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Demand Shifting With Thermal Mass in Light and Heavy Mass Commercial Buildings

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ABSTRACT

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. This project studied the potential of pre-cooling and demand limiting in a heavy mass and a light mass building in the Bay Area of California. The conclusion of the work to date is that pre-cooling has the potential to improve the demand responsiveness of commercial buildings while maintaining acceptable comfort conditions. Results indicate that pre-cooling increases the depth (kW) and duration (kWh) of the shed capacity of a given building, all other factors being equal. Due to the time necessary for pre-cooling, it is only applicable to day-ahead demand response programs. Pre-cooling can be very effective if the building mass is relatively heavy. The effectiveness of night pre-cooling under hot weather conditions has not been tested. Further work is required to quantify and demonstrate the effectiveness of pre-cooling in different climates. Research is also needed to develop screening tools that can be used to select suitable buildings and customers, identify the most appropriate pre-cooling strategies, and estimate the benefits to the customer and the utility.

Key words: Pre-cooling, demand response, thermal mass

INTRODUCTION

The structural mass within existing commercial buildings can be effectively used to reduce operating costs through simple adjustments of zone temperature setpoints within a range that doesn't compromise thermal comfort. Generally, the building is pre-cooled at night or in the early morning at moderately low cooling setpoint temperatures (e.g., 68 – 70°F) and then the cooling setpoints are raised within the comfort zone (below 78°F) during peak periods. Heating setpoints must be left unchanged or lowered to avoid unwanted increases in heating system energy. The cooled mass and higher on-peak zone setpoint temperatures lead to reduced on-peak cooling loads for the HVAC equipment, which results in lower onpeak energy and demand charges. The potential for using 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; Xu et al. 2004). This strategy appears to have significant potential for demand reduction if applied within an overall demand response program because the added demand reduction from different buildings can be large.

In the summer of 2003, Xu conducted a pre-cooling case study at an office building in Santa Rosa California (Xu et al. 2004). The research team 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 range (70°F) during the occupied hours before the peak period (8 a.m. to 2 p.m.) and floating the zone temperatures up to the high end of the comfort range (78°F) during the peak period (2 p.m. to 5 p.m.). With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft2) during peak hours without having any thermal comfort complaints submitted to the operations staff (Xu et al. 2004). In the summer of 2004, Xu conducted pre-cooling tests along with online real-time comfort surveys to determine occupant reactions to the thermal conditions in the Santa Rose building and in a Sacramento office building. The results of the comfort surveys in two large test buildings indicate that occupant comfort was maintained during the pre-cooling tests as long as the zone temperatures were between 70°F and 76°F (Xu 2006).

Although these studies were quite successful and a large peak demand shed was achieved while maintaining occupant comfort, some key questions remained unanswered, including:

- What are the metrics of the building thermal mass and how are they determined? Themal mass metrics refer to how fast the passive thermal storage can be charged and discharged. One example is the time constant for the whole building temperature change when the HVAC system is off.
- How can thermal mass be discharged more efficiently and more smoothly with no rebound? Rebound happens when the thermal storage is depleted before the end of the demand period and electricity demand reaches new high.

- How can a building's pre-cooling potential be assessed and the potential economic savings be quickly determined?
- What will be the comfort reaction if the occupants are informed in advance of the test?
- What will be the occupants' reaction if pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment?

The research team addressed several of these questions in this study and will address others in subsequent studies in a multi-year effort to understand pre-cooling thermal mass as a Demand Response (DR) strategy for commercial buildings.

The team systematically conducted more field tests for a longer period in two large commercial buildings before (Xu 2006). In that study, no comfort data were collected during the hot days and all tests were blind tests where the occupants were not informed in advance. If they were informed of the precooling tests and expected a temperature change, they might change their clothing level accordingly. Akin to commuting by mass transit or bicycle on a regional air quality "Spare the Air day," occupants may be willing to adjust to temporarily inconvenient or uncomfortable conditions that they know have long-term benefits. Since advance notice was thought to bias the tests, the tests in this study were conducted without notifying the occupants.

FIELD TESTS

To address the questions listed above, the research team selected two buildings that had participated in the Auto-CPP (Critical Peak Pricing) pilot program, a study to demonstrate the capability of automated demand shed in buildings on CPP days (Piette et al. 2006). The selection was based on location, technical feasibility, and owner intentions to participate. The two buildings selected were one museum (CSSC) and one office (OSF), both in Oakland, California. A strategy similar to the demand-shifting strategy implemented before (Xu 2006), based on zone temperature reset, was used in both buildings.

There were several reasons for picking these two buildings. First, they were both medium-sized buildings with full direct digital control (DDC) and so the zone temperatures set points could be changed directly. Second, CSSC is a heavy mass building and a large portion of the floor area is exposed concrete. OSF is a very light office building with full glazing on the west and east façade. Studying buildings at the two ends of the building mass spectrum provides the opportunity to test and verify the thermal mass metrics and methods that developed in parallel. Third, the owners occupy both buildings, except one floor in OSF. The building owners and property management teams were innovative and interested in trying new ideas and methods to reduce their utility costs. More detailed building descriptions can be found in later sections of this paper.

OCCUPANT SURVEYS

Demand shifting and load shedding strategies should be acceptable from the perspective of the building users so that employee productivity and customer satisfaction are not hampered. The team surveyed building occupants to learn about their comfort levels during the tests. Occupants were surveyed in the morning, early afternoon, and late afternoon to assess the effects of the pre-cooling period, the moderate shed period, and the high shed period.

The web-based comfort survey had three pages, preceded by a welcome page. The welcome page informed the users of the purposes of the survey, its voluntary, confidential, and anonymous nature, and the expected time to complete it. On the first survey page, the users were asked to fill in their office or cubicle number to identify their locations in the building for later analysis with temperature logs. The second survey page contained questions about the occupants' current clothing and activity. This faciliated the calculation of their cloth value and metabolic rate, and to evaluate whether people take off/put on clothing as the temperature shifts in order to keep themselves comfortable. On the third page, two questions were asked. One is to assess sensation and comfort, and the other polled the respondents for their opinion of the effect of the temperature on their productivity. It should be noted that both questions are self- assessment questions rather than objective questions based on physical measurements. Both questions use seven-point scales for the users' responses. The information collected in the survey, along with the detailed thermal measurements recorded in proximity to the occupants, also enabled us to calculate the Predicted Mean Vote (PMV)[1] for comparison with the actual comfort vote.

