Application of Building Precooling to Reduce Peak Cooling Requirements

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Abstract

A building cooling control strategy was developed and tested for a 1.4 million square foot (130,000 square meter) office building located in Hoffman Estates, IL. The goal of the control strategy was to utilize building thermal mass to limit the peak cooling load for continued building operation in the event of the loss of one of the four central chiller units. The algorithm was first developed and evaluated through simulation and then evaluated through tests on two identical buildings. The east building utilized the existing building control strategy while the west building used the precooling strategy developed for this project. Consistent with simulation predictions, the precooling control strategy successfully limited the peak load to 75% of the cooling capacity for the west building, while the east building operated at 100% of capacity.

Precooling of the building mass provided an economical alternative to the purchase of an additional chiller unit. The estimated cost of installing an additional chiller was approximately $500,000. Computer models developed for this project also showed that precooling based upon cooling cost minimization could result in savings of approximately $25,000 per month during the peak cooling season. The building model was validated with experimental results and could be used in the development of a cost minimization strategy.

Key Words: HVAC, Precooling, Building Cooling, Simulation, Peak Demand, Cooling Capacity

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Introduction

Precooling the thermal mass of a building is an innovative thermal storage approach for cooling of commercial buildings. Simulation studies and experimentation have demonstrated that to successfully utilize building mass thermal storage while maintaining occupant comfort, the control strategy must be matched to the particular application [Ruud et al. 1990, Braun 1990, Morris et al. 1994].

This paper describes the development and application of a building precooling strategy for a large office building located approximately 15 miles (24 kilometers) west of Chicago, IL. The facility considered in this project has been experiencing growth in both personnel and the computing equipment required to support these employees. This growth has directly added to the cooling load requirements of the building. Currently, the loss of one chiller on a hot summer day could result in uncomfortable conditions and limit operations. Precooling the thermal mass of the building can shift cooling load to the night period thereby allowing the existing cooling equipment to meet the cooling load during the day, even if one chiller is not operational.

The objective of this project was to develop a control strategy for operating the HVAC system when one of the chillers is not operational. The control strategy was designed to allow continued building operation while limiting the peak cooling load to 75% of the capacity of the existing equipment with a minimal impact on occupant comfort. The control strategy was developed using computer simulations and tested using identical buildings. A follow-up study will demonstrate the cost savings potential for precooling of this building. This paper presents estimates of the savings obtained through simulation.

Control Strategies

The precooling control strategy used in this study is depicted in Figure 1 along with conventional night setup control. Precooling is controlled at a constant temperature setpoint designated as T_{pre}. This is not the most energy or cost efficient strategy for precooling, but it is conservative in that it charges the building mass as completely as possible. The warm-up period is used to reset the zone air temperature setpoint so that the cooling system turns off without calling for heating. During this time, the zone air warms due to lighting and equipment loads.

The occupied setpoint (T_{occ}) is set to a value low in the comfort region so that the building mass charge is held as long as cooling capacity is available. This setpoint is maintained until the limit on cooling capacity is reached. After this point, the temperatures in the zones will "float" upwards and the "cooling" stored in the building thermal mass will be discharged. If the precooling and occupied setpoints have been chosen properly, the zone conditions will remain within the comfort region throughout the occupied period with the capacity limit in place.

Night setup control was used as the baseline for evaluation of the performance of the precooling strategy. Under night setup control, the zone temperature setpoint is set to a constant value at the upper end of the comfort region during the occupied period. At night, the temperature setpoint is reset to a high value which prevents the cooling plant from operating when the building is unoccupied.

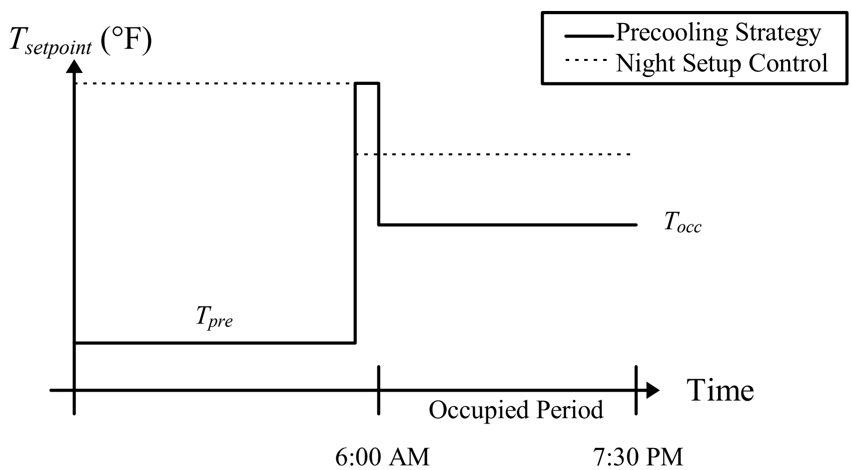

Figure 1: Zone air temperature setpoints

The precooling strategy is an emergency procedure to allow building operation when a chiller is not available. For this particular application, indoor plant grow-lights and decorative fountain pumps were identified as non-essential electrical loads which should be turned off while the strategy is in effect. The fountain pumps are not major electrical loads, but the spraying water adds directly to the cooling coil latent load.

