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ABSTRACT

The objective of this study was to demonstrate the potential for reducing peak-period electrical demand in moderate-weight commercial buildings by modifying the control of the HVAC system. An 80,000 ft^2 office building with a medium-weight building structure and high window-to-wall ratio was used for a case study in which zone temperature set-points were adjusted prior to and during occupancy. HVAC performance data and zone temperatures were recorded using the building control system. Additional operative temperature sensors for selected zones and power meters for the chillers and the AHU fans were installed for the study. An energy performance baseline was constructed from data collected during normal operation. Two strategies for demand shifting using the building thermal mass were then programmed in the control system and implemented progressively over a period of one month.

It was found that a simple demand limiting strategy performed well in this building. This strategy involved maintaining zone temperatures at the lower end of the comfort region during the occupied period up until 2 pm. Starting at 2 pm, the zone temperatures were allowed to float to the high end of the comfort region. With this strategy, the chiller power was reduced by 80-100% (1 – 2.3 W/ft^2) during normal peak hours from 2 – 5 pm, without causing any thermal comfort complaints. The effects on the demand from 2 – 5 pm of the inclusion of pre-cooling prior to occupancy are unclear.

Introduction

The value of thermal mass has long been recognized as a resource when optimizing the thermal control of buildings. However, in practice, conventional controls treat the thermal mass as an obstacle rather than an asset. Under the conventional control, such as morning warm up, minimum energy consumption results in the case when there is no thermal mass at all [Braun 2003]. However, the thermal mass of the building can be used to reduce the peak load. For example, in summer, the building mass can be cooled during non-peak hours in order to reduce the cooling load in the peak hours. As a result, the cooling load is shifted in time and the peak demand is reduced. The building mass can be cooled most effectively during unoccupied hours because it is possible to relax the comfort constraints.

Thermal mass control strategies differ in the way they store and release heat from the mass. The building mass may be cooled by natural or mechanical ventilation, with or without mechanical cooling. Pre-cooling can be performed either during the unoccupied hours or during the occupied non-peak hours, usually in the morning. In climates with a large diurnal temperature swing, it may be possible to pre-cool the building mass without mechanical cooling. If there is sufficient pre-cooling and the daytime cooling load is relatively low, it may be possible for the indoor air temperature to remain within the comfort range during the peak hours without any mechanical cooling. Cooling energy stored in the mass can be discharged during the peak hours by either demand limiting the cooling plant and distribution system or by zonal temperature reset.

Strategies to improve building control by using thermal mass have been investigated in the past years through simulation studies and by experiments in laboratories and occupied buildings. Using simulation, Braun (1990) demonstrated 10-35% peak load reductions and 10-50% cost savings from a series of pre-cooling strategies. Andresen and Brandemuehl (1992) demonstrated 10-50% peak load reductions by simulating one zone of an office building. In a more recent simulation study, intensive night ventilation and regular cooling effectively reduced peak demand by 43%-56% (Becker and Paciuk 2002).

Significant load shifting and peak load reduction was also observed in laboratory tests. Conniff (1991) demonstrated small effects of pre-cooling in a laboratory facility. The peak demand was reduced by 3%. Morris et al. (1994) continued the study by using the same facility but a better pre-cooling strategy, which was optimized with a simulation tool. 40-51% of the cooling peaking load was shifted to the off-peak hours.

In field tests, the results were mixed. Some achieved a high peak demand reduction, while others got modest reduction or no reduction. Ruud et al (1990) performed several pre-cooling experiments in an office building in which air was supplied at low temperature during the nighttime. About 18% of the load was shifted from day to night with no comfort complaints. Keeney and Braun (1997) achieved a more significant shedding in a large office building in Chicago. The peak demand load was reduced by 25% with a simple pre-cooling control strategy. There was also a successful study performed in California by Mahajan et al. (1993). A large university classroom building was used to study the effects of nighttime forced ventilation cooling and the HVAC peak load was reduced by as much as 100% from 2 pm to 6:30 pm.

The simulation studies have demonstrated there is a high potential to reduce peak cooling loads with thermal mass control. Results from laboratory and field studies are mixed for various reasons. There are many practical issues associated with control and mechanical systems that make it hard to implement these strategies successfully. Even more importantly, it is difficult to document peak load savings through building thermal control because field experiments are not repeatable.

