

Consider a batch process which discharges 20 000 L of 90°C water to drain. By adding a 20 000 L capacity holding tank and a heat exchanger system, some of the heat energy from the waste water can be transferred to the make-up water. If the waste water temperature is reduced to 30°C as it is drained through the heat exchanger, the heat stored in the waste water tank for each drain cycle can be calculated.

$$E = \frac{M \text{ x } cp \text{ x } DT}{1000}$$

$$= \frac{20\,000 \text{ x } 4.1855 \text{ x } (90 - 30)}{1000}$$

$$= 5023 \text{ MJ}$$

As the hot water passes through the heat exchanger, about 80 per cent of the stored heat is transferred to the fresh inlet water. Approximately 20 per cent of the heat is lost to evaporation and thermal losses from the tank and piping. One thousand drain cycles are scheduled per year.

The recovered heat reduces gas-fired boiler preheating of the make-up water. The annual value of the recovered heat for gas costing \$0.14/m^3 can be calculated.

$$\text{Annual dollar savings} = \frac{E \text{ x } Ef_e \text{ x } Cf \text{ x } N}{Ef_b \text{ x fuel heating value}}$$

Where, E = Energy in tank (MJ)

Ef_e = Heat exchanger efficiency (assume 0.80)

Ef_b = Boiler efficiency (assume 0.70)

N = Number of tank cycles per year

Cf = Fuel cost (\$/m^3)

$$\text{Annual dollar savings} = \frac{5023 \text{ x } 0.8 \text{ x } 0.14 \text{ x } 1000}{0.7 \text{ x } 37.2}$$

$$= \$21{,}604$$

The estimated cost for the heat exchanger, tank and associated piping is \$60,000.

$$\text{Simple payback} = \frac{\$60{,}000}{\$21{,}604}$$

$$= 2.8 \text{ years}$$

The thermal storage capacity required for this application depends on the volume of liquid drained per cycle and the temperature difference between the water entering and leaving the heat exchanger or heat pump. Filtration may be required to remove contaminants which could foul the heat exchanger and reduce the heat transfer effectiveness.

3. Identifying Demand Charge Reductions

This example demonstrates the use of Worksheet 19-1 to identify and quantify potential demand charge reductions by shifting loads to low activity periods through the use of thermal storage. For examples of demand load reductions by limiting the connected load see Electrical, Module 3.

Consider a manufacturing plant where process and building heating and cooling equipment operates during nonproduction or low activity periods. The peak electrical demand as billed by the utility was recorded as 470 kW. During low activity periods, the load dropped to an average of 130 kW. Power readings for normal operation and low activity periods were recorded for all equipment considered suitable for thermal storage. Nameplate or equipment capacities were also recorded.

A comparison of equipment loads operating during low capacity periods indicated a potential demand saving of 170 kW could be realized. If the utility demand charge is $6 per kW, total demand charges can be reduced by $1,020 per month.

4. Building Addition

Additional boiler or chiller capacity is often required when adding processes or enlarging a building. A thermal storage system may eliminate the need to add new thermal storage equipment and permit the existing equipment to operate more efficiently. By storing thermal energy during low activity periods, heating or cooling load requirements may be satisfied. The increased load can be supplied by drawing energy out of storage. The cost of thermal storage equipment could be less than that of a new boiler or chiller. Energy costs would be lower because of lower demand charges.

The following example uses Worksheet 19-2 to estimate the storage capacity required to avoid the requirement for a new chiller. This worksheet can also be used for heating system thermal storage evaluation.

