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

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final report for the Demand Shift with Building Thermal Mass Project, 500-03-026 Task 4.2, conducted by the Lawrence Berkeley National Laboratory. The report is entitled "Demand Shifting with Building Mass in Large Commercial Buildings: Field Tests, Simulations and Audits". This project contributes to the Energy Systems Integration Program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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EXECUTIVE SUMMARY

The principle of pre-cooling and demand limiting is to pre-cool 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 summer 2003, a pre-cooling case study was conducted at the Santa Rosa Federal Building. 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 range (70^{o}F) during the occupied hours before the peak period and floating the zone temperatures up to the high end of the comfort range (78^{o}F) during the peak period. With this strategy, the chiller power was reduced by 80 to100% (1 to 2.3 W/ft^{2}) during peak hours from 2 pm to 5 pm without having any thermal comfort complaints submitted to the operations staff.

In summer 2004, we conducted pre-cooling tests along with online real-time comfort surveys to determine occupant reactions to the thermal conditions. The results of the comfort surveys in two test large buildings indicate that occupant comfort was maintained for the pre-cooling tests as long as the zone temperatures were between 70 and 76^{o}F.

Although the initial study was quite successful, some key questions remained unanswered, including: What was the actual comfort reaction if occupants were notified in advance? What are the metrics of the building thermal mass and how are they determined? How can thermal mass be discharged more efficiently and more smoothly with no rebound?

In order to address these questions, field tests were performed in two buildings in 2005. Tests were performed in two medium size commercial buildings in Oakland. One is the Oakland Space and Science Museum, a heavy mass building with large areas of exposed concrete slab. The other is the Oakland Scientific Facility, a light office building with large portion of window facade. A key feature of the 2005 study was the building thermal mass metrics modeling. Two methods were developed and used in the field tests to assess thermal mass and determine the optimal temperature reset strategies in the afternoon peak hours [Lee and Braun, 2006]. To supplement the field tests of 2004, we tested different reset strategies in the afternoon in both buildings and assessed the impact of these strategies and the method to avoid rebounds and maximize load reduction.

The results of the comfort surveys in the two test buildings indicate that occupant comfort was maintained in the pre-cooling tests in general. Night-time pre-cooling was found to have limited effects on the light office buildings in the tested weather condition, but significant effects on the heavy mass building. We found it was important to manage the afternoon load shedding by ramping the zone temperature set-points exponentially rather than stepping them up or ramping them up linearly [Xu, 2006]. This can be particularly important on hot days or in buildings with smaller thermal time constants, where air conditioning-related electrical power could

“rebound” and exceed the peak demand typically seen under normal operation. Field tests of the various reset strategies demonstrated that the exponential temperature reset strategy for the thermal mass discharge period is the best of all the three thermal mass discharge strategies studied.

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. Night pre-cooling can be very effective if the building mass is relatively heavy. The effectiveness of night pre-cooling under hot weather condition has not been tested. Further work is required to quantify and demonstrate the effectiveness of pre-cooling in different climates and 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.

1. INTRODUCTION

The structural mass within existing commercial buildings can be effectively utilized to reduce operating costs through simple adjustments of zone temperature setpoints in a range that doesn't compromise thermal comfort. Generally, the building is pre-cooled at night or in the early morning at moderately low setpoint temperatures (e.g., 68 – 70 ^{o}F) and then the setpoints are raised within the comfort zone (below 78 ^{o}F) during peak periods. The cooled mass and higher on-peak zone temperatures lead to reduced on-peak cooling loads for the HVAC equipment, which results in lower 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, Xu et al., 2003, Xu et al., 2005). This technology appears to have significant potential for demand reduction if applied within an overall demand response program.

Over the past two years, Lawrence Berkeley National Lab (LBNL), Center for the Built Environment (CBE) at the University of California, and Purdue University have conducted research to investigate strategies for using building thermal mass to shift building cooling load in cooperation with three utilities in California, PG&E, SCE and SMUD.

In summer 2003, a pre-cooling case study was conducted at the Santa Rosa Federal Building. It was found that a simple demand limiting strategy performed well in this building. This strategy involved pre-cooling the building at 68^{o}F prior to occupancy, maintaining zone temperatures at the lower end of the comfort range (70^{o}F) during the occupied hours before the peak period and floating the zone temperatures up to the high end of the comfort range (78^{o}F) during the peak period. With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft^2) during peak hours from 2 pm to 5 pm without having any thermal comfort complaints submitted to the operations staff.

In summer 2004, we conducted pre-cooling tests along with online real-time comfort surveys to determine occupant reactions to the thermal conditions. The results of the comfort surveys in two tested large buildings indicated that occupant comfort was maintained for the pre-cooling tests as long as the zone temperatures were between 70 and 76^{o}F.

Although the studies were quite successful and a large peak shed was achieved while maintaining the occupant comfort, some key questions remaining unanswered included:

- What will be the comfort reaction if the occupants are informed in advance of the test?
- What will be the comfort reaction when the pre-cooling strategies are performed in truly hot weather?
- What will be the occupant reaction if the pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment?

- What are the metrics of the building thermal mass and how are they determined?
- How can thermal mass be discharged more efficiently and more smoothly with no rebound?
- How can we assess a building's pre-cooling potential and determine economic saving quickly?
- All previous tests were conducted manually. One the tests days, the building operators change the temperature set points following the pre-cooling strategies manually. The automation of the demand shed is demonstrated successfully in the previous auto DR projects. It is worthy investigating the possibility of implement the pre-cooling strategies automatically or semi-automatically, with a notice one day in advance.

LBNL conducted more field tests systematically and for a longer period in two large commercial buildings in the 2005's study. In 2004, no comfort data were collected during the hot days. In the meantime, all the tests in 2003 and 2004 were blind tests where the occupants were not informed in advance. If they were informed of the pre-cooling tests in advance and expected a temperature change, they might change their clothing level accordingly. Akin to commuting by carpool or bicycle on a "spare the air day," occupants may be willing to adjust to temporarily inconvenient or uncomfortable conditions that they know have long-term benefits.

This research in 2005 was conducted as part of the Auto-CPP Project, funded by PG&E and the California Energy Commission's PIER-funded Demand Response Research Center.

2. PRE-COOLING FIELD STUDY

2.1 Introduction

In 2004, we experienced electrical power rebounds in both buildings tested in late afternoon following an early afternoon step increase in setpoint temperatures. It is essential to develop and test better discharge and recovery methods during the peak hours. In 2005, we tested various discharge and recovery methods and strategies. These strategies and methods were developed and studied in the simulation environment in 2004 but had not been tested in real buildings [Xu, 2006]. How to discharge cooling energy in building mass is as important as how to store them in the mass successfully in the first place.

We offered to conduct a web-based occupant survey in each building as part of the vetting process. The core CBE Occupant IEQ Survey polled occupants for their general satisfaction with the environmental quality in the workplace, including questions about thermal comfort, air quality, and other factors [Zagreus et al., 2004]. The survey took about 10 minutes to complete and was taken once by each occupant.

We developed and tested metrics to describe building thermal mass. Two parameters affect a building's pre-cooling performance: the building thermal mass, and the heat transfer rate between thermal mass and the zone air. The first parameter determines how much cool energy can be stored in the mass, while the second one determines how fast the thermal mass can be charged and discharged. A single parameter, the building time constant, describes the combined effects of the two factors, which then determines how much and how long the power shed is. Very few studies can be found in literature on how to determine the time constant. We implemented the method for learning the effective time constant of the building thermal mass at appropriate field sites. These tests were performed on non-CPP days. The resulting demand-limiting strategy was implemented manually on CPP days and tested on some additional non-CPP days [Lee and Braun, 2006].

We first developed and tested the pre-cooling strategies in the buildings on non-CPP days. Then, we tested the strategies in real CPP days under the pilot program, while the price signal was sent one day ahead. We worked with building owner and programmed the pre-cooling strategies in the EMCS and in order to activate the pre-cooling strategies automatically.

2.2 Methodology

In order to address the questions listed above, we selected two buildings that participated in the Auto-CPP (Critical Peak Pricing) pilot program (Piette et al., 2006). The selection was based on locations, technical feasibility, and owner intentions. A strategy similar to the demand-shifting strategy implemented in 2004, based on zone temperature reset, was used in both buildings. Two buildings selected are Chabot Space and Science Museum (CSCM) and the Oakland Scientific Facility (OSF). They are both in Oakland, California.

There were several reasons for picking these two buildings. First, they are both middle-sized buildings with full DDC control and so we are able to change the zone temperature directly. Second, CSCM 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 gives us the opportunity to test and verify the thermal mass metrics models and methods that developed in parallel at Purdue University [Lee and Braun, 2006]. Third, the owners occupy both buildings, except one floor in OSF. The building owners and property management teams are innovative and they are interested in trying new ideas and methods to reduce their utility costs. A more detailed building description can be found in later sections of this report.

2.2.1 Surveying occupants

The 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. CBE 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 price period, and the high price period.

2.2.1.1 Employee web-based 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 230 office buildings in North America and Europe. For the 2004 tests, CBE developed a customized comfort survey instrument to assess employees' thermal sensation, comfort and productivity ratings. The same survey instrument was employed during the 2005 tests.

The web-based comfort survey has three pages, preceded by a welcome page. On the welcome 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 complete. 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 allowed us to calculate the clo value and metabolic rate, and to evaluate whether people take off/put on clothing as temperature shifts in order to keep themselves comfortable. One the third page, as shown in Figure 1, two questions were asked. One 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 productivity. It should be noted that both questions are self-assessment questions instead of being 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 enables us to calculate the Predicted Mean Vote (PMV) for comparison with the actual comfort vote. The entire survey instrument is included in Appendix III - Web-based survey instrument for employees.

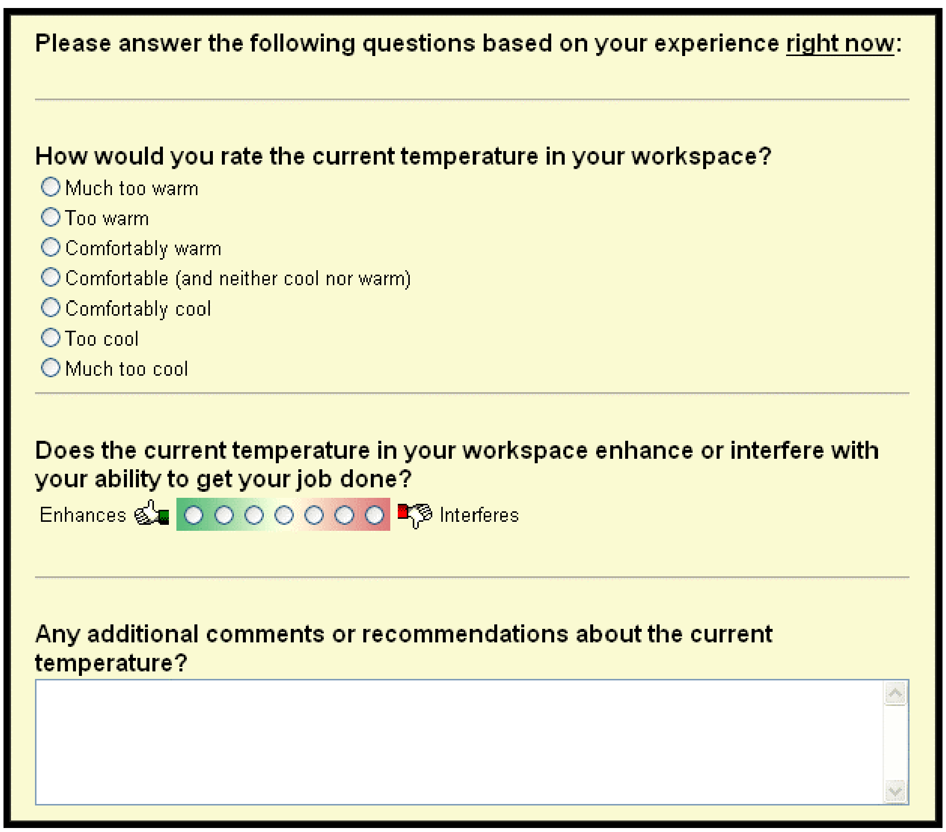

Figure 1. Screenshot of web-based comfort survey for employees

2.2.1.2 Inviting employees

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, with meetings and the like, made the success of this approach unlikely. Further, we were wary of demanding too much of the occupants. During the 2004 tests, we had notified the occupants at each time we wanted them to take the survey, and we learned that some of the employees had found the multiple emails intrusive. During the 2005 tests, we therefore attempted to minimize the communication impact. This was apparently a successful strategy at the Oakland site, but we had low participation from the employees at the Echelon and Chabot sites.

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. See Appendix IV for employee survey informational emails and invitations.

In some cases, CBE sent the invitation directly to the occupants. In others, our contact in the building sent out the invitation. In general, it is 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 are often busy or unavailable, and prefer that CBE send out the notifications.

2.2.1.3 Polling station

Owners of retail spaces want to know how demand shifting/shedding strategies may affect customers as well as employees. As Internet access is usually not easily available in such scenarios, CBE developed stand-alone polling stations for surveying customers in retail spaces (see Figure 2). This device asks about sensation/comfort using a single 5-point scale question. During the 2005 tests, the device was employed in the Chabot site to gather sensation votes of the museum visitors. One device was situated near the museum café, and on some test days UC Berkeley students facilitated the survey by approaching visitors with the devices.

Figure 2. Polling station for surveying visitors

2.2.2 Monitoring thermal conditions

During the study period, LBNL monitored the study sites via the EMCS system, and CBE logged continuous thermal measurements in the spaces using hundreds of hobo temperature loggers, one humidity sensor per floor, and Indoor Climate Monitors (ICMs) previously developed by CBE for use in such studies. The ICMs log ambient temperature, radiant temperature, and air speed. Along with the humidity readings, this allows us to calculate MRT and thus operative 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 expected to be important in assessing thermal comfort in this study, because the building surfaces should be cooler as a result of the pre-cooling. The time stamp on the thermal measurement logs and survey responses allowed perceived comfort to be analyzed alongside measured conditions.

Figure 3. Indoor Climate Monitor (ICM) with (from left to right) shielded dry bulb sensor, anemometer (air speed sensor), and globe temperature sensor

2.2.3 Weather and test conditions

During the 2004 tests, the weather was not as hot as hoped for at the test sites, so the majority of those tests were conducted in warm weather. The 2005 tests were similarly subject to weather conditions that were cooler than desired. All the surveys were conducted between August 8, 2005 and October 14, 2005. The tests were conducted on mostly cool days and a few warm days. Cool days are defined as days when the peak outside air temperature was below 85°F and warm days are defined as days when the peak outside air temperature was at or above 85°F.

2.3 Test Site 1 – Chabot Space and Science Museum

2.3.1 Test Site Description

Chabot Space & Science Center 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 2.1). The cooling plant has a 230-ton centrifugal chiller with a variable pumping chilled water loop. There are eight air-handling units located in 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 units and one is a constant volume unit. A newly installed Envision DDC control system provides indoor comfort control.

Figure 2.1 Chabot Space & Science Center

The building has independent HVAC systems serving each major exhibition area and the office area. CO_2 sensors are installed throughout the exhibition area and outside air ventilation rate is adjusted automatically to keep the CO_2 levels in the zones within the desire ranges. The supply and return fans for the dual duct system are equipped with variable frequency drives (VFD). There are about 40 zones in the building. Although the building is fully equipped with digital direct control (DDC), it has no global zone temperature reset capability before the study. This function was added into the program as part of this study.

Operationally, the building is typical of many museums. The building is closed for visitors on Monday and open on Saturday and Sunday. Since all the PG&E CPP days are on weekdays, the CPP program is financially less attractive to this building than other buildings since the load of this building in CPP days is lower than that on weekends anyway. The HVAC system starts at 5 am and pre-heats or pre-cools the building until 8 am, depends on the outside weather conditions. The occupied hours are from 8 am to 5 pm. Before the tests, no major faults in the mechanical system were apparent in this building except some controllers have not been tuned properly and certain valves and dampers are oscillating during operation. There were no comfort complaints in the both office and exhibition area. The building operators have worked at the building for a long time and are quite confident and familiar with its mechanical system.

2.3.2 Test Strategies

The pre-cooling and zone temperature reset strategies that were tested are shown in Figure 2.2. The building was normally operated at a constant set point of 72^{o}F throughout the startup and occupied hours. After 8 pm, the system was shut off and zone temperatures started to float. Under normal operation, the set-points in individual zones ranged from 70 to 75^{o}F, with an average value of about 72^{o}F.

The first strategy tested was termed "pre-cooling + linear zonal set up". The HVAC system was turned on earlier in the morning than in normal operations to pre-cool the building to 68 ^{o}F from 3 am to 7 am. Because the weather was relatively cool at the Oakland Hill in the summer and the outside air temperature was in low 60s ^{o}F in the mornings, the HVAC system could cool the building with the economizers and no chiller operation. From 7 am to 12 pm, the occupied hours, all the zone temperature set-points were reduced to 70°F. From 12 pm to 6 pm, the CPP moderate and high rate periods, the set-points were raised linearly to 78°F. After 6 pm, before the system was shut off, the set points were kept at 78 °F. The second strategy is called "pre-cooling + agg linear set up". Everything else was same as the strategy above except the temperature set-points were raised up more aggressively in the afternoon. The set-points were raised to 76 °F at 3pm, instead of to 74 °F in the first strategy. The next strategy was termed "pre-cooling + exponential set up". The temperatures were raised up exponentially rather than linearly in the afternoon period. The last strategy is called "No pre-cooling + linear set up". The zone temperature was raised up linearly in the afternoon in the same way as the first strategy, but with no pre-cooling from 3am to 7am. One aim of the tests was to determine the effect of the extended pre-cooling on the second peak demand shedding.