This paper presents a preliminary case study of a moderate-weight commercial building that demonstrates the potential of peak demand saving using pre-cooling and zonal temperature reset and provides a better understanding of the implementation requirements. This paper presents the results of two pre-cooling and zonal temperature reset strategies that were tested in the building under a limited range of summer weather conditions. In the tests, both strategies reduced the peak demand substantially. The test site and the control strategies adopted are described in detail and results for both whole building and component level performance are presented. The lessons learned and the needs for future work are also discussed.

Methods

Test Site Description

The building selected for the study is a medium-sized governmental office building located in Santa Rosa, CA. The floor area is ~80,000 ft^2 and about half of the space is for offices and half for courtrooms. It has three stories with moderate structural mass, having 6” concrete floors and 4” exterior concrete walls. The office area has a medium furniture density and standard commercial carpet on the floor. The building has a window-to-wall ratio of 0.67, with floor-to-ceiling glazing on the north and south façades and significantly smaller glazing fractions on the east and west. The windows have single-pane tinted glazing. The internal equipment and lighting load are typical for office buildings. The total number of occupants in the office areas is approximately 100 ($400ft^2$/person).

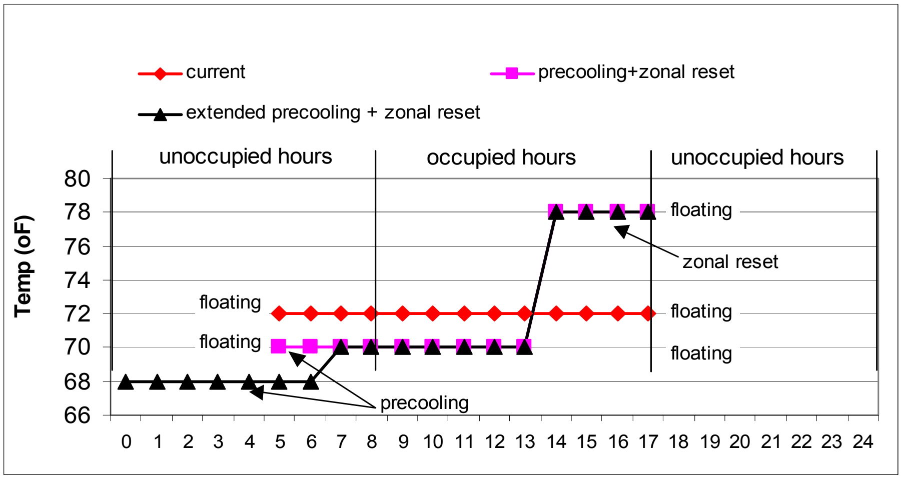
The building has independent HVAC systems for the west wing and the east wing. On the west wing (office side), there are three 75-ton, 30-year old air-cooled chillers. Two dual-duct VAV (variable air volume) air handlers deliver conditioned air to the zones. On the east side, there are two 60-ton, 10-year old air-cooled chillers with three single duct VAV air handlers. There is one constant-speed water pump for each chiller. All the chillers have two stage compressors. The supply and return fans for the dual duct system are controlled by variable frequency drives (VFD). The single duct system has constant speed fans with inlet vane controls. There are ~ 50 zones in the building. The building is fully equipped with digital direct control (DDC), but had no global zone temperature reset strategies implemented before the study.

Operationally, the building is typical of many office buildings. The HVAC system starts at 5 am and pre-heats or pre-cools the building until 8am. The occupied hours are from 8 am to 5 pm. No major faults in the mechanical system were apparent except for one undersized cooling coil and some air balance problems in the duct system. There are also some minor temperature control problems caused by lack of reheat coils. There are relatively few comfort complaints, averaging ~ 2-3 hot/cold calls per month. The building operator has worked at the building for a long time and is quite confident and familiar with the system.

