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Advanced Integrated Systems Technology Development: Personal Comfort Systems and Radiant Slab Systems

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ADVANCED INTEGRATED SYSTEMS TECHNOLOGY DEVELOPMENT:

Personal Comfort Systems and Radiant Slab Systems

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PREFACE

The California Energy Commission Energy Research and Development Division 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 Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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ABSTRACT

To achieve the radical improvements in building energy efficiency being called for by the State of California, it will be necessary to apply an integrated approach involving new designs, new technologies, new ways of operating buildings, new tools for design, commissioning and monitoring, and new understanding of what comprises a comfortable and productive indoor environment. This project, which is an amendment to CEC Contract 500-08-044, has focused on two space conditioning technologies that were part of the original project and showed significant potential to dramatically improve traditional levels of energy efficiency while also increasing occupant satisfaction and thermal comfort. The amendment allowed us to extend our ongoing research on these two promising technologies: personal comfort systems , and radiant heating and cooling systems.

The work done under this project has advanced the understanding of personal comfort systems and radiant heating and cooling systems, and has generated the following findings and recommendations: (1) four field demonstration studies with personal comfort systems technologies showed evidence of reduced zone heating energy use (as much as 46-75 percent for one study) while also dramatically improving occupant comfort under a variety of challenging thermal situations; (2) the personal comfort systems components tested in the four demonstration field studies included foot warming devices, leg warming devices, chairs that provide both heating and cooling, and small desk fans for cooling; (3) the results of the personal comfort systems field studies demonstrated that personal comfort systems have reached a level of performance that supports commercial market introduction; (4) building energy performance data, occupant satisfaction assessments, and valuable lessons learned from two successful and well-performing radiant slab office buildings; (5) development of an online map of buildings using radiant technologies to provide resources to building stakeholders who are interested in their implementation; (6) laboratory experiments comparing zone-level sensible cooling loads between radiant chilled ceiling and overhead air distribution systems confirmed the fundamental differences and implications for cooling load calculation methods; (7) two energy simulation studies showed that the David Brower Center design and heating, ventilating and air conditioning strategy present a viable design option in terms of predicted energy use and thermal comfort over a range of California climates, and demonstrated the potential impact of more accurately specifying furniture and contents (i.e., internal mass) on predicted zone peak cooling loads.

Keywords: Personal comfort systems (PCS), radiant heating and cooling systems, integrated systems, field studies, laboratory studies, thermal comfort, energy simulation, building energy use, cooling loads.

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EXECUTIVE SUMMARY

Introduction

The State of California is calling for radical improvements in building energy efficiency. The goals will not be met without an integrated approach involving new designs, new technologies, new ways of operating buildings, new tools for design, commissioning and monitoring, and new understanding of what comprises a comfortable and productive indoor environment. Many of these new developments are being worked on at the Center for the Built Environment and elsewhere, but the pace is not adequate to support the great changes rightfully being demanded of the building industry.

This project, which is an amendment to California Energy Commission (Energy Commission) Contract 500-08-044, has focused on two space conditioning technologies that were part of the original project and showed significant potential to dramatically improve traditional levels of energy efficiency while also increasing occupant satisfaction and thermal comfort. The amendment allowed us to extend our ongoing research on these two promising technologies, by adding two tasks to the original scope of work: Task 5 – Personal comfort systems (PCS), and Task 6 – Space conditioning in near zero-net-energy (ZNE) buildings. Task 6 focused on radiant heating and cooling systems. In addition, the research team continued to report on Task 4 – Technology transfer activities.

Project Purpose

The overall goal of this project was to support the building industry to overcome barriers in creating energy efficient buildings of high indoor environmental quality. The project focused on two advanced and innovative technologies, personal comfort systems (PCS) and radiant systems, both of which provide opportunities for disruptive breakthroughs on the design and operation of integrated building systems leading to deep energy reductions while also improving thermal comfort for building occupants. The deliverables will support the energy-efficiency goals being prescribed for buildings by the State. The work was performed in close collaboration with a broad consortium of building industry partners, and was appropriately interdisciplinary in scope.

The goals of each of the technical project tasks were as follows:

Task 5: Personal Comfort Systems (PCS)
The goals of this task were to demonstrate the energy and comfort impacts of PCS in different types of buildings, both conventional and energy-efficient; to demonstrate how PCS should be integrated with existing building controls to harvest the energy-savings made possible by PCS; and to influence the manufacturing of future PCS through presentations to the building industry and specifications for clients and standards organizations.

Task 6: Space Conditioning in Near Zero-Net-Energy (ZNE) Buildings
The goal of this task was to provide to the professional design community new and improved information, guidance, and tools for designing and operating near ZNE buildings using radiant

heating and cooling systems. This was accomplished by conducting two thorough case studies of existing near ZNE buildings using radiant systems. The two buildings studied were selected from a list of candidate buildings provided by Center for the Built Environment, University of California, Berkeley (CBE) industry partners and other sources. In addition to performance data and occupant satisfaction survey results from the case studies, improved understanding of optimized control strategies for radiant slab systems were developed through a series of fundamental laboratory experiments. All findings from the case studies and laboratory testing were supplemented with whole-building energy simulations using EnergyPlus, allowing a sensitivity analysis of climate and control strategies.

Task 4: Technology Transfer (continued from the previous phase of the project)
The goal of this task was to make the knowledge gained, experimental results and lessons learned available to key decision-makers. This includes encouraging that revisions to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards be done in an energy-conscious manner, reflecting the full range of design and technology choices available today. Work was also be performed to assist ASHRAE in developing Handbook chapters, the revised Underfloor Air Distributuion (UFAD) Design Guide, and Special Publications that adequately reflect new technologies and advanced design concepts.

Project Results

Personal comfort systems (PCS)

Overview

Designers and engineers expect modern buildings to provide satisfactory comfort for 80 percent of their occupants. Some buildings do better than this, and many do worse. One of the difficulties is that different occupants have different requirements for comfort; some like it cooler, some like it warmer, some prefer more air movement, others less. The same occupant may have different preferences at different times of day, when wearing different clothing, or perhaps after having just walked up a few flights of stairs.

The concept of a PCS is equipment that individuals can use to provide the environment they prefer at any particular moment, right where they are. With PCS, potentially 100 percent of the people in a building can be comfortable.

Fundamental lab studies at CBE on thermal comfort led to the concept of providing localized conditioning. Practical PCS have been in development for some time under different names, such as Task-Ambient Conditioning and Personal Environmental Controls. The field studies in this project were the first to demonstrate how PCS perform in real buildings, both qualitatively to provide comfort and quantitatively to save energy. They show that PCS have reached a level of performance that supports commercial market introduction, but also that further development is called for.

At present, the PCS components consist of foot warming devices, leg warming devices, chairs that provide both heating and cooling, and small desk fans. Other components are under consideration, and all of the current devices are in active development, at CBE and by a startup firm licensing the technology. The studies also provided invaluable feedback for improving these components, and for assessing their effectiveness.

Results from Field Studies

Four field studies were carried out, three on the University of California Berkeley campus and one at an advanced zero-net-energy building in San Jose, California. Two Berkeley studies were facilitated by California Institute for Energy and the Environment (CIEE) Deputy Director, Karl Brown. CIEE has been extremely helpful at arranging tests and demonstrations on University of California campuses, which contain a wide variety of building types and uses in most California climate zones. The CIEE program bridges the gap between laboratory scale testing and market introduction, providing an incubator where concepts and products can be improved and tested at scale.

These two studies were also funded by the CIEE State Partnership for Energy Efficient Demonstrations (SPEED) and have been reported on separately through that program. They are also included here because they were an essential part of the PCS development and testing, occurred during the time frame of the Public Interest Energy Research (PIER) amendment, and involved the same CBE researchers. In other words, they are synergistic and complementary, terms that apply to much of the valuable work facilitated by SPEED. The two SPEED studies took place in the Bancroft Library and the Cesar Chavez Student Union.

The library study served as the basis for a master's degree for Mallory Taub, who has now moved into private industry in the San Francisco Bay Area. This field study report was condensed from her thesis. The library study began with a week-long baseline comfort survey of the sixteen participants, and then the research team installed foot warmers and desk fans. (PCS chairs were not yet at that time available in volume.) An immediate improvement of comfort was indicated by the surveys following installation.

Over the course of a six-month winter season, in one degree Fahrenheit (F) steps, the heating set point was lowered from the initial 70 degrees F, followed by a one or two week-long survey. This continued down to a set point of 66 degrees F. Good comfort was maintained until the lowest set point, during which cold sensation began to affect comfort. The temperature was thereafter stepped back to the original set point in the same fashion. Comfort improvements and satisfaction were indicated both by survey results and exit interviews, although the latter indicated a number of improvements that could be made to the PCS devices. Zone heating energy savings ranged from 46 to 75 percent, depending on the set point and outdoor weather conditions.

The student union is a lightly conditioned building with high internal loads; at the time of the study it had ventilation and heating but no air conditioning. Thus, it provides a demonstration of the effectiveness of PCS in a space that might be uncomfortable in warm weather. The study included 18 participants, 14 used PCS chairs and 4 used fans and foot warmers. This study continued for six months over a heating and cooling season. Results indicated well over 80 percent comfort rate with PCS between 68 degrees F and 80 degrees F, while without the PCS, the average satisfaction rate was around 50 percent, with no period over 70 percent.

The third field study took place over 16 months in Stanley Hall, a nearly new laboratory building on the Berkeley campus that is both a large energy consumer and a source of comfort complaints. The building facility managers, Harry Stark and David Rogers, and their crew, especially Venzi Nikiforov, have been actively addressing these performance issues, and were invaluable in assisting this project, as was campus energy manager Chuck Frost. This study demonstrates the value of PCS in mitigating comfort issues while a heating, ventilating and air conditioning (HVAC) system is being worked on. The main problem was untuned controls that resulted in swings between too hot and too cold. The problem was eventually mitigated by adjusting and reducing airflow set points, which saved energy, and adding the PCS, which improved comfort significantly. Following introduction of the PCS, the average satisfaction rate soared from 56 percent to over 80 percent under all test conditions. Zone energy savings were also high, 60 percent in heating and 40 percent in cooling.

The fourth field study took place at the Integrated Design Associates (IDeAs) Z2 Design Facility in San Jose, built by David Kaneda and now a part of Integral Group. It is an advanced, radiantly heated and cooled building which received one of the earliest certifications as a zero-net-energy building. An interesting natural experiment took place during the winter in this three-month study; the heating was completely and unintentionally turned off for a period of approximately three weeks, unwittingly testing the limits to which the PCS chairs could provide comfort in very cold conditions. The research staff is grateful to the participants in the study, who are all enthusiasts for energy efficiency, for their cheerful patience through this difficult period and for their valuable suggestions.

In this study the energy savings due to temperature set backs were modest, because the building is so efficient to begin with. The PCS, as usual, substantially improved comfort.

In all, these field studies indicated the ability of PCS to dramatically improve comfort under a variety of challenging thermal situations, even while the exit interviews indicated room for even more improvement.

Commercialization and Development

Anticipating the marketability of the PCS concept, the CBE patented several aspects of it through the University. Learning of it through outreach at the CBE meetings, a highly regarded building mechanical engineer is beginning to commercialize the PCS chairs. At least 50 of the heated and ventilated chairs have been manufactured to date under the license. The PCS chair caught the eye of a local television news affiliate, which sponsored an informative broadcast segment covering it.

The field studies have revealed several ways the PCS can be improved. Beyond a more comfortable and visually attractive chair, participants indicated a need for finer control over heating functions. Additionally, work is beginning to develop a means to charge the chair battery without having to plug in.

Other components of the PCS are also being improved. A number of participants indicated the foot warmer hit their shins or altered their posture, and work is beginning to resolve this. Other approaches will also be developed, based on wireless power transfer. Modifications to the fan design were also suggested, and these are under consideration and development.

Standards were considered for the PCS, as it is evident that if PCS were deployed throughout a building, that building could use a much smaller HVAC system and still provide superior comfort. First-cost savings from this, plus the energy savings from operations, would easily recoup the cost of PCS. Before this can be realized, much more technical development and wider commercial deployment of PCS is needed, as well as performance standards for this equipment. This project brought that day substantially closer.

Space conditioning in near zero-net-energy buildings

Overview

Radiant cooling and heating systems provide an opportunity to achieve significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems. As a result, application of these systems has increased in recent years, particularly in ZNE and other advanced high performance buildings. A status report by New Buildings Institute (NBI) on 160 ZNE commercial buildings in North America shows a trend away from forced-air HVAC systems and increased adoption of radiant systems by these exemplary buildings [NBI 2014]. A recent article reported on a large side-by-side comparison between an optimized variable-air-volume (VAV) system and a radiant slab system with a dedicated outdoor air system (DOAS) [Sastry and Rumsey 2014]. The 250,000 ft^2 building, located in hot and humid Hyderabad, India - a very challenging climate for radiant systems - was divided into two identical halves. Each half was conditioned by just one of the systems so that a fair comparison could be made. After the first two years of operation, it is reported that the radiant system has used 34 percent less energy compared to the VAV system and the results of an occupant satisfaction survey also indicate greater satisfaction with thermal comfort for the radiant half of the building (63 percent satisfaction rate for radiant vs. 45 percent satisfaction rate for VAV system).

The goal of research on this task is to provide to the professional design community new and improved information, guidance, and tools for designing and operating near ZNE buildings using radiant heating and cooling systems. The research has generated (1) an online map listing buildings using radiant systems to support the exchange of information on radiant technologies and help identify potential case study sites, (2) occupant satisfaction survey results, energy use data, and valuable lessons learned from two case studies on the David Brower Center, Berkeley, CA, and the Sacramento Municipal Utility District (SMUD) East Campus Operations Center, Sacramento, CA, (3) improved fundamental understanting from the results of a full-scale laboratory experiment to investigate cooling load differences between radiant and air systems, (4) simulation studies using EnergyPlus to investigate application of the David Brower Center design to different California climates, and dynamic energy impacts of thermal mass, and (5) development of presentation material on the design and control of radiant slab systems for use in near ZNE buildings.

Online map of buildings using radiant technologies

In this task, we developed an online map of buildings using radiant technologies to provide resources to building stakeholders who are interested in their implementation. The collected information was also helpful in selecting case study sites for this project. The online map can be accessed at: http://bit.ly/RadiantBuildingsCBE.

Case studies of near ZNE buildings using radiant systems

In this task, we conducted case studies in two Leadership in Energy and Environmental Design (LEED) Platinum office buildings with radiant slab systems, as summarized below.

Case Study #1: David Brower Center. The David Brower Center (DBC) is a 4-story 45,000-ft^2 LEED Platinum certified office building located in downtown Berkeley, California. The building was completed and first occupied in May 2009. It contains lobby and public meeting space on the first floor and open plan office spaces on the 2nd – 4th floors that primarily house non-profit environmental activist organizations. Integral Group (formerly Rumsey Engineers) was the mechanical design engineer on the project and, working with the architect (Solomon E.T.C.–WRT) and other design specialists, put together a design promoting low energy consumption. The primary space conditioning subsystem is hydronic in-slab radiant cooling and heating that is installed in the exposed ceiling slab of the 2nd – 4th floors of the building. A DOAS provides ventilation air using underfloor air distribution.

The overall conclusions from this case study are:

- The Brower Center is a good example of a high performing building in terms of energy, indoor environmental quality (IEQ), and occupant satisfaction.
- The building demonstrated exceptional energy performance, achieving an Energy Star rating of 99, well above the threshold of 75 to qualify for an Energy Star label. The rating was based on utility bill data for electricity, steam, and water from calendar year 2014.
- The radiant slab system, in combination with advanced shading, underfloor air distribution, operable windows, thermally massive concrete structure and other design features, is performing well. Although there have been instances when inside temperatures during warm weather have reached higher levels, overall the advance integrated design and mild Berkeley weather have produced an indoor environmental quality that the occupants are quite satisfied with, as reported by the occupant survey. The building operator also expressed satisfaction with the building.

Case Study #2: SMUD East Campus Operations Center. The (SMUD) East Campus Operations Center is a 200,000 ft^2 LEED Platinum certified office building. The building was designed by Stantec [Architecture and Mechanical, Electrical and Plumbing (MEP)] and includes a great number of energy efficient technologies and design strategies: thermally activated building system (TABS), radiant embedded surface ceiling system, chilled beams, geothermal exchange, thermal energy storage tanks, heat recovery wheel, ceiling fans, high thermal mass, advanced window blinds that redirect solar energy onto ceiling, etc. The site also integrates a large area of solar photovoltaic panels that enable the whole campus (five buildings in total) to approach ZNE. The SMUD building was completed and occupied during the summer of 2013. The building uses an exposed radiant ceiling slab for primary space conditioning in combination with an overhead DOAS for ventilation and latent load control.

In this field study the research team had a unique opportunity to conduct a detailed review and analysis of the building's performance through access to a full set of trend log data from the building management system (BMS) in combination with additional data from an array of 50 wireless sensors installed by the research team. We focused our attention on the operation and control of the radiant slab system on one representative floor (level 2) of the 6-story office building. When the research team first began monitoring the building, we found that many of the control settings for the radiant slab system were more representative of how a quick-response all-air system would be controlled. Key observations and findings derived from our review of the operation and control of the radiant slab system are listed below.

- A preferred approach is to adjust the controls so that the slab is precooled in the early morning, thereby avoiding the need for active cooling during the middle of the day and shifting system cooling loads to more efficient and cost-effective nighttime hours.
- After control adjustments were made following the above strategy, the building was able to successfully maintain comfortable zone temperatures throughout hot summer days by precooling the radiant slab during the night.
- Changes were made to the original heating and cooling setpoint schedule for the radiant slab zones that widened the deadband and added nighttime and weekend setbacks. After implementation, heating and cooling activity in all zones was significantly reduced. This represents a control strategy that is more energy efficient, reduces wear and tear on the hydronic system, and recognizes that radiant slab systems require some sort of anticipatory control.
- It was observed that perimeter zone thermostats, embedded in the exterior wall, were unsealed and exposed to airflow in the wall cavity (when the air distribution system was turned off at night), thereby causing the thermostats to measure nighttime temperatures during winter months that were about 5 degrees F cooler than the actual zone air temperatures. After sealing and insulating the thermostats, this pattern was eliminated, which helped to reduce unnecessary heating by the radiant slab system during the night. It is important to ensure that thermostats used for radiant system control are representative of zone temperatures, since slab systems often operate at night.

