Case Study of Demand Shifting with Thermal Mass in Two Large Commercial Buildings

Peng Xu, PhD, PE
Member ASHRAE

Philip Haves, PhD
Fellow ASHRAE

ABSTRACT

The idea of precooling and demand limiting is to precool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads during the peak periods. Savings are achieved by reducing on-peak energy and demand charges. The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies.

In a preliminary case study in a government office building in California in summer 2003, it was found that a simple demand-limiting strategy reduced the chiller power by 80%-100% (1-2.3 W/ft^2, 11-25 W/m^2) from 2 p.m. to 5 p.m. without causing any thermal comfort complaints. This paper describes a follow-up study in 2004 in which tests were performed in two office buildings over a wider range of conditions. A Web-based comfort survey instrument was developed and used in the field tests to assess thermal sensation, comfort, and perceived productivity ratings in these two buildings.

The results of the comfort survey indicate that occupant comfort was maintained in the precooling tests as long as the room temperatures were within the range of 70°F-76°F (21.1°C-25.6°C). Nighttime precooling was found to have varying effects on the magnitude of the peak the following day, with a number of factors affecting its effectiveness. It was found to be important to manage the afternoon load shedding by ramping the zone temperature setpoints rather than stepping them up. This is particularly important on hot days or in buildings with smaller time constants, where electrical power could "rebound" and exceed the peak demand under normal operation.

INTRODUCTION

The idea of precooling and demand limiting is to precool buildings at night or in the morning during off-peak hours, storing cooling in the building thermal mass and thereby reducing cooling loads during the peak periods. Savings are achieved by reducing on-peak energy and demand charges. The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies (Braun 1990; Ruud et al. 1990; Conniff 1991; Andresen and Brandemuehl 1992; Mahajan et al. 1993; Morris et al. 1994; Keeney and Braun 1997; Becker and Paciuk 2002). This technology would appear to have very significant potential for demand reduction if applied within an overall demand-response program.

In the late summer of 2003, a precooling case study was conducted in a commercial building in California (Xu et al. 2004). The objective of the 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. 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 air-handling unit (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 into 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

Peng Xu is a mechanical engineer and **Philip Haves** is a staff mechanical engineer with Lawrence Berkeley National Laboratory, Berkeley, Calif.

region (70°F [21.1°C]) during the occupied period up until 2 p.m. Starting at 2 p.m., the zone temperatures were allowed to float to the high end of the comfort region (78°F [25.6°C]). With this strategy, the chiller power was reduced by 80%-100% (1–2.3 W/ft^2 [11-25 W/m^2]) during normal peak hours from 2 p.m. to 5 p.m. without causing any thermal comfort complaints to operations staff. 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. An example of the test results is shown in Figure 1.

Although the study was quite successful, some key questions remains unanswered:

- What was the actual comfort reaction? Even though the occupants in this study made no complaints, 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.
- What is the effect of extended (nighttime) precooling on the following day peak shed? Although the peak load was reduced significantly in all the tests, the benefits of nocturnal precooling were unclear. There was insufficient evidence to demonstrate that the extended precooling had any significant effect on the peak demand. This might be because the precooling 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 precooling needs to be performed for more than a week to see any effects.
- What will happen in really hot weather? Does the temperature rise faster in the afternoon than in the cases that were studied? The maximum outside air temperature in the 2003 tests was 88°F (31.1°C), which is significantly lower than the 2.5% cooling design temperature of 95°F (35.0°C).

