Demand Response Research Center

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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 (Energy 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.

PIER funding efforts are focused on the following six RD&D program areas:

- 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 Lawrence Berkeley National Laboratory. The report is entitled "Demand Shifting With Thermal Mass in Large Commercial Buildings." This project contributes to the Energy Systems Integration Program.

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

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Abstract

The potential for utilizing building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies. This project studied the potential of pre-cooling and demand limiting in a heavy mass and a light mass building in the Bay Area of California. The conclusion of the work to date is that pre-cooling has the potential to improve the demand responsiveness of commercial buildings while maintaining acceptable comfort conditions. Results indicate that pre-cooling increases the depth (kW) and duration (kWh) of the shed capacity of a given building, all other factors being equal. Pre-cooling and demand shed strategies worked well in both the light and heavy mass buildings. A properly-controlled *exponential temperature set up* strategy in the shed period discharged thermal mass smoothly in both buildings. The optimal strategy for avoiding rebound was an *exponential temperature reset* strategy. Pre-cooling was very effective even in cool weather conditions in the heavy mass building. Night pre-cooling had noticeable effects on the second day cooling load in the heavy mass building. Night pre-cooling reduced both HVAC peak demand and energy consumption in cool weather in the heavy mass building. Due to the time necessary for pre-cooling, it is only applicable to day-ahead demand response programs. The effectiveness of night pre-cooling under hot weather conditions has not been tested. Further work is required to quantify and demonstrate the effectiveness of pre-cooling in different climates. Research is also needed on occupant response with advance notification of the pre-cooling DR event. Further work is necessary to develop screening tools that can be used to select suitable buildings and customers, identify the most appropriate pre-cooling strategies, and estimate the benefits to the customer and the utility.

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

Executive Summary

Introduction

The principle of pre-cooling for demand shifting and shedding is to pre-cool buildings during off-peak hours (at night or in the morning), cooling the building thermal mass and thereby reducing cooling loads during the peak hours. 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.

Purpose

This research project studied the potential of pre-cooling and demand limiting in a heavy mass and a light mass building in the Bay Area of California in 2005. This research study followed two other studies conducted by Lawrence Berkeley National Laboratory (LBNL) on the potential for pre-cooling and demand limiting in large commercial buildings. The first of these studies was a 2003 pre-cooling case study at the Santa Rosa Federal Building. The second was a 2004 pre-cooling study along with occupant comfort surveys in office buildings. Additional studies on pre-cooling were performed in 2006 and 2007.

Project Objectives

Although the 2003 case study was quite successful, some key questions remained unanswered, including:

- 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?
- What will be the comfort reaction when the pre-cooling strategies are performed in truly hot weather (peak outside air temperature higher than 95°F)?
- What will be the comfort reaction if the occupants are informed in advance of the test?
- What will be the occupants' reaction if pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment?
- How can a building's pre-cooling potential be assessed and the potential economic savings be quickly determined?

To address these questions, LBNL and the Center for the Built Environment (CBE) at University of California Berkeley performed field tests in 2005 in two medium-sized commercial buildings in Oakland. One building was the Chabot Space and Science Center (CSSC), a heavy mass building with large areas of exposed concrete slab. The other building was the Oakland Scientific Facility (OSF), a light mass office building with a large portion of window facade. A key feature of the 2005 study was the building thermal mass metrics modeling. The team developed and used two methods 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, the team tested different reset strategies in the afternoon in both buildings and assessed the impact of these strategies and methods to avoid rebounds and maximize load reduction.

Project Outcomes

Night-time pre-cooling was found to have limited peak demand reduction effects on the light office buildings, but to have significant peak demand reduction effects on the heavy mass building, in the tested weather condition (moderately warm). The comfort survey results from the two test buildings indicate that occupant comfort was generally maintained in the pre-cooling tests. The research team found that it was important to manage the afternoon load shedding by ramping up the zone temperature setpoints exponentially rather than stepping them up or ramping them up linearly (*exponential temperature set up* strategy). This could be particularly important on hot days or in buildings with smaller thermal time constants, where air conditioning-related electrical power could *rebound* (electricity load rising sharply right after the demand shed period ends) 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 the four thermal mass discharge strategies studied.

Conclusions

The conclusion of the work is that pre-cooling has the potential to improve the demand responsiveness of both heavy and light mass commercial buildings while maintaining comfort conditions acceptable to the occupants. Results to date indicate that pre-cooling increases the depth (kW) and duration (kWh) of the shed capacity of a given building, all other factors being equal. Due to the time necessary for pre-cooling, it is only applicable to day-ahead demand response programs. Pre-cooling can be especially effective if the building mass is relatively heavy.

- Pre-cooling and demand shed strategies worked well in both the light and heavy mass buildings. In the light mass building (OSF), the strategies reduced cooling load significantly (~35% on cool days, ~25% on warm days) with no comfort complaints. In the heavy mass building (CSSC), the load reduction was even more significant; the peak HVAC load was reduced by 50% using the most effective strategy. These test results are consistent with conclusions drawn from the 2003 and 2004 studies.

- A properly-controlled *exponential temperature set up* strategy in the shed period discharged thermal mass smoothly. The use of an *exponential temperature reset* strategy successfully avoided rebound in both buildings for all the tests. The exponential temperature set up strategy created very flat load curves during the peak hours in both buildings.

- Night pre-cooling had noticeable effects on the second day cooling load in the heavy mass building. In the earlier studies of a lighter mass building, in moderately warm weather conditions, night pre-cooling had a marginal effect during the following morning and had no discernible effect during the on-peak period. However, in these tests of a heavy mass building, night pre-cooling clearly reduced the load during both morning and afternoon periods on the following day.

- In the heavy mass building, night pre-cooling reduced both HVAC peak demand and energy consumption in cool weather. The energy consumption reduction was mostly due to the fact that the summer mornings in Oakland were relatively cool and the HVAC could pre-cool the building without running the chiller.

Recommendations

This study has established the potential for pre-cooling and demand shed strategies, and it has also identified several uncertainties that should be resolved before pre-cooling can be reliably implemented in large commercial buildings. We recommend the following future works:

- **Perform additional tests in hot climate conditions in Southern California.** In the previous phases of this overall effort, data were not obtained in very hot conditions (>100°F). 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.

- **Study occupant response when the building occupants are informed in advance of a pre-cooling DR event.** Also, consider conducting tests of occupant response during pre-cooling events of longer duration when they have opportunities to adjust to the new thermal environment.

- **Further test the method to determine building thermal mass metrics.** In this study the research team developed and tested a method to calculate the temperature trajectory in the afternoon in the two buildings in this study. Further research is recommended to test the temperature trajectory method with the building time constant in other buildings under a wider range of weather conditions.

- **Develop a screening tool.** There is a need for an assessment tool that utilities and potential adopters can use to evaluate demand reduction and cost savings for individual buildings for applying building mass strategies that respond to utility price signals. Such a tool could 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.

- **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. A detailed guide to selecting, implementing and testing demand-shifting control strategies by building mechanical system and control type is needed to support their routine use.

- **Assess the market potential.** Assessment tools for small and large commercial buildings could be used to estimate the statewide potential in California for demand reduction in commercial buildings. Building stock statistics could be used along with estimates of demand reduction potential according to building type and location determined using the screening tool and guidelines described above. Information from such a study would be extremely useful in identifying appropriate utility incentives for demand reduction according to building type and location.

Benefits to California

Reducing electrical peak electrical has a huge economic and environmental benefit to California. Most existing buildings do not have space to install active thermal mass storage system and the capital investment is not cost effectiveness from the current tariff. This study demonstrated that passive demand shedding can be as useful as active system and the load shed in this study is consistent with the results from the previous tests. In average, with this approach, commercial office buildings in California can reduced the peak load by 15 - 30%, with no complication to the thermal comfort.

The research reported in this paper was conducted in 2005 as part of the Auto-Critical Peak Pricing (CPP) Project, funded by Pacific Gas and Electric Company (PG&E) and the Energy Commission's PIER-funded Demand Response Research Center.

1.0 Introduction

1.1. Background and Overview

The structural mass within existing commercial buildings can be effectively used to reduce operating costs through simple adjustments of zone temperature setpoints within 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 cooling setpoint temperatures (e.g., 68 – 70°F) and then the cooling setpoints are raised within the comfort zone (below 78°F) during peak periods. Heating setpoints must be left unchanged or lowered to avoid unwanted increases in heating system energy. The cooled mass and higher on-peak zone setpoint temperatures lead to reduced on-peak cooling loads for the HVAC equipment, which results in lower on-peak energy and demand charges. The potential for using building thermal mass for load shifting and peak demand reduction has been demonstrated in a number of simulation, laboratory, and field studies (Braun 1990; Ruud et al. 1990; Conniff 1991; Andresen and Brandemuehl 1992; Mahajan et al. 1993; Morris et al. 1994; Keeney and Braun 1997; Becker and Paciuk 2002; Xu et al. 2003, 2004). This strategy 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 Berkeley, California and Purdue University (West Lafayette, Indiana), in cooperation with three California utilities (PG&E, SCE and SMUD), have conducted research to investigate strategies for using building thermal mass to shift building cooling load in northern California buildings.

In the summer of 2003, LBNL conducted a pre-cooling case study at the Santa Rosa Federal Building. The research team found that a simple demand limiting strategy performed well in this building. This strategy involved maintaining zone temperatures at the lower end of the comfort range (70°F) during the occupied hours before the peak period (8 a.m. to 2 p.m.) and floating the zone temperatures up to the high end of the comfort range (78°F) during the peak period (2 p.m. to 5 p.m.). With this strategy, the chiller power was reduced by 80 to 100% (1 to 2.3 W/ft^2) during peak hours without having any thermal comfort complaints submitted to the operations staff (Xu et al. 2004).

In the summer of 2004, LBNL conducted pre-cooling tests along with online real-time comfort surveys to determine occupant reactions to the thermal conditions in the Santa Rose Federal building and in a Sacramento office building. The results of the comfort surveys in two large test buildings indicate that occupant comfort was maintained during the pre-cooling tests as long as the zone temperatures were between 70°F and 76°F (Xu 2006).

1.2. Project Objectives

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

- What are the metrics of the building thermal mass and how are they determined?
- How can thermal mass be discharged more efficiently and more smoothly with no rebound?
- What will be the comfort reaction when the pre-cooling strategies are performed in truly hot weather (peak outside air temperature higher than 95°F)?
- What will be the comfort reaction if the occupants are informed in advance of the test?
- What will be the occupants' reaction if pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment?
- How can a building's pre-cooling potential be assessed and the potential economic savings be quickly determined?

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

All the previous tests were conducted manually. On the test days, the building operators manually changed the temperature setpoints following the pre-cooling strategies. The automation of this demand shed was demonstrated successfully in previous automated demand response (DR) projects (Piette et al. 2006). This study investigated the potential from implementing the pre-cooling strategies automatically or semi-automatically, with notice one day in advance to the building operators.

LBNL systematically conducted more field tests for a longer period in two large commercial buildings in the 2005 study. In 2004, no comfort data were collected during the hot days. 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 and expected a temperature change, they might change their clothing level accordingly. Akin to commuting by mass transit or bicycle on a regional air quality "Spare the Air day," occupants may be willing to adjust to temporarily inconvenient or uncomfortable conditions that they know have long-term benefits. Since advance notice was thought to bias the tests, the 2005 tests were conducted without notifying the occupants.

1.3. Report Organization

Chapter 1 is the introduction with the previous studies, the theory and the objectives of this research. Chapter 2 is the filed test results, covering the load shed and thermal comfort survey in the two tested buildings. Chapter 3 is the conclusion and the recommendations for the future work. Chapter 4 is the thermal comfort survey results for another office building with demand shed, but no pre-cooling.

2.0 Pre-Cooling Field Studies: Project Approach and Results

2.1. Introduction

In 2004, electrical power rebounds (electricity load rising sharply right after the demand shed period ends) were experienced in both buildings tested in the late afternoon following an early afternoon step increase in setpoint temperatures. Since it is essential to develop and test better discharge and recovery methods during the peak hours, in 2005 the research team tested various such strategies. While these strategies and methods were developed and studied in the simulation environment in 2004, they had not been tested in real buildings (Xu 2006). The methods for discharging cooling energy in building mass are as important as the methods for storing it in the mass.

The research team offered to conduct a web-based occupant survey in each building. The core CBE Occupant Indoor Environmental Quality (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.

The research team 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 cooling (Btu) can be stored in the mass, including both building structure and furniture, for a given temperature change, while the second one determines how fast the thermal mass can be charged and discharged (the heat transfer rate in Btu/h). A single parameter, the building time constant, includes the combined effects of the two factors, which then determines the magnitude and the length of the power shed. The building time constant (1/s) is calculated by dividing the thermal capacity by the heat transfer rate, which determines the timescale of the building response to increases in zone temperature setpoint. Very few studies can be found in the literature on how to determine the time constant for buildings as a whole. The research team implemented the method to determine the effective time constant of the building thermal mass at appropriate field sites (Lee and Braun 2006). These tests were performed on non-CPP (critical peak pricing) days. The resulting demand-limiting strategy determined by the time constant methods was implemented manually on CPP days and tested on some additional non-CPP days (Lee and Braun 2006).

The research team first developed and tested the pre-cooling strategies in the buildings on non-CPP days. Then, the team tested the strategies on actual PG&E CPP days under the pilot program, when the price signal was sent one day ahead. The team worked with building owners and programmed the pre-cooling strategies in the energy management control system (EMCS) and to activate the pre-cooling strategies automatically.

2.2. Methodology

To address the questions listed above, the research team selected two buildings that had participated in the Auto-CPP pilot program, a study to demonstrate the capability of automated demand shed in buildings on PG&E CPP days (Piette et al. 2006). The selection was based on location, technical feasibility, and owner intentions to participate. The two buildings selected were the Chabot Space and Science Center (CSSC) and the Oakland Scientific Facility (OSF), both in Oakland, California. A strategy similar to the demand-shifting strategy implemented in the 2004 study, based on zone temperature reset, was used in both buildings.

There were several reasons for picking these two buildings. First, they were both medium-sized buildings with full digital direct control (DDC) and so the zone temperatures could be changed directly. Second, CSSC is a heavy mass building and a large portion of the floor area is exposed concrete. OSF is a very light office building with full glazing on the west and east façade. Studying buildings at the two ends of the building mass spectrum gave LBNL 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 were innovative and interested in trying new ideas and methods to reduce their utility costs. More detailed building descriptions can be found in later sections of this report.

2.2.1. Occupant surveys

Demand shifting and load shedding strategies should be acceptable from the perspective of the building users so that employee productivity and customer satisfaction are not hampered. 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 shed period, and the high shed period.

Employee web-based survey

CBE had developed a web-based occupant indoor environmental quality survey that had 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 comfort survey instrument was employed during the 2005 tests.

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

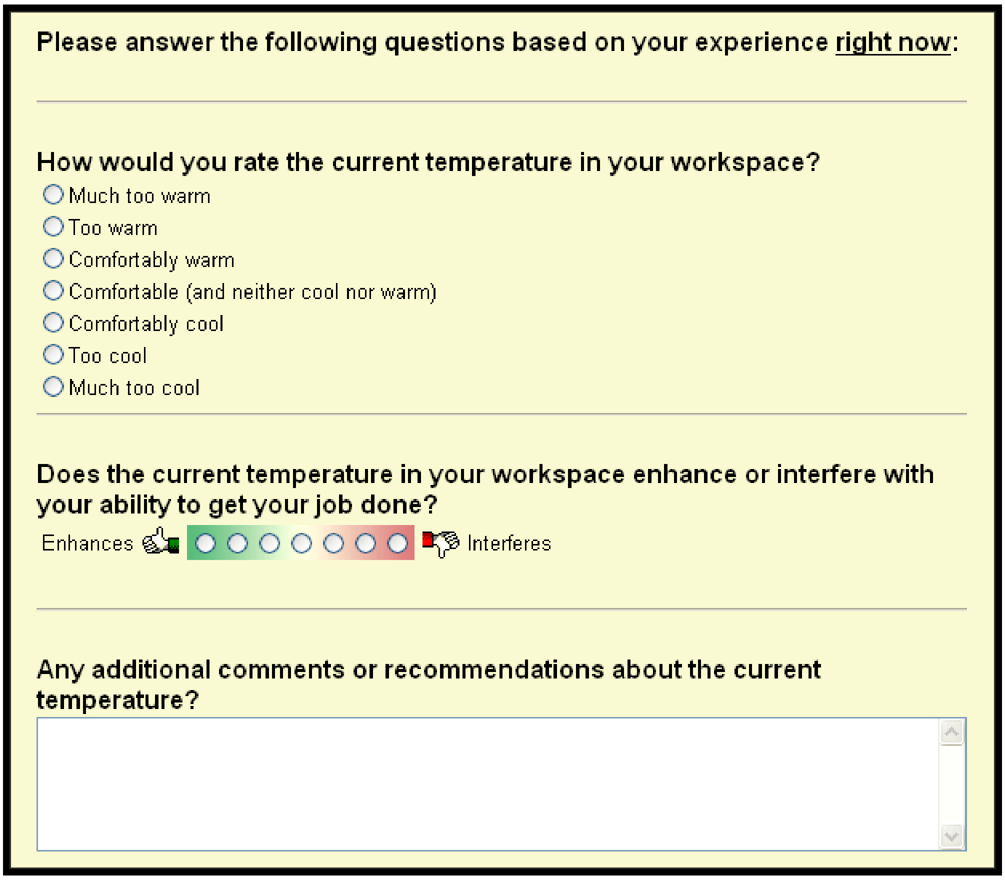

Figure 1. Polling station for surveying visitors

Employee invitations

Employees were asked by email to take the survey at least twice per day (once in the morning and once in the afternoon) and more often if possible. The survey was brief and took 2 - 3 minutes to complete on the first viewing and about 1 minute thereafter. Although it would have been ideal to have all employees take the survey at frequent, specified times throughout the day, the reality of the typical office schedule made the success of this approach unlikely. Further, the research team were wary of

[1] Predicted Mean Vote is the average expected comfort response (vote) based on indoor air climate conditions.

demanding too much of the occupants. During the 2004 tests, the team had notified the occupants each time they wanted them to take the survey, and learned that some of the employees had found the multiple emails intrusive. During the 2005 tests, the team therefore attempted to minimize the communication impact. This was apparently a successful strategy at the Oakland site, but there was low participation from the employees at the Chabot site.