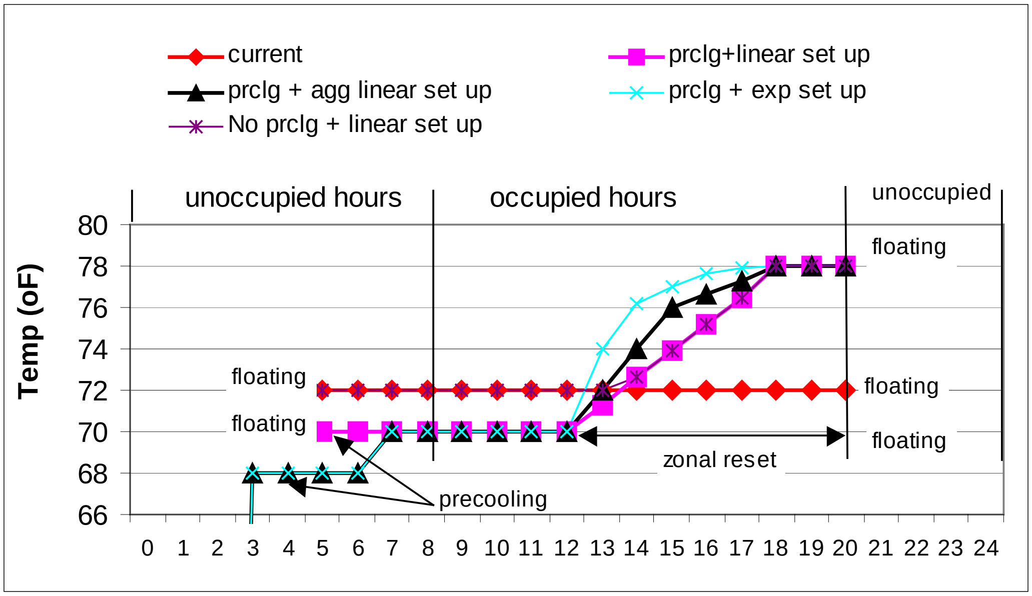

Figure 2.2 Pre-cooling and demand shed strategies (Chabot Space and Science Museum)

2.3.3 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 zone were recorded through the building control system. The temperature data were compared with indoor air measurements from devices installed by UCB in both office and exhibition areas.

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

2.3.4 Weather and Test Scenarios

In the 2003 and 2004 study, the expected strong correlation between peak outside temperature and whole building power was observed in the all tested buildings [Xu et al., 2005]. Therefore, 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 till early October 2004. Cool days are defined as days when the peak outside air temperature was between 72°F and 75°F and warm days are defined as days when the peak outside air temperature was around 85°F. That is the hottest temperature observed in the Oakland Hill in the summer of 2005.

In total, we conducted eleven tests in this study, as listed in Table 2.1. 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 two "No pre-cooling + zonal reset tests", two "pre-cooling + linear set up" tests, and two "pre-cooling + aggressive linear set up" tests. All tests were duplicated except for the "pre-cooling + exponential set up" test. This test was not duplicated because of the time constraint. The remaining two days were "baseline survey" days on which no intervention occurred.

Table 2.1. Pre-Cooling and Zonal Reset Test Scenarios

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 °F, Warm ~ 85 °F)

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 makes it very easy to administer, and thus we collected survey data on several additional days as well. These are all considered "baseline" days and are included in the analysis of survey responses. They are not included in the energy use analysis. There were also two days (8/5 and 10/15) when no survey data was collected. See Appendix V for the list of all days on which survey data was collected.

The building operator sent the web-based survey invitations to employees. Of 48 invited, 10 individuals participated, and 52 valid observations were recorded. All of these could be matched up with nearby thermal conditions.

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 it or record erroneous votes. 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. In other museum locations, visitors were surveyed by UC Berkeley students who carried the stations and asked visitors to take the survey. It is hard to know exactly how many were invited to take the survey as we do not know how many people saw the device at the café and chose not to use it. 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 matched up with nearby thermal conditions.

2.3.5 Results

2.3.5.1 Energy use

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

Cool days. Figure 2.3 shows chiller power measurement for the “pre-cooling + linear zonal reset” and “pre-cooling + exp zonal reset” on the moderately warm days. The power usages for cooling on the baseline days and test days were similar in the morning. At 12 pm, when the zone temperatures set-points started to rise, the chiller power was reduced dramatically on the pre-cooling test days. The chiller load was reduced by as much as 50% in the high price period from 3 pm to 6 pm. In the tests of both linear reset and exponential reset, we observed no rebound for chiller power before 6pm, 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. It was mostly because of the effects of the night pre-cooling. The building structure was much cooler on the pre-cooling test days than that on the baseline days. In normal operation, the chiller was automatically turned off at 6 pm because of the cool weather. For the two pre-cooling days, the chillers were still running at 6pm. The load was shifted successfully from the peak hours to the after peak hours after 6pm. 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.

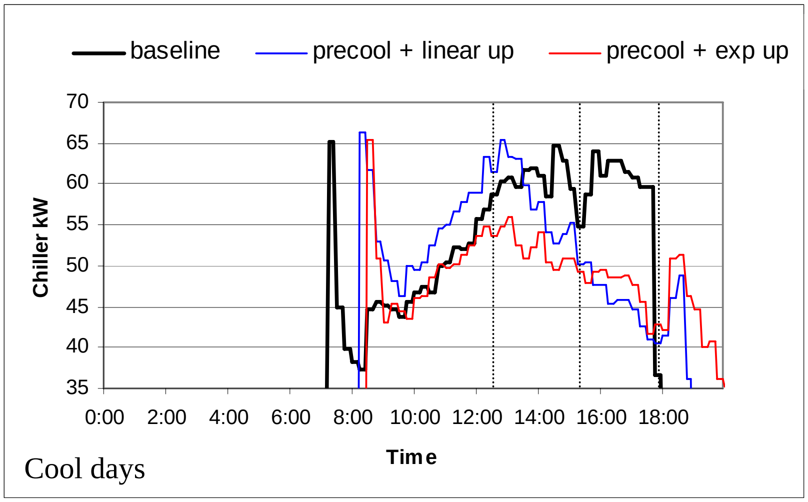

Figure 2.3 Cooling power reduction on pre-cooling test days under cool weather conditions (Chabot Space and Science Museum)

Effects of pre-cooling. The effects of night pre-cooling on the second day load were very obvious. Figure 2.4 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, we observed similar results as in Figure 2.3. 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 had a large effect on the whole building electricity consumption during the overall day period. The tests results are helpful in addressing questions from tests performed in 2003 and 2004. The results from both 2003 and 2004 tests in lighter thermal mass building indicated that night pre-cooling has 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.

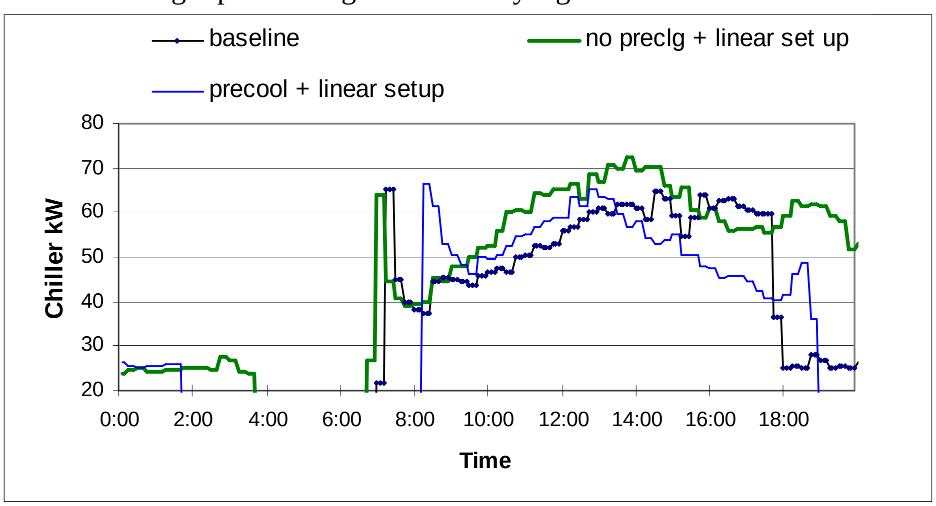

Figure 2.4 Effects of night pre-cooling on the second day cooling load (Chabot Space and Science Museum, Moderately warm days)

Warm days. Figure 2.5 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, 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 in the tests with the exponential temperature reset, where the chiller electrical load was reduced almost by half.

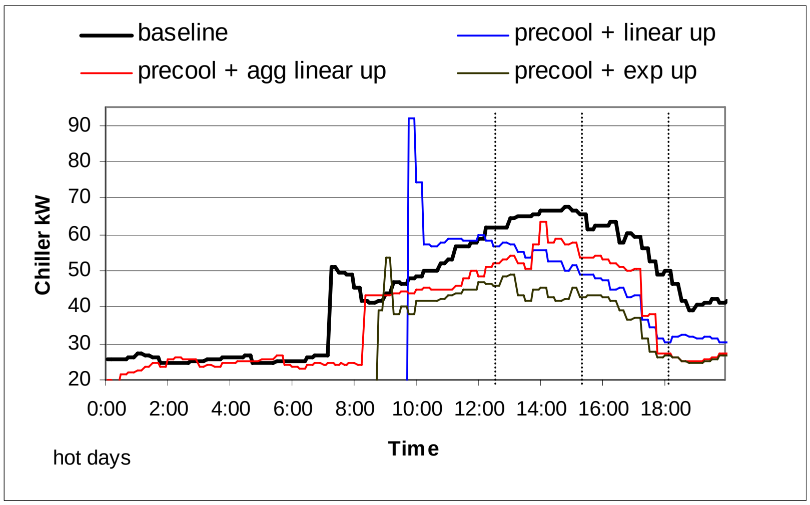

Figure 2.5 Effects of night pre-cooling on the second day cooling load (Chabot Space & Science Center, Warm days)

Compared with the test results on warm days in 2004, the reduction in demand did last till the unoccupied hours [Xu et al., 2005]. There were no "rebounds" in the afternoon for all the tests. Two factors could contribute to the difference. First, the test days in 2004 were hotter than the corresponding test days in 2005. The maximum outside air temperature in 2004 was 96°F, compared with 85°F in 2005. This increase in outside temperature increased the cooling load during the peak hours significantly, 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", because of exposed concrete in the exhibition area. Third, we were very careful in implementing the strategies in 2005. In order to prevent rebounds, we tested the least aggressive strategy (linear reset) first and the most aggressive strategy (exponential reset) later. In the meantime, the final strategy was backed up with a simulation analysis.

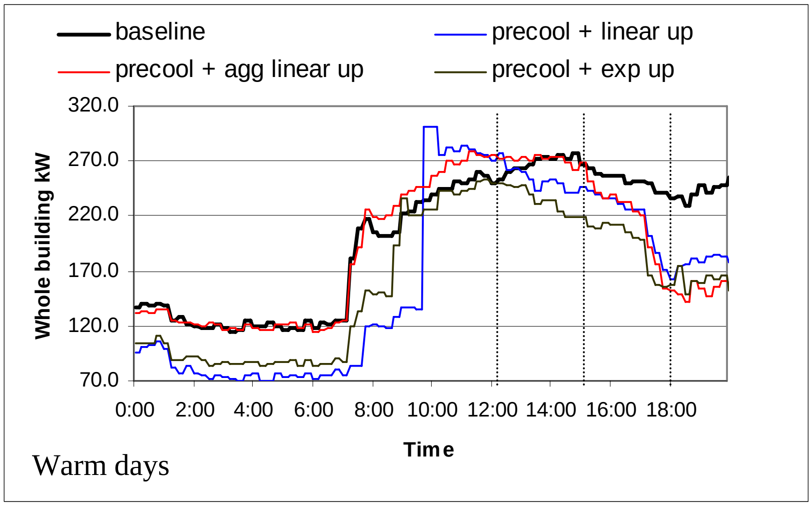

Figure 2.6 Whole building power reduction of pre-cooling test days (Chabot Space and Science Museum)

Whole building. The reduction in the whole building power was about 30 kW (~15%) during the moderate CPP price period (12-3pm) and 50 kW (~20%) during the high price CPP period (3-6pm). 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 tests, the power reduction was the largest. In the morning after 10 am, there was little difference between the electrical power consumption between the tests and the baselines. Part of the reason was that the HVAC system was not running close to its full capacity on these warm days. It is believed that the response would be different under the different pre-cooling scenarios if the HVAC system was close to its full capacity.

Figure 2.7 shows the Chabot daily HVAC energy consumption for the pre-cooling days. HVAC energy consumption was reduced significantly. The most successfully strategies, pre-cooling plus exponential set up in the afternoon, can reduce the HVAC energy consumption by up to 40%.

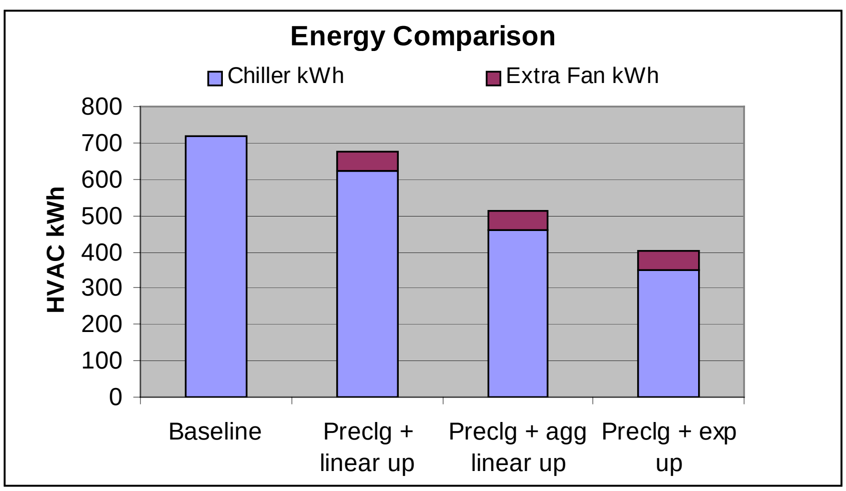

Figure 2.7 Energy usage of different pre-cooling strategies

2.3.5.2 Occupant comfort

Participation by employees was low, and there were few test days (particularly warm test days). Therefore the employee and visitor data has been combined for the analysis in this report.

Figure 4 shows that comfort rates were comparable between baseline and test days for all periods. In fact none of the differences are statistically significant.

Looking at data from cool days only (the vast majority of the data), the same trend occurs, as shown in Figure 5. Warm days are shown in Figure 6, however the amount of data collected on test days is too small to draw any statistically valid comparisons. Only 7 responses were collected in each of the morning and early afternoon periods, and only 4 in the late afternoon period.

