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Publication Date

1986-05-01

LBL-20180 c.2

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APPLIED SCIENCE DIVISION

To be presented at the 21st Inter-society Energy Conversion Engineering Conference, San Diego, CA, August 25-29, 1986

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May 1986

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Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

IMPACT OF OPERATION AND CONTROL STRATEGY ON THE PERFORMANCE OF A THERMAL ENERGY STORAGE SYSTEM*

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ABSTRACT

The method of operation and control of a thermal energy storage system will have significant impact on the value of the system to both the customer and the utility. The annual performance for different operating and control strategies of thermal energy storage systems can be compared by simulation analysis. In the paper, simulation of the annual performance of a thermal storage system is based on hourly cooling loads generated with a DOE2 simulation for a typical small office building. The thermal storage system is sized to meet the maximum daily load for the building. The comparable conventional system is sized to meet the typical building peak load. The operation of the thermal storage system in then modeled hour by hour.

Results of the simulation analysis show that while chiller priority control achieves the desired peak load reduction, only that part of the cooling load greater than the chiller capacity is shifted to partial-peak or off-peak hours. The chiller continues to run, charging storage, through the evening hours. Application of storage priority control shifts a greater portion of the annual cooling from on-peak to partial-peak and off-peak hours. This results in greater cost savings to a utility customer on time-of-day rates.

BACKGROUND

Thermal-energy storage provides many opportunities for load management by electric utilities and for utility customers to reduce their cooling energy costs by shifting electrical energy usage to off-peak periods. These opportunities are leading many electric utilities to encourage their customers to adopt strategies to reduce power consumption in buildings during peak operating hours. It is important to determine how well this new technology can in fact meet the needs of the electric utility industry and its customers.

The method of operation and control of ice energy-storage systems has a major impact on the system's value to both the customer and the utility. The issue of control of ice-storage systems has been raised by several authors (1,2,3). The annual performance of different operating and control strategies for ice-storage systems can be compared by simulation analysis. This paper presents results of annual performance simulations that indicate the importance of control strategy to achieving peak load reduction, load shifting, and energy cost savings.

* This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Solar Buildings Technology Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

METHOD OF ANALYSIS

The annual performance of an ice-storage system is determined using a special purpose computer program that models the operation of the storage system and chiller hour by hour in response to the hourly cooling loads of a hypothetical office building. The variation of chiller efficiency with weather conditions and with evaporator temperature are included in the simulation program. The hourly cooling loads are calculated using the DOE-2.1 (4) load and system simulation for a representative building with a variable-air-volume system and are extracted from an hourly system output file. A typical small 10,000-ft^2 (930-m^2) office building is used as a representative building (5). For a system with no thermal storage, the chiller is sized to meet the peak building cooling load. For a system with thermal storage, the chiller is sized to meet the maximum daily load for the building over the period of chiller operation, and the storage is sized to accommodate the ability of the chiller to make ice when there is no cooling load.

Performance of partial-storage systems with chiller- and storage-priority control are compared for days of maximum, average, and minimum cooling load. Annual energy use during peak, partial-peak, and off-peak periods is computed for different control strategies. For a given utility rate structure, the annual energy cost and energy cost savings can be computed for each system.

Load Analysis

Table 1 shows the distribution of hourly cooling loads for a 930-m^2 (10,000-ft^2) light commercial building in Sacramento, CA. The hourly cooling loads are binned at one-ton intervals. The maximum cooling load of 17.5 tons is used as the peak load for sizing the conventional cooling system and represents the coincident block load for the building. These cooling loads were calculated assuming that the building is served by a VAV system with an outdoor air economizer and represent the load at a cooling coil with a chilled water temperature of 45 $^{\circ}$F. The table also indicates the cumulative hours that the hourly load is greater than a certain value. There are only 5 hours when the load is greater than 16 tons, the value taken as the nominal chiller design size for a typical chilled water-system. There are 207 hours when the cooling load is greater than 12 tons, and 864 hours when the load is greater than 5 tons.

The daily cooling loads in Sacramento are shown in Table 2, binned at 10-ton-hr intervals. The maximum daily load is 166.8 ton-hrs. The daily design load is 160 ton-hrs. The number of days that the daily load is greater than a certain value is also indicated in the table. There are 14 days when the daily load is greater than 120 ton-hrs, and 57 days when the daily load is greater than 80 ton-hrs, showing that most of the year the daily cooling load is less than one half the peak day. Thus, the operation of the thermal storage system on days other than peak days is crucial to annual performance. Table 3 shows the design conditions for loads in three cities: Sacramento, CA, Miami, FL, and Phoenix, AZ.