Laboratory testing

Radiant cooling systems work fundamentally differently from air systems by taking advantage of both radiant and convective heat transfer to remove space heat. However, in current practice, the same design cooling load calculation methods for radiant systems are used as the convection-only-based air systems. In 2013, we conducted laboratory experiments comparing zone-level sensible cooling loads between radiant chilled ceiling and overhead air distribution systems to verify the differences observed during our previous simulation studies.

The experiments were conducted in the Hydronic Test Chamber at CBE partner Price Industries in Winnipeg, Manitoba. Four tests with two heat gain profiles were carried out in the full-scale climatic chamber. For each profile, two separate tests were carried out to maintain a constant operative temperature: one with radiant chilled ceiling panels; and a second with an overhead mixing air distribution system. The experiments show that, during the periods the heat gain was on, the radiant system has on average 18–21 percent higher instantaneous cooling rates compared to the air system, and 75–82 percent of total heat gains were removed, while for the air system only 61–63 percent were removed. Based on the study, we conclude that a new definition must be used for radiant system cooling load. Peak cooling loads for radiant systems may be higher or lower than those for air systems, depending on how the systems are configured and operated. For example, active nighttime pre-cooling of the slab during warm weather can allow the radiant system to be turned off during the following day's peak cooling period while still maintaining comfortable space conditions. This was demonstrated during the case study of the SMUD office building.

Energy simulations studies

Two simulation studies were carried out to improve our understanding of radiant system performance under different climate conditions and to investigate the impact of furniture and internal thermal mass on building energy performance, as described below.

Application of Brower Center design to different California climates. The goal of this simulation study was to evaluate the applicability of the main features of the DBC design and HVAC strategies (e.g., TABS, mixed-mode ventilation based on the combination of UFAD and natural ventilation, no chiller, evaporative cooling tower, high performance envelope, exterior sun shading devices) to three California cities/climates: Oakland, Los Angeles and Sacramento.

We learned that the DBC design and HVAC strategy present a viable design option in terms of predicted energy use and thermal comfort for these three cities. Overall energy consumption is low and quite typical for an energy efficient building. The ASHRAE 55-2013 target of 80 percent satisfied is reached for over 90 percent of the time (weighted by occupancy) for the three cities. This supports the idea that a radiant slab system using a pre-cooling strategy based on evaporative cooling sources (cooling tower) only, without the need for a chiller, is an appropriate HVAC design approach over a range of California climates.

Dynamic energy impacts of thermal mass. In our ongoing energy simulation studies of advanced low-energy HVAC systems, including radiant and UFAD, we have become aware of the importance of thermal mass in the building, particularly when illuminated by direct solar radiation. This simulation study focused on the effect that internal mass has on cooling loads, and how current simulation tools model these effects. There is considerable debate whether current practices yield sufficiently accurate instantaneous peak cooling load estimates. This also applies to heating loads, but is less critical because heating energy costs are not as time and peak sensitive as cooling energy costs.

In this study we assessed the impact that furniture and contents (i.e., internal mass) have on zone peak cooling loads using a perimeter zone model in EnergyPlus across 5400 parametric simulation runs. The HVAC system types investigated were overhead, underfloor, and TABS. Overall, adding internal mass changed peak cooling load by a median value of −2.28 percent (−5.45 percent and −0.67 percent lower and upper quartiles respectively) across the studied parameter space. Though the median is quite low, this study highlights the range of effects that internal mass can have on peak cooling loads depending on the parameters used, and the discussion highlights the lack of guidance on selecting reasonable values for internal mass parameters. Based on this we recommend conducting an experimental study to answer outstanding questions regarding improved specification of internal mass parameters.

Presentation material for ZNE building performance seminar

During the past six months, CBE has been developing a set of slides to introduce radiant systems to the professional design community. We were assisted in this effort by CBE Partner Viega LLC, manufacturer of crosslinked polyethylene (PEX) tubing for radiant slab systems (TABS). The presentation material covers the following topics related to radiant slab systems for ZNE buildings:

- How radiant systems work with a focus on radiant slabs (TABS);
- Heat transfer fundamentals;
- Energy use;
- Thermal comfort in comparison to conventional all-air systems;
- Project examples;
- Design guidance.

Project Benefits

Personal comfort systems

PCS are a promising technology for both improving occupants' thermal comfort and simultaneously reducing buildings' heating and cooling energy. PCS save energy by enabling the ambient air temperature to be less controlled. In U.S. commercial buildings, a typical temperature range between setpoints for heating and cooling systems (setpoint deadband) is between 71 degrees F and 73 degrees F. Each 1 degree C (1.8 degrees F) broadening of this deadband reduces annual HVAC energy use by approximately 10 percent [Holt et al. 2015]. A recent laboratory study has established that PCS can produce comfort across ambient temperature ranges in the vicinity of 64-86 degrees F [Pasut et al. 2015]. This implies that a building can be controlled with an extended thermostat deadband while still maintaining occupants’ thermal comfort.

To estimate the project benefits associated with installing PCS in office environments, we applied the following assumptions.

- PCS technology is suitable for large and small office buildings, and colleges, new and existing. The California Commercial End-Use Survey (CEUS) database was used to estimate appropriate square footage and total energy use for heating (natural gas) and cooling (electricity) of these building categories in California.
- Following the predicted energy savings from Holt et al. (2015), we assumed that the average baseline temperature deadband of 71-73 degrees F could be broadened to 1 degree F below the lower end of the ASHRAE Standard 55-2013 [ASHRAE 2013] comfort zone (67 degrees F) and 1 degree F above the upper end of the comfort zone (80 degrees F). This resulted in an assumed heating energy savings of 20 percent and cooling energy savings of 42 percent.
- The market penetration for PCS technology was assumed to be 25 percent.

With the above assumptions, the benefits of PCS technology are:

- 5.1 million therms per year of natural gas savings
- 267 million kilowatt hour (kWh) per year of electricity savings
- $40.9 million per year of energy cost savings (at rates of $0.68 per therm & $0.14 per kWh)
- 141,000 tons of carbon dioxide equivalent (CO_2e) emissions per year avoided [at 11.7 pounds (lbs) per therm and 0.83 lbs per kWh]

Radiant heating and cooling systems

The California Public Utilities Commission strategic plan requires that all new buildings and 50 percent of all existing buildings are ZNE by 2030 [CPUC 2011]. More than 50 percent of ZNE buildings use hydronic radiant systems [NBI 2012], despite the lack of design and operational guidance for these systems. Recent studies have shown that hydronic radiant systems are far more efficient that even best-practice all-air systems. Depending on the study, values for HVAC energy savings range from 34 percent up to 67 percent [Sastry and Rumsey 2014, Leach et al. 2010, Thornton et al. 2009, Moore 2008]. We use the above assumptions to determine a projected number of radiant buildings by 2030[1], and take the lowest energy savings estimate (34 percent) to calculate the estimated energy savings based on the outcomes of this project:

1) 34 percent HVAC energy savings on a modest 2 percent of the building stock– the estimated increase in installations of radiant systems directly attributable to the findings of this project, specifically due to:

[1] The fraction of applicable buildings used in these savings calculations were reduced for certain Commercial End Use Survey categories: 50 percent for the college, restaurant and miscellaneous sectors due to high levels of internal heat gains that may preclude radiant systems as an option; 75 percent for the health sector, where high ventilation requirements may make all-air systems a more realistic choice for many zones; and (100 percent) refrigerated warehouses were entirely excluded due to the limitations of radiant systems at very low temperatures. To a certain extent, buildings in any category that are not suitable for radiant systems are captured by the existing 50 percent projection for ZNE buildings that do not use radiant systems, however conservative figures were chosen and estimates were further reduced.

a. Improved understanding of fundamentals leading to well-defined standards, more reliable systems, improved sizing methods, and detailed guidance regarding design considerations and limitations.
b. Increased visibility of survey data highlighting the success of buildings that use these systems, as well as in-depth case studies that show *how and why* these buildings succeed in delivering higher energy efficiency, and the particular problems they may have faced during design and operation.
c. Improved understanding of operations and controls of radiant systems.

2) 55 percent cooling energy savings from improved controls for radiant systems that capitalize on the benefits made possible by TABS [Feng 2014], applied to the total projected percentage of the building stock using radiant systems (27 percent).

These assumptions (27 percent of the commercial building stock using radiant systems by 2030) imply a rate of update of 1.8 percent per annum in the 15 years between project end in 2015 and 2030.

Additionally, the amount of savings were assessed due to peak demand reduction using time dependent valuation (TDV) values for California [Energy and Environmental Economics 2011], which shows that the energy cost per unit of electricity generated is an annual average of 30 percent higher during the hours of 12-4 pm across all 12 climate zones. We assume that on average 1.5 W/ft2 of peak electricity demand is due to cooling energy, and estimate that we can save a higher percentage (70 percent) of this during this period through advanced controls (slab cooling in pre-peak periods) and other design considerations.

Given the above assumptions, the estimated savings across all California building types is 844 GWh/yr, $165 M/yr, and 496M pounds of CO2e/yr by 2030. In addition to these savings, we estimate a reduction in peak electricity demand of 104 MW, corresponding to an additional $46 M/yr per year in TDV-weighted electricity costs.

References

ASHRAE. 2013. ANSI/ASHRAE Standard 55-2013, "Thermal environmental conditions for human occupancy." Atlanta: ASHRAE.

CPUC. 2011. CA Energy Efficiency Strategic Plan: January 2011 Update. California Public Utilities Commission, San Francisco, CA.

Energy and Environmental Economics. 2011. Time Dependent Valuation of Energy for Developing Building Efficiency Standards: 2013 Time Dependent Valuation (TDV) Data Sources and Inputs. Energy and Environmental Economics, Inc., San Francisco, CA.

Feng, J. 2014. Design and control of hydronic radiant cooling systems. PhD Dissertation, Department of Architecture, University of California, Berkeley, CA.

Hoyt, T., E. Arens and H. Zhang. 2015. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. *Building and Environment*, Vol. 88, June, pp. 89–96; doi:10.1016/j.buildenv.2014.09.010.

Leach, M., C. Lobato, A. Hirsch, S. Pless and P. Torcellini. 2010. Technical support document: Strategies for 50 percent energy savings in large office buildings. NREL, Golden, CO.

Moore, T. 2008. Simulation of radiant cooling performance with evaporative cooling sources. Summary Report, Center for the Built Environment, University of California, Berkeley, CA.
NBI. 2014. Getting to Zero 2014 Status Update. Research report, New Buildings Institute, Vancouver, WA.
NBI. 2012. Getting to Zero 2012 Status Update: A first look at the costs and features of zero energy commercial buildings. Research report, New Buildings Institute, Vancouver, WA.
Pasut, W., E. Arens, H. Zhang, and Y. Zhai. 2015. Energy-efficient comfort with a heated/cooled chair: Results from human subject tests. *Building and Environment*, Vol. 84, January, pp. 10-21; doi:10.1016/j.buildenv.2014.10.026.
Thornton, B. A., W. Wang, M. D. Lane, M. I. Rosenberg and B. Liu. 2009. Technical support document: 50 percent energy savings design technology packages for medium office buildings. Pacific Northwest National Laboratory, Richland, WA.
Sastry, G., P. Rumsey. 2014. VAV vs. radiant: Side-by-side comparison. *ASHRAE Journal,* 56 (5).

CHAPTER 1:
Personal Comfort Systems

Designers and engineers expect modern buildings to provide satisfactory comfort for 80 percent of their occupants. Some buildings do better than this, and many do worse. One of the difficulties is that different occupants have different requirements for comfort; some like it cooler, some like it warmer, some prefer more air movement, others less. The same occupant may have different preferences at different times of day, when wearing different clothing, or perhaps after having just walked up a few flights of stairs.

The concept of Personal Comfort Systems (PCS) is equipment that individuals can use to provide the environment they prefer at any particular moment, right where they are. With PCS, potentially 100 percent of the people in a building can be comfortable.

Fundamental lab studies at Center for the Built Environment (CBE) on thermal comfort led to the concept of providing localized conditioning. Practical PCS have been in development for some time under different names, such as Task Ambient Conditioning and Personal Environmental Controls. The field studies in this project were the first to demonstrate how PCS perform in real buildings, both qualitatively to provide comfort and quantitatively to save energy. They show that PCS have reached a level of performance that supports commercial market introduction, but also that further development is called for.

At present, the PCS components consist of foot warming devices, leg warming devices, chairs that provide both heating and ventilation, and small desk fans. Other components are under consideration, and all of the current devices are in active development, at CBE and by a startup firm licensing the technology. The studies also provided invaluable feedback for improving these components, and for assessing their effectiveness.

Four field studies were carried out, three on the University of California Berkeley campus and one at an advanced zero-energy building in San Jose, California. Two Berkeley studies were facilitated by California Institute for Energy and the Environment (CIEE) Deputy Director, Karl Brown. CIEE has been extremely helpful at arranging tests and demonstrations on University of California campuses, which contain a wide variety of building types and uses in most California climate zones. The CIEE program bridges the gap between laboratory scale testing and market introduction, providing an incubator where concepts and products can be improved and tested at scale.

Two of the studies were also funded by the CIEE State Partnership for Energy Efficient Demonstrations (SPEED) and have been reported on separately through that program. They are also included here because they were an essential part of the PCS development and testing, occurred during the time frame of the Public Interest Energy Research (PIER) amendment, and involved the same CBE researchers. In other words, they are synergistic and complementary, terms that apply to much of the valuable work facilitated by SPEED. These were the studies in the Bancroft Library and the Cesar Chavez Student Union.

The library study served as the basis for a master's degree for Mallory Taub, who is now employed in a major international engineering practice in the San Francisco Bay Area. This field study report was extracted from her thesis and from the subsequent peer-reviewed paper now published in Energy and Buildings, (final draft presented in Appendix 1.1.1).

The student union is a lightly conditioned building with high internal loads; at the time of the study it had ventilation and heating, but no air conditioning. Thus, it provides a demonstration of the effectiveness of PCS in a space that might be uncomfortable in warm weather.

The third field study took place in Stanley Hall, a nearly new laboratory building on the Berkeley campus that is unfortunately a large energy consumer and also the source of comfort complaints. The building facility managers, Harry Stark and David Rogers, and their crew, especially Venzi Nikiforov, have been actively addressing these issues, and were invaluable assisting on this project, as was campus energy manager Chuck Frost. This study demonstrates the value of PCS in mitigating comfort issues while an HVAC system is being worked on.

The fourth field study took place at the Integrated Design Associates (IDeAs) Z2 Design Facility in San Jose, built by David Kaneda and now a part of Integral Group. It is an advanced, radiantly heated and cooled building which received one of the earliest certifications as a zero energy building. An interesting natural experiment took place during the winter months of this study; the heating was completely and unintentionally turned off, unwittingly testing the limits to which the PCS chairs could provide comfort in very cold conditions. The research staff is grateful to the participants in the study, who are all enthusiasts for energy efficiency, for their cheerful patience through this difficult period and for their valuable suggestions.

Anticipating its marketability, the CBE, through the university, patented several aspects of the PCS concept. Through outreach at the CBE semiannual meetings, a licensing agreement was established with a mechanical engineer and an advanced HVAC equipment manufacturer who have started an effort to commercialize the PCS chairs.

The field studies also indicated several ways the PCS can be improved. Exit interviews revealed that users wanted stronger fans, finer adjustment of heating in the chairs, and better ergonomics for the foot warmers.

Performance standards were considered for the PCS, which will require developing a standard method of test. Developing these standards, and wider use of the PCS as a means of handling individual comfort issues, can eventually lead to acceptance of them as a means of providing improved comfort conditions in buildings, even with a broader range of indoor temperatures.

In this scenario, PCS will enable energy savings and allow a smaller, less expensive HVAC system, or in some cases, no HVAC system at all. First-cost savings from smaller HVAC, plus energy savings from more efficient operations, will more than recoup the additional cost of PCS. This project brought this scenario of improved comfort combined with large energy savings substantially closer.

1.1 Bancroft Library Doe Annex

1.1.1 Overview

From October 2012 until April 2013, CBE researchers studied the effects of PPCS on office worker thermal comfort and overall energy use in the Doe Annex of the Bancroft Library on the

University of California, Berkeley (UCB) campus. Figure 1.1-1 shows the library and office characteristics.

The objectives were to determine if the PCS could maintain adequate comfort while zone temperatures were reduced to a level, which would normally produce cold complaints, and to determine the energy savings. Because the study was limited to the colder months of October through April, the savings were in heating energy.

During the initial week in October, temperature set points were maintained at 70 degrees Fahrenheit (F). The sixteen workers in the study were then given foot warmers and personal desk fans, and week-by-week the temperatures were gradually reduced down to 66 degrees F, and then gradually raised back to 70 degrees F by April. Workers were surveyed several times each day for perceived comfort and thermal sensation using the CBE comfort survey. Energy use of the PCS and the HVAC systems were monitored throughout the study period. At the end of the study period each worker was interviewed for his or her opinions on the PCS.

Figure 1.1-1: Bancroft Library and office layout

Photo Credit: Center for the Built Environment

1.1.2 Building, Equipment, and Climate

1.1.2.1 Personal Comfort System Devices

The researchers chose a foot warmer and a personal fan combination for the experiment. The fan sits atop the desk and is powered by a universal serial bus (USB) connection. It includes an occupancy sensor, a temperature sensor, and a variable speed control, which the user can adjust by turning a knob on the fan's base. The power consumption of this fan is extremely low; at maximum output it uses just 3 W.

The foot warmer is a sturdy steel box, open in the front, which uses four incandescent reflector lamps to radiate heat towards the top of the feet. A spring plate inside the box turns on the lights when depressed by the users feet. The foot warmer is also variable power, from 0 to 160W, which is conveniently adjusted by another knob on the fan base. The fan and foot warmer are thus an integrated system, which was developed at CBE. The system is illustrated in Figure 1.1-2.

Figure 1.1-2: Fan/Foot warmer PCS

Photo Credit: Center for the Built Environment

1.1.2.2 Building Characteristics

The researchers selected Doe Annex because it is a relatively isolated from the main library, allowing precise energy use determinations, and is used by a gender-diverse group who spend most of their workday programming at their desks. It is conveniently located near the CBE laboratories, has a cooperative staff, and a suitable space conditioning system. Most windows in the space face north, reducing sunlight penetration as an issue for comfort studies. The area included in the study was 2957 ft^2 of open plan office and 420 ft^2, total, in two private offices.