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

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

Polling station

CBE also set up a polling station to survey users of the buildings on their comfort level. Owners of retail spaces want to know how demand shifting and 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 the comfort votes of the center visitors. One device was situated near the center café, and on some test days UC Berkeley students facilitated the survey by approaching visitors about the devices.

Figure 2. Indoor climate monitor

2.2.2. Monitoring of 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 calculation of mean radiant temperature (MRT) and thus operative temperature.[2] Because of the radiant effect, operative temperature is a better indicator of the thermal comfort than the dry bulb air temperature. Operative temperature 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.

[2] Operative temperature is the mean of the mean radiant temperature and dry bulb temperature.

Figure 3. Indoor climate monitor with (from left to right): shielded dry bulb sensor, anemometer (air speed sensor), and globe temperature sensor

2.2.3 Weather and test conditions

The 2005 tests were subject to weather conditions that were cooler than desired. During the 2004 tests, the weather was also not as hot as hoped for at the test sites, so the majority of those tests were conducted in moderately warm weather. All of 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 Center

2.3.1. Test site description

Chabot Space and Science Center (CSSC) 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 4). The building is a heavy mass building with lots of exposed concrete on the first floor. The walls are well insulated and the windows are small to have a better control of lighting levels inside.

The cooling plant has a 230-ton centrifugal chiller with a variable pumping chilled water loop. There are eight air-handling units located on the roof using chilled water to condition outside air and provide air circulation throughout the entire facility. Seven of them are single duct variable air volume air handling units and one is a constant volume unit. A newly installed Envision DDC control system provides indoor comfort control.

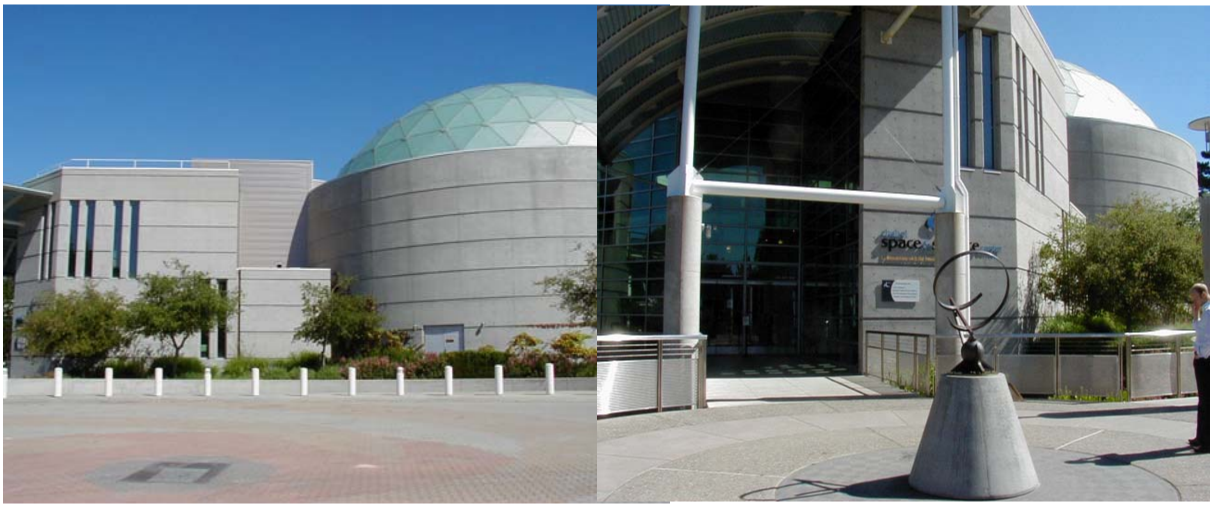

Figure 4. Chabot Space and Science Center

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 DDC, it had no global zone temperature adjustment capability before the study. This function was added to the DDC system's program as part of this study.

The building's operation is typical of that of many museums. The building is open to visitors from Tuesday through Sunday. Since all the PG&E CPP days are on weekdays, the CPP program is financially less attractive for this building than for other buildings since the load of this building on CPP days is lower than that on weekends. The daytime occupied hours are from 8 a.m. to 5 p.m. In normal operation, the HVAC system starts at 5 am and pre-heats or pre-cools the building until 8 am, depending on the outside weather conditions. Before the tests, no major faults in the mechanical system were apparent in this building; however, some controllers had not been tuned properly and certain valves and dampers were oscillating during operation. There were no comfort complaints in either the office or the exhibition areas. The building operators had worked at the building for a long time and were 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 5. The building was normally operated at a constant setpoint of 72°F throughout the startup and occupied hours. After 8 p.m., the system was shut off and zone temperatures started to float. Under normal operation, the setpoints in individual zones ranged from 70 to 75°F, with an average value of about 72°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 operation to pre-cool the building to 68°F from 3 a.m. to 7 a.m. Because the weather was relatively cool in the Oakland Hills location in the summer and the outside air temperature was in the low 60s°F in the mornings, the HVAC system could cool the building with outside air using the economizers and no chiller operation. From 7 a.m. to 12 p.m., mostly occupied hours, all the zone temperature setpoints were reduced to 70°F. From 12 p.m. to 6 p.m., the CPP moderate and high price periods, the setpoints were raised linearly to 78°F. After 6 p.m., before the system was shut off, the setpoints were kept at 78°F.

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

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

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

Figure 5 shows the setpoints for the existing (baseline) operation and the four demand shed strategies.

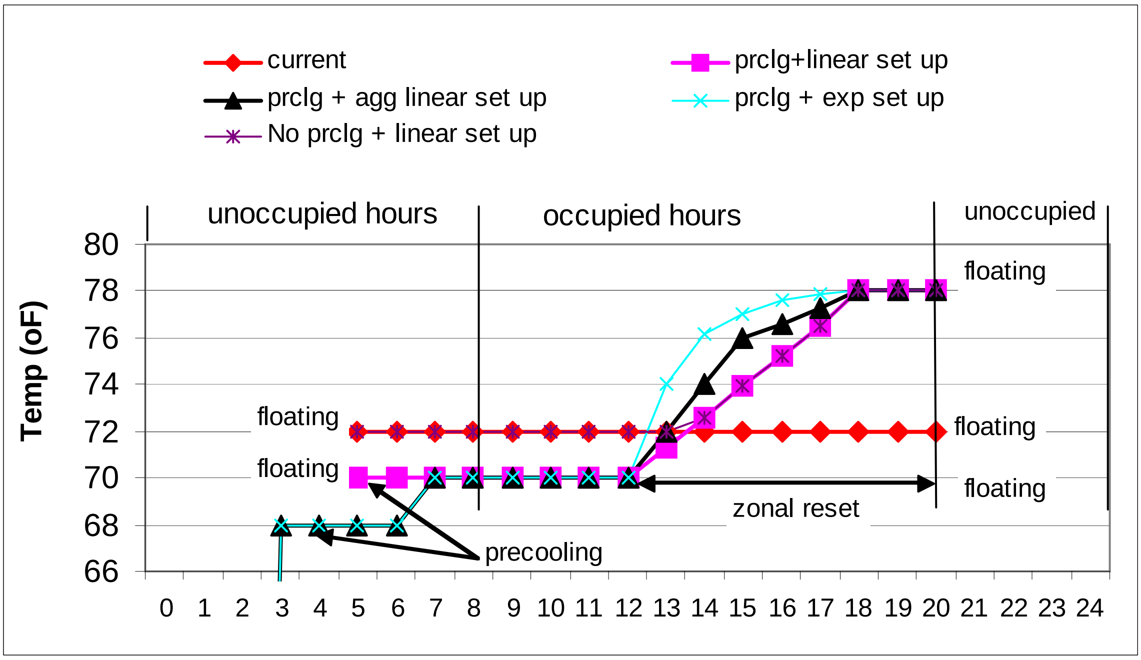

Figure 5. Cooling and demand shed strategies, CSSC

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 zones were recorded through the building control system. These temperature data were compared with indoor air temperature measurements from devices installed by CBE in both the office and exhibition areas.

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

2.3.4. Weather, test scenarios, and surveys

In the 2003 and 2004 studies, the expected strong correlation between peak outside temperature and whole building power was observed in the all tested buildings (Xu et al. 2004). Therefore, for this study baseline days for each test day were selected based on similarity of peak outside air temperature.

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

In total, the research team conducted eleven tests in this study, as listed in Table 1. 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 *pre-cooling + linear set up* tests, two *pre-cooling + aggressive linear set up* tests, one *pre-cooling + exponential set up* test, and two *non-pre-cooling + zonal reset* tests. All tests were duplicated except for the *pre-cooling + exponential set up* test, which was not duplicated because of time constraints. The remaining two days were *baseline survey* days on which no intervention occurred. Table 1 shows the dates, strategies, and weather conditions for the tests.

Table 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 ^{o}F, Warm ~ 85 ^{o}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 made it very easy to administer, and thus survey data were collected on several additional days as well. These additional days, when no strategies were employed, were considered *baseline* days and were included in the analysis of survey responses, but they were not included in the energy use analysis. There were also two days (August 5 and October 15) when no survey data were collected. See Appendix F for the list of all days on which survey data were collected.

The building operator sent the web-based survey invitations to employees. Of 48 employees invited, 10 individuals participated, and 52 valid observations were recorded. All of the resulting data could be correlated with nearby air temperature measurements.

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

2.3.5. Results

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 6 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 p.m., when the zone temperatures setpoints started to rise, the chiller power was reduced dramatically on the pre-cooling test days. The chiller load was reduced by as much as 50% in the high price period from 3 p.m. to 6 p.m. In the tests of both *linear temperature reset* and *exponential temperature reset*, the research team observed no rebound for chiller power before 6 p.m., which indicated that the large thermal mass had not been fully discharged in this building. In the *exponential reset* test, the load reduction was much higher than for the linear reset tests, which indicated that the exponential reset was probably a better reset strategy in this building.

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

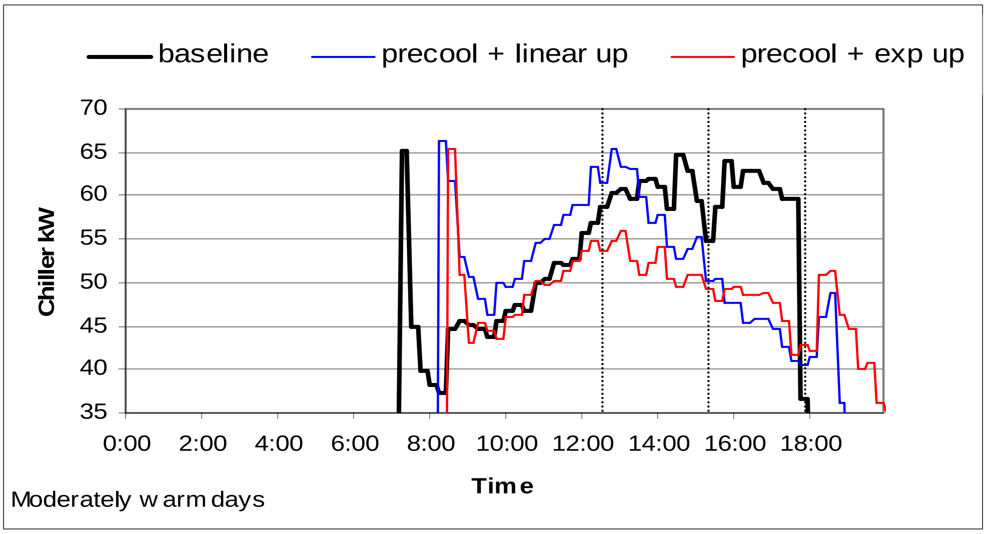

Figure 6. Cooling power reduction on pre-cooling test days - cool days, CSSC

Effects of pre-cooling. The effects of night pre-cooling on the upcoming day load were very obvious. Figure 7 shows two tests that used the same linear reset strategy in the afternoon where one was with night pre-cooling and the other was without night pre-cooling. First, the research team observed similar results as in Figure 6. 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.

These test 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 had very limited effects on afternoon electrical demand, especially on relatively cool days. This study indicated that, for heavy mass buildings, the effect of night pre-cooling could be very significant.

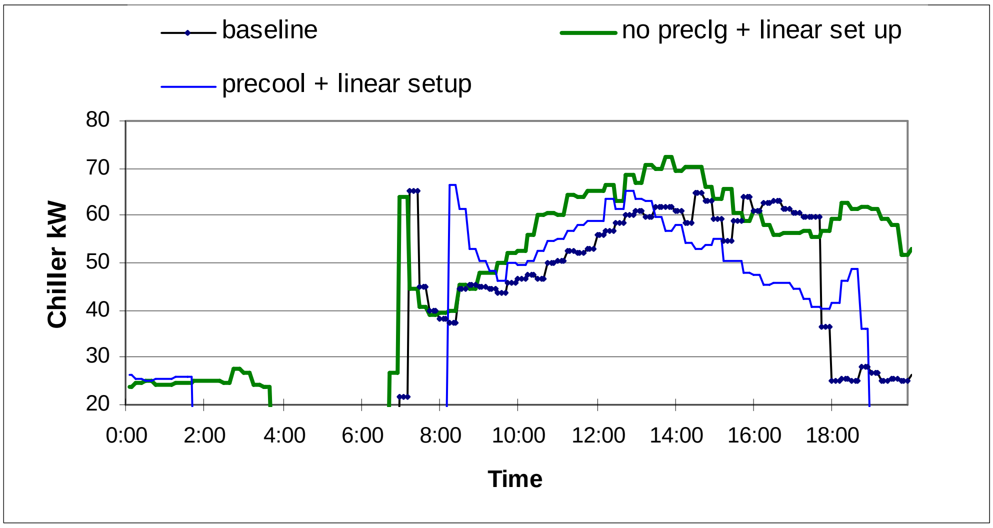

Figure 7. Effects of night pre-cooling on upcoming day cooling load - moderately warm days, CSSC

Warm days. Figure 8 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.

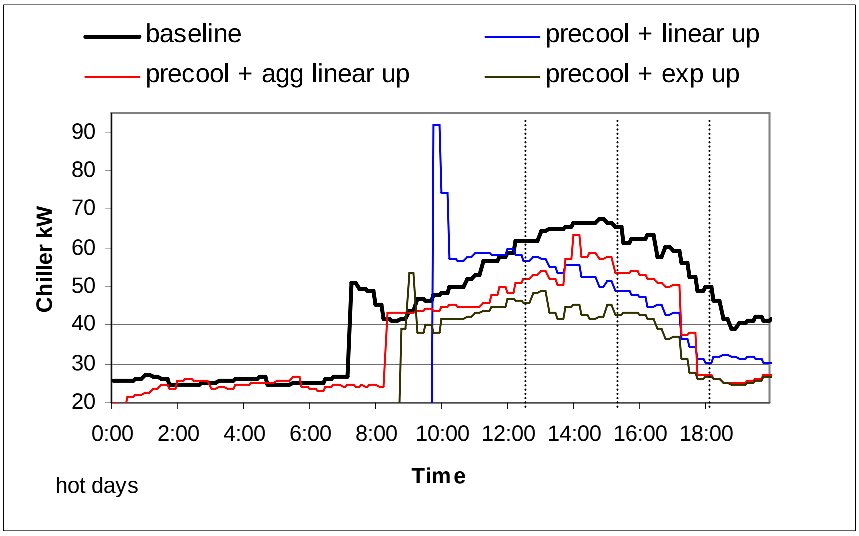

Figure 8. Effects of night pre-cooling on second day cooling load – warm days, CSSC

Compared with the test results on warm days in 2004, the reduction in demand did last till the unoccupied hours (Xu et al. 2004). There were no rebounds in the afternoon for these 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. In 2004, these higher outside temperatures meant a significantly higher cooling load during the peak hours, especially the outside air load. Second, the thermal mass of this building is much heavier than that of the buildings tested in 2004 and most of the mass is *accessible* (i.e. more cooling can be stored), because of exposed concrete in the exhibition area. Third, the research team was very careful in implementing the strategies in 2005. In order to prevent rebounds, the team tested the least aggressive strategy (linear reset) first and the most aggressive strategy (exponential reset) later. In the meantime, the last strategy tested was backed up with a simulation analysis.