System Description and Modeling

The facility considered in this study is a modern three story office building with an overall occupied area of approximately 1.4 million square feet (130,000 square meters). The building uses energy efficient glazing, heavy weight wall construction, and exposed concrete which make it a good candidate for building precooling. The facility is an ideal location for control strategy testing due to the layout of the building. Two identical buildings connected by a large separately cooled entrance area have similar internal gains and solar radiation loads. The cooling loads for one of the buildings can be compared to the other for evaluation of potential control strategies. The chilled water system was split so that the cooling loads of the east and west buildings could be differentiated. The east building was used as the control zones for the tests, while the west building was used for testing the performance of the precooling strategy.

Four equally sized 900 ton vapor compression chillers are currently used to provide chilled water to the air handling units. The loss of one chiller will result in a 25% reduction of the total system capacity. This condition was simulated by limiting the vane position of the two chiller units which cool the west building to 75%. The capacity limitation was imposed directly at the chiller control panels.

A modern digital cooling control system (DCS) with programming capabilities is installed in the facility. When the precooling strategy was used, the local zone cooling setpoints were overridden by a scheduled setpoint block at each main controller unit. This setpoint block transmitted a new zone temperature setpoint for cooling to the local controllers. All zone temperature setpoints were identical when the precooling strategy was employed. The implementation of the precooling strategy could be improved by allowing local control of individual zone cooling setpoints. The DCS was also used to record cooling plant operating conditions during the tests. In addition, thermal comfort was monitored during the tests with the Bruel and Kjaer (B&K) Model 1213 indoor climate analyzer.

The electric utility rate structure consists of a time of day electricity usage rate in conjunction with a monthly demand charge. The on-peak period occurs on weekdays from 9 AM to 10 PM during which the electric usage charge is \$0.052 (US) per Kilowatt-hour. All other times are considered off-peak when the rate is \$0.023 per Kilowatt-hour. The demand charge for this facility is $16.41 per Kilowatt and is based on the average of the three highest demands for a billing month.

A detailed computer model of the building and cooling equipment was used to develop the precooling control strategy and to estimate the savings potential under a cost minimization cooling control strategy. The simulation tools consist of a transfer function based thermal building model coupled to cooling plant equipment models. Details of the simulation tools are given in Keeney and Braun [1995, 1996]. For development of the emergency strategy, the building model was used to determine the precooling setpoints which would achieve the project cooling demand objective without compromising occupant comfort.

In order to evaluate the cost savings potential for precooling this facility, the building and cooling plant models were used with numerical optimization to calculate the control strategy which minimized cooling costs. In this case, the power consumption of the cooling plant equipment (cooling tower, fans, pumps etc.) was modeled using a simplified model representative of the cooling plant equipment installed at the test facility [Braun 1990].

Simulation Results

The simulation tools were used to determine the control strategy setpoints depicted in Figure 1. To demonstrate the potential for reducing peak cooling loads using building precooling, simulations were performed using a simplified model of the facility. Figure 2 shows the cooling load profiles for a design cooling day in Chicago under conventional night setup control and the precooling strategy. Under night setup control, the cooling plant was operating at about 95% of plant capacity at peak load. With building precooling, the peak load dropped to the target value of 75% of plant capacity. The precooling (T_{pre}) and occupied (T_{occ}) temperature setpoints required to meet the objective of this project were found to be 68°F (20.0°C) and 71°F (21.7°C), respectively. Note that the simulation tool can also develop an optimal strategy which meets a target demand value and minimizes the total cooling energy costs.