Table 1
Distribution of hourly cooling loads
for a light commercial building
in Sacramento based on DOE-2 simulations

Cooling Load (tons)	Number of Hours	Cumulative Hours	
17-18	1	1	Maximum 17.5
16-17	4	5	
15-16	19	24	
14-15	47	71	
13-14	67	138	
12-13	69	207	
11-12	88	295	
10-11	137	432	
9-10	113	545	
8- 9	77	622	
7- 8	78	700	
6- 7	69	769	
5- 6	95	864	
4- 5	96	960	
3- 4	126	1086	
2- 3	196	1282	
1- 2	229	1511	
0- 1	7249	8760	(off)

Table 2
Distribution of daily total cooling loads for a light commercial building in Sacramento based on DOE-2 simulations

Cooling Load (ton-hrs/day)	Number of Days	Cumulative Days	
160-170	1	1	Maximum 167
150-160	2	3	
140-150	0	3	
130-140	3	6	
120-130	8	14	
110-120	10	24	
100-110	9	33	
90-100	9	42	
80- 90	14	56	
70- 80	18	74	
60- 70	15	89	
50- 60	13	102	
40- 50	8	110	
30- 40	8	118	
20- 30	13	131	
10- 20	22	153	
0- 10	212	365	(off)

Table 3
Load analysis and sizing requirements for an ice storage system

City	Sacramento	Miami	Phoenix
Peak Hourly Load	17.5 tons	25.5 tons	34.6 tons
Design Hourly Load	16.0 tons	25.0 tons	34.0 tons
Peak Daily Load	166.8 ton-hrs	308.8 ton-hrs	358.5 ton-hrs
Design Daily Load	160.0 ton-hrs	300.0 ton-hrs	360.0 ton-hrs
No Storage			
Nominal Chiller Capacity	16.0 tons	25.0 tons	34.0 tons
Partial Storage			
Average Chiller Capacity	6.7 tons	12.5 tons	15.0 tons
Nominal Chiller Capacity	8.0 tons	15.0 tons	18.0 tons
Storage Size	64 ton-hrs	120 ton-hrs	140 ton-hrs
Full Storage			
Average Chiller Capacity	8.9 tons	16.7 tons	20.0 tons
Nominal Chiller Capacity	11.4 tons	21.4 tons	25.6 tons
Storage Size	90 ton-hrs	170 ton-hrs	200 ton-hrs

Storage and Chiller Sizing

The sizing of thermal-storage systems is based on the number of peak, partial-peak, and off-peak hours, the number of hours with load, and the chiller capacity and number of hours available for charging. The load periods assumed for this study are: off-peak (10 hours), 00:01 - 08:00 hrs and 22:01 - 24:00 hrs; partial-peak (8 hours), 08:01 - 12:00 hrs and 18:01 - 22:00 hrs; and peak period (6 hours), 12:01 - 18:00 hrs. Because of the hourly basis of the modeling, it was assumed that the load period intervals coincided with the beginning of an hour. There are 18 hours in the off- and partial-peak periods during which the chiller operates in a full-storage system. Analysis of the occupancy schedule of the building indicated a 12-hour period without load during which the thermal storage could be charged.

The chiller was modeled as a compressor, evaporator, and cooling tower. The performance of the compressor is based on manufacturers' data for capacity and electric power consumption over a range in saturated suction temperatures from 10 ^{O}C to -20 ^{O}C (50 ^{O}F to -5 ^{O}F) and in saturated discharge temperatures from 29 ^{O}C to 57 ^{O}C (85 ^{O}F to 135 ^{O}F). In this simple model, the saturated suction temperature is assumed to be 3.3 ^{O}C (38 ^{O}F) when chilling water and -6.7 ^{O}C (20 ^{O}F) when making ice. The saturated discharge (condenser) temperature at full load is assumed to be 11 ^{O}C (20 ^{O}F) above the ambient wet bulb temperature. The nominal capacity of the chiller is based on operation of a compressor at an evaporator (saturated suction) temperature of 3.3 ^{O}C (38 ^{O}F) and a condenser (saturated discharge) temperature of 95 ^{O}F. The nominal operating dry bulb/wet bulb temperatures are 35/24 ^{O}C (95/75 ^{O}F). In the absence of thermal storage, the chiller operates to make chilled water, +3.3 ^{O}C (38 ^{O}F) evaporator, at all times. The average capacity is more or less equal to the nominal capacity. If the evaporator temperature is lowered to -6.7 ^{O}C (20 ^{O}F), the actual capacity of the compressor is reduced to 67% of the nominal capacity.

Much of the time the chiller operates at full capacity, so that the temperature approaches on the condenser and evaporator will be near design values. The part-load operating characteristics of the chiller assume that at 66% of capacity at a given operating condition, the electrical use is 74%, at 33% of capacity, 39%. At less than 33% capacity the chiller is assumed to cycle. Estimates of the fan energy and pumping power are added to the compressor energy.