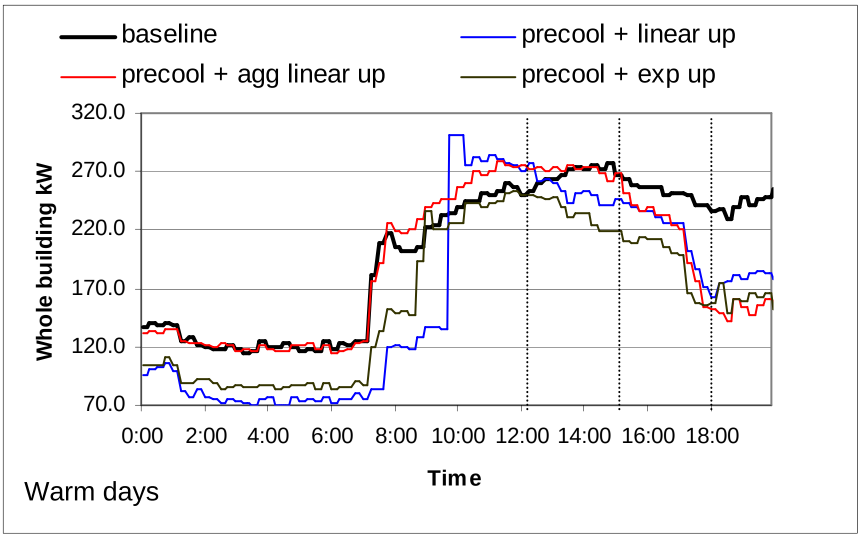

Figure 9. Whole building power reduction on pre-cooling test days, CSSC

Whole building. As shown in Figure 9, the reduction in the whole building power was about 30 kW (~15%) during the moderate CPP price period (12 p.m. to 3 p.m.) and 50 kW (~20%) during the high price CPP period (3 p.m. to 6 p.m.). The power reduction in the morning period was obvious because the chillers were turned on later than for the baseline days. In the exponential temperature reset tests, the power reduction was the largest. In the morning after 10 am, there was little difference between the electrical power consumption between the test days and the baseline days. Part of the reason was that the HVAC system was not running close to its full capacity on these warm days. The research team thinks that the response would be different under the different pre-cooling scenarios if the HVAC system was close to its full capacity.

Figure 10 shows the daily HVAC energy consumption for the pre-cooling days. HVAC energy consumption was reduced significantly. The most successful strategy, *pre-cooling plus exponential set up* in the afternoon, reduced the HVAC energy consumption by up to 40%.

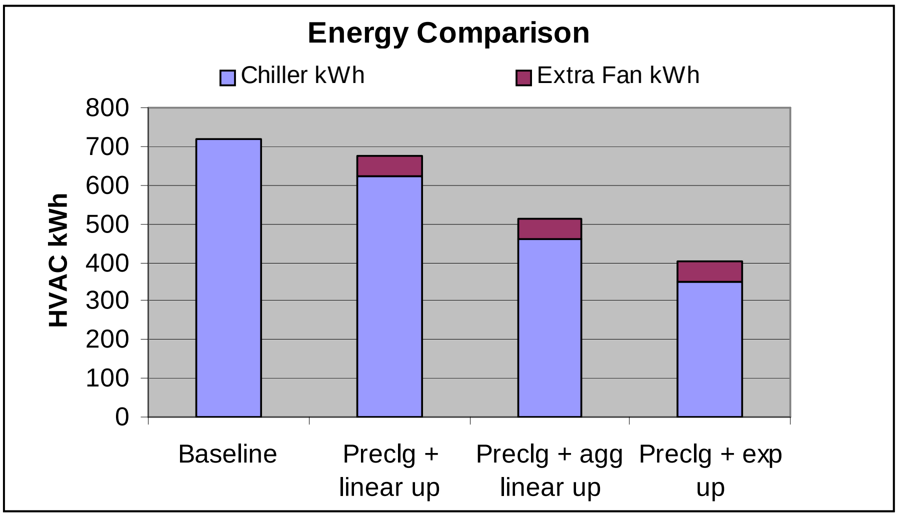

Figure 10. Energy usage of pre-cooling strategies, CSSC

Occupant comfort

Survey participation by employees was low, and there were few test days (particularly warm test days). Because of the small dataset, the employee and visitor data were combined for the analysis in this report.

Figure 11 shows that comfort rates were comparable between baseline and test days for all periods. In fact, none of the differences are statistically significant.

Data from cool days only (the vast majority of the data) followed a similar trend, as shown in Figure 12. Warm days are shown in Figure 13; however, the amount of data collected on warm test days is too small to draw any statistically valid comparisons. Only 7 responses each were collected in the morning and early afternoon periods, and only 4 in the late afternoon period.

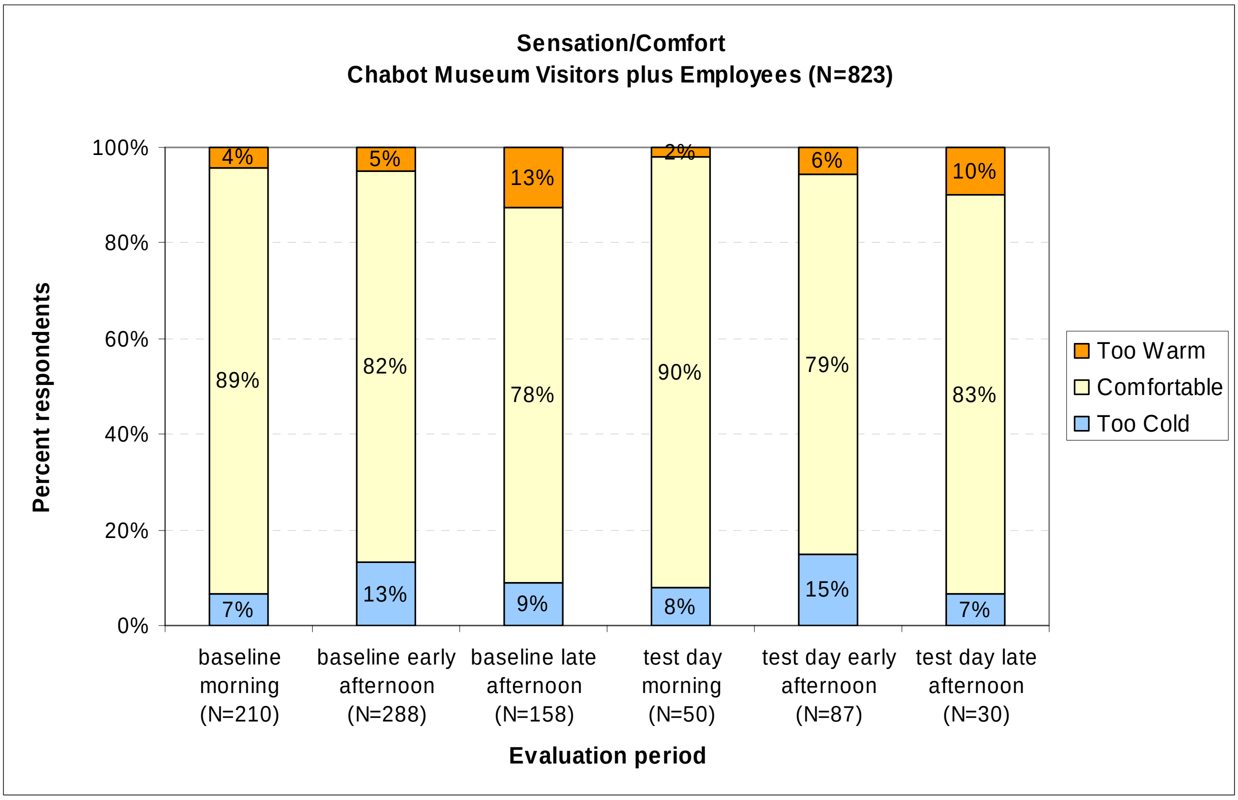

Figure 11. Sensation/comfort on baseline vs. test days, CSSC

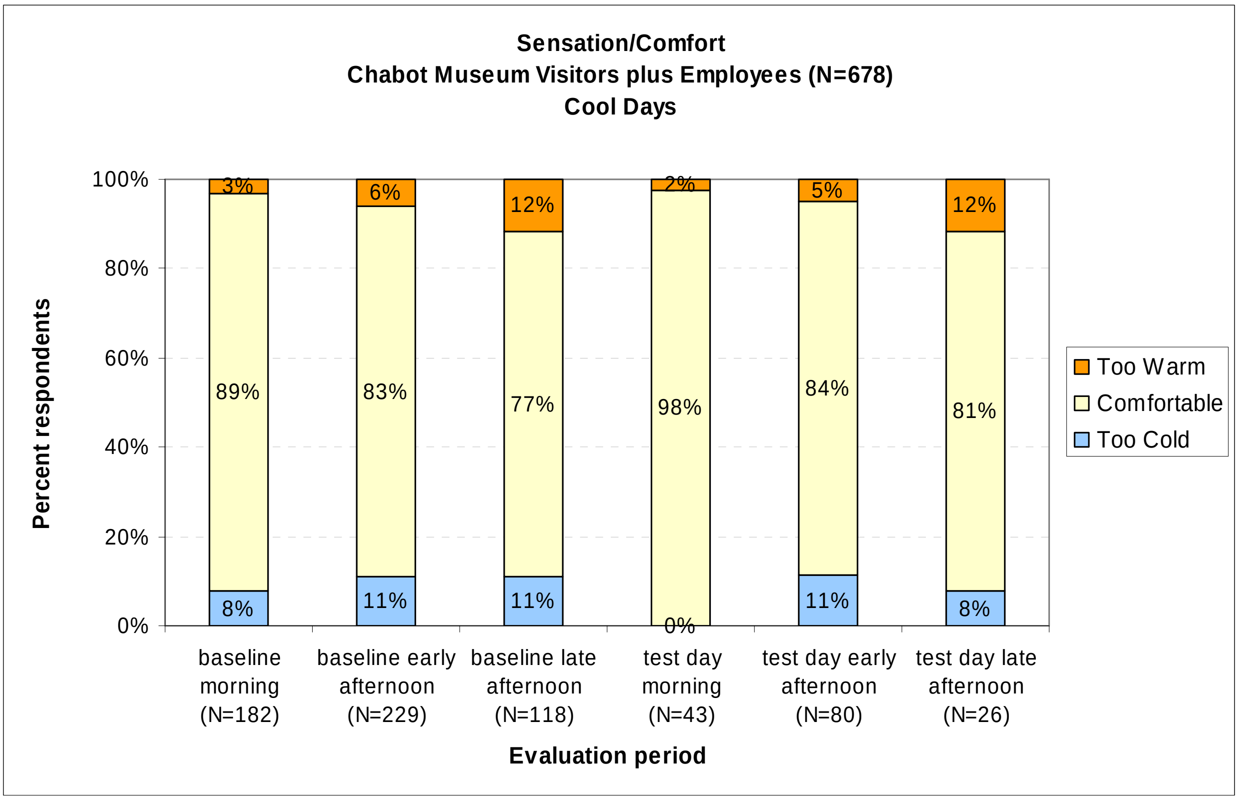

Figure 12. Sensation/comfort on baseline vs. test days - cool days, CSSC

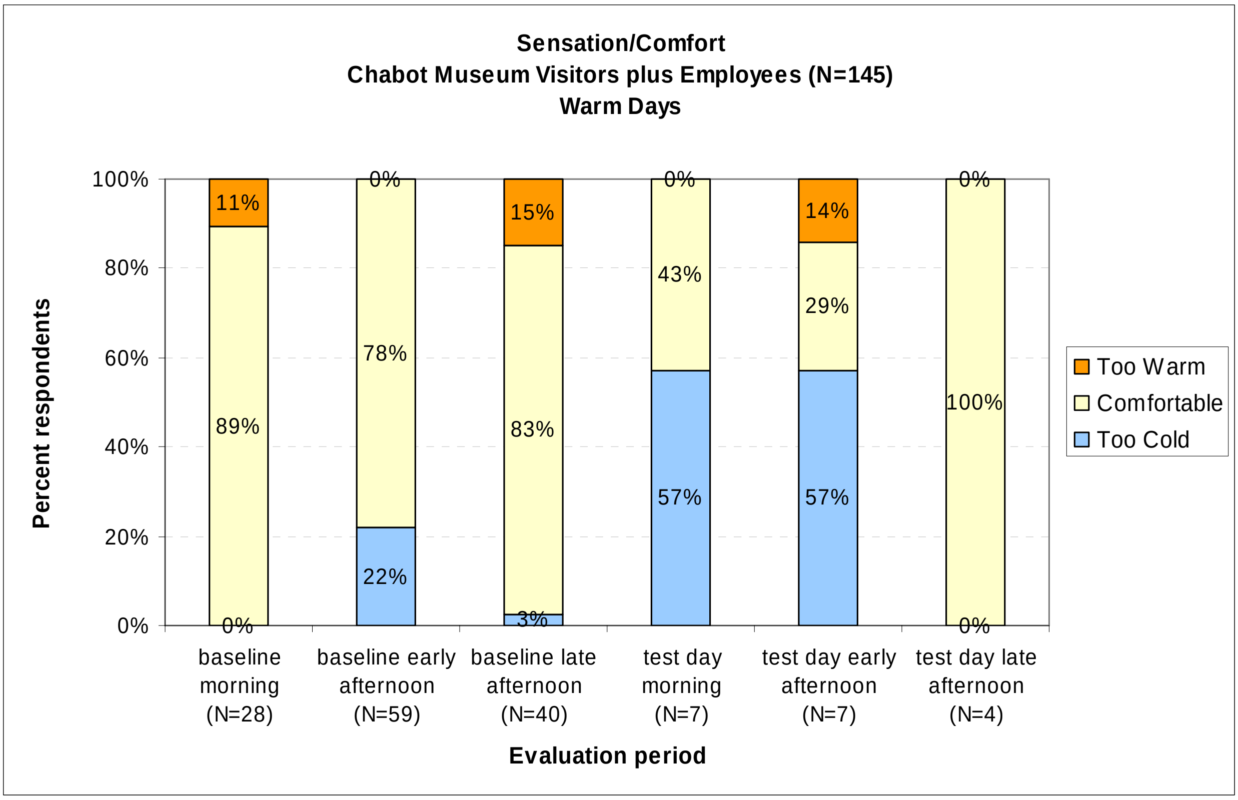

Figure 13. Sensation/comfort on baseline days vs. test days – warm days, CSSC

2.4. Test Site 2 – Oakland Scientific Facility

2.4.1. Test site description

The second test site, Oakland Scientific Facility (OSF), is a 90,000 ft^2 office building (with 70,000 ft^2 conditioned space) in Oakland, California (Figure 14). Lawrence Berkeley National Laboratory and the University of California jointly occupy it. The first floor is a data center, which houses a large computer center. The electrical demand of the computer center is about 1 MW, constant throughout the year. The data center requires cooling throughout the year also. The peak load for the entire building is about 1.5 MW.

Figure 14. Oakland Scientific Facility

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

The building has typical 4-inch concrete floors and very light walls. The office area has a medium furniture density and standard commercial carpet on the floor. On the west and east side, the building has a window-to-wall ratio of almost one. The windows are single-pane tinted in green. The internal equipment and lighting load are typical for office buildings. The number of occupants in the office areas is approximately 120. The maximum allowable zone temperature in summer is 78°F 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 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 a.m. and pre-heats or pre-cools the building until 8 am. The occupied hours are from 8 a.m. to 5 p.m. No major faults in the mechanical system were apparent and there were relatively few comfort complaints, averaging about one to two hot or cold calls per month. The building has no on-site operators; operators from 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, the research team tested the pre-cooling strategies only 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 15. In total the research team tested four different pre-cooling and temperature reset strategies in the office portion of the building. The building is normally operated at a constant setpoint of 72°F throughout the startup and occupied hours. After 6 p.m., the system is shut off and zone temperatures started to float. Under normal operation, the setpoints in individual zones range from 70°F to 76°F, with an average value of 72°F. All of the zone temperature setpoints are lowered to 70°F from 6 a.m. to 12 p.m. on the pre-cooling test days. On non-pre-cooling days, the setpoints in the morning are the same as for normal operation. The research team tested three different temperature reset strategies in the afternoon: *two-step set up*, *linear set up*, and *exponential set up*. The two-step set up strategy increases the building zone setpoints in two steps, one from 70°F to 74°F and the other from 74°F to 78°F. The linear set up and exponential set up strategies are similar to the strategies used in CSSC. After 6 p.m., the system is shut off, as is done in the regular operational mode.