Employees were asked by email to take the survey at least twice per day (once in the morning and once in the afternoon) and more often if possible. The survey was brief and took 2 - 3 minutes to complete on the first viewing and about 1 minute thereafter. Although it would have been ideal to have all employees take the survey at frequent, specified times throughout the day, the reality of the typical office schedule made the success of this approach unlikely. Further, the research team were wary of demanding too much of the occupants. During the previous tests (Xu et al, 2004), the team had notified the occupants each time they wanted them to take the survey, and learned that some of the employees had found the multiple emails intrusive. During the 2005 tests, the team therefore attempted to minimize the communication impact. This was apparently a successful strategy at both Oakland sites, but there was low participation from the employees at the site.

As a first step, an email was sent to all building occupants to explain the purpose of the survey and to ask the recipient to fill out the survey on the days before the pre-cooling tests to construct a baseline. Then a brief note was sent the day before a test or baseline day to remind people to participate.

In some cases, the invitation was sent directly to the occupants. In others, a project contact in the building sent out the invitation. In general, it has been preferable to have the occupants receive the invitation from a known, respected person in the building, such as a supervisor or facilities manager. This can foster good response rates because it conveys a sense of importance and sanctions the taking of the survey during working hours. However, such contacts were often busy or unavailable, and preferred that the team send out the notifications.

TESTS IN BUILDING 1: HEAVY MASS BUILDING

TEST SITE DESCRIPTION

The museum is an 86,000-square-foot, state-of-the-art science and technology education facility on a 13-acre site in the hills of Oakland, California (see Figure 1). The building is a heavy mass building with lots of exposed concrete on the first floor. The walls are well insulated and the windows are small to have a better control of lighting levels inside.

The cooling plant has a 230-ton centrifugal chiller with a variable pumping chilled water loop. There are eight air-handling units located on the roof using chilled water to condition outside air and provide air circulation throughout the entire facility. Seven of them are single duct variable air volume air handling

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1 Predicted Mean Vote is the average expected comfort response (vote) based on indoor air climate units and one is a constant volume unit. A newly installed DDC control system provides indoor comfort control.

The building has independent HVAC systems serving each major exhibit area and the office area. CO2 sensors are installed throughout the exhibit area and outside air ventilation rate is adjusted automatically to keep the CO2 levels in the zones within the desire ranges. The supply and return fans for the single duct system are equipped with variable frequency drives (VFD). There are about 40 zones in the building. Although the building is fully equipped with DDC, it had no global zone temperature adjustment capability before the study. This function was added to the DDC system's program as part of this study.

The building's operation is typical of that of many museums. The building is open to visitors from Tuesday through Sunday. Since all the CPP days are on weekdays, the CPP program is financially less attractive for this building than for other buildings since the load of this building on CPP days is lower than that on weekends. The daytime occupied hours are from 8 a.m. to 5 p.m. In normal operation, the HVAC system starts at 5 am and pre-heats or pre-cools the building until 8 am, depending on the outside weather conditions. Before the tests, no major faults in the mechanical system were apparent in this building; however, some controllers had not been tuned properly and certain valves and dampers were oscillating during operation. There were no comfort complaints in either the office or the exhibit areas. The building operators had worked at the building for a long time and were quite confident and familiar with its mechanical system.

TEST STRATEGIES

The pre-cooling and zone temperature reset strategies that were tested are shown in Figure 2. The building in average was normally operated at a constant setpoint of 72°F (22.2^{o}C) throughout the startup and occupied hours. After 8 p.m., the system was shut off and zone temperatures started to float. Under normal operation, the setpoints in individual zones ranged from 70 (21.1) to 75°F (22.2^{o}C), with an average value of about 72°F (22.2^{o}C).

The first strategy tested was termed pre-cooling + linear zonal reset. The HVAC system was turned on earlier in the morning than in normal operation to pre-cool the building to 68°F (20.0^{o}C) from 3 a.m. to 7 a.m. Because the weather was relatively cool in the Oakland Hills location in the summer and the outside

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conditions

air temperature was in the low 60s°F in the mornings, the HVAC system could cool the building with outside air using the economizers and no chiller operation. From 7 a.m. to 12 p.m., mostly occupied hours, all the zone temperature setpoints were reduced to 70°F (21.1°C). From 12 p.m. to 6 p.m., the CPP moderate and high price periods, the setpoints were raised linearly to 78°F (25.6°C). After 6 p.m., before the system was shut off, the setpoints were kept at 78°F (25.6°C).

The second strategy was called pre-cooling + aggressive linear reset. This strategy was the same as the strategy above except that the temperature setpoints were raised more aggressively in the afternoon. For example, the setpoints were raised to 76°F (24.4°C)at 3 p.m., instead of to 74°F (25.6°C) as in the first strategy.

The third strategy was termed pre-cooling + exponential reset. The temperatures were raised up exponentially rather than linearly in the afternoon period.

The fourth strategy was called no pre-cooling + linear reset. The zone temperatures were raised linearly in the afternoon in the same way as the first strategy, but there was no pre-cooling from 3 a.m. to 7 a.m. One aim of the tests was to determine the effect of the extended pre-cooling on the upcoming peak demand shedding period.

MONITORING

The building has a whole building power meter and no other sub-meters. There is a weather station measuring outside air temperature and humidity. The HVAC performance data were recorded using the building control system. Roughly 200 data points were collected at 15-minute intervals. One power meter was installed on the chiller to determine the impact of control strategies on the cooling load and cooling power. Temperatures in the zones were recorded through the building control system. These temperature data were compared with indoor air temperature measurements from devices installed by us in both the office and exhibit areas.

The team placed thermal measurement equipment in the office space on August 4, 2005, and throughout the museum spaces on August 5, 2005. These sensors were placed in concealed locations in the museum so as to avoid distracting visitors from the exhibits or tampering. In a few locations (the planetarium and outside), a suitably concealed location was not available; those sensors disappeared and were not recovered.

WEATHER AND TEST SCENARIOS

In the previous studies, the expected strong correlation between peak outside temperature and whole building power was observed in the all tested buildings (Xu et al. 2004). Therefore, for this study baseline days for each test day were selected based on similarity of peak outside air temperature.

The tests were conducted on cool and warm days starting from early August through early October 2005. Cool days are defined as days when the peak outside air temperature was between 72°F (22.2^{o}C) and 75°F (23.9^{o}C) and warm days are defined as days when the peak outside air temperature was around 85°F (29.4^{o}C), the hottest temperature observed in the Oakland Hills in the summer of 2005.

