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TECHNOLOGY ASSESSMENT: THERMAL COOL STORAGE IN COMMERCIAL BUILDINGS

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THERMAL COOL STORAGE IN COMMERCIAL BUILDINGS

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TECHNOLOGY ASSESSMENT: THERMAL COOL STORAGE IN COMMERCIAL BUILDINGS

PREFACE

This report, one of a series of end-use energy technology assessment reports, investigates the current and potential use of thermal storage systems for cooling commercial buildings. The aim of these investigations is to synthesize current information from both published and unpublished sources so that utilities, state regulatory commissions, and others can better identify, evaluate, and select demand-side resources to meet their needs. The material covered in these reports is not limited to "success stories" but also includes failures, barriers, uncertainties, and information gaps. In addition, we attempt to identify and, if possible, reconcile variations or discrepancies among data sources. The technology assessment reports are designed to be easily updated in the future as the technologies develop and better data become available.

To highlight the importance of technology assessment and the need to study the impact of new technologies we quote Peter Drucker:

> "Technology monitoring is a serious, an important, indeed vital task. But it is not prophecy. The only thing possible, in respect to a new technology, is speculation with about one chance in a hundred of being right. And there is a much better chance of doing harm by encouraging the wrong new technology or discouraging the most beneficial one.
>
> What needs to be watched is "young technology," one that has already had a substantial impact, enough to be judged, to be measured, to be evaluated." (Teich, 1981)

1.0 SUMMARY AND KEY FINDINGS

Although the use of thermal storage for cooling commercial buildings has grown steadily in the past ten years, it still represents a small segment of the commercial sector. A cool storage system is any system that relies on stored cooling energy to meet some of the cooling load, rather than using a chiller or other air-conditioning equipment directly. Our major findings regarding commercial cool storage systems are as follows:

- Cool storage is not a new technology. Historically it has been used whenever cooling loads are large and intermittent, as in theaters and assembly buildings, and in food processing, especially by the dairy industry.
- Cool storage systems are most common in areas where electricity rates have a significant price differential between on- and off-peak energy or peak demand charges.
- There are an estimated 1000 cool storage systems operating in the United States; the majority are located in office buildings. These systems are most commonly used in new buildings, but are also applicable to existing buildings.
- Over two dozen manufacturers, four times as many manufacturers as in 1980, now produce equipment specifically designed for commercial cool storage. Several hundred systems are being added each year. It is estimated that about 200 new cool storage systems were installed in 1986, about double that of 1985; a similar doubling was anticipated for 1987.
- There is no ''best'' system. System choice is dictated by factors such as building type, load profile and climate, status of existing equipment, first costs (considering utility or tax incentives), and electricity rate structures.
- Costs for cool systems vary widely and any assessment of cost-effectiveness is highly sensitive to the definition of a base case. Estimated payback periods for partial-storage systems tend to be shorter than for full-storage systems. Costs for cool storage systems range from zero incremental first cost to over $1200/kW. Average costs are about $500/kW to $850/kW. Similarly, ice systems appear to have lower first costs than chilled water systems. The use of eutectic salts is growing.
- The Electric Power Research Institute (EPRI) estimates that thermal cool storage systems could avoid 17 GW of U.S. summer peak demand by the year 2000, or about 10 percent of the commercial sector cooling peak.
- Many utilities have incentive or technical assistance programs to encourage the use of cool storage by their commercial customers. Several of these programs, with incentives ranging from $100 to $550 per kW shifted, are summarized (Table 9). Many other utilities are considering such programs.
- Research and development is underway on more efficient refrigeration systems, ice building and storage techniques, and advanced phase change materials. Some performance monitoring of installed systems is also occurring, although there is little consistency in the data collection and analysis techniques from one monitoring project to another. Comparative long-term performance data are not available.

- About one-fourth to one-third of the total installed tonnage in the commercial sector in 1985 was in water chillers, the rest is in packaged cooling units. Packaged cool storage systems, which have a significant market potential, are becoming available. Most estimates of cool storage load-shifting potential have not included the use of cool storage with packaged units. EPRI's national estimate of a 17 GW shift by the year 2000 would increase with the inclusion of packaged cool storage systems.
- The most common strategy to encourage the implementation of cool storage is to design electricity rates with significant on-peak to off-peak price differentials. About 20 utilities offer customers direct payments for cool storage systems, while many more utilities are considering such programs. Another implementation strategy gaining momentum is that energy service companies are considering financing and managing cool storage projects.

2.0 TECHNOLOGY OVERVIEW

2.1 General Description

2.1.1 Background

With economic growth and development in the United States has come a parallel growth in energy use and electrification. As a result, some utilities faced a shortage of electric generating capacity until new plants could be constructed. Furthermore, the inflation in the late 1970s affected the cost of building new plants and many utilities began to explore new means of meeting electrical demand, including "demand-side" resources. Because utility rates were increasing, many building owners, to lower costs, became interested in energy efficiency and reducing or shifting their peak electric demand. One of the most promising load-management technologies examined was thermal energy storage.

Thermal storage can take on many different forms. Daily heat storage is often used in regions where utilities face winter peaks. Numerous buildings rely on seasonal cool and/or heat storage in underground aquifers or soil. Building mass has been used for heat storage and cool storage for centuries. Smaller residential buildings have used rock-bed storage, where air circulates through a rock bed for heating and cooling. In this report we focus on the fastest growing application of thermal storage for commercial buildings: "active" (non-building mass) cool storage.

Although cool storage is not a new technology, its widespread application in today's commercial buildings has required many new developments. Most important among them have been improvements in equipment and operating strategies for various load conditions to optimize costs under today's electricity rate schedules. About 40 years ago, many churches were fitted with ice storage plates because they were cheaper than large air conditioners (MacCracken, 1987). The technique has also been used in the food and dairy industries. In recent years, with the rise of strong daytime summer peaks related to the use of air conditioning devices, and resultant time-of-use (TOU) rate differentials and increasing use of demand charges, this technology is being used in many commercial buildings. Electricity demand for cooling commercial buildings currently represents 30% of the U.S. summer peak demand (MacCracken, 1987).

2.1.2 Operating Principles

Commercial cool storage is generally used as a load-management strategy to reduce on-peak electric demand (kW) by shifting the compressor's operation to off-peak hours when energy costs and demand charges are lower. Cooling energy is then stored in the evening, using a medium such as water or ice, to be used the next day during occupied hours, when energy rates and demand charges are higher. This strategy benefits building owners and managers who wish to lower their electricity costs, and electric utilities who generally want to increase load factors and delay the need for new peak generating capacity. Chillers for cool storage systems are downsized compared to conventional systems. Building owners benefit from the lower first-cost outlay for installing a smaller chiller, which pays for some or all of the costs of the storage. Costs can be further reduced with the use of low temperature air systems because fans, pumps, and other auxiliaries are downsized. Although low temperature air distribution may reduce first cost, they may also reduce economizer effectiveness. Another tradeoff is that low temperature air distribution can increase latent loads, thereby requiring larger storage capacity.

Most commercial cool storage systems use standard cooling equipment. The heart of the cooling system, the chiller, combines a compressor, condenser, and evaporator. Three general types of chillers are manufactured:

- reciprocating (small, less than 250 tons*, 1.25 kW/ton);
- screw or centrifugal, (medium sized, 100-750 tons, 0.85 to 0.90 kW/ton); and
- absorption, (100 tons and up)

Three fundamental choices, all important determinants of thermal storage system performance, must be made at the design stage. These are: the storage media, the operational strategy, and the equipment sizing. Each of these factors is discussed below.

2.1.3 Comparison of Ice and Chilled Water Systems

The most common cool storage media are water and ice, but a growing number of buildings are using phase change materials (PCMs). Selection of the type of storage depends on various site-specific factors (see Table 1) which are discussed below.

Chilled Water Systems. Chilled water storage has often been installed locally by companies not specializing in tank fabrication, although a few manufacturers are beginning to specialize in chilled water tank design. One advantages of chilled water storage systems is there is a better possibility of using existing chillers in retrofit applications because of higher allowable chiller operating temperatures, as compared with ice systems. Also, engineers and technicians are more familiar with chilled water systems as opposed to ice or PCM cool storage systems. Chilled water tanks are generally used for large installations (greater than 2000 ton-hours), mainly because of economies of scale. That is, first costs for water storage, unlike those for ice systems, gradually diminish with increasing storage size. Another advantage of water tanks is that they can store heat energy in winter and thus provide additional savings. Dual season heating and cooling energy storage systems can be economical under some TOU and seasonal rate schedules. Most of these systems are installed for the purposes of peak shaving as well as heat recovery.

*See the Appendix for the definition of a cooling ton and other cooling parameters.

Table 1
Ice vs. Chilled Water Storage
(assuming identical cooling loads)

FACTOR	ICE	CHILLED WATER
DESIGN		
Space Requirements	1/4-1/3 of Chilled Water	Large
Compressor Size Availability	Limited [1]	Various
Designer and Operating Experience [2]	Limited	Widely Available
Size Flexibility	Good, Modular	Limited
Design Constraints [3]	Few	Many
Air Distribution First Costs	Low	Moderate
Packaged System Availability	Good	Limited
Interfacing with Existing Systems	Complicated	Simple
Heating Capability	Poor	Good
First Cost for Large Systems [4]	High	Low
OPERATION		
Power Requirements	0.85-1.5 kW/ton	0.75-1.25 kW/ton
Chilled Water Operating Temps	32-60^{0}F	45-60^{0}F
Chilled Water Pumping Power	Low	High
Storage Control	Difficult to Measure Ice	Simple
Heat Loss	Low	Moderate
MAINTENANCE		
Maintenance [5]	Moderate	High
Warranty Availability	Good	Limited

Sources: Tamblyn, 1986 and EPRI, 1982.

Notes:

1. Many ice storage systems require direct expansion units, which generally require reciprocating or screw compressors. These are not available in very large sizes. Chilled water storage systems often use centrifugal compressors.
2. Ice storage systems often require large direct expansion or flooded coil refrigeration systems which are unfamiliar to building designers and operators.
3. Ice storage systems are indifferent to the water temperature range and designers can use preferred hardware unsuitable for wider range. Chilled water storage systems require wider temperature ranges that require controls that may be unfamiliar to many designers.

4. Ice storage systems often have lower first costs for smaller systems (less than 2000 ton-hours). Water storage systems become more competitive in larger sizes.
5. Maintenance requirements are site- and installation-specific. Because ice systems do not have the extra circulating pumps and heat exchangers that water systems do, maintenance costs may be lower for ice systems.

One disadvantage of water storage is that the tanks must be larger than those for ice and therefore require more floor space than ice storage. Furthermore, water storage tanks are available in a limited number of standard sizes and, not being modular in construction, are generally less flexible than those used to store ice. In addition, water storage tanks are usually built in the field and consequently have more problems with leakage. Another problem that has plagued water storage technology is the difficulty of avoiding the mixing of water from the chiller and the warmer return water. A variety of techniques, such as using temperature stratification membranes, have been employed to separate chilled and return water, but many such methods have encountered problems with too much blending (ASHRAE TC 6.9, 1987). Recent research found that for normal operating conditions, the performance of tanks having no physical barriers to separate the warmer from the cooler water can be equal or greater than systems with barriers (Wilden, 1985). An alternative of using an empty tank to receive the warmer return water requires additional space. In general, ''standby'' storage losses have been associated with a five to ten percent loss in performance. Although such losses also occur in ice storage, thermal losses are usually higher for water storage because of the greater tank volumes and thus greater surface areas, despite lower ice storage temperatures (Ayres, 1985).