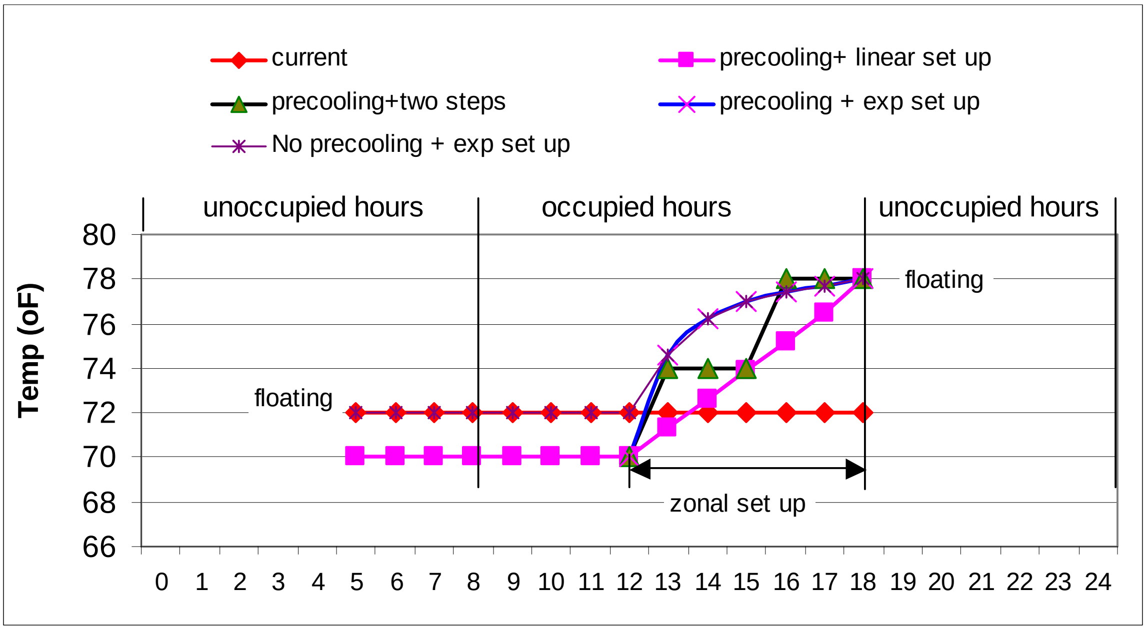

Figure 15. Pre-cooling test strategies for OSF

2.4.3. Monitoring

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

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

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

2.4.4. Weather and test scenarios

All the tests were conducted during the summer of 2005. As discussed earlier, it was a relatively cool summer and the peak outside air temperatures were between 75°F and 85°F. The research team separated the tests into two groups based on the weather conditions. Tests were conducted on cool days, when the peak outside air temperature was between 72°F and 75°F, and on warm days when the peak outside temperature was about 85°F. In total, the research team completed nine tests, two of them on warm days and seven of them on moderately warm days (see Table 2). Moderately warm day is defined as when the peak outside air temperature is between 80°F to 90°F. The team 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. Pre-cooling test schedule, OSF

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

Note: Peak Outside Air Temperature (cool ~75 ^{o}F, warm ~ 85 ^{o}F)

The nature of the web-based survey for employees makes it very easy to administer, and thus survey data were collected on several additional days as well. These were considered baseline days and were included in the analysis of survey responses, but were not included in the energy use analysis. There were also several days (August 10, August 11, August 12, August 22, October 6, and October 15) when no survey data were collected. See Appendix F for the list of all days on which survey data were collected.

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

2.4.5. Results

Energy use

Reset strategies. Figure 16 shows the cooling load profile under different pre-cooling temperature reset strategies. Under normal operation (baseline), the cooling load normally peaked between 12 p.m. and 4 p.m. In the *linear set up* test, the peak load was reduced by about 15%. Because the temperature was raised linearly, the load reduction was small at 12 p.m., becoming larger in the later afternoon. In the *two- step set up* tests, the temperature rise was faster than the liner set up test, so the load reduction was larger. The peak cooling load was reduced by 50% from 1 p.m. to 6 p.m. However, because the temperature was raised in two steps, right after the first step, the load curve was a small dip and a rebound, so the load profile was not completely flat. Among all the tests, *exponential temperature reset* achieved the most flat power profile in peak hours of all the scenarios. In this strategy, the power was essentially constant during the on-peak period and there was no rebound.

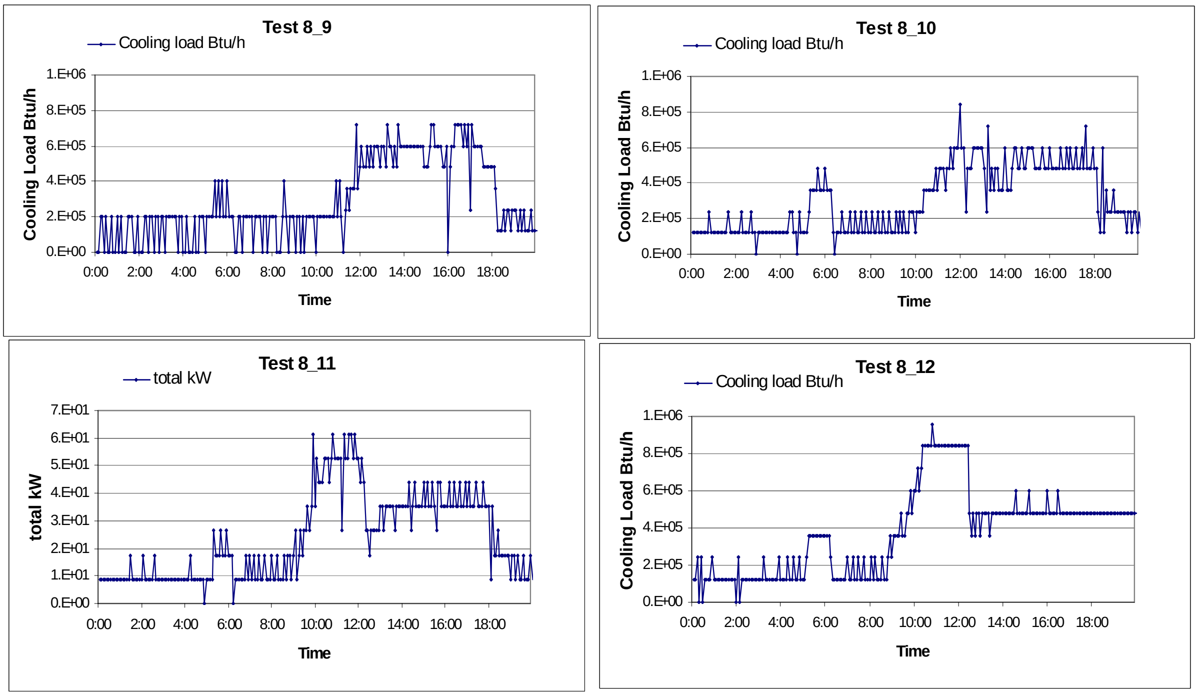

Figure 16. Comparison of different temperature reset strategies, OSF

Pre-cooling versus non-pre-cooling. Figure 17 shows the effects of the temperature reset with and without pre-cooling on the cooling load. Compared with the load in the non-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°F lower than that on the baseline days. During the peak period, the load reduction on pre-cooling days was slightly larger. However, the difference between the *pre-cooling* and *non-pre-cooling* strategies is not significant. Zonal reset without pre-cooling produced a demand shed of almost the same magnitude as that for pre-cooling tests in this light mass building under the moderately warm weather condition.

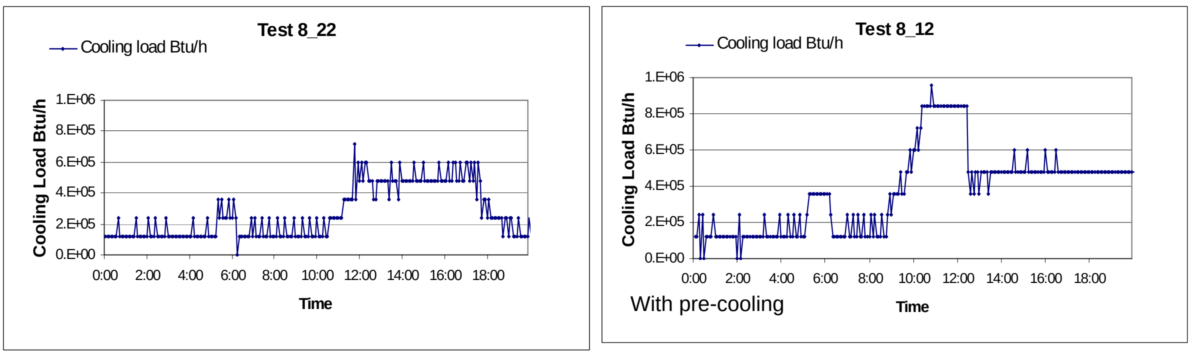

Figure 17. Comparison of cooling loads with exponential set up

Zone temperatures. Figure 18 shows return air temperature (RAT), a good indicator of average zone temperature, under different test scenarios. As the temperature reset got more aggressive, the zone temperatures in the afternoon went up faster and the peak temperatures were higher. However, the return air temperatures were never higher than 76°F, two degrees lower than the highest temperature setpoint of 78°F. The temperature data also indicates the benefits of the morning pre-cooling. In the non-pre-cooling tests, the peak zone temperatures were roughly about 2°F higher than those with pre-cooling. If the building was pre-cooled in the morning, the occupants would be more comfortable in the afternoon because the zone temperature would rise slower and peak at a lower temperature value.

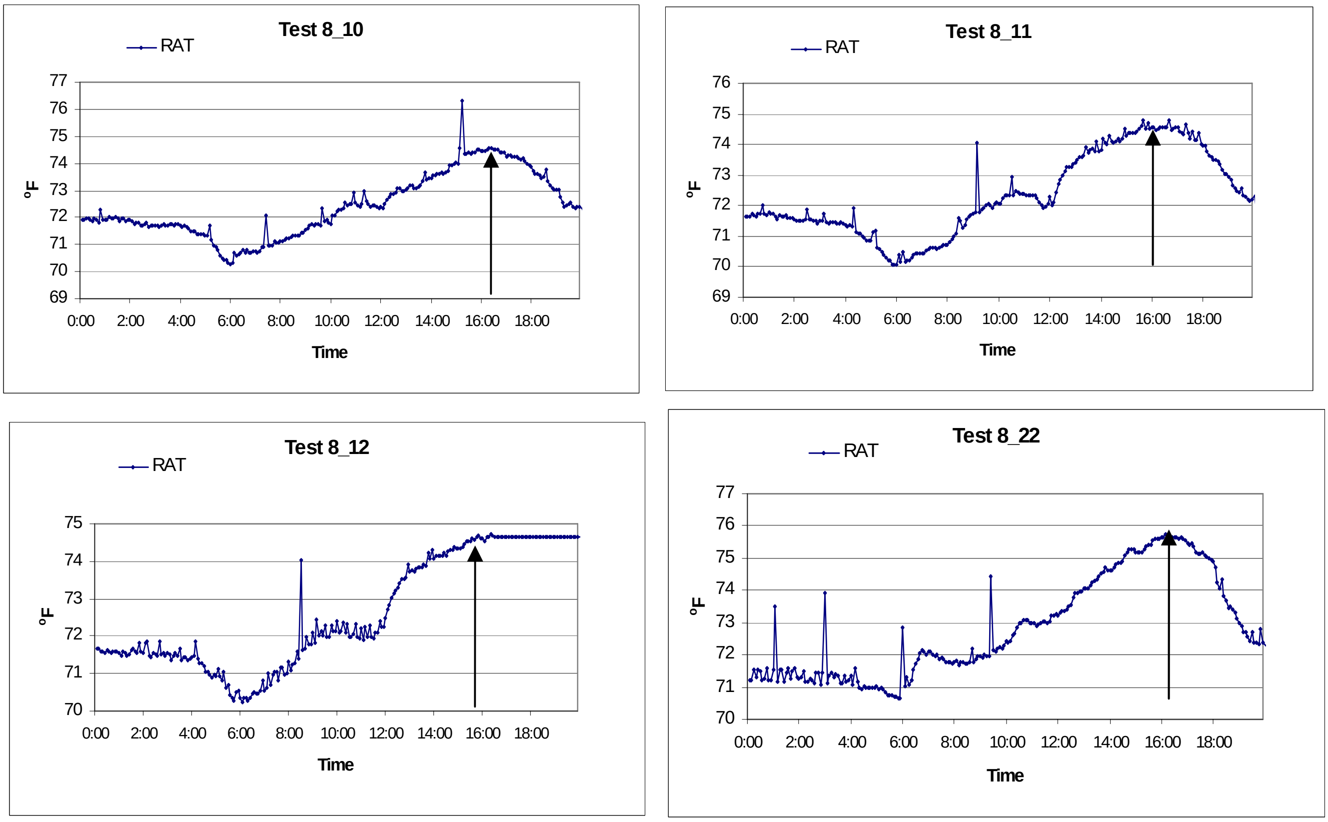

Figure 18. Comparison of return air temperatures with exponential temperature adjustment

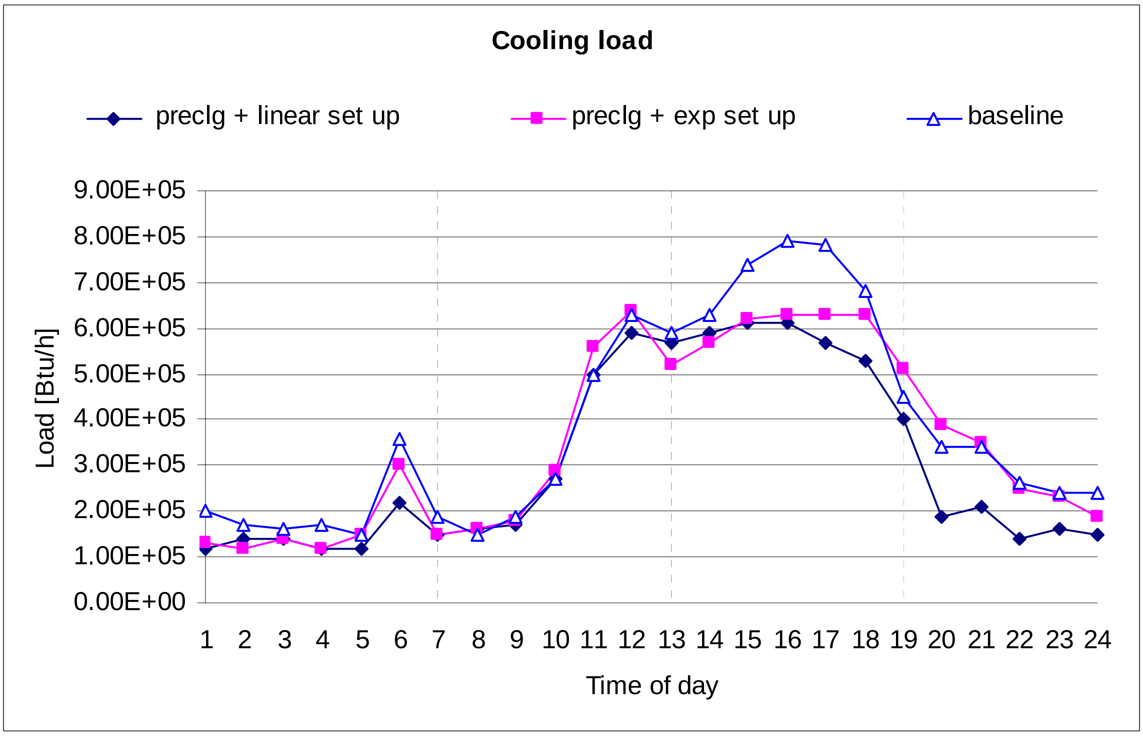

Figure 19. Cooling load shed on warm days, OSF

Warm days. Figure 19 shows the peak cooling load reduction in the warm day tests for the *linear set up* and the *exponential set up* strategies. 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 12 p.m. was slightly larger than that of the *linear set up* strategy.