Test Strategies

The two pre-cooling and zone temperature reset strategies that were tested are shown in Figure 1. The building was normally operated at a constant set point of 72^oF throughout the startup and occupied hours. After 5pm, the system was shut off and zone temperatures floated. Under normal operation, the set-points in individual zones ranged from 70 to 75^oF, with an average value of 72^oF. The first strategy tested was termed "pre-cooling + zonal reset". From 5am to 2pm, all the zone temperature set-points were lowered to 70^oF. From 2 pm to 5pm, the set-points were raised to 78^oF. After 5 pm, the system was shut off, as in regular operation. The second strategy was termed "extended pre-cooling + zonal reset". The system was turned on at midnight and the zone temperature set-points were set to 68^oF from 12 am to 5 am. The aim was to cool a significant depth of the exposed structural concrete. From 5 am to 2 pm, the set-points were raised to 70^oF and, after 2 pm, raised to 78^oF. The difference between the two strategies is the extension of the pre-cooling period. One aim of the tests was to determine the effect of the extended pre-cooling on the peak demand shedding.

Figure 1. Pre-Cooling and Zonal Temperature Reset



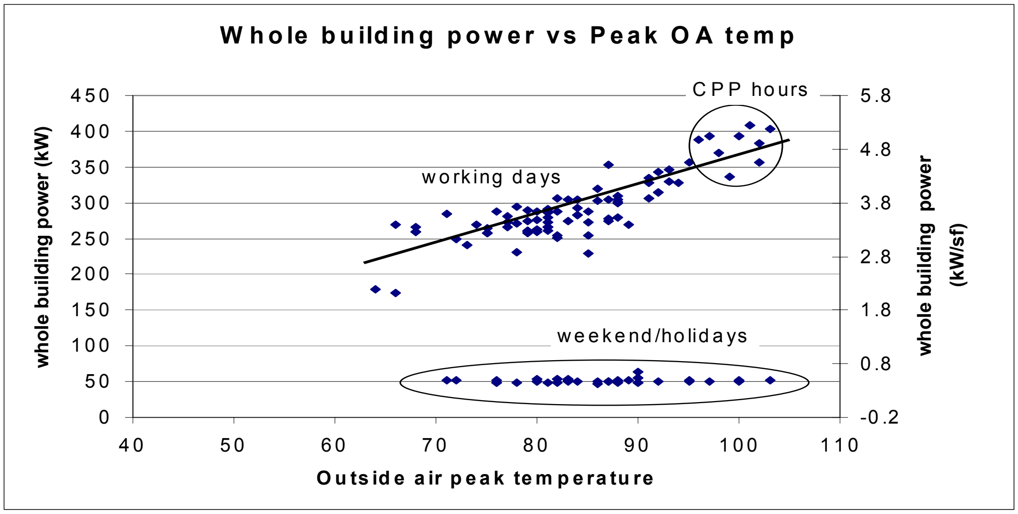
Monitoring

The building has a whole building power meter and five permanent chiller power meters. There is a weather station measuring outside air temperature and humidity. The HVAC performance data were recorded using the building control system. Roughly 500 data points were collected at 15-minute intervals. Four temporary fan power meters were installed on the air handling unit fans for this study to determine the impact of control strategies on the air distribution system. Twelve operative temperature sensors were installed in the buildings. The operative temperature sensors consist of temperature sensors enclosed in hollow spheres and measure a weighted average of the radiant temperature and dry bulb air temperature. Because of the radiant effect, the operative temperature is a better indicator of the thermal comfort than the dry bulb air temperature. This was thought to be important in assessing thermal comfort in this study, because the building surfaces should be cooler as a result of the pre-cooling.

Weather and Test Scenarios

The baseline for the pre-cooling tests was defined based on the peak outside air temperature. The utility and weather data for a period of regular operation were analyzed to determine the correlation between the daily peak outside air temperature and the daily peak demand. As shown in Figure 2, there is a strong correlation between the peak building power demand and the peak outside temperature. Baseline days for each test day were selected based on similarity of peak outside air temperature.

