MEASURED ENERGY PERFORMANCE OF COOL STORAGE IN COMMERCIAL BUILDINGS: AN UPDATE OF BECA-LM*

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ABSTRACT

Over the past several years, numerous utilities and state agencies have sponsored programs and offered incentives to encourage improved energy efficiency in buildings. Many recent efforts have been in the area of load management. One of the most promising load management technologies is the application of thermal storage for cooling commercial buildings. Cool storage is generally used as an electrical load management strategy to reduce on-peak electric demand by shifting the compressor's operation to off-peak hours, when electricity costs are lower.

There have been very few studies to assess the performance of cool storage installations. This paper contains information on the performance of eleven actual installations. These data are contained in the BECA (Buildings Energy Use Compilation and Analysis) data bases as part of BECA-LM (load management). Our analysis consists of organizing the performance data into six general categories, which fall into a three-by-three matrix. The three categories of performance data are: 1) the cooling system, 2) the whole-building data, and 3) the economics (incremental costs and electricity charges). For each of these categories we compare three system configurations: 1) the actual measured performance, 2) the estimated "design" performance, and 3) the estimated conventional (base case) system performance. Subcategories of data include parameters such as load factors, electric peak demand intensities, system efficiencies, operating costs, and payback times.

Cost-effectiveness of the cool storage systems vary greatly for the buildings examined. Simple payback periods of less than one year have been observed, yet the payback periods for many systems are much longer. Average system efficiencies vary from 1.4 kW/ton (for a chilled water system) to 2.4 kW/ton (for an ice storage system). Most of the buildings experience a significant "shake down" period of one or more years (i.e. performance improves over the first few years). Lack of experience by building operators and difficulties with controls, such as controlling ice building, are typical problems.

Collecting the necessary data has been difficult. Since savings are based on a comparison between the actual system and a conventional one, cost-effectiveness depends on the definition of base case performance. We note inconsistencies in the definitions of both first costs and operating costs. Few buildings have been monitored in detail, nor has monitoring been done in a consistent manner across buildings.

Cool storage shows great promise for load shifting capabilities. First costs appear to be coming down, and design engineers and building operators are gaining important experience with the technology.

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INTRODUCTION

Over the past several years, numerous utilities and state agencies have sponsored programs and offered incentives to encourage improved energy efficiency in buildings. Many recent efforts have been in the area of load management. One of the most promising technologies is the application of thermal storage for cooling commercial buildings.

Commercial cool storage addresses the growth in commercial space cooling, which currently accounts for about 20 to 40 percent of most utilities' summer peak demand (MacCracken, 1987). It is applicable to both new and existing buildings. The basic approach is to reduce on-peak electric demand (kW) by shifting the compressor's operation to off-peak hours, when electric service charges are lower. Cooling energy is stored in the evening (using a medium such as water or ice) to be used the next day during occupied hours, which also coincide with higher peak-period utility rates. Operating savings in electricity charges are greatest when demand or energy charges are time-differentiated. The technology benefits both building owners and managers who wish to lower their electricity costs, and electric utilities who generally want to increase load factors and defer the need for new generating capacity. For new buildings, first-cost savings from downsizing the chiller capacity pay for some, and in some cases all, of the costs for storage. Because of lower operating temperatures, fans, pumps, and ducts can also be downsized, further reducing first costs. There are numerous approaches to and a wealth of information on cool storage design (Reeves, 1985 and ASHRAE TC 9.6, 1987).

There have been very few studies to assess the performance of actual cool storage installations. Our overall goal is to identify cool storage designs that are successful by assessing the limited data that are available. This paper contains information on eleven actual installations. Much of our effort to date has consisted of developing performance indicators which allow us to present the data using a consistent framework. This effort is part of the "BECA" (Buildings Energy-Use Compilation and Analysis) data base project by the Buildings Energy Data Group at Lawrence Berkeley Laboratory, which has been compiling and analyzing measured data for commercial and residential buildings that have incorporated energy-saving and load management techniques. BECA-LM (Load Management) contains brief characteristics data for 382 cool storage installations and more detailed performance data for eleven commercial buildings.

DESCRIPTION OF BECA-LM DATA

Information such as a general description of the physical and operating characteristics, energy saving and load management features, energy and power consumption data, and economics data are sought for each building in all BECA commercial data bases. The data are encoded and entered into a computerized data base management system. The information available for each building varies in both quality and quantity.