Partial Storage Sizing

A partial-storage system serves the peak building cooling load demand by running the chiller at the same time cooling from storage is used. For a partial storage system, when the cooling load is greater than the capacity of the chiller, the chiller will operate at nominal capacity as a conventional water chiller. This is accomplished by using a separate chiller barrel (evaporator) in the case of an ice-builder system, or by running water over the unfrozen evaporator surface in the case of an ice harvester. Cooling load in excess of the chiller capacity is met by melting ice from storage. When the cooling load is less than the ice-making capacity of the chiller, the chiller will make ice and serve the cooling load by melting ice. If there is no cooling load the chiller will make ice to recharge storage. At the lower evaporator temperature, -6.7 ^{O}C (20 ^{O}F), the actual chiller capacity will be about 67% of the nominal capacity.

A partial-storage system reduces the size of the chiller so that on a design day the chiller will run 24 hours to meet the daily cooling load. The average chiller size to meet a 160-ton-hr daily cooling load in Sacramento is given by:

$$\text{Average Chiller Capacity} = 160 \text{ ton-hrs}/24 \text{ hours} = 6.7 \text{ tons} \quad (1)$$

During a peak day the partial-storage system operates to chill water for about 12 hours. For the remaining 12 hours it makes ice. The average capacity of the chiller on the peak day will be about 84%, (12*100% + 12*67%)/24, of the nominal capacity, so that the nominal chiller capacity is 8.0 tons.

$$\text{Nominal Chiller Capacity} = 6.7 \text{ tons}/0.84 = 8.0 \text{ tons} \quad (2)$$

The storage size is given by the ability of the chiller to recharge the system over the 12-hour period without cooling load. A system with a nominal capacity of 8.0 tons will have a reduced capacity (67%) to make ice, so that the quantity of ice that can be made and stored is 64 ton-hrs:

$$\text{Storage} = 0.67 * 8.0 \text{ tons} * 12 \text{ hours} = 64 \text{ ton-hrs} \quad (3)$$

The nominal chiller capacities and the ice storage capacities for partial-storage systems are shown in Table 3.

Full Storage Sizing

There are 18 hours in the off- and partial-peak periods during which the chiller can operate to serve the load and charge storage in a full-storage system. The chiller is locked out during the 6-hour peak period. The average chiller capacity for a full-storage system in Sacramento is given by:

$$\text{Average Chiller Capacity} = 160 \text{ ton-hrs}/18 \text{ hours} = 8.9 \text{ tons} \quad (4)$$

On a peak day the full-storage system operates to chill water for about 6 hours through the morning hours. For 12 hours at night it makes ice. The average capacity of the chiller on the peak day is about 78%, (6*100% + 12*67%)/18, of the nominal capacity, so that the nominal chiller requirement would be 11.4 tons.

$$\text{Nominal Chiller Capacity} = 8.9 \text{ tons}/0.78 = 11.4 \text{ tons} \quad (5)$$

The storage size is given by the ability of the chiller to recharge the system over the 12-hour period without cooling load. A system with a nominal capacity of 11.4 tons has a reduced capacity (67%) to make ice, so that the quantity of ice that can be made and stored is given by

$$\text{Storage} = 0.67 * 11.4 \text{ tons} * 12 \text{ hours} = 92 \text{ ton-hrs} \quad (6)$$

The nominal chiller capacities and the ice storage capacities for full-storage systems are shown in Table 3.

CHILLER AND STORAGE CONTROL STRATEGIES

Partial Storage/Chiller Priority

In this work two control strategies for partial-storage systems are evaluated: chiller-priority control and storage-priority control. In chiller-priority control, the smaller chiller is operated during cooling demand to satisfy the load. If the load exceeds the chiller capacity, the thermal storage satisfies the remaining load. Chiller-priority control is simple to implement and achieves the desired peak load reduction, but does not fully utilize the capabilities of storage.

Chiller-priority control is simple to implement in a thermal-storage system. The chiller runs whenever there is load, or when the storage is not fully charged. Since the compressor is running as a water chiller in parallel with the thermal-storage system, it runs with good efficiency. However, a system with chiller-priority control shifts only a small amount of the electrical cooling load to the off-peak period. The cost savings of this type of system result primarily from reduced electrical peak demand.

Figure 1 shows the hourly cooling load and chiller operation for a partial-storage system under chiller-priority control on an average load day in Miami. The nominal chiller capacity is 15 tons and the storage capacity is 120 tons-hrs. With chiller-priority control the chiller begins to chill water with the morning load at a capacity of about 15 tons and runs at maximum capacity through the day. At the end of the day the chiller continues to run, but at a lower capacity of about 10 tons to make ice. The storage system is completely charged by about 20:00 hrs (10 PM). Figure 2 shows the storage capacity at the end of each hour. Storage is only partially discharged and only serves that load greater than the chiller capacity. The storage is quickly charged after the end of the peak period. On the day depicted in Figure 2, the peak demand is reduced by about 5 kW, and some cooling load has been shifted from the afternoon to the early evening partial-peak period.