Figure 2. Correlation Between Whole Building Peak Demand and Peak Outside Air Temperature



All the tests were conducted during the month of October 2003 (factors beyond the control of the authors prevented the tests being performed earlier in the summer). The tests days were classified into three groups depending on their peak outside air temperature, as shown in Figure 3. Cool days were defined as days when the peak outside air temperature was between 72°F and 78°F. Warm days were between 78°F and 84°F and hot days were between 84°F and 90°F. Because the tests were conducted in the fall, no tests were conducted under extremely hot conditions, such as when the outside air temperature is 100°F or above. Figure 4 shows more detailed comparisons of the outside air temperatures for the baseline and test days. Both the peak temperatures and the temperature variations are similar for the baseline and test days for

Figure 3. Outside Air Temperatures in the Test Month

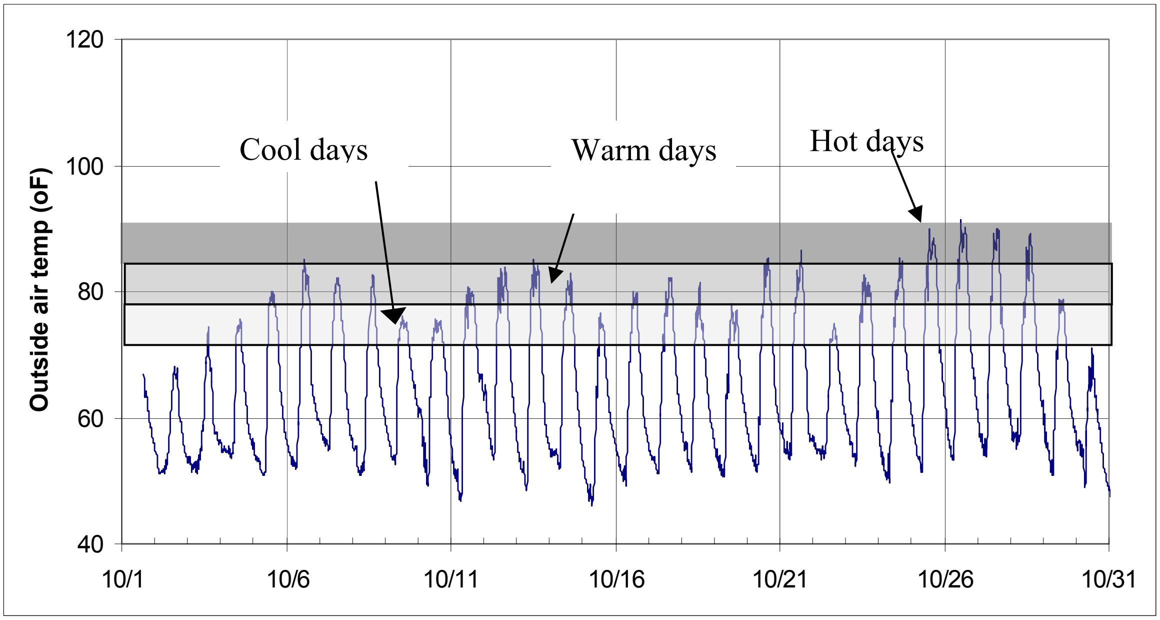
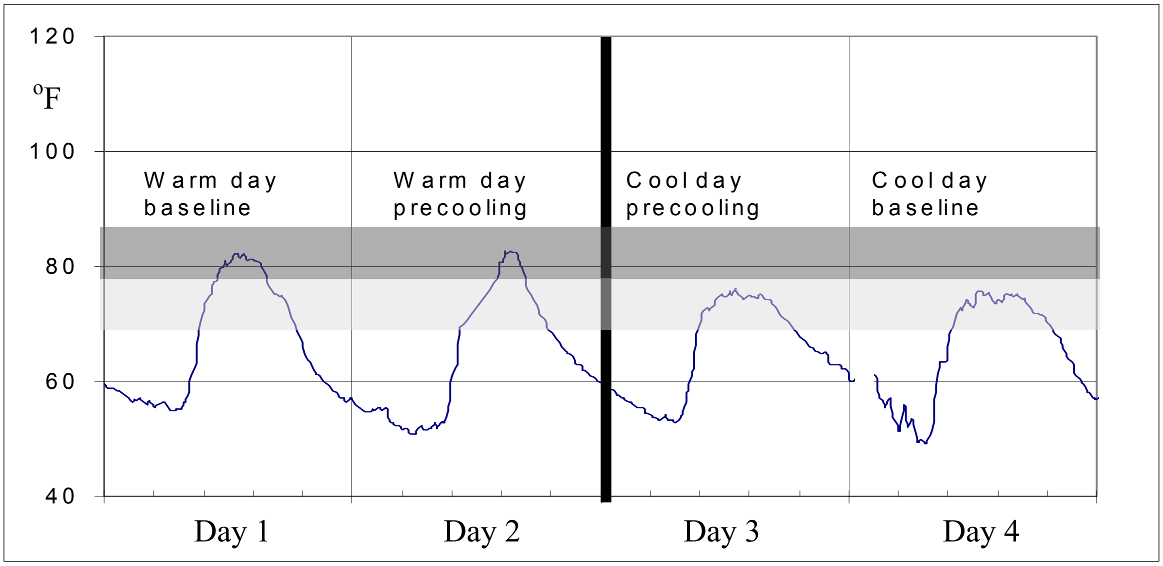