Figure 1.1-3: Doe Annex Office floor plan

Floor Plan courtesy UC Berkeley Physical Plant Office

1.1.2.3 Heating, Ventilation and Air Conditioning System Characteristics

The Doe Annex uses an Air Handling Unit (AHU) with heating and cooling coils for space conditioning. (Figure 1.1-4) The AHU supplies seven Variable Air Volume (VAV) air terminal units with air temperature maintained at a constant 56 degrees F (Figure 1.1-5). Each air terminal unit is equipped with a reheat coil to control zone temperatures in each of seven zones. For this study each of the seven wall thermostats were programmed to act only as temperature sensors so the set points could be controlled by the Automated Logic Corporation (ALC) building control system. Data from this control system were accessible to sMAP (simple Measurement and Actuation Profile) a system developed by the computer science department at UCB for collecting, analyzing and acting upon system data. The researchers used sMAP to log temperature data for energy analysis.

Figure 1.1-4: HVAC system schematic diagram

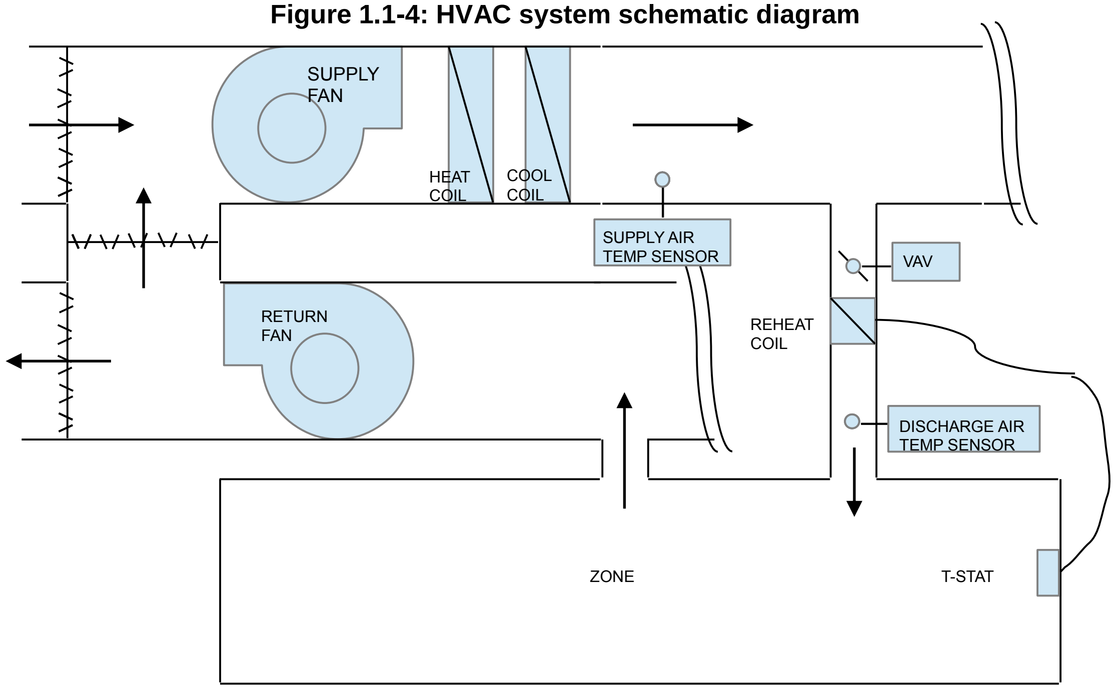


Figure 1.1-5: Temperature control zone plan in Doe Annex

Prior to data collection, airflow through the VAV boxes was calibrated at three flow settings using a laboratory-grade flow measurement hood (Figure 1.1-6). The airflows reported by the ALC system agreed to within 1.5 percent of the flow measurement hood.

Figure 1.1-6: Airflow calibration process and measured airflow values

VAV Box	Damper Position	BMS Airflow (cfm)	Actual Airflow (cfm)	Slope of linear regression of actual vs BMS airflow
2.8	55	1163	1169	1.01
	33	627	647	
	15	143	194	
2.10	55	834	796	0.95
	40	560	525	
	25	282	258	
2.13	55	569	559	0.94
	35	358	309	
	25	206	178	
2.14	55	259	236	0.90
	35	119	109	
	30	88	71	
2.18	55	632	682	1.06
	35	413	432	
	20	227	225	

Photo Credit: Center for the Built Environment

1.1.2.4 Local Climate Data

Berkeley is in ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) climate zone 3 and California Energy Commission climate zone 3. Figure 1.1-7 shows that between October and April, at the nearby Oakland Airport, buildings with small internal loads will typically require some heating. Hourly temperature and humidity data at

Oakland Airport are shown in Figure 1.1-8, with the time period of the study outlined. Because of the season available for the study, the research focused on heating comfort that could be provided by the PCS.

Figure 1.1-7: Heating and cooling degree-days at Oakland International Airport

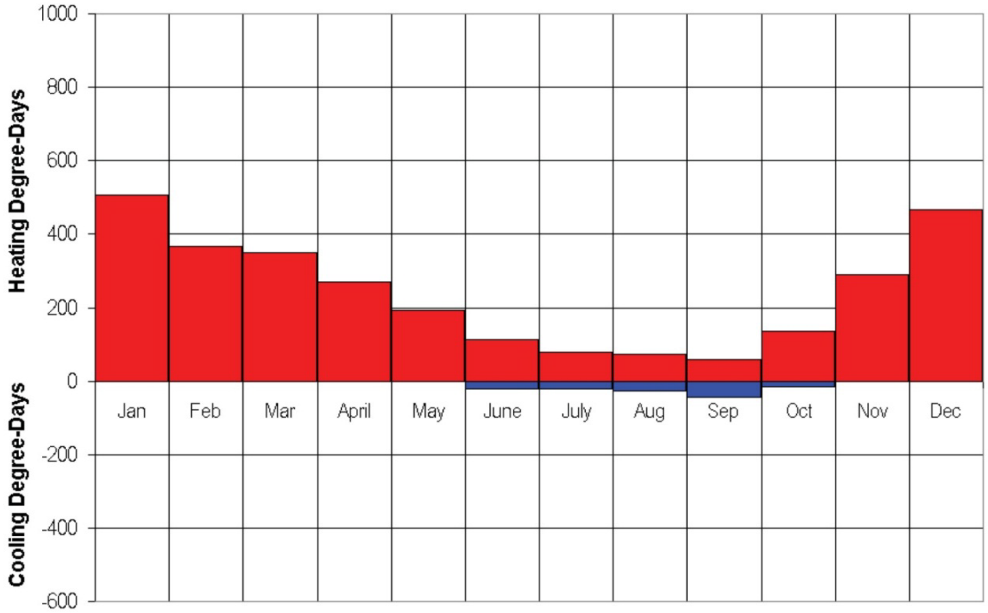


Figure courtesy Pacific Energy Center

Figure 1.1-8: Typical hourly temperatures and relative humidity at Oakland International Airport

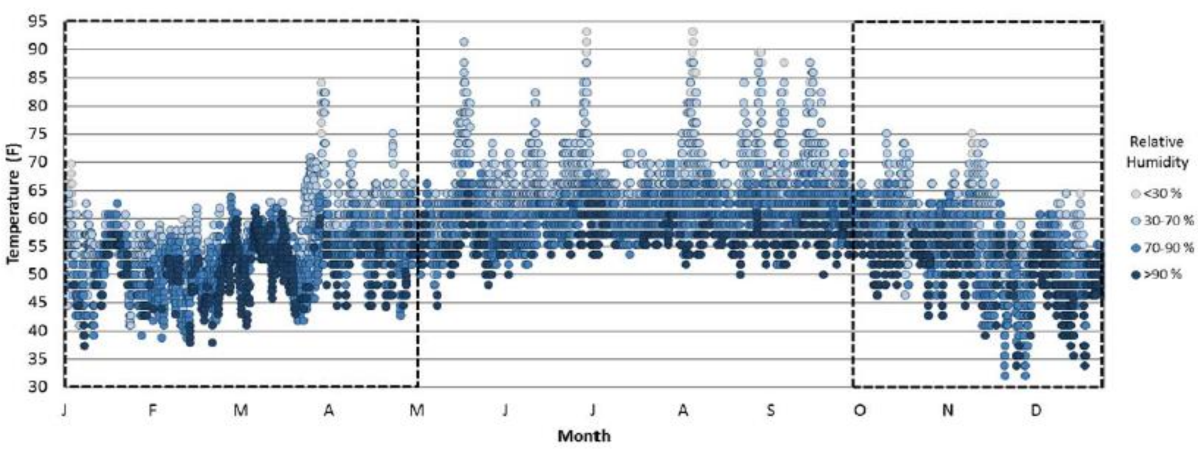


Figure courtesy Pacific Energy Center

1.1.3 Experimental Methodology

1.1.3.1 Physical Measurements

Since the study needed to integrate comfort perceptions with energy analysis, both physical and subjective information had to be integrated in the study. HVAC information was recorded through the ALC system, to determine the energy provided by the HVAC system. Plug loads in the individual cubicles, including the computer, foot warmer, and fan, were logged by ACme power meters (an open source hardware and software platform that enables wireless energy/power measurement and control of alternating current devices), which enabled wireless data transfer and data access through sMAP. Because of the distinct power profiles of the foot warmer, the computer, and the monitor, it was not difficult to separate the energy consumption of the foot warmer. The desk fan would count as part of the computer load, but since it only consumes 4W, it is essentially negligible. Figure 1.1-9 shows all the physical data that was logged and used in the energy calculations.

Figure 1.1-9: Physical data logged for energy calculations

Data	Source	Measurement Frequency	Application
PCS Power Usage	ACme Meter (one per workstation)	Interpolated to even 15 minute intervals from more frequent data captures	Needed to calculate change in plug load use
Room Temperature (T_{rm})	BACnet	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Discharge Air Temperature (DAT)	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Supply Air Temperature (SAT)	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Airflow from each VAV box	sMAP	every minute	Required for HVAC airside energy balance to calculate HVAC energy consumption
Return Air Temperature	PointSix wireless Sensors	every 30 seconds	Useful as a check for the accuracy of T_{rm} data trends
Outdoor Air Temperature	weather station	every 15 minutes	Useful for determining HVAC energy relative to outdoor weather conditions
Solar Radiation	weather station	every 15 minutes	Useful for determining if occupant comfort was influenced by solar radiation

Figure 1.1-10: Timeline showing temperature set points during study period

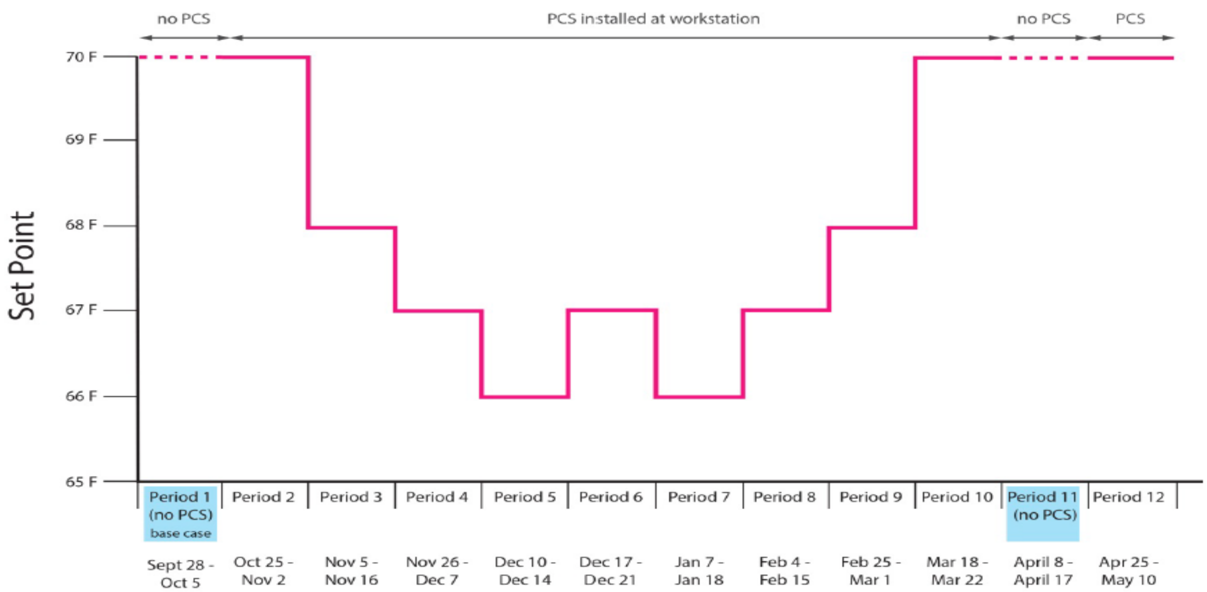


Figure 1.1-11: Daily perimeter and core temperatures during occupied hours

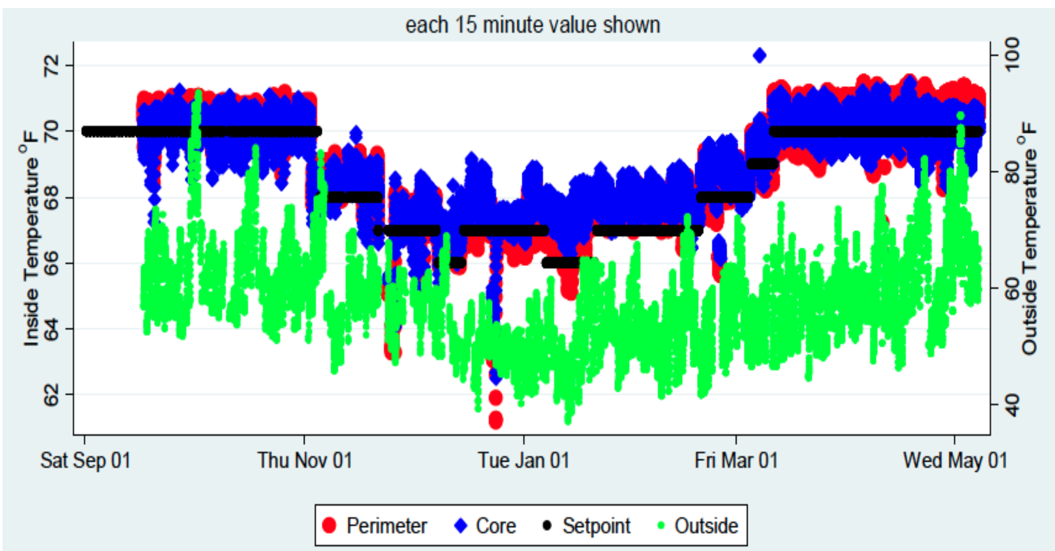


Figure 1.1-12: Daily average perimeter and core temperatures during occupied hours

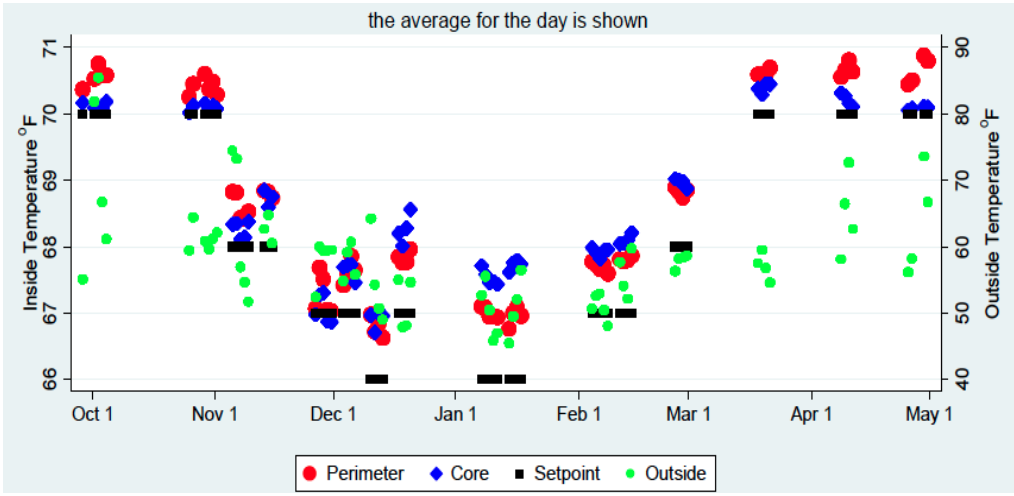
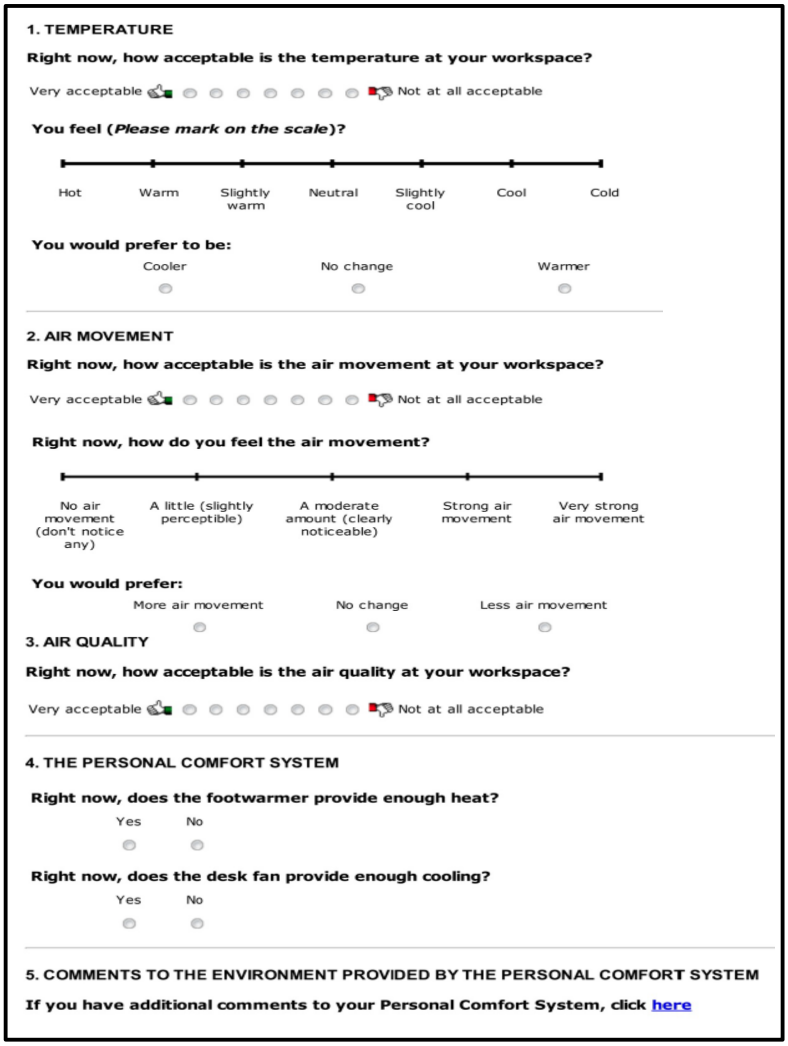


Figure 1.1-10 shows the temperature set points for the study period, and Figures 1.1-11 and 1.1-12 show actual zone temperatures during the study period, which correspond well with set points. Figure 1.1-12 shows there is very little difference in average temperature between perimeter and core zones in the study space. This information is tabulated in Figure 1.1-13.