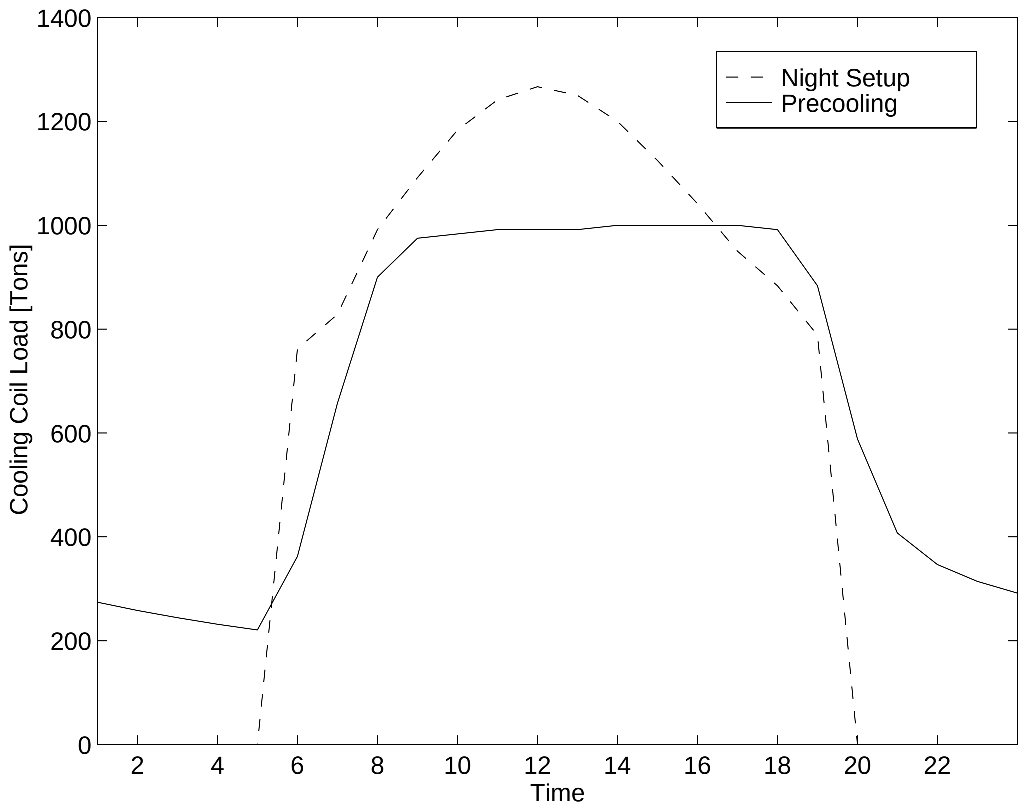

Figure 2: Cooling load under night setup and optimal precooling control

Figure 3 shows the estimated occupant comfort given in Predicted Mean Vote (PMV) units [Fanger 1970]. Under the PMV system, a value of zero represents neutral comfort, positive values indicate a warm environment, and negative values indicate a cool environment. The limits on PMV under current ASHRAE guidelines are -0.5 and 0.5 [ASHRAE 1989]. Under night setup control, a fixed temperature setpoint within the comfort limits is maintained while the building is occupied. When the building is unoccupied, the cooling equipment is turned off and the space temperature rises resulting in a warm comfort index value. Under the precooling strategy, the cooling equipment is run during the night period. During the occupied period, the zone warms as the thermal mass is discharged. Occupant comfort is not compromised while the building is occupied under the precooling strategy.

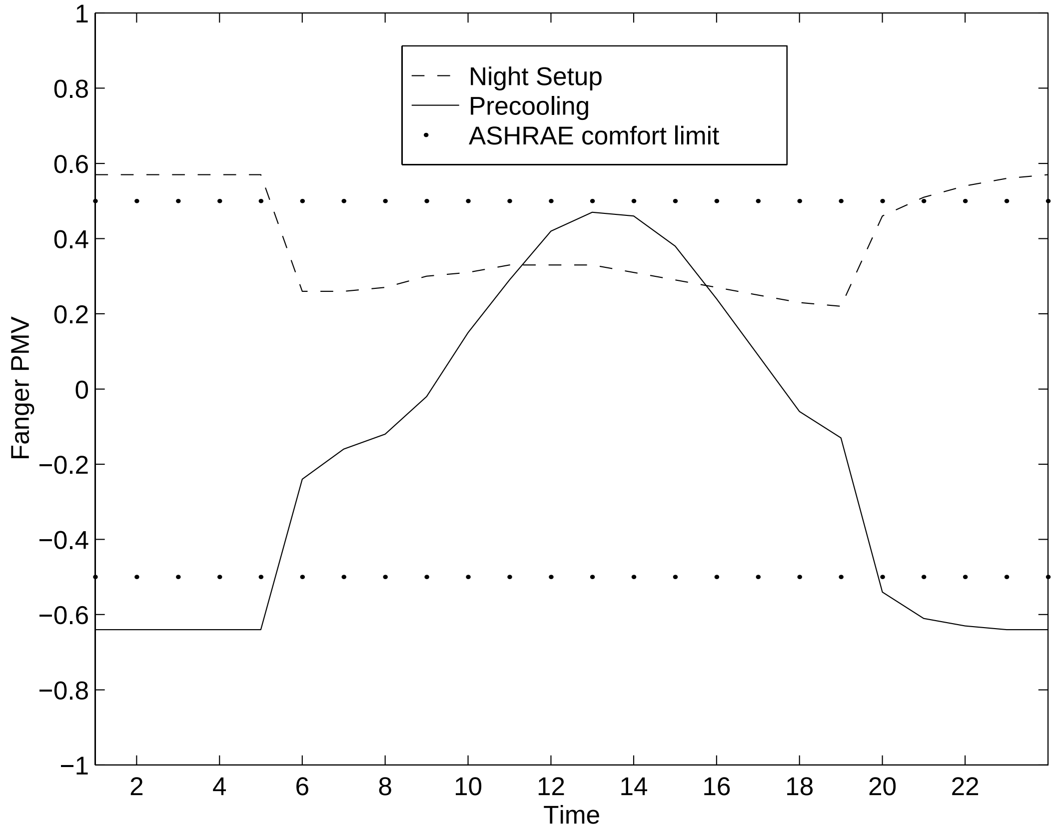

Figure 3: Estimated occupant comfort

Thermal comfort is a function of the activity and clothing of the occupants. During the first site visit, the building usage patterns and the dress and activity of typical occupants were documented. This information was then factored into the comfort models which were used to estimate the upper and lower limits for zone air temperature setpoints. Table 1 shows the upper and lower limits for zone temperature as predicted by the comfort models. The comfort model predicted that the neutral comfort setpoint for this facility was 73°F (23.8°C) which corresponds to the fixed night setup control temperature setpoint used in the facility.