Ice Systems. In comparison to chilled water storage systems, ice systems have a greater cooling storage density because they take advantage of the phase change of water to ice. Another advantage is the availability of packaged systems with manufacturer's warranties which usually mean greater reliability and ease in finding suppliers. Furthermore, because lower storage temperatures translate into lower costs for pumping and air distribution, pipes, fans, ducts, and pumps can be downsized. Unfortunately, the necessity for lower chiller suction temperatures (around 23 °F) often precludes compatibility with existing chillers. Lower suction temperatures reduce thermodynamic efficiency and ice systems thus require about 15 to 20 percent more electric energy.

There are five basic types of ice systems:

- static ice (ice-on-coil),
- brine-coil ice builders,
- brine-solid ice builders,
- dynamic ice (ice harvesters), and
- slush (slurry) ice generators (ASHRAE TC 6.9, 1987).

Until recently, the most common designs were static systems where the refrigerant is circulated in a coil inside a tank of water and ice builds around the coil. To extract the stored cooling energy, cooling water is circulated inside the tank and pumped through the HVAC (heating, ventilation, and air-conditioning) cooling coils. These simple systems are available in a wide range of sizes and are sold off the shelf in capacities of 50 to 680 ton-hours of storage. One drawback to ice-on-coil systems is that the evaporator surfaces are not easily accessible for maintenance. Another difficulty is that they are subject to a rapid drop in efficiency as ice builds on the coils, acting as an insulator. Brine-coil ice builders circulate brine through the coils and have the advantage of decreasing the refrigerant inventory. The disadvantage is that a heat exchanger is needed between the chiller and the storage tank. Brine-solid ice builders consist of rolled plastic mats containing the brine coils inside a cylindrical tank. Ice builds up on the coils until all of the water freezes in a solid block of ice.

Dynamic systems, the ice harvesters (also called plate ice makers) build layers or cubes of ice, as in the familiar ice-making machines used in restaurants. Ice is collected from the ice builder, crushed, and stored in a tank. Water to be used for cooling is circulated in this tank. In comparison to static systems, a smaller compressor is required. Because harvested ice is less dense than coil-built ice, a somewhat larger storage tank is needed. An advantage is that the volume of ice can be more easily measured; many thickness sensors for static systems have had reliability problems.

Ice slurry systems use a binary solution of ethylene glycol and water that flows through an ice-slurry generator and is pumped to the storage tank. Inside the tank the ice crystals form a floating porous ice pack. Returning solution, warmed from the cooling load, is sprayed into the top of the tank and is cooled by the melting of ice crystals. The temperature can be adjusted by varying the composition of the binary solution. This system, and the plate ice makers, have been used primarily for industrial cooling since they can both be discharged very rapidly.

Packaged Unitary Rooftop Systems. Until recently, thermal storage has been used mainly in buildings having centrally located chilled-water systems. Such systems tend to be found in larger buildings and owner-occupied buildings. However, a few manufacturers are beginning to offer packaged unitary rooftop air conditioning units with ice storage. These units use either brine or refrigerant circulation. Both systems are available in full or partial-storage systems. Both can be operated in compressor or storage priority modes (discussed below). Brine systems can also be used as heat pumps. One manufacturer is designing rooftop equipment to retrofit existing units by adding an ice storage unit, combined with an accumulator-heat exchanger, air pump, and other accessories in the field. Existing evaporator coils can be used. (See section 2.3.1, Availability.)

2.1.4 Phase-Change and Other Storage Media

PCMs incorporate benefits of both water and ice; they take advantage of the high heat of phase change (like ice), but do not require such low suction temperatures as does ice. Current PCMs exhibit a heat of fusion in the range of 46 to 61°F and now seem to be free of the technical problems initially encountered of incongruous (uneven) melting. Such mediums are being used in a growing number of buildings (McCannon, 1987), as further discussed below. In general, PCMs can be used with existing chillers, and compared with ice systems, can result in more favorable chiller efficiencies because of their higher phase-change temperature.

Clathrates are crystalline materials in which a noble gas is mixed within a structure of water molecules. The resulting compound raises the phase-change temperature of water to about 48 °F while lowering the heat of fusion of ice by fifteen percent. The product is technically attractive, but is still in the development stage. Success in the marketplace rests on a reduction in its cost.

Although space requirements are only slightly larger than those for ice systems, major shortcomings of alternative media include high first costs and unknown long-term performance. Another difficulty with eutectic salts is that about one ton of salt is needed per ton of cooling (MacCracken, 1986). Shipping and loading the salt into a tank is substantial. See section 2.3.2, Research and Development, for further comments about PCMs.

2.1.5 Design and Operating Strategies

Three basic design strategies can be employed:

1) ''Partial'' storage system where the chiller is downsized compared to a conventional cooling system and runs continuously. Reduced cooling loads at night allow the chiller to have the capacity to recharge the storage, and thus help meet the following day's peak cooling load.

2) ''Full'' storage where the chiller runs only during off-peak (and maybe partial-peak) hours with peak-period cooling met by storage only.

3) ''Demand-limited'' system where the chiller runs during all periods *except* during hours of maximum non-cooling demand.

Figures 1.A. through 1.D. show the differences in load profiles under a conventional system and under each of these strategies, and Table 2 summarizes the differences among the three cool storage strategies. For *partial storage* (Figure 1.B) the power requirements of the cooling system can be reduced by approximately 40 to 50 percent since the chiller runs continuously and the cooling load is met over a full day. With ''full'' or ''demand-limited'' storage systems, which require on-and-off control, the actual sizes of both the chiller and storage device are dependent on the TOU schedule affecting the building. For full storage (Figure 1.D), the storage size must be large enough to completely meet the daily peak cooling load without benefit of the chiller. The longer the on-peak period, the shorter the charging time. Full storage requires more storage capacity than partial storage. The peak cooling electric demand can be reduced by 80 to 90 percent compared with a conventional cooling system. Cooling may account for about half of the total electric demand at the peak hour, so demand may be reduced about 40 to 45 percent. Full storage is most feasible when on-peak cooling loads are of relatively short duration.

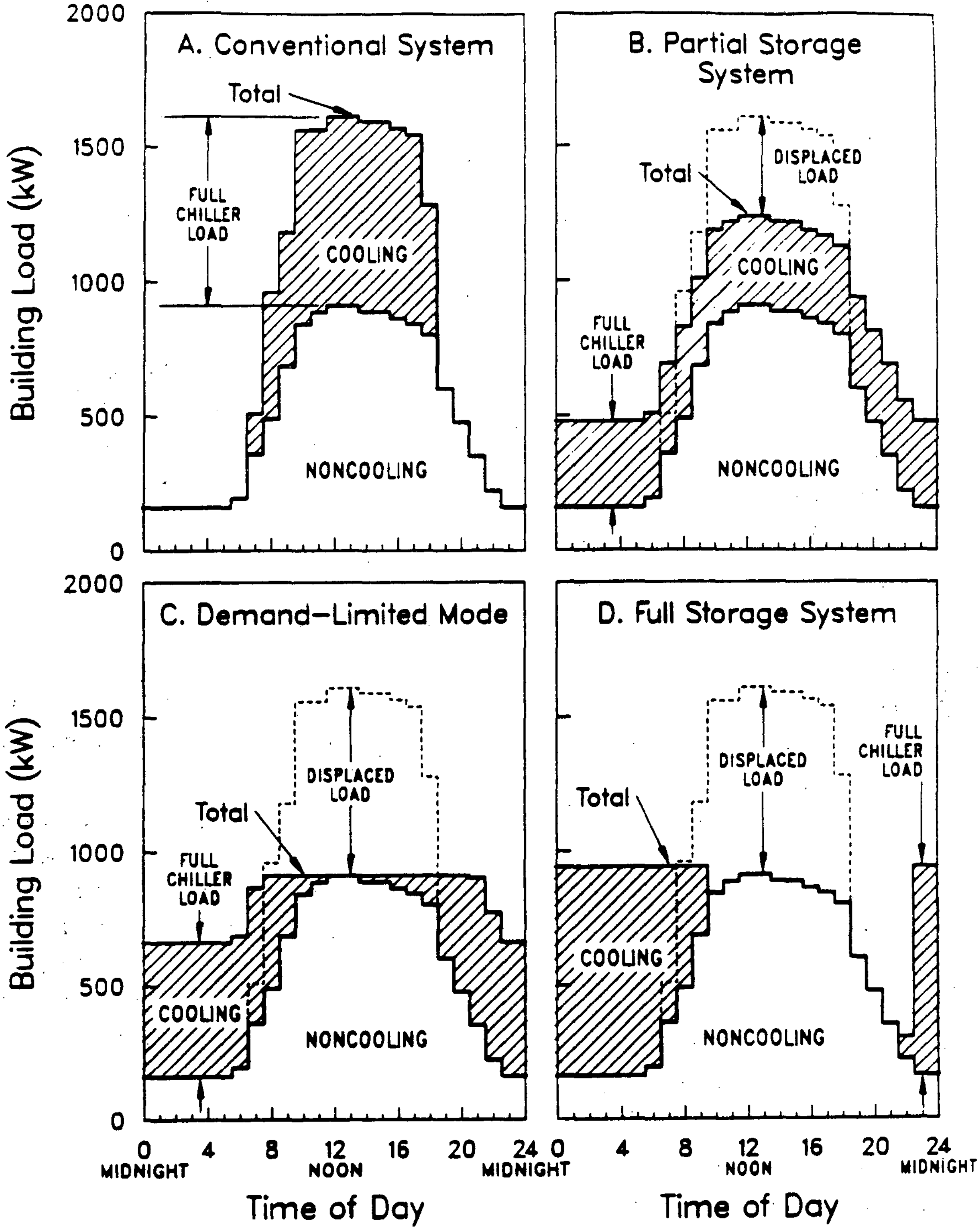

Figure 1.A.-1.D. Coventional, partial-storage, demand-limited storage, and full-storage systems. Hourly load profile for a building with a conventional cooling system on the design day compared with three cool storage load profiles. The partial-storage system has the smallest chiller (smaller full chiller load), yet shifts the least amount of peak demand (displaced load). The full-storage and demand-limited systems shift similar amounts. While the demand-limited system has a smaller chiller than the full-storage system, the controls are more sophisticated.

Table 2
Comparison of Operating Strategies
(assuming identical cooling loads)

FACTOR	FULL	DEMAND-LIMITED	PARTIAL
Cooling Plant First Cost Reduction	Low	Medium	High
Storage Capacity	High	Medium	Low
Chiller Size/Conventional	50-70%	40-60%	30-50%
Peak Power Shifted	80-90%	80-90%	40-50%
Year-round Utilization (Load factor)	Low	Medium	High
Ease of Control [1]	Medium	Difficult	Simple
Operational Savings [1]	Medium	High	Low

Notes:

1. For optimized operation with full and demand-limited storage, the daily cooling load must be estimated to determine the amount of ice or chilled water to store. For demand-limited storage the non-cooling loads must be estimated as well.

A *demand-limited* (Figure 1.C) strategy is a type of partial storage with more sophisticated controls. Since the objective is to minimize the cooling contribution to the peak demand, a non-cooling "baseload" demand must be established and this demand is never exceeded during on-peak hours. The chiller operates during hours *other than* the hours at which baseload demands are at their peak. This strategy is best suited for large baseload demands and short occupancy periods that allow greater storage-charging time. In addition to looking at the load profile when selecting the appropriate system, one must consider the building's electricity rates. Demand limiting is most applicable in buildings having significant peak-demand charges but not a steep differential between on-peak and off-peak energy charges.