In total, the research team conducted eleven tests in this study, as listed in Table 1. All days in the table were weekdays. Each test lasted for one day. There were nine pre-cooling and zonal reset tests, seven of them were on cool days and two of them were on warm days. There were three pre-cooling + linear reset tests, three pre-cooling + aggressive linear reset tests, one pre-cooling + exponential reset test, and two non-pre-cooling + zonal reset tests. All tests were duplicated except for the pre-cooling + exponential reset test, which was not duplicated because of time constraints. The remaining two days were baseline survey days on which no intervention occurred. Table 1 shows the dates, strategies, and weather conditions for the tests.

One polling station for museum visitors was stationed during the entire test period near the museum café and collected survey responses nearly every day. In addition, the nature of the web-based survey for employees made it very easy to administer, and thus survey data were collected on several additional days as well. These additional days, when no strategies were employed, were considered baseline days and were included in the analysis of survey responses, but they were not included in the energy use analysis. There were also two days (August 5 and October 13) when no survey data were collected.

The building operator sent the web-based survey invitations to employees. Of 48 employees invited, 10 individuals participated, and 52 valid observations were recorded. All of the resulting data could be correlated with nearby air temperature measurements. Museum visitors were surveyed via the polling stations. It was important to place the stations in such a way that children visiting the museum could not tamper with them or record erroneous votes. For example, one station was placed in the cashier line at the museum café, and an adult would have had to hold a child up to the device to play with it. The research team cannot judge participation rate, because it is not known how many people saw the device at the café and chose not to use it. In other museum locations, visitors were surveyed the reseachers who carried the stations and asked visitors to take the survey. The students facilitating the polling stations reported that the vast majority of those asked took the survey, but to some degree these were selected by the facilitators as they did not ask people who appeared to be too busy minding children. Also the stations failed to record votes on two occasions. The student polling stations received 248 votes and all were valid observations. The café polling station received 535 votes and of these, 523 valid observations were recorded. Of these 771 valid observations, all were correlated with nearby air temperature measurements.

RESULTS

The test data showed significant peak demand savings for all the pre-cooling strategies in both cool and warm conditions.

Cool days. Figure 3 shows chiller power measurement for the “pre-cooling + linear zonal reset” and “pre-cooling + exp zonal reset” on the warm days. The power usages for cooling on the baseline days and test days were similar in the morning. At 12 p.m., when the zone temperatures setpoints started to rise, the chiller power was reduced dramatically on the pre-cooling test days. The chiller load was reduced by as much as 30% in the high price period from 3 p.m. to 6 p.m. In the tests of both linear reset and exponential reset, the research team observed no rebound for chiller power before 6 p.m., which indicated that the large thermal mass had not been fully discharged in this building. In the exponential reset test, the load reduction was much higher than for the linear reset tests, which indicated that the exponential reset was probably a better reset strategy in this building.

On both pre-cooling days, the chiller came online about an hour later than that of the baseline. This was mostly because of the effects of the night pre-cooling. The building structure was much cooler on the pre-cooling test days than it was on the baseline days. In normal operation, the chiller was automatically turned off at 6 p.m. because of the cool weather. For the two pre-cooling days, the chillers were still running at 6 p.m. The load was shifted successfully from the peak hours to the after- peak hours after 6 p.m. Night pre-cooling reduced the cooling load in the morning, while the afternoon temperature reset shifted the cooling load from peak hours to non-peak hours.

Effects of pre-cooling. The effects of night pre-cooling on the upcoming day load were very obvious. Figure 4 shows two tests that used the same linear reset strategy in the afternoon where one was with night pre-cooling and the other was without night pre-cooling. First, the research team observed similar results as in Figure 3. On the test day with night-pre-cooling, the chiller started much later than on days without night pre-cooling. Second, on the night pre-cooling day, the load reduction in the afternoon was much more than on the days with no night pre-cooling but only linear reset in the afternoon. The night pre-cooling not only had a strong effect on the morning load reduction, but also on the afternoon load reduction. In these particular tests, compared with morning pre-cooling, the night pre-cooling produced large reductions in the cumulative whole building electricity consumption over the day.

These test results are helpful in addressing questions from tests performed before. The results from both 2003 and 2004 tests in lighter thermal mass building indicated that night pre-cooling had very limited effects on afternoon electrical demand, especially on relatively cool days. This study indicated that, for heavy mass buildings, the effect of night pre-cooling could be very significant.

Warm days. Figure 5 shows the effects of various pre-cooling strategies on warm days. On warm days, the load reductions during the peak hours were much more obvious than the cool days, because the cooling loads themselves were much larger. The peak outside air temperatures on both days was 85°F (28.9 ^{o}C), with little difference in the solar radiation. The outside air temperature was measured by the weather station on top of the roof. Because of the night pre-cooling, the morning start-up times for the chillers on the tests days were much later than that on the baseline day. In the afternoon temperature reset period, the load reduction became larger and larger as the reset strategies were became more aggressive. The largest load reduction occurred when the chiller electrical load was reduced almost by half.

Compared with the test results on warm days before, the reduction in demand did last till the unoccupied hours (Xu et al. 2004). There were no rebounds in the afternoon for these tests due to carefully impletement reset strategies. Two factors could contribute to the difference. First, the test days before were hotter than the corresponding test days in 2005. The maximum outside air temperature in 2004 was 96°F (35.6^{o}C), compared with 85°F (28.9^{o}C) in 2005. In 2004, these higher outside temperatures meant a significantly higher cooling load during the peak hours, especially the outside air load. Second, the thermal mass of this building is much heavier than that of the buildings tested in 2004 and most of the mass is accessible (i.e. more cooling can be stored), because of exposed concrete in the exhibit area. Third, the research team was very careful in implementing the strategies in 2005. In order to prevent rebounds, the team tested the least aggressive strategy (linear reset) first and the most aggressive strategy (exponential reset) later. In the meantime, the last strategy tested was backed up with a simulation analysis.

Whole building. As shown in Figure 6, the reduction in the whole building power was about 30 kW (~11%) during the moderate CPP price period (12 p.m. to 3 p.m.) and 50 kW (~20%) during the high price CPP period (3 p.m. to 6 p.m.). The power reduction in the morning period was obvious because the chillers were turned on later than for the baseline days. In the exponential temperature reset test, the power reduction was the largest. In the morning after 10 am, there was little difference between the electrical power consumption between the test days and the baseline days. Part of the reason was that the HVAC system was not running close to its full capacity on these warm days. The research team thinks that the response would be different under the different pre-cooling scenarios if the HVAC system was close to its full capacity. The lag between the temperature reset control signal and the electiricty load shed was about 15 minutes.

Figure 7 shows the daily HVAC energy consumption for the pre-cooling days. HVAC energy consumption was reduced significantly. The most successful strategy, pre-cooling plus exponential reset in the afternoon, reduced the HVAC energy consumption by up to 40%.