In addition to collecting this type of general performance data for the eleven BECA-LM buildings, additional details about the description and performance of cool storage systems are collected. We are most interested in buildings where the cool storage systems have been submetered, since the performance of the cooling system cannot be readily determined from whole-building data. Cooling system submetering, with disaggregation by major component, such as chillers, fans, and pumps, is preferable to total cooling system submetering. An important benefit of this disaggregation is that it allows one to compare the components included in "total cooling energy use", since what is included under "cooling" may differ depending on submetering configurations. At a minimum, we compile monthly data, with daily and hourly data compiled when available. To assess operating costs, the monthly data should reflect the building's rate schedule; e.g., we collect peak demands and energy consumption by time-of-use

(TOU) when applicable.

Numerous characteristics of the cool storage system are collected, such as the type of storage medium, operating strategy, storage and chiller capacity, and operating temperatures. Often the most difficult item to assess is the system's incremental first cost over a conventional system. This difficulty is related to the problem of defining a "base case" for performance comparisons, discussed further below.

Although the focus of this paper is on the eleven buildings for which actual performance data have been collected, we briefly discuss other sources of information on actual cool storage installations. For example, we have compiled basic system description data on nearly four hundred commercial cool storage installations that have been identified from past surveys (Hersh, 1984 and ASHRAE, 1984), journal articles, newsletters (ITSAC, 1986 to 1988), utility cool storage program participation lists, and so forth. Such data allow us to study the market penetration of cool storage and follow trends in system type, sizing, etc.

ANALYSIS: DETERMINING PERFORMANCE

Cost-effectiveness is often considered the "bottom-line" criteria for evaluating the success of a new technology. We also assess physical performance parameters. Evaluating a variety of performance indicators is especially important when analyzing load management technologies, where, for example, the timing of energy use relative to a building's electricity rate schedule requires special attention. The two most important basic questions regarding the performance of cool storage: 1) when is the system operating (relative to the rate schedule), and 2) how efficiently does it operate (in kW/ton)?

Defining a Base Case

Determining cost-effectiveness of a cool storage system requires a comparison with a base-case cooling system. The base case for a cool storage system added to an existing building is the pre-retrofit energy performance. To compare pre- and post-retrofit performance, changes in the building that affect cooling (or whole-building) energy use--in addition to the installation of the cool storage system--should be considered. The base case for a new building is based on a hypothetical "conventional" system in the same building. Results of comparisons between cool storage systems and conventional systems are, therefore, very sensitive to changes in the specified characteristics of the "conventional" system. The difference in cost between a cool storage system and a conventional system also depends on how the base-case system is defined.

Simulation tools are often used to calculate how the base-case cooling system might perform. The most precise performance comparisons are based on actual submetered cooling loads and cooling system energy use, which involve modeling the part-load efficiency characteristics of the conventional system's compressor based on the actual hourly cooling load data.

System efficiency data are important output from modeling the base case. Cool storage systems efficiencies are often poor compared with those of conventional cooling systems primarily due to differences in operating temperatures. The system efficiency (kW/ton) is defined as the energy (kWh) required to deliver a certain amount of cooling (ton-hours). The system efficiency is affected by numerous factors. System efficiencies for ice systems tend to be about ten to fifteen percent poorer (i.e., require more kWh for each ton-hour) than conventional systems because of the lower evaporating temperatures needed to build ice. Outdoor temperatures impact the system efficiency through the condensing temperature. Thermal losses through storage tanks also affect the system efficiency.

Performance Parameters

We have identified six general categories (and numerous subcategories) of performance indicators that fall into a three-by-three matrix. The three categories of data are:

1. the cooling system performance,
2. the whole-building performance, and

3. the economics (equipment costs and electricity costs).

Where appropriate the data have been normalized by building floor area to allow comparison among the buildings. Performance indicators discussed include: load factors (the ratio of average demand to peak demand), energy use (kWh/ft^2) and electric peak demand intensities (W/ft^2), system efficiencies (kW/ton), percent of energy used in on- and off-peak periods, shifted demand (W or W/ft^2), operating costs and savings ($/$ft^2$) and payback periods (years). All cost data have been adjusted to first quarter 1987 dollars using Gross National Product deflators.

For each of these categories we compare three system configurations:

1. the actual measured performance,
2. the estimated "design" performance, and
3. the estimated (or measured) conventional (base case) performance.

The three most complete examples from the eleven BECA-LM buildings are presented below.

TRENDS AND PERFORMANCE RESULTS

We begin this section with a description of the status of cool storage in the United States and an introduction to the eleven BECA-LM buildings. This is followed with a discussion of the performance data for seven of the eleven buildings. We conclude with some discussion of related cool storage data and data issues.

