Development of a Procedure for the Predictive Control Strategy of a Chilled Water Storage System

Guanghua Wei
Senior Research Associate
Energy Systems Lab
Texas A&M University
College Station, TX 77843

Yasuko Sakurai
Research Assistant
Energy Systems Lab
Texas A&M University
College Station, TX 77843

Mingsheng Liu, Ph.D., P.E.
Associate Professor
Architectural Engineering
University of Nebraska
Omaha, NB 68182

David E. Claridge, Ph.D., P.E.
Professor
Energy Systems Lab
Texas A&M University
College Station, TX 77843

Dan Turner, Ph.D., P.E.
Director, Professor
Energy Systems Lab
Texas A&M University
College Station, TX 77843

ABSTRACT

Thermal energy storage systems store the thermal energy produced by the chiller plant in periods of off-peak electrical demand or when cheaper electricity is available. The stored thermal energy is then withdrawn from the reservoir to satisfy cooling load during peak demand periods. This paper discusses the development of a simplified predictive control strategy for a 7000 ton-hour chilled water storage system serving a hospital. Control strategies are developed for both on-peak and off-peak months to minimize demand charges. By optimizing the operation of the building air handling units (AHUs), chilled water pumps, chiller plant and the thermal storage system, the storage tank is better charged while chiller run time is reduced. Both on-peak and off-peak electrical demands are expected to be reduced significantly.

INTRODUCTION

Thermal energy storage (TES) systems store the thermal energy produced by the chiller plant in periods of off-peak electrical demand or when cheaper electricity is available. The stored thermal energy is then withdrawn from the reservoir to satisfy cooling load during peak demand periods. Common control strategies include chiller-priority and storage-priority. The chiller-priority control method uses the storage to match the difference between building load and chiller capacities. The storage-priority control method maximizes the storage usage during the on-peak electrical periods (Braun 1992).

In recent years, various control strategies have been developed to optimize the operation of TES systems. Tamblyn (1985) discussed several control concepts for TES systems. Rawlings (1985) presented methods for optimizing demand reduction obtained from an ice storage system. Shavit and Goodman (1985) described control of TES systems by defining several modes of operation. Ferrano and Wong (1990) developed a neural network program to predict the next day's cooling requirements. The prediction was entered into a real-time expert system for the control of nighttime chiller operation and ice storage production. Spethmann (1993) described some application considerations in optimal control of cool storage. Variables such as utility rate schedule, type and relative size of cool storage, and the load profiles of energy uses were examined for their influences on the optimal control strategy. Kimbara et al. (1995) developed a load profile prediction algorithm for use in the optimal operation of a storage system. More recently, Krarti et al. (1999) performed a parametric analysis to determine the required length of planning period. Cooling load, weather, and utility rates need to be predicted during that period for the optimization to be performed. Henze and Krarti (1999) studied the effect of forecasting uncertainty on the performance of a predictive optimal controller for TES systems.

Most of the previous work was conducted for partial chilled water storage or ice storage systems, with emphasis on development of accurate load predicting models for the control of chiller plant operations.

This paper discusses the development of a simplified predictive control strategy for a full chilled water storage system in a hospital. One of the main objectives is to reduce the off-peak demand charge. By optimizing the operation of the building air handling units (AHUs), chilled water pumps, chiller plant and the thermal storage system, building comfort is improved; chiller operating time is reduced and the storage system is better charged; electrical demand for both on-peak and off-peak months is expected to be reduced significantly, and chiller efficiencies will be improved.

METHODOLOGY

In this section, the system and the utility rate schedule are described first; followed by the development of new control procedures for on-peak and off-peak month operations.

Site Description

The system for this case study is a hospital with 12 major buildings. There are four chillers located in 3 different chiller plants, with total cooling capacities of 1325 tons (two 425 ton, one 275 ton, and one 200 ton). There is one thermal storage tank with 7000 ton-hour capacity. The storage tank is in parallel with the chillers. The design chilled water return temperature is 56°F. The chiller plants and the thermal storage tank are connected through the campus chilled water loop. Every building chilled water pump is equipped with a variable frequency drive (VFD). Figure 1 is a schematic of the chilled water system.