Partial Storage/Storage Priority

In storage-priority control the cooling load is satisfied by melting ice so long as sufficient storage remains to get through the peak period. The key to storage-priority control is to establish the desired level of ice storage at each hour of the day so that 1) there will be sufficient storage to meet the cooling load during the remaining part of the day, and 2) the storage will be fully or adequately charged by the beginning of the next cooling-load period. The need for storage for the following day could be established either by 1) always assuming that the next day is a peak day, or 2) using experience or a weather model to estimate the next day's cooling requirements. When the chiller is run to supplement the ice storage, it runs at reduced capacity as a water chiller. The chiller is run to make ice only when there is no cooling load and the amount of ice in storage needs to be built up.

Implementation of storage-priority control requires an algorithm to balance the cooling from storage with the operation of the chiller. For this analysis we assume that the required storage has uniform charging over the 9 hours from 18:00 to 3:00 hrs and uniform discharge over the 12 hours from 6:00 to 18:00 hrs. This required storage profile was selected arbitrarily with the primary goal of conserving ice storage for use in the afternoon peak period. The choice of the required storage profile for storage-priority control depends on the predicted load. Further work is required to establish the optimal or ideal profile. Development of new algorithms for the control of thermal-storage systems to achieve optimum performance with specific building cooling load profiles is an important area of research.

Figure 3 shows the hourly cooling load and chiller operation for a partial-storage system operating under storage-priority control on an average-load day in Miami. The nominal chiller capacity is 15 tons and the storage capacity is 120 tons-hrs. The chiller operates to charge storage, making ice with a capacity of about 10 tons during the early morning hours. When the building load begins at 5:00 hrs, the chiller makes chilled water up to a maximum capacity of 15 tons until 12:00 hrs. This conserves the ice storage for use in the afternoon. In the afternoon priority is given to cooling from storage, but the chiller continues to making chilled water at a capacity of about 6 tons so that the ice is rationed throughout the afternoon. The chiller delays recharging ice storage until 20:00 hrs (8 PM), when it resumes charging storage.

Figure 2 shows the storage capacity at the end of each hour under storage-priority control. The discharging follows the required storage specified in the control algorithm. In this case the storage was not fully charged. For a commercial building operated on a normal 5-day-per-week schedule, the peak building loads typically fall on Mondays when the heat that has accumulated in the building over the weekend must be discharged, and the storage is fully charged. The storage-priority strategy depletes the storage further than the chiller-priority strategy by the end of the day and runs the chiller less during the day. It also begins charging later in the evening, shifting more of the load from the partial-peak to the off-peak period.

The operation of the storage system under storage-priority control assures that the storage is used to the maximum and that charging of storage is delayed to the night-time off-peak hours. As the total daily cooling load decreases, the storage-priority strategy shifts a greater percentage of the load to the nighttime hours.

The storage sizing was based on the capacity of the chiller to meet design-day cooling loads. On a maximum-load day both chiller-priority and storage-priority control strategies perform similarly, depleting storage by the end of the day with the chiller operating as a water chiller during the morning partial-peak period to supplement storage and making ice through the evening partial-peak and off-peak periods. On a minimum-load day, the chiller under storage-priority control remains off through the day, shifting the total cooling load to the off-peak period. As the total daily cooling load decreases, the storage-priority strategy shifts a greater percentage of the load to the off-peak hours. This results in greater cost savings to a utility customer on time-of-day rates. Results of the simulation analysis show that while chiller-priority control achieves the desired peak load reduction, only that part of the cooling load greater than the chiller capacity is shifted to partial-peak or off-peak hours.

Implementing storage-priority control requires an ongoing measurement or estimate of the state of ice storage and establishing the required storage necessary at each hour to get through the afternoon cooling peak and to determine when to begin charging storage at night. With microprocessor-based controls, a storage priority control strategy should not be difficult to implement. It may be useful to incorporate prediction of cooling loads on the following day into the storage priority control algorithm.

Full-Storage Systems

In a full-storage system the chiller is locked out during peak hours and the cooling load is satisfied from storage. During partial-peak and off-peak hours the chiller is operated to satisfy the load or to charge storage. If the cooling load exceeds the chiller capacity, the thermal storage satisfies the remaining load. Full-storage systems are typically operated under chiller-priority control, which achieves the desired peak load reduction, but does not fully utilize the capabilities of storage.

Figure 4 shows the hourly cooling load and chiller operation for a full-storage system on an average-load day in Miami. The nominal chiller capacity is 21.4 tons and the storage capacity is 170 tons-hrs. The chiller comes on with the morning load with sufficient capacity to make chilled water. The chiller is locked out from 12:00 to 18:00 hrs. At 19:00 hrs (7 PM), the chiller resumes operation to make ice with a capacity of about 14 tons to charge storage. The chiller makes ice until about 2:00 hrs the following morning, when the storage is fully charged. Figure 2 shows storage capacity at the end of each hour for a full storage system. During the peak period the storage is depleted from 170 to 75 ton-hrs.