Table 1: Comfort model results

	Fanger PMV	Zone Temperature
Upper Comfort Limit	+0.5	69°F
Neutral Comfort	0.0	73°F
Lower Comfort Limit	-0.5	77°F

Testing Results

The first testing period was from Monday, July 31, 1995 to Friday, August 4, 1995. These tests were primarily designed to check the implementation of the control algorithm and verify that the data acquisition systems were working properly. Several problems in algorithm implementation were identified and corrected during these tests. The initial testing period was also used to gauge the effectiveness of the warm-up period on occupant comfort. Based on this testing period, the warm-up period was reduced from one hour to 30 minutes. It was also found that draft problems were occurring in areas which were located across from the supply ducts on the main building corridor. This problem was corrected by resetting the zone cooling setpoints of the affected zones to 73°F (22.8°C).

The second set of on-site tests were conducted from Saturday August 12, 1995 to Friday August 18, 1995. Precooling of the thermal mass had already been implemented into the conventional control strategy by maintaining the occupied setpoint for the top floor of the facility. This was necessary to maintain comfort conditions with full cooling capacity on "hot" days. Figure 4 shows the total chiller coil load for the east and west buildings for the second test week. There are several interesting features in these results.

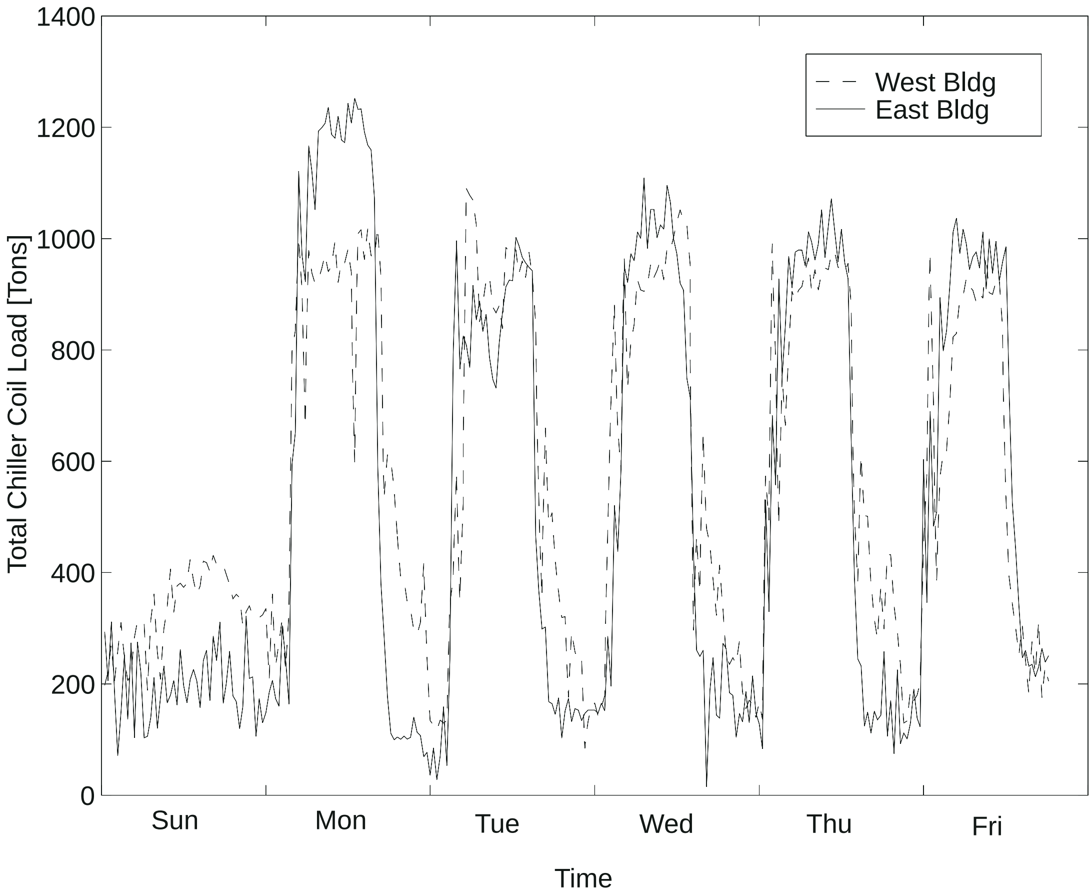

Figure 4: Total coil load for east and west chiller units

The cooling coil load profile on Monday is the most dramatic example of the load shifting during this test period. The peak cooling load for this facility often occurs on Monday morning. The cooling limit was achieved on Monday during a period in which a heat emergency had been declared in the city of Chicago. The severe ambient conditions were compounded by a power outage which caused a loss of the west side chiller units for approximately 20 minutes. Under these demanding conditions, the precooling strategy maintained occupant comfort while successfully limiting cooling demand of the west side of the building to less than 75% of that for the east side.