There are about 1000 cool storage systems in the United States. Over the past few years the number of systems installed each year has doubled (MacCracken, 1987). There are slightly more ice storage systems than chilled water systems in the U.S. Chilled water systems are more common abroad. A growing number of installations are using eutectic salts as prices continue to come down for these systems. Of these latter systems, most are in Southern California. Cool storage installations are most common in areas where a significant differential exists between day and night demand charges or TOU energy charges. Growth is strongest in areas where utilities offer direct incentives; about 25 utilities currently offer direct rebates for cool storage systems (ITSAC, March 1988). Of the 14 utilities that offer a fixed rebate for each kW shifted the average rebate is $225/kW; the range is from $60/kW to $500/kW. Based on feasibility study data from 13 utilities, cool storage systems shift an average of about 420 kW/site (Piette, 1988).

We have compiled performance data for ten submetered cool storage systems and one building with whole-building data. This later building is a retrofit where two years of pre-retrofit utility bills serve as the base case. Overall, four of the eleven systems are retrofits. Table 1 summarizes the building and system characteristics for the eleven buildings. Actual or estimated simple payback periods and average system efficiencies are also shown. Eight of the buildings are offices, ranging from 12,000 to 1,500,000 ft^2. The third column under "System Characteristics" lists whether the operating strategy was full, partial, or demand-limited storage. Figures 1.A. through 1.D. show the impact of each of these strategies on whole-building and cooling-system hourly load profiles. Full storage systems are designed to allow the storage to meet all of the on-peak period cooling requirements. Partial storage systems have smaller chillers than full storage systems. With partial storage the chiller runs continuously to both charge the storage at night and help meet cooling loads during peak periods. For demand-limited systems, which are a type of partial storage, chillers may run at any time except when the whole-building demands reaches a set maximum: the demand limit. As expected, the buildings with the largest installed storage are those with full storage (Buildings 2, 4, 7, 9, and 10), ranging from 14 to 29 ton-hours/kft^2. The four partial storage systems range from 4 to 9 ton-hours/ft^2. Many early cool storage designs were full storage systems. Partial storage systems are becoming the most common due to their lower first cost.

Table 2 contains a summary of the difficulties for Buildings 1 through 10. About half of the systems were improperly sized. Control failures were also common. In six of the ten cases time clock malfunctions were reported. Inexperienced operators were also cited as a problem in six of the ten cases. Fortunately, in almost every case the system performance is expected to improve as experience is gained with equipment.

Cool Storage Retrofits

Building 1. This is one of the four BECA-LM buildings that is owned and occupied by the utility for demonstration purposes. The metering configuration differs from the others in that the cool storage system is part of a larger, multiple-building cooling system. The cool storage system was designed to meet only a small part of the complex's cooling load (Hersh, 1984). The initial estimate for the payback period was 5.7 years, as listed in Table 1. Based on the submetering, the payback period is about 5 times longer than the original estimate. Initial problems, although minor, have included time clock malfunctions, a refrigerant leak, and a compressor failure, as shown in Table 2. Building engineers have been generally satisfied; performance is expected to improve.

Building 7. Energy use data for this retrofit of a conventional direct-expansion cooling system consisted of submetering for 20 months over two years (Ayres, 1985), which included three weeks of metering the original conventional system prior to the installation of the ice storage system. Overall, the performance of the ice storage system was poor. The system shifted an average of about 3.2 W/ft^2, or 15.6 kW of the on-peak demand during the summer test period. Energy use was 19 percent higher for the ice system because the system efficiency averaged 2.4 kW/ton, versus 1.5 kW/ton for the conventional system.

The poor efficiency was largely due to an undersized refrigerant receiver. Other problems included ice thickness control setting difficulties, poor water flow through storage, inadequate tank insulation, and time clock malfunctions (Table 2). The system's peak demand occurred at 8 P.M. when the compressor came on, yet the on-peak demand period extends to 9 P.M. This exemplifies the difficulty of using storage when the electricity rate schedule has a long on-peak period. Short off-peak periods may not be long enough to allow a chiller to fully charge the storage. For Building 7, if charging begins at 9 P.M. (after the on-peak period ended), the apparent 11 hour charge time would extend to 8 A.M. and add to the start-up peak. That would be an improvement only with dependable controls, because if the chiller did not cut off before 9 A.M., a peak might occur that would be larger than the 8 P.M. peak.