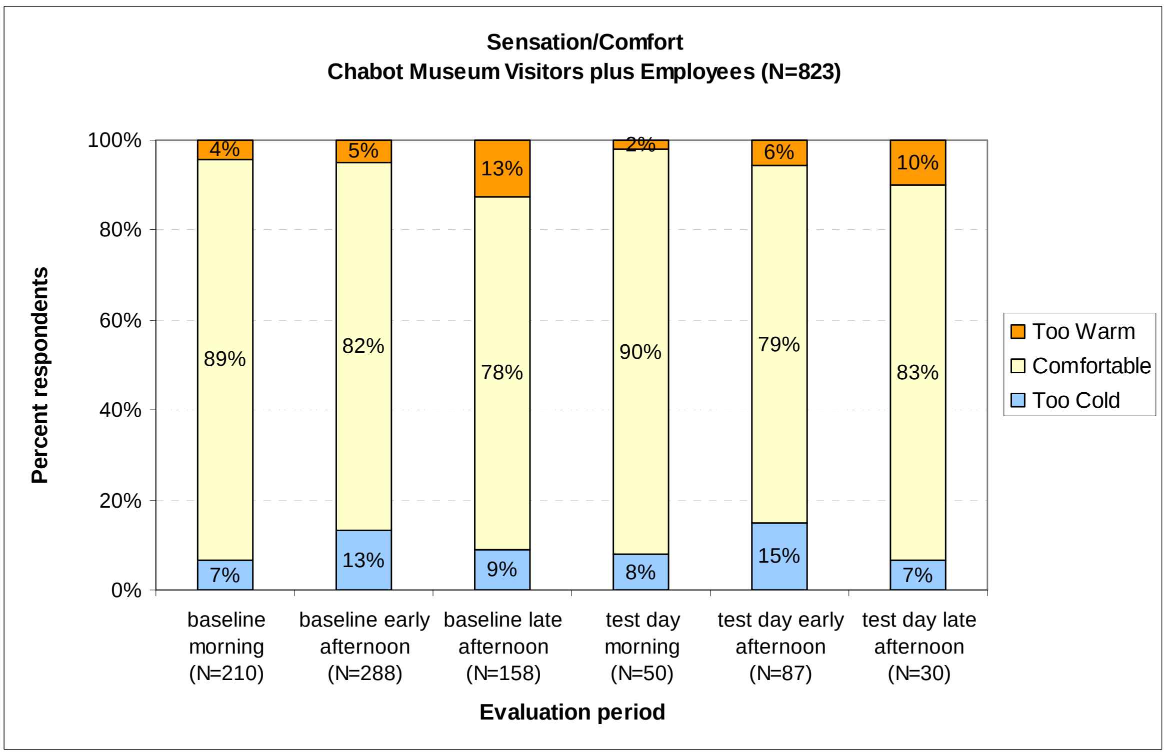

Figure 4. Chabot baseline vs. test days – Sensation/Comfort

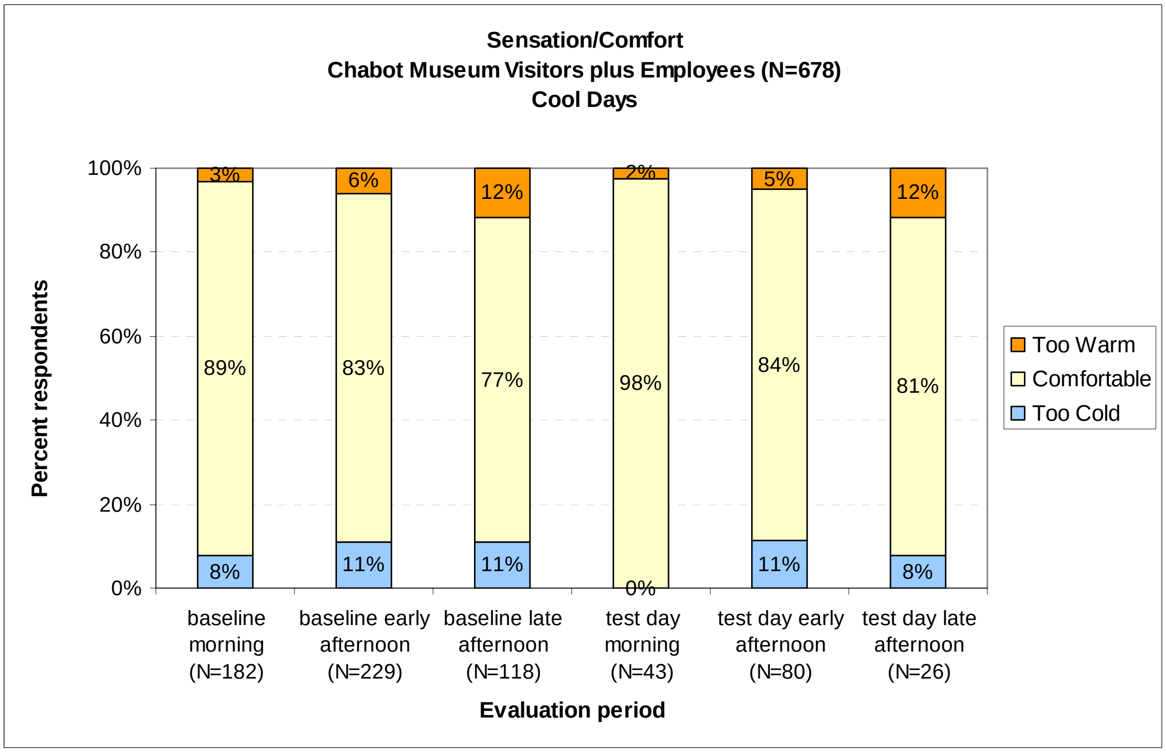

Figure 5. Chabot baseline vs. test days – Sensation/Comfort - Cool days

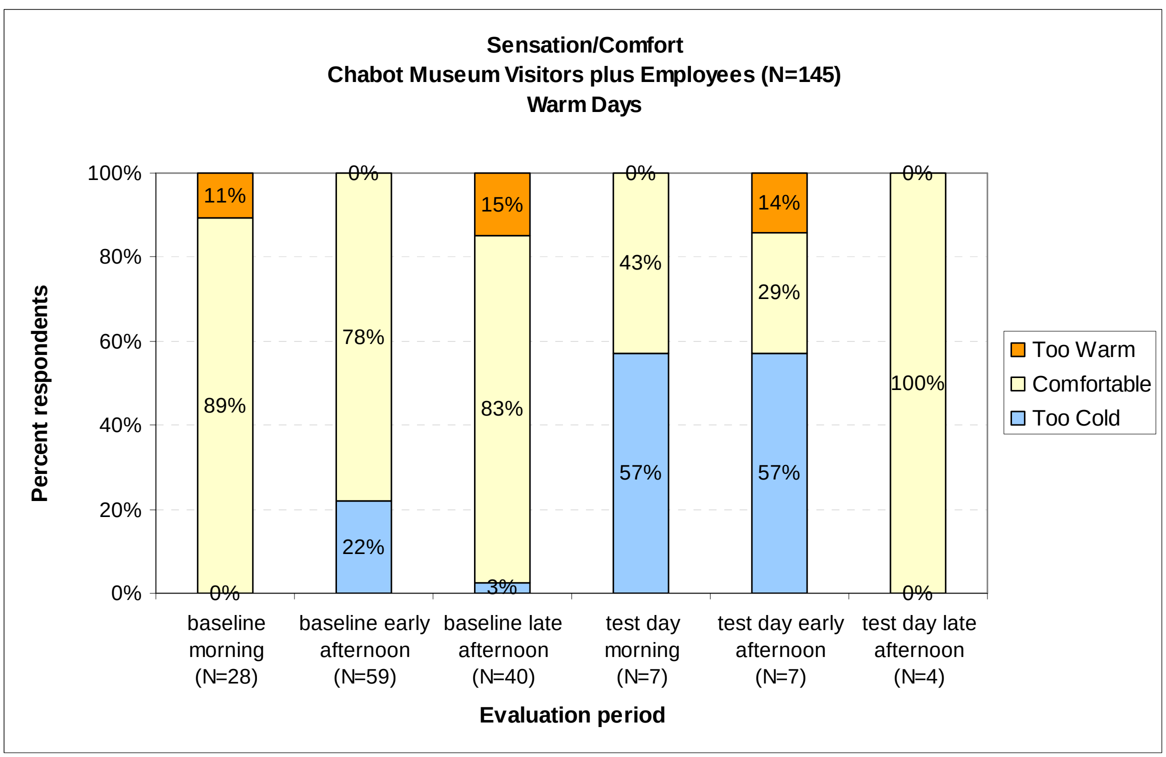

Figure 6. Chabot baseline vs. test days – Sensation/Comfort - Warm days

2.4 Test site 2 – Oakland Scientific Facility

2.4.1 Test Site Description

The second test site, Oakland Scientific Facility, is a 90,000 ft^2 (70,000 ft^2 conditioned) office building in Oakland, California (Figure 2.8). Lawrence Berkeley National Lab and University of California jointly occupy it. The first floor is a data center, which houses a large computer center. The electrical requirements of the computer center are roughly about 1 MW, constant throughout the year and the data center always requires cooling throughout the year also. The peak load for the entire building is about 1.5 MW.

Figure 2.8 Oakland Scientific Facility, Oakland, California

The building has a variable air volume 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 set point is 74 ^oF in the office areas and 70 ^oF 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 ^oF.

The building has moderate structural mass, with 4" 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^{o}F because of a contract agreement between UC and LBNL.

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 digital direct control (DDC), but with no global zone temperature reset before this study.

Operationally, the building is typical of many office buildings. The HVAC system starts at 6 am and pre-heats or pre-cools the building until 8 am. The occupied hours are from 8 am to 5 pm. 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-sites operators and the operators in LBNL 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, we only tested the pre-cooling strategies in the office portion of the building.

2.4.2 Test Strategies

The pre-cooling and zone temperature reset strategies tested are shown in Figure 2.11. In total we tested four different pre-cooling and temperature reset strategies in the office portion of the building. The building was normally operated at a constant set point of 72°F throughout the startup and occupied hours. After 6 pm, the system was shut off and zone temperatures started to float. Under normal operation, the set-points in individual zones ranged from 70 to 76 °F, with an average value of 72°F. All of the zone temperature set points were lowered to 70 °F From 6 am to 12 pm on the pre-cooling test days. On none pre-cooling days, the set points in the morning were the same as for normal operation. We tested three different temperature reset strategies in the afternoon. They are "two step set up", "linear set up", and "exponential set up". After 6 pm, the system was shut off, as was done in the regular operational mode.

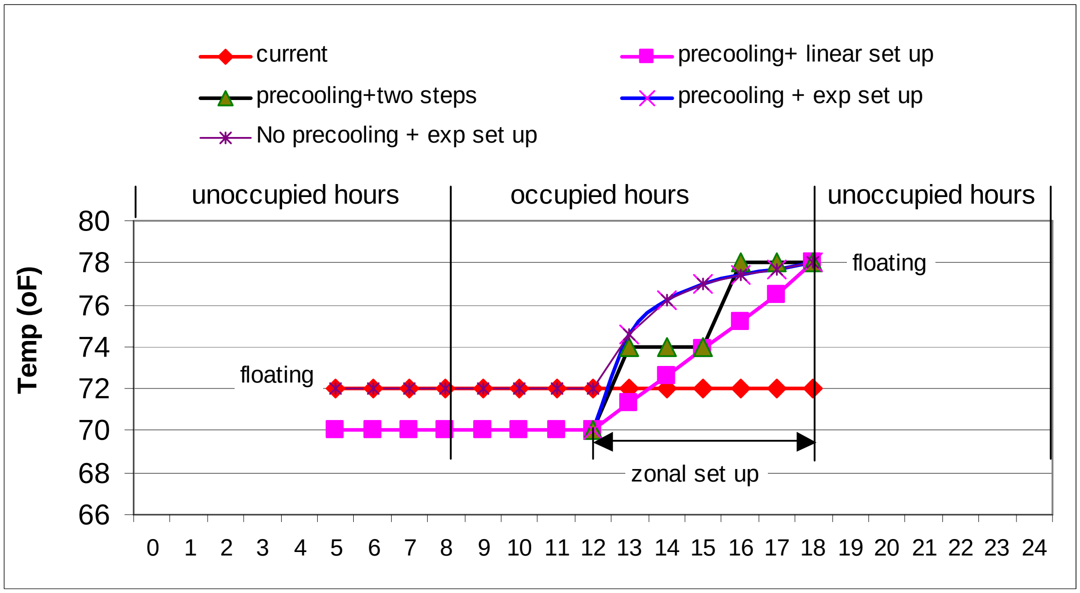

Figure 2.11 Pre-cooling test strategy for Oakland Scientific Facility

2.4.3 Monitoring

The building has a whole building power interval meter, but has no sub-metering for the office area. 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.

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

CBE placed thermal measurement equipment on the 2nd and 4th floors on August 18. Permission was later secured to install the equipment on the 3rd floor and that was completed on August 23.

2.4.4 Weather and Test Scenarios

All the tests were conducted during the summer 2005. It was a relatively cool summer and the peak outside air temperatures were between 75 and 85 ^{o}F. We 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^{o}F and 75^{o}F, and warm days when peak outside temperature is about 85 ^{o}F. In total, we completed nine tests, two of them on warm days and seven of them on moderately warm days (Table 2.2). We conducted baseline surveys on two days, one on a cool day and the other on a warm day. Most of the pre-cooling strategies were tested twice, except the exponential reset strategy. Each test lasted one day.

Table 2.2 Pre-cooling test schedule (Oakland Scientific Facility)

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, warm ~ 85 ^{o}F)

Precl

The nature of the web-based survey for employees makes it very easy to administrate, and thus we collected survey data on several additional days as well. These are all considered “baseline” days and are included in the analysis of survey responses. They are not included in the energy use analysis. There were also several days (8/10, 8/11, 8/12, 822, 10/6, and 10/15) when no survey data was collected. See Appendix V for the list of all days on which survey data was collected.

Preclg

CBE sent the survey invitations directly to 2nd floor occupants. Department supervisors sent out invitations to 3rd and 4th floor occupants. Of all people invited, 79 individuals participated, and 414 valid observations were recorded. Of these, 374 could be matched up with nearby thermal conditions.

2.4.5 Results

2.4.5.1 Energy use

Different reset strategies. Figure 2.12 shows the cooling load profile under different pre-cooling temperature reset strategies. Under normal operation (baseline), the cooling load normally peaked between 12 and 4pm. In the linear set up test, the peak load was reduced by about 15%. Because the temperature was raised linearly, the load reduction was small at 12pm and getting larger in the later afternoon. In the two-step set up tests, the temperature rise was faster than the liner set up test and so the load reduction was larger. The peak cooling load was reduced by 50% from 1pm to 6pm. However, because the temperature was raised in two steps, right after the first step, the load curve was a small dip and a rebound and so the load profile was not completely flat. Among all the tests, the exponential temperature reset achieved the best power profile of all the scenarios. The power was essentially constant during the on-peak period and there was no "rebound".

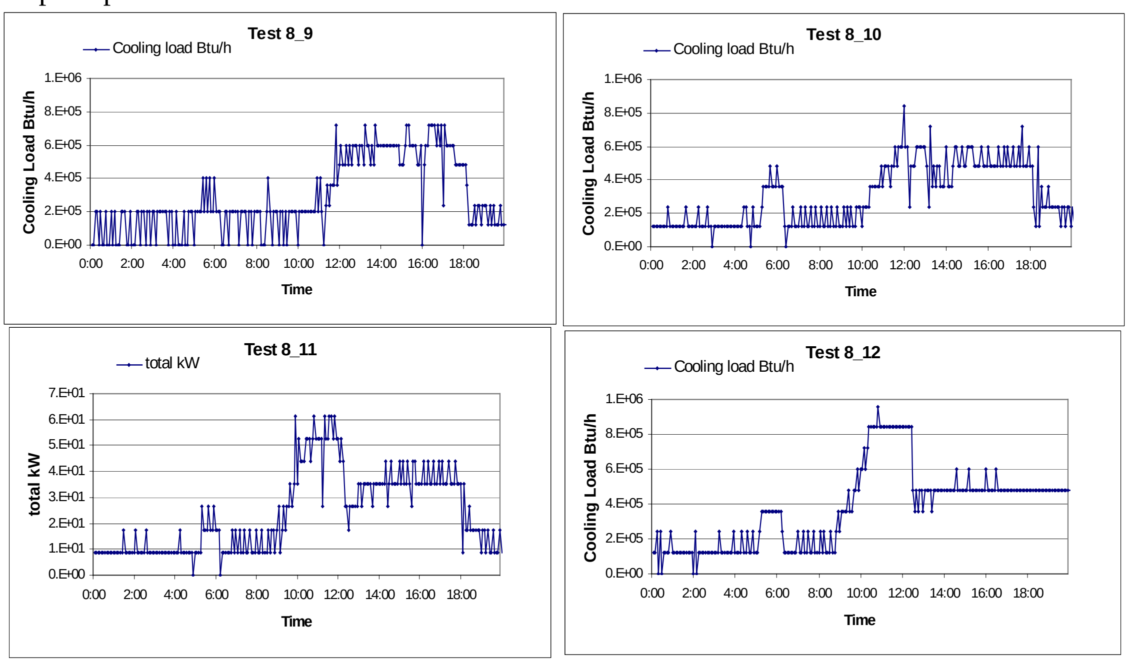

Figure 2.12 Comparison of different temperature reset strategies

Pre-cooling versus no pre-cooling. Figure 2.13 shows the effects of the temperature reset with and without pre-cooling. Compared with the load in the no pre-cooling days, the load for pre-cooling was a bit higher in the morning before the peak period. This was essentially due to the fact that the zone temperature on pre-cooling days was 2 degrees lower than that for the baseline days. During the peak period, the load reduction on pre-cooling days was slightly larger. However, the difference is not significant. Zonal reset without pre-cooling produced a load shed of almost the same magnitude as that for pre-cooling tests in this light mass building under the moderately warm weather condition.

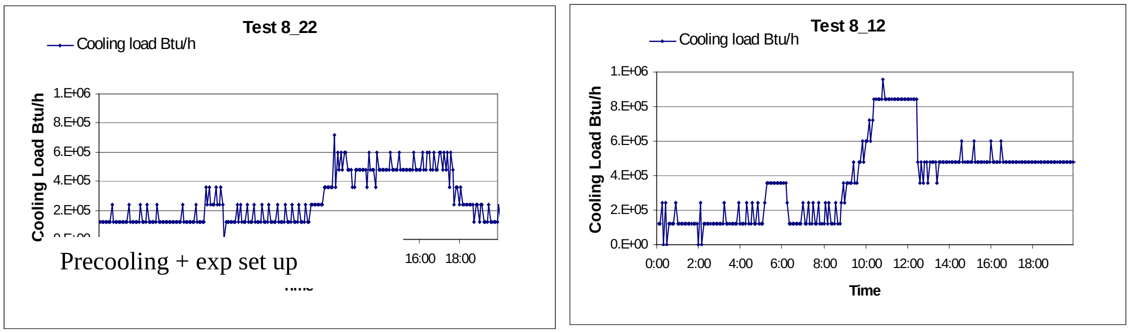

Figure 2.13 Comparison of the temperature reset with and w/o pre-cooling in the morning

Zone temperatures. Figure 2.14 shows the return air temperature, a good indicator of the averaged zone temperatures, under different tests 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 ^{o}F, two degrees lower than the highest temperature setpoint of 78 ^{o}F. The temperature data also indicates the benefits of the morning pre-cooling. In the no pre-cooling tests, the peak zone temperatures were roughly about 2 ^{o}F higher than that 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.