The east side cooling requirement was at or below the 75% chiller capacity target for Tuesday through Friday so the emergency precooling strategy was not necessary. For these off-design days, the emergency strategy is not effective in reducing the on-peak cooling requirements because discharge of the mass is not initiated when the capacity is below the target. The thermal mass remains charged so that peak reduction would occur if the target value on the off design days was reset to a lower value.

The cooling load data were also used to validate the ability of the simulation tool to estimate the cooling load profiles under the precooling control strategy. Figure 5 compares the cooling load data for Thursday, August 17 with the simulation tool results for a similar weather day. Overall, the simulation tool does a good job of capturing the building cooling dynamics. The total cooling load for the test data and the computer model differed by 7.7%. Further improvements could be made by using a more detailed accounting of the internal gains and occupancy schedules in the simulation tool.

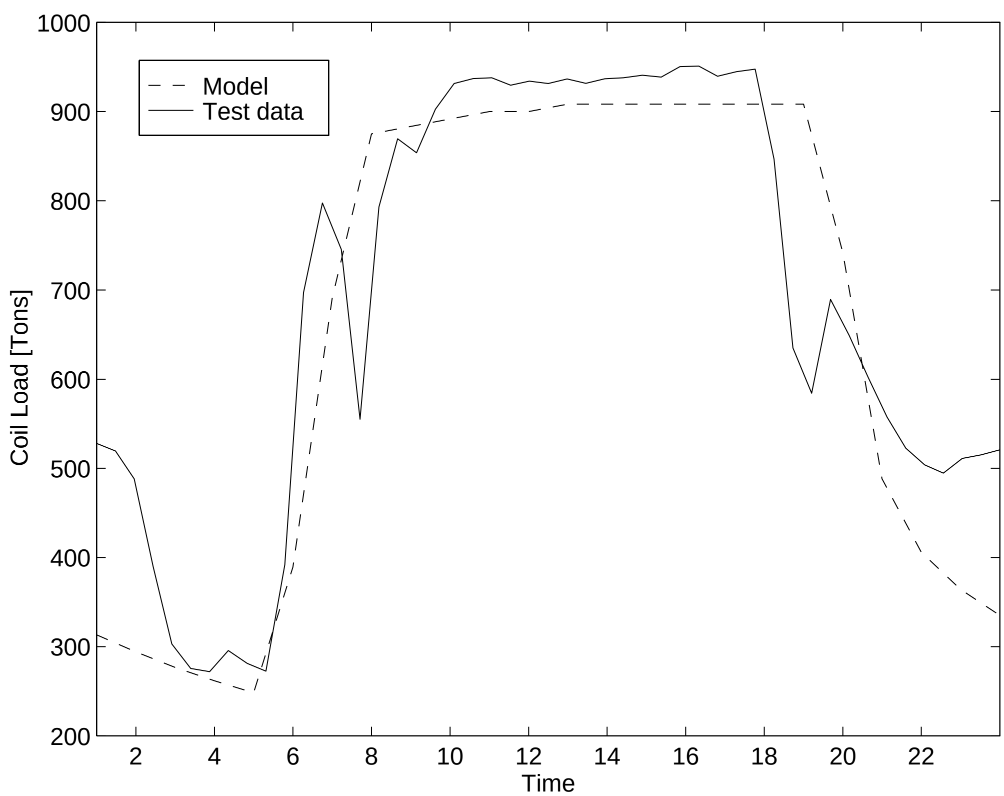

Figure 5: Comparison of simulation tool and test data

Figure 6 gives the total chiller electricity consumption of the east and west chillers for the testing period. The chiller power consumption closely matches the cooling load profiles shown in Figure 4. The limit on chiller capacity also limited the cooling power demand of the chiller units. The total electrical usage was greater for the precooled west building, however the strategy was designed as an emergency strategy and does not attempt to minimize costs. Analysis of the electric meter data for the chillers showed that the electricity usage charge was approximately $700 per week higher under the precooling strategy when compared to night setup control. The reduction in demand results in a monthly savings of approximately $2600 which almost exactly offsets the increased usage charges. Estimates of cost savings potential for building precooling are presented in the next section.