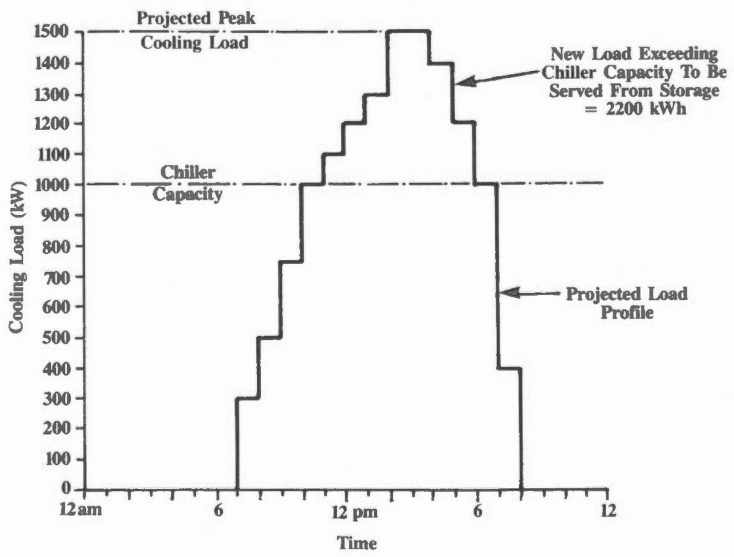
A building extension will increase the peak cooling load to 1500 kW of refrigeration, and the existing chiller has 1000 kW capacity. The new load could be directly satisfied with the addition of 500 kW of refrigeration capacity, but this would require a large capital expenditure and increased operating costs.

As an alternative, thermal storage could be provided to meet the new peak thermal load. The projected daily thermal load profile of the facility is shown in Column A on Worksheet 19-2 and plotted in Figure 26. Column C shows that the existing chiller will be overloaded from 11 am to 6 pm. Column E shows that between 7 pm and 10 am there is surplus chiller capacity which could be used to charge a storage system.

The total of Column C shows that 2200 kWh of refrigeration would have to be drawn from storage to meet the new load. The total of Column E reflects the amount of cooling which could be put into storage. As this capacity of 13 050 kWh is greater than the needed 2200 kWh of storage, the existing chiller will have adequate capacity to operate a storage system and meet all thermal load requirements.

Adding 500 kW of chiller capacity would require a new chiller, pumps, starters, wiring, piping, and controls. Construction costs for a thermal storage system consisting of storage tanks, pumps, piping, wiring, automatic controls and structural changes to accomodate the tanks normally are substantially less.

Electrical demand for cooling would be limited to 285 kW using the existing chiller (1000 kW divided COP of 3.5), rather than increasing to 430 kW (1500 kW divided by 3.5). This is a reduction of 145 kW in demand.



Thermal Load Profile For Retrofit
Worked Example 4
Figure 26

Demand Charge Reduction

Worksheet 19-1

Page 1 of 1

Company: WORKED EXAMPLE 3 Date: JUNE 86

Location: RETROFIT By: MBE

Electrical peak demand as billed by utility 470 kW (1)

Average measured facility demand – low activity periods (base load) 130 kW (2)

Demand charges are optimized when demand remains constant.

$$= \frac{(1) + (2)}{2} = \frac{470 + 130}{2}$$

= 300 kW (3)

Maximum potential demand savings when thermal storage is used to transfer loads to low activity periods. 470 (1) – 300 (3)

= 170 kW (4)

Suggested Systems Suitable For Thermal Storage	Equipment Capacity (kW)	Existing Load During Operating Period (kW)	Existing Load During Low Activity Period (kW)	Thermal Storage Potential (kW)
Elect. Process – Heating	200	200	50	150
Elect. Process – Cooling	100	80	20	80
Space Heating	50	0	25	0
Space Cooling	50	50	0	50
DHW Heating	10	10	2	8
Other	5	5	5	0
Totals	415	345	102	288 (5)

If (5) is greater than (4) maximum potential demand savings may be realized.

If (5) is smaller than (4) potential savings will be less attractive.

Potential demand savings can be calculated.

Demand charges by utility $ 6 /kW/month (6)

Demand reduction: the lessor of (4) or (5) 170 kW (7)

Maximum potential cost savings = $ 6 (6) x 170 (7)

= $ 1020 /month

Notes:

1. Identify systems and equipment that have the most thermal storage potential.
2. Make sure that charging of a thermal storage system does not create a new higher billing demand in the low activity period.
3. If the maximum potential cost savings are significant, a specialist should be retained to provide an in-depth analysis.

Determination of Thermal Storage Charging Capacity of Existing Equipment and Waste Streams

Worksheet 19-2

Page 1 of 2

Company: WORKED EXAMPLE 4 Date: MARCH 1986

Location: RETROFIT By: MBE

Steps

(1) Predict the peak day mean hourly heating or cooling load on existing equipment being considered. Such equipment may be a boiler, a chiller or a new process. Put these hourly predictions in column A.

