Title
Thermal Energy Storage for Cooling of Commercial Buildings

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Publication Date
1988-07-01

LBL--25393

DE91 000179

THERMAL ENERGY STORAGE FOR COOLING OF COMMERCIAL BUILDINGS

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July 1988

Presented at the NATO Advanced Study Institute on Energy Storage Systems: Fundamentals & Applications, Izmir, Turkey, June 27-July 8, 1988.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Building Systems Division of the U.S. Department of Energy, and by the U.S. Agency for International Development, through the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

THERMAL ENERGY STORAGE
FOR COOLING OF COMMERCIAL BUILDINGS

ABSTRACT

The storage of "coolness" has been in use in limited applications for more than a half century. Recently, because of high electricity costs during utilities' peak power periods, thermal storage for cooling has become a prime target for load management strategies. Systems with cool storage shift all or part of the electricity requirement from peak to off-peak hours to take advantage of reduced demand charges and/or off-peak rates. Thermal storage technology applies equally to industrial, commercial, and residential sectors. In the industrial sector, because of the lack of economic incentives and the custom design required for each application, the penetration of this technology has been limited to a few industries. The penetration rate in the residential sector has been also very limited due to the absence of economic incentives, sizing problems, and the lack of compact packaged systems. To date, the most promising applications of these systems, therefore, appear to be for commercial cooling.

In this report, the current and potential use of thermal energy storage systems for cooling commercial buildings is investigated. In addition, a general overview of the technology is presented and the applicability and cost-effectiveness of this technology for developed and developing countries are discussed.

KEYWORDS: chilled water storage / commercial cooling / demand-limited storage / electric load management / full storage / ice storage / partial storage / phase change / thermal energy storage / utility incentives.

LBL-25393

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1. INTRODUCTION

Cool storage technology was first applied more than half a century ago. However, widespread use of the technology had been limited because of the increased efficiency and reliability of conventional cooling systems and the decreasing cost of producing electricity. Recently, as fossil fuel resources have become increasingly less available and more expensive, many energy conservation strategies have become more viable. (Although nuclear power plants are available for electricity production, their future, at this time, is uncertain due to higher risks involved during nuclear reactor accidents, as demonstrated by the most recent accident in Cheronobyl, USSR, 1986.) Even though energy conservation is highly publicized and studied, peak load energy conservation was not addressed until recently [1-3]. Peak demand is important because utilities are faced either with investing in new generation capacity or purchasing electricity from neighboring utilities—or even from neighboring countries—to accommodate expected increases in peak demand. Peak load energy is also more expensive to generate owing to the use of less efficient generators which use more expensive fuels (e.g., oil or gas).

Most conservation strategies are not necessarily designed to make their most significant impact during peak load times. In fact, various conservation strategies may have a positive, neutral, or even negative impact on peak load [4]. To promote load management strategies which reduce utility demand peaks but increase off-peak electricity sales, utilities have recently begun to (1) offer incentives to customers who are willing to shift their loads on the utility system from peak to off-peak periods, and (2) design and impose different rate structures so that higher electricity rates are applied to the on-peak hours. Because of the offered incentives and varying rate structures, cool storage technology has re-emerged as the most advanced and cost-effective load management measure for space cooling [5].

Systems with cool storage shift all or part of the electricity requirement from on-peak to off-peak hours and take advantage of reduced demand charges and/or off-peak rates. Cool storage technology has been used in industrial refrigeration processes and in space cooling for both residential and commercial buildings. The most promising applications of these systems, however, appear to be in the cooling of commercial buildings. With the application of the technology, electricity is used when it is least expensive to charge a storage tank. The storage is then used to cool the building during the time when electricity is most expensive. Thermal storage can reduce peak electrical demand without sacrificing the comfort of building occupants.

This paper investigates the current and potential use of thermal energy storage systems for cooling commercial buildings. In addition, a general overview of the technology is presented and the applicability and cost-effectiveness of this technology for both developed and developing countries are discussed.

2. AN OVERVIEW OF COOL STORAGE TECHNOLOGY

Cool storage systems are often classified according to the storage medium used, i.e., water, ice, and phase change systems. Of these systems, water and ice systems are the most commonly used. Although phase change systems are available, their use has been limited because of the technical problems encountered due to uneven melting. Cool storage systems can also be characterized based on the mode of operation which determines the required storage size to accommodate building peak demand, i.e, partial, demand-limited, and full storage systems. In general, the two types of classifications are inseparable and used together—for example, ice-based full storage, water-based partial storage, etc.

A simple schematic circuit diagram for a thermal storage system with water is given in Ref. [6] and reproduced in Figure 1. The chiller produces cold water during the charging period (lower portion of the loop) and stores it in a storage tank. During discharging periods, the cold water from the storage tank is used to cool the building (upper portion of the loop). With partial storage systems, both loops operate in parallel; during peak hours both the chiller and the storage contribute to cooling the building.

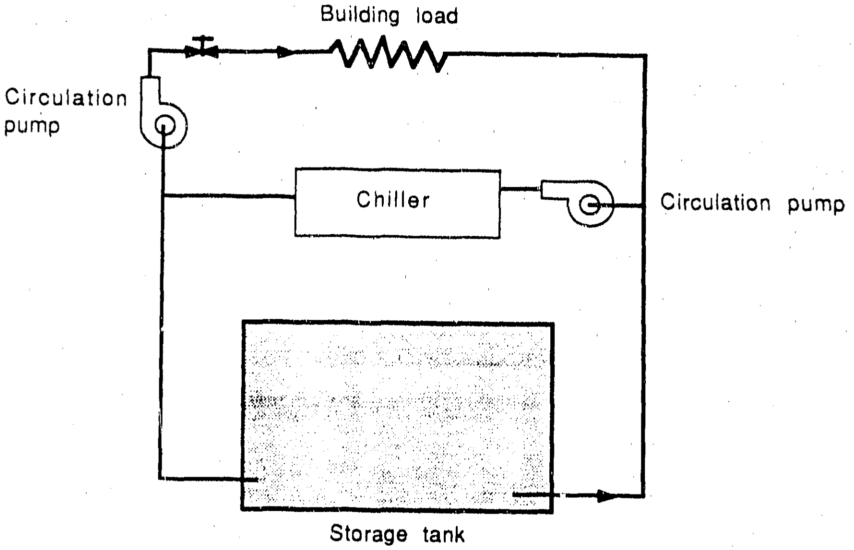

Figure 1. Schematic of Building Circuit for Thermal Energy Storage

In the following sections, factors affecting the design of thermal cool storage systems, such as storage media, operational strategy, and equipment sizing will be discussed.

2.1. Cool Storage Media

A cool storage system requires a medium to hold cooling energy for later use. Energy can be stored either as sensible (e.g., chilled water) or latent heat (e.g., ice or other phase change materials). One of the important requirements of the storage media is a high thermal capacity so that a large storage volume is not needed. Water meets that requirement and it is also easily available and inexpensive. It is therefore commonly used for cool storage in commercial buildings in the form of either chilled water or ice. Other storage media such as phase change materials and clathrates (mixtures of water and refrigerant) are also being developed.

2.1.1. Chilled Water Storage Systems. Chilled water systems are sensible heat storage systems which use the thermal capacitance of water. In general, conventional chilled water cooling systems produce chilled water at about 6°C· the water is then circulated to cool the building. With the addition of cool storage capability, chilled water is stored at night in a container and circulated during daytime through the cooling coil to accommodate the required comfort level for the building occupants. Because of its similarity to conventional air-conditioning systems, chilled water storage systems have several advantages over the ice and phase change systems [7-9]:

(1) the possibility of using conventional chillers, piping, and air-handling equipment with broad selection and competitive pricing,

(2) the likelihood of using existing chillers in retrofit applications,

(3) the familiarity of engineers in designing systems based on a supply water temperature used in conventional cooling systems,

(4) higher operating efficiencies are realized because storage occurs during nighttime when lower ambient temperatures improve the performance of heat rejection equipment,

(5) the reduction in first costs when larger (< 2000 m^3) storage tanks are used, and

(6) the reduction in the amount and complexity of training for operating and maintenance personnel owing to the use of conventional equipment and controls.

Chilled water systems are not free of disadvantages, mostly because of the requirement of large storage volumes relative to the other systems. These include [7-9]:

(1) the space required to locate large storage tanks,

(2) the higher thermal losses to the surrounding environment owing to large surface areas,

(3) the requirement of expert construction to avoid cracks and leaks in the storage tank (chilled storage tanks are generally built at the job site; therefore, the stringent standards met in factory-built tanks cannot be applied),

(4) the higher cost of maintenance and water treatment,

(5) the difficulty in adjusting chilled water storage to variations in cooling system sizing because of non-standardized and non-modular tank constructions, and

(6) the technical difficulties encountered in avoiding mixing of chilled water from the chiller and warmer return water.

A variety of techniques have been used to prevent the mixing of chilled and warmer return water. For example, one of the techniques is to use temperature stratification membranes (or baffles) to separate chilled and return water. In practice, adding membranes have not sufficiently stopped mixing of hot and cold streams; hence, the efficiency of storage systems has not improved. Recently, Wilden and Truman [10] showed that, under normal operating conditions, the performance of storage tanks without baffles can be equal to or greater than the ones with baffles. Another alternative is to use two separate tanks for warm and chilled water [11]. This method would double the cost and space required for storage.

2.1.2. Ice Storage Systems. Water is also used as a phase change storage media to take advantage of a higher storage capacity due to heat from fusion removed during the charging cycle which results in conversion of water to ice. Systems with ice storage are generally classified as either static or dynamic systems, as shown in Figures 2 and 3, respectively. In static ice systems, ice is formed on the evaporator surface and remains there until it is melted by the building cooling load. In dynamic systems, ice is formed in one place (i.e, the evaporator) but stored elsewhere (i.e., storage bins or containers).

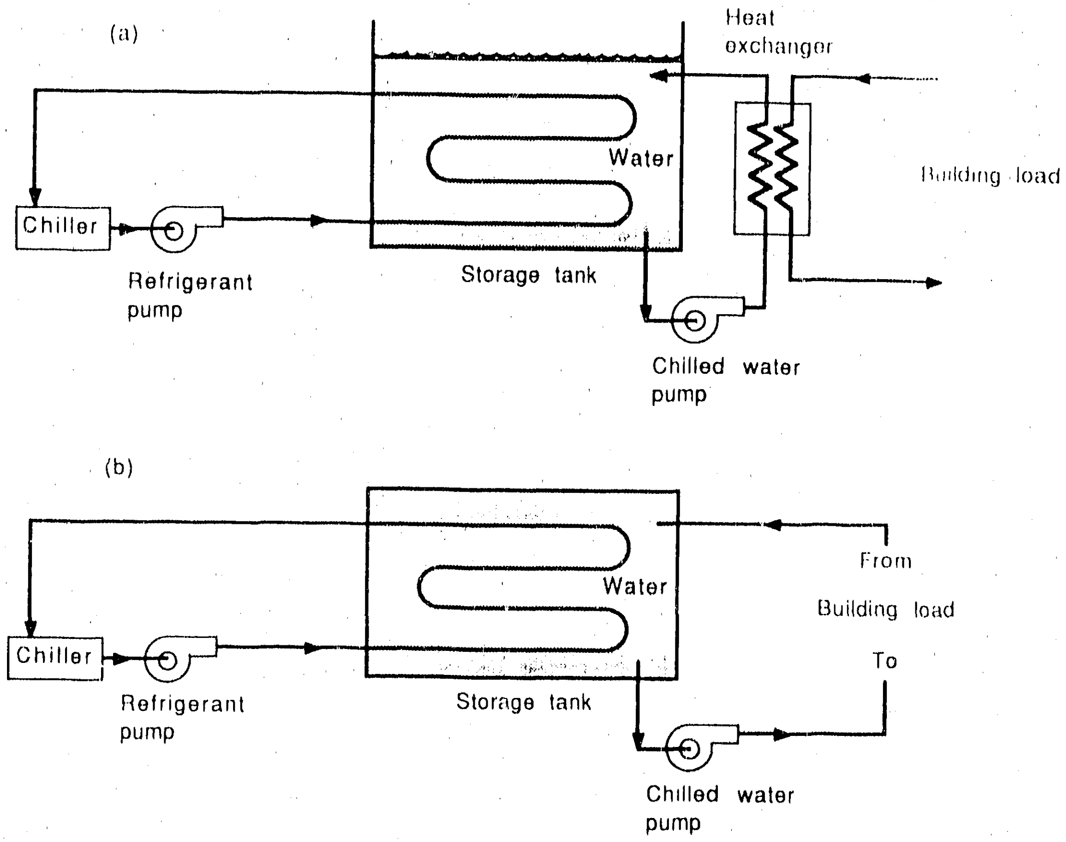

Figure 2. Static Ice Storage Systems: a) open system; b) closed system

Static Ice Systems: Static ice systems are usually known as "ice builders" because of the formation of ice on the outer surfaces of evaporator tubes. These systems may be built as either open or closed as shown in Figures 2(a) and (b), respectively [12]. In open systems, a heat exchanger usually provides a separation between the water surrounding the ice and water circulated through the building, so that contamination of water in the building circuit is eliminated. Since the top of the storage tank is open, the water coming from the tank can be contaminated by the dust particles in the environment. Open storage tanks can be installed on the rooftop to save space. In closed systems, the storage tank is covered and is therefore suitable for direct burial so that no additional space in the building is required. In a closed system, the cooling demand is satisfied by circulating the water (surrounding the iced coils) directly through the building circuit.