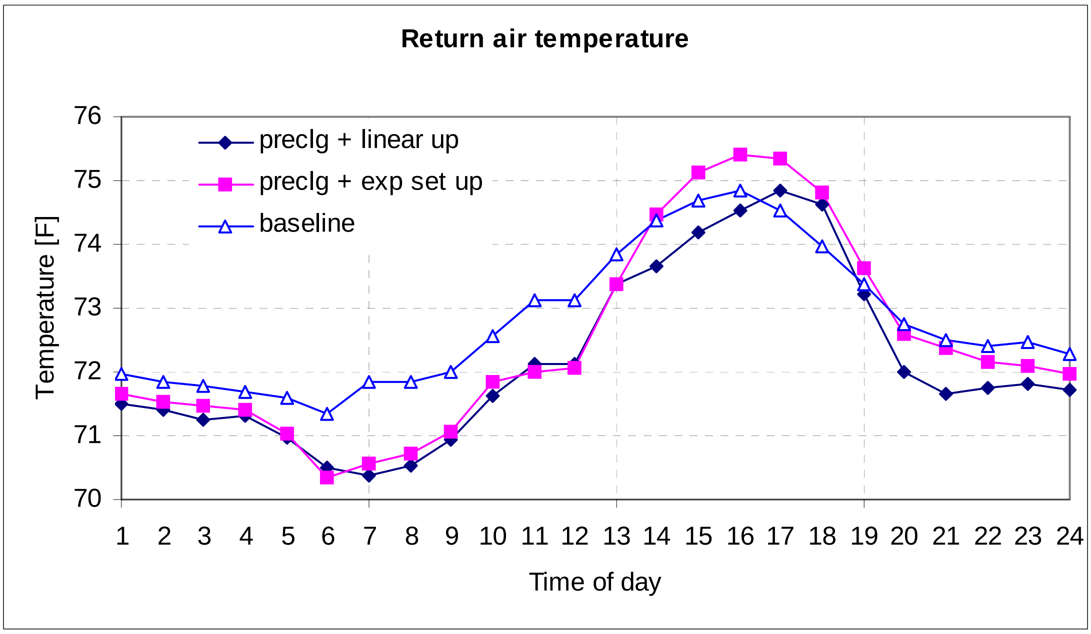

Figure 20. Return air temperatures on warm days, OSF

The return air temperatures shown in Figure 20 for the warm day tests showed similar results to those for the tests on the moderately warm days. In the afternoons, the peak return air temperatures were only about 2°F higher than those of the baseline. The return temperatures were never higher than 76°F, let alone the maximum setpoint of 78°F.

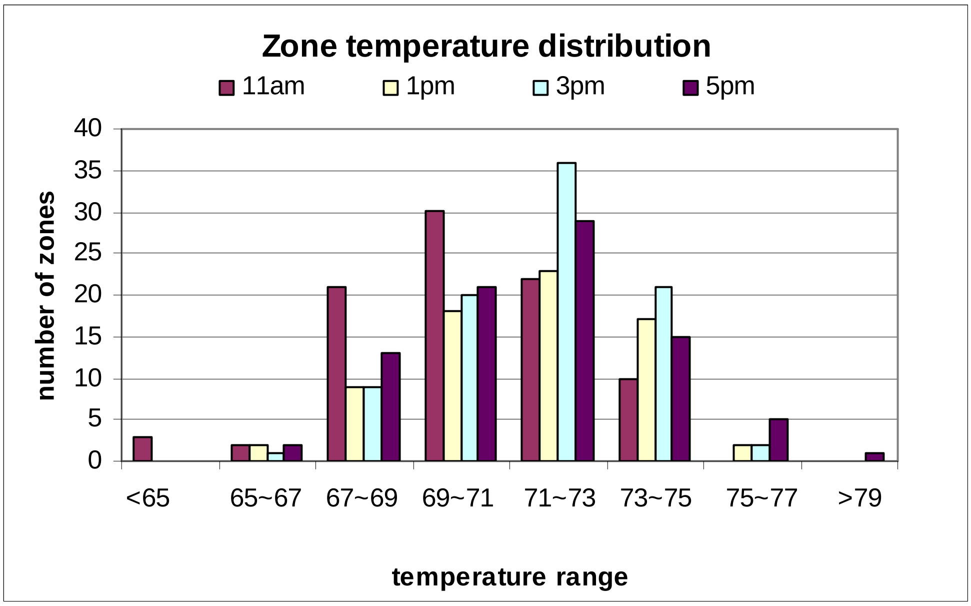

Figure 21. Zone temperature distribution on typical baseline day, OSF

Temperature distribution. Although the return temperatures were never higher than 76°F in all the tests, the individual zone temperatures were not necessary always lower than 76°F. Figure 21 shows the zone temperature distribution in the building on a baseline day. There was a big temperature variation across the building. In the 88 zones, the space temperatures ranged from 65°F to 79°F. The actual zone temperature was affected both by the location and by the operation hours. Generally in the afternoon, the zone temperature was normally higher than in the morning and the building had certain zones that were either too cold or too hot. The distribution patterns were essentially the same for both the baseline and the test days.

Occupant comfort

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

Therefore much of the analysis in this report evaluates the data at a rather coarse level of granularity so that the calculations are statistically valid. Taken as a whole, people's comfort levels in the comfortable range on test mornings and late afternoons met or exceeded comfort levels on baseline days (see Figure 22). Comfort levels on test early afternoons were lower than those on baseline day early afternoons. People tended to express discomfort in the cooler range on test days than on baseline days. This suggests that the morning pre-cooling strategies were effective, but may need to be run at a higher setpoint or for a shorter duration to avoid adversely affecting occupant comfort. However, more data should be collected during test conditions to verify this. The research team also observed that in general, people tended to feel a bit cold in this building.

As shown in Figure 23, 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 22.

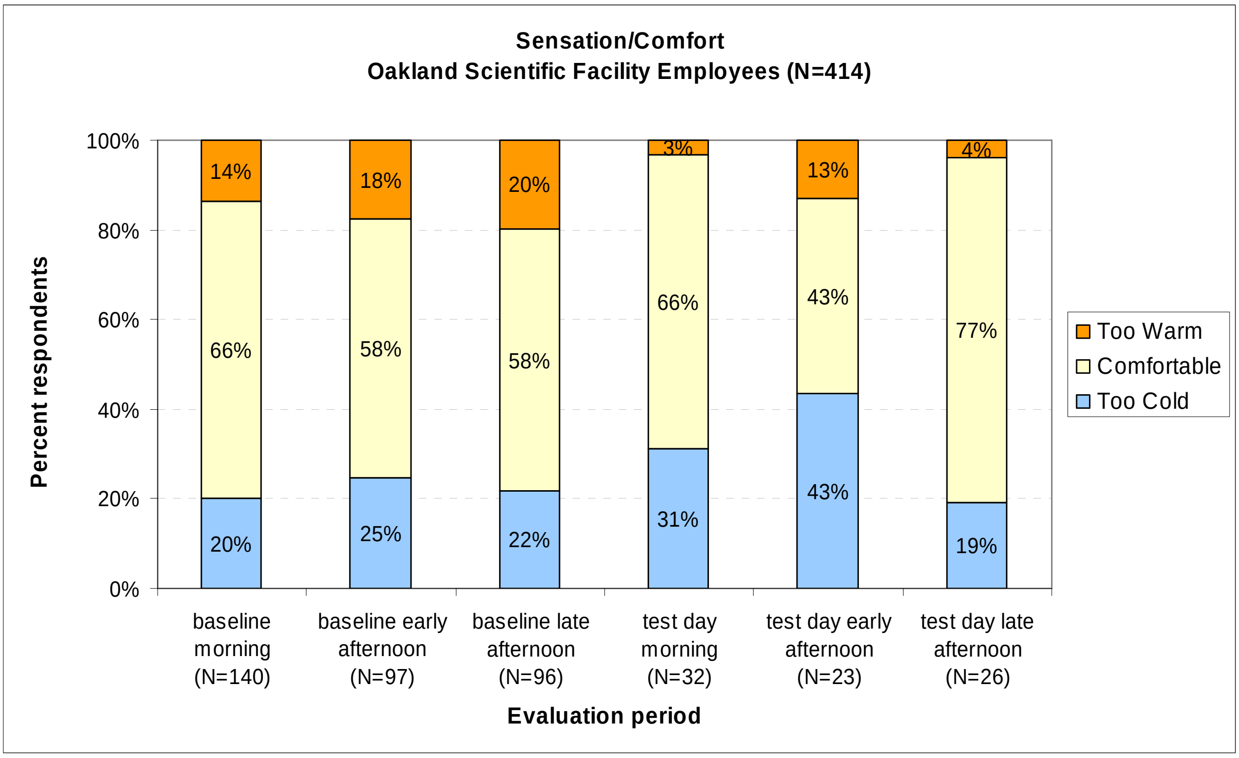

Figure 22. Sensation/comfort on baseline days vs. test days, OSF

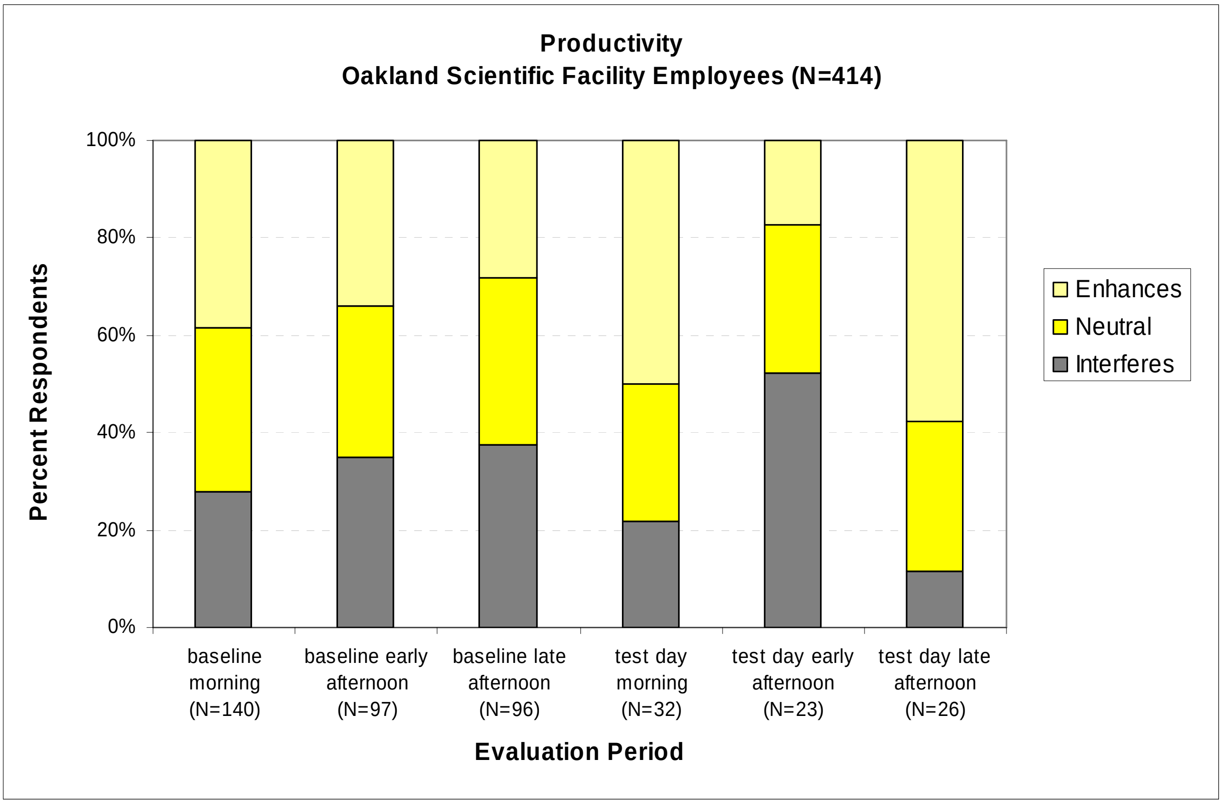

Figure 23. Productivity on baseline days vs. test days, OSF

Plotting the relationship between comfort and perceived productivity another way (Figure 24), people 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 accounted for only 7% of the responses.

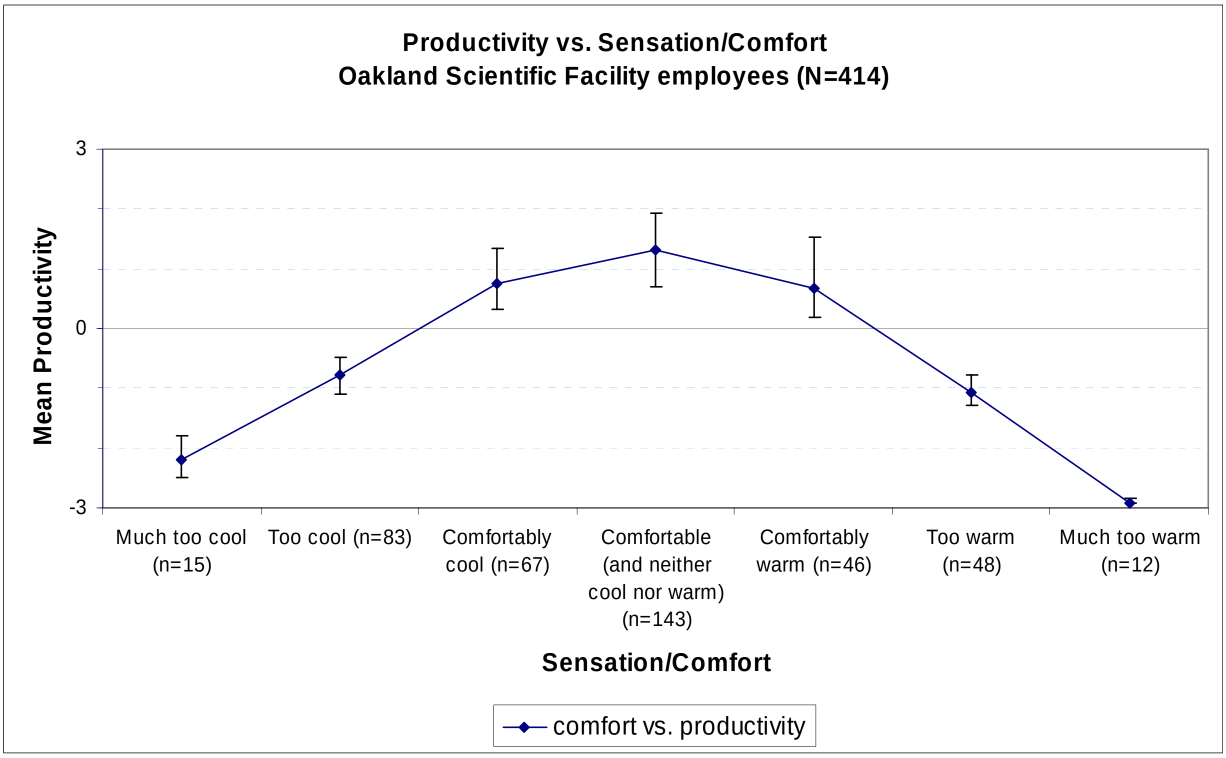

Figure 24. Average productivity vs. sensation/comfort, OSF

Figure 25 and Figure 26 show the trends for cool days and warm days, respectively. On warm days, the trends are same as above: comfort levels on test days are at or above those on baseline days, except in early afternoons. The research team focused on warm days because those are the days on which these strategies are most likely to be employed.

Figure 27 shows the data based on pre-cooling strategy. The above trend is particularly pronounced on test days employing pre-cooling in the morning, with *linear set up* in the afternoon. As shown in Figure 28, employing the *exponential set up* strategy in the afternoons does not produce a large proportion of "too cool" responses. This suggests that the exponential rise method produces more comfortable results; however, more data need to be gathered before drawing such a conclusion.