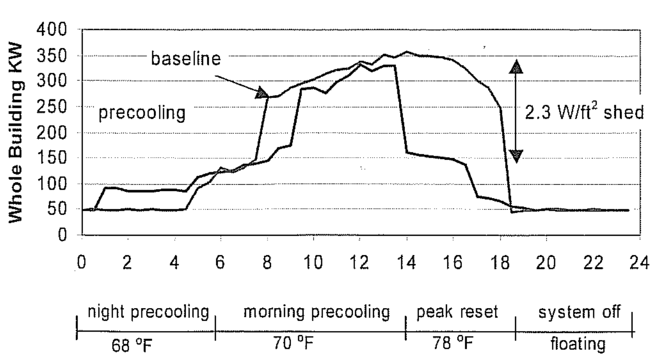


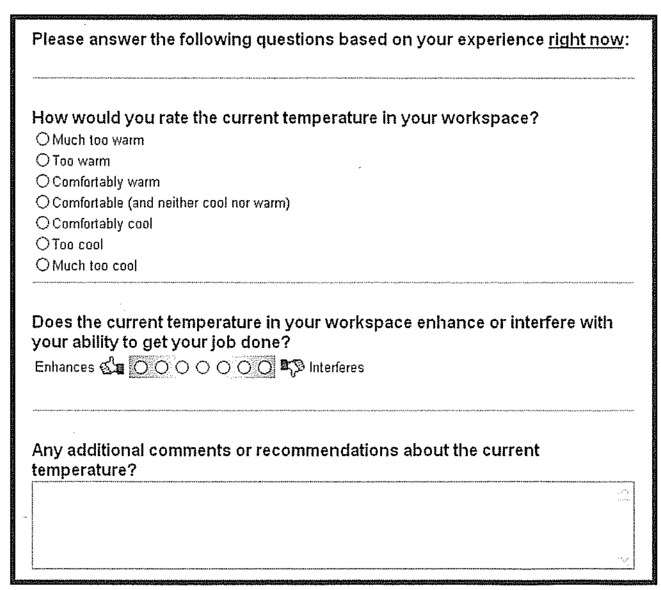
Figure 1 *Sample result from the preliminary precooling tests, 2003 (Xu et al. 2004).*

In order to address these questions, field tests were scaled up to two buildings in 2004. The selection was based on location, technical feasibility, and owner intentions. A strategy similar to the demand-shifting strategy implemented in 2003 was used; this strategy is based on zone temperature reset.

COMFORT SURVEY

One key feature of the 2004 study is the comfort survey. The Center for the Built Environment (CBE) at the University of California-Berkeley, has developed a Web-based occupant indoor environmental quality survey, which has been conducted in more than 170 office buildings across North America and Europe. A customized comfort survey instrument was developed by CBE to assess thermal sensation, comfort, and perceived productivity ratings in these two buildings.

The Web-based comfort survey used in this strategy had three pages. On the first page, the users were informed about the purposes of the survey—that it is voluntary, confidential, and anonymous—and how long it will take to finish. On the second page, the users were asked to fill in their room and phone number to identify their locations in the building for later analysis with temperature logs. One the third page, two questions were asked, as shown in Figure 2. The first question employs the Bedford scale to assess sensation and comfort, and the other polls the respondents for their opinion of the effect of the temperature on their perceived productivity. It should be noted that both questions are self-assessment questions instead of objective questions based on physical measurements. Both questions use seven-point scales for the users' responses. The survey is very short and takes less than one minute to finish.



Please answer the following questions based on your experience right now:

How would you rate the current temperature in your workspace?
- Much too warm
- Too warm
- Comfortably warm
- Comfortable (and neither cool nor warm)
- Comfortably cool
- Too cool
- Much too cool

Does the current temperature in your workspace enhance or interfere with your ability to get your job done?
Enhances O O O O O O O Interferes

Any additional comments or recommendations about the current temperature?

Figure 2 *Web-based comfort survey questions.*

First, contact was made with the building owner and the facility manager to obtain a master e-mail list of the building occupants. This list allowed contact to be made with the occupants directly in a timely fashion. Initially, the owners and facility manages were reluctant to provide this information because they did not want to have the occupants disturbed. Later, they agreed to release the e-mail address list when they saw the benefit of understanding occupants' attitudes toward the building's thermal environment.

Since there was a temperature difference between mornings and afternoons, the e-mail survey requests were sent twice a day, once in the morning and once in the afternoon. As a first step, an e-mail was sent to all building occupants to explain the purpose of the survey and to ask the recipients to fill out the survey on the days before the precooling tests to construct a baseline. Then during the test days, e-mail requests were sent twice a day to collect the comfort data.

In all the e-mails sent to the occupants, no details of the precooling tests were released to them. They were aware of an energy efficiency project going on in the building, but they had no knowledge of the details. This was done deliberately to avoid their changing their clothing level if they expected a cooler environment in the morning and warmer environment in the afternoon. This was a conservative approach with respect to comfort response. It may well be that occupants would tolerate a wider temperature range if they were informed in advance and had the opportunity to adjust their clothing levels.