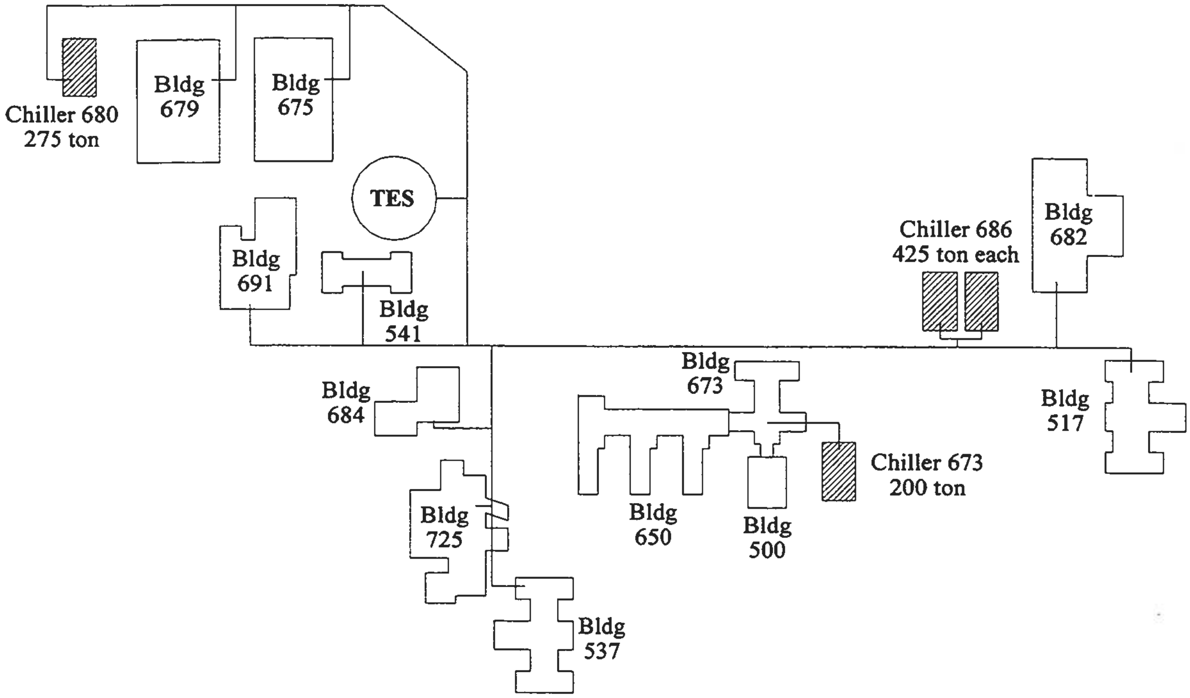

Figure 1. Schematic of the chilled water system.

Demand Determination

Demand for calculation of monthly utility bills is determined in accordance with the following provisions:

a) Demand is the smaller of:
   1) current month kW;
   2) on-peak kW plus 25% of the current month kW in excess of the on-peak kW.
b) But is not less than the highest of :
   1) 80% of on-peak kW;
   2) 50% of contract kW;
   3) 50% of annual kW.

Definitions of some of the terms mentioned above are explained here:

- Current month kW is the highest 15-minute kW recorded during the current month.
- On-peak kW is the highest 15-minute kW recorded during the weekday on-peak hours (between 12 noon and 8 pm) during the billing months of June through September.
- Contract kW is the maximum kW provided by the electric power company.
- Annual kW is the highest 15-minute kW recorded in the 12-month period ended with the current month.

The procedure for calculating the monthly billing demand is illustrated in a flowchart as shown in Figure 2.

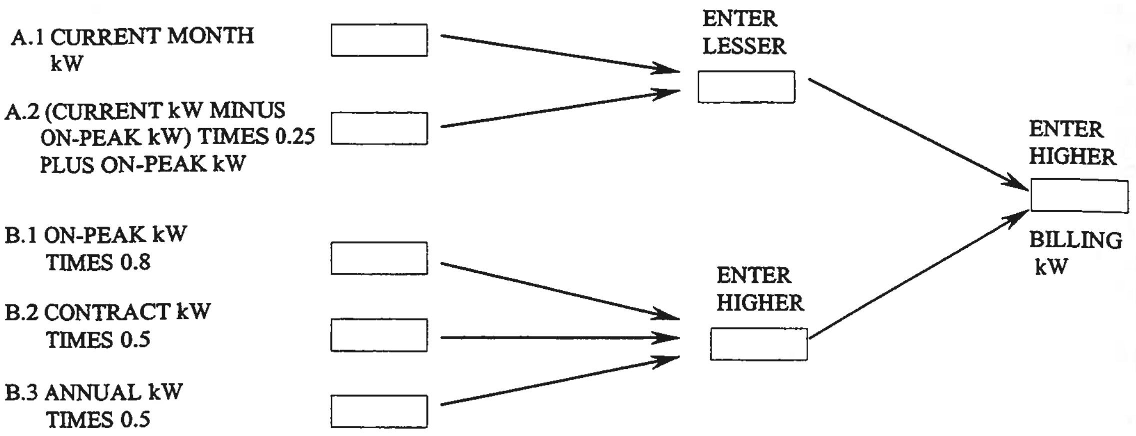

Figure 2. Flowchart for the calculation of monthly billing demand.

The hospital has a contract demand of 2800 kW, which means that the minimum monthly billed demand is 1400 kW. It is important to note that there is a clause in the rate schedule such that a single mistake made during the on-peak hours will result in penalties for the next 12 months. However, a blunder caused by a system failure or operator mistake in one month does not mean the end of story. A closer analysis of the rate schedule shows that opportunities still exist even after a disaster. Figure 3 presents the demand penalties under different current month demand values when on-peak demand has been set at different levels.