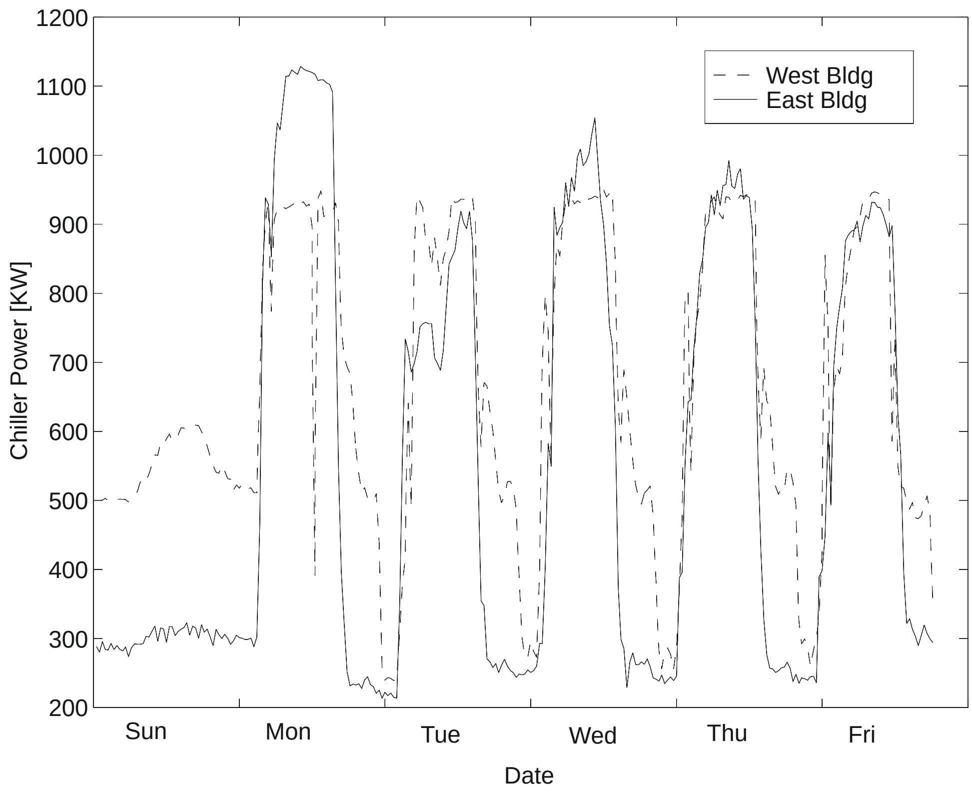

Figure 6: Electric power consumption for east and west chillers

Occupant comfort must also be considered in the final evaluation of the precooling strategy. Test equipment was used to measure the environmental variables which play a role in thermal occupant comfort. The B&K model 1213 indoor climate analyzer recorded the room air temperature, humidity level, air velocity, and radiant temperature at ten minute intervals throughout the precooling tests. The comfort monitoring instrumentation was placed in a representative open plan workstation on the second floor of the west building. The data recorded were then processed by a thermal comfort model to yield an estimate of the Fanger PMV comfort index under the precooling strategy.

Figure 7 shows the PMV index plotted as a function of time for Wednesday August 2 under the precooling strategy. At night, the zone conditions were below the ASHRAE limit for occupant comfort. Just prior to occupancy, the warm-up period was initiated which quickly returned the zone conditions to the comfort region. For the remainder of the occupied period, the zone was maintained at cool conditions to continue to charge the thermal mass of the building. During the test day depicted in Figure 7, the limit on cooling capacity was not reached and the comfort conditions remained at a relatively constant level through the day. If the entire comfort range were utilized, additional on-peak load reduction would have occurred. However, cost savings was not the intent of the precooling strategy.