(2) Determine the capacity of the existing equipment or waste stream and compare with numbers in A. Into column B insert the lower of A or equipment capacity.

(3) Subtract B from A and insert result in column C.

(4) The size of new equipment to install if storage is not used, is the highest value in C.

(5) Amount of useable storage required to avoid adding new equipment is the total of C.

(6) Insert the higher of A or equipment capacity into column D.

(7) Subtract A from D and insert result in column E.

(8) Total of E is storage charging capacity. If total of Column E is smaller than total of Column C then not all required storage can be regenerated and some new equipment capacity will be required.

Determination of Thermal Storage Charging Capacity of Existing Equipment and Waste Streams

Worksheet 19-2

Page 2 of 2

Company: WORKED EXAMPLE 4 Date: MARCH 1986

Location: RETROFIT By: MBE

HOURS	PREDICTED LOAD PROFILE (kW) A	LOWER OF A OR CAPACITY (kW) B	OVERLOAD A-B (kW) C	HIGHER OF A OR CAPACITY (kW) D	EXCESS CAPACITY D-A (kW) E
12pm-1am	0	0	0	1000	1000
1am-2am	0	0	0	1000	1000
2am-3am	0	0	0	1000	1000
3am-4am	0	0	0	1000	1000
4am-5am	0	0	0	1000	1000
5am-6am	0	0	0	1000	1000
6am-7am	0	0	0	1000	1000
7am-8am	300	300	0	1000	700
8am-9am	500	500	0	1000	500
9am-10am	750	750	0	1000	250
10am-11am	1000	1000	0	1000	0
11am-12am	1100	1000	100	1100	0
12am-1pm	1200	1000	200	1200	0
1pm-2pm	1300	1000	300	1300	0
2pm-3pm	1500	1000	500	1500	0
3pm-4pm	1500	1000	500	1500	0
4pm-5pm	1400	1000	400	1400	0
5pm-6pm	1200	1000	200	1200	0
6pm-7pm	1000	1000	0	1000	0
7pm-8pm	400	400	0	1000	600
8pm-9pm	0	0	0	1000	1000
9pm-10pm	0	0	0	1000	1000
10pm-11pm	0	0	0	1000	1000
11pm-12am	0	0	0	1000	1000
		TOTAL	2200 kWh		13050 kWh

APPENDICES

A Glossary
B Tables
C Common Conversions
D Worksheets

Glossary

Audit, diagnostic— The analysis of a potential opportunity to save energy which could involve the assessment of the current process operation, records, calculation of savings, and estimates of capital and operating costs so that financial viability can be established.

Audit, walk through — The visual inspection of a facility to observe how energy is used or wasted.

Degradable — Capable of being chemically broken down to change the physical properties.

Degree Days — A totalization of the difference between the mean daily outdoor dry bulb temperature and a reference temperature. For example, ten heating degree days below 18°C is equivalent of one day at 8°C or ten days at 17°C. Degree days may be referred to as either "heating" or "cooling".

Energy — The capacity for doing work; taking a number of forms that may be transformed from one into another, such as thermal (heat), mechanical (work), electrical, and chemical; measured in kilowatt-hours (kWh) or megajoules (MJ).

Energy, waste — Energy which is lost without being fully utilized. It may include the energy in the form of steam, exhaust gases, discharge water or even refuse.

Load, base — The thermal or electric loads that occur continually and at about the same level. For example, in a cooling system the electrical base load could consist of fans and pumps that operate continuously, and the chillers would be fluctuating loads not usually included in that base load.

Load, peak — The highest electrical or thermal load occurring during the period of time being considered.

Make-up Air — Outside air that is added to a building to replace air lost by exhaust or exfiltration.

Make-up Water — Water that is added to a domestic or process water system to replace water lost to evaporation, bleed-off and drain.

Off-peak — Times when the power requirement or load on a machine is lower than the peak requirement. Off peak times usually occur when occupancy and activity levels are low.

Sacrificial Anode — An electrode that slowly decays to protect other equipment against corrosion.

Seasonal Boiler Efficiency — A total heat energy output divided by the total energy input over the period of a full heating season.