2.1.6 Control Strategies

There are three basic types of control strategies for cool storage. Chiller priority and storage priority are the most common types; the third is called constant proportional control (Rawlings, 1985). These strategies pertain primarily to partial-storage systems in that both the chiller and storage are used at the same time to meet daily cooling loads. The choice among control systems is often a choice between reliability and complexity. Complex control systems often offer greater opportunity for cost savings but require greater sophistication to operate. The control system selected determines the load-shape characteristics, which greatly affect the cost effectiveness, or operating costs, of a cool storage system.

In *chiller priority control* the chiller operates as much as possible. It is run any time there is load *or* when the storage needs charging, and consequently operates at high efficiency because it is more fully loaded. The storage is used only when the cooling demands exceed chiller capacity. This method is simple to operate; a timer is used to switch the system into an ice-making mode at night, therefore first costs for controls can be low. However, since demand reductions are not maximized smaller utility cost savings will be realized. A demand-limited system is a sophisticated chiller-priority system in which the chiller is operated whenever the whole-building demand is under a certain set level.

Storage priority control draws on the storage to satisfy the cooling load, while the chiller runs only to maintain the minimum storage charge necessary. Utilization of storage energy is maximized in this mode. By operating the chiller less often during the day, more of the load is shifted from these hours to evening hours. Using storage priority the percentage of load shifted to off-peak increases as the daily cooling load decreases (from design day to average-load day). The resulting savings in utility charges are usually greater than the increase in electrical use from running the chiller at reduced capacity.

Storage priority control takes three forms: predictive, reactive, and storage inventory sensing (Rawlings, 1985). Predictive control involves predicting hot days soon enough to bring on chiller capacity and preserve ice. Reactive control involves either monitoring the building's return-water temperature and bringing on the successive stages of the chiller as needed. This method, the simplest of the three, is similar to the normal way of controlling a chiller but set points are higher. Inventory sensing is a technique where the status of storage is measured throughout the day and balanced with the chiller operation to establish or maintain the necessary cooling in storage at each hour. Inventory sensing may also be used as a secondary or back-up control method to bring on chiller capacity if the storage is nearly depleted.

Constant proportion control is a compromise between chiller and storage priority methods where the storage and the chiller handle a certain percentage of the load that remains constant under all load conditions. This method allows the building's peak demand to be reduced compared with chiller priority control. Constant proportion control has a lower first cost than storage priority controls, and a higher first cost than chiller priority control. Similarly, operating costs fall between storage and chiller priority controls.

In practice, controlling cool storage systems has been difficult, as discussed below. The simplicity of constant proportion control should be viewed with this in mind. Additional performance experience results are needed to more thoroughly evaluate the merits of each technique.

2.1.7 Chiller and Storage Sizing

Chiller and storage sizing issues are important to understand because sizing of equipment and tanks has a major effect on first costs. For partial and demand-limited storage systems the chiller must operate in two modes: 1) to meet the cooling load of the building, and 2) to charge the storage. In these two modes the system performs at different efficiencies. When direct cooling occurs, the chiller operates around design temperatures (for condenser and evaporator) and its average capacity is essentially the rated capacity (Warren, 1985). For charging conditions, the evaporator temperature is lower than the design temperature, reducing the actual capacity of the chiller to about 70 percent of its full value (Warren, 1985). At these operating temperatures a chiller generally consumes more energy to produce the same amount of cooling. For full-storage systems the evaporator temperature is also low, but because the chiller is operated during the nighttime when condensing temperatures are lower, the system's overall performance improves.

For partial and demand-limited storage systems, chiller sizing is based on the average capacity and must be determined by summing the product of chiller output and number of hours at this level of operation, and then dividing by the total number of operating hours. Since the chiller for a full-storage system designed to charge storage, it is sized by dividing the capacity-averaged number of non-peak hours into the daily load (Reeves, 1985).

Storage size depends on both chiller output and the number of hours available for recharging. Both partial- and full-storage operation are based on the product of the nominal chiller capacity, the number of storage charging hours, and the chiller rating in storage mode. In the demand-limited case, where the chiller meets some of the cooling load directly while at the same time partially charging the storage, the size of the storage is based on the summation of the difference between building load and chiller output over the hours the difference is positive.

With conventional cooling, chillers are sized to meet cooling loads on the peak day of the year, whereas with cool storage sizing, a complete load profile must be determined for the peak day. Simulation research is underway to assist engineers in predicting cooling loads and in sizing cool storage equipment (ASHRAE TC 6.9, 1987, Kammerud, 1987). Designers must be cautious not to underestimate cooling loads and hours of occupancy, which is a common design problem. The impact of correct sizing of cool storage systems is different than for a conventional system. For example, an undersized conventional system continues to work when overloaded--there will be some temperature rise in the building. In comparison, if the storage system is undersized, under extremes, when storage is depleted, the cooling capacity vanishes and the building may become unoccupiable. The ''cost'' of design errors can be very large.

2.2 Market Trends

2.2.1 Load Growth From Commercial Cooling

The total commercial floor space in the United States space totals about 50 billion square feet (EIA, 1986). Cooling is the largest single contributor to the summer electric peak demand for the commercial sector, which accounts for about 20 to 40 percent of most utilities' summer peak demand for all sectors (MacCracken, 1987). This load is expected to grow; how much is unknown but it is a subject of considerable interest. One source of information on the potential load-shifting capabilities of thermal storage comes from the application of an end-use planning model, called COMMEND, to building energy survey data covering the entire nation's commercial sector. This application of the COMMEND model predicts that the national summer peak demand from the commercial sector may reach nearly 170 GW by the year 2000 (Lann, 1986). It is now a bit over 140 GW. This growth is based on projections of future fuel prices, employment, and population figures.

Summer peak demands were calculated for ten U.S. geographical regions. The commercial sector was found to be summer peaking in all but one region, the pacific northwest, which includes Oregon, Washington, and Idaho. By the year 2000, three of the nine other regions are predicted to switch from summer to winter peaking because of increasing sales of electric space heating. Of the ten regions, the highest summer peak growth rate will occur in the southeast, estimated to be 2.6 percent per year. Other areas of high growth in summer peak demand include the west coast, far midwest, and the remaining southern states.

Results from the COMMEND model are useful for developing general trends, but should be interpreted with caution. For example, consider the assumptions incorporated into the model, such as the set of the building prototypes used to develop the building energy end-use breakdowns, which are based on data from three utilities and the Northwest Power Planning Council. These data are based on engineering estimates rather than measured end-use breakdowns, which may greatly differ from estimates (Piette, 1986). Another consideration is the evidence that load shapes for the commercial sector may be changing because of increasing electrification of office equipment such as computers and copy machines (Squitieri, 1986). This shift would intensify the cooling peak issue. Not only is on-peak electric demand increasing to meet the added non-cooling load, but cooling loads increase because of additional waste heat generated by electronic equipment.

2.2.2 The Potential of Cool Storage

Part of EPRI's use of the COMMEND model was to project the impact cool storage might have on electricity sales and peak loads under a plausible penetration scenario (Lann, 1986). Under the scenario developed, the EPRI study projects that by the year 2000, cool storage can reduce the commercial sector summer peak by 17 GW, or 10 percent. Also, electricity sales may increase 479 GWH, or 0.1 percent of commercial sector annual sales because of an assumed 1 percent efficiency loss.

To develop the above estimates the market was divided among: (1) new and existing buildings, (2) segments by building size, and (3) degree of potential based on cooling loads (a function of building type). Maximum penetration rates from 0 to 80 percent were applied to the resulting 24 market segments. One of the most significant developments that might affect these projections are, as mentioned above, the relatively recent marketing of rooftop packaged units for cool storage. Estimating the potential market penetration of packaged cool storage is not simple because there is little detailed information on which systems are currently in place in the commercial sector. An indication of the size of the market can be gleamed from current sales data. Based on sales data for 1985, 625,000 unitary package units and 11,780 chillers were sold (ITSAC, March 1987). ITSAC assumed 5 tons per unitary package and 100 tons per chiller. Therefore, package units represent 73 percent of the tonnage installed in 1985, a sizable portion of the commercial space cooling market (ITSAC, March 1987). ITSAC and Calvin MacCracken are currently circulating a questionnaire designed to help evaluate the potential for rooftop storage (ITSAC, March 1987).

2.2.3 Applications for 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. For thermal storage to be cost-effective, not only must electricity rates encourage load shifting, but a building must have appropriate load profiles (Gatley, 1987). For example, office buildings are ideal for cool storage because they generally have low cooling requirements in the morning followed by high peak demands in the afternoon. HVAC systems are generally turned down in the evening, from about 6 P.M. to 7 A.M. Four to five hours of low loads in the morning and four to five hours of higher loads in the afternoon result in the equivalent of six to ten full load hours of capacity per peak day and a long charging period. Many retail buildings may have similar load profiles.

Hotels may be good candidates for partial-storage systems, especially if compressor heat is recovered for perimeter heating or service hot water. Full storage is not usually a good option for hotels because of their typical 24-hour cooling loads and long peak period from 11 A.M. to 8 P.M. One possibility is to design the cooling system with very efficient chillers that operate around the clock, and can meet the first 50 to 60 percent of the on-peak cooling load.

One ideal application for cool storage systems is in an existing facility undergoing an expansion which requires adding capacity to a central chilled water system (Tamblyn, 1987). Instead of adding new chillers, the extra nighttime capacity of existing chillers can be used to charge a storage tank to serve the new floor space. The cost of a cool storage system may be lower than that of an additional chiller. Facility expansions are common for college campuses, and many campuses have chilled water systems. The Association of Physical Plant Administrators reports that about 250 of their 1200 members have such systems (Tamblyn, 1987).

In the above discussion we have focused on building type and its relation to load shape, which is, in turn, affected by climate, occupancy patterns, and various other characteristics of the building shell and the building's operations. Heating loads are also important in determining the applicability of cool storage, and dictating system choice, as noted with regard to hotels. For buildings that require morning warm-up and afternoon cooling, for example, double bundled chillers can often provide much of the needed heat. See section 2.2.5, Competing or Complementary Technologies, for more information on recoving waste heat.

2.2.4 Current Market Penetration

The number of cool storage systems in the United States is growing rapidly but most strongly in areas where utilities offer direct incentives to building owners to install cool storage. It is estimated that 200 new cool storage systems were installed in 1986, about double that of 1985. A similar doubling was estimated for 1987 (MacCracken, 1987). In total there are probably around 1000 installations. MacCracken also estimates that about 90 percent of the current building projects involve partial-storage systems, since first costs are lower. About 25 percent of the current building projects are retrofits (MacCracken, 1986). Earlier surveys showed different trends, as discussed below.

One source of information on trends in system installations is the Buildings Energy Data Group at Lawrence Berkeley Laboratory, where such data are being collected as part of the Buildings Energy Use Consumption and Analysis Data Base -- Load Management in Commercial Buildings (BECA-LM) (Piette, 1987). Table 3 summarizes data on 382 buildings in the United States and abroad. The data have been compiled from numerous sources which include surveys, journal articles, and miscellaneous technical reports. Although not a representative sample of current market penetration, these data show that about 42 percent of the installations are ice, 36 percent chilled water, 9 percent eutectic salt, and 14 percent unknown.

Table 3

Number of Identified Cool Storage Installations as of 1987

Type of Medium	U.S.	International	Total
Chilled Water	118	44	162
Ice	141	4	145
Eutectic Salts	29	-	29
Other/Unknown	46	-	46
Total	334	48	382

Source: Piette, 1987.

Notes:

1. These data are not a statistical sample. They have been compiled from numerous data sources that contain reference to specific buildings with cool storage systems.

An earlier survey (1983) showed that two-thirds of the systems used ice and about one-third used chilled water. (These data have been included in the BECA-LM list). Results from this same survey showed that about half of the buildings installed full-storage systems and half installed partial-storage systems (Hersh, 1984). As mentioned, MacCracken's 1987 estimates indicate a shift toward partial-storage systems.