Figure 1.1-13: Average temperatures during study periods

Survey Period	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Setpoint	(no PCS) 70.0	70.0	68.0	67.0	66.0	67.0	66.0	67.0	68.0	70.0	(no PCS) 70.0	70.0
Perimeter Temp (all OAT)	70.6	70.4	68.7	67.5	66.7	67.8	67.0	67.8	68.8	70.6	70.7	70.7
Core Temp (all OAT)	70.1	70.1	68.5	67.4	66.9	68.2	67.6	68.0	68.9	70.4	70.2	70.1
Avg. Zone Temp (all OAT)	70.3	70.2	68.4	67.3	66.5	67.6	66.8	67.5	68.5	70.4	70.3	70.3
Avg. Zone Temp (OAT 55 – 60F)	70.2	70.3	68.4	67.4	66.5	67.8	66.9	67.5	68.5	70.3	70.4	70.2
Avg. Zone Temp (OAT 52 – 57F)	70.2	70.5	68.3	67.3	66.6	67.7	66.8	67.5	68.7	70.4	70.5	70.2
Avg. Outdoor Temp (F)	69.8	61.4	62.3	57.8	54.0	51.8	52.3	56.3	58.7	58.4	64.8	71.9

Figure 1.1-14: Online 'Just Now' Survey



1. TEMPERATURE

Right now, how acceptable is the temperature at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

You feel (*Please mark on the scale*)?

Hot | Warm | Slightly warm | Neutral | Slightly cool | Cool | Cold

You would prefer to be:

Cooler ○ | No change ○ | Warmer ○

2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

Right now, how do you feel the air movement?

No air movement (don't notice any) | A little (slightly perceptible) | A moderate amount (clearly noticeable) | Strong air movement | Very strong air movement

You would prefer:

More air movement ○ | No change ○ | Less air movement ○

3. AIR QUALITY

Right now, how acceptable is the air quality at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

4. THE PERSONAL COMFORT SYSTEM

Right now, does the footwarmer provide enough heat?

Yes ○ No ○

Right now, does the desk fan provide enough cooling?

Yes ○ No ○

5. COMMENTS TO THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT SYSTEM

If you have additional comments to your Personal Comfort System, click here

1.1.4 Results from Comfort Surveys

Each of the 16 participants was reminded by email to take a 'Just Now' survey 3 times daily, at 9AM, 11AM, and 2PM. The participants were asked to complete the survey if they had been at their workstation for at least 15 minutes and had not filled out a survey for two hours. Figure 1.1-14 shows the on-line survey, which has 10 questions and normally takes about 1 minute.

The 16 subjects asked to return at least 10 surveys per week for 12 survey periods, totaling 1920 surveys. In total 2774 surveys were recorded over the period.

Boxplots conveniently display the data results. The box contains the central half of the data points, with the median indicated by the internal line crossing the box. 'Whiskers' going out to as much as 1.5 times the 'interquartile range' indicate the upper and lower quarters, or interquartile range (IQR), which is simply the length of the box. Data falling outside the whiskers may be indicated as outliers (Figure 1.1-15).

Figure 1.1-15: Structure of a boxplot

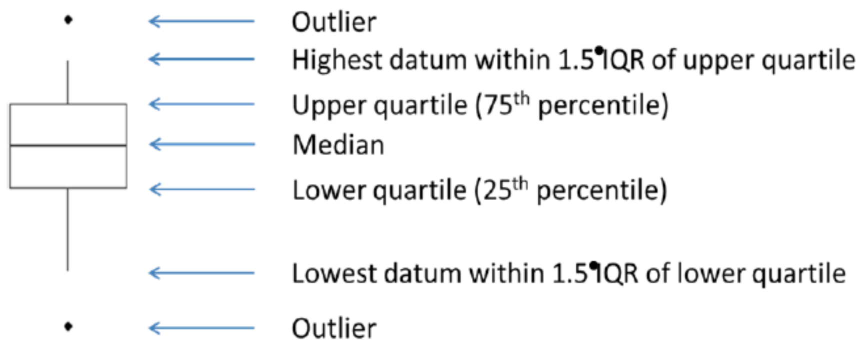


Figure 1.1-16: Overall thermal acceptability

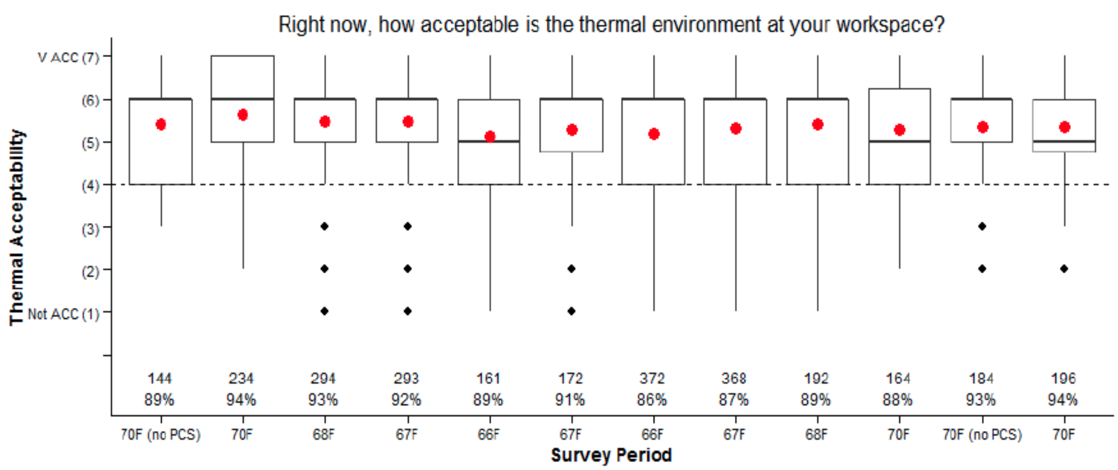


Figure 1.1-16 shows that overall thermal acceptability remained high throughout the experiment, ranging from 86 to 94 percent acceptable. This is consistently above the 80 percent acceptable standard for thermal comfort in buildings expressed in in ASHRAE Standard 55.

On the next page, Figure 1.1-17 shows that the overall body sensation throughout the study periods for most people was slightly cool. The votes dip towards a slightly cooler sensation as the temperature is reduced, but perhaps due to the foot warmers the environmental acceptability remains positive.

Figure 1.1-17: Whole body thermal sensation

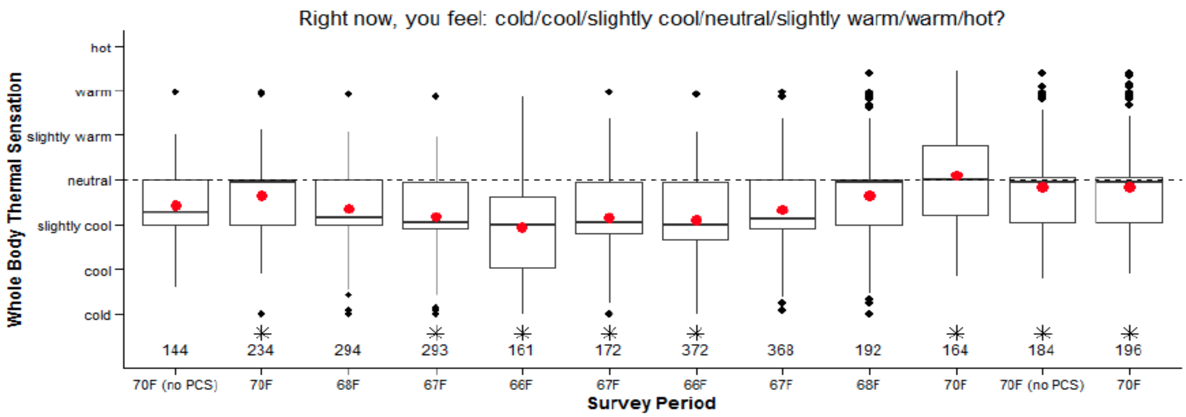


Figure 1.1-18: Feet thermal sensation

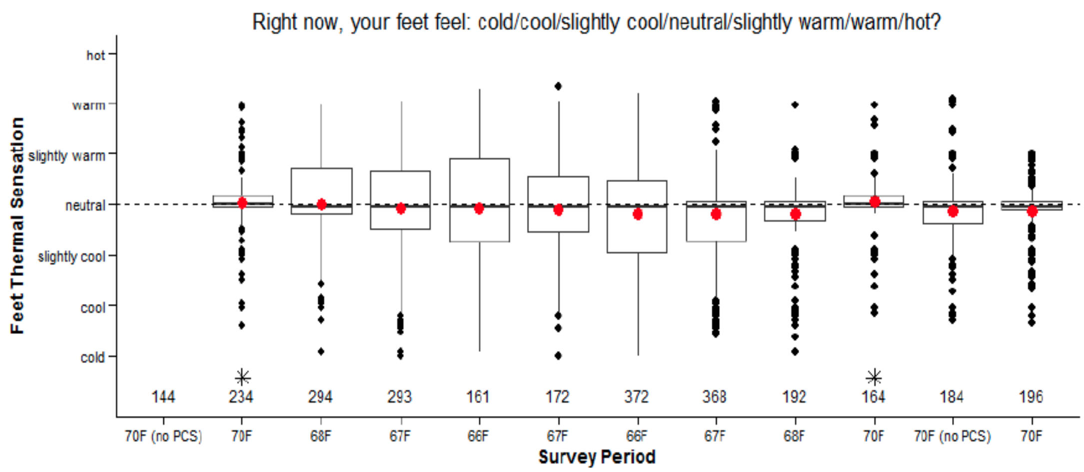
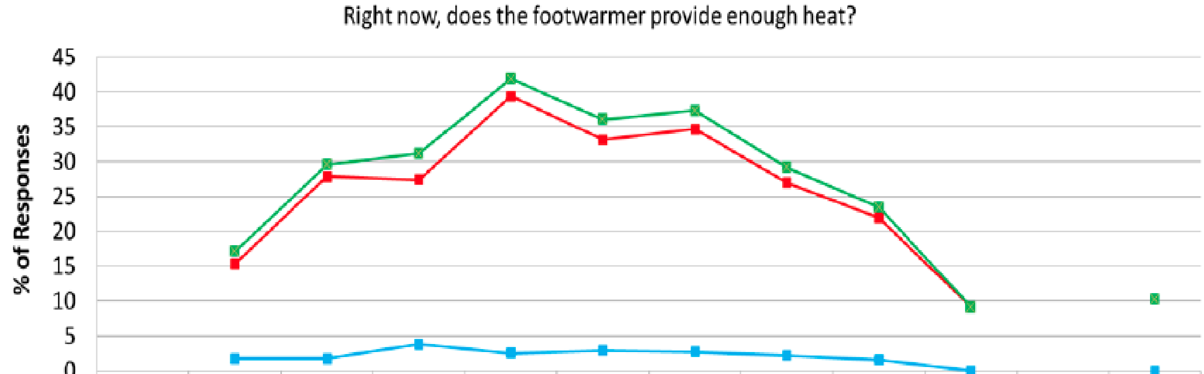


Figure 1.1-18 shows that throughout the test period, the feet thermal sensation stayed near neutral, above the overall body sensation, and reflecting the use of foot warmers. A substantial number of people did not use the foot warmers, but those who did apparently benefitted.

Figure 1.1-19 shows that as the temperature dropped, foot warmer use increased, and that people generally felt it provided enough heat, with a few exceptions. As the temperature was raised at the end of the study period use of the foot warmer diminished. People may have found it most useful during the cooler phases.

Figure 1.1-19: Foot warmer usage and satisfaction



	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
yes		15	28	27	39	33	35	27	22	9		10
no		2	2	4	3	3	3	2	2	0		0
in use		17	30	31	42	36	37	29	23	9		10

1.1.5 Energy Calculations

HVAC heating energy was calculated based on the amount of heat added to 56 degrees F supply air in order to maintain space temperature. The formula used to calculate this energy is shown below:

Reheat Power (kW) = $Q * \Delta T_F * k$

Where:

Q = Airflow in cubic feet per minute (cfm)

ΔT_F = [Discharge Air Temperature (F)] – [Supply Air Temperature (F)]

k = conversion factor

= 0.0003176 kW/cfm -T_F

where:

cfm = 0.000472 m^3/s

$T_K = 5\ T_F/9$

ρ_{air} = density of air = 1.204 kg/m^3

C_p = specific heat capacity of air = 1006 Joules / kg-T_K

$k = (m^3/35.31ft^3)(min/60sec)(1.204kg/m^3{}_{air})(5T_K/9\ T_K)(1006J/kg\text{-}\ T_K)(sec\text{-}kW/1000J)$

As the zone temperature dropped over the weeks of the experiment, the reheat energy decreased, because less heat was lost to the surroundings. As the outdoor air temperature decreased, the reheat energy needed to maintain a fixed zone temperature increased, because *more* heat was lost to the surroundings. This relationship can be seen in Figure 1.1-20, which plots reheat energy used in each 15-minute period against outside air temperature for each of four zone temperature set points. Plots occurring during each of the four-zone temperature are identified by different colors. A solid line of each color indicates where half the measurements are above and half below, thus a median value.

Figure 1.1-20: Heating power vs. Outside air temperature

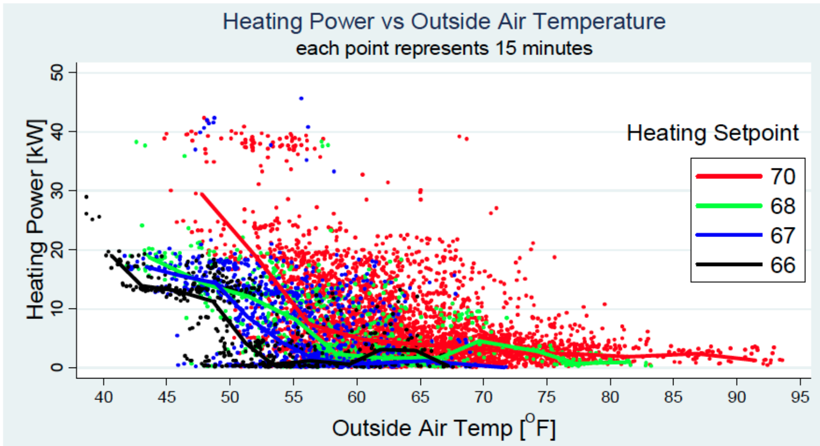


Figure 1.1-21: ACme power meter and representative power signature

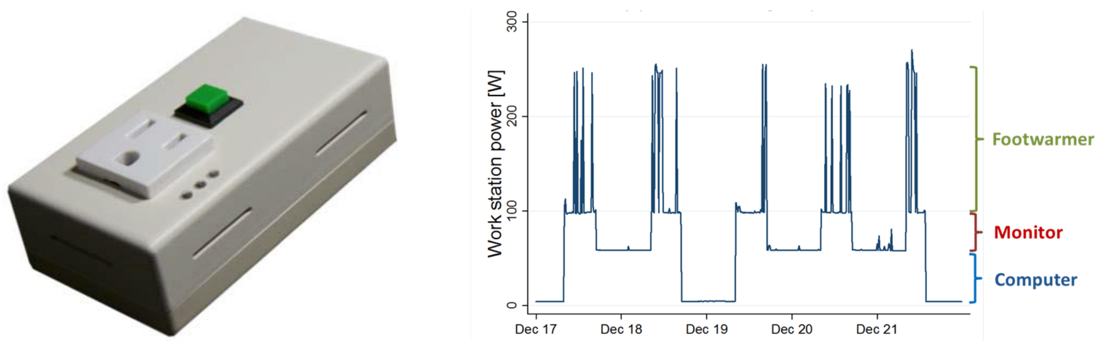


Photo Credit: Center for the Built Environment

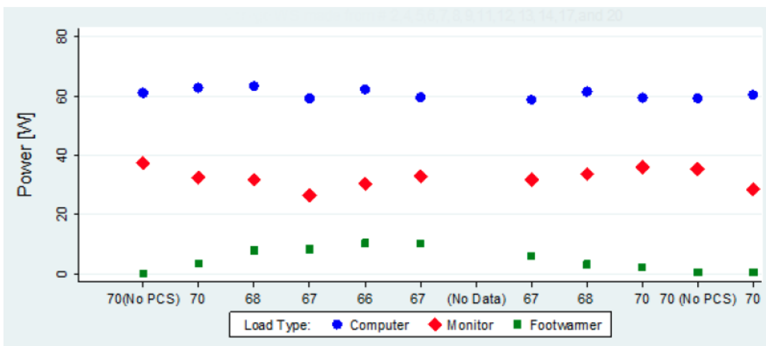
Plug load energy was monitored using ACme power meters, which were developed by another group of UCB students. Data from these devices can be retrieved through a wireless network, facilitating easy data collection. The largest loads were typically the foot warmer, the computer, (which included the tiny desk fan powered through a USB port) and the computer video monitor. A typical profile is shown in Figure 1.1-21. Because of the distinct profile, it is quite easy to separate out the power used by the foot warmer.

People tended to use their foot warmers sporadically through the day. Because the foot warmers include a paddle switch activated by foot pressure, they only use power when people actually put their feet inside. Even though the foot warmers draw 160W at full power (and people did mostly use them at full power), Figures 1.1-22 and 1.1-23 show the aggregate energy use was quite low, because of the limited amount of time they were actually in use.