Static systems are also classified according to the type of coolant used (e.g., refrigerant or antifreeze mixture of water and glycol). Direct expansion systems (or DX systems) use refrigerant directly as the coolant while "brine" type systems use an antifreeze fluid. In other words, the ice-holding coils are the evaporators for the refrigeration equipment in a DX ice builder and, in brine ice builders, an antifreeze fluid is cooled by a packaged chiller to a subfreezing temperature [7].

In general, static ice systems are available in sizes ranging from 48 to 1200 ton-hours and all packaged units can be connected to an existing or new building's chilled water system [13].

Dynamic Ice Systems: In these systems, ice is formed on the evaporator surface and, once a certain ice thickness is achieved, it is removed and stored in a storage container (cf. Figure 3) [12]. Ice can be removed from the evaporator either by mechanical means or by injecting hot gas into the evaporator plates. Most dynamic systems require that the ice-producing unit be located over the storage container.

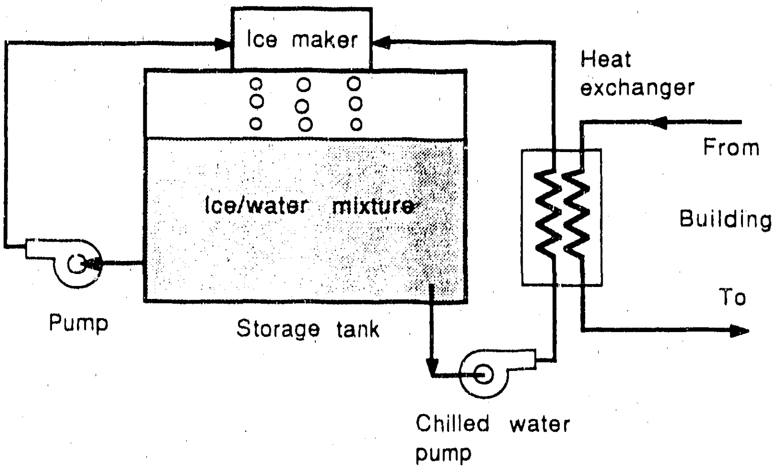

Figure 3. Dynamic Ice Storage System

Ice systems have several advantages over chilled water systems as a direct consequence of the compactness of storage volume used [7,8]:

1. larger cooling capacity for a given storage volume,
2. less space requirement, making it attractive for retrofit applications as well as in new construction,
3. less thermal losses to the surrounding environment owing to smaller surface area,
4. fewer design restrictions, for example, elimination of stratification requirement within the storage tank,
5. greater reliability due to the availability of packaged systems which usually carry manufacturers' warranty,
6. accurate estimation of the storage cost during the design phase of the project (due to availability of packaged systems),
7. lower cost of maintenance and water treatment (because of packaged design and less circulating water),
8. lower storage temperature, reducing the cost of pumping and air distribution (consequently, downsizing pipes, ducts, pumps, etc.), and
9. modularity of storage tank, permitting the use of factory-built tanks.

Some of the disadvantages of ice systems are [7,8]:

1. limited selection and less competitive pricing because of lower chiller suction temperature,
2. reduction in the efficiency of the refrigeration cycle due to the lower suction temperature,
3. use of unconventional equipment resulting in increase in the amount of training for operating and maintenance personnel, and
4. existence of some control problems, especially with static systems, owing to the measurement of ice level.

Available in packaged design, ice storage systems have opened the market to small and medium-sized buildings. Lower initial cost appears to be the reason for this trend.

2.1.3. Phase Change Storage Systems. As an alternative to ice, other phase change materials have been developed to store "coolness" by using heat of fusion during phase change. Salt hydrates—a mixture of water and salt—are frequently used. The mixture is also known as "eutectic salt" and usually freezes in the range of 8-16°C. The major disadvantage is that most of the eutectic salts melt incongruently or semi-congruently so that, during melting, the heavier solid particles settle out. During freezing, the previously settled salt does not recombine with the saturated solution to form the original compound; therefore, the latent heat of the bulk material is reduced [11].

Another alternative is clathrates (or gas hydrates). Clathrates are compounds formed by trapping molecules of gas in a lattice structure of water molecules. This is accomplished by bringing the gas and water into close contact under a proper pressure and temperature [14]. Among the commonly used gases that form clathrates with water are refrigerants R-11 (Trichlorofluoromethane, CCl_3F), R-12 (Dichlorodifluoromethane,

CCl_2F_2) and R-22 (Chlorodifluoromethane, $CHClF_2$)[15]. The resulting compound usually increases the phase change freezing temperature of the water mixture from 5 to 13°C.

Phase change materials are either encapsulated in the heat transfer fluid passing outside of capsules to freeze or thaw the solution, or placed inside bulk storage tanks with heat exchanger tubes distributed throughout the compound. The major disadvantage is that most hydrates are highly corrosive; therefore, special care must be taken in the selection of container material [11].

2.2. Operational Strategy

Most of the storage installations use one of the three basic operational strategies—full, partial, or demand-limited storage. These three strategies are shown in Figure 4, along with a conventional cooling system (see Figure 4(a)) which operates during the occupied hours of the building to satisfy the occupants' comfort level [9].

2.2.1. Full Storage. Full storage minimizes the cost of cooling a building by shifting the use of energy from on-peak to off-peak hours (cf. Figure 4(b)). In full storage systems, the size of the chiller and storage tank are dependent on the time-of-use (TOU) rate schedule of the building. With TOU rate, the primary cooling equipment does not operate during on-peak hours; all of the cooling requirement for the building is supplied from storage. Full storage, therefore, requires larger storage volume than the other operational strategies.

The major advantages and disadvantages of full storage can be summarized as follows:

Advantages

(1) maximum reduction in utility bill,

(2) use of simple and inexpensive controls, and

(3) well suited for use with existing refrigeration system.

Disadvantages

(1) requirement of largest storage volume and cooling equipment capacity,

(2) highest initial cost of equipment and storage, and

(3) largest space requirement.

Using a full storage strategy, the peak cooling electric demand could be reduced by 80 to 90 percent compared with a conventional cooling system [9]. The reduction in peak load is shown as displaced load in Figure 4(b).

2.2.2. Partial Storage. In partial storage, the chiller is downsized compared to a conventional cooling system and runs at a steady rate over 24 hours. Figure 4(c) illustrates a design load profile for a partial storage system. Compared with a conventional system (cf. Figure 4(a)), the use of a partial storage strategy can significantly reduce building peak load. In partial storage, the storage requirement is smaller than for the full and demand-limited strategies because of the continuous operation of the chiller. Although the system operates continuously, the storage does not meet peak demand, but supplements the full output of the chiller. Partial storage systems have the following advantages over the others [7]:

(1) minimal required storage and cooling equipment capacity,

(2) minimum space requirement for cooling equipment,

(3) minimum first cost (comparable with the cost of conventional system; downsizing the chiller will pay for the storage cost), and

(4) use of simple and inexpensive controls which reduces training time for maintenance and operating personnel.

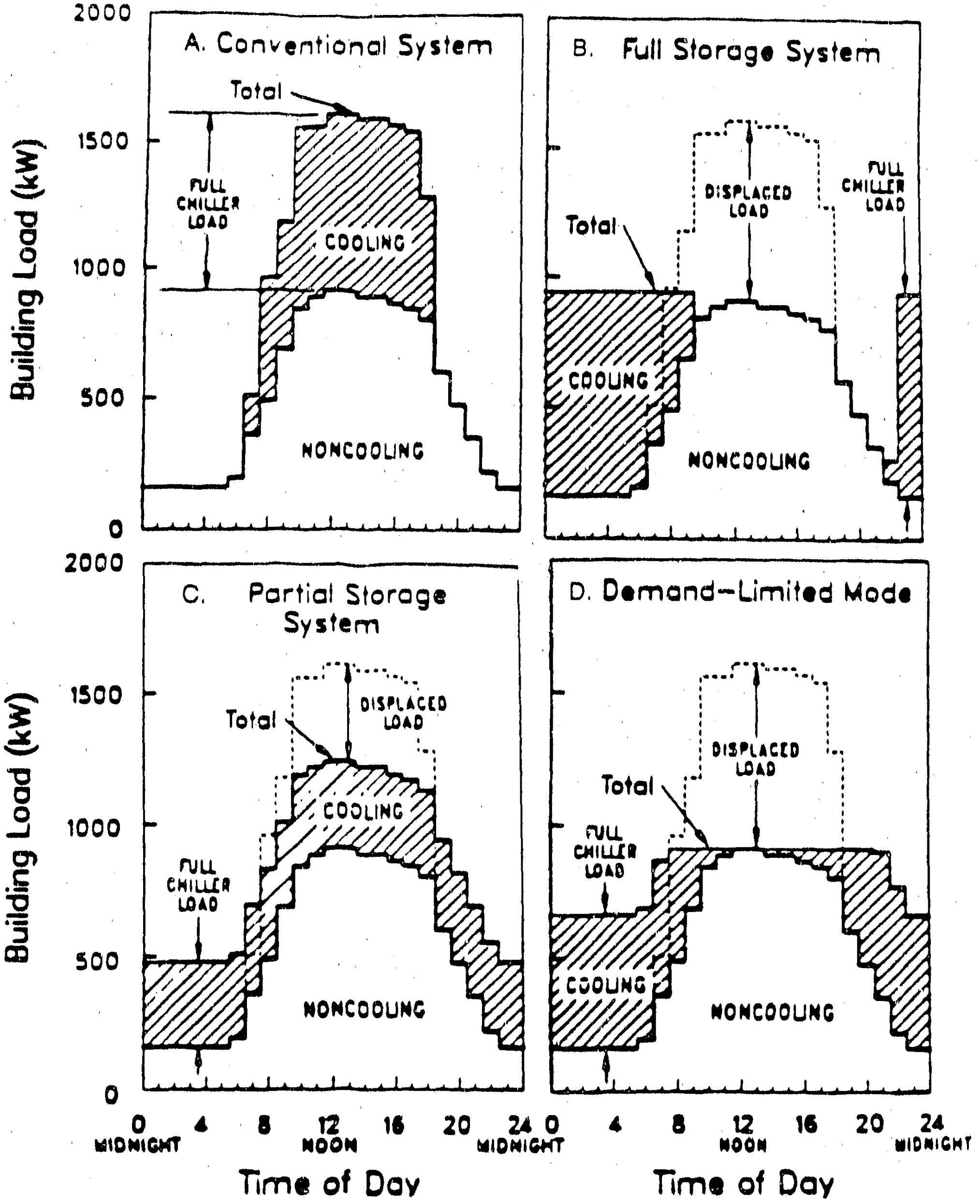

Figure 4. Design Day Hourly Load Profile for a Building with a Conventional Cooling System Compared with Three Cool Storage Strategies.