Applications of PCMs are also growing. Whereas the Hersh survey found only two (out of 76) of eutectic salt systems, the BECA-LM characteristics data base uncovered 29. Eighteen of these 29 PCM systems have been installed (or are planned) in the 68 cool storage systems in Southern California Edison's (SCE) Off-Peak Cooling Program (McCannon, 1987).

2.2.5 Competing or Complementary Technologies

Generally speaking, commercial cool storage is a load-shifting technology designed to reduce operating costs. As discussed above, not all buildings are candidates for cool storage, and not all cool storage buildings should have thermal storage for 100 percent of their cooling requirements. Furthermore, some of the techniques described below are more effective when used in combination with cool storage. Before considering the technologies for satisfying or shifting cooling demands, we discuss a few techniques to reduce heat gains. The applicability of these techniques will differ for new and existing buildings.

Reduction of Internal Loads. Reducing heat gains from equipment, especially lighting, is an important technique for controlling cooling loads. Use of energy-efficient fluorescent lamps, for example, not only saves electricity directly, it saves on electricity use for cooling. For retrofit applications, reducing lighting energy use by 2 kWh/ft^2-year could save 1 kWh/ft^2-year in cooling energy use, or 0.5 W/ft^2 in cooling peak demands (Usibelli, 1985). Variations in savings are primarily due to variations in the efficiency of cooling systems. Another method for reducing the cooling load contribution of internal heat gains is to vent part of the gain to the outdoors. For example, heat-removing luminaires in new buildings typically save about 0.1 to 0.3 kWh/ft^2-year in cooling energy use and slightly reduce the peak demand (about 0.02 to 0.03 W/ft^2-year) (Usibelli, 1985).

Reduction of External (Shell) Loads. Reducing heat gains from other sources--conduction, solar radiation, and humidity--can be accomplished in numerous ways. Various window treatments, roof and wall insulation, and the use of light colors on exterior surfaces are effective. Reducing outside-air ventilation rates 0.05 cfm/ft^2 in over-ventilated buildings can save 0.01 to 0.06 kWh/ft^2-year, and reduce peak demand 0.05 to 0.23 W/ft^2 (Usibelli, 1985). Energy savings from installing an 0.15 cfm/ft^2 air-to-air heat exchanger can reach 0.13 kWh/ft^2-year, with demand savings ranging from 0.15 to 0.45 W/ft^2. Increasing thermostat settings also reduces loads from outside air (Usibelli, 1985). Many of these techniques will also reduce heating costs.

Cooling Equipment Technologies. Many cost-effective HVAC technologies are available to meet cooling demands, while saving energy and reducing peak demands as well (Usibelli, 1985). High-efficiency chillers, economizers, and variable-air-volume systems are common examples. Direct or indirect evaporative cooling can be cost-effective in dry climates. Where natural gas rates are low compared to on-peak electricity, installing a two-stage direct-fired absorption chiller should be considered for all, or the last increment, of the cooling (Grumman, 1986). Mass storage and night venting should also be considered for certain climates and occupancy patterns.

Emergency Generation. For buildings with emergency electricity generation, such as hospitals, emergency generators may be used for peak shaving.

Heat Recovery. For buildings that require morning warm-up and afternoon cooling, double bundled chillers can provide useful heat. The recovered waste heat can be: 1) used with a hydronic heat pump, 2) stored for later use, or 3) used directly for heating. In some buildings, chilled water tanks are used for heat storage in the winter (Tackett, 1987).

Cogeneration. Cogeneration could be considered for larger facilities with substantial heating loads. Ice storage usually costs less then cogeneration units and it may be cost-effective to replace half the cogeneration unit with ice storage and run the cogeneration unit steadily (MacCracken, 1986). The use of thermal storage permits downsizing the cogeneration plant and improves the plant's load factor. Such a system is installed in a hospital in California, where a eutectic ice storage system of 3100 ton-hours is combined with a 350-kW gas-fired cogeneration system. Although buildings with substantial cooling and heating loads may find this technique cost-effective, utility financial incentives for cool storage systems are often not available to buildings that cogenerate (ITSAC, March 1987). See section 4.2.1, Direct Incentive Payments, for more information on financial incentives.

2.3 Technology Status

2.3.1 Availability

An increasing number of U.S. manufacturers are producing cool storage products. Table 4 indicates the manufacturers of different types of cool storage equipment. Compared with the six manufacturers of commercial cool storage equipment in 1980, there are now about 26, excluding manufacturers of the compressors most commonly used with cool storage systems (McCannon, 1987). The majority of these manufacturers (19 of 26) produce ice builders. Manufacturers of phase-change cool storage equipment and specialized, chilled water storage tanks have also entered the market, as discussed below. Of the 19 U.S. manufacturers of ice storage systems (ITSAC, Dec. 1986), about half produce static, ice-on-coil systems. Similarly, about half of the 19 manufacturers supply refrigeration equipment to accompany their ice builders. Most manufacturers have their own market niche. For example, one company has a good percentage of the retrofit market because its system is compatible with most existing chillers.

Table 4
Manufacturers of Cool Storage Products

TYPE OF SYSTEM	NO. OF MANUFACTURERS
ICE STORAGE	19
Ice-on-Coil Tanks	(9)
Brine Coil and Brine Solid Builders [1]	(2)
Plate Ice Makers (Ice Harvesters) [1]	(5)
Ice Slurry	(3)
PHASE CHANGE MATERIALS [2]	5
CHILLED WATER TANKS [3]	2
COMPRESSOR MANUFACTURERS [4]	11
TOTAL	37

Source: "Manufacturers of Cool Storage Products," *ITSAC, Thermal Storage Technical Bulletin,* Dec. 1986. Includes name and address of manufacturers, and product description. See Chapter 46 "Thermal Storage" of *1987 ASHRAE Handbook: HVAC Systems and Applications,* for ice system descriptions.

Notes:
1. Includes one product under development or in demonstration phase.
2. Includes two products under development.
3. Tanks specifically designed for chilled water storage. (Most tanks are custom designed and field constructed.)
4. Manufacturers of compressors specific to cool storage applications.
5. Two of the 19 ice storage manufacturers are also producing rooftop packaged unit cool storage systems.

Rapid market expansion is taking place. Some of the manufacturers included in Table 4 are currently in the process of developing or testing their commercial cool storage products. A few such products are from companies producing ice harvesters adapted from industrial ice-making equipment. Some manufacturers install the systems on a turnkey basis. At least one firm will lease, operate, and maintain the systems (Teji, 1986).

There are several manufacturers of alternative storage media. As shown in Table 3, about nine percent of U.S. commercial buildings use (or are planning to use) PCMs. One company recently introduced a system using clathrates. One of the largest PCM companies uses plastic containers filled with phase-change salts, which change phase at 8°C. A small percent of commercial buildings now use this technology. A French company produces a type of plastic ball containing eutectic salts, which operates at a similar phase-change temperature. In the United States only a few buildings appear to use this product.

Most chilled water storage tanks are custom designed and field constructed. As Table 4 shows, however, two manufacturers furnish factory-built tanks designed for chilled water storage. These "packaged" tanks include insulation, instrumentation, corrosion protection, and stratification systems.

Nearly all current cool storage technologies require chilled water distribution systems to be in place, and such equipment tends to be found in larger buildings. However, equipment for packaged rooftop air-conditioning cool storage units are newly available and are undergoing testing by a number of utilities (ITSAC, March 1987). These systems bring the technology much closer to cost effective residential application.

2.3.2 Research and Development Efforts

Continuing basic research in thermal cool storage can be divided into three general categories: refrigeration systems, the making and storing of ice and chilled water, and alternative storage media.

In terms of the refrigeration systems, the use of evaporative or water-condensers and liquid overfeed systems has been found to decrease compressor demands. Another area of interest is in binary mixtures of refrigerants that exhibit low-cycle pressures and allow for the use of plastic tubing, thereby decreasing costs. More research is needed to improve the thermal conductivity of plastics (Hausz, 1983). Transmission fluids are also being developed to reduce friction flow in cold and hot water circulation are also being developed (ITSAC, April 1987).

As we mentioned in the previous section, new types of ice-building equipment are currently being developed and tested. Configurations to avoid build up of ice on the evaporator, such as pumping subfreezing brine or glycol-water solution through an intermediate heat exchanger loop, are being explored. Active ice shuckers have had problems with ice sticking to the freezer surface; alternative designs for passive ice shuckers, those with no moving parts, are being considered. Pumpable phase-change slurry particles, such as ice crystals, are being developed to improve bulk convective energy transfer are being developed (ITSAC, April 1987). Several methods of preparing slurries are under consideration.

Chilled water storage techniques are also under study. Temperature stratification research has concluded that simple buoyancy water storage, in which the density gradient between warm and cold water keeps them separate, is the most cost-effective technique for storage. Because of wide variations in construction costs and problems with leakage in concrete tanks, new design and construction techniques are being studied (ITSAC, March 1987).

Alternative cool storage materials fall into four categories: salt hydrates, clathrates, desiccants, and partially miscible fluids. Salt hydrates, or eutectic salts, with fusion temperatures higher than that of ice, improve the efficiency of the compressor cycle. If materials cost could be brought down to $0.50/lb with a heat of fusion of 70 Btu/lb, these alternatives could be competitive (Hausz, 1983). Fundamental research on clathrates is being conducted by the Department of Energy at Oak Ridge National Laboratory. Desiccants are materials that can store energy because they absorb water vapor at low temperatures and release the water at higher temperatures. Since the latent load in hot, humid climates is a significant part of the air conditioning load, desiccants can be used during peak hours for dehumidification. Regeneration during off-peak hours can be done with resistance heating or a heat pump.

Partially miscible liquids are liquids that absorb heat (get cooler) when mixed. The process is reversible, and is equivalent to a PCM. Similarly, complex compounds using a solid-vapor reaction of an absorbant, a metal in organic salt, and absorbate, sodium bromide/ammonia system have recently been developed (Rockenfeller, 1986). Complex compounds, like many of the advanced materials, can be used for heat as well as cool storage.

In addition to the basic research occurring in the three categories mentioned above, performance monitoring of existing cool storage systems is also underway. Such research programs cover numerous aspects of the operation and control of actual, in-place systems (ITSAC, March 1987). Low-temperature air distribution systems are also being studied (ITSAC, Oct. 1986), and computer simulation tools are being developed (ASHRAE TC 6.9, 1987, Kammerud, 1987).

2.4 Environmental Effects

One indirect benefit of thermal storage is that with smaller chillers the number of chlorofluorohydrocarbons (CFCs) released into the atmosphere is lowered. CFCs are believed to be involved in two environmental phenomena--ozone depletion and climate modification or "the green house effect." There is a great deal of current legislative action regarding possible restriction on the use of certain CFCs (R-11, R-12, R-113) (Cox, 1987).

Alternative CFCs are being studied. R-22 (or CFC-22) is believed to be less of a threat to the atmosphere and may be applicable in situations where large compressors are used. For low population areas, ammonia (or R-717) is another alternative. One recent ice storage installation used a 200-ton ammonia chiller. For this application design engineers used computer simulations to compare the performance of the installed system with various other chiller configurations, with ammonia, and with R-22 refrigerants. R-22 compared favorably under certain operating conditions (Richards, 1987).

Another indirect benefit of cool water storage systems is that the stored water can be incorporated into fire safety systems.