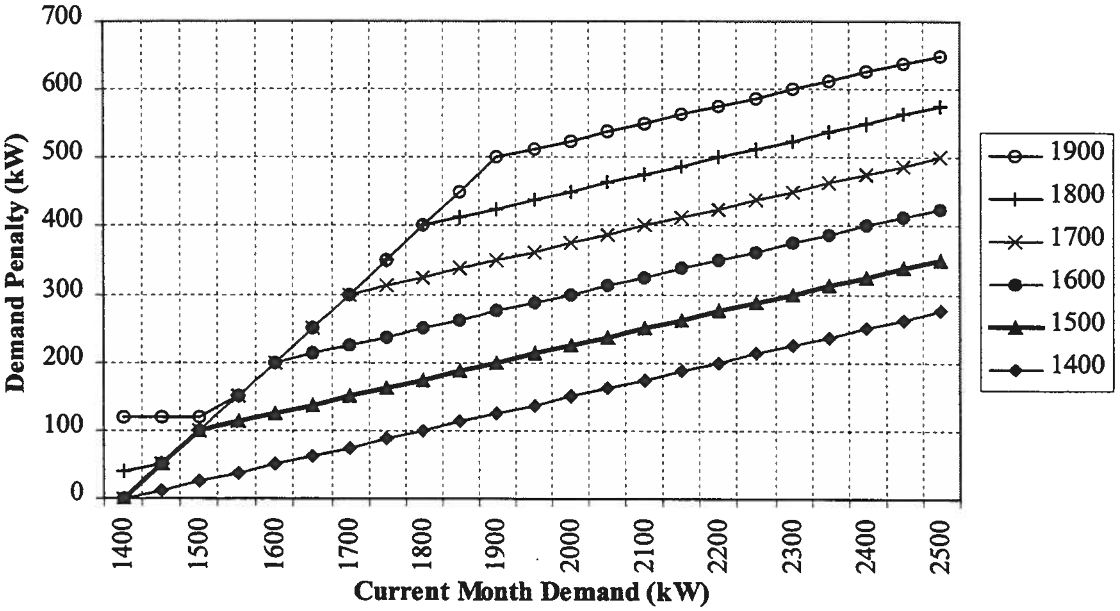

Figure 3. Demand penalties under different current month demand values when on-peak demand has been set at different levels (from 1400 kW to 1900 kW).

The demand penalty is the extra demand charge when the current month demand is higher than 1400 kW. Under this particular rate schedule, it can be seen that the penalty of not being able to control the current month demand under 1400 kW is greatly influenced by the on-peak demand record. For example, if the on-peak demand record is set at 1400 kW, the demand penalty will be 125 kW if the current month demand is 1900 kW instead of 1400 kW. If the on-peak demand record is 1500 kW, the demand penalty will be 200 kW if the current month demand is 1900 kW instead of 1400 kW. In other words, the bigger the previous mistake, the greater of the demand saving opportunity if the current month's demand is under control.

It will be shown in later sections that the base load electrical demand for this hospital is less than 1400 kW throughout the year, which make it possible to set 1400 kW as the target during most of the off-peak periods.

Control Strategy Development

In this section, the existing operating and control sequences are examined and evaluated first. The whole campus electrical and thermal load profiles are presented next. Finally, the development of new control strategies for on-peak and off-peak months is described.

Existing operating schedule.

A typical on-peak months daily electrical demand profile is shown in Figure 4. It can be seen that from 11:30 am to 8 pm, the chillers are shut down while the tank is in the discharge mode. When the on-peak hour ends at 8 pm, chillers start up and the demand jumps to as high as 2030 kW. By 5 am, the demand steadily drops to 1820 kW. This is in part due to decreased building cooling load. At the same time, the chiller load decreases as the tank becomes close to fully charged and is returning relatively low temperature chilled water to the chillers. By early morning, the demand starts to increase again as the day starts. Cooling load continues to increase as ambient temperature warms up. The load peaks in late morning at 2356 kW when the kitchen and laundry activities go to full swing before the chillers shut down at 11:30 am.