Figure 1.1-22: Average power use of plug loads vs. Zone temperature

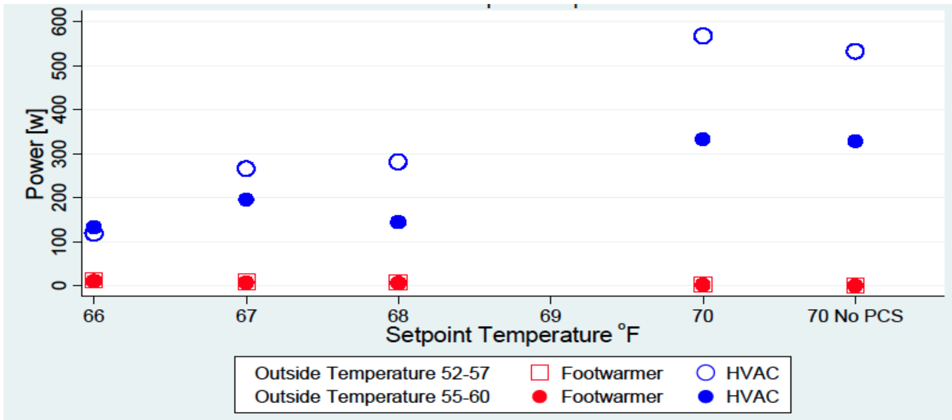
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
	70F (no PCS)	70F	68F	67F	66F	67F	66F	67F	68F	70F	70F (no PCS)	70F
Computer (W)	60.4	65.2	64.2	61.6	63.1	60.7	NA	61.4	62.5	63.7	60.0	63.8
Monitor (W)	36.7	33.1	33.0	26.4	30.9	32.2	NA	31.8	33.7	38.9	33.0	31.2
Ftwmr (W)	0.0	3.5	8.3	8.6	11.0	10.8	NA	5.7	3.1	2.6	0.5	0.4

Figure 1.1-23: Average power use of plug loads over study periods



By adding the power of the foot warmers to the HVAC power used over a period and dividing by the number of workstations, we can calculate the heating energy used per workstation during each zone temperature regime. This is shown for two bins of outdoor air temperatures in Figure 1.1-24. Note that HVAC heating energy use is significantly higher when outdoor air temperatures are lower.

Figure 1.1-24: Heating power per work station vs. Zone temperatures



Based on energy use for a 70 degrees F set point at similar outdoor air temperatures, as shown by Figure 1.1-20, the energy savings from reduced zone temperatures combined with foot warmers are significant, as shown in Figure 1.1-25. Figure 1.1-26 shows energy normalized for area (heating density).

Figure 1.1-25: Heating energy use and savings from foot warmers vs. Zone temperatures

	Setpoint 66F	Setpoint 67F	Setpoint 68F	Setpoint 70F	Setpoint 70F (no PCS)
Heating Power Density (W/sf) (OAT 55 – 60)	0.12	0.17	0.13	0.29	0.29
Heating Power Density (W/sf) (OAT 52 – 57)	0.11	0.24	0.25	0.50	0.47

Figure 1.1-26: Heating energy use and savings vs. Zone temperature normalized for area

	Setpoint 66F	Setpoint 67F	Setpoint 68F	Setpoint 70F	Setpoint 70F (no PCS)
Footwarmer Power (W) (OAT 55 – 60)	12	8	7	2	0
Heating Power (W) (OAT 55 – 60)	133	195	145	332	328
Percent Savings (from 70F no PCS) (OAT 55 – 60)	56%	38%	54%	-2%	NA
Footwarmer Power (W) (OAT 52 – 57)	12	8	8	2	0
Heating Power (W) (OAT 52 – 57)	119	265	281	567	532
Percent Savings (from 70F no PCS) (OAT 52 – 57)	75%	49%	46%	-7%	NA

1.1.6 Exit Interviews

Each of the 16 participants was interviewed following the experiment. Their comments are summarized in Figure 1.1-27.

Figure 1.1-27: Summary of exit interviews

	Workstation Number															
Comment	1	2	3	5	6	7	8	9	11	12	13	14	15	17	20	24
Always used footwarmer	x				x				x			x	x		x	x
Sometimes used fortwarmer		x		x		x										
Never used footwarmer			x				x	x		x	x					
Issues with footwarmer hitting shin or affecting posture	x		x	x						x	x	x		x		
Always used fan		x												x	x	
Sometimes used fan				x		x			x				x			
Never used fan			x		x		x			x		x				
Fan not strong enough		x						x								
Didn't like occupancy control on fan			x										x		x	
Perceived air quality problem								x								

Seven people always used the foot warmer; five never used it. Of the five who didn't use the foot warmer, four also never used the fan. Of the seven who always used the foot warmer, two never used the fan, and two sometimes did.

Three people always used the fan, of these three, two never used the foot warmer and one always did. Seven indicated issues with the foot warmer, most commonly complaining that it affected their posture, or bumped their shins. This was an issue for three who stated they never used the foot warmer. One person (WS-8) was pretty clearly dissatisfied with the equipment, never using *any* of it because of the shin and posture shortcomings, and also didn't like the occupancy control on the fan. Many of the occupants liked the concept and used the equipment occasionally, even if they thought the designs needed improvement.

This makes clear the diversity of perceptions, and points out one of the primary benefits of the PCS: people have different physiologies, wear different clothing, and feel different in the same environment. Of course, the environment may not be as similar as we assume. One person may be sitting next to a drafty window or under a diffuser that gives more than their share of cool air. Someone else may be in a stuffy corner, or next to a printer. PCS can provide mitigation in a variety of situations.

1.1.7 Comfort Model Analysis

Although the field study was not able to assess a baseline comfort level at the reduced ambient temperatures without PCS, the sophisticated CBE comfort model can provide an estimate. With an air velocity of 30 Feet Per Minute (FPM), an ambient temperature of 50 degrees F at 50 percent relative humidity, and wearing an office suit with a clothing insulation value (clo) of 0.8, the comfort model calculates that 40 percent of occupants would be dissatisfied.

This is expressed as a 'Percent Mean Vote' (PMV) of -0.8 in the technical jargon of comfort analysis. This compares with an actual tally of 14 percent dissatisfied using the PCS. For reference, 20 percent dissatisfied is considered to be normal for a well-designed building, so using the PCS actually produced better comfort at 66F than a reference building operated at a set point of 70 degrees F would expect. If occupants were wearing heavier clothing, with a clo value of 1.0, the predicted dissatisfaction value would be 25 percent, still significantly higher than the 14 percent actually obtained using the PCS.

1.1.8 Discussion

This field study has provided solid evidence that the PCS is a valid concept, with the potential to save large amounts of building energy even while improving comfort. The PCS has low barriers to market entry, as it is not inherently expensive equipment, can be deployed incrementally, and requires no disruptive renovations. Thus, the PCS is ideal for attacking the energy and comfort problem in the existing building stock.

This project also provided substantial guidance for how existing devices might be improved, which will be treated in subsequent reports. Much more information and analysis regarding the Bancroft Library study is contained in the attachment, 'Power to the People' by Mallory Taub, a master's degree thesis submitted to the UCB Graduate Division of Architecture, Fall 2013.

1.2 Cesar Chavez Student Union Field Study

1.2.1 Overview

The Cesar Chavez Student Union (SU) on UCB's campus was selected for the second demonstration. Similar to many campus buildings, the building had no mechanical cooling prior to and during this study (it has been added since). In warm weather, untempered outside air was provided by the overhead air distribution system for ventilation purposes. As a result the building had a tendency to overheat. The building is also poorly insulated and, therefore, indoor air temperatures can change significantly during the course of a day.

1.2.2 Objective

The goal of this demonstration study was to evaluate occupant comfort with existing wide-ranging temperatures, including potential improvements obtained by providing occupants with PCS systems (including PCS chairs).

1.2.3 Approach

1.2.3.1 Descriptions of the PCSs used in the study

Two types of PCS systems were used in the study in the Cesar Chavez Student Union.

1.2.3.1.2 Heated/cooled chair

The PCS chair is made from a normal mesh chair into which three fans were integrated, two in the seat and one in the back, and two heating elements. The fans, located inside reflective plenums in the seat and back, generate an isothermal cooling air flow parallel to the user. In cold conditions the heating elements locally heat the back and the seat of the chair, and the reflective material reflects back part of the radiant heat emitted by the body.

The chair has a switch with settings for heating, cooling, on or off, and the power level is controlled by a knob. The measured power is 14 W at maximum heating, and 3.6W at maximum cooling. With such low energy consumption the chair can use a rechargeable battery. The chair needs no electrical cord when in operation; the battery (below the seat) has capacity for 2 – 4 days operation, and is recharged at night when needed. There is an occupancy sensor that shuts off heating and cooling automatically when the chair is unoccupied, minimizing energy use and extending operation between charges. For this study, a small personal USB-powered desk fan (2.2W max) was provided to the occupant along with the PCS chair.

Figure 1.2-1: Heated/cooled chair and fan used in Cesar Chavez Student Union

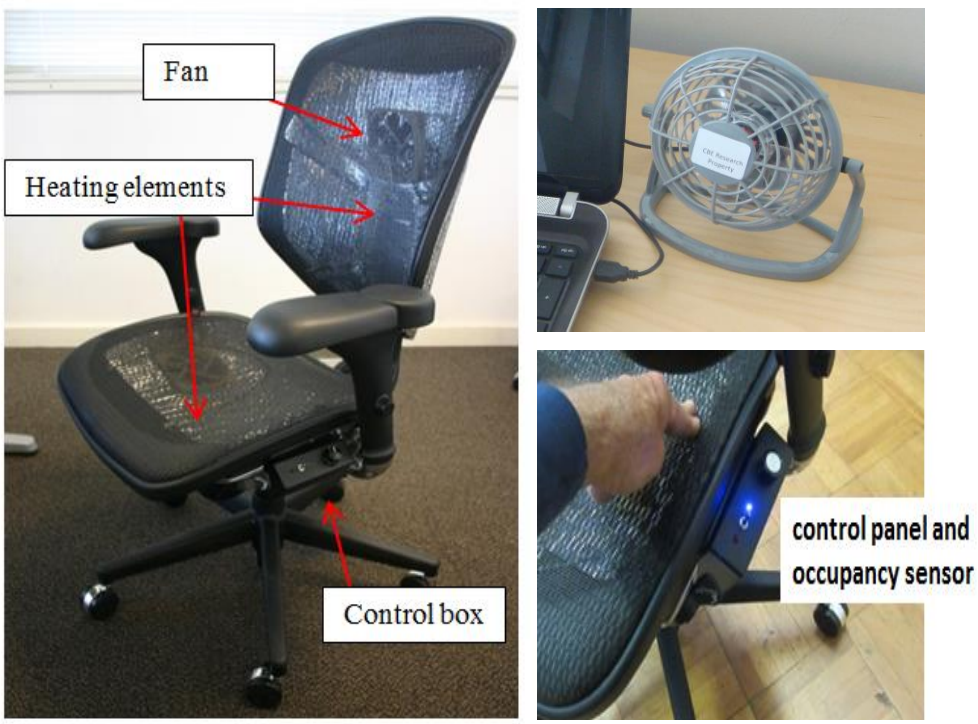


Photo Credit: Center for the Built Environment

1.2.3.1.2 Foot warmer (with Personal Fan)

The foot warmer PCS is typically paired with a small personal fan that also provides user control and communication interface for monitoring. The system provides air movement for head cooling (using less than 4W) and carefully focused radiation for foot warming. The foot warmer, by enclosing the foot area in a highly reflective insulated shell, provides carefully focused radiation for foot or leg warming. The foot warmer uses a 100W array of heating elements (dimmable R14 reflector bulbs).

The foot warmers were typically operated intermittently, consuming 20Won average. The foot warmer power level is controlled by one knob on the desktop fan, the other controls the fan speed. Like the PCS chair, both fan and foot warmer have occupancy sensors that shut off power when unoccupied. There is a software interface to show the user their heating and cooling usage along with the ambient air temperature measured in the fan, as well as optional internet connectivity for transmitting temperature and state data to the internet.

Figure 1.2-2: Foot warmer and fan developed by CBE

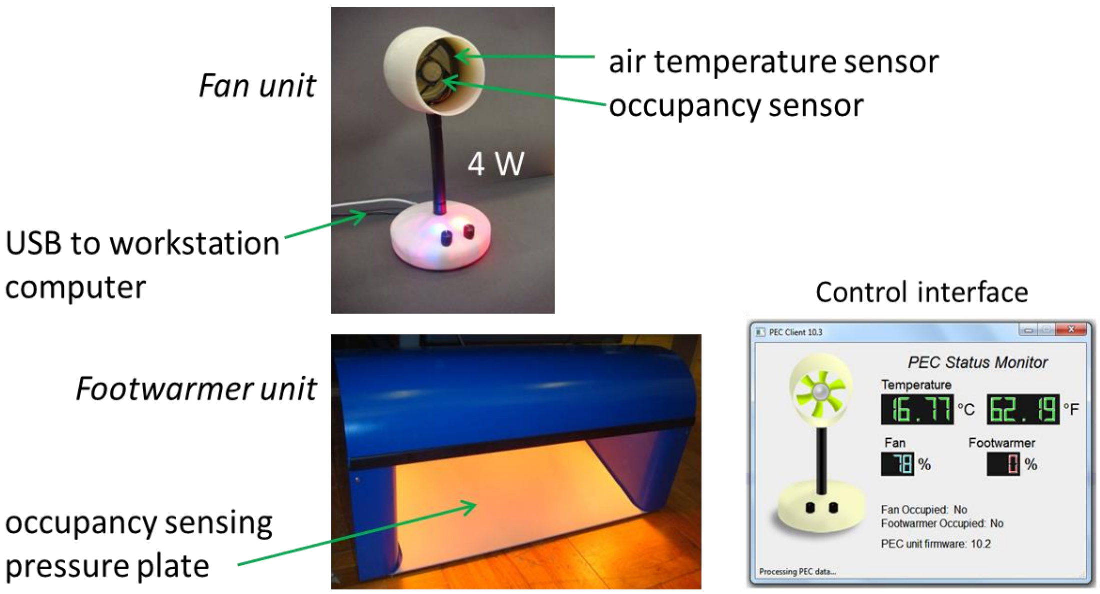
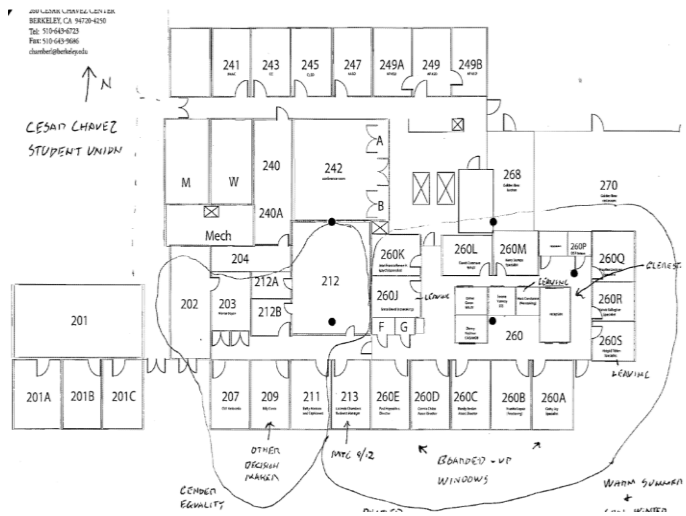


Photo Credit: Center for the Built Environment

1.2.3.2 PCS distribution

A total of 18 people from two working groups on the second floor were invited to participate in the study. Half of the people were located in the perimeter zone and the other half were located in the core zone. Windows in the perimeter zone were not operable. In an unforeseen development, they were blocked during part of the testing period by plywood boards for reducing noise from new construction nearby. Later, the boards were removed and sunlight was allowed to enter into the building's interior. This is addressed in more detail in Section 5.

Figure 1.2-3: Plan view of the study area



The research team provided two training sessions for the 18 occupants on how to use the PCS. Then each participant chose the PCS system configuration they wanted to use. They chose 14 heated and cooled chairs and 4 linked fan/foot warmers. Chair users also received a small independently controlled 2W USB-powered desk fan. Figure 1.2-4 shows a chair user. Wireless zone air temperature sensors were installed for all the 18 workstations and the occupant satisfaction survey was started at the end of September 2013.