The major disadvantage of this strategy is that it does not reduce the customers' utility bills to the maximum possible extent. Partial storage saves about 40 to 60 percent of peak cooling electric demand [9].

2.2.3. Demand-Limited Storage. A demand-limited storage system is a variation on partial storage; the chiller runs 24 hours except during hours of maximum non-cooling demand as shown in Figure 4(d). This strategy, therefore, requires complicated control systems since the peak demand must be met through the storage. A demand-limited strategy is most applicable to buildings with significant demand charges and short occupancy periods that allow greater storage-charging time [9]. The advantages of demand-limited storage are:

(1) reduction in peak demand,
(2) less chiller and storage capacity than the full storage system, and
(3) less prone to allow accidental peak demand because of the use of sophisticated controls which monitor building demand directly.

2.3. Cooling System Sizing

Cooling system size is determined by the maximum cooling demand of the building and the operational strategy adopted for the storage, if there is a storage. Conventional cooling systems are designed to satisfy the maximum cooling load of the year based on estimates of the maximum building peak cooling demand. With the inclusion of a storage capability, the cooling system can be downsized (maximally for partial storage) because part of the cooling load is satisfied directly by the chiller and the remaining part from the storage. Therefore, for systems with storage, the sum of the chiller and storage outputs must equal the total daily cooling load of the building. In partial storage, the chiller runs 24 hours, so the cooling load is met over a full day. Hence, the chiller size is reduced to the minimum. With full or demand-limited systems, however, the cooling system size depends on the TOU schedule. For example, in full storage mode, the storage capacity must be large enough to completely meet the daily cooling load of the building. Since the charging of the storage is done during off-peak hours, the chiller capacity must be selected to fully charge the storage so the daily total cooling load is met.

2.3.1. Chiller Sizing. A conventional chilled water system produces chilled water to meet the building load and operates at or around design temperatures for condenser and evaporator during cooling of the building. Therefore, averaged capacity of a conventional chiller is essentially the rated capacity. Systems with storage perform two different operations: 1) provide direct cooling to the building, and 2) to the storage. For chilled water storage system, the chiller operates at the rated capacity during both direct cooling and charging. For the ice storage system, during direct cooling, the chiller operates at the rated capacity; however, during charging, the capacity drops to about 70% of the rated capacity [16]. The reduction in capacity is attributable to the evaporator temperature which is usually lower than the design temperature of a nominal chiller. Since the system size depends on the mode of operation (full, partial or demand-limited storage), the operation strategy for the building must be decided in advance of the system sizing. However, to optimize the system size, different design strategies are usually tried.

Based on the operating mode, the chiller capacity is calculated by dividing the total daily building cooling load by the average capacity in the case of partial or demand-limited strategies, and by the capacity-averaged number of non-peak hours for the full storage strategy [8,9,13]. For example, the averaged chiller capacity, CC, for partial storage is calculated as follows [8]:

$$CC=(t_{dc} + f\ t_{cs})/24$$

where t_{dc} is the total number of hours used for direct cooling, t_{cs} is the total number of hours spent to charge the storage, and f is equal to 1 and 0.7 for chilled water and ice storage, respectively. As the chiller averaged-capacity is known, the chiller size, C (in tons), is obtained from:

$$C = BL/(24CC)$$

where BL is the total building cooling load given in ton-hours.

2.3.2. Storage Sizing. Storage size depends on both chiller output and number of charging hours available for storage. In partial and full storage strategies, the storage size is given by the product of chiller capacity, number of hours used for storage, and the chiller rating while charging the storage. However, in the demand-limited case, part of the cooling load is met directly by the chiller while simultaneously charging the storage. Therefore, storage size is given as the sum of the load met by the storage when the chiller is not operating and the summation of the difference between building load and the chiller output for all other hours [8,9]. Note that systems with storage are sized to meet the maximum daily integrated cooling load, whereas conventional systems are sized to meet the annual peak cooling load [13].

3. MARKET TRENDS

Cooling is the largest contributor to the summer electric peak demand for the commercial sector. Recent studies [17] indicate that cooling for the commercial sector accounts for 20 to 40 percent of summer peak demand for most of the utilities in the United States. Commercial sector electricity consumption is, therefore, a significant portion of the total electricity use in both developed and developing countries. However, the percentage of electricity consumption in the commercial sector in developing countries is increasing much faster than in the developed countries. For example, the commercial sector electricity use in the United States in 1983 was growing approximately 2.2 percent per year [18]; however, during 1980-1984, the growth of electricity consumption within the commercial sector in Singapore, Malaysia, Indonesia, Philippines, and Thailand averaged at 4.3, 10.5, 3.0, 4.3 and 5.9 percent, respectively [19]. This can be attributed to the higher expansion rate of their economies.

3.1. The Potential of Cool Storage

3.1.1. Developed Countries (the United States). The market projection studies for cool storage performed for the Electric Power Research Institute (EPRI) indicate that cool storage can reduce the commercial sector summer peak by 17 GW (10%) by the year 2000 [20]. The estimate was obtained by segmenting the market by new and existing buildings, and by building size, and evaluating the potential for cool storage in each market segment. This estimate could be significantly affected by the recent development and marketing efforts of rooftop packaged units for cool storage. Based on the sales data for 1985, 625,000 unitary packaged cool storage and 11,780 chillers were sold [21]. By assuming 5 tons per unitary package and 100 tons per chiller, it can be easily shown that package units represented about 73 percent of the commercial cooling market in 1985.

The number of cool storage systems is growing rapidly in states where utilities offer direct incentives to install cool storage for building owners . Recently, Florida Power and Light Company initiated a study in which the market penetration of cool storage technology in both commercial and industrial sectors was estimated for the service area of the utility company [22]. The project was conducted in two phases: (1) exploratory assessment of cool storage market characteristics, identification of the major factors affecting cool storage market penetration, and design of a field survey to characterize and quantify the market potential, and (2) analysis of the survey data to quantify the market potential and the incremental market penetration resulting from utility programs and incentives. To estimate the impact of thermal energy storage, building prototypes were developed from a sample of 300 customers. The sample was drawn from the fourteen building types shown in Table 1.

Table 1: Sample size and megawatts (MW) deferred by cooling storage by building stratum in year 2001 for rebate incentives program of Florida Power and Light Company [22].

Building Type	Sample Size	Megawatts Deferred New MW	Existing MW	Total MW	Percent %
Large Office Bldg	40	53.1	27.9	81.0	42.1
Shopping Center	15	0.5	0.0	0.5	0.3
Large Retail Store	30	23.0	7.0	29.9	15.6
School	22	11.0	17.2	28.2	14.6
Higher Education	20	2.4	0.0	2.4	1.2
Hospital	20	12.2	0.0	12.2	6.3
Hotel	30	6.8	0.0	6.8	3.5
Restaurant	14	0.6	0.0	0.6	0.3
Civic Center	22	1.6	0.0	1.6	0.8
Movie Theater	14	0.0	0.0	0.0	0.0
Church	17	1.5	0.0	1.5	0.8
Food Industry	18	0.0	0.0	0.0	0.0
Apparel, Furn. & Printing	18	1.3	0.0	1.3	0.7
Assembly Industry	20	22.0	4.6	26.6	13.8
Total	300			192.5	100.0

A detailed hourly simulation of the loads was performed for each prototypical customer along with a detailed analysis of the potential application of cool storage technologies. Using the results of the cool storage analysis, the load profile with and without cool storage was analyzed by applying the existing rate structures to determine the potential savings to the customer from the installation of cool storage. In the final analysis step, the results of savings to the customer were used to identify potential market penetration of cool storage for each customer segment. Comparison studies of the economics between the three types of storage strategies indicate that partial storage systems have shorter payback times than the other two storage strategies; full storage has the longest payback. The total megawatt deferred due to cool storage for alternative programs offered by Florida Power and Light Company were also estimated by using the market penetration model. Figure 5 summarizes the total forecasted megawatt deferred in the year 2001 for six alternative programs: (1) nothing—base penetration with no programs, (2) information program, (3) performance guarantees—the utility guarantees the system performance so that owners are willing to invest, (4) low interest loans—loans are offered at 2 percent lower than the market interest rate, (5) guaranteed payback—the utility provides a rebate so that any system with a payback of less than 7 years would be guaranteed a payback of only 3 years, and (6) rebates—a rebate of $100 for each kilowatt deferred. Figure 5 clearly shows that the rebate program has the strongest effect on the penetration of the cool storage market. The breakdown of this rebate incentive program by building type is shown in Table 1. As seen from the table, large office buildings account for over 40 percent of the deferred capacity in the year 2001. This study clearly indicates that, for a strong penetration of the cool storage technology in the developed countries, incentives and rebates should be offered by utilities.

Since 1981, Texas electric utility companies have encouraged the installation of thermal storage systems in commercial buildings by offering a monetary incentive to qualified commercial customers and by applying special rate structures based on a TOU rate. (The on-peak period of this TOU is from noon to 8 p.m.) The Texas experience is a clear indication of the importance of the utilities' participation in accelerating penetration of this technology. In Dallas, for example, thermal cool storage installation in newly-constructed commercial buildings in that city increased in 1982 and 1983 by 21 and 30%, respectively. By 1984, 38% of the new office buildings used thermal storages [23]. Thus, the rapid increase in two years (81% increase in 1984) clearly indicates that there is a growing interest in thermal cool storage among customers in commercial sectors where there is active participation by utilities.

3.1.2. Developing Countries. A detailed preliminary study of the applicability and potential of cool storage technology in the Association of South-East Asian Nations (ASEAN), which includes Indonesia, Malaysia, the Philippines, Singapore, and Thailand, was carried out by Wyatt and de la Moriniere [8]. In this study, the emphasis was on in-depth analyses of key parameters relevant to the feasibility of the cool storage technology; these parameters are utility load curves, load factors, rates, capital and operational costs, dependence on imported oil, lead time between planning and building of new capacity to accommodate the peak demand, and losses during transmission and distribution of the electricity. Since thermal storage is a load management strategy, the most important parameter investigated was the shape of the utility load curves. For potential use of thermal cool storage, a utility load curve must show a well-defined peak which coincides with the cooling load profile in commercial buildings, which then become possible candidates for thermal storage.