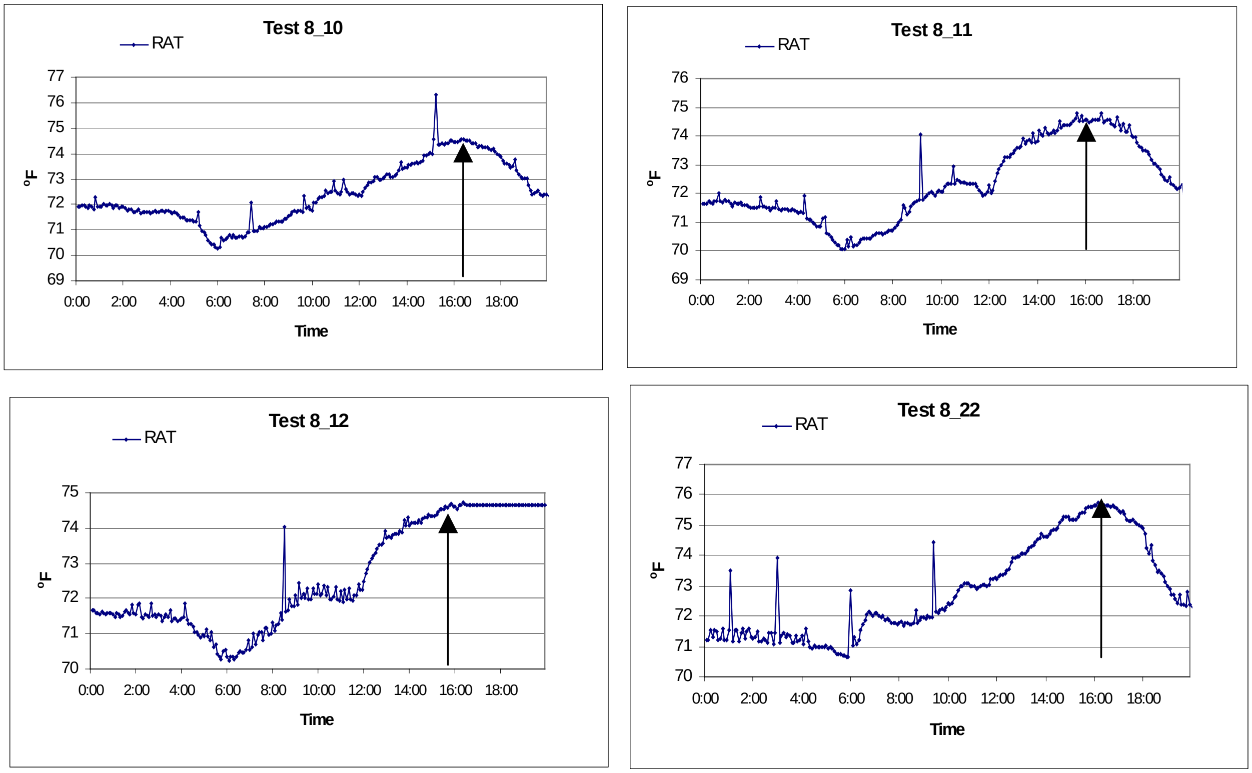

Figure 2.14 Comparison of the temperature reset with and w/o pre-cooling in the morning

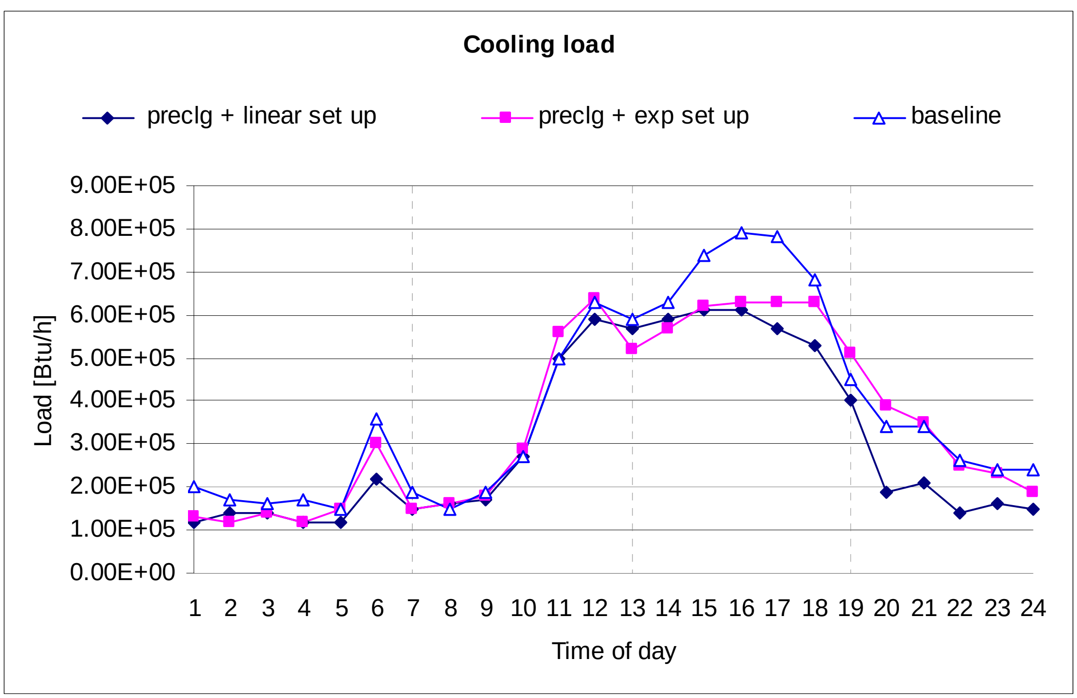

Figure 2.15 Cooling load shed on the warm days (Oakland Scientific Facility)

Warm days. Figure 2.15 shows the peak cooling load reduction in the warm day tests. In both pre-cooling tests, the load reductions were about 25% of the peak cooling load. The load profiles were almost identical from the two tests of different temperature set up strategies. In the exponential set up tests, the load reduction right after 12pm was slightly larger than that of the linear set up strategy.

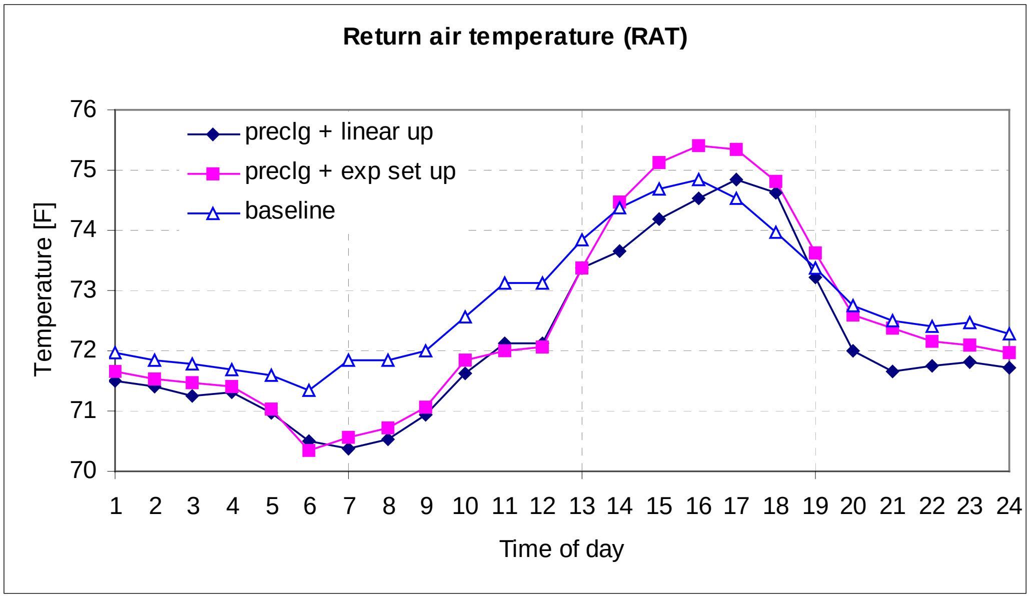

Figure 2.16 Return air temperature on the warm day tests (Oakland Scientific Facility)

The return air temperature for the warm day tests showed similar results as for the tests on the moderately warm days. In the afternoons, the peak return air temperatures were only about 2 degree higher than that of baseline. The return temperatures were never higher than 76 ^{o}F, let alone the maximum set point of 78 ^{o}F.

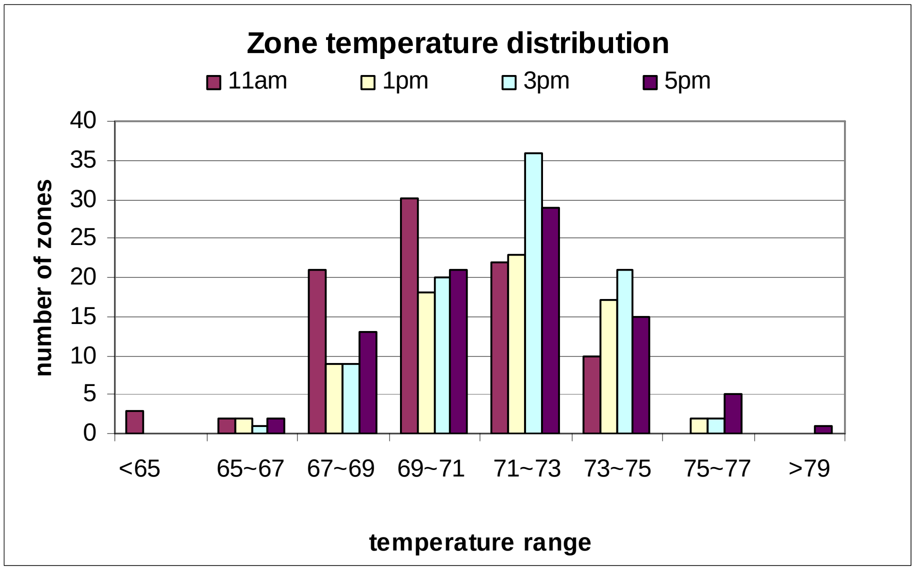

Figure 2.17 Zone temperature distribution on a typical baseline day. (Oakland Scientific Facility)

Temperature distribution. Although the return temperatures were never higher than 76 ^{o}F in all the tests, the individual zone temperatures were not necessary always lower than 76 ^{o}F. Figure 2.17 shows the zone temperature distribution in the building on a baseline day. There was a big temperature variation across the building. In all 88 zones, the space temperatures ranged from 65 to 79 ^{o}F. The real zone temperature was affected both by the location and by the operation hours. Generally in the afternoon, the temperature was normally higher than in the morning and the buiding always exists certain bad zones that were either too cold or too hot. The distribution patterns were essentially same for both baselines and all the test days.

2.4.5.2 Occupant comfort

Though in this study we hoped to focus primarily on warm days as that's the kind of weather in which these strategies are likely to be employed, we did not collect a lot of survey data on warm days, particularly warm test days. Upon setting up the equipment, there was a prolonged cool spell, and the weather never got truly hot. Although the weather was somewhat warmer on a few days, little survey data was 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 report evaluates the data at a rather coarse level of granularity in order that the calculations are statistically valid. Taken as a whole (see Figure 7), those indicating sensation in the comfortable range on test mornings and late afternoons met or exceeded comfort levels on baseline days. Comfort levels on test early afternoons were lower than on baseline days. Those expressing discomfort on test days tended to be concentrated more in the cooler range than on baseline days. This suggests that the morning precooling strategies were effective, but may need to be run at a higher setpoint or for a shorter duration in order to avoid adversely affecting occupant comfort. However more data should be collected during test conditions to state this conclusively. We can also observe that in general, people tend to be on the cool side in this building.

As shown in Figure 8, perceived productivity was closely linked with sensation and comfort. The proportion of those stating that the temperature either enhanced or had no effect on their ability to get their job done (in essence an absence of interference) is nearly identical to the proportion of those within the comfortable range in Figure 7.

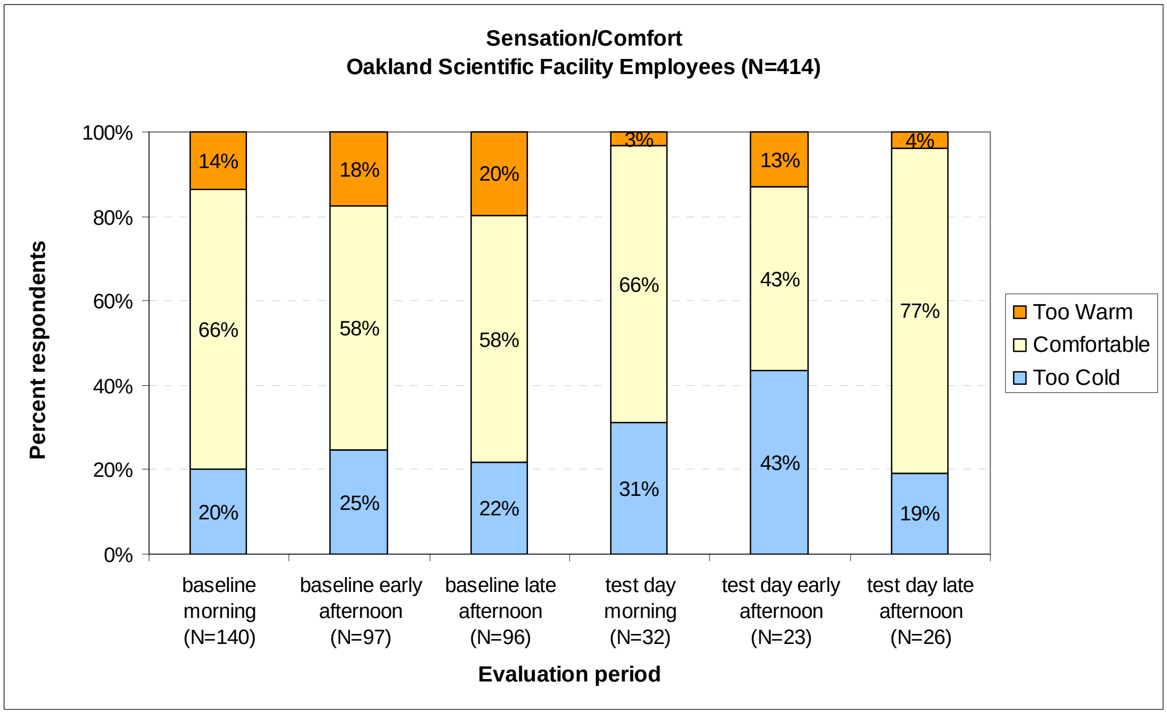

Figure 7. Oakland baseline vs. test days – Sensation/Comfort

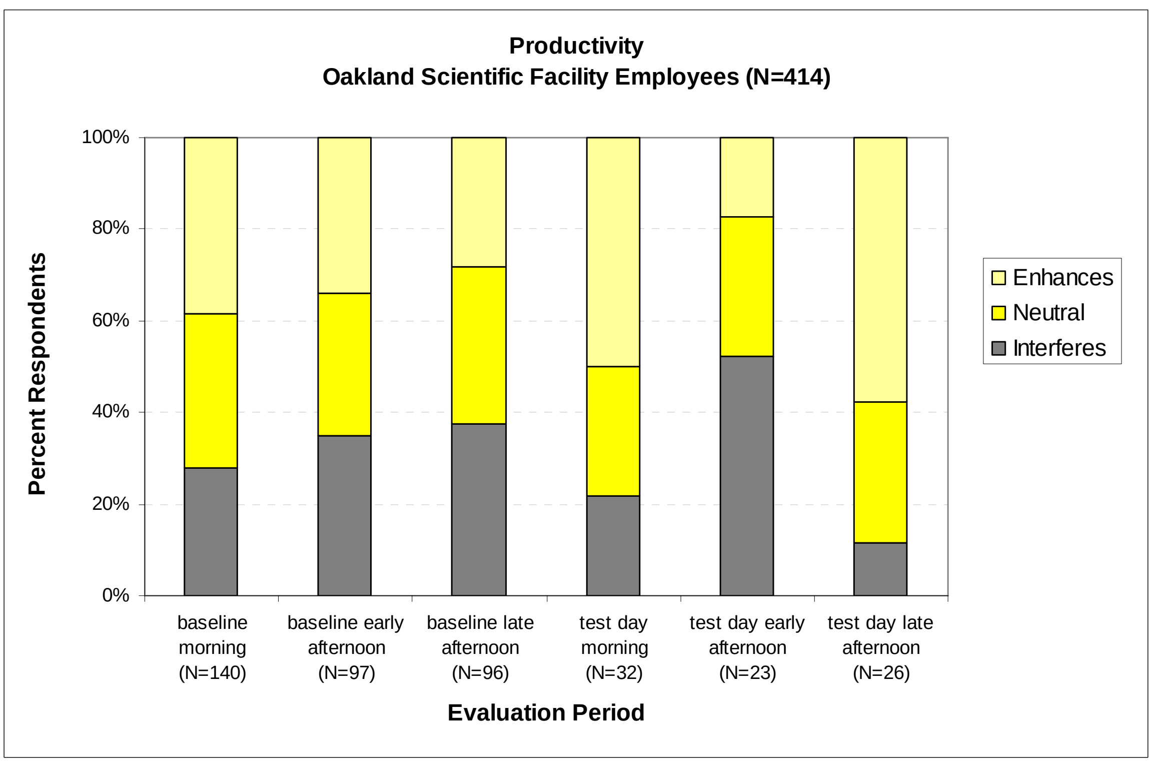

Figure 8. Oakland baseline vs. test days – Productivity

Plotting the relationship between comfort and perceived productivity another way (Figure 9), we see that those in the comfortable range (the middle three points on the x-axis) indicated a slight to moderate enhancement to their productivity on average. Those who were somewhat too cool or too warm indicated a slight interference (-1 on the 7 point scale) with their productivity. The few on the extreme endpoints (much too cool or warm) indicated a pronounced interference with productivity. However this last group accounts for only 7% of the responses.