ANNUAL SIMULATION RESULTS

Cooling Load

The annual performance of several chiller and storage-control strategies have been calculated using cooling loads for a small commercial building in three cities. The cooling and electrical energy use for the peak, partial-peak, and off-peak periods are compared in Table 4.

On an annual basis, storage-priority partial-storage, and full-storage systems shift significant cooling load and electricity consumption away from the peak period. This is beneficial to utility customers in areas with large differences between peak, partial-peak, and off-peak electricity costs. A system under storage-priority control can shift most of the annual cooling load away from the peak period, and can potentially shift much of the partial-peak load to the off-peak period. This has particular significance to electric utilities that are interested in "valley filling," that is, shifting their kilowatt demand into the late-night and early-morning hours. The partial-storage system under chiller-priority control will shift only a small portion of the peak cooling load to the partial-peak and off-peak periods. The properly sized full-storage system will shift the cooling load into the evening hours with some of the load appearing late at night. Application of storage-priority control could also increase the shift in annual energy use to late night for full-storage systems. The peak electrical demand for cooling, also shown in Table 4, is reduced by about 50 % for a partial-storage system, and by 100% by a full-storage system.

Chiller efficiency varies depending on whether the compressor is making chilled water or ice, and whether the machine is operating at full load or partial load. At dry bulb/wet bulb temperature design conditions of 35/24 ^{o}C (95/75 ^{o}F), the chiller has an efficiency of 0.82 kW/ton when making chilled water and 1.16 kW/ton when making ice. The average annual chiller efficiency during peak, partial-peak, and off-peak periods are indicated in Table 4. For a system without storage, the annual average chiller efficiency ranges from 0.95 to 1.05 for the three cities. During off-peak periods there is very little cooling load and the part-load efficiency of the chiller is lower. The water chiller is less efficient in Phoenix because of the higher daytime outdoor temperatures.

The partial-storage system under chiller-priority control operates as a water chiller to supplement the storage during the morning partial-peak period and the afternoon peak period, since the chiller operates fully loaded most of the time. It has relatively good performance of about 0.93 kW/ton and it does not make a lot of ice except during the peak cooling season.

The partial-storage system under storage-priority control operates as a water chiller to supplement the storage during the morning partial-peak period. During the afternoon peak period it typically operates less efficiently at part load. During the off-peak period it operates fully loaded and makes ice when the outdoor temperatures are cooler. The partial-storage system under storage-priority control makes much more ice than the chiller-priority control system, even though the chiller and the storage are the same size.

The full-storage system operates most of the time in the ice-making mode and consequently has a higher electricity consumption, 1.08 to 1.10 kW/ton. The full-storage system makes much more ice than either partial-storage system.

Table 4. Cooling load by load period for a representative commercial building in Miami, Phoenix, and Sacramento.

Item	Chiller tons	Storage ton-hrs	Peak ton-hrs	Peak kW-hrs	Peak kW	partial-ton-hrs	partial-kW-hrs	off-ton-hrs	off-kW-hrs	Average kW/ton
Phoenix, AZ										
No Storage	34.	0.	13,789	14,423	23.9	8,054	8,544	5,522	5,721	1.05
Partial Storage										
Chiller Priority	18.0	140.	13,742	12,790	14.8	8,319	7,952	5,304	4,992	0.94
Storage Priority	18.0	140.	1,403	1,668	14.7	6,495	6,554	19,468	20,053	1.03
Full Storage	25.6	200.	0	0	0.0	20,065	21,922	7,300	8,211	1.10
Miami, FL										
No Storage	25.	0.	18,942	18,376	21.2	13,022	12,790	9,160	9,293	0.98
Partial Storage										
Chiller Priority	15.0	120.	17,577	15,802	12.8	14,474	13,858	9,072	8,626	0.93
Storage Priority	15.0	120.	3,944	4,429	12.7	12,744	12,843	24,375	25,402	1.04
Full Storage	21.4	170.	0	0	0	26,230	27,806	14,893	16,700	1.08
Sacramento,CA										
No Storage	16.0	0.	6,956	6,306	13.2	2,908	2,960	613	703	0.95
Partial Storage										
Chiller Priority	8.0	64.	5,989	5,142	6.6	3,656	3,531	832	1,055	0.93
Storage Priority	8.0	64.	1,899	1,709	6.6	2,286	2,466	6,292	6,722	1.04
Full Storage	11.4	90.	0	0	0	7,438	7,811	3,040	3,477	1.08

Energy Costs

Several different rate structures were used to evaluate the sensitivity of the results, as shown in Table 5. Pacific Gas and Electric Co. (PG&E) has a small demand charge and a large difference between off-peak and peak electricity rates. San Diego Gas and Electric (SDG&E) has high demand charge and a small off-peak-to-peak rate differential. Southern California Edison (SCE) has a modest demand charge and a low off-peak-to-peak rate differential.