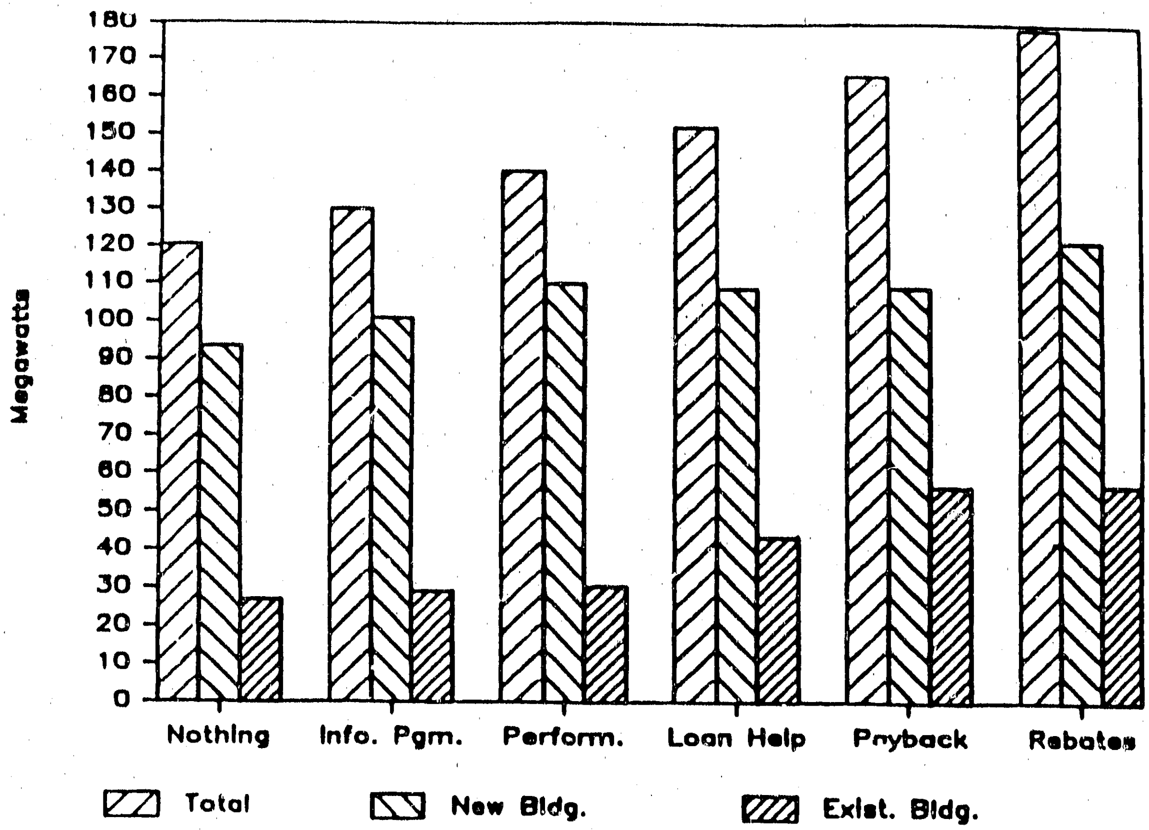

Figure 5. The Effect of Utility Incentive Programs on Summer Peak Megawatt Saving for Florida Power and Light Company in Year 2001. **Nothing**: base penetration; **Info. Pgm**: an information program that increases the market size by 4%; **Perform**: performance guaranteed by utility; **Load Help**: low interest loan at 2% below the market; **Payback**: guaranteed 3 years payback; **Rebates**: a $100/kW deferred rebate.

For the initial assessment of the potential for storage, the utility load profiles for the ASEAN countries were plotted to see whether they fall within the required pattern. It was found that a peak existed from late morning to late afternoon, with a "plateau" during this period, for Malaysia (see Figure 6b). The demand curve for the Philippines showed a late morning and evening peak as shown in Figure 6c. In Thailand, the demand increased during the day and reached the peak value in the early evening (see Figure 6d). The utility load curve for Indonesia, however, is found to be different from the other ASEAN nations; the utility faces an evening peak resulting from use of electricity in residences (see Figure 6a). The commercial and industrial sectors are very small, and, therefore, they do not contribute significantly to the demand.

The ASEAN countries have the same business hours in the commercial sector as in the United States (8 a.m. to 5 p.m.). The utilities peak demand period in Malaysia, the

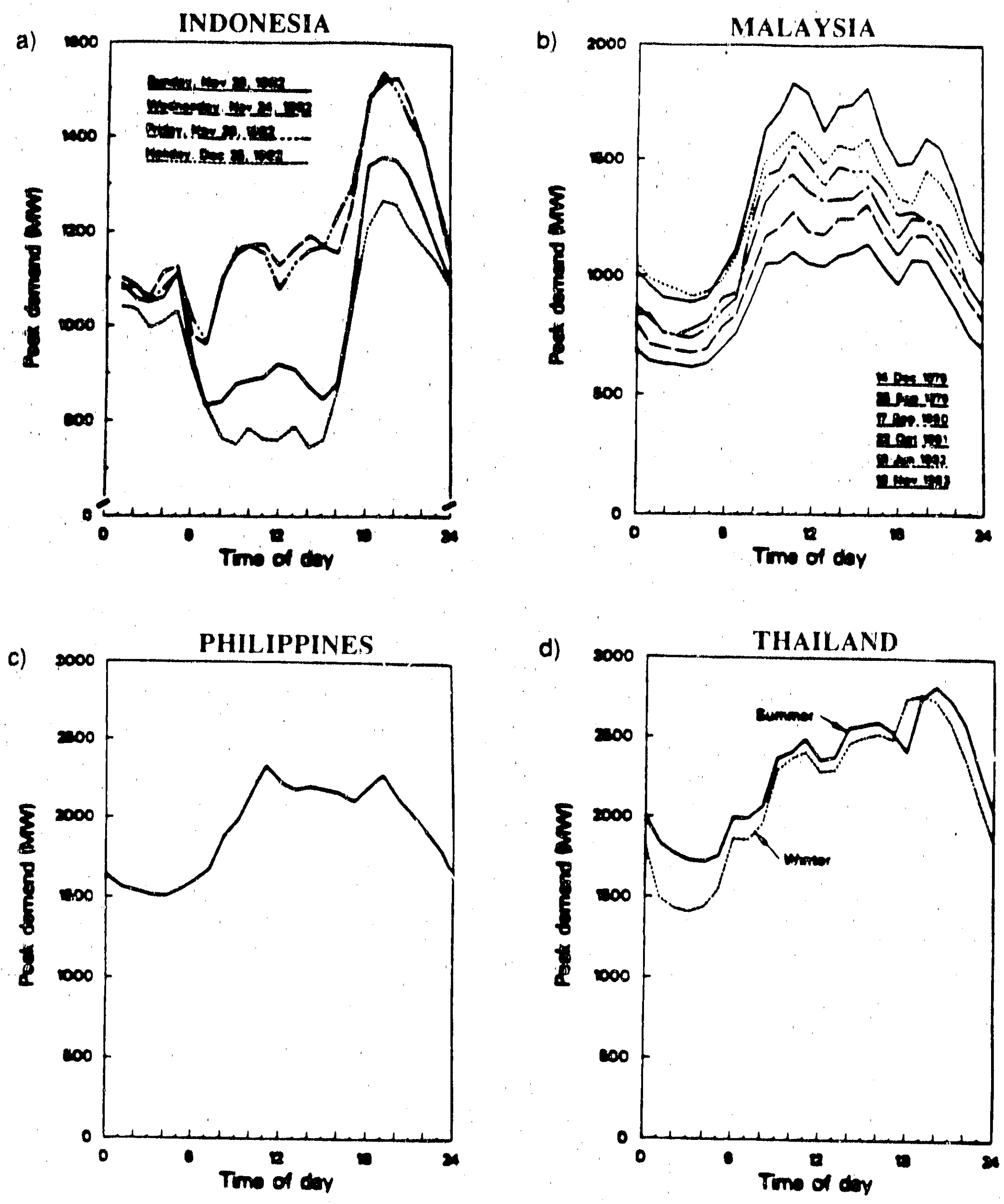

Figure 6. Typical Electricity Daily Load Profiles for ASEAN Countries. (a) Indonesia, (b) Malaysia, (c) Philippines, and (d) Thailand.

Philippines, (and Singapore, not shown in Figure 6) occurs during these business hours, suggesting that thermal cool storage may be feasible in these countries. On the other hand, in Thailand and Indonesia, the commercial cooling load does not contribute significantly to the peak demand; therefore, cool storage may not be as appropriate as in the other ASEAN countries at this time.

3.2. Applications for Commercial Cool Storage Systems

Thermal storage is most economical in buildings where cooling demands significantly contribute to high demand charges or where there is a significant differential between day and night or TOU energy rates. Office buildings are ideal for cool storage installations because they have short occupancy periods and, therefore, narrow cooling loads. Another application for cool storage systems occurs in an existing facility undergoing an expansion which requires additional capacity to the central chilled water system [24]. Instead of adding new chillers, the extra nighttime capacity of existing chillers can be used to charge a storage tank to serve the new floorspace.

One of the most interesting new uses of cool storage is in aircraft cabin cooling [25]. The Delta Airline cabin cooling project at O'Hare International Airport is the first known application of storage cooling to aircraft docked at airport gates. The system used is a full-storage ice system of 1000 ton-hours capacity. Delta Airlines plans to equip all major gates in its system with some form of fixed ground air-conditioning system. For example, in Dallas/Fort Worth International Airport, a partial ice storage system will be installed with continuously operating chillers in series with an ice bank of approximately 600 ton-hours capacity. In the United States, conventional ground cooling operation costs the airline industry over $100 million per year in fuel cost alone. Therefore, it is expected that the other airlines will soon follow Delta Airlines in installing storage system for cabin cooling.

4. ECONOMICS OF THERMAL ENERGY STORAGE

Many factors affect the decision leading to installation of cooling storage for a building. One, and perhaps the most important one, is the electricity cost consisting of demand charges ($/kW) and the differential between the cost of electricity at peak hours and off-peak hours ($/kWh). Under constant rates (no demand charge and no TOU rates), all hours are essentially on-peak. Thermal energy storage strategy helps the utility to shift its peak to off-peak. However, the customer does not benefit by shifting the peak demand to off-peak under constant rate structure.*

The savings in the cost of electricity could result from either decreasing the demand charges ($/kW) or lowering the electricity cost ($/kWh) by shifting the operation of chillers from peak to off-peak hours or both. Many utilities offer rate schedules which include both demand and varying kWh charges. It is this rate schedule that makes thermal energy storage attractive (or not attractive) to the customer. Changes in the demand charges and TOU electricity rate would change the economic attractiveness of thermal energy storage. As an example, the electricity rate schedules in two neighboring utilities (San Diego Gas and Electric Company, SDG&E, and Los Angeles Department of Water and Power, LADWP) are such that the annual savings due to thermal energy storage is twice as attractive in SDG&E's service area than in LADWP's (cf. Figure 10).

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* In developing countries, where the supply of electricity has not grown at the same rate as growth in demand, there are usually several hours of brown-out for part of the grid during peak hours. The lack of electricity during the peak hours in the commercial sector affects the comfort condition and hence productivity of the occupants. Therefore, installation of thermal energy storage would have the additional benefit of providing comfort under such conditions.

The other parameters affecting the decision include existing equipment and operation of the building (base case), storage strategy, the cost and economics of the system compared to the base case (including rate of return, net present value, annual dollar savings, etc.), and the operational and control sophistication of the thermal energy storage.

Recently, Rosenfeld and de la Moriniere [5] studied the cost-effectiveness of commercial cool storage and developed a generalized framework for comparing partial and demand-limited thermal energy storage strategies. Three economic indicators—simple payback time (SPT), net present value (NPV), and cost of avoided peak power (CAPP)—were selected for comparative study.

To analyze the economics of thermal storage, a simplified cooling load, as shown in Figure 7, has been assumed to represent a typical base case commercial building load profile. In the base case, a chiller with capacity L operates during occupied hours. However, for the partial storage, a chiller with a reduced capacity of C (= 0.375L) operates continuously. In the case of demand-limited storage (in this example, the same as full storage), a chiller with the capacity of 0.53L operates at all hours except during building peak hours (11 a.m. to 6 p.m. as shown in the figure).

The storage and chiller costs have been obtained from available sources. The costs for various storage and chiller sizes are shown in Figures 8 and 9, respectively. On average, the chiller cost is about $340 per ton with storage costs from $40 to $100 per ton. To calculate the annual dollar savings, an on-peak period of 6.5 hours and a cooling season of 6 months are assumed for the commercial building studied.

Based on these assumptions, the annual savings of shifting one kW from on-peak to off-peak are calculated and presented in Figure 10. Figure 10 shows the lines of constant annual savings on a graph of demand charges versus electricity differential charge between on-peak and off-peak periods. Electricity rate schedules for several utilities in the United States and some developing countries are also shown in Figure 10. For the developing countries, because of the lack of data, we have conservatively assumed that there is no differential rate structure, but demand charges are assumed. Therefore, the annual savings for these countries indicate the minimum saving potential of thermal energy storage.

The simple payback time is calculated using the annual savings and cost of storage and chiller and is summarized in Figure 11. As is seen, partial storage is far more economically attractive than demand-limited storage. For example, in Southern California Edison's (SCE) service area ($50/kW savings per year), the payback periods for partial and demand-limited storages at a cost of $50/ton-hour are estimated from Figure 11 to be approximately 2 and 5 years, respectively.