Figure 4. Outside Air Temperatures in Baseline and Pre-Cooling Test Days



both cool and warm day testing. In total, eleven tests were conducted in this study, as listed in Table 1. Each test lasted for one day. There were eight pre-cooling and zonal reset tests, three of them were on cool days and five of them were on warm days. There were three 'extended pre-cooling + zonal reset tests'. One of them was on a warm day and two of them were on hot days. For warm days, both pre-cooling and extended pre-cooling tests were performed to assess the effect of the extended pre-cooling.

Table 1. Pre-Cooling and Zonal Reset Test Scenarios

	Pre-cooling + zonal reset	Extended pre-cooling + zonal reset
Cool days	3	
Warm days	5	1
Hot days		2

Results

The test data showed significant peak demand savings for both pre-cooling strategies. Sample results are shown in Figures 5-11. Figure 5 shows whole building power results for the pre-cooling + zonal reset tests on the cool days. The power levels for the baseline and test days were similar in the morning. At 2 pm, when the zone temperatures set-points were reset to 78 °F, the cooling plant shut off automatically because the cooling demand fell to zero and the whole building electric load dropped by 1 W/ft^2 (for comparison, Figure 2 indicates that the baseline value of the whole building peak demand is ~3.5 W/ft^2). The cooling plant stayed off until 5pm, when the mechanical system was completely shut off. The cooling demand remained at zero because the zone temperatures never reached the set-point of 78 °F (see section on thermal comfort). Figure 6 shows results of the pre-cooling + zonal reset on the warm days. As with the tests on the cool days, the cooling plant turned off at 2 pm because the increased zone temperature set-point resulted in zero cooling demand. The whole building power demand was reduced by 1.4 W/ft^2.

Figure 7 shows a comparison of the limited pre-cooling and the extended pre-cooling on the warm days. In the extended pre-cooling tests, the power increased at night compared to the baseline because the system turned on to provide pre-cooling at midnight. In the morning period, there was a small reduction in the electrical power compared with the limited pre-cooling test. The small differences in daytime demand for the two pre-cooling tests could be the result of weather or occupancy differences and are not significant.

Figure 8 shows results for the extended pre-cooling tests on the hot days. Compared with the baseline, the building power for the two test days was a little lower in the morning. The power was reduced by 2.3 W/ft^2 in the afternoon peak hours. In the extended pre-cooling test 1, the cooling plant turned on a few times in the afternoon before 5 pm because the global temperature reset control strategy was not working properly and several zone temperature set-points failed to rise to 78 °F as planned. The chillers turned back on when the temperatures reached the unmodified set-points. After the problem was fixed, the cooling plant stayed off till 5 pm as in the other tests.