Building 9. Building 9 also suffered from poor design. Following the retrofit the whole-building annual peak demand did not decrease, but slightly increased in the two post-retrofit years. Maximum peak demand intensities were 5.1 and 6.1 W/ft^2 in the last two years with the conventional system, and 6.1 and 6.5 W/ft^2 for the first two years with the cool storage system. Energy use rose about seven percent with the installation of the cool storage system. Changes in building conditions other than the installation of the cool storage system may have contributed to the changes in energy use and peak demands, but details are not available. Among other problems, the storage was greatly oversized. Performance for Building 9 is expected to improve with system modifications, such as readjusting the ice thickness sensors.

Building 11. No submetered data are available for this building. Utility bills indicate there has been significant reduction in peak demands due to the installation of the cool storage system. This building exemplifies the high cost-effectiveness of cool storage when old chillers need replacement and smaller chillers can be used. For three years prior to the installation of the ice storage system, comfort had been maintained by only one of the two 50 ton compressors, which were installed when the building was built in 1959 (PEPCO, 1984). The current cooling load was calculated to be only 46 tons, not 100 tons.

Two options for cooling system modifications were examined: 1) replace the compressor with a new 50 ton water-cooled compressor to be used with the existing cooling tower, or 2) replace the entire cooling system with a 15 ton air-cooled chiller with three ice banks. The cool storage system had an incremental cost of $3053 over option 1 (in first quarter 1987 dollars). During the first year of operation of the cool storage system the electricity costs were $2181 below the previous year, yielding a simple payback of 1.4 years. Based on a comparison with the two preceding years, there was a reduction in the annual peak demand of 2.1 W/ft^2 (35 percent reduction) in August, the month of the highest post-retrofit demand, and of 3.9 W/ft^2 (56 percent) in June, the month of the highest demand shift.

Additional Cost-effective Retrofits. Two other highly cost-effective retrofit scenarios are worth noting. First is the use of cool storage in a facility with multiple chillers, when one chiller needs replacement. With the installation of cool storage, there may be no need for new chiller capacity. Plus, the remaining chillers operate more fully loaded, causing the overall efficiency to improve. Second is the use of cool storage for facility expansion. Here again the cost of storage may be lower than that of adding a new chiller (Tamblyn, 1987).

Cool Storage in New Buildings

In this section we discuss the three buildings with the most complete performance data to illustrate our analytical methods and performance results.

Building 4. Along with having the most complete data, this building is also the most successful in terms of cost-effectiveness. This site is the only one we examined for which the reported cool storage system costs were below the cost of a conventional system, as shown in the "Costs" section of Table 3 (McNeil and Mathey, 1986). Cooling system data are shown in the first section of Table 3. As expected, the system efficiencies for the actual building were slightly worse for the cool storage system than the estimates for a conventional system. This resulted in slightly higher energy use for the ice system than that which would have been consumed by a conventional system. Although the compressor efficiency for the conventional chiller was a low 0.77 kW/ton--well below the cool storage chiller's 1.03 kW/ton--the auxiliary loads are much smaller for the cool storage system, so the total efficiencies compare well. The auxiliary loads are smaller for the cool storage system because of the use of smaller fans and pumps. The average efficiency for the cool storage system in 1985 was 1.77 kW/ton and the average efficiency for the conventional cooling system was 1.56 kW/ton. Furthermore, unlike the cool storage system with an air cooled compressor, the conventional system would have used a cooling tower, which lowers efficiency.

At first glance the cool storage system efficiency seemed poor (McNeil, 1986). Each night the system was becoming fully charged, but not all of the ice was "burned-off" each day. The insulating effect of the remaining ice inhibits heat transfer and causes degradation of compressor efficiency. The system controls could be modified to improve the efficiency by "burning-off" all ice before building additional ice. However, the system successfully accomplishes its design goal of reducing peak demands; therefore, modifying the system is not a priority for the owners.

Given summertime energy use and on-peak demand data for the cooling system it is useful to calculate an "on-peak cooling load factor". This load factor was 0.34 for the summer of 1983, but was estimated to be greater than one if the system is working at its optimum. Load factors greater than one 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.

The cool storage system performance improved over the first few years, a common experience with cool storage systems. This is seen by comparing 1983 data, which is the second year of performance, with 1985 data, as shown in Table 3. Whole-building performance did not improve, largely because of increasing computer energy use. The whole-building data in Section 2 of Table 3 also show the peak demand shift for the month with the highest demand (Max month), and the maximum monthly shift (Max shift). The Max shift is one of the most common performance indicators for cool storage systems. Utilities that offer rebates for cool storage often use this value to calculate the size of the rebate for a particular system (i.e. $/kW shifted). Rebates are generally based on the design estimate of the maximum shift, not on the actual demand shift by system. The Max month is of interest because it shows how much was shifted on the day that demand was highest, a trying time for a cool storage system, especially if the rate schedule includes a ratchet. (A ratchet is an electricity rate schedule in which past maximum demands are taken into account to establish bills for a given period.)