TESTS IN BUILDING 1

Test Site Description

The first building selected for the study is a medium-sized governmental office building located in Santa Rosa, California. The floor area is ~80,000 ft^2 (7,400 m^2) and about half of the space is for offices and half for courtrooms. It has three stories with moderate structural mass, having 6 in. (0.15 m) concrete floors and 4 in. (0.1 m) 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 (400 ft^2/person [37 m^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 variable air volume (VAV) 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 (VFDs). The single-duct system has constant-speed fans with inlet vane controls. There are ~50 thermal zones in the building. The building is fully equipped with direct digital control (DDC), but it 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 a.m. and preheats or precools the building until 8 a.m. The occupied hours are from 8 a.m. to 5 p.m. No major faults in the mechanical system were apparent except for one undersized cooling coil and some air balance problems. 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 precooling and zone temperature reset strategies that were tested are shown in Figure 3. The building was normally operated at a constant setpoint of 72°F (22.2°C) throughout the startup and occupied hours. After 5 p.m., the system was shut off and zone temperatures floated. Under normal operation, the setpoints in individual zones ranged from 70°F (21.1°C) to 75°F (23.9°C), with an average value of 72°F (22.2°C). The first strategy tested was termed "precooling + zonal reset." From 5 a.m. to 2 p.m., all the zone temperature setpoints were lowered to 70°F (21.1°C). From 2 p.m. to 5 p.m., the setpoints were raised to 76°F (24.4°C). After 5 p.m., the system was shut off, as in regular operation. The second strategy was termed "extended precooling + zonal reset." The system was turned on at midnight and the zone temperature setpoints were set to 68°F (20.1°C) from 12 a.m. to 5 a.m. The aim was to cool a significant depth of the exposed structural concrete. From 5 a.m. to 2 p.m., the setpoints were raised to 70°F (21.1°C) and after 2 p.m. were raised to 76°F (24.4°C). The difference between the two strategies is the extension of the precooling period. One aim of the tests was to determine the effect of the extended precooling on the peak demand shedding.

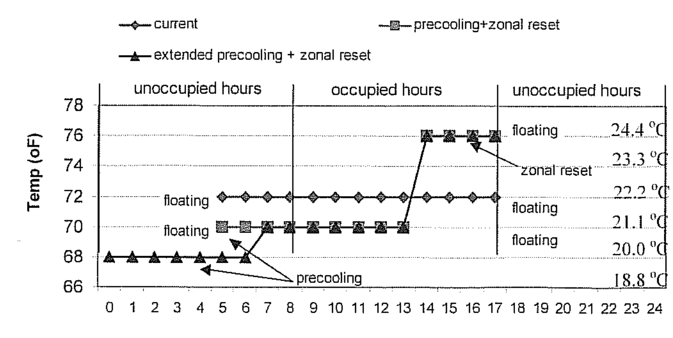


Figure 3 *Precooling and demand shed strategies (Building 1).*

The temperature reset used in the 2004 study is more conservative than that used in the 2003 study; the setpoint in the afternoon was 76°F (24.4°C) instead of 78°F (25.6°C) as in 2003. This was not a result of comfort complaints in 2003 (there were none); the building owner requested a more conservative approach.

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 that 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 thermal comfort than the dry-bulb air temperature. This was expected to be important in assessing thermal comfort in this study because the building surfaces should be cooler as a result of the precooling.

Weather and Test Scenarios

In the previous study, the expected strong correlation between peak outside temperature and whole building power was observed (Xu et al. 2004). Therefore, baseline days for each test day were selected based on similarity of peak outside air temperature. All the tests were conducted during late September and early October 2004. The tests were conducted on both cool days and hot days. Cool days are defined as days when the peak outside air temperature is between 72°F (22.2°C) and 75°F (23.9°C) and hot days are defined as days when the peak outside air temperature is above 95°F (35.0°C). No days with peak outside temperatures between 75°F (23.9°C) and 95°F (35.0°C) occurred during the period of the tests.

In total, eight tests were conducted in this study, as listed in Table 1. Each test lasted for one day. There were four precooling + zonal reset tests; three of them were on a cool day and one of them was on a hot day. There were four extended precooling + zonal reset tests. Three of them were on a cool day and one of them was on a hot day. For hot days, both precooling and extended precooling tests were performed to assess the effect of the extended precooling.

Table 1. Precooling and Zonal Reset Test Scenarios

	Precooling + Zonal Reset	Extended Precooling + Zonal Reset
Cool days	3	3
Hot days	1	1

Results

The test data shows significant peak demand savings for both precooling strategies. Sample results are shown in Figures 4 and 5. Figure 4 shows whole building power results for the precooling + zonal reset tests on the cool days. The power levels for the baseline and test days were similar in the morning. At 2 p.m., when the zone temperatures setpoints were reset to 76°F (24.4°C), the cooling plant shut off automatically because the cooling demand fell to zero and the whole building electric load dropped. The cooling plant stayed off until 5 p.m. except on one test, when the mechanical system was completely shut off. The cooling demand mostly remained at zero because the zone temperatures did not reach the setpoint of 76°F (24.4°C). In this particular test, compared with morning precooling, the extended precooling makes little difference to the whole building electricity consumption during the day. However, it did consume fan energy during the previous night. The tests results are consistent with the results of the 2003 study. The results from both the 2003 and 2004 studies indicate that, for this particular building, extended precooling and precooling only in the morning have similar effects on the demand in the afternoon.