COMFORT

Survey participation by employees was low, in particularly warm test days. Because of the small dataset, the employee and visitor data were combined for the analysis in this paper. Figure 8 shows that comfort rates were comparable between baseline and test days for all periods. In fact, none of the differences are statistically significant. Similar trends were observed when the data was divided into two sets corresponding to cool days and warm days.

TESTS IN BULDING 2: LIGHT MASS BUILDING

TEST SITE DESCRIPTION

The second test site, OSF, is a 90,000 ft2 office building (with 70,000 ft2 conditioned space) in Oakland, California (Figure 9). The first floor is a data center, which houses a large computer center. The electrical demand of the computer center is about 1 MW, constant throughout the year. The data center requires cooling throughout the year also. The peak load for the entire building is about 1.5 MW.

The building has a variable air volume (VAV) system with 94 VAV boxes. The data center has its own cooling system, but shares the chilled water from the center cooling plant that serves the entire building. The temperature setpoint is 74°F in the office areas and 70°F in the data center. The cooling plant has three 800-ton variable speed chillers. The cooling load for the data center is much larger than the load in the office area. The supply chilled water temperature is 44°F (6.7^{o}C).

The building has 4-inch concrete floors and very light walls. The office area has a medium furniture density and standard commercial carpet on the floor. On the west and east side, the building has a window-to-wall ratio of almost one. The windows are single-pane tinted in green. The internal equipment and lighting load are typical for office buildings. The number of occupants in the office areas is approximately 120. The maximum allowable zone temperature in summer is 78°F (25.6^{o}C) because of a labor contract agreement.

The building has two air-handling units, each serving half of the office area of the building. The supply and return fans in the units are controlled by variable frequency drives (VFD). The air distribution system is a single duct VAV. The building is fully equipped with DDC, but with no global zone temperature reset before this study. Global temperature reset refers to a function in the control system that is able to change all zone temperature set points together with one single command.

Operationally, the building is typical of many office buildings. The HVAC system starts at 6 a.m. and pre-heats or pre-cools the building until 8 am. 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 about one to two hot or cold calls per month. The building has no on-site operators; operators control the building remotely.

The temperature requirement in the data center is very strict and the cooling load in that area is mostly from the computer itself. Therefore, the research team tested the pre-cooling strategies only in the office portion of the building.

TEST STRATEGIES

The pre-cooling and zone temperature reset strategies tested are similar to the first test site. In total the research team tested four different pre-cooling and temperature reset strategies in the office portion of the building. The building is normally operated at a constant setpoint of 72°F (22.2^{o}C) throughout the startup and occupied hours. After 6 p.m., the system is shut off and zone temperatures started to float. Under normal operation, the setpoints in individual zones range from 70°F (21.1^{o}C) to 76°F (24.4^{o}C), with an average value of 72°F (22.2^{o}C). All of the zone temperature setpoints are lowered to 70°F from 6 a.m. to 12 p.m. on the pre-cooling test days. On non-pre-cooling days, the setpoints in the morning are the same as for normal operation. The research team tested three different temperature reset strategies in the afternoon: two-step reset, linear reset, and exponential reset. The two-step reset strategy increases the building zone setpoints in two steps, one from 70°F (21.1^{o}C) to 74°F (23.3^{o}C) and the other from 74°F(23.3^{o}C) to 78°F (25.6^{o}C). The linear reset and exponential reset strategies are similar to the strategies used in CSSC. After 6 p.m., the system is shut off, as is done in the regular operational mode.

MONITORING

The building has a whole building power interval meter, but has no sub-metering for the office area. The interval meter measures and records the power consumption every 15 minutes. There is a weather station measuring outside air temperature and humidity. Two temporary power meters were installed on the two air handling units during this study to determine the impact of the control strategies on fan powers. The Btu meter on the chilled water to the office area was tested and recalibrated before the tests in order to measure the change of the cooling load in the office area in various test conditions.

The research team analyzed the trending of HVAC performance data, such as supply air temperature and duct static pressure before the pre-cooling tests. The team used these data later to analyze the impact of pre-cooling on HVAC performance.

The team placed thermal measurement equipment on the 2nd and 4th floors on August 18, 2005. Permission was later secured to install the equipment on the 3rd floor; that process was completed on August 23, 2005.

WEATHER AND TEST SCENARIOS

All the tests were conducted during the summer of 2005. As discussed earlier, it was a relatively cool summer and the peak outside air temperatures were between 75°F (23.9°C) and 85°F (29.4°C). The research team separated the tests into two groups based on the weather conditions. Tests were conducted on cool days, when the peak outside air temperature was between 72°F (22.2°C) and 75°F (23.9°C), and on warm days when the peak outside temperature was about 85°F (29.4°C). In total, the research team completed nine tests, six of them on cool days and three of them on warm days (see Table 2). Warm day is defined as when the peak outside air temperature is between 80°F (26.7°C) to 90°F (32.2°C). The team conducted baseline surveys on two days, both of them are on warm days. Most of the pre-cooling strategies were tested twice, except the exponential reset strategy. Each test lasted one day. The nature of the web-based survey for employees makes it very easy to administer, and thus survey data were collected on several additional days as well. These were considered baseline days and were included in the analysis of survey responses, but were not included in the energy use analysis. There were also several days (August 10, August 11, August 12, August 22, October 6, and October 15) when no survey data were collected.

The survey invitations were sent directly to 2nd floor occupants. Department supervisors sent out invitations to 3rd and 4th floor occupants. Of all the people invited, 79 individuals participated, and 414 valid observations were recorded. Of these, 374 could be correlated with nearby air temperature measurements.

RESULTS

Reset strategies. Figure 10 shows the cooling load profile under different pre-cooling temperature reset strategies. Under normal operation (baseline), the cooling load normally peaked between 12 p.m. and 4 p.m. In the linear reset test, the peak load was reduced by about 11%. Because the temperature was raised linearly, the load reduction was small at 12 p.m., becoming larger in the later afternoon. In the two- step setup tests, the temperature rise was faster than the liner reset test, so the load reduction was larger. The peak cooling load was reduced by 30% from 1 p.m. to 6 p.m. However, because the temperature was raised in two steps, right after the first step, the load curve has a small dip and a rebound, so the load profile was not completely flat. Among all the tests, exponential temperature reset achieved the flattest power profile during peak hours of all the scenarios. In this strategy, the power was essentially constant during the on-peak period and there was no rebound.