Building 3. The next example is a 1,500,000 ft^2 office building in Texas that uses a heat recovery system along with the chilled water system. Heat recovered from the condenser is used for perimeter space heating. Table 4 shows the performance matrix for Building 3. Cooling system performance data are unavailable for this building, although some submetering has occurred (Tackett, 1987). The cool storage system shifted a total of 1.71 W/ft^2 in the summer month with the highest peak demand, or 2565 kW. The operational savings of $\$0.11/ft^2$ and the 5.3 year payback is based on the differences between total demand charges for the actual building and the estimates for the same building with a conventional system, not on the total electricity charges. The electricity rate structure for Building 3 includes a ratchet, which causes each month's billed demand to include a fraction of the maximum peak demand that occurred during the previous summer. Table 4 excludes the savings in electricity charges resulting from the heat recovery system because we are primarily concerned with the cool storage system. When the savings from heat recovery are included along with the cost of the heat recovery system, the payback reduces to 4.1 years.

Building 2. Our final example again illustrates the need to examine the details of rate schedules (Table 5). Though not many cool storage systems have been submetered, many are simulated at the design stage and an estimate of the performance of a conventional system is generated. This type of comparison is common, but can be inaccurate if actual building conditions differ significantly from the simulated base-case conditions. Comparing the simulation results and the actual building performance is of interest in this case because it illustrates the need to look at each component of electricity costs.

As shown in Table 5, most of the cooling system energy use was successfully shifted off-peak (89 percent), which is important since TOU energy charges were applicable to this building. Unfortunately the off-peak maximum cooling demand (4.5 W/ft^2) was not far below the on-peak demand (5.1 W/ft^2), showing that the compressor occasionally operated during on-peak hours (9 A.M. to 10 P.M.). As is common for buildings with cool storage systems, the whole-building maximum *summer* peak demand (9.7 W/ft^2) was well below the estimate for the building with a conventional system (12.6 W/ft^2), yet slightly above the design estimate for the cool storage system (9.1 W/ft^2). The actual annual maximum peak demand occurred in the *winter*, making winter demand costs 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 building with a conventional system, but less than those for the conventional system when the winter demand charges are not included in the comparison. There would be greater annual savings if the differential between the on- and off-peak energy charges were increased.

A final comment on Building 2: the only cool storage system cost data are available for this building consist of an early design cost estimate. Substantial costs, totaling about 70 percent of this design estimate, were incurred in the first few years of operation to put the system in proper working order. This was, however, an early cool storage system, and the costs are not considered representative of current cool storage costs.

Additional Cool Storage Data and Data Issues

Although commercial cool storage is installed most often in areas where utility rebates are available, we have been unable to look at the impact of rebates on cost-effectiveness due to a lack of data for buildings that have received rebates. Had rebates been available when cool storage was installed in the eleven BECA-LM buildings, payback periods would have been shorter. One source of information on the impact of rebates comes from studies for 40 cool storage systems in Southern California installed in new and existing buildings. When the utility's rebate was included, the average estimated payback period for cool storage was 4.4 years, with a minimum of 0.63 years and a maximum of 9.7 years (Hassan, 1986). The rebate consisted of $200/kW with a $100,000 limit.

As utilities increase the differentials between on- and off-peak energy and demand charges, thermal storage becomes more cost-effective. Southern California Edison (SCE) instituted a "super-off-peak" (SOP) rate, under which cool storage systems are separately metered. All other building electricity uses remain on the conventional TOU rate. Under the 1987 SOP rates, the average estimated payback for the 40 cool storage buildings reduced to 2.6 years, with a range from 0 to 6.5 years. Not only did the SOP rates increase the cost-effectiveness of cool storage, but the separate meters provide useful electricity load profile data for the cooling system. Unfortunately, SCE's electricity rates have changed during 1988 and the cost-effectiveness of cool storage has diminished.