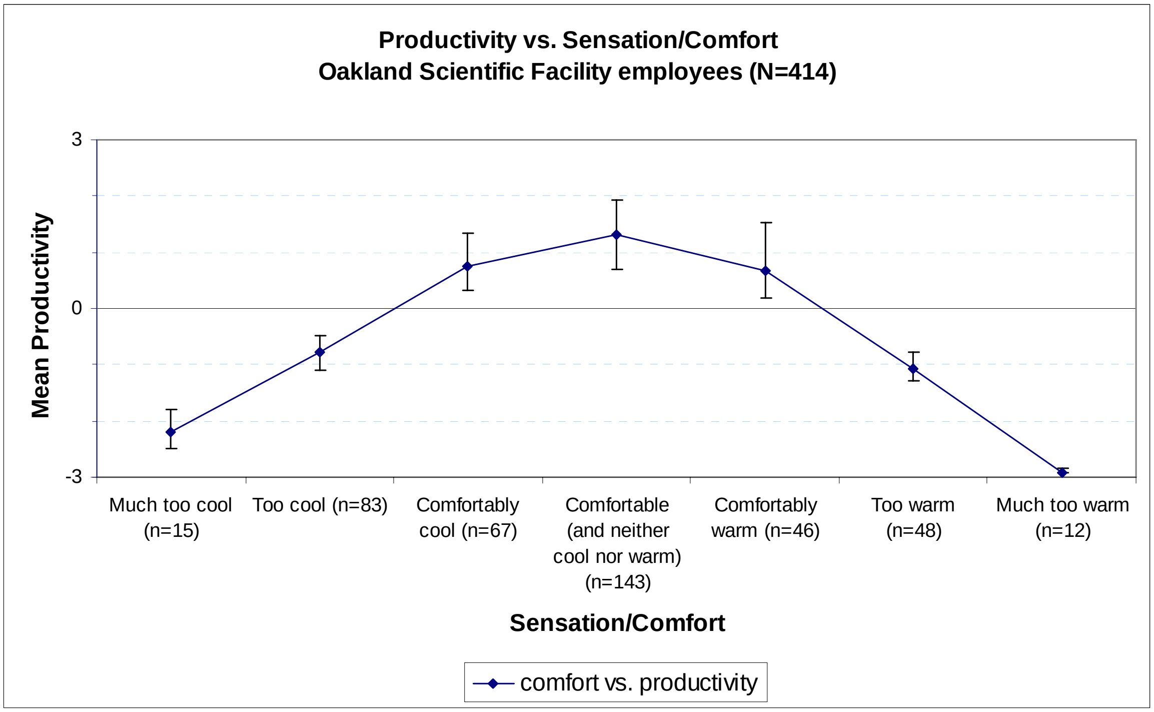

Figure 9. Oakland - average productivity plotted against sensation/comfort

Splitting up the data between cool days (Figure 10) and warm days (Figure 11), and then focusing on warm days, trends are same as above: comfort levels on test days are at or above those on baseline days, except in early afternoons. We focus on warm days because those are the days on which these strategies are most likely to be employed.

Splitting up the data based on test method, the above trend is particularly pronounced on test days employing pre-cooling in the morning, with linear rise in the afternoon, as shown in Figure 12. We do not see the large proportion of too cool responses during the test days employing exponential rise in the afternoons (Figure 13). This suggests that the exponential rise method produces more comfortable results – however more data needs to be gathered before drawing such a conclusion.

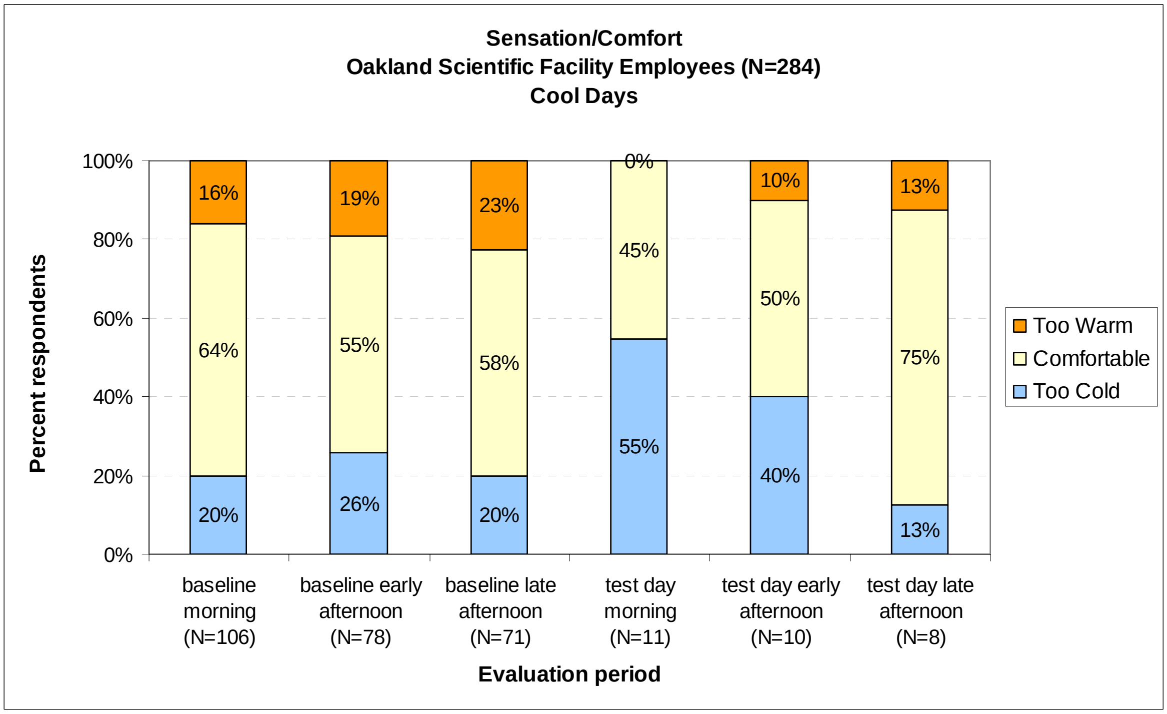

Figure 10. Oakland baseline vs. test days – Sensation/Comfort - Cool days

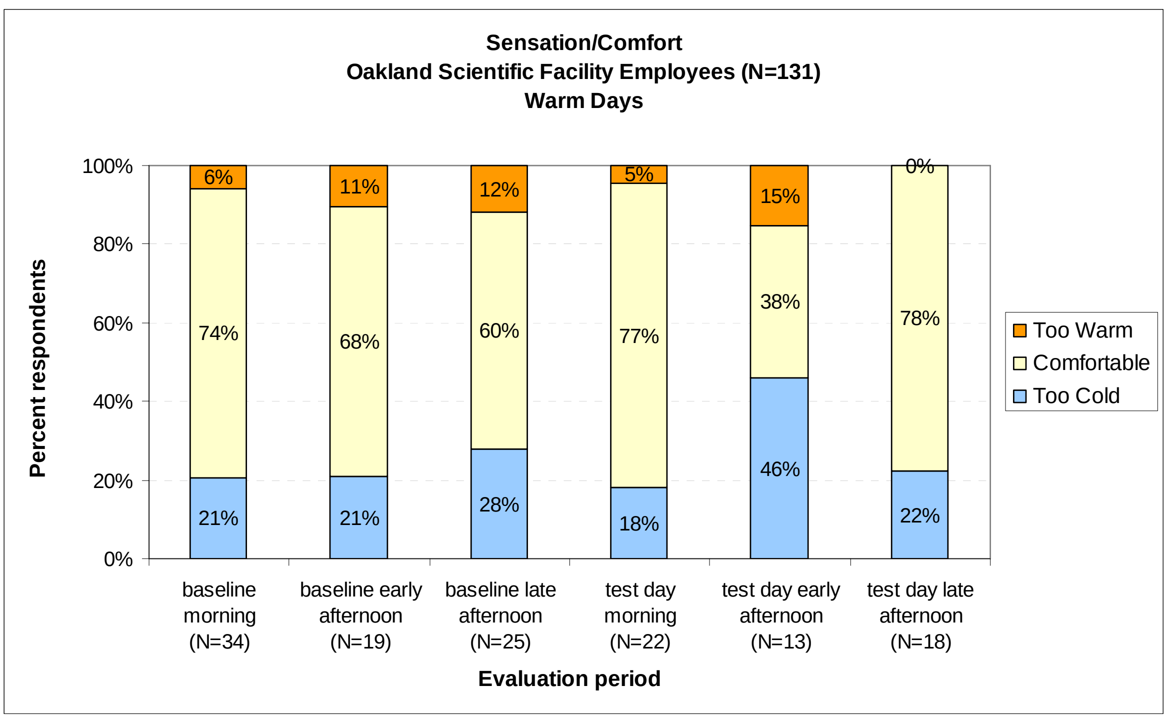

Figure 11. Oakland baseline vs. test days – Sensation/Comfort - Warm days

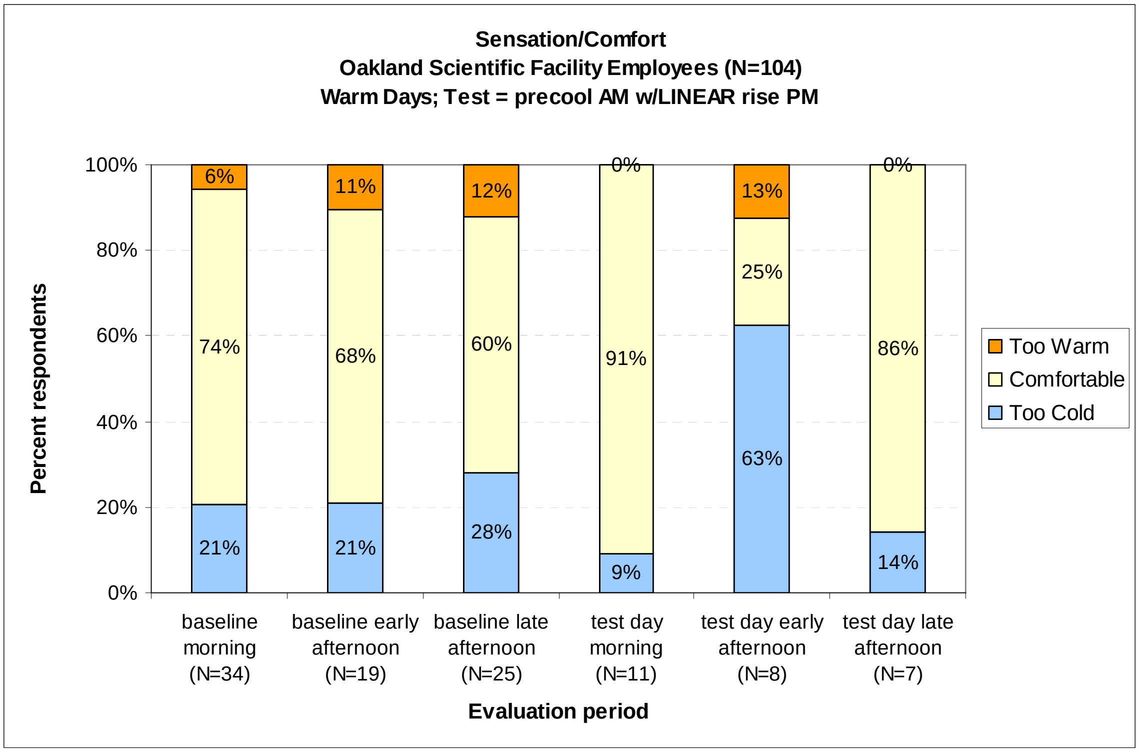

Figure 12. Oakland baseline vs. test days – Sensation/Comfort – Warm days – Linear rise

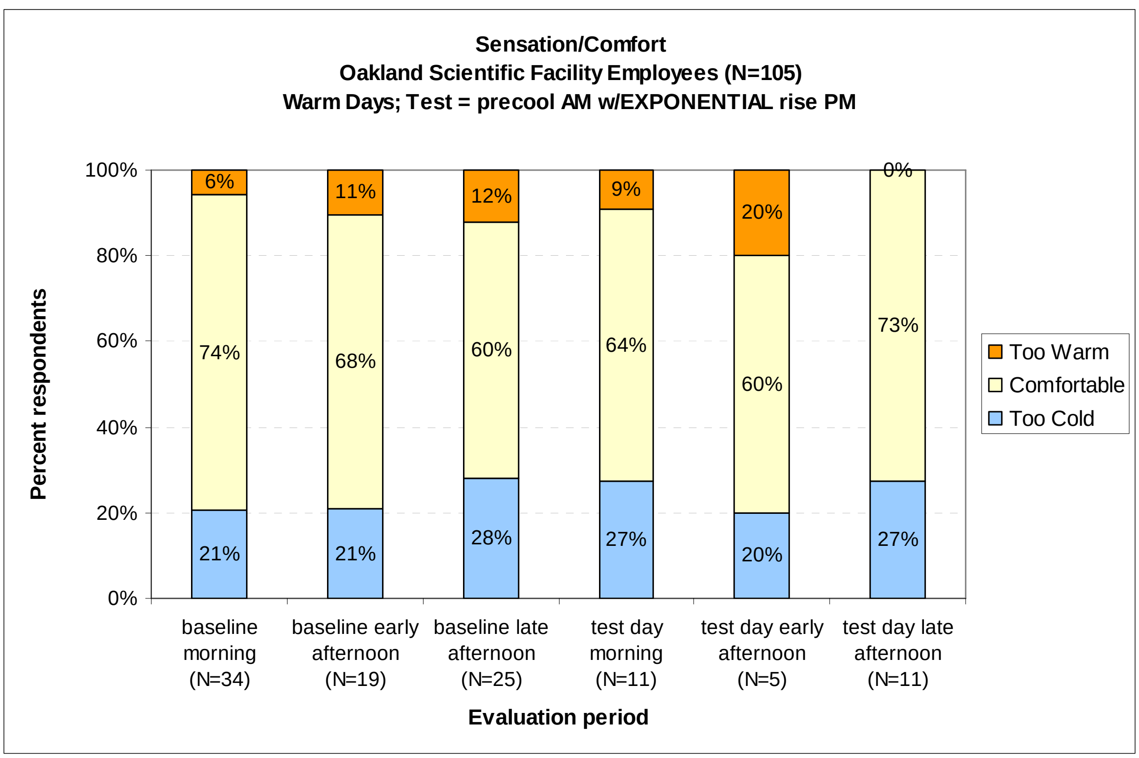

Figure 13. Oakland baseline vs. test days – Sensation/Comfort – Warm days – Exponential rise

3. CONCLUSIONS AND DISCUSSION

3.1 Conclusions

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

1. It was found that pre-cooling and demand shed strategies worked well even in the light office building and were able to reduce cool load significantly (~35% on cool days, ~25% on warm days), with no comfort complains. In the heavy mass building, the load reduction was even more significant. This test results are consistent with conclusions drawn from the 2003 and 2004 studies.

2. Properly controlled exponential temperature setup in the shed period can discharge thermal mass smoothly and with no rebound. We successfully avoided any rebounds in both buildings for all the tests. The exponential temperature set up created very flat load curves during the peak hours in both buildings.

3. Night pre-cooling has noticeable effects on the second day cooling load in heavy mass buildings. In the study 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 2004 results from the Santa Rosa Federal building are similar to those obtained in 2003. In the moderately warm weather condition, the night pre-cooling has a marginal effect during the following morning, but has no discernible effect during the on-peak period in Santa Rosa Federal building. However, in the heavy mass building we tested this year, the effect was very clear. The night pre-cooling can reduce the load during both morning and afternoon periods on the following day.

4. In heavy mass buildings, night pre-cooling can reduce both HVAC peak demand and energy consumption in cool weather. In Chabot Space and Science Museum, the total energy consumptions in various pre-cooling tests were lower than for non-pre-cooling days. This was mostly due to the fact that the summer morning in Oakland was relatively cool and the HVAC can pre-cool the building without running the chiller.

3.1 Future Work

This study has identified several uncertainties that should be resolved before pre-cooling can be reliably implemented in large commercial. The following work is proposed:

- **Additional tests in hot climate conditions.** In previous studies, significant demand reduction has been demonstrated through testing within both large and small commercial buildings with relatively small impacts on occupant comfort. However, in the previous phases of this overall effort, data were not obtained at very hot conditions. There is a need to demonstrate demand reduction and evaluate occupant comfort under the more extreme conditions during which critical peak pricing would typically be invoked. Furthermore, there is a need to develop a better fundamental understanding of the impact of short-term zone temperature variations on occupant comfort to determine the extent to which setpoints should be raised during demand-limiting periods.

- **Develop screening tool.** The opportunities for demand reduction and cost savings for use of building thermal mass vary tremendously with building type and location. There is a need to have an assessment tool that utilities and potential adopters can use to evaluate demand reduction and cost savings for individual buildings when applying building mass strategies that respond to utility price signals. In order to be useful, the tool needs to provide a quick assessment with minimal parameter inputs. This means that the parameters that have the greatest influence on demand reduction and cost savings need to be identified. A small commercial building assessment tool was developed as part of a previous phase of this research effort called DLAT (Demand-Limiting Assessment Tool). This tool will be expanded to consider a wide range of building types and locations within California and an appropriate user interface will be developed.

- **Develop guidelines for appropriate control strategies according to building characteristics.** Different buildings with different mechanical systems and different levels of control may require different pre-cooling strategies. For example, the zone temperature set-point 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.

- **Assess the market potential.** The assessment tools for small and large commercial buildings will be used to estimate the statewide potential in California for demand reduction in commercial buildings. This work will require an estimate of the building stock within different climate zones within California. The building stock statistics will be used along with estimates of demand reduction potential according to building type and location determined using the assessment tools Information from this study will be extremely useful in identifying appropriate utility incentives for demand reduction according to building type and location.

- **Further test the method to determine building thermal mass metrics.** We developed a method to calculate the temperature trajectory in the afternoon and we tested the method in these two buildings in this study. There are two key parameters affecting pre-cooling 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 one 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 set-point. We want to further test the method in other buildings under a wider range of weather conditions.

4. RELATED FIELD WORK: OTHER AUTOMATED LOAD SHEDDING STRATEGIES

Echelon Corporation is an office building located in San Jose, California. CBE surveyed employees and took thermal measurements on all floors of the 3-story building in the same manner as the pre-cooling test sites. During the test period, maximum outside temperatures were measured at NOAA station 724945 (San Jose International Airport) and ranged from 72 to 90 °F.

Participation for this building was secured late in the test period. The building employed automated shed strategies, such as dimming lights and adjusting supply air temperature and pressure of fans, and did not use pre-cooling. CBE placed thermal measurement equipment at the site on September 9. Survey data was collected on 5 cool baseline days, 9 warm baseline days, 1 cool test day, and 3 warm test days. See Appendix V for details of the tests that were conducted, the days that survey and thermal data were collected, and the maximum outside temperature.