Zone temperatures. Figure 11 shows return air temperature (RAT), a good indicator of average zone temperature, under different test scenarios. As the temperature reset got more aggressive, the zone temperatures in the afternoon went up faster and the peak temperatures were higher. However, the return air temperatures were never higher than 76°F (24.4^{o}C), two degrees lower than the highest temperature setpoint of 78°F (25.6^{o}C). The temperature data also indicates the benefits of the morning pre-cooling. In the non-pre-cooling tests, the peak zone temperatures were roughly about 2°F (1^{o}C)higher than those with pre-cooling. If the building was pre-cooled in the morning, the occupants would be more comfortable in the afternoon because the zone temperature would rise slower and peak at a lower temperature value. The spikes in the temperature data were the data noise caused by the control system data archieving.

OCCUPANT COMFORT

In this study the research team hoped to focus primarily on warm days, since that's the kind of weather in which these strategies are likely to be employed. However, that goal was not achieved, since after the equipment was set up there was a prolonged cool spell and the weather never got above 90°F (32.2^{o}C). Although the weather was somewhat warmer on a few days, little survey data were collected on warm test days because they were so infrequent, and some respondents may have had survey fatigue by the time the weather became warmer.

Therefore much of the analysis in this paper evaluates the data at a rather coarse level of granularity so that the calculations are statistically valid. Taken as a whole, people's comfort levels in the comfortable range on test mornings and late afternoons met or exceeded comfort levels on baseline days (see Figure 12). Comfort levels on test early afternoons were lower than those on baseline day early afternoons. People tended to express discomfort in the cooler range on test days than on baseline days. This suggests that the morning pre-cooling strategies were effective, but may need to be run at a higher setpoint or for a shorter duration to avoid adversely affecting occupant comfort. However, more data should be collected during test conditions to verify this. The research team also observed that in general, people tended to feel a bit cold in this building.

SUMMARY AND DISCUSSION

The following conclusions can be drawn from the field tests of pre-cooling strategies in the two commercial buildings:

- Pre-cooling and demand shed strategies worked well in both the light and heavy mass buildings. In the light mass building (OSF), the strategies reduced cooling load significantly (~35% on cool days, ~25% on warm days) with no comfort complaints. In the heavy mass building (CSSC), the load reduction was even more significant; the peak HVAC load was reduced by 30% using the exponential temperature adjustment strategy. These test results are consistent with conclusions drawn from the 2003 and 2004 studies.
- A properly controlled exponential temperature reset strategy in the shed period discharged thermal mass smoothly and with no rebound in both buildings. The research team successfully avoided any rebounds in both buildings for all the tests. The exponential temperature reset strategy created very flat load curves during the peak hours in both buildings.
- Night pre-cooling had noticeable effects on the second day cooling load in the heavy mass building. In the studies of 2003 and 2004, the night pre-cooling had varying effects on the magnitude of the peak the following day, with a number of factors affecting its effectiveness. The results from the previous field tests in SRFB building (Xu, et al., 2004) were similar to those obtained in 2003. The SRFB is a lighter mass building than CSSC, and in the warm weather condition, night pre-cooling had a marginal effect during the following morning and had no discernible effect during the on-peak period. However, in the 2005 tests of CSSC with its heavy mass, night pre-cooling clearly reduced the load during both morning and afternoon periods on the following day.
- In the heavy mass building (CSSC), night pre-cooling reduced both HVAC peak demand and energy consumption in cool weather. The total energy consumption in various pre-cooling tests was lower than for non-pre-cooling days. This was mostly due to the fact that the summer mornings in Oakland were relatively cool and the HVAC could pre-cool the building without running the chiller.

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Table 1. Pre-Cooling and Zonal Reset Test Scenarios, CSSC

Number	Date	Stragtegies	Weather
1	8/5/2005	No precooling + linear set up	Cool
2	8/8/2005	No precooling + aggressive linear set up	Cool
3	8/12/2005	Precooling + linear set up	Cool
4	8/26/2005	Precooling + aggressive linear set up	Cool
5	8/31/2005	Baseline survey	Warm
6	9/1/2005	Precooling + linear set up	Cool
7	9/28/2005	Precooling + linear set up	Warm
8	9/29/2005	Precooling + aggressive linear set up	Warm
9	9/30/2005	Baseline survey	Warm
10	10/6/2005	Precooling + aggressive linear set up	Cool
11	10/13/2005	Precooling + exponential set up (WA/SA)	Cool

Note: Peak Outside Air Temperature (Cool ~75 ^{o}F (23.9^{o}C), Warm ~ 85 ^{o}F (29.4^{o}C)

Table 2. Pre-cooling test schedule, OSF

Number	Date	Strategies	Weather
1	8/10/2005	Precooling + linear set up	Cool
2	8/11/2005	Precooling + two steps set up	Cool
3	8/12/2005	Precooling + exponential set up	Cool
4	8/22/2005	No precooling + exponential set up	Cool
5	8/31/2005	Baseline survey	Warm
6	9/1/2005	Precooling + linear set up	Cool
7	9/28/2005	Precooling + linear set up	Warm
8	9/29/2005	Precooling + exponential set up	Warm
9	9/30/2005	Baseline survey	Warm
10	10/6/2005	Precooling + exponential set up	Cool
11	10/13/2005	No precooling + exponential set up (WA/SA methods)	Cool

Note: Peak Outside Air Temperature (Cool ~75^{o}F (23.9^{o}C), Warm ~ 85^{o}F (29.4^{o}C)

Figure 1. Museum (CSSC)