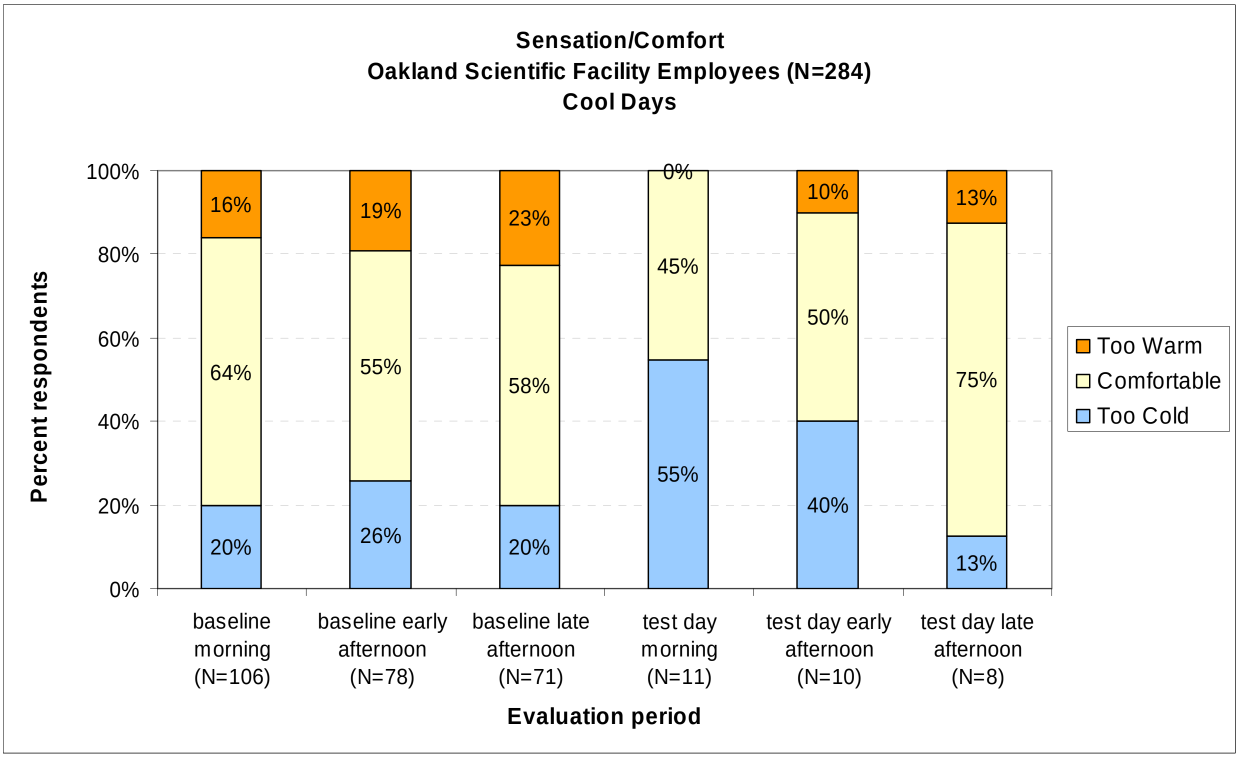

Figure 25. Sensation/comfort on baseline days vs. test days - cool days, OSF

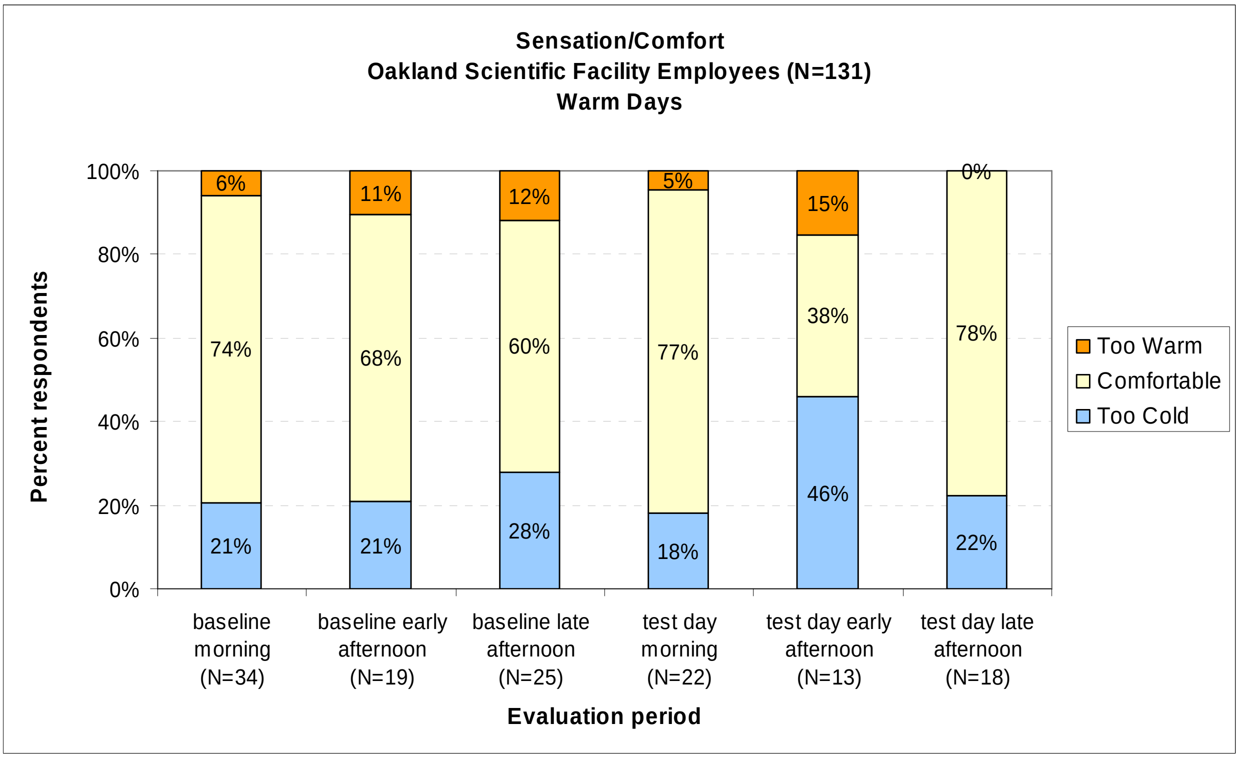

Figure 26. Sensation/comfort on baseline days vs. test days - warm days, OSF

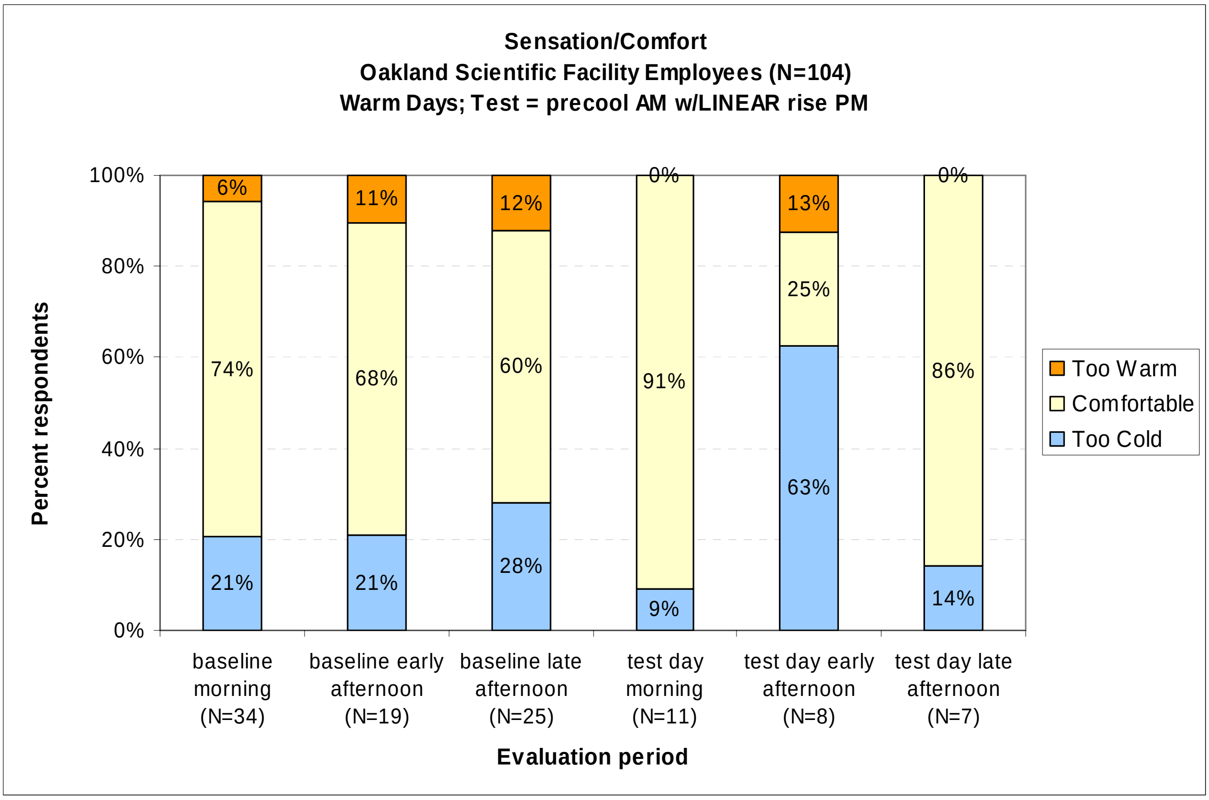

Figure 27. Sensation/comfort for linear set up on baseline days vs. test days - warm days, OSF

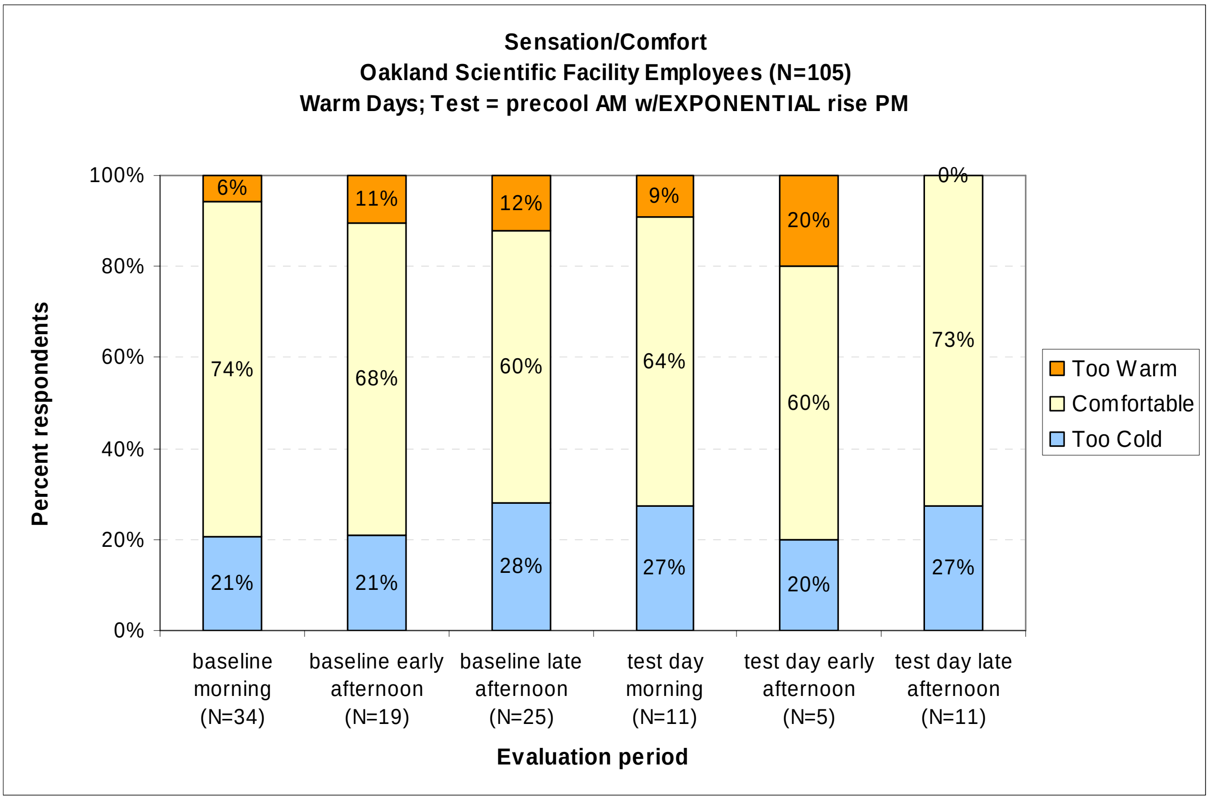

Figure 28. Sensation/comfort for exponential set up on baseline days vs. test days - warm days, OSF

3.0 Conclusions and Recommendations

This study focused on the following project objectives, whose findings are discussed in the conclusions or recommendations sub-sections.

- What are the metrics of the building thermal mass and how are they determined? (*Conclusions*)
- How can thermal mass be discharged more efficiently and more smoothly with no rebound? (*Conclusions*)
- What will be the comfort reaction when the pre-cooling strategies are performed in truly hot weather (peak outside air temperature higher than 95°F)? (*Recommendations*)
- What will be the comfort reaction if the occupants are informed in advance of the test? (*Recommendations*)
- What will be the occupants' reaction if pre-cooling persists for a longer period and they have opportunities to adjust to the new thermal environment? (*Recommendations*)
- How can a building's pre-cooling potential be assessed and the potential economic savings be quickly determined? (*Recommendations*)

3.1. Conclusions

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

- Pre-cooling and demand shed strategies worked well in both the light and heavy mass buildings. In the light mass building (OSF), the strategies reduced cooling load significantly (~35% on cool days, ~25% on warm days) with no comfort complaints. In the heavy mass building (CSSC), the load reduction was even more significant; the peak HVAC load was reduced by 50% using the exponential temperature adjustment strategy. These test results are consistent with conclusions drawn from the 2003 and 2004 studies.

- A properly-controlled *exponential temperature set up* strategy in the shed period discharged thermal mass smoothly. The use of an *exponential temperature reset* strategy successfully avoided rebound in both buildings. The exponential temperature set up strategy created very flat load curves during the peak hours in both buildings.

- Night pre-cooling had noticeable effects on the second day cooling load in the heavy mass building. In the studies of 2003 and 2004, the night pre-cooling had varying effects on the magnitude of the peak the following day, with a number of factors affecting its effectiveness. The 2004 results from the Santa Rosa Federal building (SRFB) were similar to those obtained in 2003. SRFB is a lighter mass building than CSSC, and in the moderately warm weather condition, night pre-cooling had a marginal effect during the following morning and had no discernible effect during the on-peak period. However, in the 2005 tests of CSSC with its heavy mass, night pre-cooling clearly reduced the load during both morning and afternoon periods on the following day.

- In the heavy mass building (CSSC), night pre-cooling reduced both HVAC peak demand and energy consumption in cool weather. The total energy consumption in various pre-cooling tests was lower than for non-pre-cooling days. This was mostly due to the fact that the summer mornings in Oakland were relatively cool and the HVAC could pre-cool the building without running the chiller.

3.2. Recommendations

This study has established the potential for pre-cooling and demand shed strategies, and it has also identified several uncertainties that should be resolved before pre-cooling can be reliably implemented in large commercial buildings. The following work is proposed; some of this work has already been included in the next phase of the pre-cooling for commercial buildings research effort.

- **Perform additional tests in hot climate conditions in Southern California.** In this and previous studies, significant demand reduction has been demonstrated through testing in 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 in very hot conditions (>100°F). 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.

- **Study occupant response when the building occupants are informed in advance of a pre-cooling DR event.** Also, consider conducting tests of occupant response during pre-cooling events of longer duration persists when they have opportunities to adjust to the new thermal environment.

- **Further test the method to determine building thermal mass metrics.** In this study the research team developed and tested a method to calculate the temperature trajectory in the afternoon in the two buildings in this study. Further research is recommended to test the temperature trajectory method with the building time constant in other buildings under a wider range of weather conditions.

- **Develop a screening tool.** The opportunities for demand reduction and cost savings for use of building thermal mass vary tremendously by building type and location. There is a need for an assessment tool that utilities and potential adopters can use to evaluate demand reduction and cost savings for individual buildings for applying building mass strategies that respond to utility price signals. The screening 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). DLAT could be expanded to cover a wide range of building types and locations within California. An appropriate user interface also needs to 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 setpoint strategies studied in the work reported here are only practical if the zone temperatures are controlled by networked digital controllers. A detailed guide to selecting, implementing and testing demand-shifting control strategies by building mechanical system and control type is needed to support their routine use.

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

3.3. Benefits to California

Reducing electrical peak electrical has a huge economic and environmental benefit to California. Most existing buildings do not have space to install active thermal mass storage system and the capital investment is not cost effectiveness from the current tariff. This study demonstrated that passive demand shedding can be as useful as active system and the load shed in this study is consistent with the results from the previous tests. In average, with this approach, commercial office buildings in California can reduce the peak load by 15 to 30%, with no complication to the occupants' thermal comfort.

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5.0 Glossary

CBE	Center for the Built Environment
CEC	California Energy Commission
CPP	Critical peak pricing
CSSC	Chabot Space and Science Center
DDC	Digital direct control
DLAT	Demand-Limiting Assessment Tool
DR	Demand response
DRRC	Demand Response Research Center
EMCS	Energy management and control system
EPA	Environmental Protection Agency
GSA	General Services Administration
HVAC	Heating, ventilating, and air conditioning
ICM	Indoor climate monitor
IEQ	Indoor environmental quality
LBNL	Lawrence Berkeley National Laboratory
MRT	Mean radiant temperature
PG&E	Pacific Gas and Electric
PMV	Predicted mean vote
OSF	Oakland Scientific Facility
RAT	Return air temperature
SCE	Southern California Edison
SMUD	Sacramento Municipal Utility District
SRFB	Santa Rosa Federal Building
VAV	Variable air volume
VFD	Variable frequency drive

Appendix A. 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 was done in 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 study period.

The building employed automated demand shed strategies, such as dimming lights and adjusting supply air temperature and fan pressures; it did not use pre-cooling. CBE placed thermal measurement equipment at the site on September 9, 2005. Survey data were collected on 5 cool baseline days, 9 warm baseline days, 1 cool test day, and 3 warm test days. See Appendix F for details of the tests that were conducted, the days that survey and thermal data were collected, and the maximum outside temperatures.

A department vice president at Echelon sent out survey invitations to occupants. Of 170 people invited, 48 individuals participated, and 174 valid observations were recorded. Of these, 161 could be correlated with nearby air temperature measurements.

As shown in Figure A-1, comfort rates on test days were at or above baseline levels on test mornings and early afternoons, but were lower on late afternoons. Figure A-2 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 A-3 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, the research team needs to gather more data before drawing general conclusions about occupant comfort in response to these load shedding strategies.