Setback — Temperature setting when a thermostat is lowered during unoccupied periods.

Simple Payback — The time required for an expenditure to be repaid by the related annual dollar savings.

Standby Heat Losses — Refers to the energy that is lost from the thermal storage medium because of heat transmission through the walls of storage tanks and system piping.

State — Solid, liquid or gas.

Storage Capacity — The amount of thermal energy that can be stored in a storage system, expressed in kWh or MJ.

Storage System — Any tank, vessel, enclosure, bin or container with accessories such as pumps and controls, for storing thermal energy.

Stratification — The temperature layering effect in slow moving masses of air or liquid caused by differences in density between the warmer and cooler fluids. Buoyancy causes the less dense warm air or liquid to move to the top of any room or container. Cold air or liquid falls. The interface between the fluids of different temperature is called the thermocline.

Surplus Heat — Heat created by processes, occupants, or lights which is more than needed to maintain equilibrium in space or process temperatures.

Temperature Degradation — Temperature reduction within a heat energy storage medium, or temperature increase in a cooling energy storage medium, caused by blending and heat transfer through tank walls and floor.

Temperature, Mean — The average of the minimum and maximum temperatures.

TYPICAL SPECIFIC HEATS AND DENSITIES FOR SELECTED MATERIALS
TABLE 1

Material	Specific Heat [kJ/(kg·°C)]	Density (kg/m³)
Brick	0.80	1920
Concrete	0.65	2300
Clay Tile	0.92	1000
Concrete Blocks	0.92	—
Limestone	0.91	1650
Ice (at 0°C)	2.04	921*
Water (at 20°C)	4.1855	998
Hardwoods	1.63	550
Softwoods	1.63	430
Gypsum Plaster	1.09	2110
Paraffin Wax	2.90	900

*Ice at 0°C is less dense than water; for the purposes of this module, use a value of 1000 kg/m^3 for approximation purposes.

CHARACTERISTICS OF THERMAL STORAGE SUBSTANCES
TABLE 2

	Required Volume (L/MJ)	Temperature (°C)	Installation	Temperature Degradation	Life Of Material
LIQUIDS					
Chilled Water	30	5 to 10 Range	Large	Blending Problem	Permanent
Hot Water	30	38 to 90 Range	Large	Some Blending	Permanent
PHASE CHANGE					
Solid Ice	3.0	−5 to +10 Range	Distributed	No	Permanent
Flake Ice	3.0	−5 to +10 Range	Large	No	Permanent
Glauber's Salt	2.3	Freezing Point 32	Distributed	No	Limited
Calcium chloride hexahydrate	3.4	Freezing Point 29	Distributed	No	No Known Limit
Magnesium eutectic salt	4.9	Freezing Point 58	Distributed	No	No Known Limit
Magnesium nitrate hexahydrate	4.0	Freezing Point 89	Distributed	No	No Known Limit
SOLIDS					
Rocks	76	—	Large	No	Permanent
Sand	100	—	Distributed	No	Permanent

COMMON CONVERSIONS

1 barrel (35 Imp gal) (42 US gal) = 159.1 litres
1 gallon (Imp) = 1.20094 gallon (US)
1 horsepower (boiler) = 9809.6 watts
1 horsepower = 2545 Btu/hour
1 horsepower = 0.746 kilowatts
1 joule = 1 N-m
Kelvin = (°C + 273.15)

1 kilowatt-hour = 3600 kilojoules
1 Newton = 1 kg-m/s^2
1 therm = 10^5 Btu
1 ton (refrigerant) = 12002.84 Btu/hour
1 ton (refrigerant) = 3516.8 watts
1 watt = 1 joule/second
Rankine = (°F + 459.67)

Cubes

1 yd^3 = 27 ft^3
1 ft^3 = 1728 in^3
1 cm^3 = 1000 mm^3
1 m^3 = 10^6 cm^3
1 m^3 = 1000 L

Squares

1 yd^2 = 9 ft^2
1 ft^2 = 144 in^2
1 cm^2 = 100 mm^2
1 m^2 = 10000 cm^2

SI PREFIXES

Prefix	Symbol	Magnitude	Factor
tera	T	1 000 000 000 000	10^{12}
giga	G	1 000 000 000	10^{9}
mega	M	1 000 000	10^{6}
kilo	k	1 000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	u	0.000 001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pica	p	0.000 000 000 001	10^{-12}