Figure 2. Cooling and demand shed strategies, CSSC

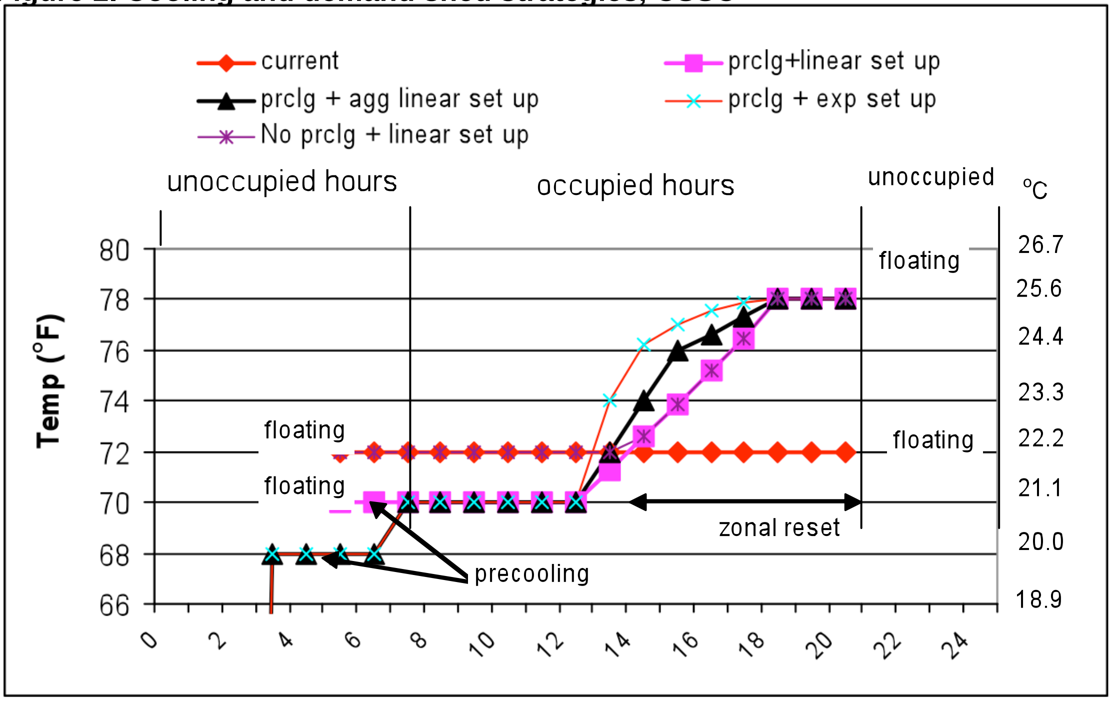

Figure 3. Cooling power reduction on pre-cooling test days - cool days, CSSC

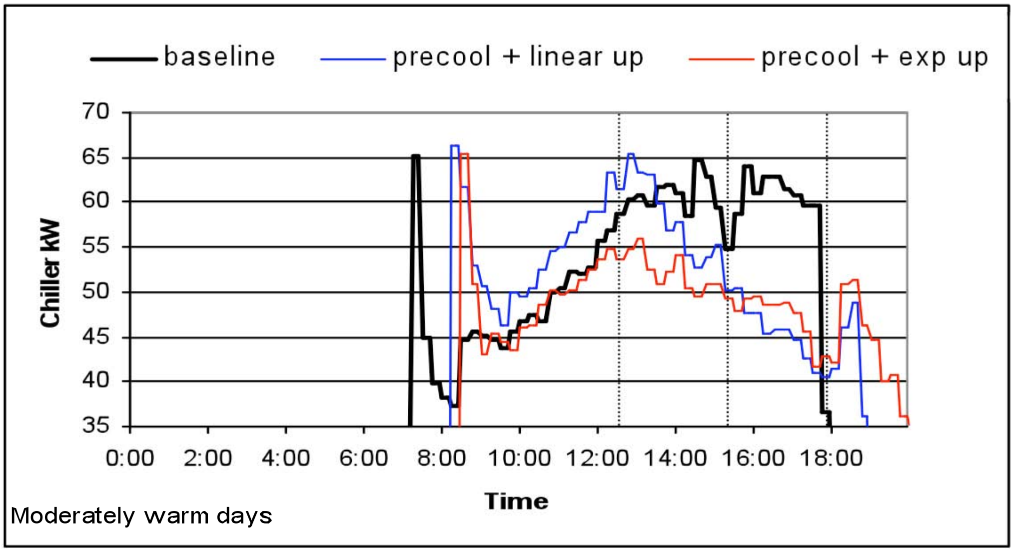

Figure 4. Effects of night pre-cooling on upcoming day cooling load - warm days, CSSC

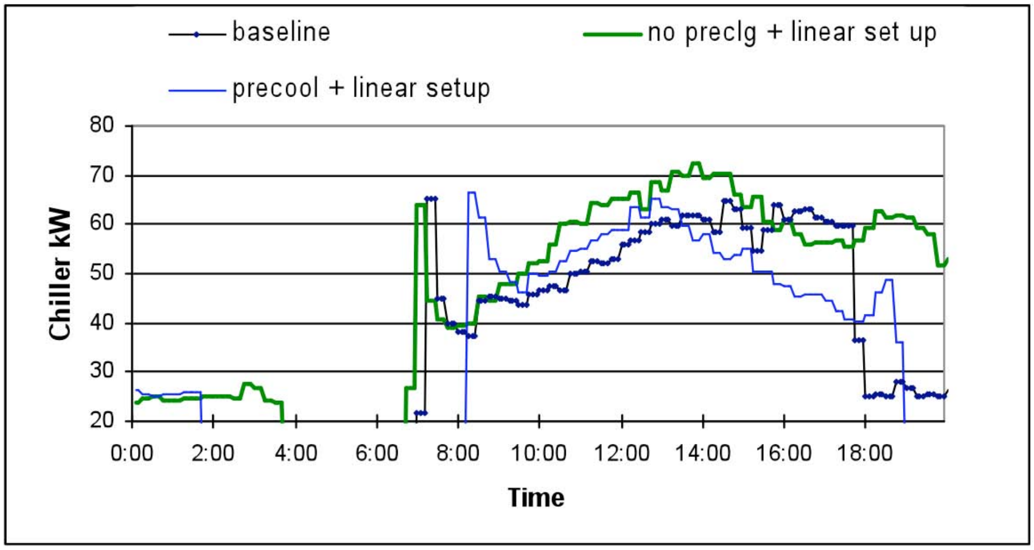

Figure 5. Effects of night pre-cooling on second day cooling load – warm days, CSSC

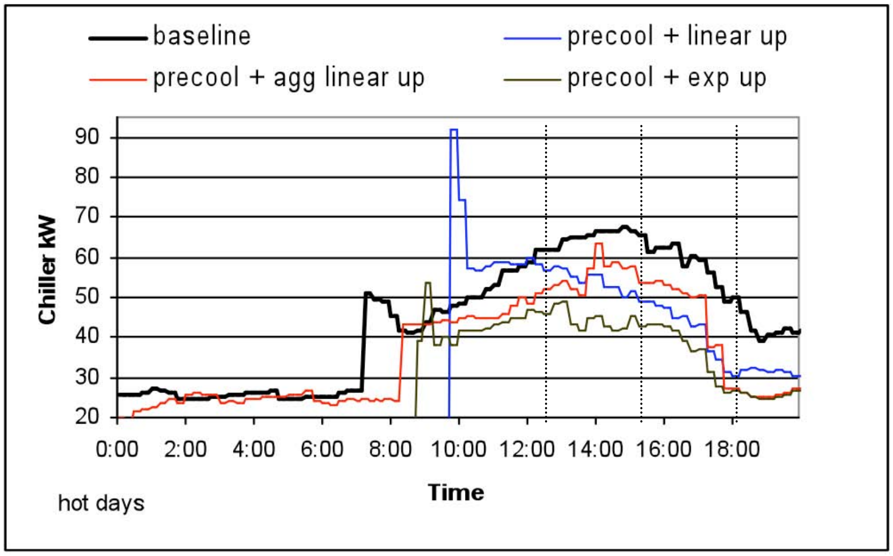

Figure 6. Whole building power reduction on pre-cooling test days, warm days, CSSC