Table 5. Utility Rate Structures

Utility	Units	PG&E	SDG&E	SCE
Off-peak	$/kW-hr	0.06507	0.09934	0.05920
Partial-peak	$/kW-hr	0.07916	0.12334	0.07090
Peak	$/kW-hr	0.13406	0.12934	0.08490
Demand	$/kW	1.70	7.31	5.05

The annual costs to deliver cooling for the representative building in three different cities under three different types of rates are shown in Table 6. The annual costs include the energy charges for each period plus the demand charge for the peak month assuming an "11-month ratchet." In evaluating the economic benefit from a thermal-storage system, one needs to consider the specific utility rate structure in effect for the particular building.

As can be seen from Table 6, the benefit to a customer of a utility whose rate structure has a low demand charge and a high differential between peak and off-peak periods, such as PG&E, is primarily in the shifting of load to the off-peak period. Storage-priority control will be desirable for a partial-storage system under these types of rates. For a utility such as SDG&E with a low off-peak differential, the demand charges have the greatest impact, and storage-priority and chiller-priority systems behave similarly. Full-storage systems yield the greatest electricity demand and cost savings, but require significantly larger storage and chiller sizes.

The average monthly peak demand is also shown in Table 6. While both chiller- and storage-priority, partial-storage systems have about the same annual peak demand reduction, the average monthly demand can be much less. For a system in Miami with a $7.31/kW demand charge, the annual cost for a ratcheted demand of 12.8 kW is $1,123. The demand charges are lower if based only on the monthly demand without a ratchet. For a chiller-priority system with an annual average demand of 12.4 kW, the annual demand charges are $1,088. For a storage-priority system with an annual average demand of 7.8 kW, the annual demand charges are $684, achieving a savings of $404 simply by changing control strategy.

Table 6. Electrical utility costs for a representative commercial building in Miami, Phoenix, and Sacramento.

	Sizing		Annual		Electricity Costs		
Item	Chiller tons	Storage ton-hrs	Average kW	Peak kW	PG&E $/yr	SCE $/yr	SDG&E $/yr
Phoenix, AZ							
No Storage	34.	0.	15.7	23.9	3,469	3,614	5,580
Partial Storage							
Chiller Priority	18.0	140.	12.5	14.8	2,971	2,843	4,430
Savings					498	717	1,150
Storage Priority	18.0	140.	4.6	14.7	2,348	2,686	4,308
Savings					1,121	928	1,272
Full Storage	25.6	200.	0	0.0	2,269	2,040	3,520
Savings					1,200	1,574	2,060
Miami, FL							
No Storage	25.	0.	17.8	21.2	4,514	4,304	6,741
Partial Storage							
Chiller Priority	15.0	120.	12.4	12.8	4,038	3,612	5,736
Savings					476	692	1,005
Storage Priority	15.0	120.	7.8	12.7	3,523	3,563	5,798
Savings					991	741	943
Full Storage	25.0	200.	0.0	0.0	3,288	2,960	5,089
Savings					1,226	1,344	1,652
Sacramento,CA							
No Storage	16.0	0.	7.9	13.2	1,394	1,585	2,406
Partial Storage							
Chiller Priority	8.0	64.	5.2	6.6	1,172	1,148	1,783
Savings					222	413	623
Storage Priority	8.0	64.	3.0	6.6	996	1,116	1,771
Savings					398	469	635
Full Storage	13.2	107.	0.0	0.0	844	760	1,309
Savings					550	825	1,097

CONCLUSIONS

Thermal-energy storage provides a good opportunity for load management by utilities and for utility customers to reduce their cooling energy costs. The value of thermal-energy storage to the utility depends on the ability of these systems to reliably reduce the electrical demand associated with cooling and to shift daytime cooling electrical demand to nighttime off-peak periods. The value of thermal-energy storage to utility customers is in its ability to reduce the first costs of major cooling components such as compressors, to take advantage of low-cost electricity during the nighttime hours, and to reduce electricity demand charges by eliminating much of the air conditioning load during the peak periods. Control strategies play a significant role in achieving significant shifts of the cooling demand to off-peak periods.

This analysis can easily be extended to other typical building types by using DOE-2 modeling to predict the building cooling load, and using the special purpose computer program to calculate storage performance. The methods of analysis and the control strategies outlined here could be incorporated into a larger simulation code. A variety of control strategies and storage configurations and more accurate modeling can be developed as the performance data on the different storage systems become available. Simulation analysis can provide a basis to determine whether systems are performing as designed, to evaluate alternative methods of control to improve peak and off-peak performance, and to extrapolate the performance of buildings with thermal-energy storage systems to other locations. The predicted peak-load shifting produced by a thermal-storage system should be compared to monitored installations to give us confidence in our predictions of energy cost savings.