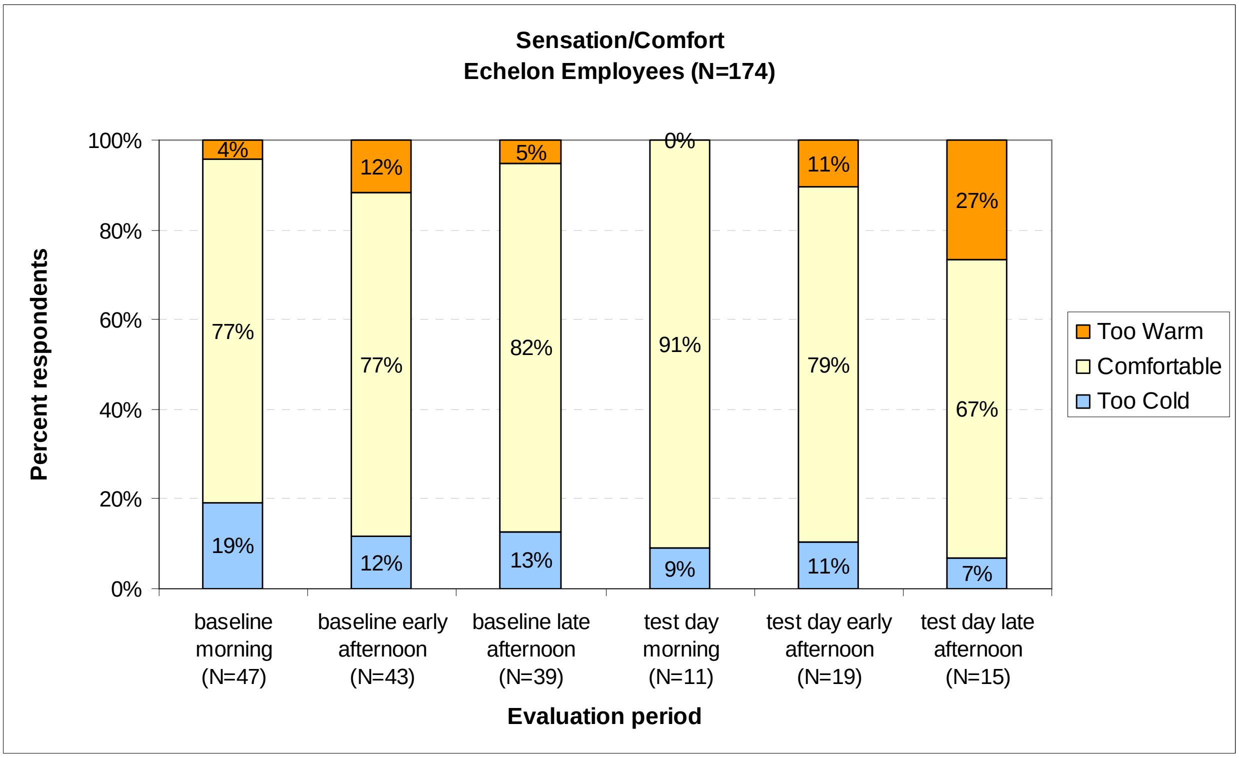

Figure A-1. Sensation/comfort on baseline vs. test days, Echelon

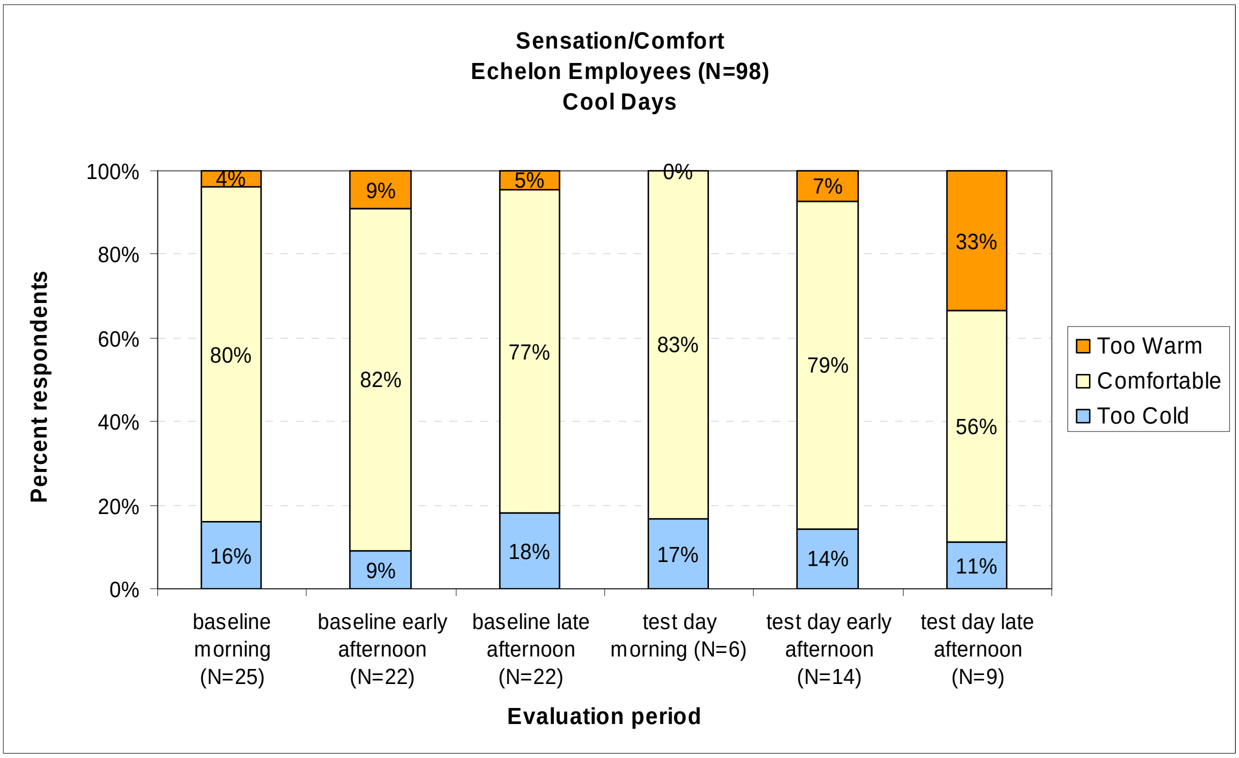

Figure A-2. Sensation/comfort on baseline vs. test days - cool days, Echelon

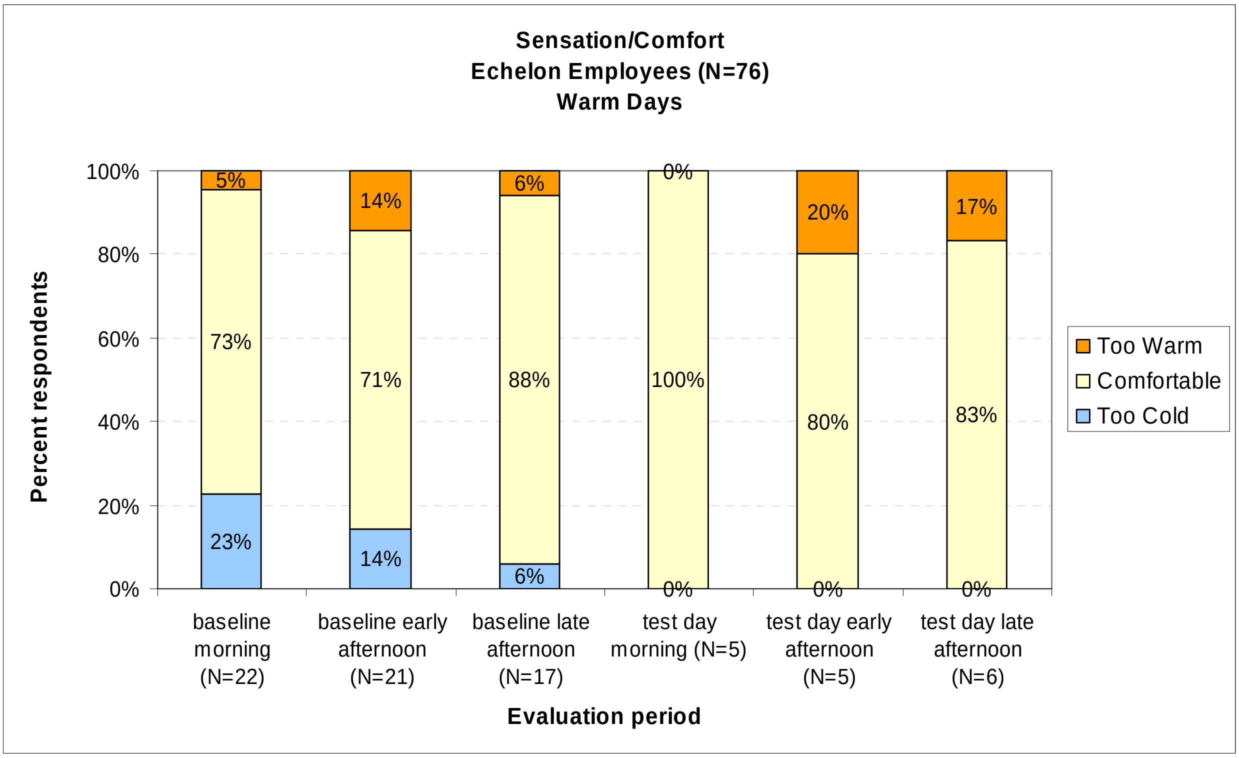

Figure A-3. Sensation/comfort on baseline vs. test days - warm days, Echelon

Appendix B. Request for Participation Summer 2005 Demand Shifting with Thermal Mass

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.

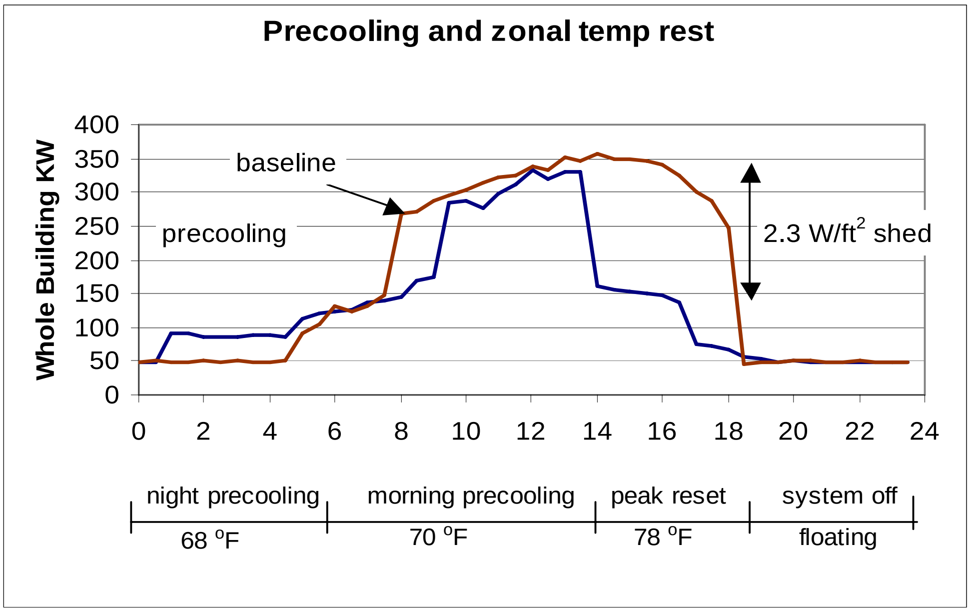

Figure B.1. Sample results of previous pre-cooling tests

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**.

Appendix C. Demand Shedding with Building Thermal Mass for Large Commercial Facilities Test Plan

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 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, the research team 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 D. Web-based survey instrument for employees