Figure 5. Pre-Cooling Tests on Cool Days

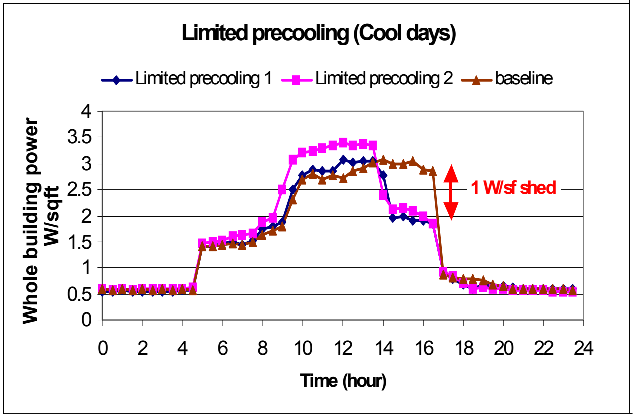


Figure 6. Pre-Cooling Tests on Warm Days

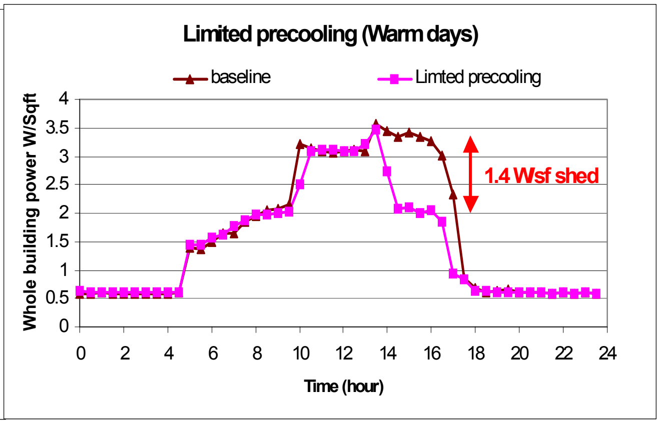


Figure 7. Comparison of the Limited Pre-Cooling and Extended Pre-Cooling Tests

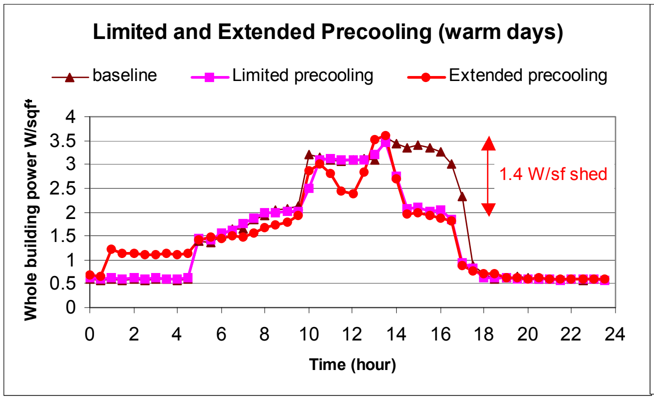
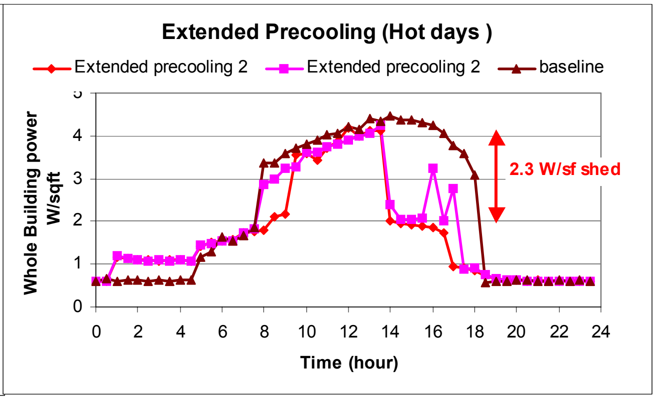


Figure 8. Extended Pre-Cooling Tests on Hot days



Component Level Comparisons

At the individual HVAC component level, load shedding was observed for both the cooling plant and air distribution system. As an example, Figure 9 shows the response of one of the chillers during one of the tests above. In the morning, there was little difference in chiller power between the pre-cooling and baseline days. When the zone temperatures set-points were reset to 78^{o}F at 2pm, the cooling plant turned off completely, except for a small amount of standby power consumption (note that the increase in power occurs before the set-point change at 2pm). Figure 10 shows one supply fan power measurement during one of the test days. The fan shedding was relatively small compared to the cooling plant and is less than would be expected for a variable-air-volume (VAV) system. This behavior will be investigated if the expected opportunity to do further experiments in the building materializes.

Thermal Comfort Comparisons

No complaints from occupants were received by the building operator throughout the tests. Conversations with the building occupants indicated that they hardly noticed any changes in the operation of the building. Although the zone set-points were increased to 78 ^{o}F in the afternoon, the actual building temperatures never reached 78 ^{o}F, except in a few zones on the hot days. Figure 11 shows zone temperatures for the worst zone during warm day tests for the baseline and pre-cooling strategies. The zone faces west and has a large area of glazing and high direct solar gain during the peak hours. This zone showed the fastest temperature rise of all the zones during the shedding period.