Figure 1.2-4: A PCS chair user

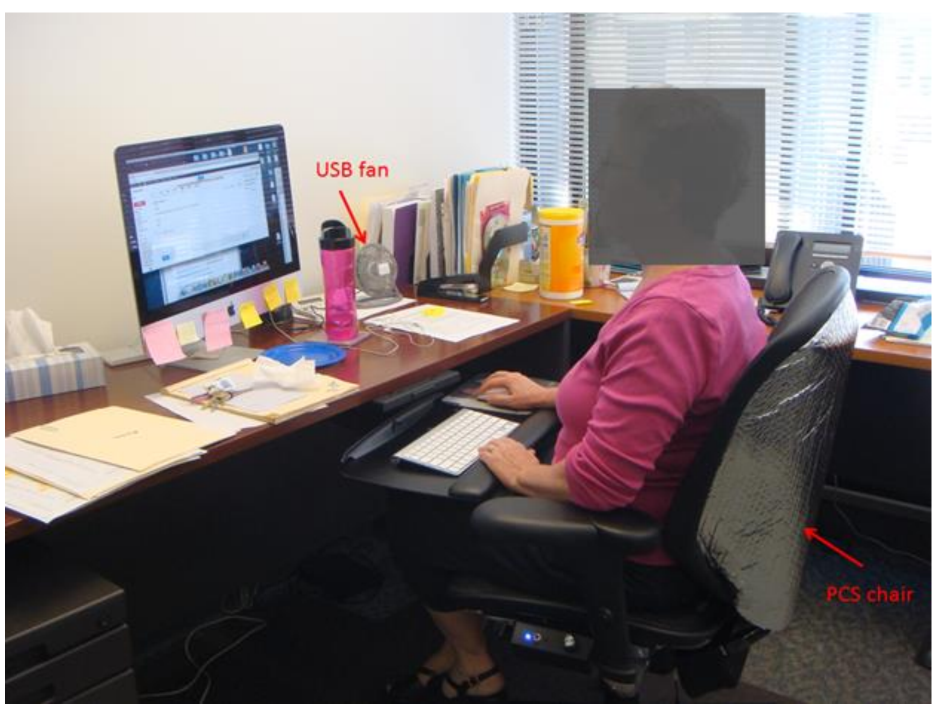


Photo Credit: Center for the Built Environment

1.2.3.3 Occupant surveys

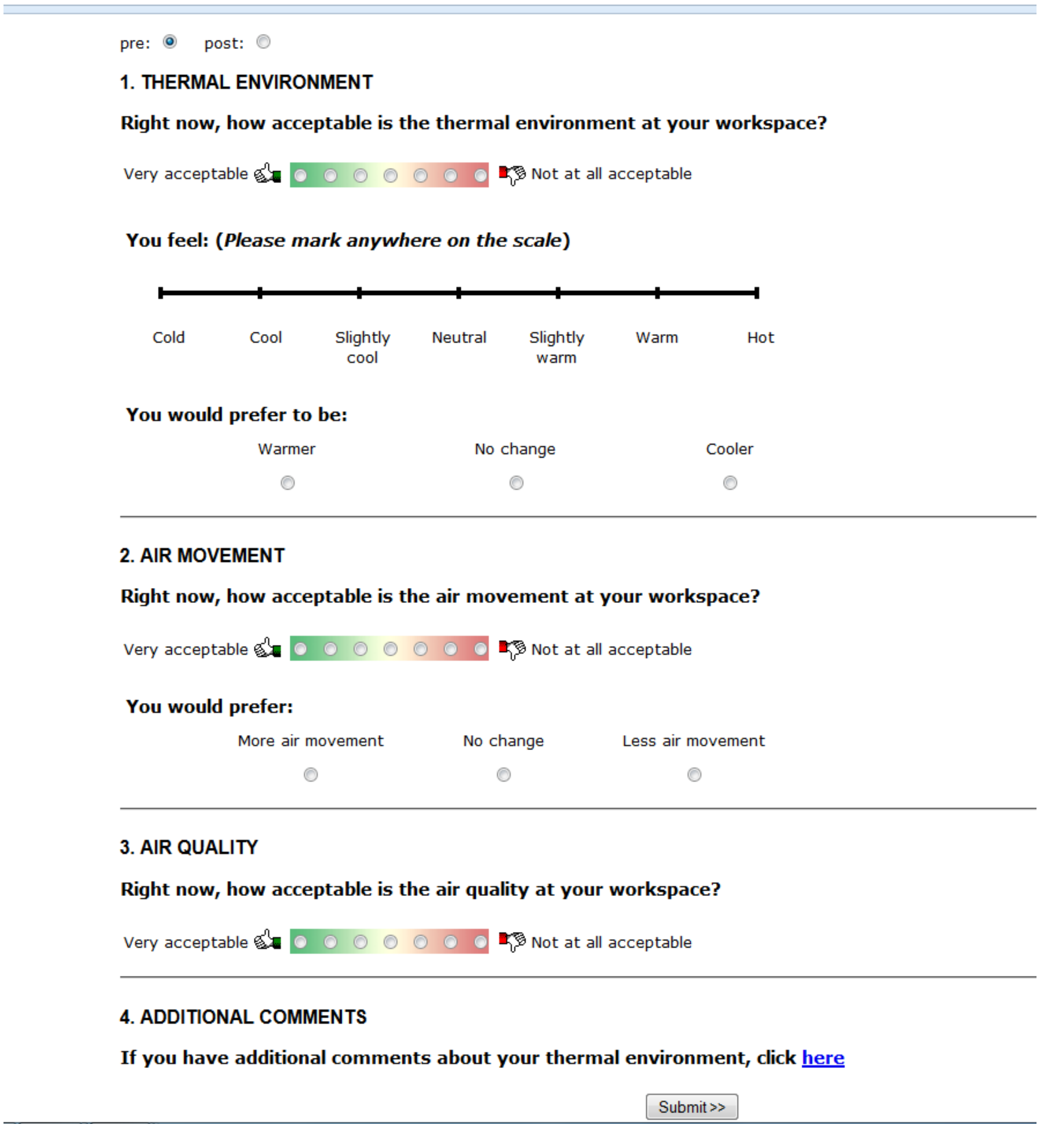
An initial survey was conducted before the PCS were distributed, over the course of two weeks, during the warm season (Sept. 25 – Oct. 8). The results of this 'pre' survey are used as a reference condition for warm conditions in the data analysis. After the pre-survey period was finished, we distributed the PCS each occupant had chosen. We then conducted 'post' surveys covering both warm (Oct. 14 –Nov. 17, 2013) and cool (Feb. 6 – 21, 2014) seasons.

The post-survey for the warm season can be compared to the preceding pre-survey to evaluate the PCS effect on cooling occupants. We could not prepare a comparable reference case for the cool season because once the occupants were using their PCS, we could not take them away to create a new precondition in the cool season. However the survey results from both warm and cool seasons allow us to evaluate comfort ranges that PCS can provide. In total, we received about 1,300 individual survey responses.

1.2.3.3.1 Occupant's satisfaction survey questions

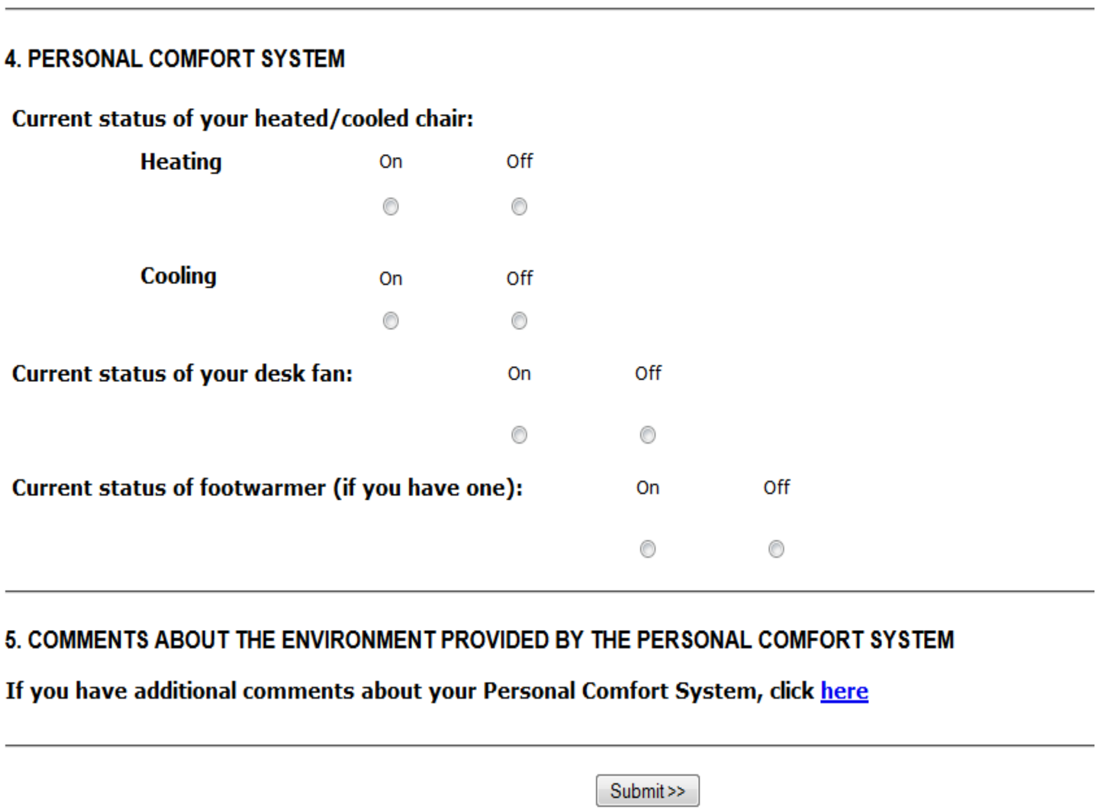
Fatigue caused by long survey questions is known to affect the accuracy of responses. In order to prevent occupant fatigue while taking repeated surveys, the survey questions were carefully designed to be as concise as possible for the project's purposes. The pre-survey questions are show in Figure 1.2-5. The questions cover 3 areas, thermal comfort, air movement satisfaction, and perceived air quality. There are 6 questions total.

Figure 1.2-5: Pre-survey questions



For the post-survey, we added another group of questions regarding use of the PCS. The additional questions are shown in Figure 1.2-6.

Figure 1.2-6: Additional questions in the post-survey questionnaire



4. PERSONAL COMFORT SYSTEM

Current status of your heated/cooled chair:

Heating — On / Off

Cooling — On / Off

Current status of your desk fan: On / Off

Current status of footwarmer (if you have one): On / Off

5. COMMENTS ABOUT THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT SYSTEM

If you have additional comments about your Personal Comfort System, click here

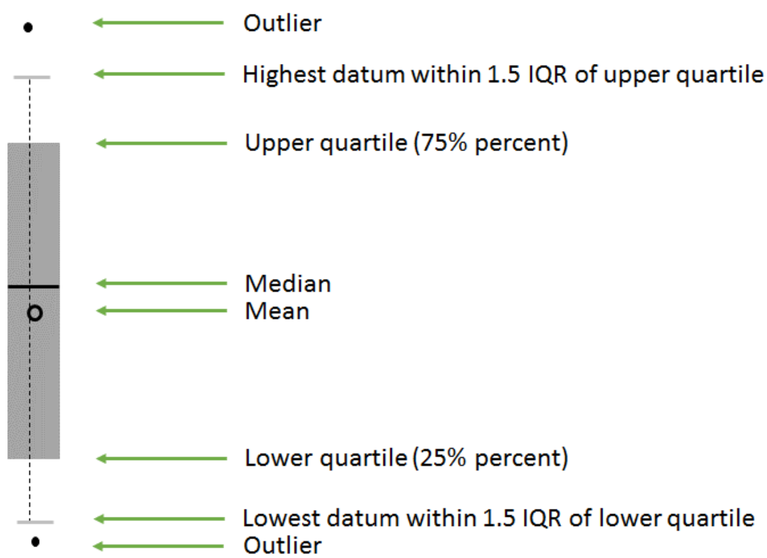
Submit>>

1.2.4 Results

The results are analyzed as two groups, one with all the PCSs included (14 chairs + 4 fan/foot warmers) and one with chairs only (not including the fan/foot warmers). The results provide a case study for the PCS in general, and for chairs specifically, since the majority of the PCSs in the demonstration are chairs.

Some of the results for acceptability and thermal sensation are presented using boxplots, a common graphing technique illustrated in Figure 1.2-7. Data are considered valid within 1.5 times the IQR in both directions. (The IQR is the range between the top and bottom quartiles of a data set—the middle 50 percent.)

Figure 1.2-7: Boxplot diagram



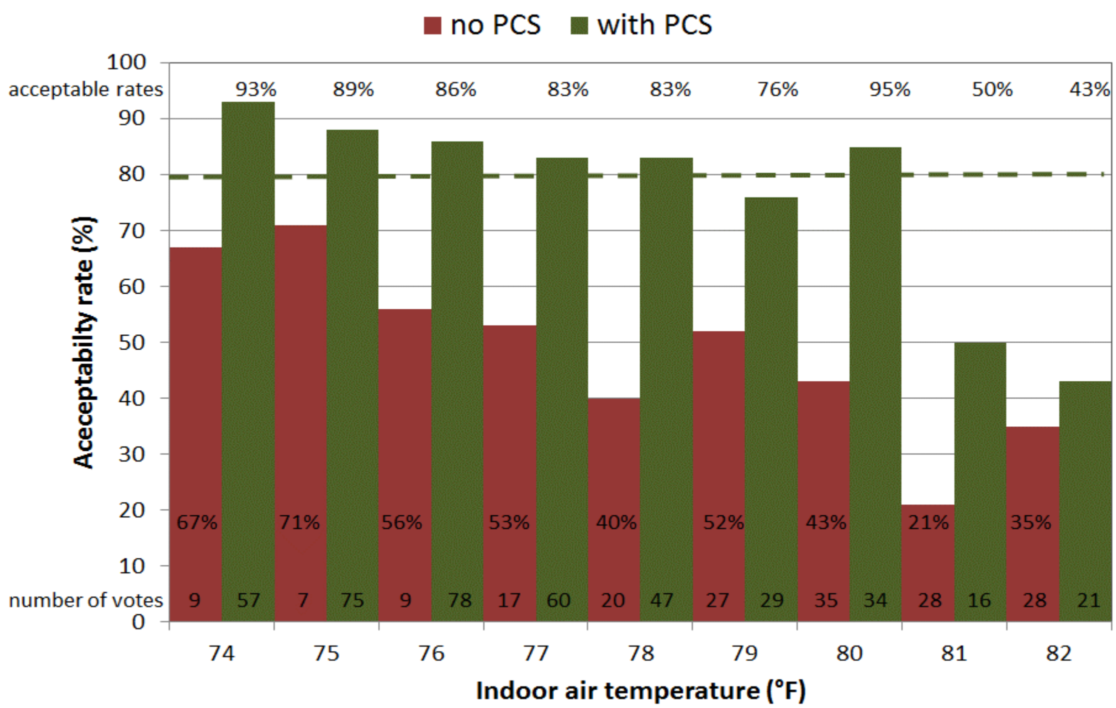
1.2.4.1 Comparisons of thermal comfort acceptability and sensation with and without PCS in summer season

1.2.4.1.1 With both types of PCS

Because this building did not have any mechanical cooling, the temperature pattern changed significantly on a daily basis. This necessitated grouping of like temperature patterns in the analysis. We first matched the subjective comfort votes with the simultaneously measured ambient air temperatures.

Figure 1.2-8 shows the thermal acceptability rates comparing pre- and post-survey periods based on binned ambient air temperatures. Because the pre-survey was conducted before the PCSs were distributed in warm season, a comparison was made between the pre-survey and the post-survey in warm season. The figure shows the comparison covering the ambient temperature range 74 – 82 degrees F. There were not as many low (74-6 degrees F) temperatures during the pre-survey period as higher (77-82 degrees F) temperatures, resulting in smaller vote numbers in the lower temperature bins, so their acceptability percentages are less solidly based than the other pre-survey and the post-survey values.

Figure 1.2-8: Thermal acceptability comparison before and after having the PCSs (both types)

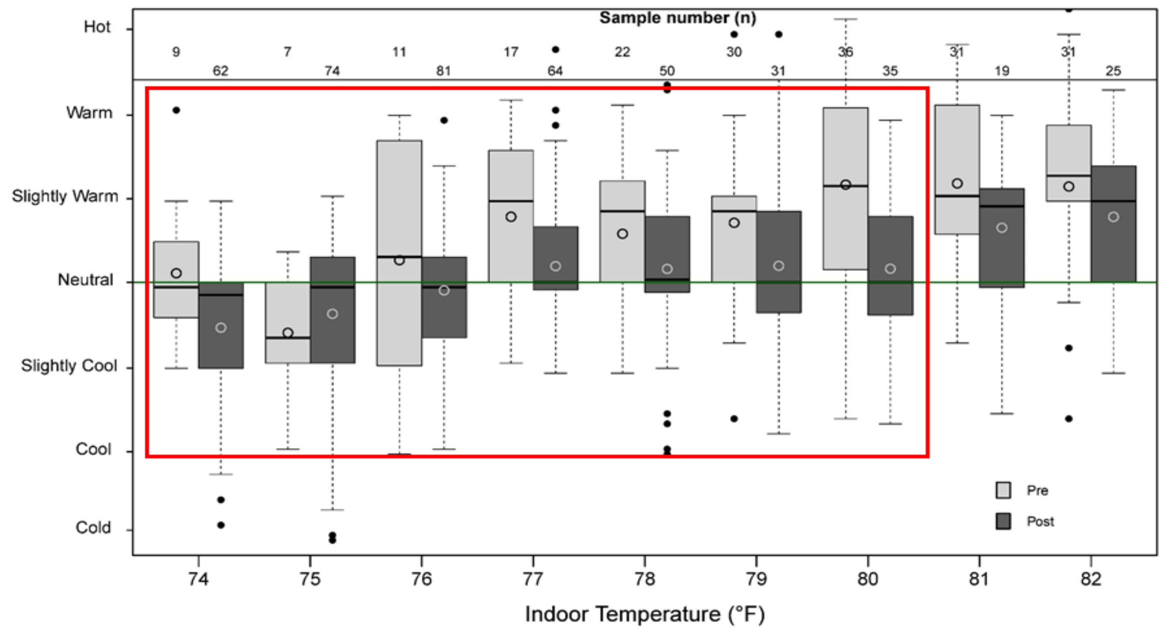


In warm weather, the PCS is able to keep occupants comfortable within and up to 80 degrees F, with acceptability above 80 percent except for one temperature bin. Beyond 80 degrees F, the acceptability rates are significantly decreased, even with the PCSs.

For the ambient air temperature range between 74 – 80 degreesF where PCS is able to maintain occupant thermal comfort, the acceptability rates without PCS are between 40 and 71 percent (number-of-vote weighted average 50 percent). They are increased to 76 – 93 percent with the PCS (number-of-vote weighted average 86 percent), 72 percent increase over the acceptability when the PCS were not available.

A box chart (Figure 1.2-9) shows that within this ambient air temperature range 74 – 80 degrees F, the average thermal sensation values with PCSs are all very close to zero or neutral sensation see median values – lines, and mean values – open circles inside the dark grey bars).