Analysis of initial cool storage system cost data is crucial to understanding cost-effectiveness, but such data are often not addressed in performance analysis. Much of the data currently available on first costs are not reported in a consistent fashion, making comparisons difficult. For example, the incremental costs of a cool storage system may include the cost of an ice builder and the additional piping required, but not the savings from downsizing the compressor or other components. There is some evidence that costs have been decreasing for cool storage, as with most new technologies (Vincent, 1987). Vincent surveyed 47 cool storage systems around the U.S. and analyzed the costs in terms of $/kW shifted. The three main conclusions were not surprising: 1) partial storage systems were less expensive than full storage, 2) new construction projects were less expensive than retrofit, and 3) small cool storage systems had a higher incremental cost, compared with conventional systems, than larger systems. Of the 47 buildings, two had lower first cost than conventional systems. Also, older systems tended to be more expensive.

Another area worthy of further research is the comparison of whole-building and end-use peak demand intensities for various buildings (Meal et al., 1985). For example, the average BECA-CN (new, energy-efficient commercial buildings) office has an annual whole-building maximum peak demand intensity of 5.5 W/ft^2, based on 61 offices (Piette and Riley, 1986). National average demand intensities for office buildings are probably much higher (Burns, 1987). Buildings with cool storage systems should generally have lower than average whole-building peak demand intensities. From Tables 3 through 5 we see that this is the case for Building 3 (2.6 W/ft^2) and Building 4 (5.3 W/ft^2 and 4.6 W/ft^2). Building 2's winter peak demand was a high 19 W/ft^2 with a high summer demand intensity of 9.7 W/ft^2. Some of this high demand is a result of very high lighting demands, which consume over 3 W/ft^2 in this building.

CONCLUSIONS AND RECOMMENDATIONS

We have taken a preliminary look at a number of submetered cool storage systems, including ice and chilled water media, and full and partial storage operation. As expected, cost-effectiveness is dependent on both the electricity rate schedule, and the characteristics of the base-case scenario. We provided actual examples of electricity savings calculations for various rate schedules. Savings calculations must consider how the whole-building peak demands relate to the cool storage system operation, especially if the building is all-electric and reaches its annual peak demand in the winter. Performance results are mixed. While two of the eleven buildings had simple payback periods of under two years, two other systems did not achieve any savings during the monitoring period. Average system efficiencies varied from 1.4 kW/ton to 2.4 kW/ton. Comparable conventional HVAC systems range from 1.1 to 1.6 kW/ton. Excessive ice building is a common cause for the poor cool storage system efficiencies. Improper sizing of compressors and condensers also contributed to poor performance.

From these limited examples there do not appear to be specific problems encountered with any particular system configurations. Rather, similar problems have been encountered across all of the system types. The most common problems with cool storage systems are improper sizing and control errors. Fortunately, system operation improved over the first few years for most of the buildings as building operators gain experience. Many of the buildings studied are older "first generation" storage systems, which may not perform as well as newer systems. There is very little information on long-term durability and reliability for cool storage. Only a few systems have been in place for five to ten years, and long-term performance results have been mixed. As with any new technology, there are financial risks associated with adopting cool storage. Electric utilities encouraging the use of cool storage should attempt to lessen the risk to the building owner. At least one utility will consider making adjustments to electricity bills if operator errors occur during on-peak hours (McDonald and Davis, 1988).

Obtaining submetered data has been very difficult. Many utilities are currently investing in one-time customer rebates for cool storage, but few are monitoring the performance of their investments. Performance data would be of use not only to utilities, but also to building operators and design engineers. At a minimum, utility bills should be collected for at least the initial cooling season and compared with predicted performance to assess whether full savings are being realized. Standardized performance analysis techniques need development (Piette, et al., 1988). Inexpensive monitoring techniques should be explored, especially the use of in-place energy management systems that may, with little or no modification, be capable of useful data acquisition (Heinemeier and Akbari, 1987).

We are continuing to compile data on buildings with cool storage systems, with a current emphasis on retrofit projects. Since the BECA data compilation project is a continuing effort, we solicit readers' comments, suggestions, and leads to additional sources of data.

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Table 1. BECA-LM Buildings with Cool Storage Performance Data.

	BUILDING CHARACTERISTICS				SYSTEM CHARACTERISTICS						
Bldg. #	Bldg. Type	State	Floor Area (kft^2)	Year Built	Year System Install.	Storage Medium	Storage Strategy [4]	Peak Cooling (Tons/ kft^2)	Storage Capacity Ton-hrs/ kft^2)	Payback (Yrs) [5]	System Effic. (kW/ ton)
1	Office [1]	MD	395	1967	1984	Ice	Partial	1.9	4	5.7	1.6
2	Office [1]	IL	18	1981	1981	Ice	Full	2.5	27	15	1.5
3	Office	TX	1,500	1982	1982	Water	Dem. Lim.	1.7	NAv	5.3	NAv
4	Office	IL	68	1982	1982	Ice	Full	2.9	29	immed.	1.2-1.7
5	Office [2]	CA	960	1982	1982	Water	Full	1.9	NAv	NAv	NAv
6	Office [1]	MD	45	1982	1982	Water	Partial	2.1	11	9	NAv
7	Office [1]	PA	12	1967	1976	Ice	Full	1.5	19	[*]	2.4
8	Office	RI	101	1980	1980	Water	Partial	2.2	7	9	1.4
9	Clinic	CA	20	1974	1981	Ice	Full	2.3	23	[*]	1.8
10	Lt. Manuf.[3]	CA	168	1979	1979	Ice	Full	2.1	14	NAv	1.9
11	Church	MD	18	1959	1984	Ice	NAv	2.8	9	1.4	NAv