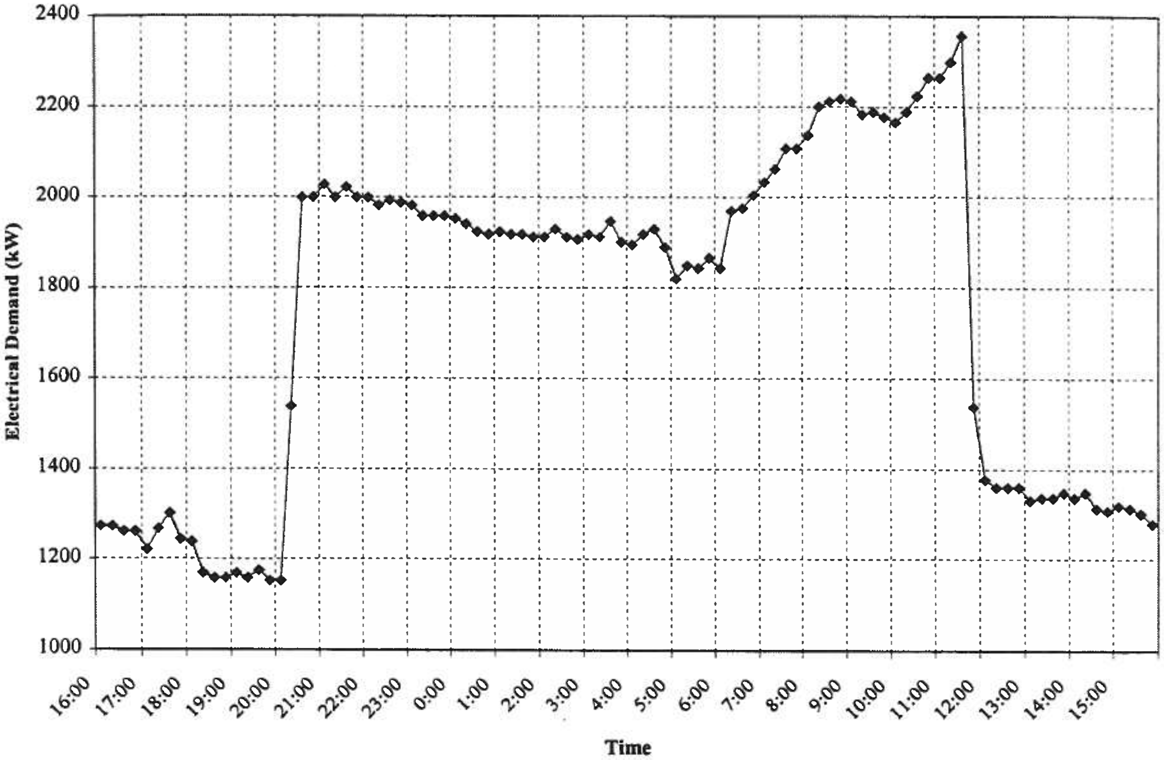

Figure 4. Typical on-peak months electrical demand profile.

Figure 5 shows a typical inventory (cooling capacity) profile of the storage tank. It increases steadily after 8 pm when the tank is in the charging mode. The storage rate slows down after 6 am when the load in the hospital starts to increase. After 11:30 am, the tank is in the discharging mode and the cooling capacity decreases from 7400 ton-hours to 1800 ton-hours by 8 pm, a reduction of 5600 ton-hours, or roughly 700 tons per hour during the discharge period.

Note that the tank is not completely depleted by the end of the on-peak hours. However, what's left in the tank is "low grade"- return chilled water with temperatures in the low 50's. This is partly due to poor control of AHU cold deck temperatures. The existence of some 3-way control valves in the buildings also contributes to the low return temperature. If return chilled water temperature can be increased by a few degrees, the tank can be discharged at a slower rate or it can start the discharge mode earlier.

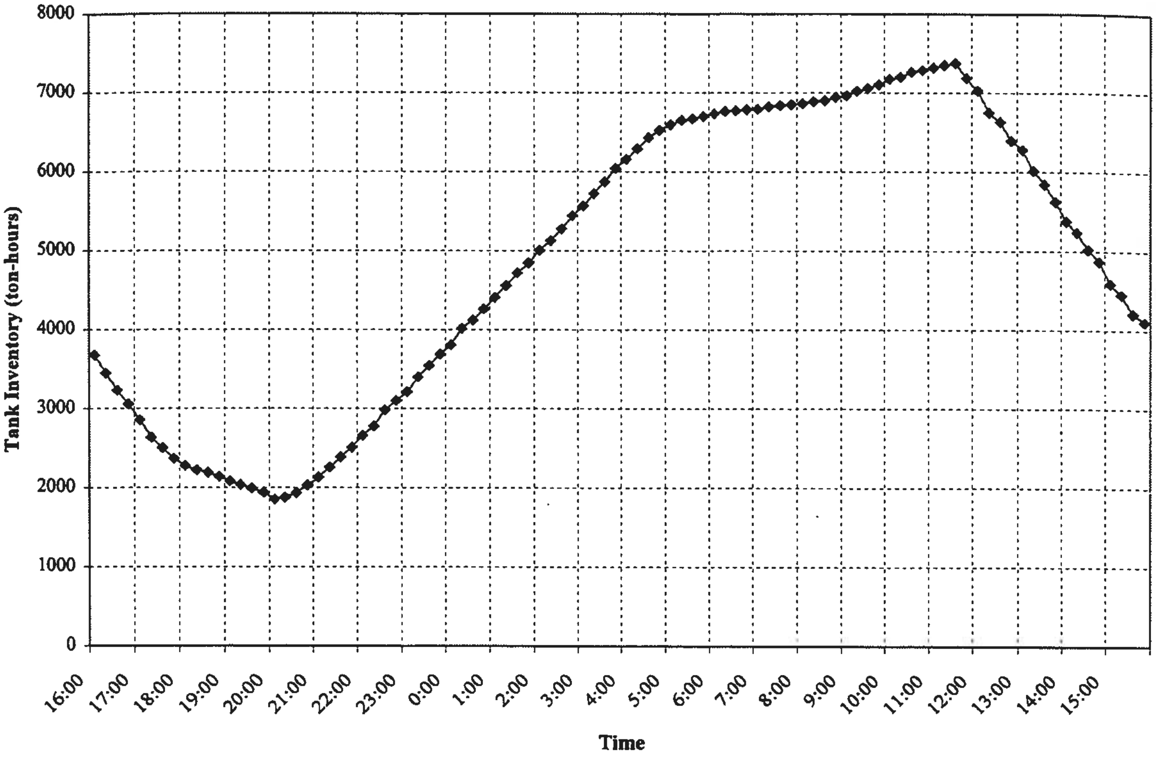

Figure 5. Typical storage tank inventory profile.