A department vice president at Echelon sent out invitations to occupants. Of 170 invited, 48 individuals participated, and 174 valid observations were recorded. Of these, 161 could be matched up with nearby thermal conditions.

As shown in Figure 14, comfort rates on test days are at or above baseline levels on test mornings and early afternoons, but are lower on late afternoons. Figure 15 indicates that most of the discomfort votes were made on cooler days (when these strategies are less likely to be employed). On warmer days, Figure 16 shows that although comfort levels on test day late afternoons are slightly lower than on baseline late afternoons, the proportion of those comfortable is still more than 80%. However, due to the small number of responses on warm test days, we need to gather more data before drawing final conclusions about occupant comfort in response to these load shedding strategies.

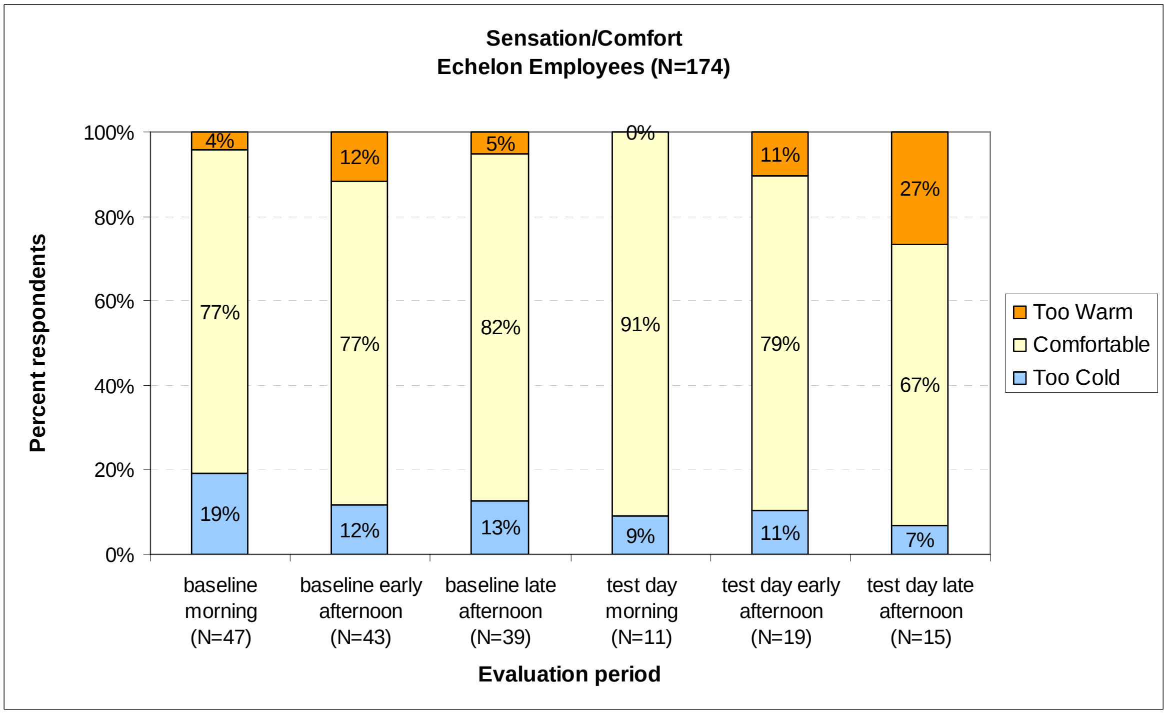

Figure 14. Echelon baseline vs. test days – Sensation/Comfort

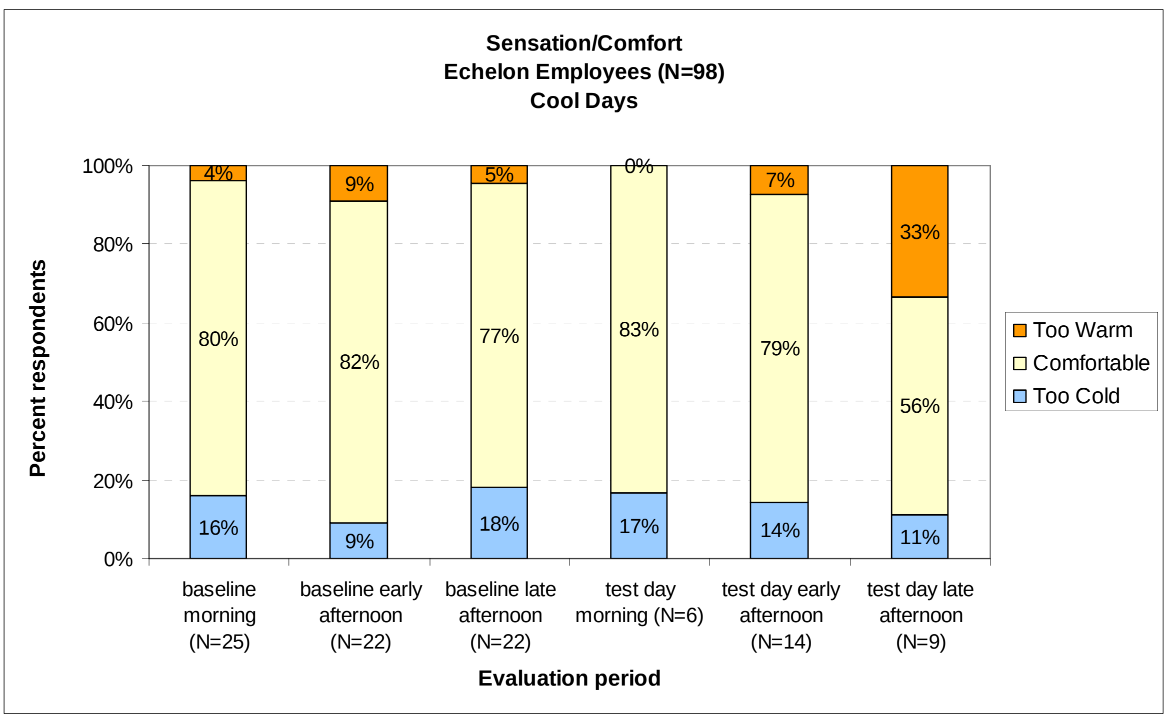

Figure 15. Echelon baseline vs. test days – Sensation/Comfort - Cool days

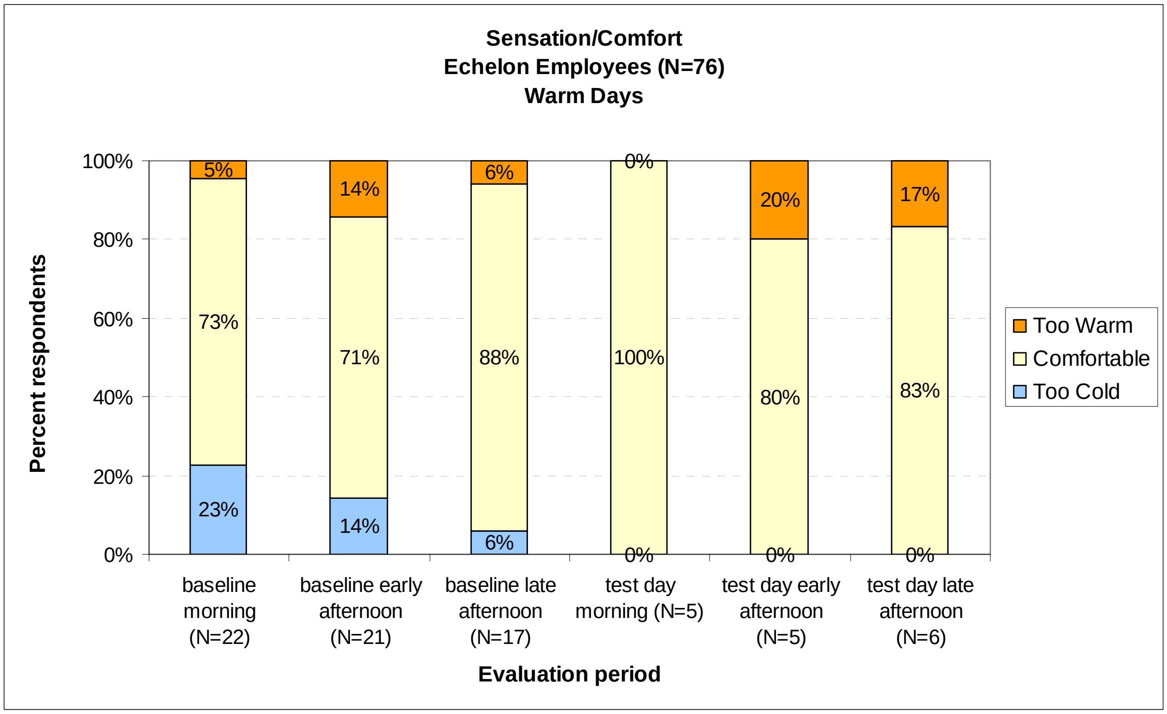

Figure 16. Echelon baseline vs. test days – Sensation/Comfort - Warm days

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Request for Participation

Summer 2005 Demand Shifting with Thermal Mass

California is embarking on a new era of dynamic pricing with the introduction of Critical Peak Pricing. This new tariff was designed to produce incentives to change building operations and manage peak-time energy use on days when the utility grid is constrained. Building owners and facility managers need to evaluate various demand shedding strategies on their sites to reduce peak-period electricity use.

Is your facility ready for using pre-cooling to shed peak demand?
The idea of pre-cooling and demand limiting is to pre-cool 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.

To know whether your facility is suitable for passive demand shifting using building thermal mass, the 2005 summer program with Automated Critical Peak Pricing (CPP) test is a low risk way to get prepared.

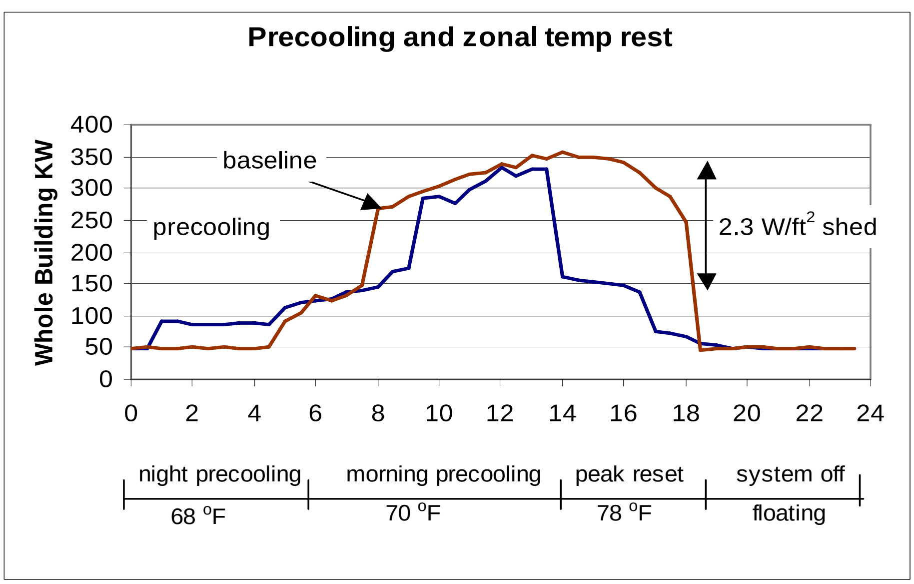


Figure 1. Sample results of the previous pre-cooling tests

Technical assistance available
LBNL will conduct two case studies of preliminary assessment of the savings from pre-cooling in two commercial buildings during the summer, 2005. Researchers at the Lawrence Berkeley National Lab (LBNL) will provide guidance to your staff in:

- Develop the pre-cooling and demand limiting strategy and assessing its impacts
- Set up the monitoring plan, install additional sensors and conduct the tests with you.
- Evaluate economic savings under CPP programs.

Site requirements
The buildings to be selected will have of a medium to lightweight mass structure in a hot (inland) climate. LBNL will first consider but not limited to buildings participating in the PG&E Automated Critical Peak Pricing Test. The ideal building to conduct case study should be:

- Located in hot climate zone
- With innovative owners and motivated operators
- With properly functioning HVAC system, ideally commissioned recently.
- With medium to light-weight mass structure, buildings with a small window to wall ratios and high accessible building mass be preferable
- With conventional VAV system equipped with central EMCS system

Implementation and Customer requirements
The case study will be conducted in the following steps

- Collect general building information and determine the feasibility of the pre-cooling.
- Working with building owners, develop pre-cooling, demand limiting strategies and data trending requirements.
- Install sensors and data loggers in the building and collect baseline performance data
- Implement pre-cooling and demand limiting strategy and collect performance data
- Analyze the data and determine economic savings

Schedule

- Site recruitment and selection before August 1st 2005
- System development in August 2005
- Conduct tests through October 2005

To sign-up and/or request more information, please contact
Peng Xu (510) 486-4549 pxu@lbl.gov

This project will be conducted through the **PIER Demand Response Research Center** (see drrc.lbl.gov) with funding from **CEC**.

DRRC Demand Response Research Center

Demand Shedding with Building Thermal Mass for Large Commercial Facilities

Test Plan

I. Background
California utilities have been exploring the use of critical peak prices (CPP) to help reduce needle peaks in customer end-use loads. CPP is a form of price-responsive demand response. Recent experience has shown that customers have limited knowledge of how to operate their facilities to reduce their electricity costs under CPP. At the same time LBNL has been conducting research to demonstrate how to use building thermal mass for passive electrical demand control. The idea of pre-cooling and demand limiting is to pre-cool 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.

II. Project Goals
The primary goal associated with the research in the report is to develop information and tools necessary to assess the viability of and, where appropriate, implement demand-response programs involving building thermal mass in buildings throughout California. The project involves evaluating the technology readiness, overall demand reduction potential, and customer acceptance for different classes of buildings. This information can be used along with estimates of the impact of the strategies on energy use to design appropriate incentives for customers.

III. Objectives
The objective of this part of the work was to evaluate and demonstrate DR technologies in real buildings. Field-testing of DR control strategies will be performed in two commercial sites in PG&E territory.

The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated by LBNL and the Center for the Built Environment (CBE) at the University of California, Berkeley in 2003 and 2004. Although the studies were quite successful and the large peak shed was achieved while maintaining the occupant comfort, some key questions remaining unanswered include:

- What will be the comfort reaction if the occupants are informed in advance of the test?
- What will be the comfort reaction when the pre-cooling strategies are performed in truly hot weather?
- What will be the occupant reaction if the pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment?
- What are the metrics of the building thermal mass and how are they determined?
- How can thermal mass be discharged more efficiently and more smoothly with no rebound?
- How can we assess a building's pre-cooling potential and determine economic saving quickly?
- All our previous tests were conducted manually. On the tests days, the building operators changed the temperature set points manually, following our pre-cooling strategies. The automation of the demand-shed has been demonstrated successfully in the previous auto-DR projects. It is worth investigating the possibility of implementing the pre-cooling strategies automatically or semi-automatically, with notice given one day in advance.

IV. Before Tests

In preparation of tests, the participating sites must work with LBNL on the following tasks:

- Provide General Site Data - LBNL will request general information about your site including: facility size, use, HVAC equipment type, etc.
- Define Electric Data Collection Methods - Most commercial sites have Web access to whole building electric data provided by their utility. If this is the case, please provide a username and password for use by LBNL staff for downloading electric data from your site. Alternately, if your site has local databases that archive data from electric meters, Energy Management Control Systems (EMCS) or Energy Information Systems (EIS) please allow for access by LBNL project staff.
- Define shed strategies using building thermal mass. LBNL will provide guidance based on the previous experience of demand shedding in commercial buildings. Building owners need to choose the pre-cooling temperature and operation schedule.
- Program the EMCS - Each site needs to program the shed strategies into their control system. The strategies can be run either manually with modest efforts or automatically.
- Develop comfort survey plan. LBNL and CBE will provide the web based online survey tool to the owners. Owners need to define a way to communicate with building occupants in a timely fashioned way, such as mail or daily paper notice.

IV. Conduct Tests

Manual test before CPP days – LBNL will work with each participating site run preliminary tests before CPP days and determine whether the temperature set points and pre-cooling schedules are appropriate. LBNL will analyze the test results and adjust the pre-cooling parameters accordingly if necessary.

Test in CPP days. LBNL and each participating site will receive a CPP notification one day ahead. LBNL will work with each participant to initiate pre-cooling events. The pre-cooling and demand limiting actions at your site will be based on the strategy created ahead of time jointly. In the mean time, LBNL will send out the comfort survey requests.

Documenting Your Shed – LBNL will collect whole-building electricity consumption data for each site in the pilot. When available, we will also collect detailed data from an EMCS or other end-use meters to help us understand the dynamics of the shed strategies.

Documenting Your Comfort and Thermal Condition – LBNL will work with CBE to collect the thermal condition and comfort survey data. The data will be later used to evaluate the changes of the thermal comfort conditions in the buildings before and during the tests.

VI. Project Report

After the test, LBNL will provide a detailed project report that evaluates the pre-cooling and demand shed strategies; and develop metrics to measure building thermal mass. The report will include the electric consumption data from your facility, a statistical analysis of the shed data (using a weather-corrected baseline), and the comfort survey or related data. These results will be presented publicly in academic and trade publications and conferences.