Figure 5 shows the effect of limited precooling and extended precooling on hot days. The peak outside air temperatures on both these days was 96°F (35.6°C), and there was

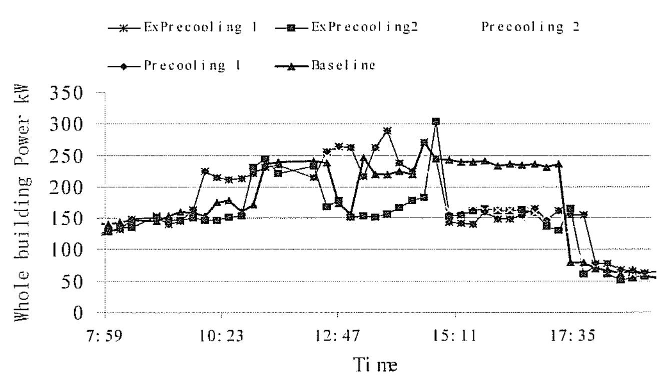


Figure 4 Precooling tests results on cool days (Building 1).

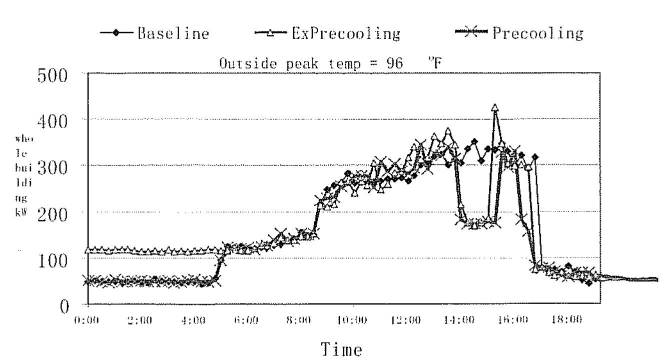


Figure 5 Precooling test results on hot days (Building 1).

little difference in the solar radiation. The reduction in the whole building power is about 150 kW for two hours. In the extended precooling tests, the power increased at night compared to the baseline because the system turned on to provide precooling at midnight. In the morning and during the shed period, there was little difference between the electrical power consumption in the extended and limited precooling tests. Part of the reason was that the HVAC system was not running close to its full capacity even on these hot days. The cooling plant is significantly oversized by as much as a factor of two. It is believed that the response would be different under the different precooling scenarios if the HVAC system were operating close to its full capacity. Although peak power use is reduced, total electricity consumption is increased slightly by the demand response actions because of the prolonged operation at night.

In contrast to the test results on hot days in 2003, the reduction in demand did not last into the unoccupied hours. There were "rebounds" at around 4 p.m. for both precooling tests. There were two factors contributing to the difference. First, the test days in 2004 were hotter than the corresponding test days in 2003. The maximum outside air temperature in 2004 was 96°F (35.6°C) compared with 88°F (31.1°C) in 2003. This increase in outside temperature increased the cooling load during the peak hours significantly, especially the ventilation load. Second, the new afternoon temperature setpoint was 76°F (24.4°C) instead of 78°F (25.6°C) so the inside temperature would have reached the setpoint more quickly even if the load had not been greater.

Comfort

Figures 6 and 7 show the comfort survey data collected from Building 1 over the test period. In these figures, the percentages of occupant responses in the different categories are used to indicate the comfort level in the building. Notice that on the days when the e-mail requests were sent, there were roughly 20-30 responses both in the morning and afternoon, accounting for 20%-30% of the building occupants. This relatively large sample size gives good confidence in the comfort estimate. There were also days when the request was not sent out but still some responses were received from the occupants. These are the days for which N is small; these data should be ignored.

As is shown in Figure 6, the percentage of people who felt too cool was no higher during the precooling period than during the baseline period. Actually, the percentage of people who felt the room was too cool decreased slightly even though the setpoint was lowered from 72°F (22.2°C) to 70°F (21.1°C) in the morning, suggesting that the differences in the data are statistically significant.

In the afternoon, when the temperatures were higher than for the baseline cases, the occupants did not indicate that the conditions were too warm. This is shown in Figure 7. The percentage of people who felt too warm did not increase from the morning to the afternoon. One limitation of these results is that all the responses were obtained on "cool" days; the phase of the study in which comfort responses were obtained ended before the period of hot weather when the "hot" day load-shedding measurements were made. Given that the air temperature is not the sole determinant of comfort in a space, it is possible that higher levels of discomfort might have been experienced on "hot" day afternoons.