3.0 PERFORMANCE CHARACTERISTICS

Although numerous documents discuss how to design cost-effective cool storage systems (Reeves, 1985, ASHRAE TC 6.9, 1987, PG&E, 1985) there are fewer sources with data on the actual measured performance of installed systems. Data collected to date vary in quality and quantity. Performance parameters have been poorly defined and comparisons among buildings are rare. This lack of Of the articles that describe particular cool storage installations, few contain energy and cost performance data based on utility bills or submetering. A few notable efforts are underway that should improve understanding of cool storage system performance: EPRI is monitoring 13 cool storage installations (ITSAC, Aug. 1986). The Pacific Gas and Electric Company has also been monitoring 12 cool storage buildings (PG&E, 1987).

In this section we present examples of measured performance data that are currently available. These data show the type of analysis that have been performed to date. We describe the numerous parameters that should be developed for a well-rounded analytical framework. Definitions for these parameters can be found in the Appendix (section 8.2 and 8.3). Cool storage systems from three buildings included in LBL's BECA-LM data base are referred to in this discussion (Piette, 1987). The BECA-LM data base currently contains submetered performance on 10 commercial buildings with cool storage systems.

3.1 Energy and Load-Profile Performance

3.1.1 Establishing a Base Case

Determining the cost-effectiveness of a cool storage system requires a comparison with a base-case cooling system. The base case for an existing building is usually the pre-retrofit condition, but comparison of pre- and post-retrofit building performance must consider other changes in the building that affect cooling (or whole-building) loads, in addition to the installation of a cool storage system. This comparison is often difficult (Meal, 1985). The base case for a new building is based on a hypothetical "conventional" system in the same building. Performance analysis for new buildings is, therefore, very sensitive to the specified characteristics of the "conventional" system, as is the incremental cost of the cool storage system.

To qualify for utility rebates (see section 4.2.1), some utilities require that certain guidelines be used in specifying the comparative base case system. PG&E, for example, requires a computer simulation that includes a 24-hour chiller load profile using an hourly simulation model with specified hourly weather data (PG&E, 1985). For new buildings, an average chiller efficiency of 0.7 kW/ton must be used. For existing buildings, the chiller efficiency is to be based on the type of chiller currently in the building. Motor efficiencies must also be specified. The rebate calculations used by SCE allow the design engineer more flexibility in defining the base case.

The most precise performance comparisons are based on metering of actual cooling loads. Once measured, cooling load data can be used to calculate how a conventional system would perform under the same conditions faced by the cool storage system.

3.1.2 Cooling System Performance

There are two parameters commonly used to describe the performance of cooling systems. One is "system efficiency" (kW/ton), which is a characteristic of a particular system. The other is "load shift potential," or kW-shifted from on-peak to off-peak periods (see Appendix). The kW shifted is the parameter most often used to calculate utility rebates. It is based on the demand shift from the on-peak to the off-peak period for the peak day, or for the maximum cooling hour (PG&E, 1985). By definition, an estimate of kW shifted requires a comparison with a base case system. Any comparison between conventional and cool storage systems should include comparisons of compressor loads, pumps, heat rejection equipment (such as cooling towers and evaporative condensers), and air-handling equipment. Similarly, calculations of efficiency should also consider all of these components of the cooling system. Unfortunately, there is no standard specification for defining the system components included in these parameters, and performance comparisons are often inconsistent.

Tables 5 through 7 present six general categories and numerous subcategories of performance data for these actual buildings. The three categories of performance data are the cooling system, whole building, and cost data. Three system configurations are compared: 1) actual measured performance, 2) estimated "design" performance, and 3) estimated "base case" performance. In this section we consider the cooling data.

Building 1 (Table 5) is a 68,000 ft^2 office with a demand-limited ice storage system (McNeil, 1985 and 1986). As expected, the system efficiencies for the actual building were slightly higher (worse) for the cool storage system than those estimated for a conventional system. This resulted in higher energy use for the ice system as compared to the conventional system--2.5 versus 2.4 kWh/ft^2 for the summer of 1983. (The system was submetered only during the summer.) Although the compressor efficiency for the conventional chiller was a low 0.77 kW/ton--well below the 1.03 kW/ton of the cool storage system's chiller--the auxiliary loads were much smaller for the cool storage system, and so the total efficiency compares well. The auxiliary loads are smaller for the cool storage system because of the smaller fans and pumps. Furthermore, unlike the cool storage system for this building, the conventional system would have used a cooling tower, which lowers efficiency. Other cooling system parameters in Table 5 include the summer electricity use, the maximum cooling system demand, and the cooling system load factor. Although there were no savings in electricity, some of the load was shifted off peak. As with Building 1, the efficiency of the cool storage system in Building 2 was worse than the efficiency of a conventional system (Table 6). For this building we show the average, maximum, and minimum efficiencies, to indicate the range in this parameter.

In Tables 5 through 7 we include the shifted kW with the whole-building data, rather than with the cooling-system data, because the electricity bills and cost-effectiveness are usually based on whole-building performance.

Table 5
Performance Summary for Building 1

Type of Data	Actual 1983	Actual 1985	Design	Conventional 1983	Conventional 1985
1. COOLING SYSTEM					
System Efficiency (kW/ton)					
Average	1.22	1.77		1.18	1.56
Annual Elec. Use (kWh/ft^2)					
% Off-Peak	70			30	
Summer (kWh/ft^2) [1]	2.5	2.0	2.5	2.4	1.8
Max. Demand (W/ft^2) [2]	2.0	0.35	0.2	2.9	
On-Peak Load Factor [3]	0.34		>1	0.24	
2. WHOLE BUILDING					
Annual Elec. Use (kWh/ft^2)	16.4	22.6			
% On-Peak	51				
% Off-Peak	49				
Summer (kWh/ft^2)	7.8	9.5	7.8	7.7	9.3
Max. Demand (W/ft^2)					
Summer [4]	5.3	4.6	3.7	6.2	9.4
Peak Shift (W/ft^2)					
Max. for Peak Month	0.9	1.6			
Max. Annual Shift	2.5	2.3			
Annual Load Factor	0.34	0.56			
3. COSTS [5]					
Total System (\$/ft^2)	2.14	2.14			
Incremental (\$/ft^2) [6]	-0.14	-0.14			
Annual Elec. (\$/ft^2)					
Summer [1]	0.63	0.65		0.69	0.77
Savings (\$/ft^2) [7]	0.06	0.11			
Payback [6]	immed.	immed.			

Building and System Description: The building is a 68,000 ft^2, three-story office in Illinois. Completed in 1982, it is occupied about 53 hours per week. The design-day cooling load was estimated to be 200 tons, with a daily load of 1584 ton-hours. Two 80,000 lb (totaling 2000 ton-hours) direct expansion ice-builders are used for the full-storage system, which uses two 45-ton reciprocating chillers. Conventional system performance are calculated from hourly submetering (McNeil and Mathey, 1986).

Rate Schedule: The rate schedule in 1983 (for buildings under 500 kW) has an on-peak period of 9 A.M. to 10 P.M. (M-F), during which the monthly peak demand is calculated. There are no TOU energy charges.

Notes:

1. Summer (the cooling season) for this building is June through October, five months. Some of the pertinent annual performance data are unavailable.
2. Maximum for the on-peak period.
3. Load factors > 1 are possible when the "on-peak" load factor is defined as the ratio of the average demand to the maximum on-peak demand, but most of the energy is used during off-peak periods.
4. The maximum demand in 1983 occurred in April (5.5 W/ft^2), a "swing-season" month. In 1985 the summer peak demand was the annual maximum demand.
5. All costs have been inflated to first quarter 1987 dollars using GNP deflators.
6. Savings in first-cost over a conventional system.
7. Summer only.

Table 6
Performance Summary for Building 2

Type of Data	Actual	Design	Conventional
1. COOLING SYSTEM			
System Efficiency (kW/ton)			
Average	1.49		1.20
Max.	1.79		1.27
Min.	0.94	1.15	
Annual Elec. Use kWh/ft^2)	4.5		
% On-Peak	11		
% Off-Peak	89		
% of Annual Total	12		
Max. Demand (W/ft^2) [1]			
On-Peak	5.1		
Off-Peak	4.5		
Cooling Load Factor	0.10		
2. WHOLE BUILDING			
Annual Elec. Use (kWh/ft^2)	36.9	29.1	30.7
% On-Peak	15.7		
% Off-Peak	84.3		
Max. Demand (W/ft^2)			
Winter	19.0	8.6	8.6
Summer	9.7	9.1	12.6
Peak Shift (W/ft^2)			
Max. month		3.1	
Avg. month		1.5	
Max. shift		3.8	
Annual Load Factor	0.22	0.37	0.27
3. COSTS [2]			
System and Installation ($/ft^2)			
Total		12.4	
Incremental		2.74	
Additional [3]	1.89		
Annual Elec. ($/ft^2)	2.81		2.76
On-Peak	0.94		1.19
Off-Peak	0.65		0.33
Winter Demand	0.80		0.61
Summer Demand	0.41		0.53
Savings ($/ft^2) [4]	0.05	0.18	
Payback		15	

Building and System Description: This 18,000 ft^2 office in Chicago, Illinois, was built in 1981 and is occupied about 53 hours per week. Performance data are for 1984-1985. The full-storage system consists of 40,800 lb. of ice with a 75 ton reciprocating chiller, which supplies 490 ton-hours. Data for the conventional system are based on an early TRACE run (Ayres, 1985).

Rate Schedule: Costs calculated using 1983 rates, which included four different kW charges: a $/kW for the first 10,000 kW, and over 10,000 kW, both differing for winter (October through May) and summer (June through September). Energy charges differentiated between on-peak (9 A.M. to 10 P.M.) and off-peak periods.

Notes:

1. Summer maximum, winter not metered.
2. All costs are inflated to first-quarter 1987 dollars using GNP deflators.
3. Needed major modifications in 1983.
4. The winter peak demand charges are not included in the comparison between the actual and base case operation.

Table 7
Performance Summary for Building 3

Type of Data	Actual	Design [1]	Conventional
1. COOLING SYSTEM [1]			
System Efficiency (kW/ton)			
Annual Elec. (kWh/ft^2)			
Max. Demand (W/ft^2)			
Cooling Load Factor			
2. WHOLE BUILDING			
Annual Elec. Use (kWh/ft^2) [2]	18.82		21.27
Max. Demand (W/ft^2)			
Winter			
Summer	2.62		4.3
Peak Shift (W/ft^2)			
Max. month	1.71		
Avg. month	1.67		
Max. shift	1.71		
Annual Load Factor	0.82		0.56
3. COSTS [3]			
System and Installation ($/ft^2)			
Total			
Incremental	0.63		
Additional	none		
Annual Elec. ($/ft^2)	0.99		1.19
Demand	0.34		0.45
Energy	0.65		0.74
Savings ($/ft^2) [4]	0.11		
Payback	5.3		

Building and System Description: Building 3 is a 1.5 million ft^2 office in Dallas, Texas which incorporates numerous energy-saving features in addition to the 1.5 million gallon chilled-water tank. It is occupied about 50 hours per week, but its large computer facility is open 24 hours a day. Heat-recovery condensers are on the two chillers that total 1160 tons. In the winter, one or two of the four concrete tanks are used to store hot water. Performance data for the conventional system are based on a computer simulation. Simulation data was augmented by some submetering of the cool storage system (Tackett, 1987).

Rate Schedule: Based on the maximum peak demand that occurs during the summer (June to September) on-peak period (12 P.M. to 8 P.M.), a billing demand is calculated for each month of the year. The algorithm for the ratchet includes each month's billing demand.

Notes:

1. Though submetered, the cooling system data are not available. Design estimates for system performance are also unavailable.
2. Includes electricity savings from the heat recovery; savings are not strictly a result of the cool storage system, but of the integrated design.
3. All costs are inflated to first-quarter 1987 dollars using GNP deflators.
4. Based on peak-demand charges only.