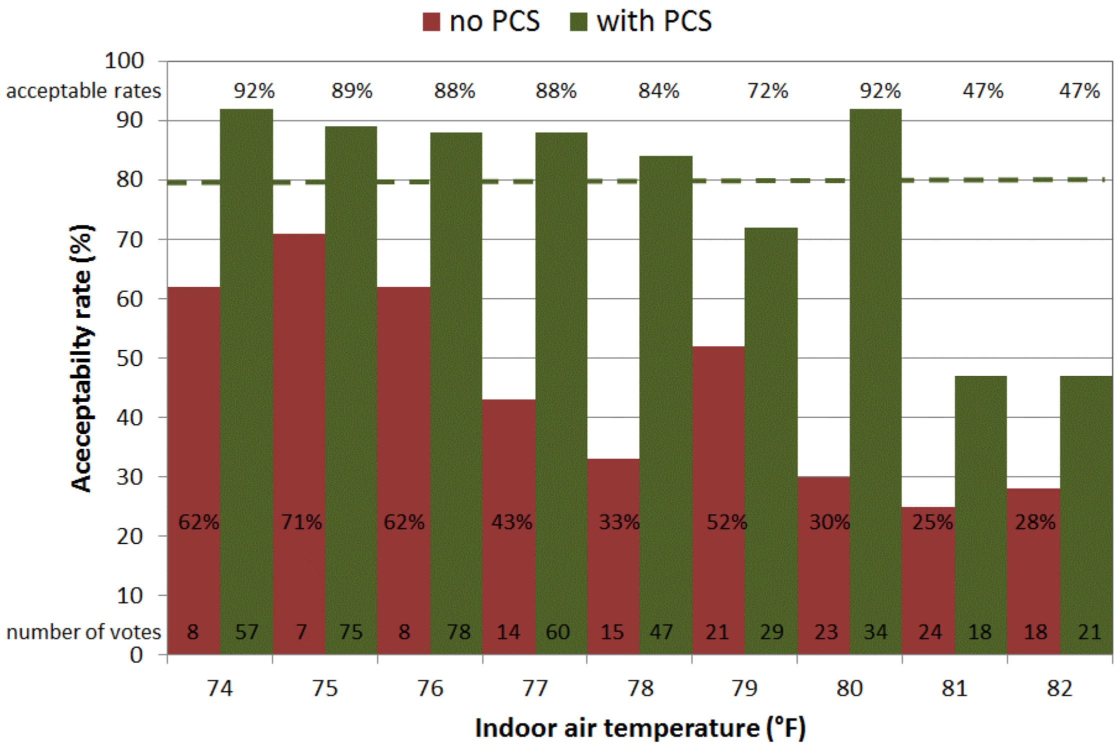
Figure 1.2-9: Thermal sensation before and after having PCSs



1.2.4.1.2 With chair only

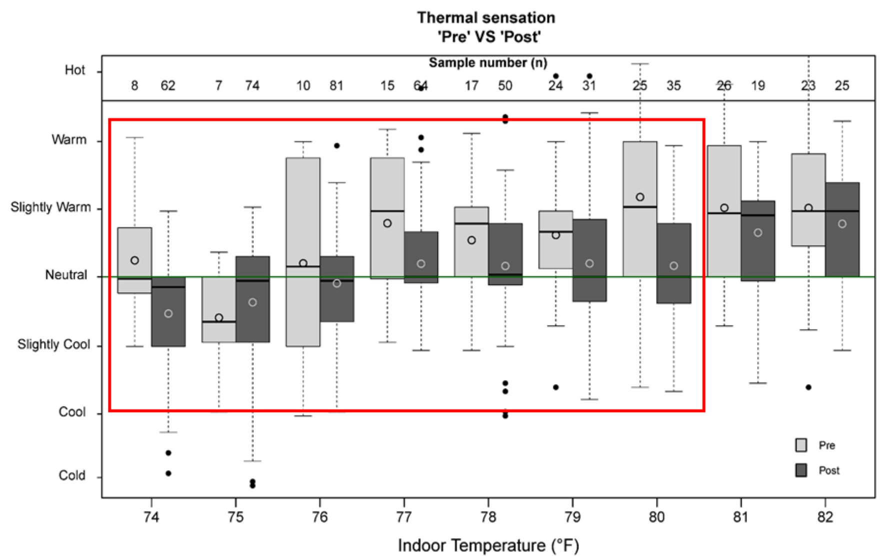
For the ambient air temperature range between 74 – 80 degrees F, the acceptability rates considering chairs only increased to 72 – 92 percent (number-of-vote weighted average 88 percent), roughly double the acceptability when the PCSs were not available. The acceptability with chair only is higher than for both the chair and the fan/foot warmer for all temperature bins except one. Beyond 80 degrees F, the acceptability rates are significantly lower, even with the PCS chairs.

Figure 1.2-10: Thermal acceptability comparison before and after having the PCS chairs



Again, the thermal sensation values with chairs are all very close to zero (neutral sensation) for ambient air temperature between 74 – 80 degrees F (Figure 1.2-11, see median values – lines, and mean values – open circles inside the dark grey bars).

Figure 1.2-11: Thermal sensation before and after having chairs



1.2.4.2 Thermal comfort ranges and sensation with PCS in both summer and winter

1.2.4.2.1 With both types of the PCS

This section shows the thermal comfort ranges with both types of the PCS. Figure 1.2-12 shows that PCS provides occupants' comfort over a range of 68 – 80 degreesF, with acceptability above 80 percent except for one temperature bin. The number-of-vote weighted average acceptability rate is 86 percent.

Figure 1.2-12: Comfortable ambient temperature range with PCS in summer and winter seasons

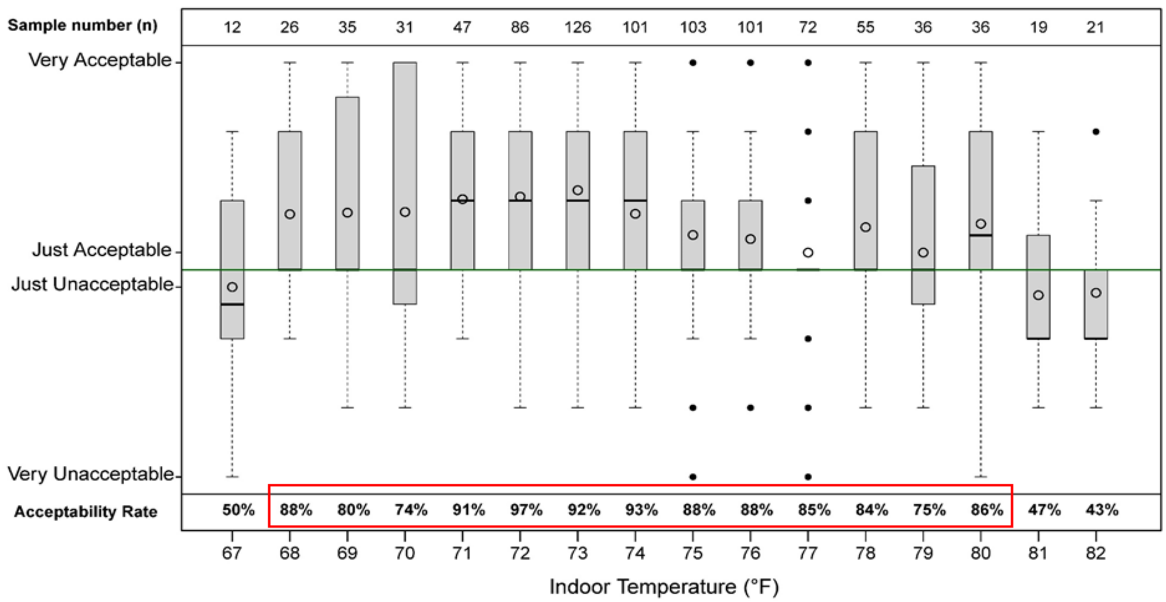


Figure 1.2-13: Comfortable ambient temperature range with PCS chairs only in all seasons

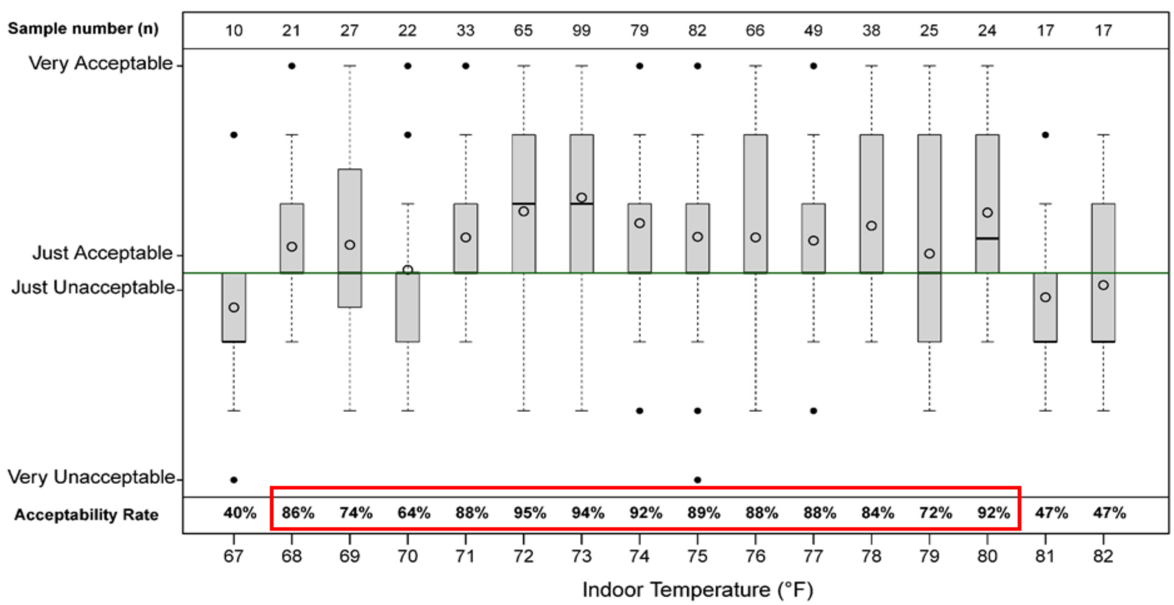
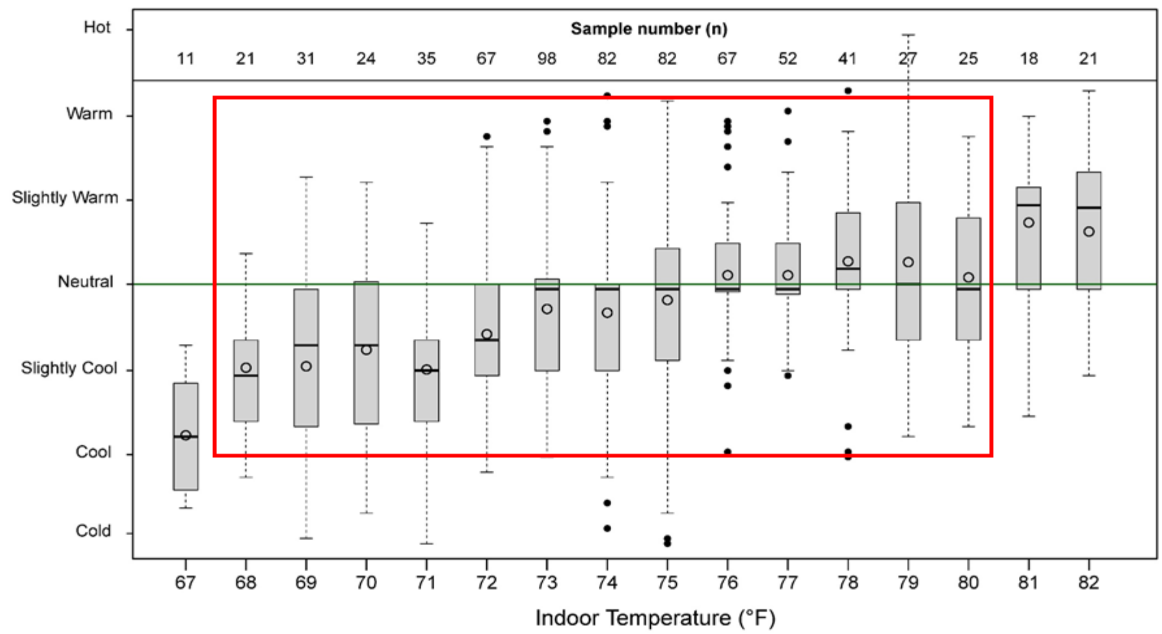


Figure 1.2-14: Thermal sensation with both PCSs covering both summer and winter seasons



1.2.5 Discussion

Since the windows in the study area are not operable, the PCS served as the only dimension of occupant control in extending the acceptable temperature range up to 80 degrees F. Operable windows would allow certain levels of air movement into the building, which may further expand the acceptable temperature range, working in concert with PCS.

To acoustically mitigate nearby construction activity, the windows were blocked with plywood boards during much of the period of the study (see Figure 1.2-15). After the Pre-survey and delivery of the PCS but right before we started the Post-survey (Oct. 14, Monday), the boards were removed (Oct. 11, Friday). Without these boards, the solar radiation would increase the mean radiant temperature (MRT) of the spaces and therefore possibly made people feel warmer. However, the research team didn't become aware of this change until a later visit, we therefore could not measure the solar radiation or change in MRT. The comparison between pre- and post-surveys under each ambient air temperature bin would be conservative for the post survey results, since the increased MRT could make people feel warmer and less comfortable at the same ambient air temperatures.

1.2.6 Conclusion

This field study has provided solid evidence that the PCS is a valid concept, with the potential to save large amounts of building energy even while improving comfort. The PCS has low barriers to market entry, as it is not inherently expensive equipment, can be deployed incrementally, and requires no disruptive renovations. Thus, the PCS is ideal for attacking the energy and comfort problem in the existing building stock.

This project also provided substantial guidance for how existing devices might be improved, which will be addressed in subsequent reports. Much more information and analysis regarding the Bancroft Library study is contained in the attachment, 'Power to the People' by Mallory Taub, a Master's degree thesis submitted to the UCB Graduate Division of Architecture, Fall 2013.

The PCS chair paired with a small personal fan performed well in the first field demonstration, providing thermal comfort over the ambient air temperature range 68 – 80 degrees F. In cool ambient conditions (between 68 – 72 degrees F), the PCS can maintain occupants' thermal sensation votes between 'slightly cool' and 'neutral'. In neutral to warm ambient conditions (73 – 80 degrees F), the PCS can maintain occupants' thermal sensation votes near 'neutral'.

Over the full temperature range, comfort acceptability was improved from 30 – 71 percent (average 44 percent) acceptability under the base-case condition to 72 – 92 percent (average 88 percent) acceptability after the PCS chairs and fan were deployed, doubling the acceptability rate.

Foot warmers paired with small fans also performed well over this temperature range, but the results were less conclusive because fewer units were deployed, providing a smaller sample size.

Figure 1.2-15: Windows blocked with plywood for acoustical mitigation of construction noise

1.3 Stanley Hall Field Study

1.3.1 Overview

Stanley Hall is a 285,000 ft^2 heavy-mass building on the UCB campus that was constructed in 2007. It houses auditoriums, offices, and 40 faculty research laboratories to primarily serve biological sciences, physical sciences, and engineering studies.

Figure 1.3-1: Stanley Hall on UC Berkeley campus

Photo Credit: Center for the Built Environment

1.3.2 Description of Heating, Ventilating and Air Conditioning System

HVAC is handled by a single-path mixed air system with variable-air volume terminal units, most with hot water reheat coils. The air system maintains a supply air temperature leaving the air handler of 55 degrees F at all times, which is a common strategy, though not optimal for energy efficiency.

The air handlers have an outside air economizer, which has dampers to mix any desired fraction of outside air with return air. As a greater fraction of outside air is brought in, the economizer exhausts the excess return air to maintain the desired static air pressure within the building. A slight positive pressure is preferred, to avoid unfiltered air from being pulled in through windows and doors. The dampers are controlled to guarantee a minimum fraction of outside air to dilute internally generated pollutants, such as volatile organic compounds from carpet and furniture, in order to maintain indoor air quality.

When the outside air temperature is above the return air temperature, the economizer dampers are adjusted to provide the minimum outside air fraction, and a cooling valve opens to allow chilled water to flow through a cooling coil. This flow is modulated by the chilled water valve to maintain supply air at the 55 degrees F temperature set point.

When outside air temperature is below return air temperature, the economizer will open its dampers to use outside air preferentially. This reduces the need for cooling by the chilled water system, thereby saving energy. When outside air temperature falls below the 55F supply air set point, the economizer dampers will modulate, mixing outside air with return air so as to maintain the 55 degrees F supply air temperature, until the outside air reaches such a low temperature that the minimum outdoor air fraction is reached. Throughout this state the system requires neither chilled water nor hot water to maintain the desired supply air temperature, hence the name, 'economizer'.

If the outside temperature falls so low that the supply air temperature is below 55 degrees F at the minimum outside air fraction, then the heating valve modulates open to allow hot water to flow through a heating coil, in order to maintain the supply air temperature at its 55 degrees F set point. This condition seldom happens in the mild climate of Berkeley.

The air from the air handler is supplied via ductwork to the air terminal units, also known as VAV boxes, which are supposed to maintain temperatures at zone set points and provide at least minimum airflow into each zone to maintain good indoor air quality. This system has temperature sensors in each zone, which report to their respective air terminal units.

Figure 1.3-2: Installing wireless sensors (left); typical air handler schematic diagram (right)

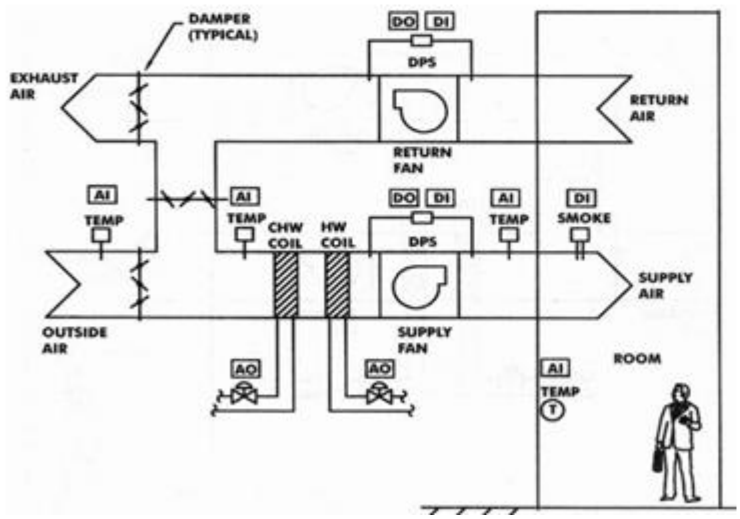


Photo Credit: Center for the Built Environment

The zone temperature set points, as well as other control attributes in this HVAC control system, which was manufactured by Barrington, are set at an operator workstation, which is a computer interface to the digital HVAC control system. The temperature set points are not adjustable at the temperature sensor as they are in most residential and small commercial systems. If the occupant wishes to have the temperature set point adjusted she must notify the operator of the HVAC control system.

At times when zone cooling is needed, the control system varies the air volume entering each zone in order to maintain zone temperature at the set point. This air volume is controlled by modulating a damper in the air terminal unit. The airflow set point is adjusted automatically between a maximum and a minimum airflow volume, which is programmed for each air terminal unit. The maximum volumes are determined so as to maintain sufficient cooling and to ensure adequate airflow in all the air terminal units connected to the air handler at times of high demand. The minimum airflow set points are determined to maintain adequate indoor air quality in the zone.

At times when heating is needed, a hot water valve is modulated to allow hot water to flow through the heating coil at the air terminal unit. This is known as 'reheat', and is used to maintain the zone temperature at set point under cold conditions. In more typical conditions requiring cooling, the airflow is varied to maintain the temperature at set point, and no reheat is used. During heating, airflows are typically maintained at the minimum volume set point, though some more advanced control strategies deviate from this practice.

In this system, there is a single temperature set point without a so-called dead band, unlike many systems, which either have a specified dead band around a single set point, or separate heating and cooling temperature set points. The purpose of the dead band is to allow the temperature to freely float within a specified range in order to save energy. This is addressed further in the discussion section.