In some cases, partial storage could be even more attractive than the conventional systems; the savings due to downsizing the chiller pays for the cost of storage. As we will review in the following section, even though this may be the case with engineering calculations, the actual savings in some cases have been much lower than estimated ones. Among many reasons for this discrepancy, one could mention errors in the sizing of the system, failure in the operation, and inexperienced operators. Figure 12 shows the actual cost of 12 thermal energy storage installation in the United States; half of these installations are clustered around an incremental first cost of zero.

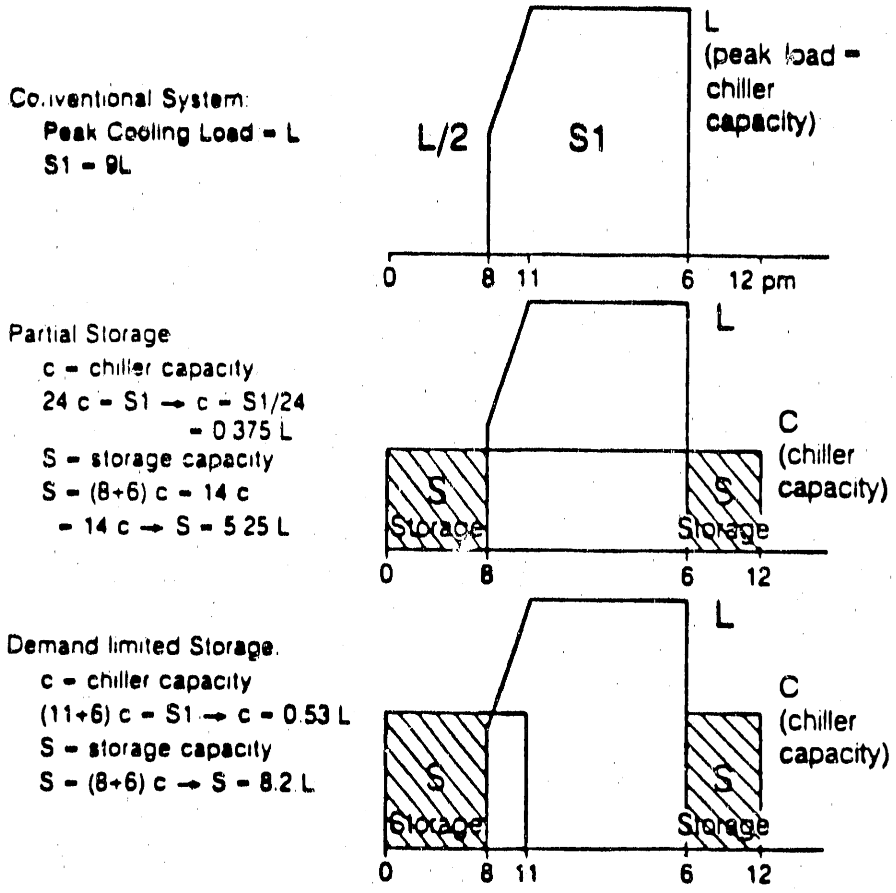

Figure 7. Calculation of the Capacities of Chiller and Storage According to the Load Profile. S1 is the daily cooling load, C the chiller capacity, and S the storage capacity.

5. EXPERIENCE WITH THERMAL COOL STORAGE SYSTEMS

Cool storage systems in commercial buildings are beneficial to both electric utilities and their customers. The penetration of cool storage systems has been slowed because of the lack of field performance data to compare with design expectations.

Field performance studies have been recently initiated by the Electric Power Research Institute (EPRI) [26] for (1) the assessment of the performance and operating experience of cool storage systems, (2) the identification of design problems, determination of possible corrective measures, and estimation of expected performance improvements, and (3) the determination of feasibility and cost-effectiveness of retrofitting to achieve performance improvements. For these purposes, five systems that were instrumented and monitored for at least one year by utilities in California, Illinois, Pennsylvania, and Rhode Island were evaluated. Four of the buildings had direct-expansion refrigeration ice storage systems operating in full storage mode and ranging in size from 150 to 2,000 ton-hours, and one had a 60,000 gallon chilled water system operated in partial storage mode.

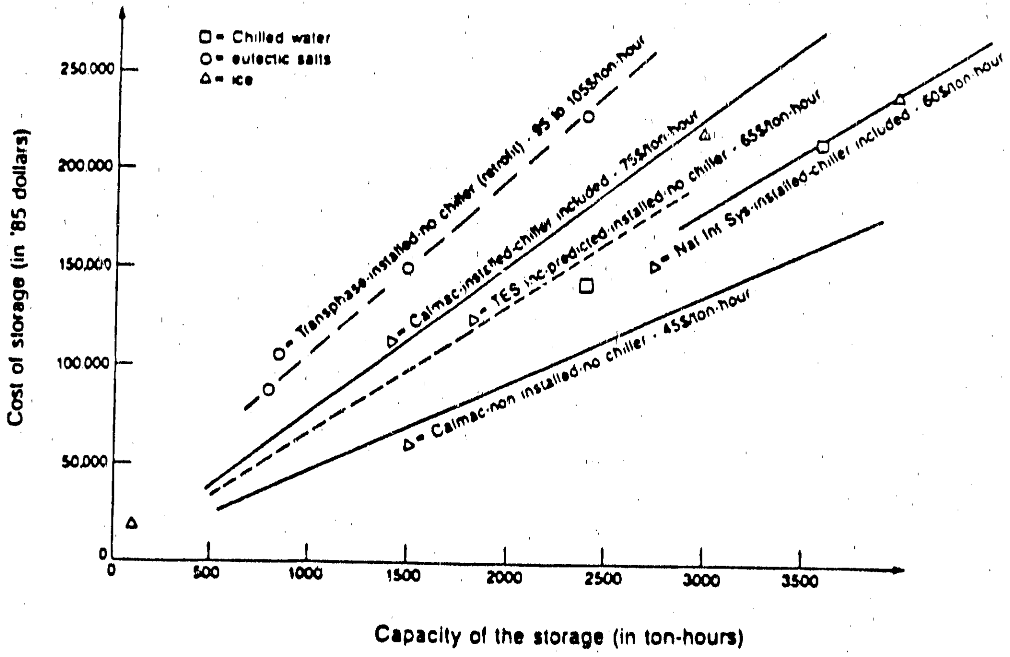

Figure 8. Installed Cost of Storage. Quoted by manufacturers (lines) and engineers who have installed cool storage (dots). Note that some data include the chiller, some not, some include installation, some not. [Source: Ref.5.]

The available field data were used to establish system performance as measured by the amount of reduction in on-peak demand and the ratio of electrical input to the delivered cooling effect in kW/ton. In addition, wherever possible, the corresponding measures were calculated for a conventional HVAC system.

In this study, Ayres, *et. al* [26] found that all of the systems suffered from technical and operational problems and classified them into four different categories:

(1) Information Availability: Lack of complete drawings, construction records, and HVAC design calculations.

(2) System Design: It was found that the systems designed by HVAC designers with little or no experience in field-erected refrigeration plants resulted in improper refrigerant line sizing, insufficient water flow through the unit to provide proper ice melting, etc.

(3) Equipment Maintenance and Operation: Most of the systems suffered from mechanical time clock failures, improper expansion valve and ice thickness control settings, and improper water treatment. In addition, all installations suffered from inadequate operator training.

(4) Monitoring System: It was also found that the monitoring sensors were improperly selected, located, maintained, and/or calibrated.

In spite of the above-mentioned problems, all of the systems were able to shift electric demands from on-peak to off- and mid-peak periods. However, they were

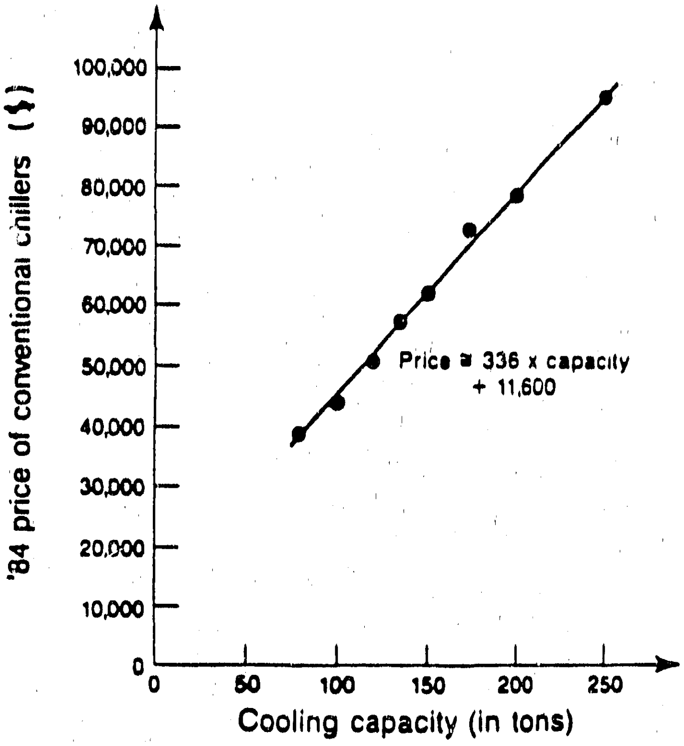

Figure 9. Installed Average Cost of Conventional Chillers (in 1984 $). Data include profit. [Source: "Means Construction Cost Data 1980" with 25% inflation from 1980 to 1984.]

occasionally activated during on-peak periods due to mechanical failures and operator errors. For ice systems, it was found that 10 to 20% of the total chilled water plant energy was consumed during on-peak periods; the energy consumed during mid- and off-peak periods ranged from 80 to 90%. The performance of the ice systems was in the range of 1.7 to 2.2 kW/ton. (The performance of comparable conventional HVAC systems ranged from 1.15 to 1.57 kW/ton.) On the other hand, the performance of the chilled water system which operated in partial storage mode was found to vary between 1.15 to 1.78 kW/ton within the five-month testing period. The energy consumption of the chilled water system during on-peak periods was found to be 47% of the chilled water plant energy. This higher energy consumption during on-peak hours may be attributable to the size of the storage tank, which was designed to provide 30% of the summer design day peak cooling load due to the owner's economic decision to locate the tank in the available space below the garage floor. Therefore, the remaining load (70% of the total cooling load) had to be met by the chiller during on-peak hours.

Similar performance studies were also carried out by the Commonwealth Edison Company in Illinois [27]. Several ice storage system installation were separately evaluated by the utility at various sub-component levels. A comparison was also made between a storage system and a simulated conventional chiller in order to determine the benefits obtained by both the utility and the consumer. The energy consumption for the conventional system was determined by using hourly weather data for the given location and the chiller model. The installation evaluated was a combination of a full storage and demand-limited storage ice system located in Riverwoods, Illinois. Although the system

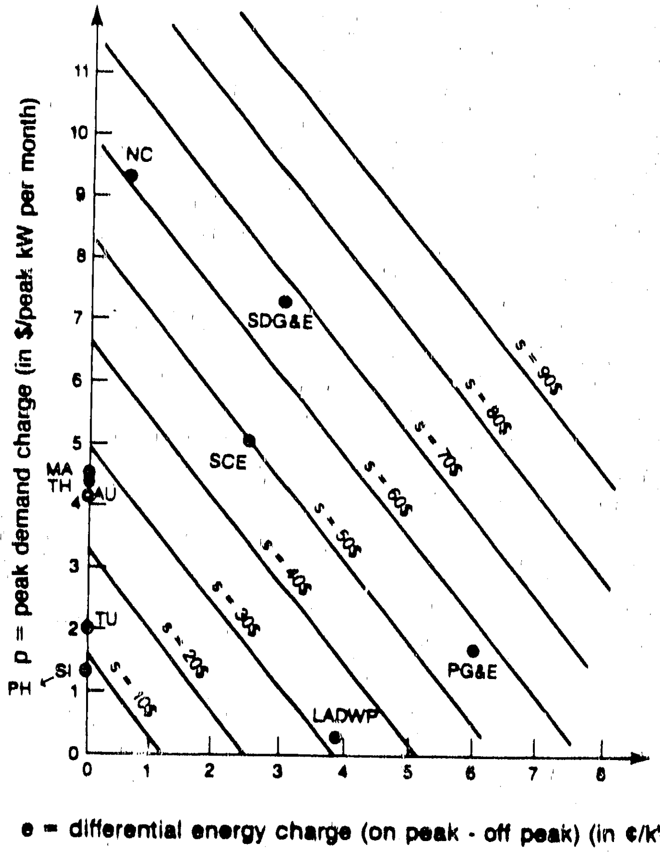

Figure 10. Annual Dollar Savings of Shifting 1 kW. Savings are estimated for shifting 1 kW for 6.5 hours from on-peak to off-peak for many utilities, characterized by their monthly demand charge "p" and their energy on-peak off-peak differential cost "e". **AU**: Austin Utility; **LADWP**: Los Angeles Department of Water and Power; **MA**: Malaysia; **NC**: North Carolina; **PG&E**: Pacific Gas and Electric; **PH**: Philippines; **SCE**: Southern California Edison; **SDG&E**: San Diego Gas and Electric; **SI**: Singapore; **TH**: Thailand; **TU**: Turkey [28].