3.1.3 Whole-Building Performance

The most common parameter for assessing whole-building performance is annual energy intensity. This parameter helps to determine whether a building is ''energy intensive'' or ''energy efficient'' (Piette, 1986). To understand the range of intensities and make valid comparisons among buildings one must examine numerous building characteristics such as operating hours, climate, HVAC and lighting systems, and special energy-conservation features. Low energy use and high load factors (or low whole-building peak demand intensities) generally translate into low electricity costs. Clearly, problems arise when cool storage performance evaluations use whole-building data, since the load characteristics of the cooling system are unknown. However, when whole-building data are used, a building with cool storage may be identifiable as a ''low power'' building when compared to others (Meal, 1985). Unlike energy intensities, little measured data is available on typical peak demand intensities of commercial buildings (Meal, 1985, Piette, 1986). The Department of Energy's Energy Information Administration is beginning to address this information gap in their commercial building data-collection activities (Burns, 1987).

Whole-building performance data can be very useful for multi-year performance assessment. Many cool storage buildings improve dramatically over their first few years (Wyatt, 1986), as did Building 1 (Table 5). For this building, although energy use increased (largely because of increasing energy use by computers), the performance of the ice-storage system improved. Whole-building peak demand performance did not greatly improve. Figure 2 shows this trend: while the average of the monthly on-peak demands for the cooling system fell from 1982 to 1985, the on-peak demand of the whole building remained fairly constant.

3.1.4 Effects on Other End-Uses and Comfort

For buildings with low-temperature air systems, fans and pumps are downsized and less energy is used for ventilation and HVAC auxiliaries. This fact should be considered when comparisons are made between cool storage buildings and conventional buildings. Conventional buildings could also use low-temperature air, but chiller efficiencies would suffer. Relative humidity may also be lower with cool storage, therefore providing comfort at higher temperature settings (MacCracken, 1986). On the other hand, reduction in air quantities may contribute to indoor air quality problems. One way to compensate for reduced air flow is to increase the level of filtration (Meckler, 1987).

3.2 Economics

Just as numerous parameters are used to evaluate the physical performance parameters of a building and its thermal systems, any discussion of cost effectiveness must also consider a number of parameters. Perhaps the most commonly used indicator of cost-effectiveness is simple payback. More thorough assessments consider the *net present value* or the *internal rate of return* of an investment. For the purpose of this discussion we will be focusing on the two values used to derive all three of these parameters: the initial cost of the cool storage system, and the annual net savings in operating costs from cool storage.

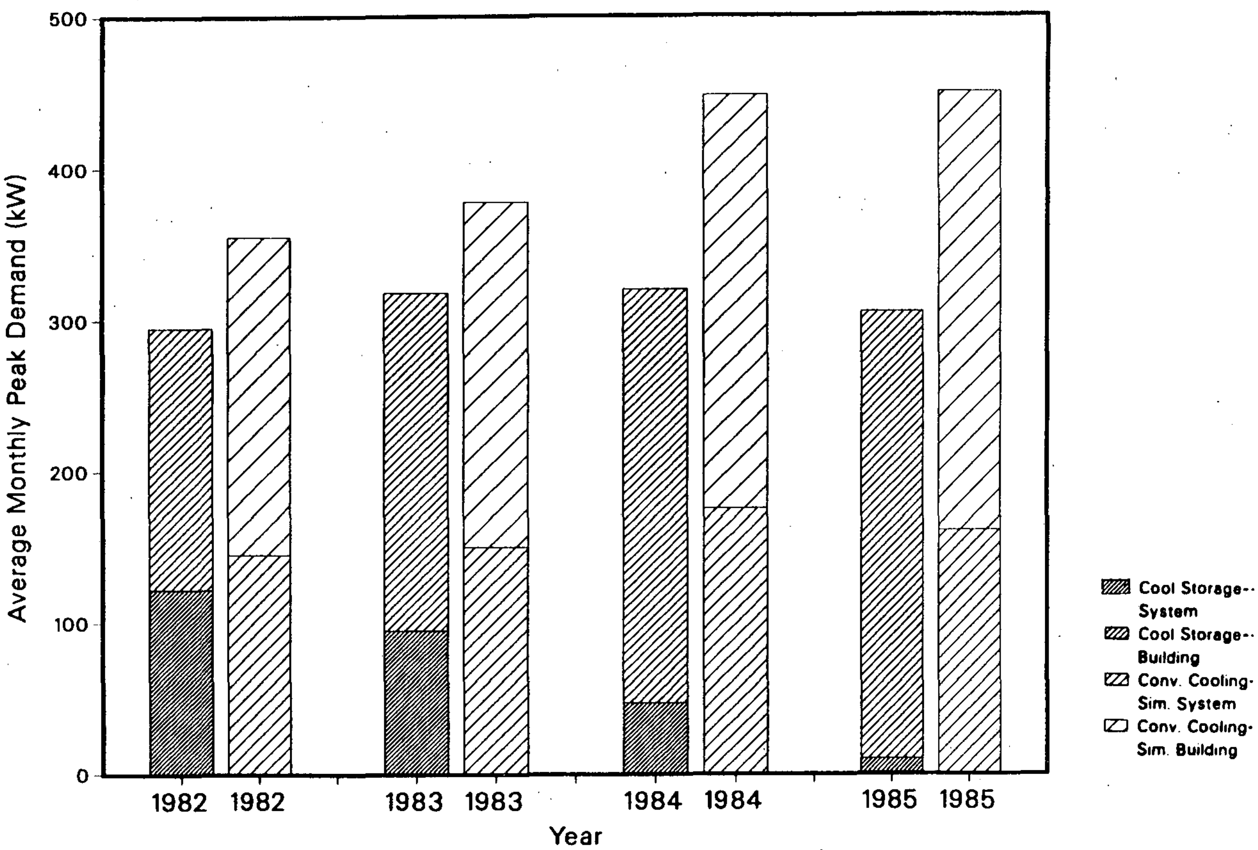

Figure 2. Comparison of peak demand in building with cool storage system vs. simulated conventional system. Average monthly demands for the whole building and for the cooling system during on-peak periods in four successive cooling seasons. The left bar for each year represents the measured peak demand for the system "as built," with the cool storage, while the right bar shows the estimated value for demand with a conventional cooling system, based on submetered cooling loads.

3.2.1 Purchase and Installation Costs

Most cool storage systems are more expensive than conventional HVAC systems. An EPRI design guide notes that the gross costs of ice storage systems range from about $1100 to $1400/ton, with relative costs as follows: 65 percent for major equipment, 24 percent for materials, 7 percent for labor, and 4 percent for miscellaneous (Reeves, 1985). Chillers alone cost from $200 to $600/ton; costs decrease for larger chillers. We have mentioned the first-cost savings from using low-temperature air systems with smaller auxiliary systems, such as cooling towers, piping, fans, pumps, and ducts. Savings are also associated with other systems. Smaller horsepower compressors allow the use of smaller, less expensive transformers, switchgear, motor starters, and power distribution cabling and conduit. Compressors can be located on grade, freeing up upper-story space. The value of upper-story space is thereby enhanced, and noise and vibration control costs may be reduced (Reeves, 1985).

Unit costs for ice storage systems vary tremendously, ranging from about $1.25/lb of capacity for small systems to about $0.45/lb for large systems. Chilled-water storage tank costs vary depending on materials, size, location, and whether the storage is for old or new construction. Installed tank costs range from nearly $0.60/gal for small tanks (under 4000 gallons), to $0.20/gallon for large tanks (over 4 million gallons). A rule-of-thumb for computing other storage-related costs to assume that other components will amount to about 50 percent of the bare tank cost (Reeves, 1985).

Unfortunately, actual data on the incremental cost of a cool storage system over a conventional system are difficult to collect because of inconsistencies in how cool storage costs are defined. For example, incremental cost calculations for a new building may simply include the cost of the ice builder and additional piping required, and ignore savings from downsizing the compressor or other components. The incremental cost is also lowered if the designer subtracts the savings from installing a smaller chiller (Rosenfeld, 1985). As noted previously, lower storage temperatures often translate into lower costs for pumping and air distribution, since pipes, fans, ducts, and pumps can be downsized (Reeves, 1985). Cost overruns can also cause actual system costs to be higher than original projections. Furthermore, biases based on the desire to promote cool storage projects may cause reported costs to be lower than actual (Vincent, 1987).

For comparisons between buildings to be valid, the incremental cost for a cool storage system must be normalized against a relevant building or HVAC parameter (e.g., floorspace, maximum tons of cooling, or shifted kW) to account for differences in design and performance characteristics of the systems. Costs-per-kW-shifted is the most common parameter used because it represents how much of the cooling load is shifted during the maximum hour of cooling. A difficulty with this parameter is that kW-shifted may not translate directly into electricity cost savings. The savings from use of a cool storage system often depend on shifted energy, as well as demand, depending on the electricity rate schedule, as we describe below. Furthermore, the savings are highly dependent on the definition of the base case. For some comparisons it may be better to normalize costs by the storage ton-hours because first costs increase as the size of the storage increases. This calculation does not rely on a base-case comparison and, because ton-hours is an energy unit, it is also useful if time-of-use energy charges are of concern.

As mentioned, the higher first costs for water in comparison to ice systems gradually diminish with increasing size of the cool storage system. A recent national survey of 45 buildings was conducted to assess the costs of cool storage, and results were consistent with this expectation (Vincent, 1987). Systems costs were reported in costs per kW shifted ($/kW). Of the 47 systems surveyed, costs ranged from zero incremental first cost to over $1200/kW. The survey also found, as expected, that the costs for the three PCM cool storage systems were relatively high. On the other hand, these systems should result in lower operating costs for electricity because of their higher freezing temperatures (lower use of auxiliary energy). The survey also found that the smallest systems were the most expensive per kW shifted; however, these higher prices may be attributed to the fact that several of the smaller systems were built under early utility-sponsored demonstration projects when engineers and manufacturers had less experience with the technology.

Costs for cool storage differ between new and existing buildings. Retrofits can be more expensive because they lose the cost reduction new buildings enjoy from downsizing equipment (ITSAC, Dec. 86). First-cost savings from use of low-temperature air distribution systems are generally not available since existing water and air distribution systems are usually used. As mentioned, one of the most cost-effective scenarios for cool storage is in the case of a building addition.

As mentioned above, when new technologies gain wider acceptance and usage their costs decrease. There is some evidence of this trend for cool storage systems. This source of cost reduction was noted in the Vincent survey and in the results from a national survey conducted in 1984 of 76 cool storage installations (Hersh, 1984). Because of the physical size and availability of cool storage systems, shipping charges become a factor in the first-cost figure. Transportation costs can add as much as three to ten percent to the cost of a delivered system (Reeves, 1985). Naturally, there tends to be greater penetration of specific types of systems near the location of specific manufacturers (McCannon, 1987).

On a per-system basis, partial-storage systems, being smaller, will have lower first costs than full-storage systems. The Vincent survey confirmed this. The average cost of the partial-storage systems was $187/kW (from a sample of 12). The average cost of the full-storage systems was $826/kW (from a sample of 27). This price differential may be overstated, however, since many of the early systems, which also tended to be the more expensive, were full-storage systems.

Section 3 of Tables 5 through 7 contains a summary of the costs of the cool storage systems for our three sample buildings. For Building 1 no first-cost increases were reported for installing the cool storage system since other equipment was down-sized. For Building 2's cool storage system only estimated design costs are available, although we know that substantial costs were incurred in the first few years of operation to make modifications to the system. This was an early cool storage system and is not representative of current system costs. In these tables all of the cost data are in dollars per square foot to show how the values compare to other floor area normalized costs.