[1] Utility owned demonstration site.

[2] Buildings 5, 9, and 11 use fossil-fuel heat, others are all-electric.

[3] Lt. Manuf. = Light Manufacturing

[4] Dem. Lim. = Demand Limited, NAv = Not Available

[5] Payback times for Buildings 3, 4, and 11 are based on actual performance. For Buildings 1, 2, 6, and 8 they are early design estimates and actual paybacks have been longer. Payback for Building 4 is immediate due to the reduction in first cost for cool storage.

[*] No savings are realized during the submetering period. Performance for both systems are expected to improve.

Table 2. Summary of Early Operating Experiences.

	Building Number										
	1	2	3	4	5	6	7	8	9	10	Total:
SYSTEM DESIGN PROBLEMS											
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 O & M PROBLEMS											
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	x	5
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	

u - undersized, o - oversized, x - problem encountered

Table 3. Performance Summary for Building 4.

	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) -					
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		NA	NA
Max Annual Shift	2.5	2.3		NA	NA
Annual Load Factor	0.34	0.56			
3. COSTS					
Total System (\$/ft^2)	2.14	2.14		2.28	2.28
Incremental (\$/ft^2) [5]	-0.14	-0.14		NA	NA
Annual Elec. (\$/ft^2)					
Summer [1]	0.63	0.65		0.69	0.77
Savings (\$/ft^2) [6]	0.06	0.11		NA	NA
Payback [5]	immed	immed		NA	NA

Building and System Description: This is a three story office in Illinois occupied about 53 hours/week. The design day cooling load was estimated to be 200 tons, with a daily load of 1584 ton-hours. Two 80,000 lb direct expansion ice-builders are used with the two 45-ton reciprocating chillers and a 90-ton evaporative condenser. Conventional system performance is calculated from hourly submetering (McNeil and Mathey, 1986).

Rate Schedule: The rate schedule in 1983, available to 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 time-of-use energy charges.

Notes:

[1] Summer (the cooling season) for this building is June through October.

[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] Savings in first-cost over a conventional system.

[6] Summer, whole-building, demand and energy costs.

NA = Not Applicable; blank fields indicate information was unavailable.

Table 4. Performance Summary for Building 3.

	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 DATA			
Annual Elec. Use (kWh/ft^2) [2]	18.82		21.27
Max Demand (W/ft^2) -			
Summer	2.62		4.3
Peak Shift (W/ft^2) -			
Max month	1.71		NA
Avg. month	1.67		NA
Max shift	1.71		NA
Annual Load Factor	0.82		0.56
3. COSTS			
System and Installation ($/ft^2) -			
Total			
Incremental	0.63		NA
Annual Elec. ($/ft^2)	0.99		1.19
Demand	0.34		0.45
Energy	0.65		0.74
Savings ($/ft^2) [3]	0.11		NA
Payback	5.3		NA

Building and System Description: Building 3 incorporates numerous energy-saving features in addition to the 1.5 million gallon chilled water tank. The building is occupied about 50 hours per week, but its large computer facility is open 24 hours a day. Heat recovery condensers on the two chillers total about 1160 tons. In the winter, one or two of the four concrete tanks can be used to store hot water. Performance data for the conventional system are based on a computer simulation. Simulation data were 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 actual demand.

Notes:

[1] Though submetered, the cooling system data are not available. Design estimates for system performance are also unavailable.

[2] Includes the electricity savings from the heat recovery, which are not strictly a result of the cool storage system, but of the integrated design.

[3] Based on whole-building peak demand charges only.

NA = Not Applicable; blank fields indicate information was unavailable.