has been in service since 1982, the study reported the system performance for the 1984 and 1985 cooling seasons only. The performance of the system was measured by analyzing the peak billing demands. The peak periods were defined as the hours between 9 a.m. and 10 p.m., Monday through Friday. Demand charges were applied only to demand registered during on-peak periods. All metering was done with a magnetic tape demand recorder at 15-minute intervals. The building was occupied between 9 a.m. and 4 p.m. The ice-making cycle was scheduled from 6 p.m. to 9 a.m. and the chilled water pumps were operated from 6 a.m. to 6 p.m.. At the end of the performance monitoring period, it was concluded that the ice storage system is an effective load management strategy from a utility standpoint. The load factor (the average to peak demand ratio) of the building was found to be significantly improved while eliminating approximately 170 kW of summer peak demand. In the first two years of operation, many on-peak demands were found to be created by an unreliable mechanical time clock. It was suggested that the operation of the system should be assigned to an

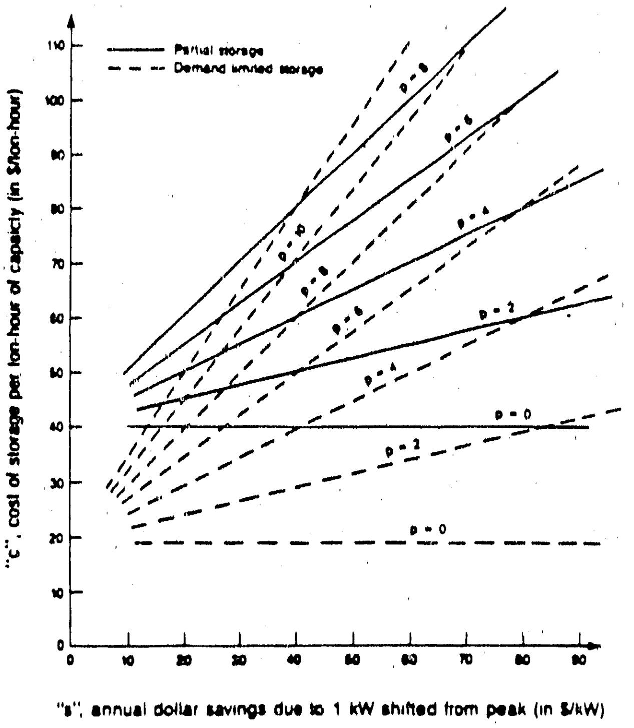

Figure 11. Payback Time. Estimated simple payback time for partial (solid lines) and demand-limited (dashed lines) strategies.

energy management system or an electronic time clock with battery back-up.

Texas Utilities Electric Company has also been actively involved in promoting thermal cool storage as a load management strategy. A recent survey indicates that there are twenty projects currently using or constructing thermal storage systems [23]. The survey also shows that, in contrast to experience in other states, most of the systems in Texas use chilled water as the storage medium. Four installations in Dallas area were studied in detail. One of the installations studied was the first major office building to use thermal storage for demand shifting. Its thermal storage system was designed in 1981 without any encouragement from the utility. The system was designed around four 375,000 gallon concrete tanks that use a flexible diaphragm to separate supply and return water. Two of the storage tanks are convertible to hot water storage during the heating season. The cooling/heating system serves a 50-story 1,500,000 ft^2 office building in downtown Dallas. During initial start-up of the system, several problems developed regarding the tank liners and the diaphragm movement within the tanks. The original rubber liners were replaced in 1983 with a spray-on/trowel-on waterproofing agent that subsequently stopped all water leaks. In 1984, the energy cost reduction of the building was estimated to be 17% due to the use of thermal storage. Half of the savings accrued from lower demand charges during the air-conditioning season; the remainder of the savings was kWh savings during the heating season.

6. CONCLUDING REMARKS

Thermal cool storage is increasingly being used in developed countries because of current utility rate structures and the additional incentives offered by utility companies to

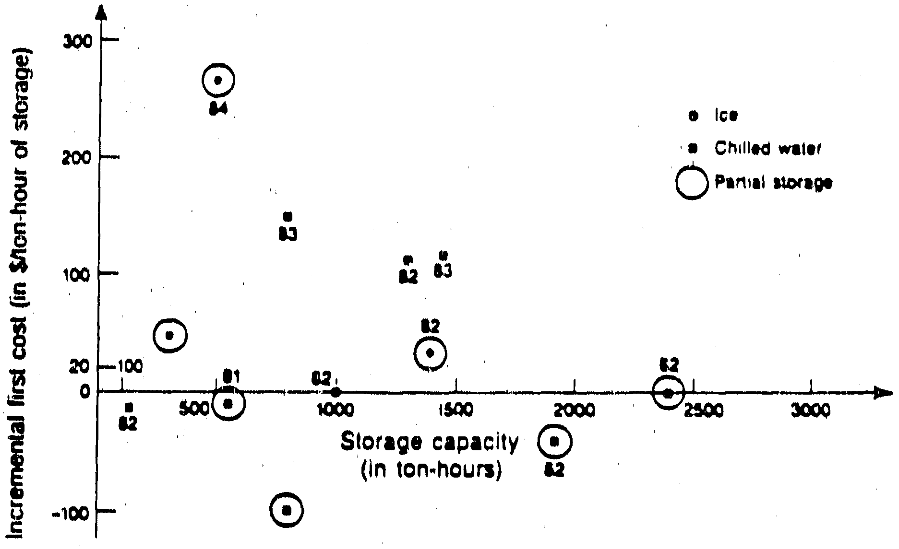

Figure 12. Incremental First Cost (Installing Storage Instead of a Conventional Chiller) from Case-Histories in Real Buildings. The costs are not representative of the average first costs faced by owners when installing a cool storage system, but they do show that compensating the first cost of the storage only by the savings from downsizing the chiller is already possible in the field. Note that more than half of the data points are clustered around zero initial differential cost.

accelerate the penetration of this technology. These incentives include (1) application of a different rate structure so that customers who do not use storage systems to shift the load to off-peak hours are penalized by higher demand and kWh charges, and/or (2) offering partial monetary refunds to the customer who installs a storage system. The number of cool storage installations in the United States has been doubling each year since 1985; about 100 installations in 1985, 200 in 1986, and an estimated 400 installations in 1987 [17]. The penetration of the technology has been higher in regions where a significant day- and night-time differential exists in the price of electricity. Most thermal storage installations are chilled water and ice storage systems. However, more installations are using eutectic storage with the recent decrease in the price of these systems.

Recently, an international thermal storage advisory committee (ITSAC) has been established to facilitate the exchange of information between users of this technology. The objectives of ITSAC are to (1) enhance the development of the technology, (2) provide a forum for technology evaluation, (3) serve as an information clearinghouse, (4) disseminate up-to-date information, and (5) encourage widespread application.

As discussed above, the incentives offered by the utility companies play an important role in accelerating the penetration rate. ITSAC has compiled incentives currently offered by the utility companies in the United States (see Appendix 1). These incentives ranges from $60 to $425 rebate per kW shifted to off-peak periods.

Even though utility companies offer *economic* incentives for the installation of the cool storage systems, there are still, however, some *practical* difficulties in the use of the technology. These difficulties include (1) errors in the sizing of the system which results in longer payback time, (2) failure in the operation of the system due to mechanical malfunctioning of equipment and control systems, and (3) inexperienced operators who could cause inefficient operation of the system; in theory, it would take only one operational failure per month to lose all the benefits of cool storage due to the increase in monthly demand. Therefore, it is vital for users of cool storage technology to exchange information regarding the difficulties and problems encountered in design and operation of the system.

The Building Energy Data Group at Lawrence Berkeley Laboratory has compiled cool storage performance data for actual installations. A list of commercial cool storage installations in the United States as well as in other developed and developing countries is provided in Appendix 2. Some of these cool storage installations have been analyzed and reported elsewhere [9]. Analysis of the performance of the actual installations has shown that many of the earlier difficulties have been resolved and cool storage is becoming more economical and operationally attractive as technology develops further.

ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy, and by the U.S. Agency for International Development, under DOE Contract No. DE-AC03-76SF00098.

We would also like to acknowledge the editorial support provided by Karen H. Olson of Lawrence Berkeley Laboratory.

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Appendix 1. Incentives Offered by U.S. Utilities

<table>
<tr><th>Utility</th><th colspan="5">Inducement Per KW of Load Shift</th><th>Maximum Per Project</th></tr>
<tr><td>Southern California Edison</td><td colspan="5">$200
F.S. = Match to 55,000</td><td>$300,000</td></tr>
<tr><td>San Diego Gas & Elec. Co.</td><td></td><td>RATE</td><td>0-200KW</td><td>201-1200 TON</td><td>1200KW</td><td>No Maximum</td></tr>
<tr><td></td><td>Retrofit</td><td>TOU</td><td>$250</td><td>$225</td><td>$200</td><td></td></tr>
<tr><td></td><td></td><td>Flat</td><td>$350</td><td>$325</td><td>N/A</td><td></td></tr>
<tr><td></td><td></td><td></td><td>0-200 TON</td><td>201-1200 TON</td><td>1200 TON</td><td></td></tr>
<tr><td></td><td>New Construction</td><td>Both</td><td>$350 per TON</td><td>$225 per TON</td><td>$200 per TON</td><td></td></tr>
<tr><td>TU Elec. Co.</td><td colspan="5">$350 - first 200 kW plus
$250 - next 300 kW plus
$200 - next 500 kW plus
$125 - all kW over 1000</td><td>No Maximum</td></tr>
<tr><td>Pacific Gas & Elec. Co.</td><td colspan="5">$200</td><td></td></tr>
<tr><td>Arizona Public Service Co.</td><td colspan="5">$250 - first kW plus
$115 - all kW over 500</td><td>No Maximum</td></tr>
<tr><td>City of Austin, TX Elec. Utility</td><td colspan="5">Variable - 3 year payback up to $300 per kW</td><td>No Maximum</td></tr>
<tr><td>City of Palo Alto, CA</td><td colspan="5">$350 New Construction
$425 Retrofit</td><td>$250,000</td></tr>
<tr><td>Public Service Elec. & Gas</td><td colspan="5">$250 - first 500 kW plus
$125 - all kW over 500</td><td>No Maximum</td></tr>
<tr><td>Salt River Project</td><td colspan="5">$250 - first 300 kW plus
$115 - next 200 kW</td><td>500 kW - $98,000</td></tr>
<tr><td>Boston Edison</td><td colspan="5">$200</td><td>No Maximum</td></tr>
<tr><td>Long Island Lighting Co.</td><td colspan="5">$300</td><td>$50,000</td></tr>
<tr><td>Los Angeles Dept. of Water & Power</td><td colspan="5">$250</td><td>40% of Cost or $150,000 per Building</td></tr>
<tr><td>Sacramento Municipal Utility District</td><td colspan="5">$250
F.S. = Limited Number</td><td>No Maximum</td></tr>
<tr><td>Oklahoma Gas & Elec. Co.</td><td colspan="5">$200</td><td>$50,000</td></tr>
<tr><td>El Paso Electric Co.</td><td colspan="5">$200
(or acceptable payback)</td><td>No Maximum</td></tr>
<tr><td>Wisconsin Elec. Power Co.</td><td colspan="5">$200 or 5yr No-Interest Loans up to $750 per kW
F.S. = Match to $5,000</td><td>No Maximum</td></tr>
<tr><td>Pennsylvania Electric Co.</td><td colspan="5">$250</td><td>No Maximum</td></tr>
<tr><td>New England Electric</td><td colspan="5">$160</td><td>No Maximum</td></tr>
<tr><td>Utilities Dept., City of Denton, TX</td><td colspan="5">$350 - first 200 kW
$250 - next 200-500 kW
$200 - over 500 kW</td><td>No Maximum</td></tr>
<tr><td>Consolidated Edison Co.</td><td colspan="5">$500
Not to exceed 50% installed cost (portion of central Manhattan only)</td><td>No Maximum</td></tr>
<tr><td>Jersey Central</td><td colspan="5">$250 - first 500 kW</td><td>$200,000</td></tr>
</table>

Power & Light Co.	$125 - over 500 kW	
Northern States Power	$175	No Maximum
Riverside Public Utilities	$200 F.S. = Match to $5,000	No Maximum
Anaheim Public Utilities	$60 F.S. = Up to $5,000	$50,000

Key: F.S. = Feasibility Study

Appendix 2.