Figure 8 is another way to illustrate the comfort level in the building before and during the test. The average values of the thermal comfort are plotted with their standard deviations. For thermal comfort, a score between –1 and +1 represents a good thermal comfort environment. In the morning, the thermal comfort in both precooling and extended precooling did not change from the baseline. The same thing happened in the afternoon. The variations of the average values of the thermal comfort were all within the error bars, and there were no clear trends of whether people felt colder or warmer either in the morning or in the afternoon. For perceived productivity, a similar conclusion can be drawn. The variation of the productivity seemed to be random with no clear trends.

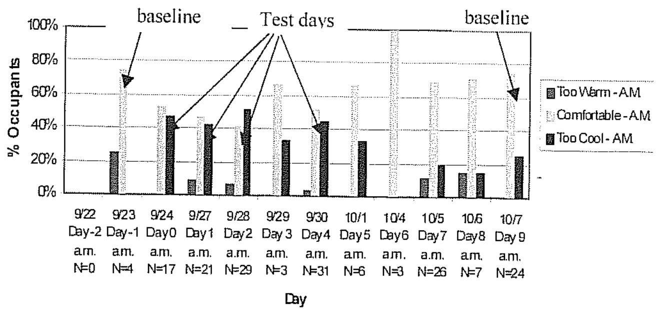


Figure 6 *The thermal comfort response in the morning (Building 1).*

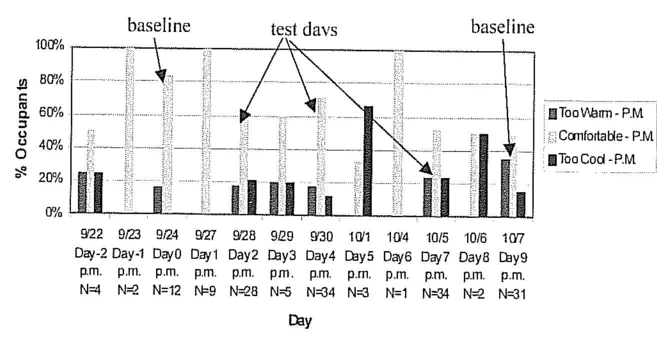


Figure 7 *The thermal comfort response in the afternoon (Building 1).*

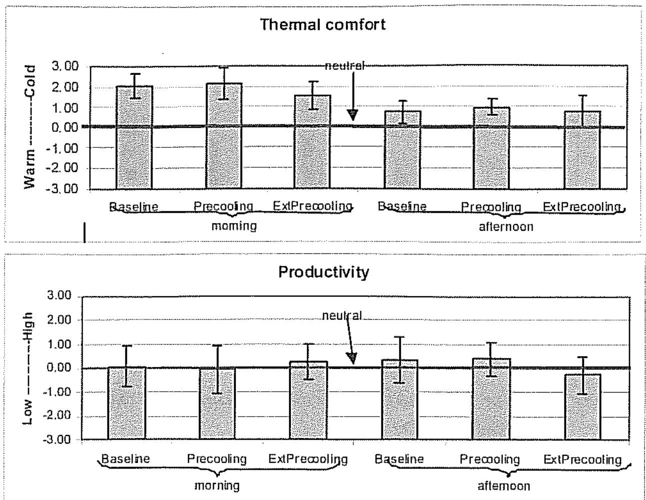


Figure 8 *Comfort and productivity levels before and during the precooling tests (Building 1).*

TESTS IN BULDING 2

Test Site Description

The second test site is an office building located at Field, near Sacramento, California. It is an 84,000 ft^2 (7,800 m^2), Class A office building that was built in 2001. It has two stories with moderate structural mass, having 4 in. (0.1 m) concrete floors and 8 in. (0.2 m) 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 0.5. The windows are single-pane glazing with green tint. The internal equipment and lighting load are typical for office buildings. The number of occupants in the office areas is approximately 125 on the first floor and 185 on the second floor. The maximum allowable temperature in summer is 78°F (25.6°C), which is specified in the contract agreement between the property management company and the tenant.

The building has two rooftop packaged units, each serving half of the building. The supply and return fans in the units are controlled by VFDs. The air distribution system is single-duct VAV. There are ~40 zones in the building. The building is fully equipped with DDC but with no global zone temperature reset strategies programmed before this study.

Operationally, the building is typical of many office buildings. The HVAC system starts at 6 a.m. and preheats or precools the building until 8 a.m. The occupied hours are from 8 a.m. to 5 p.m. No major faults in the mechanical system were apparent, and there were relatively few comfort complaints, averaging ~1-2 hot/cold calls per month. The building operation is subcontracted to a local contractor and there is no in-house building operator. The contractor controls the building remotely.