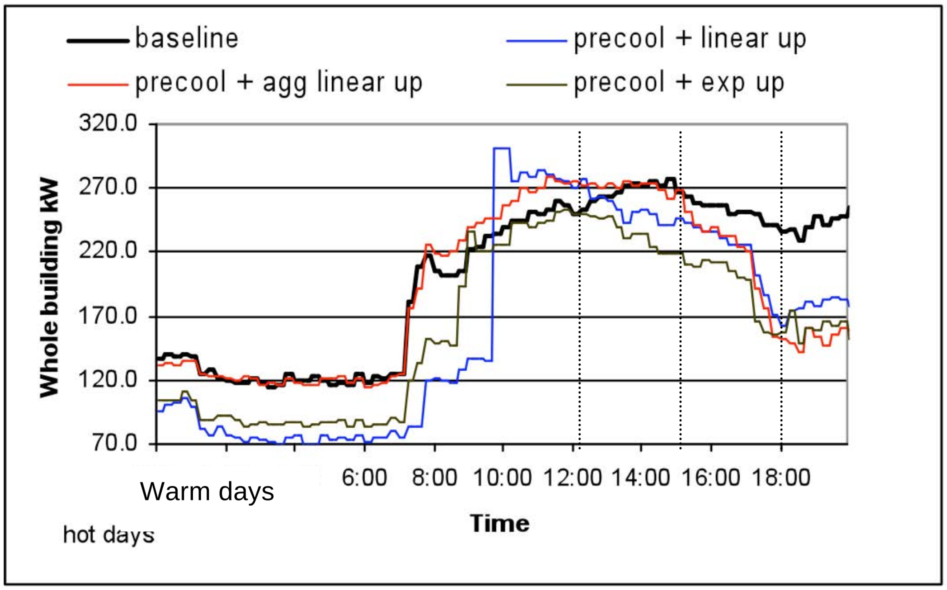

Figure 7. Energy usage of pre-cooling strategies, CSSC

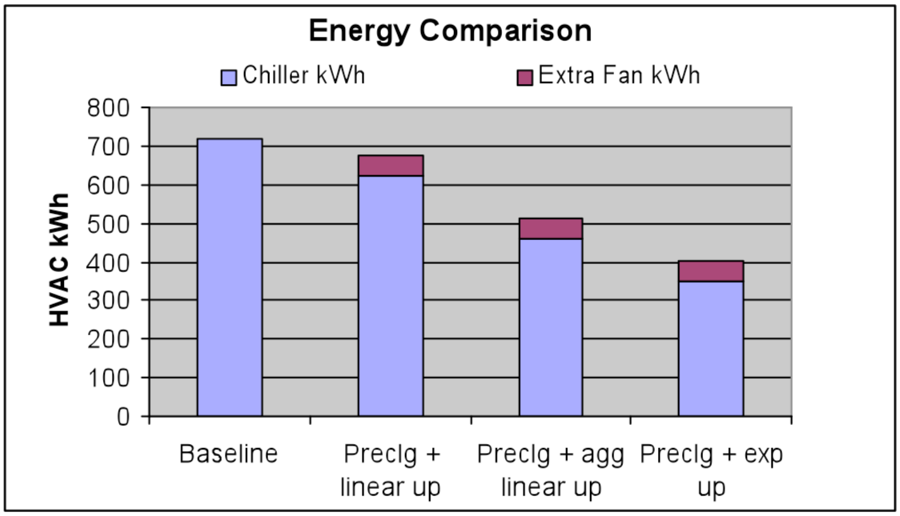

Figure 8. Sensation/comfort on baseline vs. test days, CSSC

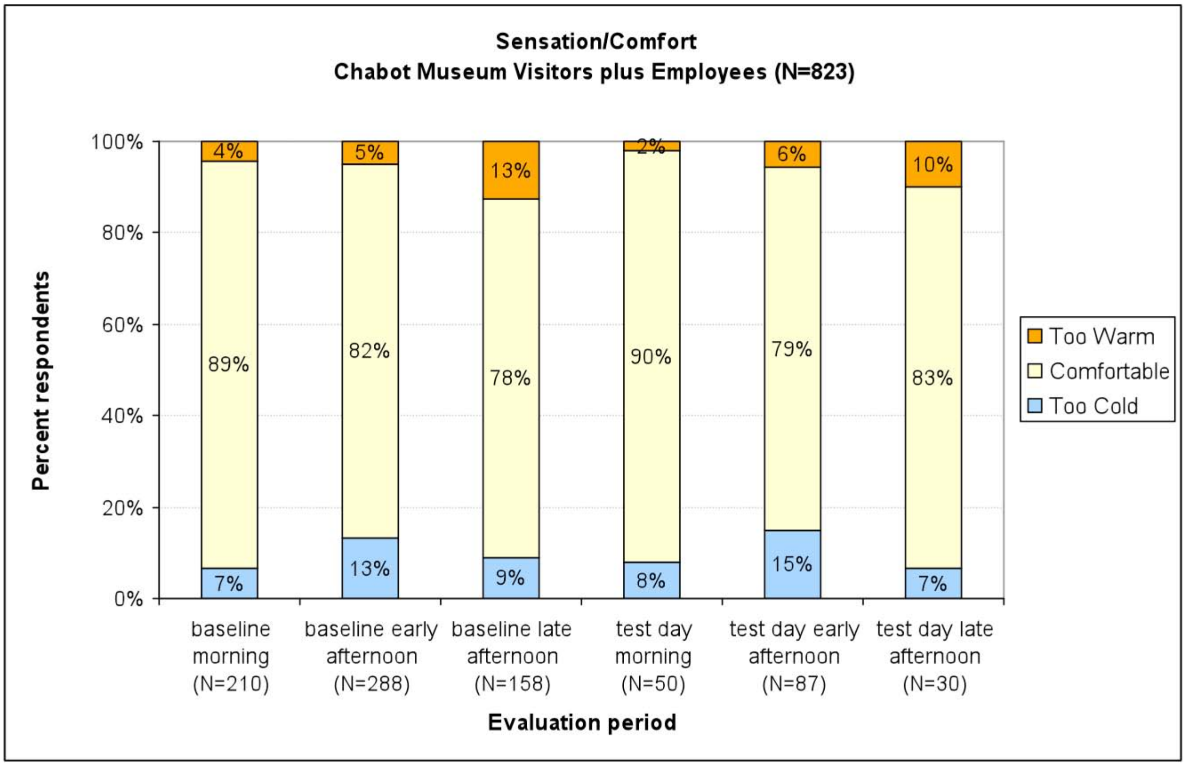

Figure 9. Office building (OSF)