BUILDINGS WITH COOL STORAGE SYSTEMS

The following 321 buildings have cold storage systems. Buildings listed with an asterisk (*) are reported to have some submetering or an energy management systems that may provide some cooling system data.

INFORMATION SOURCE CODES:

AN	- Argonne National Lab/EPRI Survey
AS	- ASHRAE Survey
CN	- BECA-CN
E	- List from Engineering Interface (March 1987)
EP	- EPRI Metering
I	- ITSAC (and month/ year)
JD	- Jacksonville Elec. Demo, maybe monitored
P	- Pacific Gas and Electric Metering
SD	- San Diego Gas & Elec. Monitoring
SM	- Sacramento Municipal Util. District Monitoring
TVA	- Tenn. Valley Authority Monitoring

STORAGE TYPE SOURCE CODE:

CW	- Chilled Water
C/HW	- Chilled and Hot Water
ES	- Eutectic System
IC	- Ice system
IC/HW	- Ice and Hot Water
u	- unknown

SUMMARY OF COOL STORAGE INSTALLATIONS

Medium Type	U.S.	International	Total
Chilled Water[1]	119	44	163
(w/heat storage[2])	(37)	(13)	(50)
Ice	130	7	137
(w/heat storage[2])	(8)		(8)
Eutectic Salts[3]	9	-	9
Other/Unknown	11	1	12
Total	269	52	321

1. 14 systems have or will be submetered
2. as a subset of chilled water and ice systems
3. 38 systems have or will be submetered

UNITED STATES BUILDINGS

TYPE	BUILDING	LOCATION	AREA (kft^2)	SIZE (klb|kgal)	SOURCE
		ALABAMA			
IC	*Alabama Power Co.	Birmingham	1200	1000	AS,AN,I
CW	Southern Co. Services	Birmingham	870		AN
IC	County school	Lower	112		AN
		ARIZONA			
IC	concrete company	Yuma			
IC	*Little Theatre	Phoenix	7		
IC	*Arizona Public Service Cntr	Phoenix			I
IC	*Central Library	Phoenix	25.6		I
IC	Fire Station #21	Phoenix	4.9		
IC	Fire Academy	Phoenix	12		
IC	Fire Support building	Phoenix	13		
IC	Maryvale Police Briefing Stn.	Phoenix	8		
IC	Pueblo Grande Museum	Phoenix	20.5		
IC	LEAP #3	Phoenix	4		
IC	Field Engineering	Phoenix	3.5		
IC	Giffen-Trane Service	Phoenix	10	13.5	AS
IC	Baptist Church	Phoenix			
CW	City Police Department	Phoenix	147		
CW	Police Academy	Phoenix	23.4		
CW	*Municipal Bldg, Police Co.	Phoenix	144		
CW	Plaza Municipal	Phoenix	34.4		
CW	City Art Museum	Phoenix	17.4		
CW	Adult Cntr	Phoenix	13.3		
CW	Century Library	Phoenix	6.5		
u	Abbott-Ross Labs	Casa Grande			
C/HW	IBM General Products Div.	Tucson	2400	5100	AS
C/HW	IBM Central Plant Bldg	Tucson	25	2700	AS
		CALIF. (CA)			
IC	100 Spear Street	San Francisco	220		AN
IC	*Sacramento Towers	San Francisco	265		AN,P
IC	*Pacific Bell	San Ramon	1800		AN,P
IC	*Bank of America	Livermore	18.8		P
u	*Graduate Theological Union	Berkeley			P
CW	*Hewlett-Packard	Sunnyvale		520	I(9/86)
IC	Gold Bldg (55 S. Mkt St)	San Jose			
CW?	Alza Co.	Palo Alto			
CW?	Ford Aerospace	Palo Alto			
CW?	Kodak	Palo Alto			
CW?	IBM	Palo Alto			
CW	Stanford Univ.	Palo Alto	central	4 000	
IC	*SRI International	Menlo Park	central		P
IC	Wells Fargo Mortgage	Santa Rosa	110		CN
IC	*Pacific Bell	Rohnert Park	80		P,AN
CW	*Pacific Bell	Chico	20		P,AN
CW	*Calif. Farm Bureau Federtn.	Sacramento	35		SM,CN
CW	Department of Justice Bldg.	Sacramento	410		CN
CW	State Bldg. Site 3	Sacramento	237	5	AN,AS
IC	State Site 3	Sacramento	225	50	AS

IC	Pac Bell Switching Office	Sonora	9		AN
IC	James Madison/Monroe Elementary	Madera			
C/HW	SCE San Joaquin Customer Serv.	Tulare	76		AS,AN
IC	mexican food factory	Tulare			I(7/86)
IC	supermarket	Porterville			I(7/86)
ES	Kings Co. Government Cntr	Hanford			I(7/86)
u	*Tenneco West	Bakersfield			EP
C/HW	U.S. Air Force	Edwards AFB			I(9/86)
IC	Jesse Ranch project	Apple Valley	2000		I(7/86)
ES	Hughes, SB Research Cntr	Santa Barbara			I(?)
CW	Thousand Oaks Library	Thousand Oaks	66		CN
IC	Whittaker Corp (Taker Systms Div)	Simi Valley			
CW	Manufacturers Life Insur.	Los Angeles	456	400	AN,CN
CW	Wells Fargo Bank	Los Angeles	1200	555	AN
u	Los Angeles World Trade Cntr	Los Angeles	420		
CW	*Prudential Airport Tower	El Segundo	960		CN
CW	Kilroy Airport Cntr	El Segundo	600		
IC	insurance company	Harbor City	32		AN
CW	1150 E 4th Street	Long Beach	50	36	AN
ES	St. Mary Med. Cntr	Long Beach			I(?)
ES	St. Bernardine Med. Cntr	San Bernardino			I(?)
u	Riverside City Hall	Riverside			
IC	Union Oil--Hartley Resrch. Cntr	Brea	420	1200	AN,AS
IC	*Cipher Data Products	Garden Grove	168	200	EP
IC	*Griffin Tower	Santa Ana	530		I(2/87),EP
ES	Hughes Aircraft	Fullerton		2000	
IC	Pacific Bell office	Tustin	240		I(7/86)
ES	Allergan Pharmaceuticals	Irvine			
ES	Leisure World/Rossmoor Towers	Laguna Hills	390		AN
ES	Orange Coast College Admin	Costa Mesa	10		AN
IC	office building & bank	El Toro			AN
u	unknown	Hemet			
IC	*Anderson's Rest. & Motel	Carlsbad			SD,AN
IC	Cathedral-of-the-Valley & School	Escondido	110		AN
IC	office park project	Escondido	18		AN
IC	Hotel Del Coronado	Coronado			I(5/87)
CW	TRW Rancho office	San Diego		500	E
IC	Park North Med Cntr	San Diego	19.9		
ES	Mercy Hospital	San Diego		200	E
IC	NCR Corporation	San Diego	85	84	AN
IC	*Four Winds Enterprises	San Diego	92		AN
IC	*IRT Corporation	San Diego	85		AN,SD(?)
IC	*Kearny Electric	San Diego	4		AN,SD
IC	*credit union	San Diego	13		AN,SD
IC	*SDGE Beach Cities Cntr	San Diego	6		SD
IC	SD State Univ Med. Cntr	San Diego			I(7/86),AN
IC	Bank of America Plaza	San Diego			
IC	Security Pacific Bank Plaza	San Diego			
IC	Central Savings Tower	San Diego			
IC	AMCC	San Diego		98	
IC	29-story Emerald-Shapery Cnt	San Diego			I(1/87)
u	Pomerado Hospital	Poway			
IC	Miles Laboratories	Covina		50	I(5/87)
IC	Cineplex-odeon theater	Universal City			I(5/87)

		COLORADO			
CW	Univ. of Colorado	Colorado Springs	53	60	AS
IC	Honeywell Manufacturing	Denver	270		AS
		CONN, (CT)			
CW	Union Carbide Co. HQ	Danbury	1320		AS
C/HW	*United Illuminating Co.	Shelton	55		AN,Demo
CW	Aetna Life Insur.			1600	E
CW	Sikorsky Aircraft (indus.)	Stratford		1200	
		DELAWARE			
IC	Nursing Home, Veterans Admin	Wilmington		1310	AS
		WASH. DC			
CW	Mobil Oil			500	E
C/HW	World Bank Bldg.		400	20	AS
C/HW	Urban Land Institute		260		
IC	Cath. Univ. of Amer., Phys. Lab		90	200	I(2/87)
		FLORIDA			
IC	Brevard County Housing Auth	Merritt Island	4.8		AN
IC	*Dallas Graham Library	Jacksonville	7.5		JD,AN
CW	*Northside Highlands Library	Jacksonvile	25		JD,AN
IC	*Florida Power & Light Marketing	Pompano Beach	8.4	150	JD,AN
IC	*Florida P & L District Office	Bradenton	24	25	JD,AN
CW	*Lakeland Dept of Elec & Water	Lakeland	25		JD,AN
CW?	Disneyworld EPCOT Cntr	Orlando		5000	
IC	Gulf Power Co. office	Panama City	30		AN
IC	Assembly of God Church	Pace City	32.1		AN
CW	Pioneer Federal Savings	Clearwater	25		AN
		GEORGIA			
IC	*real estate office	Fort Oglethorpe	2.5		AN,TVA
IC	*Georgia Power district office	Canton			
IC	*Georgia Power district office	Waycross			AS
CW	*Georgia Power HQ	Atlanta	761	300	AN,CN,AS
IC	*C & S Bank	Atlanta	6.4		AN
		IDAHO			
CW	EG&G, Willow Creek Bldg.	Idaho Falls	284	200	AS
		ILLINOIS			
IC	*State of Illinois Cntr	Chicago	1200	800	AN
C/HW	Social Security Bldg.	Chicago	750	160	AS
C/HW	General Services Admin.	Chicago	630	72	AS
IC	Merchandise Mart	Chicago	4500		I(7/86)
IC	Delta Airlines, O'Hare Int'l	Chicago		98-116	AN
IC	*CB&I Industries HQ	Oak Brook	100		AN,I(9/86)
IC	AT&T Bell Laboratory	Naperville	1500	400	AN
IC	*Federal Life Insur.	Riverwoods	68	160	AN
IC	*Commonwealth Edison HQ	Bolingbrook	17	40	AN,AS
IC	*Comm. Ed. Nuc. Training	Braidwood	60-95	80	AN
IC	*Comm. Ed. Des Plaines Valley HQ	Maywood	34	45	AN
IC/HW	Quill Corporation				
IC	Underwriter's Lab		581	40	
IC	A.C. Nielsen		350	200	
IC	Duplex Products		53.5	100	
IC	Helene Curtis		160	160	
IC	Technical Publishing		130	110	
IC	Victory Memorial Hospital	Waukegan	378	200	AN