It can be seen that during the on-peak months, the late morning electricity usage dominates the demand profile. If demand during this time period is lowered, significant savings can be achieved.

Investigation shows that for typical daily operation, the two large chillers (425 tons each) remain on throughout the off-peak hours in order to fully charge the storage tank with low temperature chilled water (~40°F). However, higher than design chilled water flow causes a low temperature difference across the chillers since there is no chilled water flow regulation at the chillers. Consequently, low temperature chilled water (~45°F) has to be passed through the chillers for the second time, which results in extended chiller run time.

Lowering the demand by reducing the number of chillers in operation during late morning is the key for successful demand reduction. That requires the tank be fully charged as quickly as possible. Once the tank is fully charged and locked off, one 425 ton chiller can be turned off. The remaining chillers (~900 tons) can handle the cooling load. Both large chillers can be turned off during high electrical base load periods. In that case, the cooling load can be satisfied by discharging the tank at low speed during late morning while operating the smaller chillers. However, how fast and how long the tank can discharge needs to be determined to avoid depleting the tank prematurely. In the following section, the whole campus building cooling and base electrical load characteristics are studied first.

Building cooling load profile.

The building cooling load is obtained using the archived data collected by the control system. Storage tank chilled water discharge rate and the difference between supply and return chilled water temperatures are used to calculate the whole campus building cooling load. The whole campus cooling load vs. ambient temperature is shown in Figure 6.

The data interval is 15 minutes. It can be seen that the cooling load varies linearly with the ambient temperature. A linear regression model is used to describe the whole campus cooling load as a function of the ambient temperature:

$$Qc = 11.80 \times Toa - 617.45 \quad (1)$$

Where

Qc = whole campus cooling load (tons)

Toa = ambient dry-bulb temperature (°F)

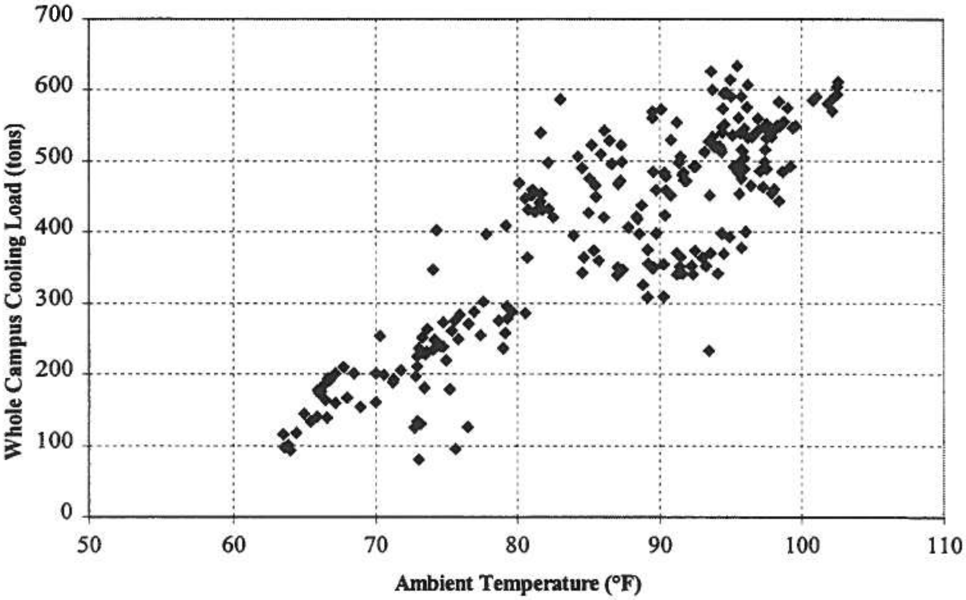

Figure 6. Whole campus cooling load vs. ambient dry-bulb temperature.

Base electrical load profile.

Typical whole campus base electrical load is presented in Figure 7. The data is obtained by subtracting the measured chiller electrical load from the measured whole campus electrical load.