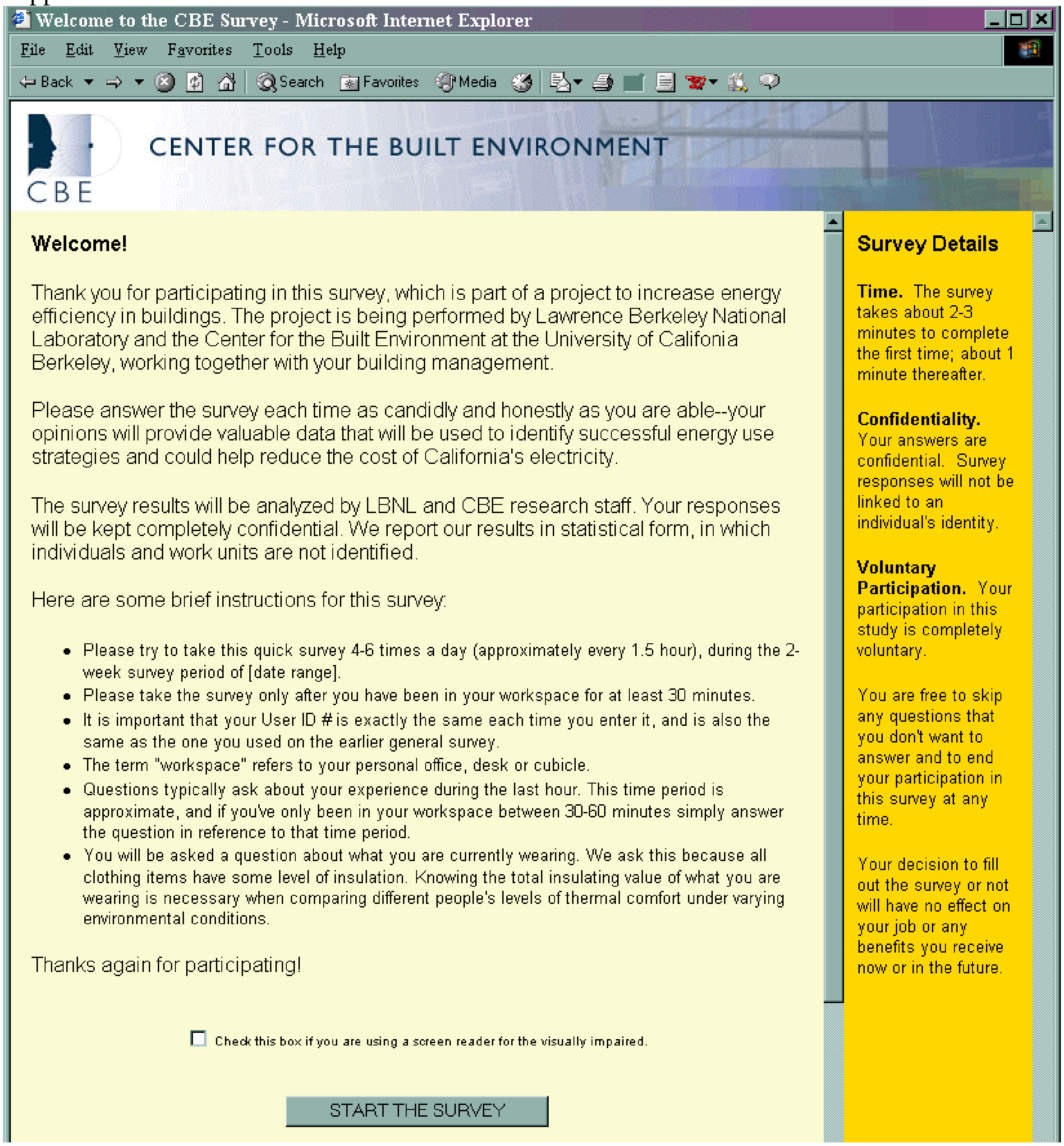
VII. Project Timeline for Auto-CPP Pilot

Activity	Date
Site selections	Now – July 30th
Plan pre-cooling strategies and preprogram	July – August
Conduct preliminary tests	August
CPP days	May - October
Data Analysis and Reporting	September - December

VIII. Staff:

LBNL Staff: Peng Xu, pxu@lbl.gov, (510)486 4549
Dave Watson , watson@lbl.gov, (510) 486-5562
Naoya Motegi, namotegi@lbl.gov, (510) 486-4082
Sila Kiliccote, skiliccote@lbl.gov, (510) 495-2615
Nance Matson, namatson@lbl.gov, (510) 486-7328
CBE Staff: Leah Zagreus, lzagreus@berkeley.edu, (510) 642-6574
Carrie Brown, carrieb@berkeley.edu, (510) 642-9205
Purdue University: James Braun, jbraun@ecn.purdue.edu, (765)494-9157

Appendix III



Welcome to the CBE Survey - Microsoft Internet Explorer

File Edit View Favorites Tools Help

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CENTER FOR THE BUILT ENVIRONMENT

CBE

Welcome!

Thank you for participating in this survey, which is part of a project to increase energy efficiency in buildings. The project is being performed by Lawrence Berkeley National Laboratory and the Center for the Built Environment at the University of Califonia Berkeley, working together with your building management.

Please answer the survey each time as candidly and honestly as you are able--your opinions will provide valuable data that will be used to identify successful energy use strategies and could help reduce the cost of California's electricity.

The survey results will be analyzed by LBNL and CBE research staff. Your responses will be kept completely confidential. We report our results in statistical form, in which individuals and work units are not identified.

Here are some brief instructions for this survey:

- Please try to take this quick survey 4-6 times a day (approximately every 1.5 hour), during the 2-week survey period of [date range].
- Please take the survey only after you have been in your workspace for at least 30 minutes.
- It is important that your User ID # is exactly the same each time you enter it, and is also the same as the one you used on the earlier general survey.
- The term "workspace" refers to your personal office, desk or cubicle.
- Questions typically ask about your experience during the last hour. This time period is approximate, and if you've only been in your workspace between 30-60 minutes simply answer the question in reference to that time period.
- You will be asked a question about what you are currently wearing. We ask this because all clothing items have some level of insulation. Knowing the total insulating value of what you are wearing is necessary when comparing different people's levels of thermal comfort under varying environmental conditions.

Thanks again for participating!

☐ Check this box if you are using a screen reader for the visually impaired.

START THE SURVEY

Survey Details

Time. The survey takes about 2-3 minutes to complete the first time; about 1 minute thereafter.

Confidentiality. Your answers are confidential. Survey responses will not be linked to an individual's identity.

Voluntary Participation. Your participation in this study is completely voluntary.

You are free to skip any questions that you don't want to answer and to end your participation in this survey at any time.

Your decision to fill out the survey or not will have no effect on your job or any benefits you receive now or in the future.

Figure 17. Comfort survey welcome screen – upper half

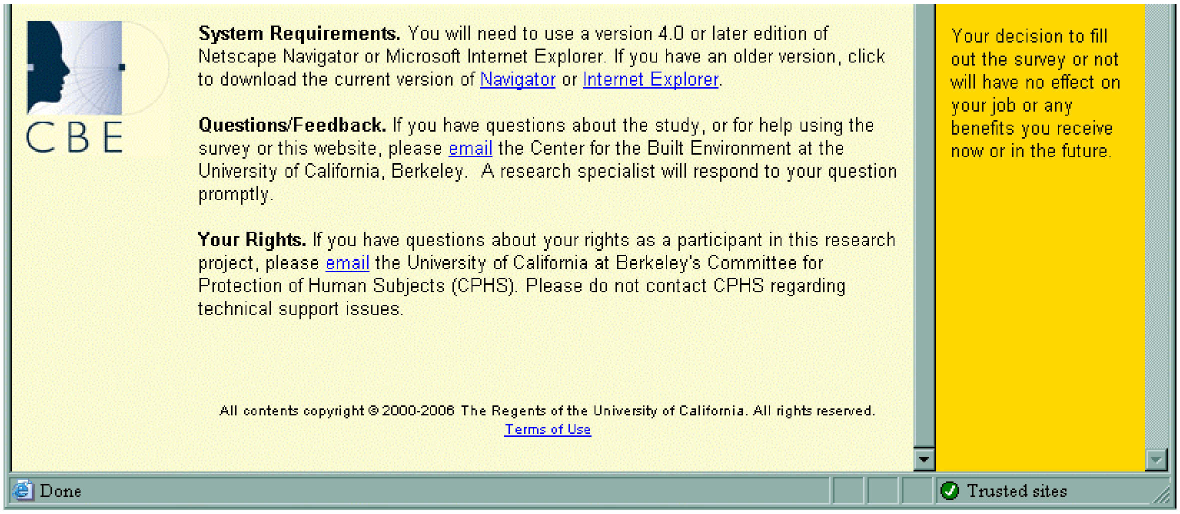


Figure 18. Comfort survey welcome screen – lower half

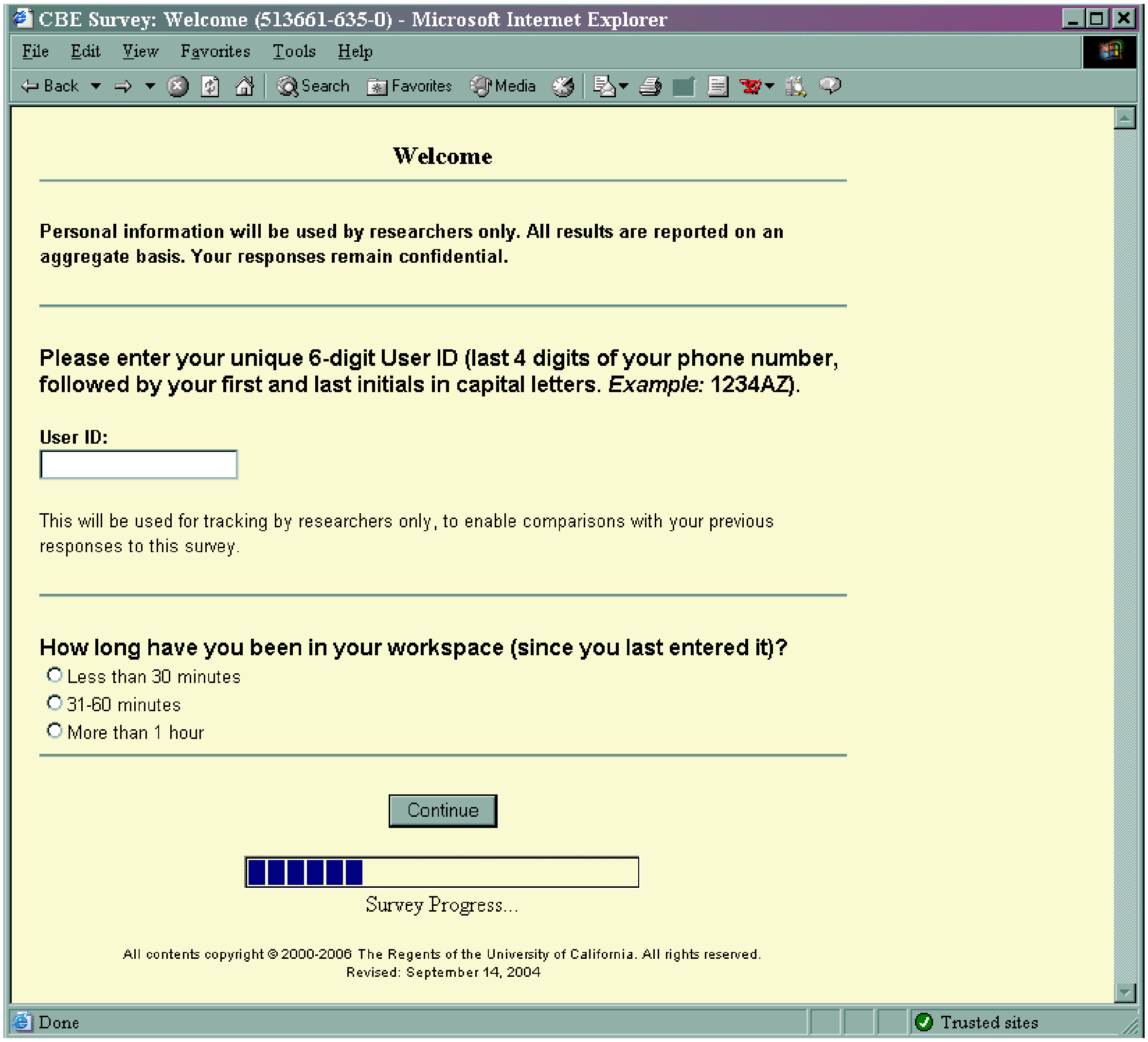
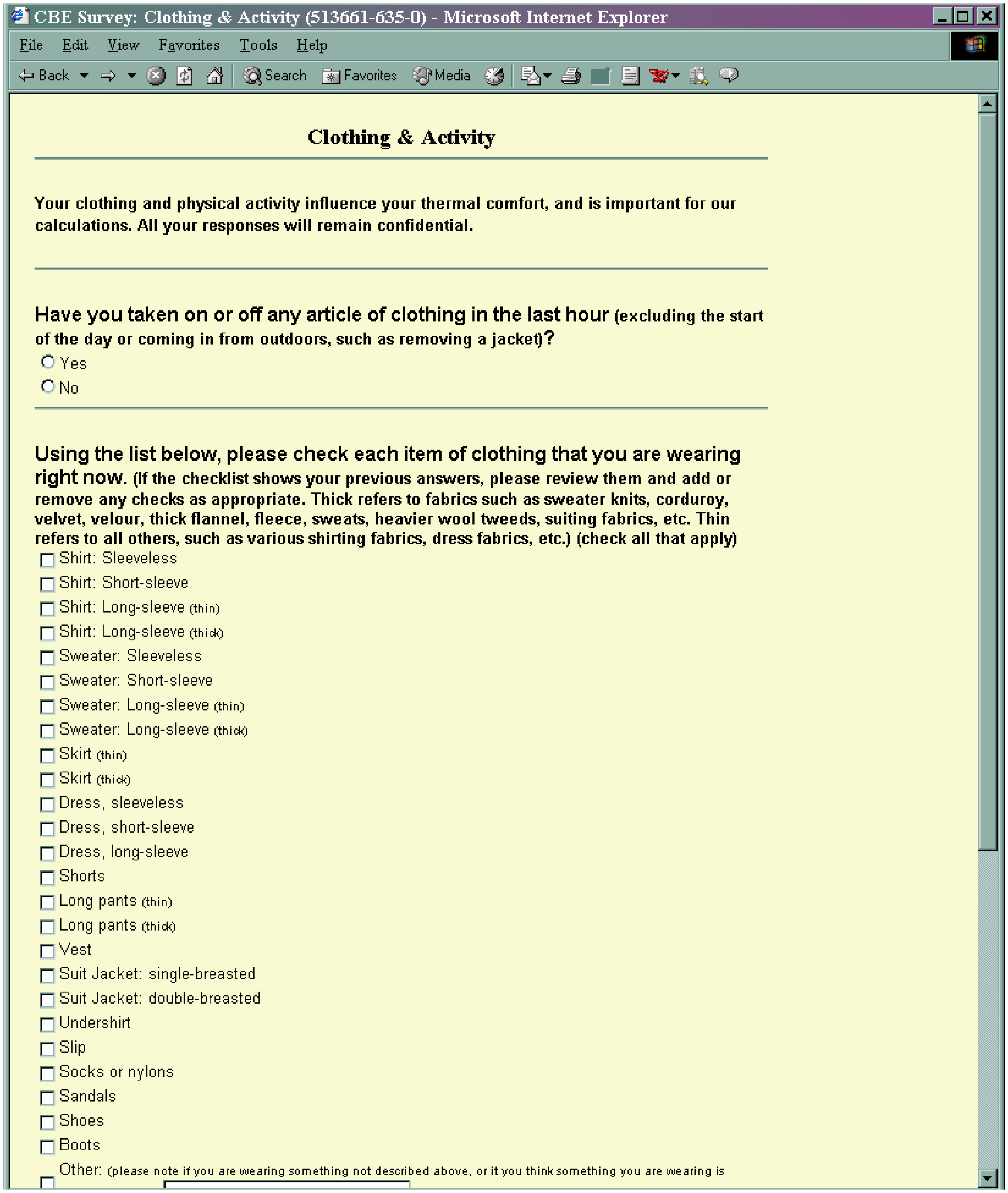


Figure 19. Page 1 collects identifier that allows responses for each individual to be confidentially tracked together, and determines that respondent has been in the space long enough (at least half an hour) to acclimate to the thermal conditions



CBE Survey: Clothing & Activity (513661-635-0) - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

Clothing & Activity

Your clothing and physical activity influence your thermal comfort, and is important for our calculations. All your responses will remain confidential.