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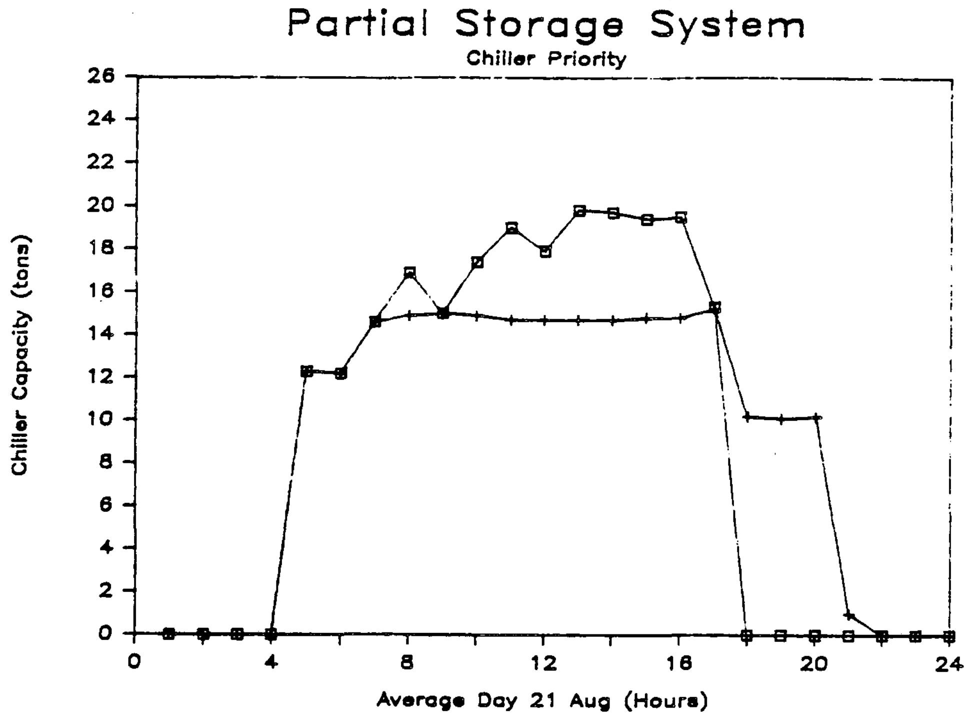

Fig. 1. - Chiller capacity and building load for an average-load day as a function of time of day for a partial-storage system operated under chiller-priority control. □ Cooling Load, + Chiller-Priority System.

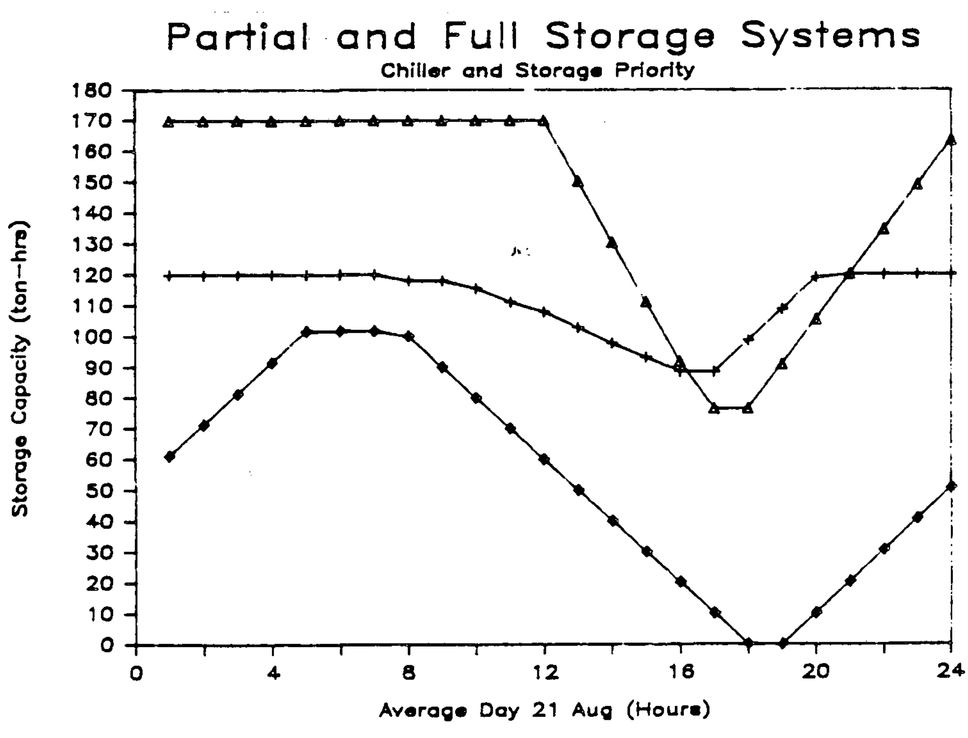

Fig. 2. - Thermal storage capacity as a function of time of day for a partial-storage system under chiller- and storage-priority control and for a full-storage system for a average-load day. Δ Full-Storage System, + Chiller-Priority System, ◇ Storage-Priority System.