Test Strategies

The precooling and zone temperature reset strategies were similar to those used with Building 1. The extended precooling was not tested in this building because of problems that were encountered in the building. The building was normally operated at a constant setpoint of 74°F (23.3°C) throughout the startup and occupied hours. After 6 p.m., the system was shut off and zone temperatures floated. Under normal operation, the setpoints in individual zones ranged from 70°F (21.1°C) to 75°F (23.9°C), with an average value of 74°F (23.3°C). On precooling test days, from 6 a.m. to 12 p.m., all the zone temperature setpoints were lowered to 72°F (22.2°C). Since the electrical summer super peak charge starts at 12 p.m., the setpoints were raised to 76°F (24.4°C) from 12 p.m. to 5 p.m. After 5 p.m., the system was shut off as in regular operation.

Monitoring

There is no whole building power interval meter or submetering in the building. There is a weather station measuring outside air temperature and humidity. Two temporary power meters were installed on the two rooftop units for this study to determine the impact of the control strategies on HVAC power. As in Building 1, eight operative temperature sensors were installed in the building. The operative temperature sensors consist of temperature sensors enclosed in hollow spheres that 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 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 precooling.

Trending of HVAC performance data, such as supply air temperature and duct static pressure, was set up using the building control system before the precooling tests. However, these data were lost accidentally by the remote operator. The only information available for this building is data logger data from the power meters and temperature sensors and weather data from the local weather station.

Weather and Test Scenarios

All the tests were conducted during late September in 2004 when the weather in the region had started to cool down. Opportunities to conduct tests in this building were limited to relatively cool days, when the peak outside air temperature was between 72°F (22.2°C) and 75°F (23.9°C). In total, three morning precooling and zonal temperate tests were conducted in this study. Each test lasted for one day.

Results

Figure 9 shows the precooling test results for Building 2. The shaded area is the amount of the electrical peak load shifted. In all three tests, the morning electrical load is almost