Four temperatures are plotted in Figure 11. The first one is the dry bulb air temperature measured by the building control system on a baseline day. The second is the dry bulb air temperature measured by the building control system on the pre-cooling test day. The third is the operative temperature measured by the temporary sensors installed on the pre-cooling test day. The forth is the whole building average zone air temperature measured by the control system on the pre-cooling test day.

Compared to the baseline, the zone was operated at a lower temperature in the morning and higher temperature in the afternoon as expected. Although this zone is the worst-case zone, the zone air temperature never exceeded than 75 ^{o}F in the afternoon. Compared to this zone, the whole building average temperature increased more slowly and stayed below 73 ^{o}F.

There was little or no difference between the dry bulb air temperature and operative temperature. In theory, the operative temperature should be lower because of the colder surface temperatures of the exposed thermal mass, though in zones with windows, the higher surface temperature of the glazing will tend to increase the mean radiant temperature. This result applied to all the operative temperature sensors installed. The small differences between the operative and air temperatures for both the baseline and pre-cooling tests indicates that the control system sensors provide a good indication of relative comfort.

Figure 9 Chiller Power in Pre-Cooling Tests

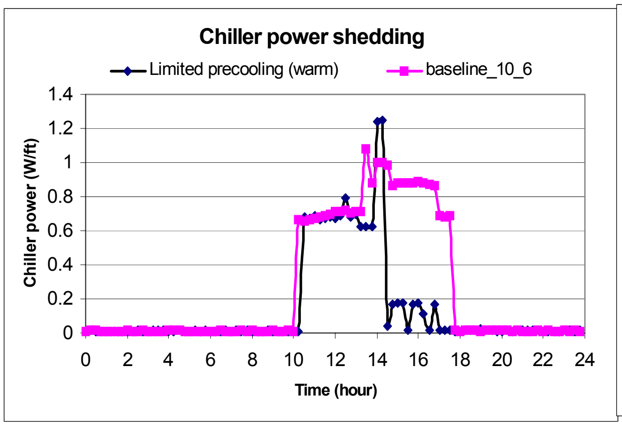
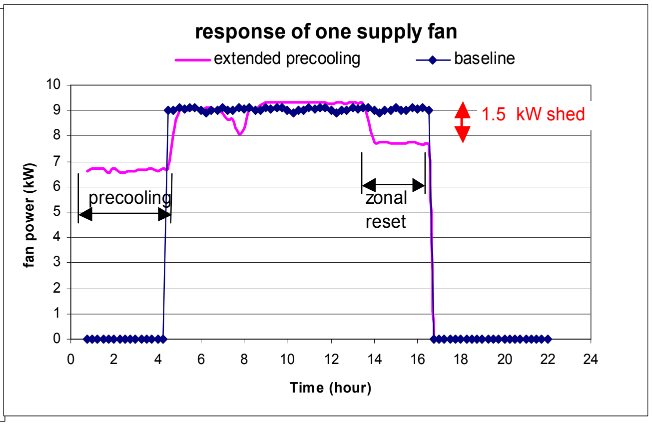