UNIT CONVERSION TABLES
METRIC TO IMPERIAL

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
amperes/square centimetre	A/cm^2	amperes/square inch	A/in^2	6.452
Celsius	°C	Fahrenheit	°F	(°C × 9/5) + 32
centimetres	cm	inches	in	0.3937
cubic centimetres	cm^3	cubic inches	in^3	0.06102
cubic metres	m^3	cubic foot	ft^3	35.314
grams	g	ounces	oz	0.03527
grams	g	pounds	lb	0.0022
grams/litre	g/L	pounds/cubic foot	lb/ft^3	0.06243
joules	J	Btu	Btu	9.480×10^{-4}
joules	J	foot-pounds	ft-lb	0.7376
joules	J	horsepower-hours	hp-h	3.73×10^{-7}
joules/metre, (Newtons)	J/m, N	pounds	lb	0.2248
kilograms	kg	pounds	lb	2.205
kilograms	kg	tons (long)	ton	9.842×10^{-4}
kilograms	kg	tons (short)	tn	1.102×10^{-3}
kilometres	km	miles (statute)	mi	0.6214
kilopascals	kPa	atmospheres	atm	9.87×10^{-3}
kilopascals	kPa	inches of mercury (@ 32°F)	in Hg	0.2953
kilopascals	kPa	inches of water (@ 4°C)	in H_2O	4.0147
kilopascals	kPa	pounds/square inch	psi	0.1450
kilowatts	kW	foot-pounds/second	ft-lb/s	737.6
kilowatts	kW	horsepower	hp	1.341
kilowatt-hours	kWh	Btu	Btu	3413
litres	L	cubic foot	ft^3	0.03531
litres	L	gallons (Imp)	gal (Imp)	0.21998
litres	L	gallons (US)	gal (US)	0.2642
litres/second	L/s	cubic foot/minute	cfm	2.1186
lumen/square metre	lm/m^2	lumen/square foot	lm/ft^2	0.09290
lux, lumen/square metre	lx, lm/m^2	footcandles	fc	0.09290
metres	m	foot	ft	3.281
metres	m	yard	yd	1.09361
parts per million	ppm	grains/gallon (Imp)	gr/gal (Imp)	0.07
parts per million	ppm	grains/gallon (US)	gr/gal (US)	0.05842
permeance (metric)	PERM	permeance (Imp)	perm	0.01748
square centimetres	cm^2	square inches	in^2	0.1550
square metres	m^2	square foot	ft^2	10.764
square metres	m^2	square yards	yd^2	1.196
tonne (metric)	t	pounds	lb	2204.6
watt	W	Btu/hour	Btu/h	3.413
watt	W	lumen	lm	668.45

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UNIT CONVERSION TABLES
IMPERIAL TO METRIC

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
ampere/in^2	A/in^2	ampere/cm^2	A/cm^2	0.1550
atmospheres	atm	kilopascals	kPa	101.325
British Thermal Unit	Btu	joules	J	1054.8
Btu	Btu	kilogram-metre	kg-m	107.56
Btu	Btu	kilowatt-hour	kWh	2.928×10^{-4}
Btu/hour	Btu/h	watt	W	0.2931
calorie, gram	cal or g-cal	joules	J	4.186
chain	chain	metre	m	20.11684
cubic foot	ft^3	cubic metre	m^3	0.02832
cubic foot	ft^3	litre	L	28.32
cubic foot/minute	cfm	litre/second	L/s	0.47195
cycle/second	c/s	Hertz	Hz	1.00
Fahrenheit	°F	Celsius	°C	(°F-32)/1.8
foot	ft	metre	m	0.3048
footcandle	fc	lux, lumen/ square metre	lx, lm/m^2	10.764
footlambert	fL	candela/square metre	cd/m^2	3.42626
foot-pounds	ft-lb	joule	J	1.356
foot-pounds	ft-lb	kilogram-metres	kg-m	0.1383
foot-pounds/second	ft-lb/s	kilowatt	kW	1.356×10^{-3}
gallons (Imp)	gal (Imp)	litres	L	4.546
gallons (US)	gal (US)	litres	L	3.785
grains/gallon (Imp)	gr/gal (Imp)	parts per million	ppm	14.286
grains/gallon (US)	gr/gal (US)	parts per million	ppm	17.118
horsepower	hp	watts	W	745.7
horsepower-hours	hp-h	joules	J	2.684×10^6
inches	in	centimetres	cm	2.540
inches of Mercury (@ 32°F)	in Hg	kilopascals	kPa	3.386
inches of water (@ 4°C)	in H_2O	kilopascals	kPa	0.2491