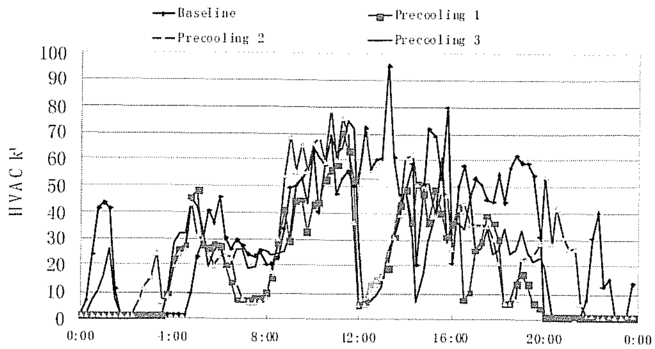


***Figure 9** Precooling test results—HVAC power (Building 2).*

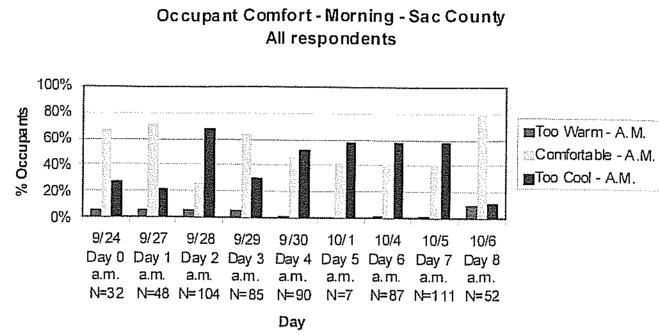


***Figure 10** The thermal comfort response in the morning (Building 2).*

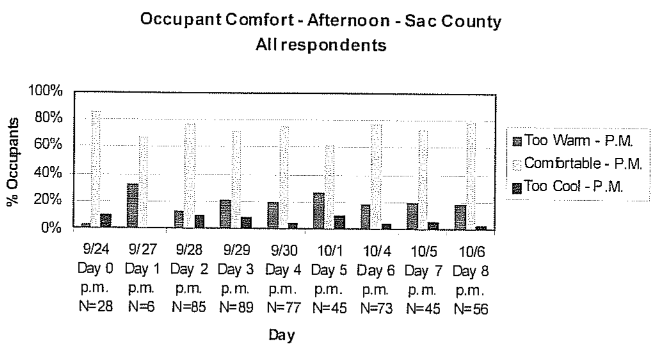


***Figure 11** The thermal comfort response in the afternoon (Building 2).*

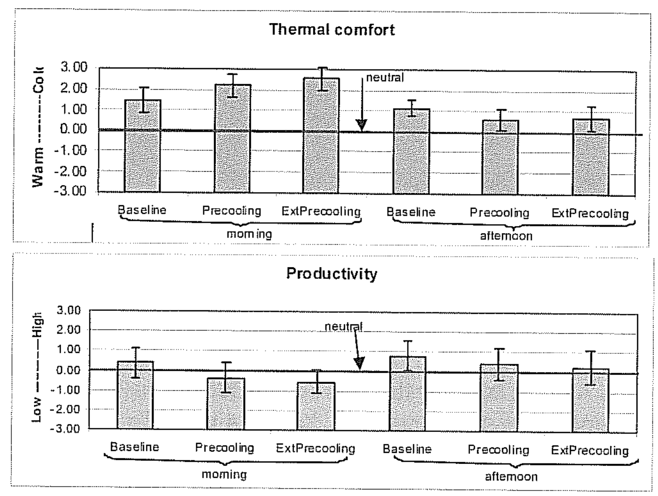


***Figure 12** Comfort and perceived productivity levels before and during the precooling tests (Building 2).*

the same as the baseline. At 12 p.m., when the zone setpoint was raised to 76°F (24.4°C), the HVAC system almost completely shut off in all three tests. The maximum shed was about 40 kW and the sheds lasted roughly two hours. The energy savings in the peak hours were roughly 100 kWh. Notice that in all three tests, the spike of the electrical peak in the baseline was avoided. Although peak power use is reduced, total electricity consumption is not increased by the demand response actions this test site.

Comfort

Figures 10 and 11 show the comfort survey data collected from Building 2 over the test period. On the days when e-mail reminders were sent out, there were roughly 80-90 responses each time, accounting for 30%-40% of the building occupants. In the morning, as is shown in Figure 10, the percentage of respondents who felt too cold increased from 20% to about 60% compared with the baseline, which indicated that the room was perceived to be significantly cooler than the baseline. However, in the afternoon, as is shown in the Figure 11, when the temperatures were higher than the baseline, the respondents did not perceive the room as warmer. The afternoon data are consistent with what was observed in Building 1. The percentage of respondents who felt warm did not increase significantly when the temperature increased by two degrees.

Figure 12 is another way to present the data in average values of the thermal comfort and perceived productivity. Similar conclusions were drawn, compared with the percentage plot. Basically, there was a decline in the thermal comfort and perceived productivity in the morning and no changes in the afternoon.

So why did people start to feel significantly cooler when the morning setpoints were decreased by only two degrees, from 74°F (24.4°C) to 72°F (22.2°C)? Why did this not happen in Building 1? The zone temperature data from the temperature logger were plotted to examine what had happened in the tests. On the test days, although the zone temperature did go below 70°F (21.1°C) occasionally, most of the time the temperature in the morning was above 72°F (22.2°C). However, in the coldest zone, the temperature went down as low as 65°F (18.3°C) in one particular test. So, for certain zones, it was cold in the morning—and much colder than we expected it should be since the setpoint was only adjusted down to 72°F (22.2°C). One possible explanation is that on cool weather days (daytime peaks of ~75°F [23.9°C]) the outside temperature in the early morning was only about 60°F (15.6°C). This would cause perimeter zones with low internal heat gains, such as zones on the second floor of the west wing, to switch into heating mode. Since the boiler had been locked out for the precooling tests, the zone temperature would fall below the cooling setpoint. One conclusion to be drawn from this is that equipment schedules should not be interfered with if the basis of the demand-shifting strategy is to change zone setpoints.

Another possible explanation is that there could have been significant temperature variations within the space so that the temperature in the vicinity of the thermostat could have met the setpoint while the temperature in the vicinity of the data logger could have been significantly lower. There were known to be air balance problems in that part of the building, which could have had this effect.

SUMMARY AND DISCUSSION

The following conclusions can be drawn from the field tests of precooling strategies in the two commercial buildings.