3.2.2 Operating Costs

Two main factors driving the choice of a cool storage system are the first cost and potential savings in electricity costs. For a given system, savings in annual operating costs depend on the rate schedule of the building. There are over 3000 electric utility companies in the United States, each having multiple rate schedules for different customer classes. In general, either a demand charge or TOU energy rate (preferably both) must be present for thermal energy storage to be cost-effective. As of 1984, TOU rates were present in 40 of the States in the U.S. (NARUC). Some systems designed with heat recovery show net decreases in energy use as well as reductions in peak demand, as was the case with Building 3.

Assessing the savings in operating costs requires comparing utility charges for a storage system with those of a conventional system: this comparison demands careful consideration of the electricity rate schedule. The electricity charges for Building 1, for example, are based on a monthly energy charge plus a demand charge for each month's maximum demand during the on-peak period; in this case the goal of the cool storage system is to reduce the maximum on-peak demand. Since the cool storage system operates from about May through October, the savings analysis focused on the summer months. As shown in Table 5, in 1985 the summer savings amounted to about $0.11/ft^2. (The cool storage system operated only in the summer so the annual energy cost savings are equal to the summer energy cost savings.)

For Building 2 we compared the actual building's energy consumption with the design stage simulation results for a conventional system. This type of comparison is common, but can be highly inaccurate if actual building conditions differ significantly from the simulated base case conditions. We mentioned that actual weather and occupancy patterns often differ from early design estimates. The comparison in this case is of interest to us because it illustrates the need to look at each component of annual electricity costs. The rates for Building 2 consisted of separate peak demand charges for winter and summer. With the cool storage system installed, the annual maximum peak demand occurred in the winter, making the winter demand charges for the actual building much greater than those for the building with a conventional system. Overall electricity costs for the actual building were greater than those for the conventional building but less than those for the conventional building when the winter demand charges were not included in the comparison. Furthermore, we see that there would be greater annual savings if the differential between the on- and off-peak energy charges were increased.

Our final example, Building 3, shows the savings for a building under a ratcheted rate schedule. Again, the savings of $0.11/ft^2 is based on the differences between demand charges for the actual and simulated building, not on the total electricity charges. Unlike for Buildings 1 and 2, we consider the total annual demand charges, not only the summer demand charges, because the summer peak demand is used in the ratchet to calculate winter demand charges.

In section 2.1.6, Control Strategies, we described the operating strategies of chiller priority and ice priority. The choice between these two strategies should be based on the electricity rate structure. It is about 10 percent less efficient in kW/ton to make ice (20 °F suction, 90 °F discharge) at night than it is to operate the chiller during the day (40 °F suction, 105 °F discharge). Therefore, if night rates are more than 10 percent below day rates, it is cost-effective to use ice rather than chiller priority (MacCracken, 1986).

Further comments about cost-effectiveness are contained in section 4.0, Implementation Strategies.

3.2.3 Maintenance Costs

Very little information is available on maintenance costs associated with cool storage systems. EPRI's design guide suggests that operating and maintenance costs may be higher for cool storage systems as compared to conventional systems because of a greater need for operating labor and supervision (Reeves, 1985). Additional materials and supplies also may be needed. On the other hand, since cool storage equipment is generally smaller than conventional equipment, water requirements may be lower, and savings in cooling tower make-up water can be significant.

4.0 IMPLEMENTATION STRATEGIES

For cool-storage technologies to be widely implemented in the commercial sector it is important that building owners and managers recognize the economic advantages of these systems. For this to occur, information about this new technology must be widely disseminated. Some of the specific elements of the electricity rate structure that constitute economic incentives are demand charges and TOU rates. Direct assistance in the form of reduced installation costs provide an additional reason to invest in this new technology.

4.1 Pricing

As we have shown, the cost-effectiveness of cool storage is highly dependent on electricity rates. Utilities nationwide are adopting rate structures that will provide greater incentive to their customers to encourage load shifting. Most of these rates differentiate demand, and/or energy charges by time of day. For cool storage to be economical the most significant rate features are the on-peak/off-peak price differential and the length of the on-peak period. Also important are seasonal price changes.

Consider, for example, the rates offered by SCE, which has been a leader in encouraging the implementation of cool storage. SCE introduced TOU rates in the late 1970s (MacCracken, et. al. 1987). They now have three TOU rates available to customers. One of the three is referred to as TOU-SOP (super off-peak). This rate includes low off-peak electricity rates but very high on-peak penalties. Separate service connections or meters are allowed at SCE's option (Smith, 1987a). This provision for separate metering allows the TOU-SOP rate to be applied to the cool storage system alone. Furthermore, the TOU-SOP rate has a short on-peak period, which allows for the use of small cool storage systems.

In California, the Public Utilities Commission has authorized a number of rate changes that encourage load shifting from on-peak periods. For SCE the Commission is considering marginal cost-based rates which further increase the cost differential between on-peak and off-peak use. Currently the TOU-SOP rate has an $8.00/kW on-peak summer demand charge. Table 8 shows the TOU-SOP rate that went into effect January 1, 1988, in which the on-peak summer demand charge for TOU-SOP is $33/kW. This is one of the highest, if not the highest, kW charge in the United States. For comparison, Table 8 also shows a conventional TOU rate for SCE.

Data collected from 40 feasibility studies was used by SCE to study the effect of SOP rates on payback periods (Hassan, 1986). With utility rebates included (discussed in the next section, 4.2.1), the average simple payback under a conventional TOU rates was 4.4 years, with a minimum of 0.63 years and a maximum of 9.7 years. Under the SOP rates the average payback period was reduced to 2.6 years, within an overall range of 0 to 6.5 years.

Minimizing the highest on-peak demands in each of the four summer months is crucial with TOU-SOP charges. A single mistake in operation during one of these hours could drastically reduce annual savings, even if the resultant increase in peak demand does no coincide with the utility system's peak. Because of concern about this, a "forgiveness" clause, perhaps for the first summer of operation, has been suggested. A benefit of the TOU-SOP rate is that load profile data for the cool storage system is available from the additional meters. Many of the buildings using the TOU-SOP rates also use Energy

Management Systems for building and system control. Data from the EMS can, in theory, be used in conjunction with the cool storage meter to create detailed performance data that could provide valuable feedback on the installed technical and economic performance of the installed system (Campoy, 1987, Heinemeier, 1987).

Table 8

Comparison of Demand and Energy Charges for Conventional Time-of-Use and Super-Off-Peak Electricity Rate Schedules

	TOU-8		TOU-SOP	
	Summer	Winter	Summer	Winter
Demand Charge ($/kW/Month)				
On-Peak	13.25	N/A	33.00	N/A
Mid-Peak	2.05	0.00	0.90	0.45
Off-Peak	0.00	0.00	0.00	0.00
Non-TOU	2.70	2.70	2.70	2.70
Energy Rate ($/kWh)				
On-Peak	0.107	N/A	0.129	N/A
Mid-Peak	0.077	0.083	0.129	0.066
Off-Peak	0.050	0.050	0.046	0.050
SOP	N/A	N/A	0.037	0.037

	TOU-8	TOU-SOP
Time of Use Periods		
Summer	July 1 - Sept. 30	July 1 - Sept. 30
On-Peak Hours On-Peak Days	1 - 6 P.M. Monday - Friday	1 - 5 P.M. Monday - Friday
Mid-Peak Hours Mid-Peak Days	8 A.M. - 1 P.M./6 - 10 P.M. Monday - Friday	10 A.M. - 1 P.M./5 - 9 P.M. Monday - Friday
Off-Peak Hours Off-Peak Days Off-Peak Hours Off-Peak Days	All Other Hours Sunday - Saturday	6 - 10 A.M./9 - 12 P.M. Monday - Friday 6 A.M. - 12 P.M. Sunday - Saturday
Super-Off-Peak Hours Super-Off-Peak Days		12 P.M. - 6 A.M. Sunday - Saturday

Source: Smith, 1987.

Notes:

Southern California Edison TOU-SOP will be effective January 1, 1988. Customer charges are $250/Month for both rates. TOU-8 is a standard SCE TOU rate.

N/A - Not Applicable.

4.2 Incentives

4.2.1 Direct Incentive Payments

Many utilities have taken an active role in promoting thermal energy storage. About 25 throughout the country offer customers direct payments called rebates, incentives, or inducements, for reducing on-peak demand. A few offer grants for feasibility studies. Table 9 shows the summarizes the plans and dollar amounts offered by utilities.

Table 9
Utility Incentives for Commercial Cool Storage Installations

Utility [1]	Inducement per kW Shifted	Maximum	Feasibility Study
Anaheim Public Utilities	$60	$50,000	$5000
Arizona Public Service [2]	$115-250	No Max	
Boston Edison	$200	No Max	
City of Austin Power & Light [3]	up to $300	No Max	
City of Denton Util. Dept. [2]	$200-350	No Max	
City of Palo Alto [4]	$350-425	$250,000	
Consolidated Edison Co.	$500	50%	
El Paso Electric Co. [5]	$200	No Max	
Florida Power & Light	$200		
Jersey Central Power & Light Co. [2]	$125-250	$200,000	
Long Island Lighting Co.	$300	$50,000	
Los Angeles Dept. of W.&P.	$250	40% or $150,000	
New England Elec.	$160	No Max	
Northern States Power	$175	No Max	
Oklahoma Gas & Elec. Co.	$200	$50,000	$500-1500
Pennsylvania Elec. Co.	$250	No Max	
Pacific Gas & Elec. Co.	$200	$150,000	
Public Service Elec. and Gas of NJ [2]	$125-250	No Max	
Riverside Public Utilities	$200	No Max	$5000
Sacramento Muni. Util. Dist.	$250	No Max	Limited No.
Salt River Project [2]	$115-250	$98,000	
San Diego Gas & Elec. [5]	$200-350	No Max	
Southern California Edison	$200	$300,000	up to $5,000
Texas Utilities Elec. Co. [2]	$125-350	No Max	
Wisconsin Elec. Power Co. [7]	$200	No Max	up to $5000

Source: ITSAC, Jan. 1988

Notes:

1. Numerous additional U.S. utilities have inducement plans under development or commission review.
2. Rebates based on number of kW shifted.
3. Rebates based on providing a 3 year payback.
4. Rebates based on whether new or retrofit project.
5. Rebates based on a negotiated payback.
6. Rebates based on number of kW shifted, whether new or retrofit project, and whether on flat or TOU rates. New construction rebates are based on installed tonnage.
7. Straight rebate offered, or five-year no-interest loan up to $750/kW.

Again, as noted above, the average simple payback period offered by SCE for the systems described in the 40 feasibility studies was 4.4 years (Hassan, 1986), with a rebate of $200/kW and a limit of $100,000. The study noted that there was a shift in cost per kW shifted for the largest eight systems, those over 500 kW. These larger systems cost $651/kW while those under 500 kW averaged $485/kW. The average payback periods in these cases were 4.6 and 3.4 years, respectively. When SCE's rebates were excluded from the calculations the average payback period rose to 7.1 years for those over 500 kW and 5.6 years for those under 500 kW.

As mentioned above, numerous assumptions go into calculations of the amount of kW shifted. Since most utility rebates are based on this value there is an incentive for engineers to maximize the estimated demand shift. On the other hand, where utility rebates are calculated to payback in a certain amount of time, there is an incentive to maximize the system cost, in order to receive a significant rebate. For these reasons, standardization of performance and cost comparisons would be of use to the utilities, building owners and operators, and design engineers. Measured performance results comparing engineers predictions with actual system performance would also help in evaluating design methods.