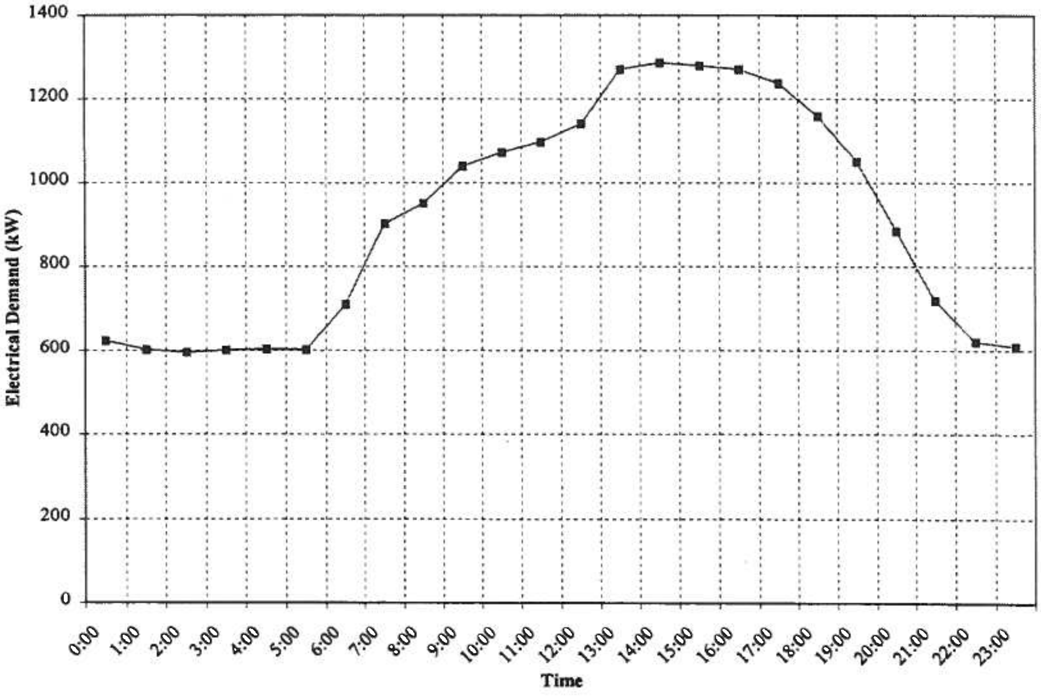

Figure 7. Typical daily base electrical load.

The graph shows a general trend of increased demand after 6 am. The base load is about 700 kW higher at early afternoon as compared to that during the nighttime. Also note that the demand begins to drop after 5 pm when most staff start to leave the hospital.

On-peak months chiller and tank operation.
The above analysis of the existing operating sequence and the load profiles indicates that several steps can be taken to reduce the on-peak demand: 1) increase the chilled water return temperature to increase the effective storage capacity; 2) improve the chilled water supply temperature control to speed up the charging process, so that one large chiller can be turned off in early morning; 3) start the discharge mode earlier when the base demand load is high while operating one or two chillers in late morning; 4) start a smaller chiller after 5 pm if the tank chilled water inventory is insufficient since the base demand is low during the three-hour on-peak period from 5 pm to 8 pm. The continuous commissioning program helped implement some of the proposed measures.

Through commissioning, the cold deck and hot deck temperatures were optimized at each AHU. Chilled water VFD pump control at each building was also optimized. These procedures helped increase the chilled water return temperature while reducing the cooling load due to simultaneous heating and cooling.

As discussed earlier, large chillers had to be operated during late morning in order to charge the tank fully, which coincided with relatively high electrical base load and resulted in very high electrical demand. Although this demand does not carry over into the next 12 months, as the on-peak demand does, it does count for the current month billing demand. To reduce demand during this time period, VFDs were installed on the chiller pumps for the two large chillers to control the chilled water supply temperatures. By controlling the chillers at near full load conditions, the tank is charged earlier and the peak demand is reduced, as can be seen in Figures 8 and 9. One of the large chillers was expected to be turned off when the tank inventory reached 7000 ton-hours. Unfortunately, the automatic control program was disabled by the operator in order to obtain higher tank inventory. Nevertheless, one 200 ton chiller was turned off at 8:00 am while the large chillers continued to operate throughout the morning. The tank inventory was pushed above 8600 ton-hours by late morning. Despite the interruption of the automatic control program, some reduction in demand was achieved.