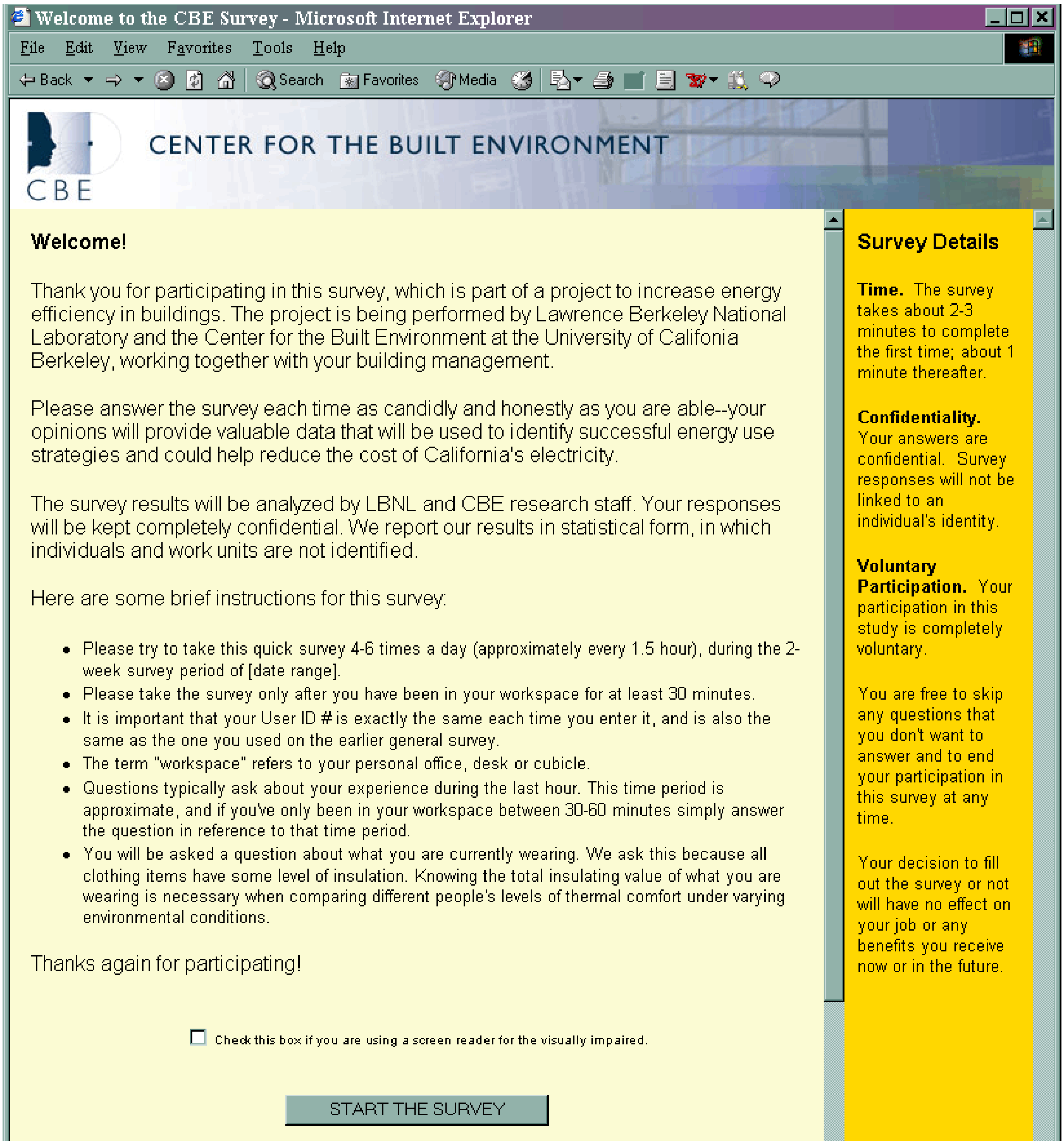

Figure D-1. Comfort survey welcome screen – upper half

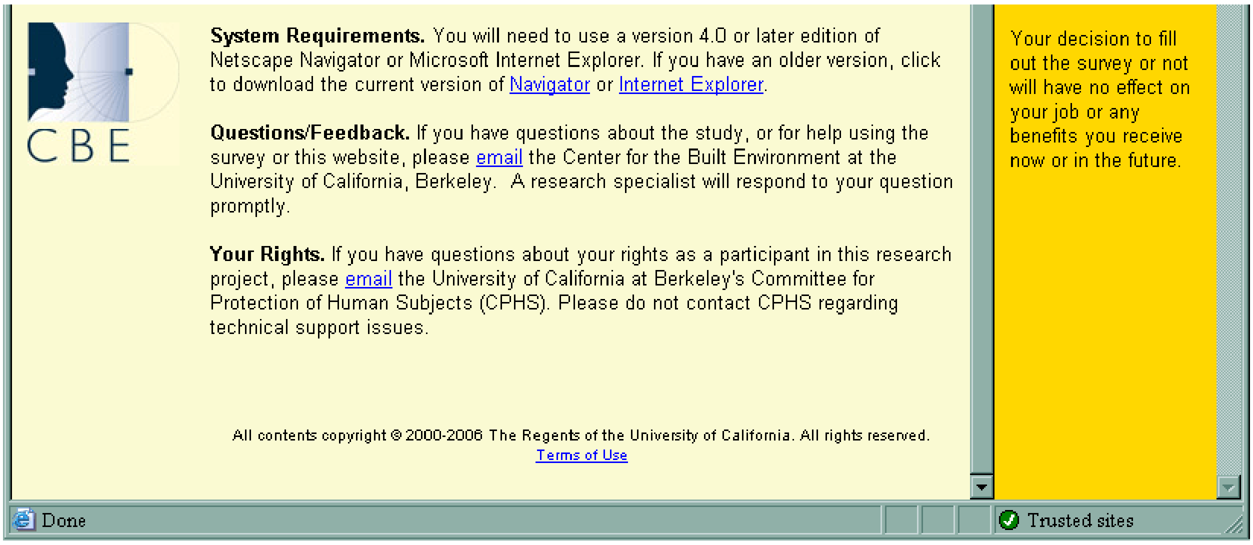

Figure D-2. Comfort survey welcome screen – lower half

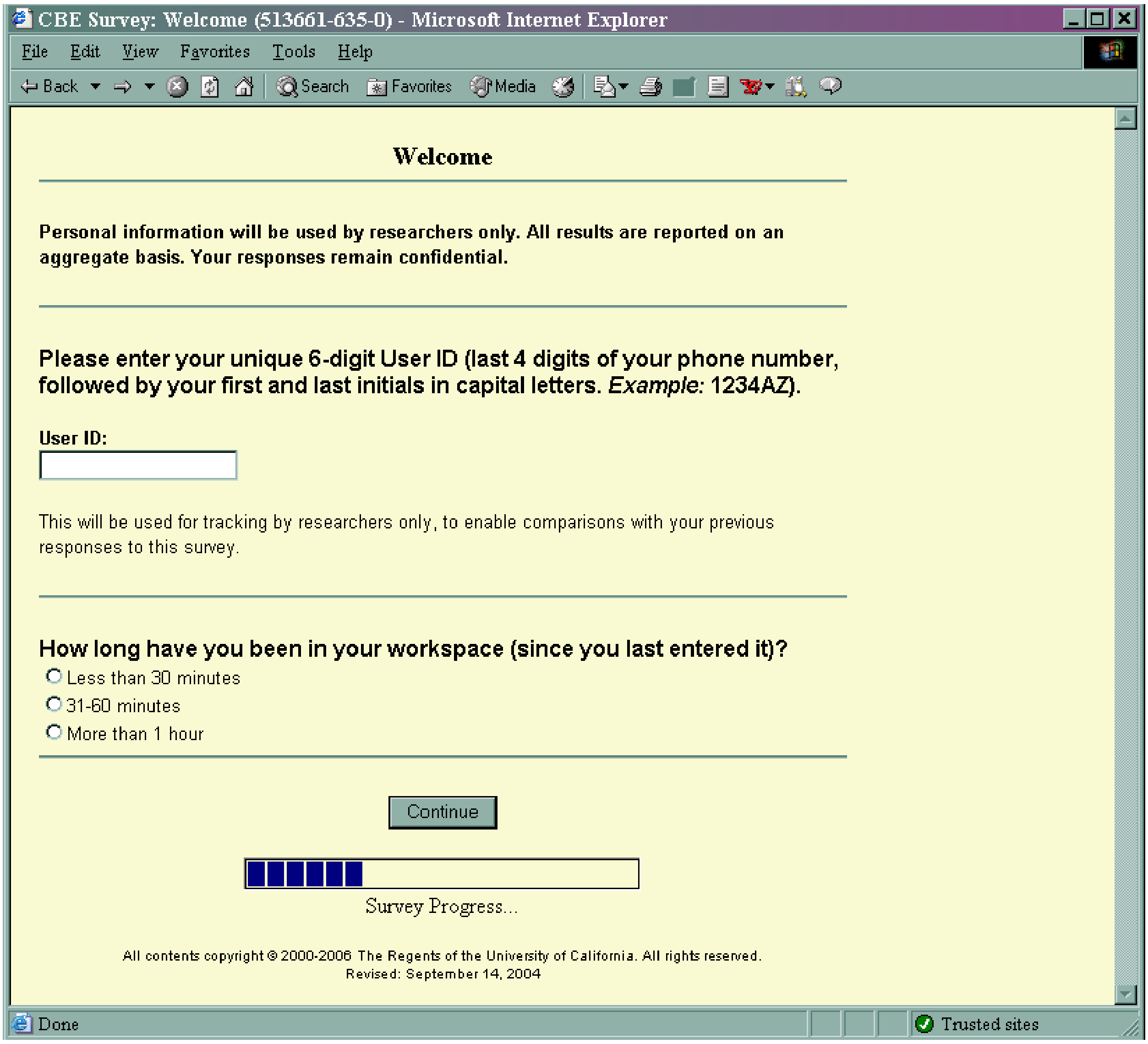

Figure D-3. Comfort survey page 1

Page 1 collects an 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.

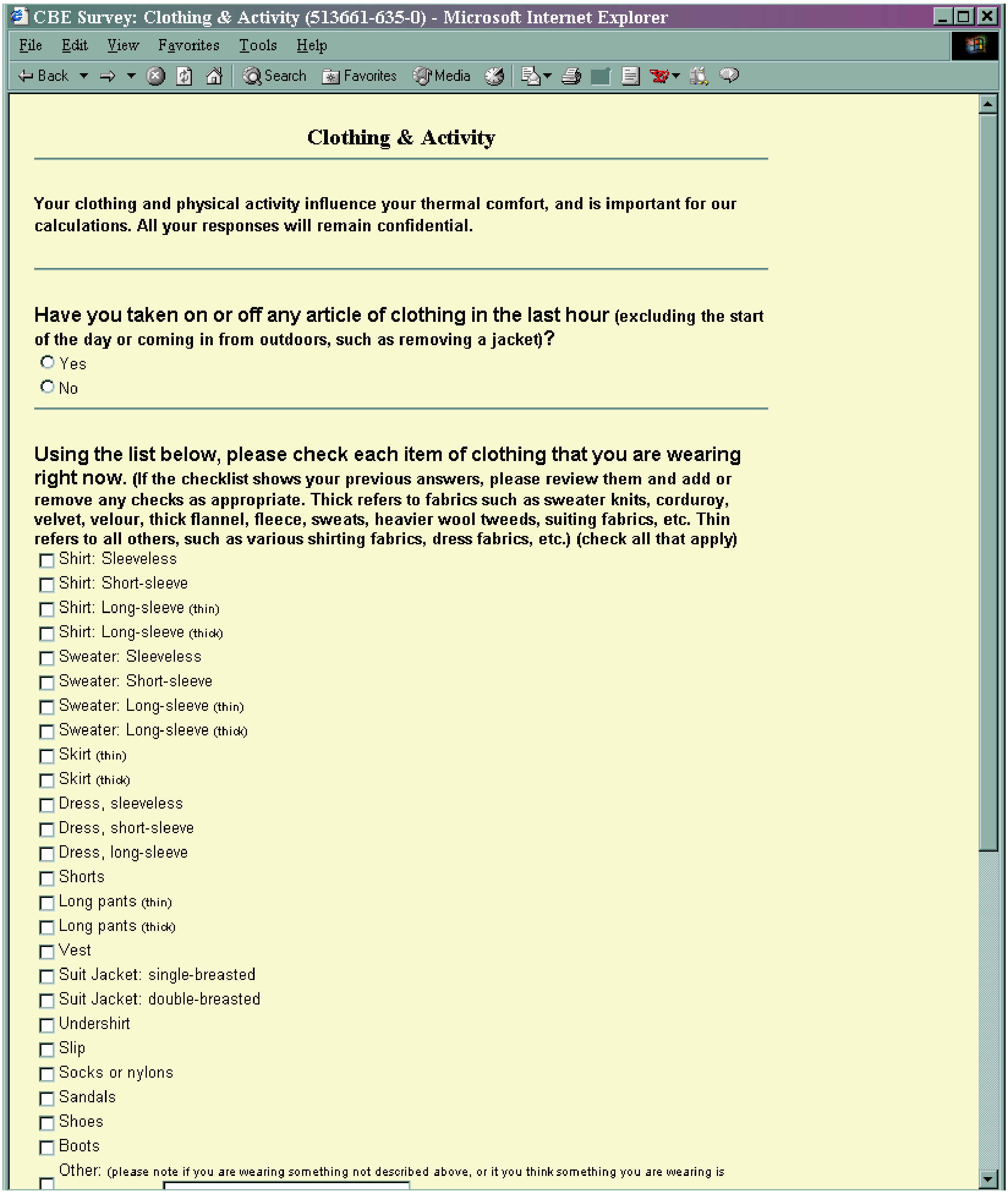

Figure D-4. Comfort survey page 2 – upper half

The upper half of page 2 collects data to calculate the participant's clo value.

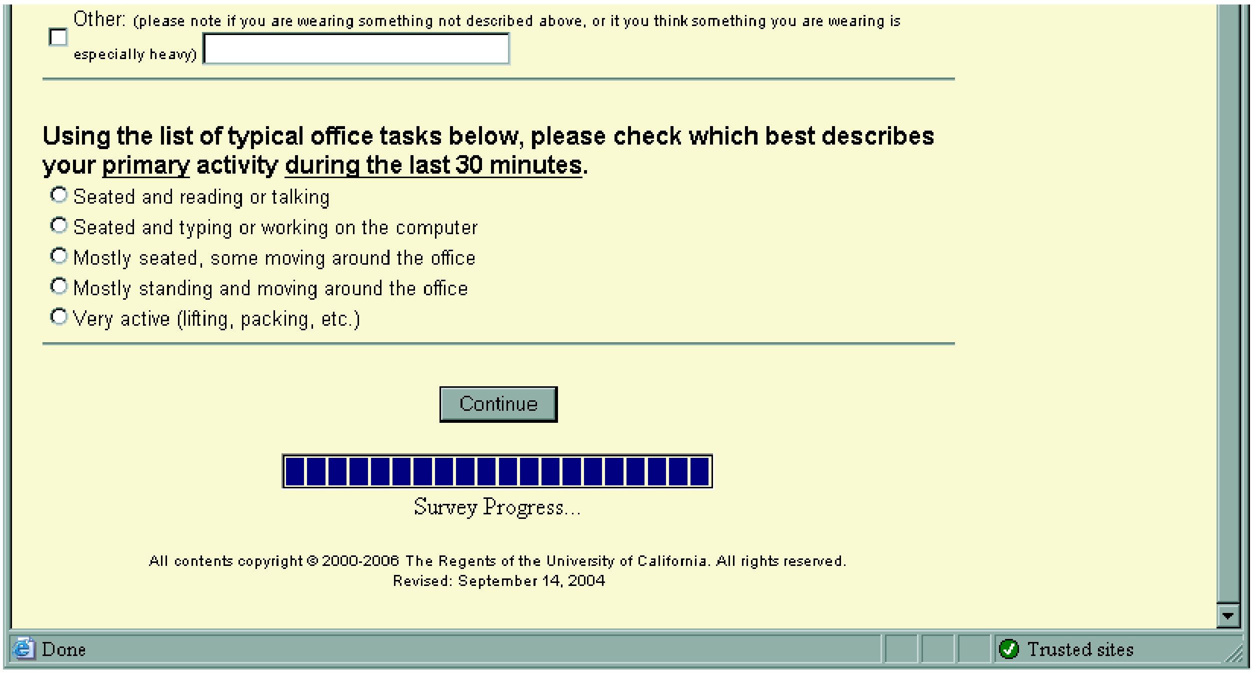

Figure D-5. Comfort survey page 2 – lower half

The lower half of page 2 collects data to calculate the participant's metabolic rate.

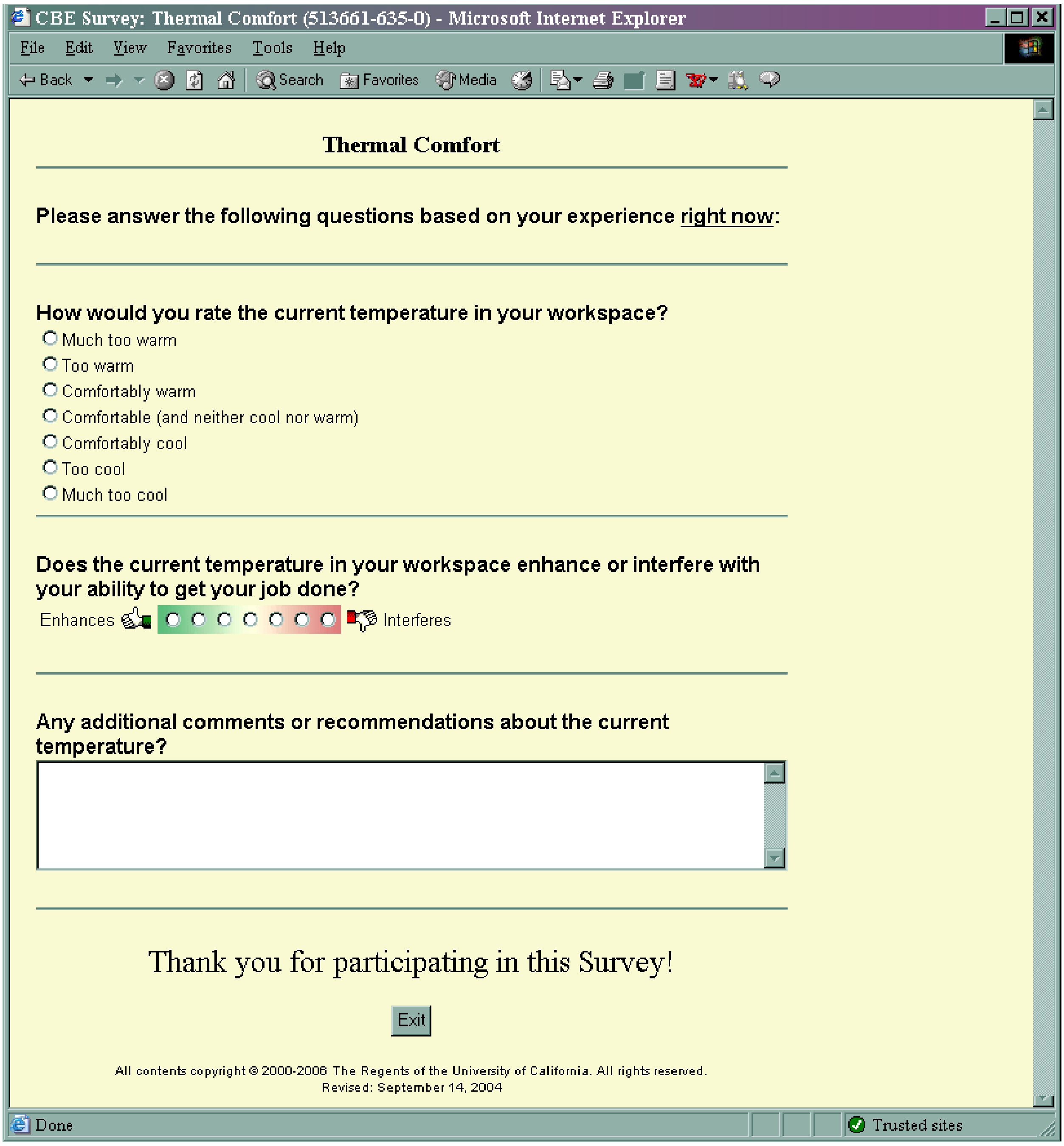

Figure D-6. Comfort survey page 3

Page 3 includes the Bedford scale to collect the participant's comfort/sensation vote, self-reported productivity affected by temperature, and an open-ended comment field.

Appendix E. Employee web-based survey invitations

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 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
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Appendix F. Survey Schedule, Strategy, and Weather by Date

Table F-1. Chabot Space & Science Center survey schedule

Date	Strategies	Weather	CIMIS[3] max Mills (°F)
8/8/2005	No pre-cooling + 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	Pre-cooling + 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	Pre-cooling + 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	Pre-cooling + 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	Pre-cooling + linear set up	Warm	86.4
9/29/2005	Pre-cooling + 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	Pre-cooling + aggressive linear set up	Cool	79.3
10/13/2005	Baseline	Cool	78.2

[3] Maximum temperature recorded at California Irrigation Management Information System (CIMIS) station at Mills College.

Table F-2. Oakland Scientific Facility survey schedule

Date	Strategies	Weather	NOAA[4] 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	Pre-cooling + 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	Pre-cooling + linear set up	Warm	81
9/29/2005	Pre-cooling + 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

Table F-3. Echelon survey schedule

Date	Morning	Afternoon	Weather	NOAA max SJC[5] (°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	

[4] Maximum temperature recorded at National Oceanic & Atmospheric Administration (NOAA), Oakland, Metro Oakland International Airport, CA (KOAK)

[5] Maximum temperature recorded at National Oceanic & Atmospheric Administration (NOAA), San Jose International Airport (SJC)

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 p.m.):
- Hallways with any ambient light turned off
- Daylit office lights turned off
- Inner office lights dimmed to 20%

High price (3 p.m. to 6 p.m.):
- 1 RTU turned off.
- The other 2 RTUs adjust the duct static pressure from 1.5 to 0.8 and the SAT from 55 F to 65 F

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