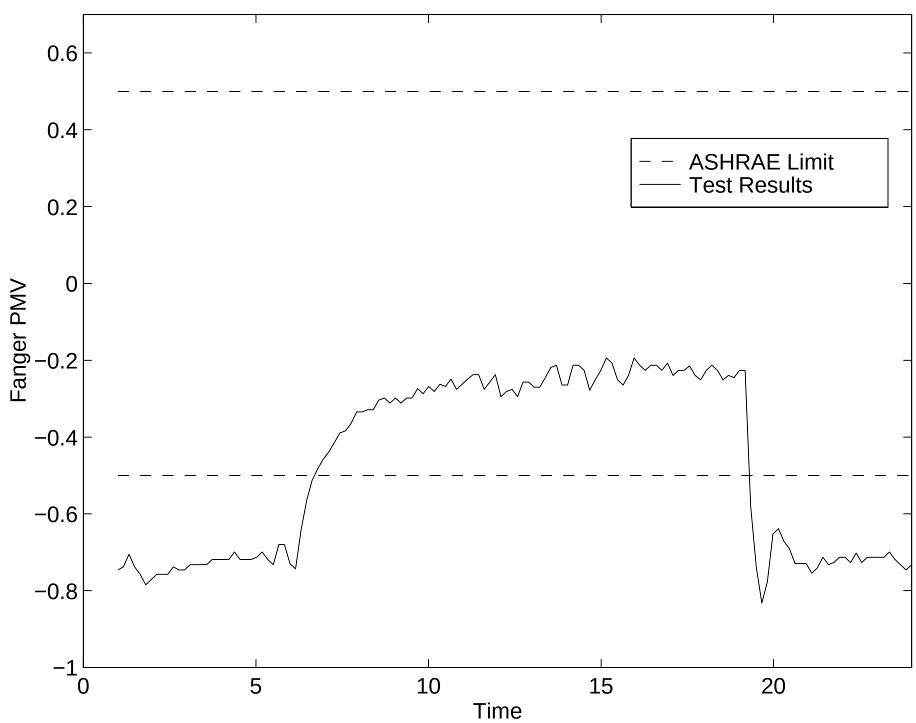

Figure 7: Measured comfort index under precooling strategy

Cooling Cost Minimization

Figure 8 shows a breakdown of the electricity costs for the month of July, 1995 for the two buildings. Two points are important to consider in the facility electricity costs. First, the HVAC related demand and usage charges make up 62% of the total electric bill for the month of July. This translates to a cost of approximately $156,000. Even a small fractional savings in the HVAC related energy costs translates to significant savings. Figure 8 also shows that the magnitude of the demand and usage charges are approximately equal. Cost minimization control strategies can reduce cooling costs by both the reduction of peak demand and by shifting usage to the off-peak period.

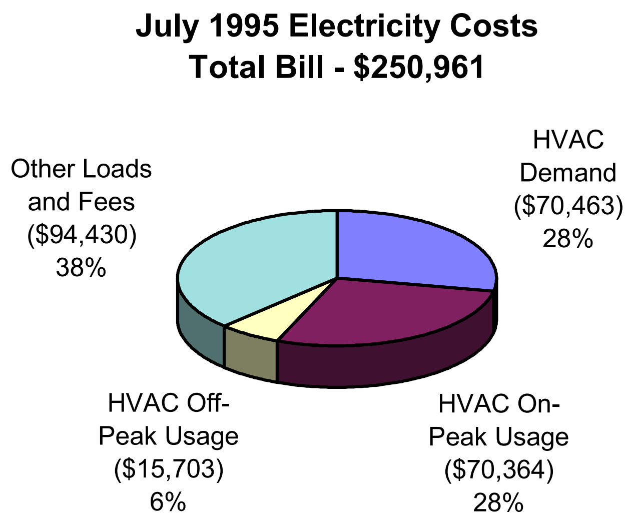

Figure 8: Electricity cost breakdown for July 1995

A constant zone air temperature setpoint was used to control precooling of the thermal mass in this study. This was done to minimize the control system programming required to implement precooling. Figure 4 shows that the cooling load under a constant temperature control decreases through the precooling period to a low value just prior to occupancy. More efficient precooling strategies would precool at a higher rate closer to the onset of the occupied period. The cooling control would also be improved during the occupied period by considering the time of use utility rate and by setting an appropriate peak cooling power target level.

The control strategy developed for this project successfully limited the chiller cooling demand to 75% of the equipment capacity. As shown in Figure 8, demand charges make up about half of the total cooling costs. In order to estimate the potential for reducing energy costs with precooling, computer simulations were used to test an energy cost minimization control strategy with the test facility building model over a single average day. This simulation used a hot day with an average outdoor temperature of 80°F (26.7°C). The cooling load for the energy cost minimization strategy is shown in Figure 9. Precooling is controlled at a nearly constant rate prior to occupancy. The cooling demand drops sharply at 9 AM when the on-peak electricity usage rate begins.