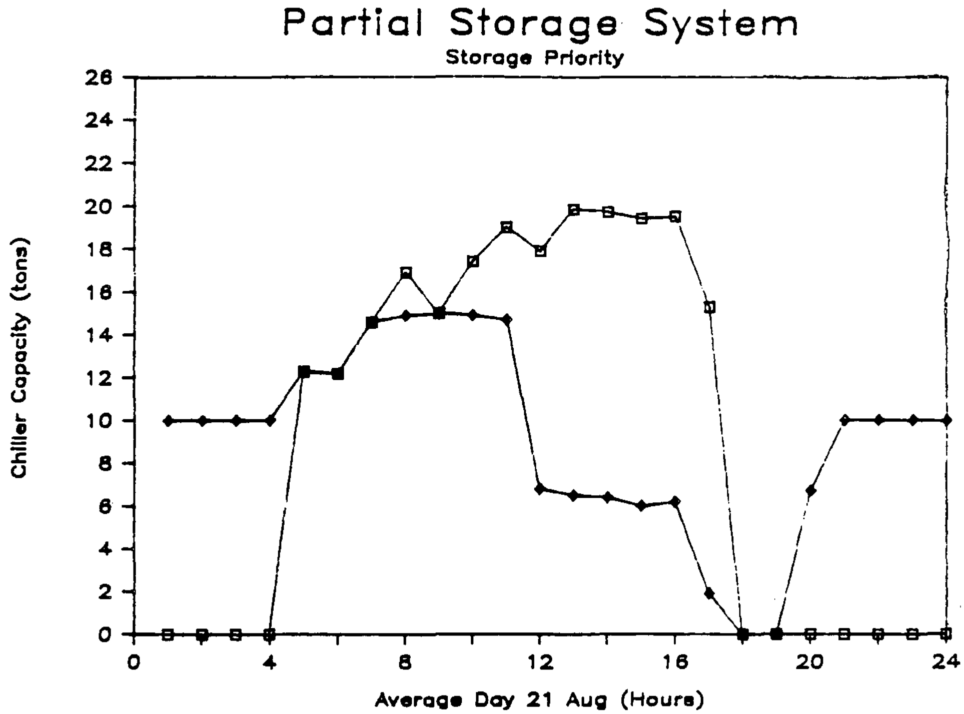

Fig. 3. - Chiller capacity and building load for an average load day as a function of time of day for a partial-storage system operated under storage-priority control. <> Storage-Priority System, □ Cooling Load.

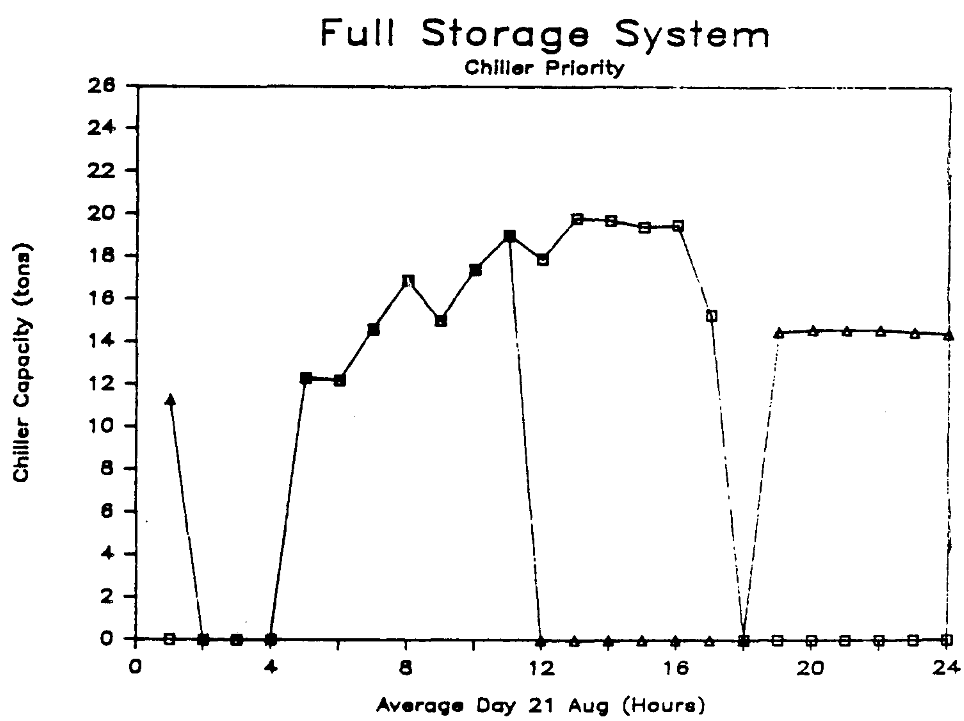

Fig. 4. - Chiller capacity and building load for an average-load day as a function of time of day for a full-storage system. Δ Full Storage System, □ Cooling Load.

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