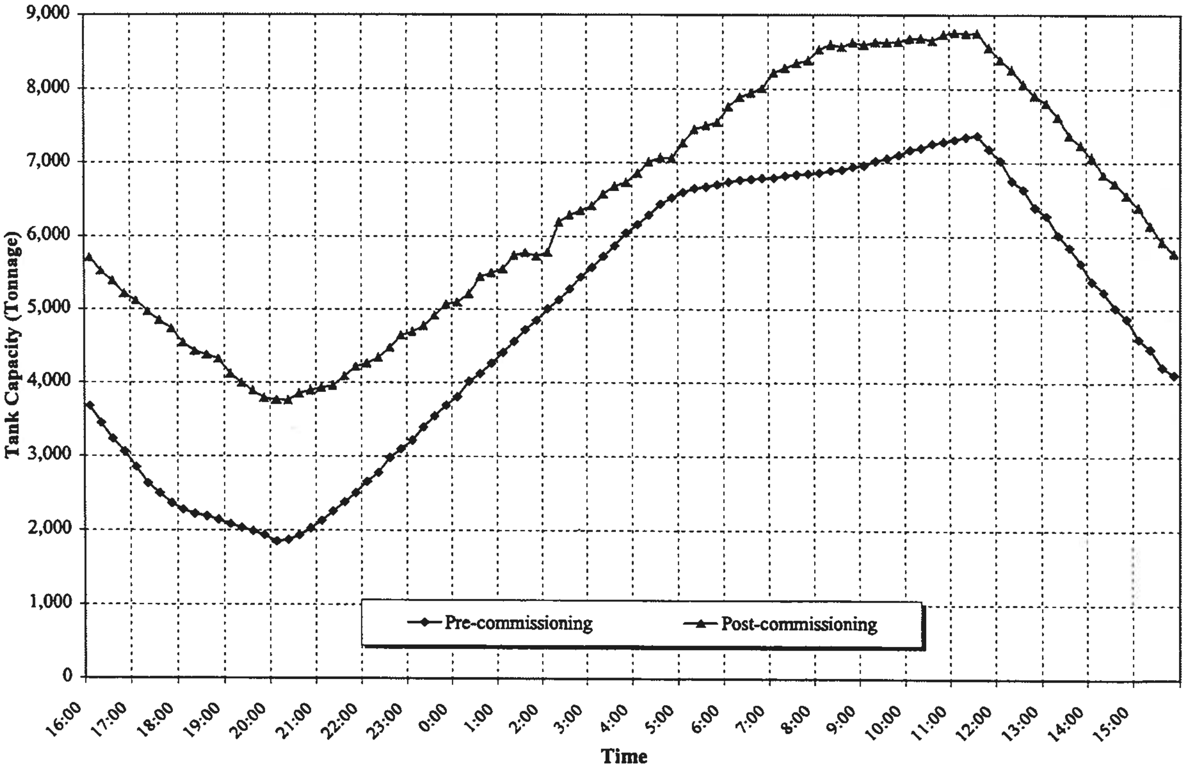

Figure 8. Comparison of storage tank inventory profile before and after the commissioning.

The late morning demand is reduced to around 2000 kW, as shown in Figure 9. Since the electrical rate schedule carries a clause that penalizes the user over the next 12 months for any new high demand set during the on-peak hours, no attempt has been made to limit the charging inventory based on predicted upcoming cooling load during the on-peak months. The storage tank is charged fully during the on-peak months to avoid operating the chillers during the on-peak hours in case of a system failure.

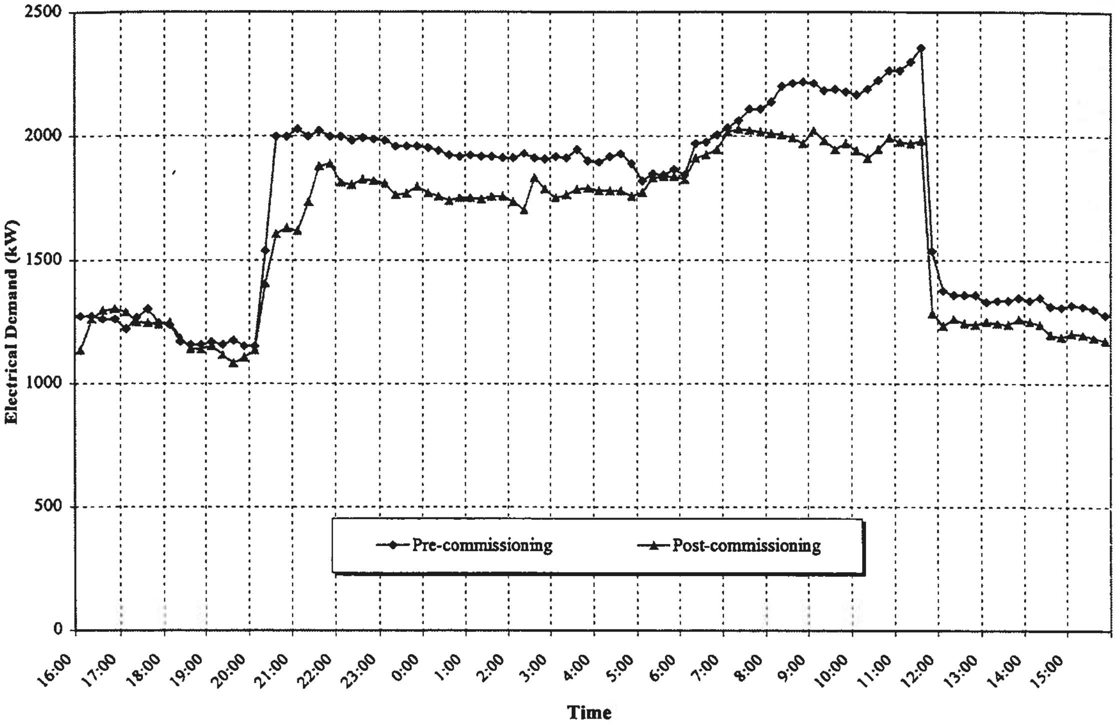

Figure 9. Comparison of typical on-peak month electrical demand profile before and after commissioning.

Off-peak months chiller and tank operation.

The electrical rate schedule indicates that the lowest possible off-peak months billing demand is 1400 kW. To avoid unnecessary demand charge, it is desirable to keep the off-peak months demand below 1400 kW. The operating strategies of the chiller and tank for hot, mild, and winter seasons are described below.

Hot season operation. While 1400 kW may not be a realistic target for the month immediately following the on-peak months when the cooling load is still relatively high, it is possible to reduce the number of chillers operating at night when the system is in the charging mode. There is no need to fully charge the tank anymore. Cooling load can be shared by the storage tank and one or two chillers during the day if it is not enough. The availability of different sizes of chillers makes the choice of operation flexible. The key for this control strategy is to minimize the difference between the demand during nighttime charge mode and the demand during daytime discharge mode with chiller operation as a supplement.