Table 5. 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			
System and Installation ($/ft^2) -			
Total		12.4	
Incremental		2.74	NA
Additional [2]	1.89		NA
Annual Elec. ($/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) [3]	0.05	0.18	NA
Payback		15	NA

Building and System Description: This office is occupied about 53 hours/week. Performance data are for 1984-1985. The system consists of 40,800 lbs of ice with a 75 ton reciprocating chiller. The conventional system data 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, which differ for winter 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] Needed major modifications in 1983.

[3] Winter peak demand charges not included in the comparison between actual and base-case operation (whole-building data).

NA = Not Applicable; blank fields indicate information was unavailable.

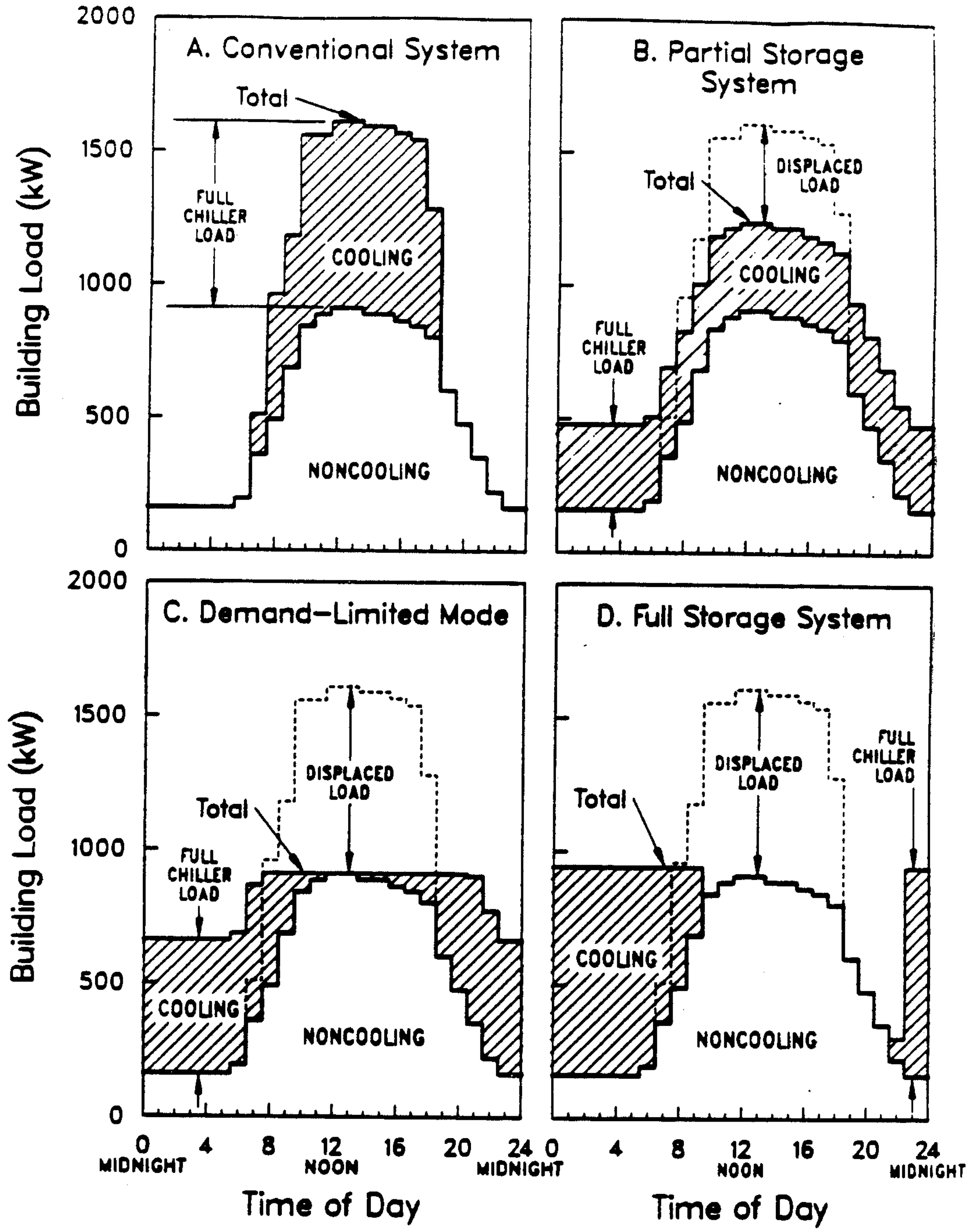

Figure 1.A.-1.D. Conventional, partial-storage, demand-limited storage, and full-storage systems. Hourly load profile for a building with a conventional cooling system on the design day compared with three cool storage load profiles. The partial-storage system has the smallest chiller (smaller full chiller 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.