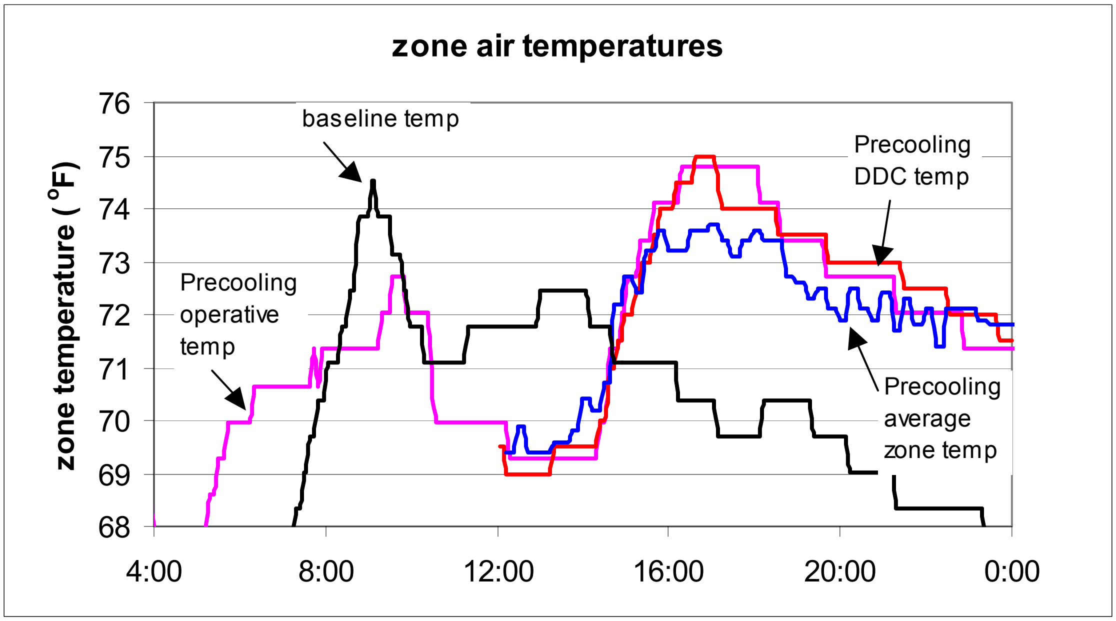
Figure 10 Supply Fan Power in Pre-Cooling Tests



Conclusions and Further Work

The two pre-cooling and zonal temperature reset strategies that were tested shifted 80 – 100% of the electric load due to the cooling plant from the on-peak to the off-peak period without comfort complaints, even with relatively high outside temperature conditions (90°F). Even though Figure 2 indicates that the peak load can vary significantly for a fixed outside temperature, the invariable reduction in demand in response to increases in set-point indicates that the observed peak demand reductions are a result of the changes in operation rather than changes in solar gain or occupancy. The building thermal mass was effective in limiting the variations in the zone temperature. The average rate of change of zone temperature was about one degree per hour. In the worst-case zone, the temperature rise was approximately two degrees per hour. Higher rates of increase may be produced when the outside temperature is

Figure 11. Zone Air Temperatures for the Pre-Cooling Tests and the Baseline



hotter than the conditions encountered in this study; further work is required to quantify this effect. Even though no complaints were made by the occupants in this study, further work should include comfort surveys to determine the extent to which thermal discomfort that is not severe enough to cause complaints occurs as a result of different degrees of demand shifting.

Although the peak load was reduced significantly in all the tests, the benefits of nocturnal pre-cooling are unclear. There is insufficient evidence to demonstrate that the extended pre-cooling had any significant effect on the peak demand. This may be because the pre-cooling tests were only performed for periods of a day or two. Longer periods are required for a steady-periodic condition to be obtained than was available for these tests. It may well be that the extended pre-cooling needs to be performed for more than a week to see any effects. A significant effort was required to prepare the HVAC control system for the implementation of thermal mass control. It is important to understand the building and commission the HVAC system before running any demand-shifting control strategies. A control system that includes digital communications with the zone temperature controllers is required to implement demand-shifting strategies based on zone temperature reset. If the control system does not support global reset of zone temperatures, strategies involving reset of supply air temperature and/or chilled water temperature and supply air static pressure reset or some other method of limiting fan power must be employed. These strategies have the disadvantage that they are likely to produce wider variations in zone temperature. Secondly, the mechanical system itself needs to be reliable enough to operate the building over a wider range of conditions than occurs during regular operation. For example, in this study, there was one undersized cooling coil in one air handling unit, which limited the pre-cooling that could be performed in the zones that it served. Another example is ductwork balancing. If the ductwork is poorly balanced, some zones will be always be too hot even if the VAV box dampers are fully open. As a result, the temperature in these zones will rise faster than in others when the set-points are increased.

Further work is needed to improve understanding of pre-cooling and its role in reducing peak demand. There are several key issues. One is the need to quantify the relationship between peak demand reduction and discomfort risk for different building and HVAC system types in different climates. Another is to understand how the different types of thermal mass (furniture, different structural elements) contribute to limiting temperature changes on relatively short time-scales (up to a few hours). Finally, if the demand-shifting potential identified in this preliminary study is confirmed, screening tools and implementation guides will be needed to help deliver pre-cooling through utility programs and alternative tariffs.

Acknowledgements

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