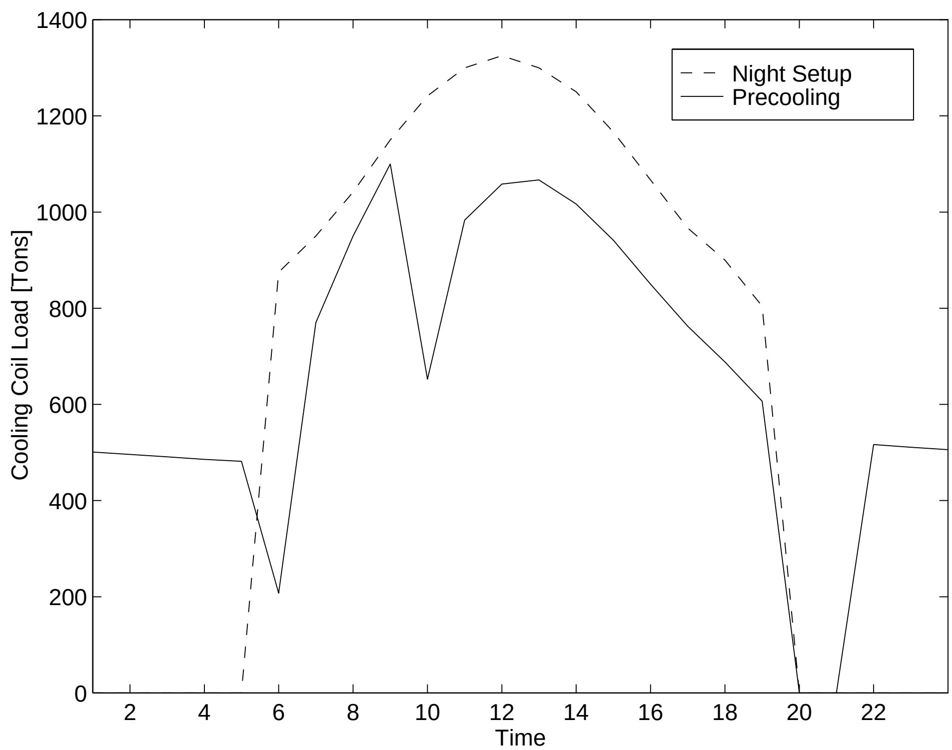

Figure 9: Cooling load under cooling energy cost minimization strategy

The energy cost minimization strategy reduced cooling energy usage costs by 15% for this day and the total cooling electricity demand was reduced by 18%. Based on the July 1995 electricity costs shown in Figure 8, the application of a similar control over the entire billing cycle would result in a savings of about $25,000 in a single month. These savings estimates are conservative because as seen in the testing results, the demand could be further reduced on "peak" days. It is important to remember that the optimal control strategy must be determined for each individual day in order to account for different weather conditions and days of the week. Work is needed to both develop and implement a "practical" cost minimization strategy.

The comfort index for the same simulation presented in Figure 9 is plotted in Figure 10. Note that under the cooling cost minimization strategy, the comfort index drifts to the top of the ASHRAE limits at the onset of the on-peak energy usage rate. The thermal mass begins to discharge when the electricity usage costs are high. Zone conditions remain within the acceptable limits throughout the occupied period.

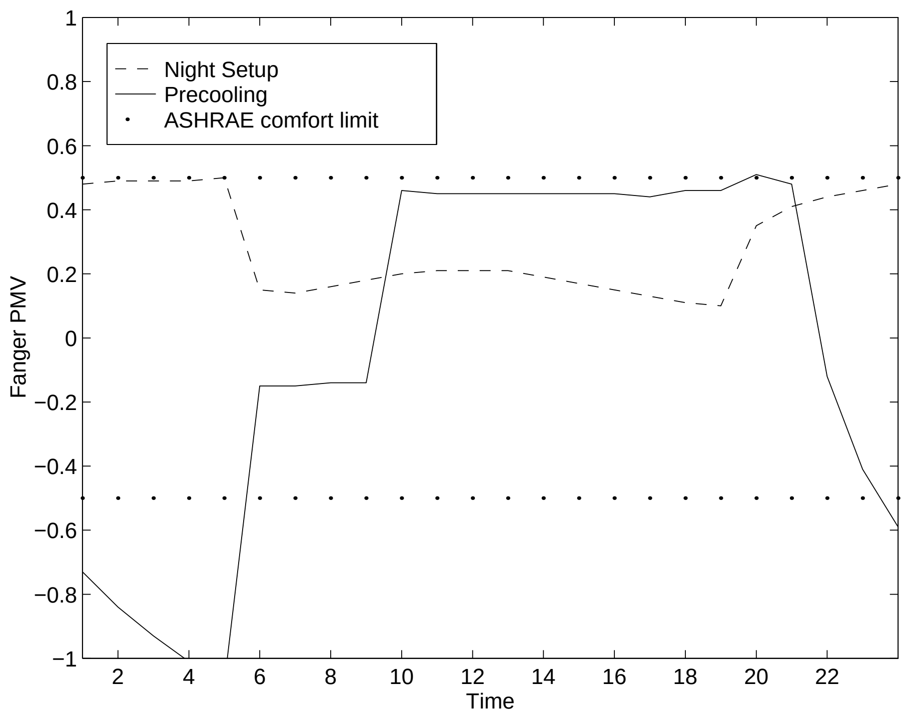

Figure 10: Comfort index under cooling energy cost minimization strategy

Conclusions and Recommendations

The results of this project were encouraging for two reasons. First, the control strategy was successful in limiting the maximum cooling demand to the target value, thus providing an alternative to the installation of an additional chiller unit for a savings of approximately $500,000. Second, this project demonstrated that savings of over $25,000 per month are possible through optimal control of building thermal mass. A research project is ongoing which will use the tools and experience gained from this project to develop and implement a cooling control strategy for this building based on cost minimization.

Further research is needed to develop a control algorithm which minimizes the total cooling energy costs when a monthly demand charge is included in the cost function. This is a challenging problem which must consider the utility rates, building usage, weather, and day of the week.

Acknowledgments

The authors wish to thank Doug Jones and Lynn Jester of Compass Management and Leasing, and Jeff Bruemmer, Tom Seliger, and Mike Durko of Johnson Controls for their support during this project. We would also like to thank Tom Kroeschell and Gary Michaels for their input and assistance.

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