IC	Epstein & Sons Publishing Co.	Barrington	135		AN
IC	*Micro-Switch Bldg.	Freeport	60-300	68	AN
IC	Rand McNally Bldg.	Skokie	277	200-240	AS,AN
u	Plaza Towers	Schaumberg	851		
C/HW	St. Charles High School	St. Charles	221	50	AS
C/HW	Wheaton College, Graham Cntr	Wheaton	185	44	AS,I(2/87)
IC	unknown	Rockford	800		I(2/87)
		INDIANA			
CW	McCormick Piano Co.	Fort Wayne			
		KENTUCKY			
CW	IBM Office Bldg.	Lexington	central		
CW	Human Resources	Frankfort	440	400	AS
CW	Toyota Auto Mfg plant			3500	I(7/86)
		LOUISIANA			
IC	Capital Bldg. & Loan	Baton Rouge			AS
		MARYLAND			
IC	Union Trust Company	Baltimore			
C/HW	Ist Federal Reserve Bank	Baltimore	230		CN,AN
C/HW	GSA Bldg., Metro West	Baltimore	1600	40	AS
IC	*Balt. Gas & Electric HQ	Baltimore	175	168	
IC	Martin Murietta	Baltimore		126	
IC	Gould Electronics	Baltimore	22		AN
CW	*PEPCO Service Cntr	Forestville	38	26	AN
IC	*PEPCO Service Cntr	Rockville			
IC	St. Ambrose Church	Cheverly			
		MASS. (MA)			
C/HW	MA State Transportn. Bldg	Boston			
IC	IBM & Arkwright Insur.450	700	I(5/87)		
C/HW	Brushhill System Office	West Springfield	73.4	8	AS
IC	Haemonetics Corporation	Braintree		84	AS
IC	Adams Russel	Amesbury		84	
		MICHIGAN			
CW	Univ of Michigan Med. Cntr	Ann Arbor			
CW	General Motors Corp. (indus.)	Detroit (Pontiac)		1500	I(9/86)
CW	Michigan State Univ.	Detroit		300-350	E
		MINN. (MN)			
C/HW	St. Paul Co. General Services	Woodbury	80	40	AS
CW	Donaldson Corporation	Bloomington	165	200	AS
C/HW	American Family Insur. #1	Eden Prairie	60	15	AS
C/HW	American Family Insur. #2	Eden Prairie	51	12	AS
C/HW	Equitable Life Insur. Bldg	Minnetonka	72	80	AS
CW	CDC Distribution Cntr	St. Paul			
		MISSOURI			
CW	Marion Laboratories	Kansas City			
		NEW JERSEY			
C/HW	*Electronics Associates	West Long Branch	320	150	AN
IC	Enerplex complex	Plainesboro	130		AN
C/HW	GPU office	Parsipanny	125	300	AN
C/HW	AT & T Branch Office	Basking Ridge	2500	60	AN
C/HW	Prudential Bldg	Iselin	248	24	AN
C/HW	Perkin-Elmer Corporation	Ocean Port	80	20	AN
		NEW MEXICO			
C/HW	Univ of New Mexico, ME bldg	Albuquerque	60	120	AS

CW	Univ of New Mexico	Albuquerque		16	
CW	Presbyterian Hospital	Albuquerque	396	360	AS
C/HW	Public Service of New Mexico	Albuquerque	278	300	AS
u	Copper Square	Albuquerque	AS		
		NEW YORK			
CW	Battery Park office	New York		3 500	
CW	HJ Kalikow, 101 Park Ave	New York	1000	300-350	AS
CW	42 story tower	New York		500	E
CW	Bloomington Store	New York		1000	E
CW	New York Univ.	New York		4000	E
CW	office building	White Plains	170		I(8/66)
C/HW	C.H. Stewart HQ	Newark	250	60	AS
C/HW	City Hall	Rochester	140	20	AS
C/HW	R. F. Communications	Rochester	130	30	AS
C/HW	School #19	Rochester	103	20	
C/HW	WHEC TV (Ch 10) Bldg	Rochester	30	10	
IC	Albany County Civic Cnt	Albany			I(2/87)
		NORTH CAR.			
CW	Sun Valley Middle School	Monroe	54.4		
IC/HW	Beaufort Middle School	Beaufort	52		
IC	Nash Central School	Nashville			AS
CW	IBM regional office	Charlotte		500	
CW	Douglas Municipal Airport	Charlotte		60	E
CW	Liberty Life HQ	Charlotte		80	E
CW	University of NC	Raleigh		400	E
		OHIO			
IC	Akron Baptist Temple	Akron	40	100	AS
IC	Ohio Edison Bldg.	Ravenna	2.6	0.2	AS
CW	Youngstown General Hospital	Youngstown		240	I(7/86)
CW	Youngstown State Univ.	Youngstown		800	E
		OKLAHOMA			
CW	Halliburton Services Lab	Duncan	280	500	AN
		OREGON			
CW	Tektronix, Inc.	Portland		1000	E
		PENN.			
IC/HW	Metropolitan Edison	Hamburg	6	15	AS
IC/HW	Millville Mutual Insur.	Millville	10		AS,AN
IC/HW	Girton Manufacturing	Millville			AS
IC	PA Power & Light Info Cntr	Limmerick	10?		
		RHODE IS.	?		
IC	*Gilbane building	Providence	90	60	AS
		SOUTH CAR.			
CW	Mack Truck Inc. (indus.)		800		
		TENN.			
C/HW	Soddy High School	Soddy-Daisy	140		AN
IC	West End Furniture	Knoxville	4		AN
IC	*Merita Bread Store	Knoxville	3		AN
CW	Karns high school	Knoxville		150	E
CW	Oliver Springs elementary school	Knoxville		100	E
IC	*film lab	Chattanooga			AN
IC	*Madison County Health Clinic	Jackson	24		AN
		TEXAS			
CW	The Crescent	Dallas	1500		AN

CW	Interfirst Plaza/Dallas Main	Dallas	200		AN
CW	Thanksgiving Tower	Dallas	1500		AN
CW	North Park IV East	Dallas	530	300	AN
CW	*Haggar Company	Dallas	73		AN
CW	Walnut Green Offices	Dallas	164		AN
CW	Lincoln Centre II & III	Dallas	1232	1000	AN
CW	Lincoln Centre IV	Dallas		800	E
IC	Southland Corporation	Dallas			
IC	Dallas Power & Light	Dallas			
CW	Opera House	Dallas		500	E
CW	Placid Elm office	Dallas	1000	500	E
CW	Prudential Realty	Dallas		600	E
IC	Sunbelt Corp. HQ	Dallas	550	600	I(2/87)
IC	Episcopal Church	Dallas	27		AN
CW	Veritas Insur. Co.	Dallas		300	
CW	Veritas HQ Office	Houston		200	E
CW	P.I.C. Realty	Irving	555		AN
IC	unknown	Fort Worth		84	
		VERMONT			
IC/HW	Brandon Coils	Brandon	8.3		AS
		VIRGINIA	.3		
C/HW	Virginia Electric Power Co.	East Richmond	18500		
IC	*Sixth St. Festival Marketplace	Richmond	150	365-420	I(2/87)
IC	*Best Products Bldg.	Richmond	230	170	I(2/87)
u	Health Affairs Blg	Richmont	60		I(2/87)
IC	*Christian Broadcasting Network	Virginia Beach	280	168	I(2/87)
IC	Christian Broadcasting Com. Cnt	Virginia Beach	250	150	I(2/87)
C/HW	Terra Centre	Burke	69		
C/HW	Terraset Elementary School	Reston	69		
C/HW	Mobil Oil Corporation	Fairfax	660	500	AS
u	County Public Schools	Chesterfield			I(2/87)
		WASH.			
CW	Farm Credit Banks Bldg.	Spokane	253		
		WISCONSIN			
IC/HW	Madison Technical College	Reedsburg	16.8		AS,AN
IC	Oshkosh Cntr	Oshkosh	66.6		
IC	WEPCO-Waukesha Cntr	Waukesha	10.8-35	25	AS
IC	Trane Company	La Crosse		119	
C/HW	Cedar Hills School	Oak Creek	39.6	10	AS
IC/HW	Gettys Manufacturing	Racine	33	112	AS
IC	Calamet Service Cntr	Milwaukee		3.1	AS
IC	WEPCO-Brown Deer Cntr	Milwaukee	35		AS

INTERNATIONAL BUILDINGS

TYPE	BUILDING	LOCATION	AREA (kft^2)	SIZE (klb|kgal)	SOURCE
		ALBERTA, CN			
C/HW	Alberta Government Telephone	Calgary	1200	900	AS
CW	Esso Plaza	Calgary	2000	800	AS
C/HW	Gulf Canada Square	Calgary	1300	1000	AS
		BRIT. COL., CN			
CW	*Robson Square/Court House	Vancouver	1187	870	AS
		NOVA SCOT., CN			
CW	Victoria Hospital	Halifax		400	E
		ONTARIO, CN			
C/HW	College Park complex	Toronto	600-861	500	AS
C/HW	*Hydro Place	Toronto	1325	1600	
CW	Bell Canada Trinity Square	Toronto	300	156-1000	E
C/HW	Public Works Canada	Toronto	600	300	AS
C/HW	Continental Bank	Toronto	1000	800	AS
C/HW	Globe & Mail Bldg.	Toronto		51	AS
CW	IBM HQ office	Toronto		945	
CW	Exchange Tower	Toronto		500	
CW	Freecool	Toronto		50	E
IC	Revenue Canada	Toronto		100	E
CW?	Metro Toronto Federal office	North York		300	E
C/HW	Toronto Federal Office Bldg	Willowdale	675	300	AS
CW	Bell Canada	Scarboro		160	AS
CW	Transport Training Institute	Cornwall		100	AS
CW	Ontario Hydro Thermal Training	Mississauga		60	AS
CW	Ministry of Government	Milton	60	30	AS
CW?	Ontario Ministry of Revenue	Oshawa		240	E
C/HW	Barrie Courthouse	Barrie	107.5	70	AS
C/HW	Court House/Registry	Newmarket	160	153	AS
C/HW	Ontario Provincial Bldg	Sudbury	207	180	AS
CW	Toyota Auto Mfg. Plant	Cambridge		1000	E
CW	Market Square	St. John?		350	E
		QUEBEC, CN			
C/HW	Canadian Printing Bureau	Hull	1033	440	AS
C/HW	Gentec Bldg.	Quebec City	15	15	AS
		SASK., CN			
CW	*Univ of Saskatchewan Eng.	Saskatoon	150	150-300	AS
		EUROPE			
CW	Royal Belge Theatre	Brussels, Belgium		350-500	I(7/86)
CW	Aquitaine HQ	Paris, France		300	AN
CW	Musee D'Orsay	Paris, France		300	I(7/86)
IC	La Residence	Geneeva, Switz.		133	
		SO. AFRICA			
CW	Menlyn Park Shopping Centre	Praetoria		600	AN
IC	Holiday Inn	Praetoria		105	
CW	Univ. of Natal	Durban		1000	E
CW	Westway Office	Durban		200	E
CW	Southern Life Office	Durban		350	E
CW	Small Business Devel. Corp.	Durban		350	E
CW	362 West Street	Durban		150	E
CW	Cowey Park	Durban		250	E

CW	Cowey Centre	Johannesbourg		150	E
CW	Kwazulu Admin. Bldg.	Johannesbourg		200	E
CW	Woolworth Co. HQ	Capetown		300	E
CW	Tyger Valley Shopping Centre	Capetown		300	E
CW	Sanlam	Bellville		300	E
		TAIWAN			
IC	Taiwan World Trade Cntr	Taipei	880	680	I(2/87)
u	Triangle Office Tower	Taiwan	600		I(2/87)
IC	Geological Science Office	Chu-Toong	26	32	I(2/87)
IC	Veteran General Hospital	Kaohsiung			I(2/87)
		BRAZIL			
IC	Citibank	Sao Paulo	505.7		

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