Mild season operation. During the mild season, it is possible to keep the demand below the target 1400 kW. The key is to avoid the operation of chillers during the daytime when the base electrical demand is high. By predicting the upcoming (24 hours) cooling load, the tank is charged to a certain tonnage at night so that it has enough chilled water for the next day.

To predict the upcoming cooling load using the existing control system, actual hourly temperature of the past day and the forecasted high and low temperatures of the next day are required. The past day's temperature profile can be obtained from the database of the control system. The forecasted high and low temperatures for the next day can be easily obtained and entered into the control system by the operator. The expected hourly temperature profile for the next day is obtained by scaling the past day's temperature profile to match the forecasted high and low temperatures of the next day.

With the forecasted hourly ambient temperature profile available, whole campus cooling load is predicted at 5 pm every day based on Equation 1. Hourly cooling load up to 5 pm of the next day is calculated and totaled every hour after 5 pm. It is then compared with the chilled water inventory in the storage tank. Chiller operation is then based on the following criteria:

If $Q_f < Q_t + 1000$	not necessary to operate the chillers
If $Q_f > Q_t + 1000$	operate the chillers and charge the tank until $C_f < Ct + 1500$

Where

Q_f = forecasted whole campus cooling load from the time it is calculated to 5 pm of the next day, ton-hours

Q_t = tank inventory, ton-hours

If the chillers are to be operated, the electrical demand is monitored to make sure that it does not surpass 1400 kW. If demand drops below 1000 kW while the 200 ton chiller is in operation, and the tank capacity is over 1000 ton-hours short, turn on the 425 ton chiller to serve the buildings and charge the tank. If the demand approaches 1400 kW, turn off the smaller chiller.

Winter season operation. The operator used to turn on several chillers during winter days and charged the tank full. The tank was then put in discharge mode for several days until it was depleted. This practice not only wasted energy, but also created unnecessarily high demand charges during the winter months. A closer analysis of the cooling load shows that during the winter, only the small 200 ton chiller needs to be turned on during the day when the outside air temperature is above 55°F and there is not enough cooling capacity in the tank. The pump at the storage tank can be turned off and the tank is put into the charge mode. Thus the chiller can operate at high efficiency and supply chilled water to the buildings as required. Any surplus chilled water is stored in the tank for future usage.

The winter season operation has been implemented as this paper is written. The demand has been under control so far. Control strategies for other weather conditions are expected to be implemented in the near future. As more 3-way control valves are removed from the chilled water loop in the near future, and the operator better understands the control strategy, system performance will continue to improve.

CONCLUSIONS

The operating and control strategy for a full chilled water storage system at a hospital is discussed and evaluated. The control strategy is optimized during a continuous commissioning program in order to reduce demand charges, especially during the off-peak months. A simplified predictive control method is proposed. Preliminary results show that the optimized control strategy is expected to save the hospital significant demand charges both in the on-peak and the off-peak months.

REFERENCES

Braun, J. E. 1992. A comparison of chiller-priority, storage-priority, and optimal control of an ice-storage system. ASHRAE Transactions, 1992, Vol. 98, Part 1, pp. 893 – 902.

Ferranto F J. and Wong, K., V. 1990. Prediction of thermal storage loads using a neural network. ASHRAE Transactions, 1990, Vol. 96, Part 2, pp. 723-726.

Henze, G. P. and Krarti, M. 1999. The impact of forecasting uncertainty on the performance of a predictive optimal controller for thermal energy storage systems. ASHRAE Transactions, 1999 summer meeting.

Kimbara, A., Kurosu S., Endo, R., Kamimura K., Matsuba T., Yamada A. 1995. On-line prediction for load profile of an air-conditioning system. ASHRAE Transactions, 1995, Vol. 101, Part 2, pp. 198-207.

Krarti, M., Henze, G., P., Bell, D. 1999. Planning horizon for a predictive optimal controller for thermal energy storage systems. ASHRAE Transactions, 1999 summer meeting.

Liu, M., Veteto, B., Claridge, D. E. 1998. Rehabilitating a thermal storage system through commissioning. Proceedings of the 11th Symposium on Improving Building Systems in Hot and Humid climates. Fort Worth, Texas, June 1 - 2, 1998.

Moor, J. E. and Harmon, J. J. 1998. Operating strategy for dynamic ice thermal storage system. ASHRAE Transactions, 1998, Vol. 104, Part 1B, pp. 1607-1611.

Rawlings, L. K. 1985. Ice storage system optimization and control strategies. ASHRAE Transactions, 1985, Vol. 91, Part 1B, pp. 12-23.

Shavit, G. and Goodman, H. 1985. Operation and control of energy storage systems. ASHRAE Transactions, 1985, Vol. 91, Part 1B, pp. 24-31.

Spethmann, D. H. 1993. Application considerations in optimal control of cool storage. ASHRAE Transactions, 1993, Vol. 99, Part 1, pp. 1009-1015.

Tamblyn, R. T. 1985. Control concept for thermal storage. ASHRAE Transactions, 1985, Vol. 91, Part 1B, pp. 5-11.