Unlike a feasibility study which helps determine whether load shifting is possible for a given building, design assistance is offered in some areas to help architects and engineers develop specific designs for energy efficiency features. One such program, beginning in the Pacific northwest, is the Energy Edge Design Assistance Program, sponsored by the Bonneville Power Administration (BPA, 1987). In some cases cool storage systems may be included in such programs.

4.2.2 Tax Credits

At least one state provides owners with tax credits for installing and using cool storage. During 1986 Hawaii passed a bill that provides 15 percent state income tax on the cost of cool storage systems. The tax credit applies to systems installed and in service after December 31, 1985 and before December 31, 1992 (ITSAC, Aug. 1986).

4.3 Energy Service Companies

Energy service companies are considering offering financing and project management or turnkey project development for cool storage systems (ITSAC, Jul. 1987). Until now there has been little (or no) experience with shared savings plans. The cool storage market appears particularly viable for energy service companies because, as a new technology for many HVAC engineers, it presents energy service companies with the opportunity to become "experts" at designing, installing, and operating cool storage systems.

4.4 Regulatory Codes

At present, most building standards in the United States address energy conservation more than peak demand savings or electric load shaping. There may be greater emphasis on shifting and shaving peak demands in the future. For example, the California Energy Commission is considering the adoption of a commercial load management standard to address load growth in the commercial sector (Smith, 1987b). In general, when standards allow for cost based comparisons, i.e. when compliance can be achieved by comparing the operating cost under the applicable rate schedule of a base-case building with the building design of interest, cool storage can often fare well. Such is the case with the proposed ASHRAE Standard 90.1P (ANSI/ASHRAE/IES, 1987).

4.5 Information Dissemination

Disseminating information about cool storage systems also encourages their implementation, just as installations of these systems generate more information and new products. Demonstration projects sponsored by EPRI and various utility companies offer customers concrete information on products and systems. The International Thermal Storage Advisory Council, one of the most updated source of information trends in the commercial cool storage industry, publishs monthly newsletters. ASHRAE has also been strongly involved in publishing information on cool storage. Cool storage is the core work of ASHRAE's Technical Committee 6.9, which sponsors research projects and conference sessions, and oversees publication of cool storage documents.

5.0 MAJOR UNCERTAINTIES AND BARRIERS

5.1 Technical Performance Concerns

The estimated economic benefits of thermal storage have to be weighed against the risks of installing a cool storage system. A number of uncertainties face a designer, the greatest being whether or not the operator can assure cost-effective operation under actual building conditions and under actual electricity rates, which might change over time. Under some rate structures there may be severe penalties for a brief, one-time increase in electrical demand due to an event such as a control failure. For example with SCE's TOU-SOP, one hour of inappropriate chiller operation during the on-peak demand period could drastically reduce annual savings.

Initial costs for cool storage systems seem to be falling, and maintenance costs appear to be slightly higher than those of conventional systems. There is little information on maintenance costs, however, and no solid experience on effective lifetimes of these systems. Reliability has been good in the dairy industry and in assembly buildings. In terms of particular system types, reliability appears to be best in ice harvester systems; it has been poorer in chilled-water systems although this may be improving.

Although risks are associated with cool storage systems, there is also safety and redundancy from stored cooling. Because they have fewer moving parts, for example, ice storage modules can be the most reliable part of an air conditioning system (MacCracken, 1986). Because of backup cooling associated with its cool storage system, a Xerox Corporation plant recently avoided about $500,000 in lost production time when a chiller went down (Racavelli, 1987).

As is common with new technologies, early cool storage installations experienced a number of problems. Table 10 contains a summary of the operating experiences for ten buildings that have been examined in detail (Piette, 1987). Many early systems were sized improperly and control failures plagued many of them. In one case the cool storage system had to be removed from the building. For six of the buildings inexperience of building operators was cited as a problem. Fortunately, in almost every case, system performance improved over the first few years as experience was gained with the equipment and building operation.

Perhaps the most widely publicized example of a troublesome cool storage system is the controversial State of Illinois Center in Chicago, where a $2 million was required to add more capacity to the undersized ice-making system and to modify other HVAC equipment (Building Design and Construction, 1986). Disputes and misunderstandings about occupancy levels and cooling loads lay behind the breakdown and resulted in the State suing the designer. It is critical that details about the building's internal loads and occupancy patterns be known by the designer and the ramifications understood by the building operators.

Table 10
Summary of Early Operating Experiences

	Building number										
	1	2	3	4	5	6	7	8	9	10	TOT:
DESIGN FACTORS											
storage sizing		u				o		u	o		4
compressor sizing						o				o	2
condenser sizing										u	1
refrigerant receiver		u					u				2
water flow inadequate							x				1
storage poorly insulated							x				1
SYSTEM OPER. & MAINT.											
control strategy unsatisfactory						x					1
improper expansion valve settings		x				x					2
time clock malfunctions	x	x					x	x	x	x	6
compressor failure		x		x		x					3
compressor control failure	x			x					x		3
refrigerant leaks	x	x					x		x		4
storage leaks				x				x			2
inexperienced maintenance personnel	x					x	x	x	x	x	6
inexperienced outside contractors	x	x			x		x			x	5
poor sensor calibration & maintenance		x						x		x	3
insufficient cooling on hottest days		x									1
excessive storage during mild weather		x					x		x	x	4
CHILLED WATER SYSTEMS											
poor tank stratification			x					x			2
ICE SYSTEMS											
ice thickness control failure		x					x		x	x	4
improper operation of ice agitator		x									1
TOTAL:	5	12	1	3	1	6	9	6	7	8	
problems corrected		x		x							

u - undersized, o - oversized

Source: Piette, 1987.

5.2 Market Barriers

HVAC engineers belong to a well established industry and, as such, have inertia behind their "tried and true" design practices. They are confronted with a lack of experience with cool storage technologies, and a lack of standard products and rating procedures for those products. As mentioned in section 4.4 on information dissemination, there are a number of organizations involved in providing information to the engineering community. ASHRAE, ITSAC, and EPRI have been most prominent.

6.0 RECOMMENDATIONS FOR FUTURE WORK

We have presented a variety of perspectives on the status and potential of cool storage systems in commercial buildings. Electric utilities are encouraging the adoption of these systems by the commercial sector, the largest contributor to peak loads. Although not a completely new technology, cool storage is being applied in new situations. There are many questions still unaddressed regarding the actual cost-effectiveness of cool storage. First costs have reportedly come down, but few data are available on the operating and maintenance costs of installed systems. Diversity in electricity rate schedules creates the need for various types of cool storage systems and control strategies. A crucial question is whether and how individual control can be optimized to create savings under the building's electricity rates.

Our recommendations for future work in the various areas covered in this report are:

Performance and cost-effectiveness documentation

- Utilities investing up-front in cool storage should monitor the performance of their investments. Less expensive monitoring techniques, such as EMSs, should be used, or modified for use as data acquisition systems whenever possible. The information gained will be of use not only to the utility, but to building operators and design engineers; it is also important for credibility purposes and to accelerate market penetration.
- Utility bills should be collected for at least the initial cooling season and compared with predicted performance. Re-assessment of conventional system performance may be necessary if internal loads, operating schedules, or weather conditions differ from design conditions.
- Better estimates of cool storage potential require more detailed data on peak demand and building characteristics than are currently available. Such data will be of value to architects, engineers, and energy planners.

Implementation

- Design assistance programs sponsored by utility companies would be a useful way to assist engineers, developers, and architects in incorporating cool storage into a building.
- Building operators require training if they are to take optimal advantage of cool storage technologies. Utilities should consider providing operating and maintenance assistance for the first summer, or few years.

Research and Development

- Standard techniques should be developed for analyzing system performance. Choosing which physical performance parameters are most relevant depends on the electricity rate schedule.
- More information is needed to assess the sensitivity of both incremental first costs and operating savings to the choice of the "base case" conventional HVAC configuration.
- Consideration of EMSs should include exploring how to adapt them to evaluate the performance of a conventional system under actual operating conditions.

- Demonstration projects provide valuable information on the feasibility of technologies in practice and should be encouraged.

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8.0 APPENDIX

8.1 Cooling System Terminology

- **Chiller capacity** is generally given in tons (also used to mean a rate of cooling). Storage capacity and cooling load are then expressed in ton-hours.
- The **chiller efficiency** is the tons of output per kW input, expressed in kW/ton. Energy input to the chiller is generally given in kilowatts, and the output of the device is in tons.
- The **coefficient of performance** (COP) expresses the efficiency of a complete cooling system and represents the ratio of the desired energy (heat to be extracted from a space) to the energy needed to obtain this result (work). It is dimensionless.
- The **cooling system** refers to all components of the system, including both the chiller (compressor, evaporator, and condenser) and the storage equipment. Often the condenser water pumps and cooling tower fans are also included.
- The **daily cooling load** is the integral of the instantaneous loads throughout the design day. Generally given in ton-hours, it is used in determining the necessary storage capacity.
- The **peak cooling load** is the maximum instantaneous cooling demand for a given period, in units of tons. The peak cooling load, estimated during the design process, occurs on the "design day" (i.e., the day with the most demanding load conditions of the year).
- **System efficiency** is the energy input required for a given cooling output: the higher this total, the less efficient the system. It is the ratio of the system's electricity consumption (kWh input) to the amount of cooling obtained, in ton-hours (output). It is generally given in kW/ton.
- A **ton of cooling** is defined as the rate of cooling equal to the melting of one ton of ice over 24 hours; based on the heat capacity of ice, this is equivalent to 12,000 Btu per hour. Since the latent heat of fusion of ice is 144 Btu per pound (335 kJ per kg), one ton of cooling is equivalent to 12,000 Btu/hour (12.66 MJ/hour). (Simple conversion between Btu and kWh yields 3.52 kWh/ton.)
- A **ton-hour** is the amount of cooling energy available or that has been expended (as work). It is expressed as the product of the cooling rate (in tons) and the number of hours of cooling at that rate. Storage equipment sizes are given in ton-hours.

8.2 Energy and Load Performance Parameters

- **Annual peak electric demand intensity** (kW/ft^2) is defined as the highest electric demand for the year for each building, normalized by the floor area.
- The **kW shifted** is usually defined as the reduction in peak demand on the peak day of the building's maximum annual peak demand. However, if the building demand peaks in the winter, the kW shift of interest may be the shift that occurs on the highest peak day of the cooling season.
- **Load factor** is the average electric demand divided by the peak demand for a given period. This ratio is dimensionless. Load factors may be calculated for the whole-building demand or the cooling-system demand. They may also be calculated for the on-peak period. Load factors are generally less than one, but may be greater then one when defined as the ratio of the average demand

(for all hours in the year) to the maximum on-peak demand, and the maximum load occurs during off-peak periods.

- The **percentage of electricity used on-peak** is the ratio of the electricity consumed during on-peak utility hours to the total electricity consumed for a given period. The value decreases as the building cooling loads are shifted from on-peak to off-peak periods. Interpretation of the parameter should consider loads such as computer or heating demands during on-peak periods.

8.3 Economics Terminology

- **Annual energy operating cost intensity** is the total annual electricity cost, including energy and demand charges, normalized by the floor area.
- The **cost per cooling ton** can be used as an inter-building comparison of capital costs, and is the ratio of system first-cost divided by the cooling load. A difficulty in comparing this ratio among buildings lies in the definition of "cooling load," which can be either a design-day cooling load, a calculated load based on measured air flow rates, or simply the capacity of the primary cooling equipment.
- The **demand costs as a percentage of energy operating costs** is the demand cost portion of total electricity costs. This figure is useful in the design stage; a high value indicates greater potential for savings from cool storage.
- **Percentage of operating costs on-peak** is the ratio of the electricity costs due to on-peak period operation divided by the total energy costs. Where a building shows a declining value, compared to a conventional system, is one indicator of economic success for cool storage.

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