UNIT CONVERSION TABLES
IMPERIAL TO METRIC (cont'd)

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
lamberts	* L	candela/square metre	cd/m^2	3.183
lumen/square foot	lm/ft^2	lumen/square metre	lm/m^2	10.76
lumen	lm	watt	W	0.001496
miles (statute)	mi	kilometres	km	1.6093
ounces	oz	grams	g	28.35
perm (at 0°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.721×10^{-11}
perm (at 23°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.745×10^{-11}
perm-inch (at 0°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4532×10^{-12}
perm-inch (at 23°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4593×10^{-12}
pint (Imp)	pt	litre	L	0.56826
pounds	lb	grams	g	453.5924
pounds	lb	joules/metre, (Newtons)	J/m, N	4.448
pounds	lb	kilograms	kg	0.4536
pounds	lb	tonne (metric)	t	4.536×10^{-4}
pounds/cubic foot	lb/ft^3	grams/litre	g/L	16.02
pounds/square inch	psi	kilopascals	kPa	6.89476
quarts	qt	litres	L	1.1365
slug	slug	kilograms	kg	14.5939
square foot	ft^2	square metre	m^2	0.09290
square inches	in^2	square centimetres	cm^2	6.452
square yards	yd^2	square metres	m^2	0.83613
tons (long)	ton	kilograms	kg	1016
tons (short)	tn	kilograms	kg	907.185
yards	yd	metres	m	0.9144

* "L" as used in Lighting

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The following typical values for conversion factors may be used when actual data are unavailable. The MJ and Btu equivalencies are heats of combustion. Hydrocarbons are shown at the higher heating value, wet basis. Some items listed are typically feedstocks, but are included for completeness and as a reference source. The conversion factors for coal are approximate since the heating value of a specific coal is dependent on the particular mine from which it is obtained.

ENERGY TYPE	METRIC	IMPERIAL
COAL		
— metallurgical	29,000 megajoules/tonne	25.0×10^6 Btu/ton
— anthracite	30,000 megajoules/tonne	25.8×10^6 Btu/ton
— bituminous	32,100 megajoules/tonne	27.6×10^6 Btu/ton
— sub-bituminous	22,100 megajoules/tonne	19.0×10^6 Btu/ton
— lignite	16,700 megajoules/tonne	14.4×10^6 Btu/ton
COKE		
— metallurgical	30,200 megajoules/tonne	26.0×10^6 Btu/ton
— petroleum		
— raw	23,300 megajoules/tonne	20.0×10^6 Btu/ton
— calcined	32,600 megajoules/tonne	28.0×10^6 Btu/ton
PITCH	37,200 megajoules/tonne	32.0×10^6 Btu/ton
CRUDE OIL	38,5 megajoules/litre	5.8×10^6 Btu/bbl
No. 2 OIL	38.68 megajoules/litre	5.88×10^6 Btu/bbl $.168 \times 10^6$ Btu/IG
No. 4 OIL	40.1 megajoules/litre	6.04×10^6 Btu/bbl $.173 \times 10^6$ Btu/IG
No. 6 OIL (RESID. BUNKER C)		
@ 2.5% sulphur	42.3 megajoules/litre	6.38×10^6 Btu/bbl $.182 \times 10^6$ Btu/IG
@ 1.0% sulphur	40.5 megajoules/litre	6.11×10^6 Btu/bbl $.174 \times 10^6$ Btu/IG
@ .5% sulphur	40.2 megajoules/litre	6.05×10^6 Btu/bbl $.173 \times 10^6$ Btu/IG
KEROSENE	37.68 megajoules/litre	$.167 \times 10^6$ Btu/IG
DIESEL FUEL	38.68 megajoules/litre	$.172 \times 10^6$ Btu/IG
GASOLINE	36.2 megajoules/litre	$.156 \times 10^6$ Btu/IG
NATURAL GAS	37.2 megajoules/m^3	1.00×10^6 Btu/MCF
PROPANE	50.3 megajoules/kg 26.6 megajoules/litre	$.02165 \times 10^6$ Btu/lb $.1145 \times 10^6$ Btu/IG
ELECTRICITY	3.6 megajoules/kWh	$.003413 \times 10^6$ Btu/kWh