1. Results from the comfort surveys indicate that comfort can be maintained in both precooling and afternoon reset if the zone temperatures are kept within the specified ranges. In Building 1, the self-assessed comfort and perceived productivity levels did not vary significantly during the precooling tests, while the zone temperatures varied in the range 70°F (21.1°C) to 76°F (24.4°C) during the occupied period. In Building 2, the comfort and perceived productivity in the afternoon were well maintained when the setpoint was raised from 72°F (22.2°C) to 74°F (24.4°C). In the morning, the comfort level was decreased only because the zone temperature was much lower than the desired setpoint of 70°F (21.1°C). Therefore, it is inferred that a properly implemented precooling strategy should not cause comfort problems in buildings.
2. It was found that nocturnal precooling has varying effects on the magnitude of the peak the following day, with a number of factors affecting its effectiveness. The 2004 results from Building 1 are similar to those obtained in 2003. The nocturnal precooling has a marginal effect during the following morning but has no discernible effect during the on-peak period in Building 1. Extended precooling was not tested in Building 2.
3. The strategy for managing the demand during the on-peak period is important, particularly on hot days or in buildings with smaller time constants, where electrical power can rebound after a short period. This was not a problem in the tests in 2003 because the on-peak setpoint was higher (78°F [25.6°C] vs. 76°F [24.4°C]) and there were no tests on very hot days, so the setpoint was not reached during the occupied period and the chillers remained off. These conditions did not apply in the 2004 tests and so avoiding significant load variations during the afternoon became an issue. An exponential zone temperature setpoint trajectory was found to produce negligible variation in load during the on-peak period and is recommended for practical implementation.
4. It is important to address any comfort problems in a building that could be exacerbated by changes in setpoint before running any demand-shifting control strategies. In some cases, the problem may be a zone temperature sensor that has drifted, causing an offset in the actual temperature relative to the desired temperature. As the setpoint moves away from the center of the comfort zone, this offset can have an increasingly greater effect on comfort. If the problem is more complicated, some degree of retro-commissioning may be required. For example, if air balance problems cause significant variations in temperature within a zone controlled by a single temperature sensor, recalibrating the sensor will not help when the strategy is to change the setpoint over the whole of the acceptable comfort range. If the whole zone is under-aired and proportional-only control (as opposed to proportional plus integral control) is used, the zone will suffer in two ways: it will be less effectively precooled and it will be less able to maintain setpoint during occupancy, both during normal periods or during periods when the setpoint is increased.

This study has identified several uncertainties that should be resolved before precooling can be reliably implemented in large commercial buildings. The following work is proposed.

1. *Conduct field tests over a wider range of conditions.* Because of funding delays in both 2003 and 2004, most of the tests were conducted at the end of the summer and only a few tests were actually conducted on hot summer days. In 2004, no comfort data were collected on hot days. All the tests in 2003 and 2004 were blind tests where the occupants were not informed in advance that the temperature would vary. If the occupants are informed of the precooling tests in advance and know to expect a temperature change, they might wear more flexible clothing ensembles (dress in layers) and adjust their clothing level in response to temperature changes, extending the comfort zone and enabling larger power sheds.
2. *Develop and test a method to determine building thermal mass metrics.* There are two key parameters affecting precooling performance: the effective building thermal mass and the thermal conductance between the thermal mass and the zone air. The first parameter determines how much heat can be stored in the mass for a given temperature change, while the second determines the heat transfer rate for charging and discharging the thermal mass. One metric

of interest is the building time constant, calculated by dividing the thermal capacity by the thermal conductance, which determines the timescale of the response to increases in zone temperature setpoint.

3. *Develop strategies for managing the demand during the on-peak period and test them in the field.* These strategies can be studied and developed using simulation and then tested in real buildings.

4. *Develop a screening tool based on simplified simulation to quickly assess demand response potentials for a specific building.* What is needed is a simple screening tool that can be used for quick assessment by analyzing the impact of the climate, the building envelope, the schedule, and the utility tariffs. The conventional way in which detailed simulation programs such as EnergyPlus are used is too expensive for this application because too many input data are required. One approach is to develop an inherently simple tool and the other approach is to develop a context-sensitive defaulting procedure for a more detailed tool such as EnergyPlus. These two approaches should be investigated before choosing which one to adopt.

5. *Develop guidelines for appropriate control strategies according to building characteristics.* Different buildings with different mechanical systems and different levels of control may require different precooling strategies. For example, the zone temperature setpoint strategies studied in the work reported here are only practicable if the zone temperatures are controlled by networked digital controllers. A detailed guide to selecting, implementing, and testing demand-shifting control strategies is needed to support their routine use.

ACKNOWLEDGMENTS

The work described in this report was coordinated by the Demand Response Research Center and funded by the California Energy Commission (CEC), Public Interest Energy Research (PIER) Program, under Work for Others Contract No. 500-03-026 and by the US Department of Energy under Contract No. DE-AC02-05CH11231.

The authors wish to thank the US General Services Administration and Shiva, Inc., for providing access to the test buildings and the Pacific Energy Center for the loan of instrumentation. We would like to thank Steve Galanter from South Carolina Edison as the project lead, and we would like to thank the following individuals and organizations for their support of this research project: Chris Scruton (CEC) and Mary An Piette (LBNL/CEC PIER Demand Response Research Center).

We would also like to thank the following members of our Technical Advisory Committee for their input, suggestions, and comments: Robert Young (Cal EPA Headquarters), Barbara Blair (Washington Mutual), Gene Ameduri (Energy Connect), Alan Gartner (Energy Connect), David Reed (Southern California Edison), Lawrence Oliva (Consultant), Lance DeLaura (Sempra), Bruce Vincent (SMUD), Mark Levi (GSA), and Mark Martinez (Southern California Edison).

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