Have you taken on or off any article of clothing in the last hour **(excluding the start of the day or coming in from outdoors, such as removing a jacket)?**

- ○ Yes
- ○ No

Using the list below, please check each item of clothing that you are wearing right now. **(If the checklist shows your previous answers, please review them and add or remove any checks as appropriate. Thick refers to fabrics such as sweater knits, corduroy, velvet, velour, thick flannel, fleece, sweats, heavier wool tweeds, suiting fabrics, etc. Thin refers to all others, such as various shirting fabrics, dress fabrics, etc.) (check all that apply)**

- ☐ Shirt: Sleeveless
- ☐ Shirt: Short-sleeve
- ☐ Shirt: Long-sleeve (thin)
- ☐ Shirt: Long-sleeve (thick)
- ☐ Sweater: Sleeveless
- ☐ Sweater: Short-sleeve
- ☐ Sweater: Long-sleeve (thin)
- ☐ Sweater: Long-sleeve (thick)
- ☐ Skirt (thin)
- ☐ Skirt (thick)
- ☐ Dress, sleeveless
- ☐ Dress, short-sleeve
- ☐ Dress, long-sleeve
- ☐ Shorts
- ☐ Long pants (thin)
- ☐ Long pants (thick)
- ☐ Vest
- ☐ Suit Jacket: single-breasted
- ☐ Suit Jacket: double-breasted
- ☐ Undershirt
- ☐ Slip
- ☐ Socks or nylons
- ☐ Sandals
- ☐ Shoes
- ☐ Boots
- ☐ Other: (please note if you are wearing something not described above, or it you think something you are wearing is

Figure 20. Page 2 – upper half collects data to calculate clo value

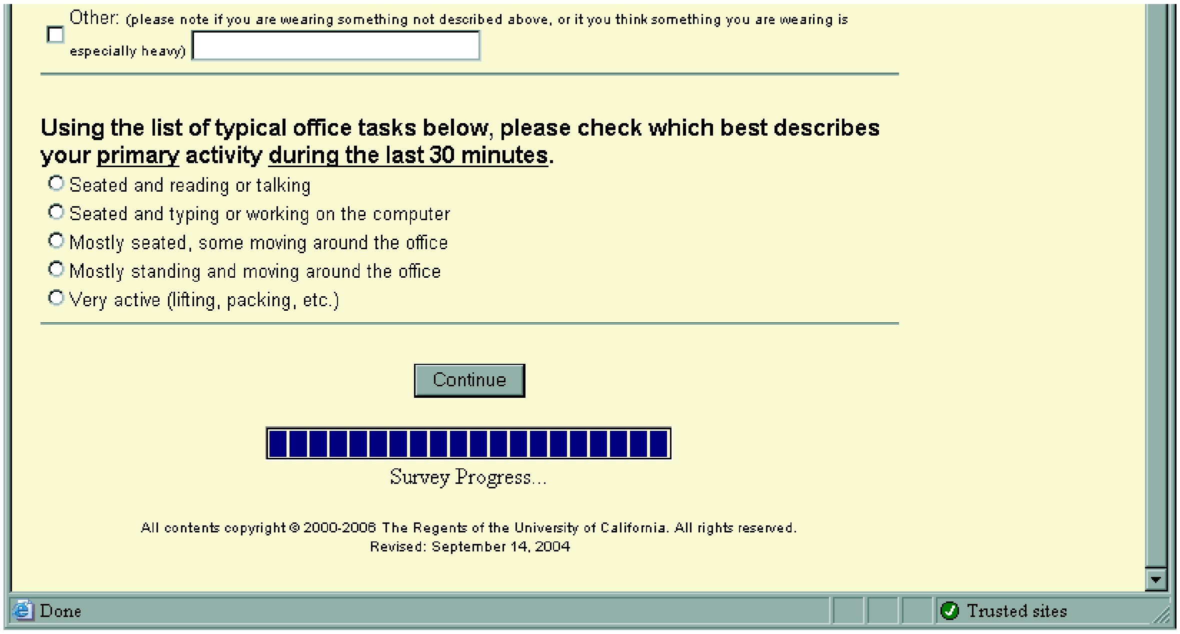


Figure 21. Page 2 – lower half collects data to calculate metabolic rate

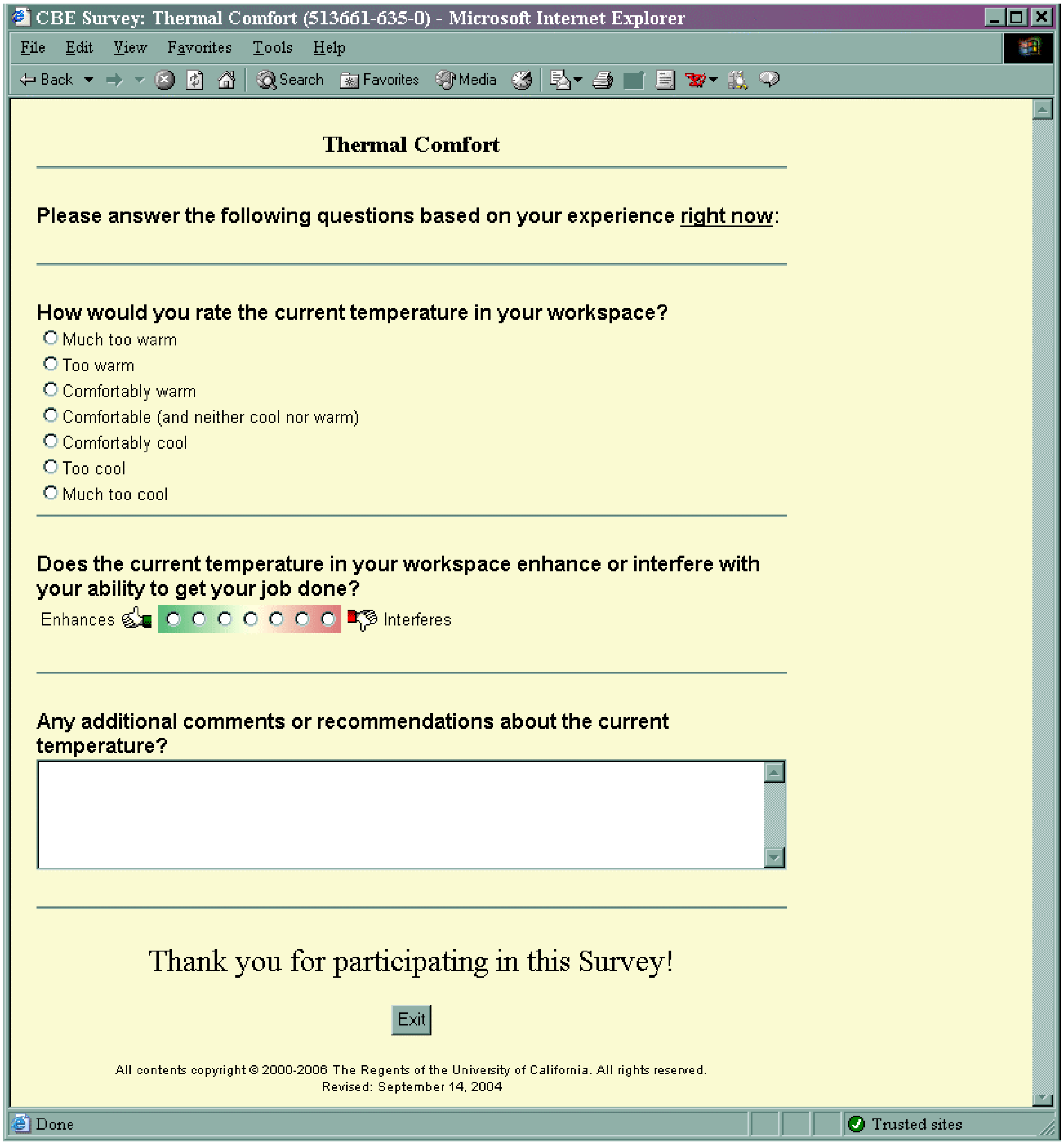


Figure 22. Page 3 includes Bedford scale to collect comfort/sensation vote, self-reported productivity affected by temperature, and open-ended comment field

Appendix IV

Dear Chabot employees:

Many thanks for your continued participation in our study of thermal conditions at Chabot Space & Science Center. For the next two days (Thursday and Friday), please take our brief survey at least twice each day:

http://www.cbesurvey.org/survey/dr/chabot

We ask that you take the survey approximately one hour after you arrive at the office at the beginning of your workday, and again at about 4pm (or earlier, if you leave the office for the day before 4). We encourage you also to take the survey at other times throughout the day, as often as once per hour.

You are, as always, welcome to take the survey on other days too (the more data the better for us), but please especially take care to do so this Thursday and Friday.

Feel free to contact me with any questions or concerns about the study.

Thank you!

Leah Zagreus
Research Specialist
Center for the Built Environment
University of California, Berkeley
www.cbesurvey.org
lzagreus@berkeley.edu
(510) 642-6574

Dear NERSC employees:

Lawrence Berkeley National Lab and UC Berkeley are conducting a study of energy-efficient strategies in this building. Your facility managers are working with PG&E to use energy more efficiently on certain days when energy is more expensive. These days are called "Critical Peak Pricing" days, and are akin to "Spare the Air" days.

As we employ strategies to shed energy load during the afternoons on CPP days, we are concerned with the effect on your comfort. We will use an on-line survey to collect your impressions of temperature sensation and comfort, and its impact on productivity.

This survey will take 1-2 minutes to complete and your responses will be kept completely confidential. We will ask that you take the survey at least twice a day on CPP days, and also a few days when the building systems run as usual. Your participation is very important to our understanding of the effectiveness of these strategies.

In addition, researchers from LBNL and UCB will be placing small, unobtrusive temperature sensors at various places throughout the building. The purpose is to monitor the thermal conditions in close proximity to the survey takers. The sensors will be placed this afternoon starting at about 3:30pm and should not significantly disrupt your work.

We appreciate your cooperation during the next few weeks as your facility takes part in this study. The results could help California conserve substantial amounts of energy.

If you have questions or concerns about the study, please contact your facility management, or me at the contact information below. Thank you in advance for your participation.

Leah Zagreus
Research Specialist
Center for the Built Environment
University of California, Berkeley
www.cbesurvey.org
lzagreus@berkeley.edu
(510) 642-6574

Dear 3rd floor occupants:

Many thanks for your continued participation in the LBNL and UCB study of thermal conditions in your building. The next two days (Thursday and Friday) will be "mock" Critical Peak Pricing days. On a real CPP day, energy would be more expensive during the afternoon, and we would be encouraged to reduce energy use towards the end of the day. (Similarly, we would be encouraged to take public transit on a "Spare the Air" day.) To do this, we will cool the building a bit more than usual during the morning, and then allow the temperature to rise slightly higher than usual during the afternoon.

We believe that this will not significantly impact your comfort, and wish to verify this with your feedback. Please take our brief survey at least twice each day:

http://www.cbesurvey.org/survey/dr/oak/short

We ask that you take the survey approximately one hour after you arrive at the office at the beginning of your workday, and again at about 4pm (or earlier, if you leave the office for the day before 4). We encourage you also to take the survey at other times throughout the day, as often as once per hour. The survey should take no more than 1-2 minutes to complete.

You are, as always, welcome to take the survey on other days too (the more data the better for us), but please especially take care to do so this Thursday and Friday.

Feel free to contact me with any questions or concerns about the study. Below I include the original information about the study for your reference.

Thank you!

Leah Zagreus
Research Specialist
Center for the Built Environment
University of California, Berkeley
lzagreus@berkeley.edu
(510) 642-6574

Dear Echelon employees:

Lawrence Berkeley National Lab and UC Berkeley are conducting a study of energy-efficient strategies in this building. Our facility managers are working with PG&E to use energy more efficiently on certain days when energy is more expensive. These days are called "Critical Peak Pricing" days, and are akin to "Spare the Air" days.

As we employ strategies to shed energy load during the afternoons on CPP days, we are concerned with the effect on your comfort. We will use an on-line survey to collect your impressions of temperature sensation and comfort, and its impact on productivity.

This survey will take 1-2 minutes to complete and your responses will be kept completely confidential. We will ask that you take the survey at least twice a day on CPP days, and also a few days when the building systems run as usual. Your participation is very important.

In addition, researchers from LBNL and UCB will be placing small, unobtrusive temperature sensors at various places throughout the building. The purpose is to monitor the thermal conditions in close proximity to the survey takers. The sensors will be placed on September 8 or 9, and should not significantly disrupt your work.

Prior to placing the sensors and taking the brief survey on CPP days, we ask that you answer a one-time survey about your general impressions of the workplace environment. This survey takes about 10 minutes to complete. The results will be used by LBNL and UCB to capture a snapshot of this building's performance before commencing the more detailed study described above. Although your individual responses will be kept completely confidential, the results will be presented in aggregate to building management and will greatly assist us in making this facility work for you.

We appreciate your cooperation during the next few weeks as we take part in this study. The results could help California conserve substantial amounts of energy. If you have questions about the study, please contact research specialist Leah Zagreus via e-mail at at lzagreus@berkeley.edu or by phone at (510) 642-6574. Thank you in advance for your participation.

Dear Echelon employees:

Thank you for accommodating us while we set up the monitoring equipment the past few days. For the next two days (Thursday and Friday), please take our brief survey at least twice each day:

http://www.cbesurvey.org/survey/dr/echelon/short

We ask that you take the survey approximately one hour after you arrive at the office at the beginning of your workday, and again at about 4pm (or earlier, if you leave the office for the day before 4). We encourage you also to take the survey at other times throughout the day, as often as once per hour. The survey should take no more than 1-2 minutes to complete.

You are, as always, welcome to take the survey on other days too (the more data the better for us), but please especially take care to do so this Thursday and Friday.

I include my original email about the study for your reference below. Feel free to contact me with any questions or concerns about the study.

Thank you!

Leah Zagreus
Research Specialist
Center for the Built Environment
University of California, Berkeley
lzagreus@berkeley.edu
(510) 642-6574

Chabot Space & Science Center

Date	Strategies	Weather	CIMIS max Mills (F)
8/8/2005	No precooling + aggressive linear set up	Cool	72.3
8/9/2005	Baseline	Cool	77.5
8/10/2005	Baseline	Cool	74.8
8/11/2005	Baseline	Warm	81.2
8/12/2005	Precooling + linear set up	Cool	76.2
8/13/2005	Baseline	Cool	66.3
8/14/2005	Baseline	Cool	68.2
8/15/2005	Baseline	Cool	68.5
8/16/2005	Baseline	Cool	74.7
8/17/2005	Baseline	Cool	70.2
8/18/2005	Baseline	Cool	64.4
8/19/2005	Baseline	Cool	66.8
8/20/2005	Baseline	Cool	69.6
8/21/2005	Baseline	Cool	68.3
8/23/2005	Baseline	Cool	74.8
8/24/2005	Baseline	Cool	70.5
8/25/2005	Baseline	Cool	73.1
8/26/2005	Precooling + aggressive linear set up	Cool	78.7
8/27/2005	Baseline	Warm	84
8/28/2005	Baseline	Warm	81.6
8/29/2005	Baseline	Cool	75.7
8/30/2005	Baseline	Warm	88.1
8/31/2005	Baseline	Warm	90.1
9/1/2005	Precooling + linear set up	Cool	72.2
9/2/2005	Baseline	Cool	69.2
9/21/2005	Baseline	Cool	74.7
9/22/2005	Baseline	Cool	73.3
9/23/2005	Baseline	Cool	65.3
9/24/2005	Baseline	Cool	75.9
9/25/2006	Baseline	Warm	82.9
9/27/2005	Baseline	Cool	75.1
9/28/2005	Precooling + linear set up	Warm	86.4
9/29/2005	Precooling + aggressive linear set up	Warm	89.9
9/30/2005	Baseline	Warm	87.7
10/1/2005	Baseline	Cool	71.7
10/2/2005	Baseline	Cool	69.7
10/4/2005	Baseline	Cool	72.6
10/5/2005	Baseline	Warm	82.4
10/6/2005	Precooling + aggressive linear set up	Cool	79.3
10/13/2005	Baseline	Cool	78.2

Oakland Scientific Facility

Date	Strategies	Weather	noaa max KOAK (F)
8/24/2005	Baseline	Cool	69.8
8/25/2005	Baseline	Cool	70
8/26/2005	Baseline	Cool	72
8/29/2005	Baseline	Cool	73.9
8/30/2005	Baseline	Warm	84.2
8/31/2005	Baseline	Warm	84.2
9/1/2005	Precooling + linear set up	Cool	86
9/2/2005	Baseline	Cool	69.1
9/7/2005	Baseline	Cool	64.9
9/8/2005	Baseline	Cool	68
9/9/2005	Baseline	Cool	68
9/14/2005	Baseline	Cool	64
9/15/2005	Baseline	Cool	64
9/16/2005	Baseline	Cool	66.9
9/19/2005	Baseline	Warm	82
9/21/2005	Baseline	Cool	71.6
9/22/2005	Baseline	Cool	71.1
9/23/2005	Baseline	Cool	68
9/26/2005	Baseline	Cool	78.1
9/27/2005	Baseline	Cool	71.1
9/28/2005	Precooling + linear set up	Warm	81
9/29/2005	Precooling + exponential set up	Warm	84.9
9/30/2005	Baseline	Warm	84.9
10/3/2005	Baseline	Cool	70
10/13/2005	Baseline	Warm	82
10/14/2005	Baseline	Warm	82

Echelon

Date	Morning	Afternoon	Weather	NOAA max SJC (F)	Comment
9/20/2005	Baseline	Baseline	Warm	86	no survey data
9/21/2005	Baseline	Baseline	Cool	78.1	
9/22/2005	None	Shed*	Cool	75.2	
9/23/2005	Baseline	Baseline	Cool	75.9	
9/26/2005	Baseline	Baseline	Warm	81	
9/27/2005	Baseline	Baseline	Cool	77	
9/28/2005	Baseline	Baseline	Warm	89.1	
9/29/2005	None	Shed*	Warm	90	
9/30/2005	Baseline	Baseline	Warm	90	
10/3/2005	Baseline	Baseline	Cool	73	
10/4/2005	Baseline	Baseline	Cool	72	
10/5/2005	Baseline	Baseline	Warm	81	
10/6/2005	None	Shed*	Warm	82.9	
10/7/2005	Baseline	Baseline	Warm	82.9	
10/10/2005	Baseline	Baseline	Warm	84	
10/11/2005	Baseline	Baseline	Warm	84	

10/12/2005	Baseline	Baseline	Warm	80.6	
10/13/2005	None	Shed*	Warm	84	
10/14/2005	Baseline	Baseline	Warm	84	
10/25/2005	None	Shed**	Cool	69.8	no survey data

*Shed strategies:
Moderate price (noon to 3 PM):
- Hallways with any ambient light turn off
- Daylit office lights turn off
- Inner office lights dim to 20%
High price (3 PM to 6 PM):
- 1 RTU turn off.
- The other 2 RTU adjust the duct static pressure from 1.5 to 0.8, and SAT from 55 F to 65 F

**The shed strategies were consistent throughout all the events, except they manually operated "slow recovery strategies" right after the end of 10/25 events.