Demand Charge Reduction

Worksheet 19-1
Page 1 of 1

Company: ______________________ Date: ______________________

Location: ______________________ By: ______________________

Electrical peak demand as billed by utility ________ kW (1)

Average measured facility demand – low activity periods (base load) ________ kW (2)

Demand charges are optimized when demand remains constant.

$$= \frac{(1) + (2)}{2} = \frac{\_\_\_\_\_\_ + \_\_\_\_\_\_}{2}$$

= ________ kW (3)

Maximum potential demand savings when thermal storage is used to transfer loads to low activity periods. ________ (1) – ________ (3)

= ________ kW (4)

Suggested Systems Suitable For Thermal Storage	Equipment Capacity (kW)	Existing Load During Operating Period (kW)	Existing Load During Low Activity Period (kW)	Thermal Storage Potential (kW)
Elect. Process – Heating				
Elect. Process – Cooling				
Space Heating				
Space Cooling				
DHW Heating				
Other				
Totals	________	________	________	________ (5)

If (5) is greater than (4) maximum potential demand savings may be realized.

If (5) is smaller than (4) potential savings will be less attractive.

Potential demand savings can be calculated.

Demand charges by utility $________/kW/month (6)

Demand reduction: the lessor of (4) or (5) ________ kW (7)

Maximum potential cost savings = $ ________ (6) x ________ (7)

= $ ________/month

Notes:

1. Identify systems and equipment that have the most thermal storage potential.
2. Make sure that charging of a thermal storage system does not create a new higher billing demand in the low activity period.
3. If the maximum potential cost savings are significant, a specialist should be retained to provide an in-depth analysis.

Determination of Thermal Storage Charging Capacity of Existing Equipment and Waste Streams

Worksheet 19-2

Page 1 of 2

Company: ____________________ Date: ____________________

Location: ____________________ By: ____________________

Steps

(1) Predict the peak day mean hourly heating or cooling load on existing equipment being considered. Such equipment may be a boiler, a chiller or a new process. Put these hourly predictions in column A.

(2) Determine the capacity of the existing equipment or waste stream and compare with numbers in A. Into column B insert the lower of A or equipment capacity.

(3) Subtract B from A and insert result in column C.

(4) The size of new equipment to install if storage is not used, is the highest value in C.

(5) Amount of useable storage required to avoid adding new equipment is the total of C.

(6) Insert the higher of A or equipment capacity into column D.

(7) Subtract A from D and insert result in column E.

(8) Total of E is storage charging capacity. If total of Column E is smaller than total of Column C then not all required storage can be regenerated and some new equipment capacity will be required.

Determination of Thermal Storage Charging Capacity of Existing Equipment and Waste Streams

Worksheet 19-2
Page 2 of 2

Company: ______________________ Date: ______________________

Location: ______________________ By: ______________________

HOURS	PREDICTED LOAD PROFILE (kW) A	LOWER OF A OR CAPACITY (kW) B	OVERLOAD A-B (kW) C	HIGHER OF A OR CAPACITY (kW) D	EXCESS CAPACITY D-A (kW) E
12pm-1am					
1am-2am					
2am-3am					
3am-4am					
4am-5am					
5am-6am					
6am-7am					
7am-8am					
8am-9am					
9am-10am					
10am-11am					
11am-12am					
12am-1pm					
1pm-2pm					
2pm-3pm					
3pm-4pm					
4pm-5pm					
5pm-6pm					
6pm-7pm					
7pm-8pm					
8pm-9pm					
9pm-10pm					
10pm-11pm					
11pm-12am					
		TOTAL	______ kWh		______ kWh