Figure 10. Comparison of different temperature reset strategies, OSF

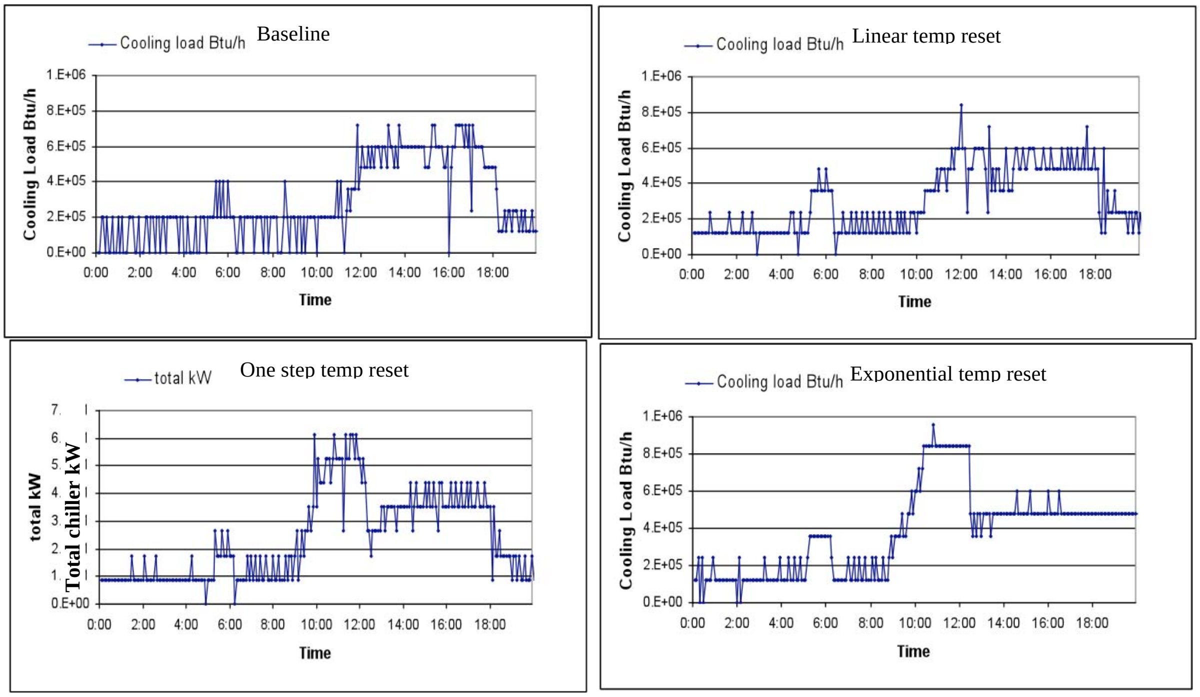

Figure 11. Comparison of return air temperatures with exponential temperature adjustment

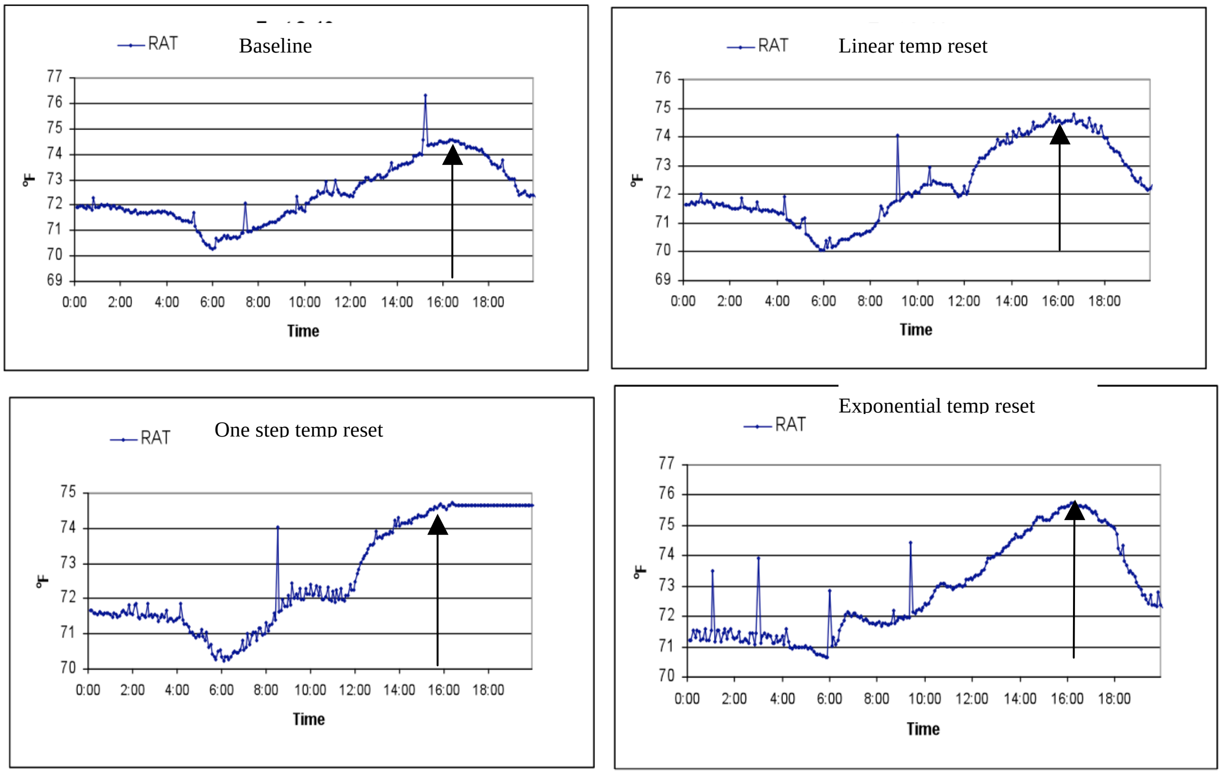

Figure 12. Sensation/comfort on baseline days vs. test days - cool days, OSF