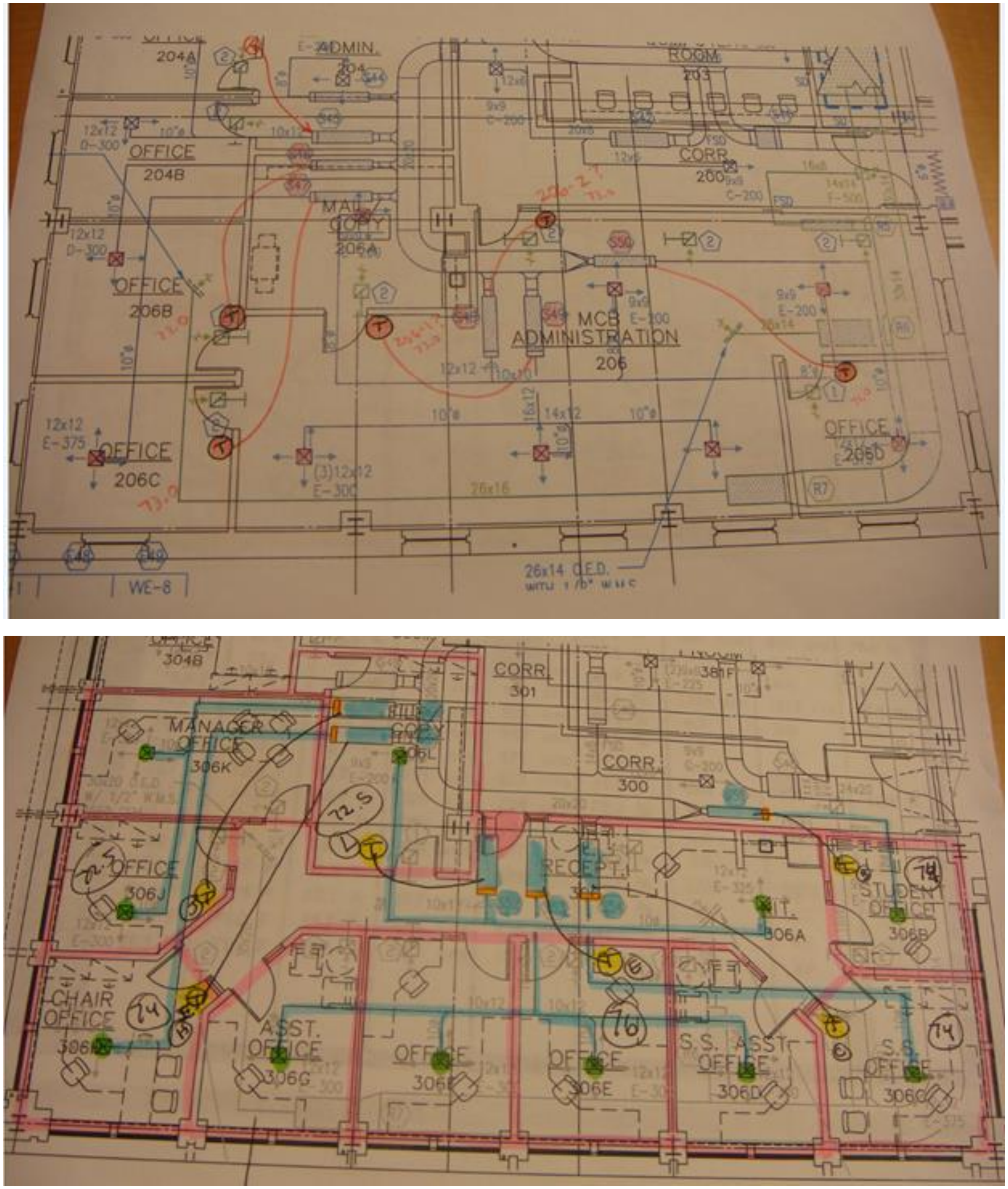
Additional control parameters, sometimes not accessible or well understood, are proportional bands and integration parameters. The measured temperature is called the 'controlled variable'. Conceptually, the output in a simple proportional control loop can be expressed by the equation: $O_{pb} = (SP-CV)/PB$, where O_{pb} is output, SP is the set point, CV is the controlled variable (in this case, temperature), and PB is the proportional band. In this case the output is proportional to the difference between the set point and the temperature, divided by the proportional band. If the proportional band is made too small, the output will respond too strongly, and the system will begin to oscillate. If the proportional band is too large, the response will never bring the controlled variable close to the set point.

Simple control loops can use proportional control only, but often integration is added to make the controlled variable converge with the set point. This means of control essentially divides the output of the proportional control function by an integration constant IC, and adds that to the final output, in an iterative fashion. $O_f = O_{pb} + \Sigma_{t=1 \text{ to } n}(O_{pb} / IC)$. As the difference between the set point and the temperature grows smaller, the amount added to the integration component grows smaller, and the output approaches the value needed to make the temperature converge with the set point. There is a process for determining the best values of proportional band and integration constants, and unfortunately technicians often don't know or don't have the time to determine optimal values.

1.3.3 Description of Study Area

The people in this study were located in two areas of approximately 2000 ft^2 each in Stanley Hall. A study area on the second floor consisted of 3 private offices of about 150 ft^2 each, with a total of 5 persons. The remainder was an open-plan office with a varying number of people, but typically about 9. The other study area, located on the third floor, was exclusively private offices, 9 in all. A total of 10 people worked in the third floor offices. The layouts of the offices are shown in the graphics below in Figure 1.3-3.

Figure 1.3-3: Floor plan of study areas in Stanley Hall; Second floor (top), third floor (bottom)



Construction Drawings courtesy of UC Berkeley Facilities

1.3.4 Objective

Prior to the study, the facilities staff in Stanley Hall was inundated with a large number of comfort complaints, primarily coming from the two regions within the study area. Through the initiative of Karl Brown of CIEE, Chuck Frost, the campus energy manager, and the Stanley Hall facilities staff, managed by Harry Stark and David Rogers, the research staff at CBE was contacted to investigate whether the PCS could help to mitigate these problems. A second priority was to determine whether, while improving comfort, the PCS could reduce energy use.

1.3.5 Approach

1.3.5.1 Pre-training workshop

The occupants in the study areas were invited to a workshop where they were introduced to the PCS available, which consisted of heated and cooled chairs, foot warmers, and legwarmers. This took place in September of 2013. The participants were taught how to use these PCS systems, and were allowed to select the single piece of PCS equipment (Figure 1.3-4), which they felt would be most beneficial. In total they chose 18 heated and cooled chairs, 4 legwarmers, and 4 foot warmers. The occupants were also taught to take the comfort surveys. The survey tool was identical to the one described for the SU study in Chapter 2.

Figure 1.3-4: Participants in Stanley Hall are oriented to PCS equipment

Photo Credit: Center for the Built Environment

1.3.5.2 Occupant satisfaction survey

On October 14, 2013, the participants took a pre-condition survey to establish a comfort baseline. Two weeks later, on October 24, the PCS were delivered and the participants began using them (Figure 1.3-5).

Figure 1.3-5: Participants in Stanley Hall with PCS equipment installed

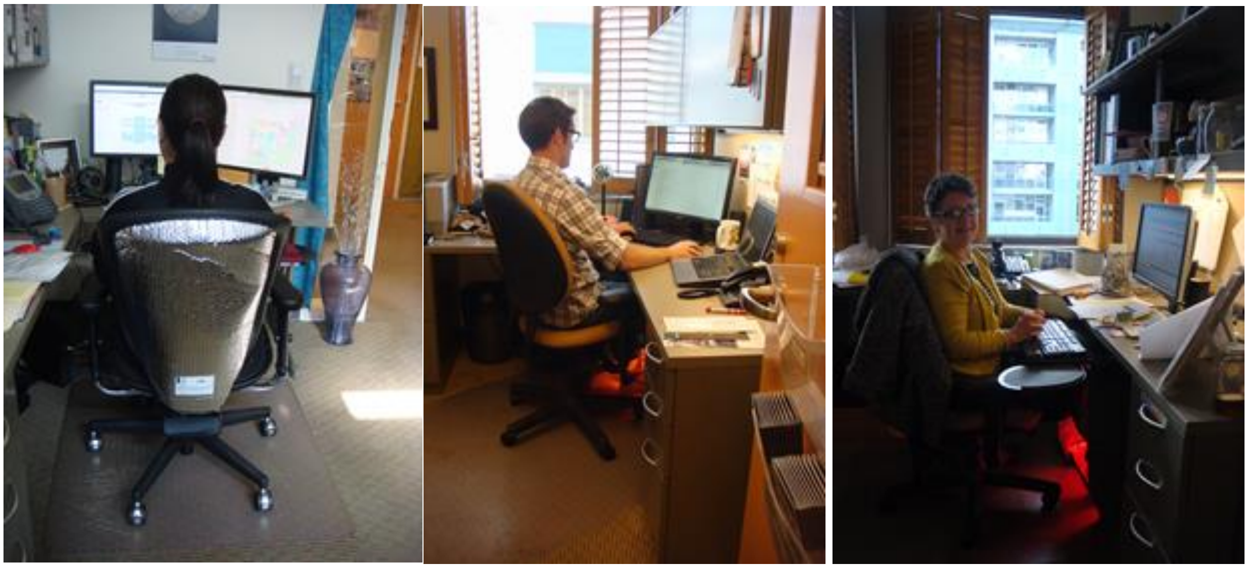
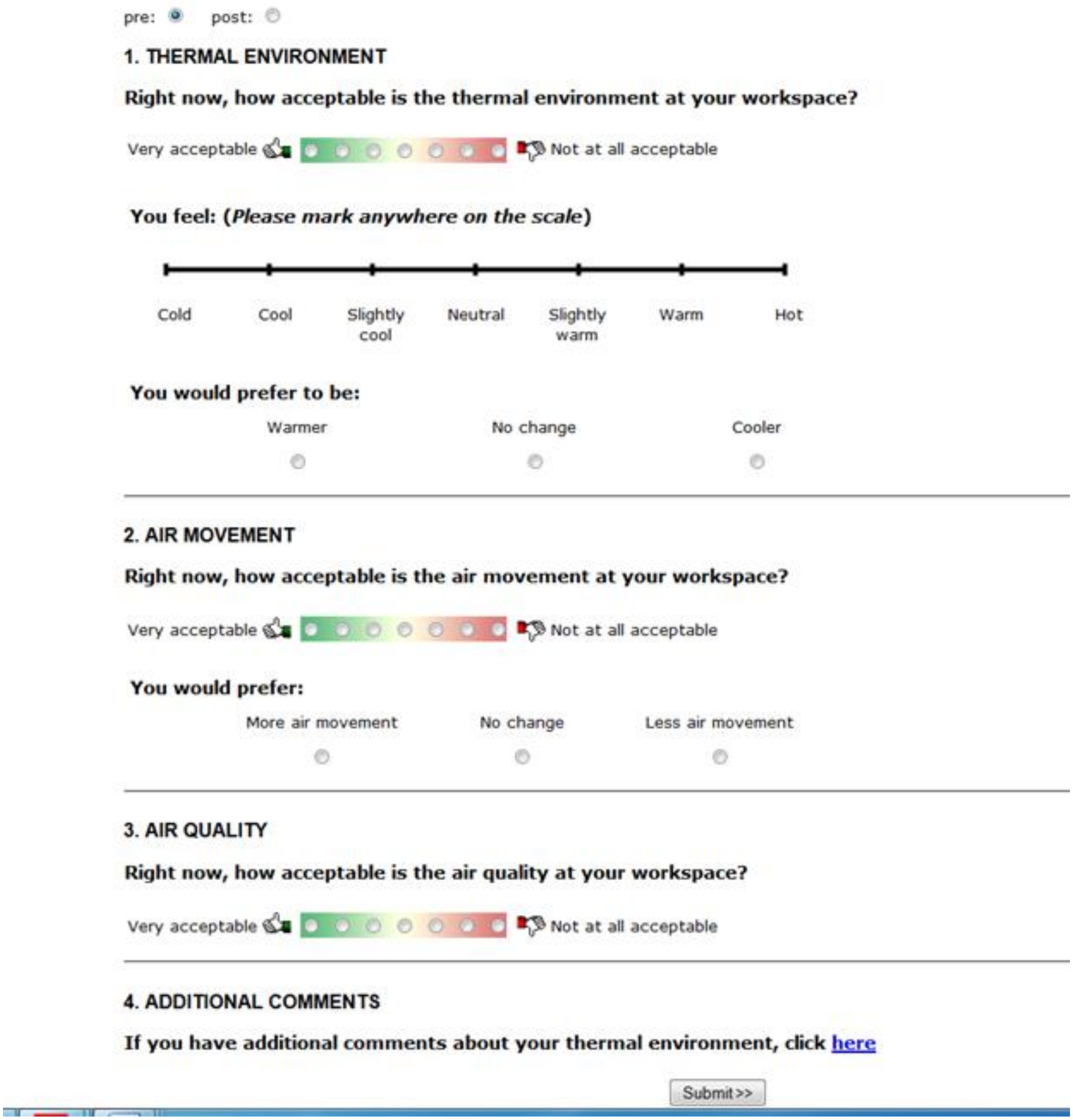


Photo Credit: Center for the Built Environment

After participants had used the PCS (chair, foot warmer or leg warmer) for a week, the research team started the 'post' surveys, to survey occupant comfort with the PCS systems. The post survey continued for 15 months, ending in February, 2015. Over the course of the 15 months, they changed the airflow rates and temperature set points to let the room temperature float up in summer and float down in winter, as described in the timeline (Table 1.3-4). The surveys continued for about 2 to 4 weeks for each change, to capture subjective responses to those changes.

During survey periods, the surveys were conducted at the frequency of twice per day. An email reminder was sent to all participants each working day at 10AM and 3PM, asking them to complete the survey if they had been in their space continuously for at least 15 minutes. The pre- and post- survey questions are presented in Figure 1.3-6 and 1.3-7. Because the survey asks for people's perceptions at the moment when they're taking the survey, we call it the 'right-now' survey.

Figure 1.3-6: Pre-condition survey



pre: ◉ post: ○

1. THERMAL ENVIRONMENT

Right now, how acceptable is the thermal environment at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

You feel: (*Please mark anywhere on the scale*)

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

You would prefer to be:

Warmer	No change	Cooler
○	○	○

2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

You would prefer:

More air movement	No change	Less air movement
○	○	○

3. AIR QUALITY

Right now, how acceptable is the air quality at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

4. ADDITIONAL COMMENTS

If you have additional comments about your thermal environment, click here

Submit>>

Figure 1.3-7: Post-condition survey

pre: ○ post: ●

1. THERMAL ENVIRONMENT

Right now, how acceptable is the thermal environment at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

You feel: (*Please mark anywhere on the scale*)

Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot

You would prefer to be:

Warmer	No change	Cooler
○	○	○

2. AIR MOVEMENT

Right now, how acceptable is the air movement at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

The air movement feels: (*Please mark anywhere on the scale*)

Imperceptible | Slightly perceptible | Clearly noticeable | Strong | Very strong

You would prefer:

More air movement	No change	Less air movement
○	○	○

3. AIR QUALITY

Right now, how acceptable is the air quality at your workspace?

Very acceptable ○ ○ ○ ○ ○ ○ ○ Not at all acceptable

4. PERSONAL COMFORT SYSTEM

Current status of your heated/cooled chair:

	On	Off
Heating	○	○
Cooling	○	○

Current status of your desk fan: On ○ Off ○

Current status of footwarmer (if you have one): On ○ Off ○

5. COMMENTS ABOUT THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT SYSTEM

If you have additional comments about your Personal Comfort System, click here

Submit >>

1.3.5.3 Exit Survey

An exit survey was conducted at the end of the study to invite the participants to assess their experience with the PCS equipment. This exit survey has been especially valuable in suggesting ways in which the PCS could be improved. Figure 1.3-8 shows the exit survey questions.

Figure 1.3-8: Exit survey questionnaire

What is your workstation number/name

[ ]

Which PCS did you have during the study?

- ○ Heated/cooled chair
- ○ Footwarmer
- ○ Legwarmer
- ○ None

Please check the following statements with which you agree regarding your experience with the PCS (chair/footwarmer/legwarmer) (check all that apply):

- ☐ I like having the PCS
- ☐ I do not like having the PCS
- ☐ The PCS provides relief from feeling cold
- ☐ The maximum setting on the PCS is not strong enough for heating
- ☐ I could not find the right heating level with the current controls
- ☐ The PCS provides relief from feeling warm
- ☐ The maximum setting on the PCS is not strong enough for cooling
- ☐ I could not find the right cooling level with the current controls
- ☐ Other

If you do not like having the PCS, why?

[ ]

Were there specific or regular times in which the PCS did not keep you warm enough at your workstation?

- ○ Yes
- ○ No

If Yes, please explain when it occured

[ ]

What suggestions do you have to change how the PCS operates (how it works)?

[ ]

What suggestions do you have to change the aesthetics of the PCS (how it looks)?

[ ]

1.3.5.4 Energy Monitoring

Wireless power monitors measured power use of plug load equipment in the space, including that of the PCS equipment. Wireless sensors measured discharge air temperatures and airflow rates from the zone ceiling air diffusers. Use of the sMAP protocol allowed data to be collected fully automatically from these wireless sensors and seamlessly integrated with data manually downloaded from the Barrington HVAC control system.

The data collected from the air terminal units via the HVAC control system included the air volume flow and the zone temperature measured by the control system temperature sensors.

This data allowed the complete evaluation of energy inputs to the zones. The purpose of this analysis was to evaluate how much energy was saved as various control attribute changes were implemented. The analysis neglects fan energy but calculates the net heat energy required to heat and cool the space at various temperature set points, both with and without the PCS.

1.3.6 Activities

During October of 2013, power monitors and temperature sensors were installed to monitor the plug loads and to perform an HVAC zone energy balance. A one-week survey of occupant's thermal comfort was conducted between October 14 and 25th, 2013 before PCS were delivered, in order to establish a baseline for comfort. Table 1.3-1 shows the pre-existing temperature set points, which varied between 71 degrees F and 75 degreesF in the zones studied.

Table 1.3-1: Pre-existing temperature set points in the study rooms

Room	Set point (F)
306E	75
306B	74
306H	75
306J	73.5
306C	74
306 L	74
206	72
206B	73
206C	73
206D	71

Results from the initial survey expressed a slightly cool sensation, on average, with a satisfaction rate of only 56 percent. 44 percent, slightly less than half the people, were dissatisfied with temperature in the zones. Surprisingly, considering the set points, a number of respondents described the space as 'cold' and their thermal environment as 'not acceptable'.

On October 24th, the 26 occupants received the heated and cooled chairs, foot warmers, legwarmers, and small fans, which they had chosen for use.

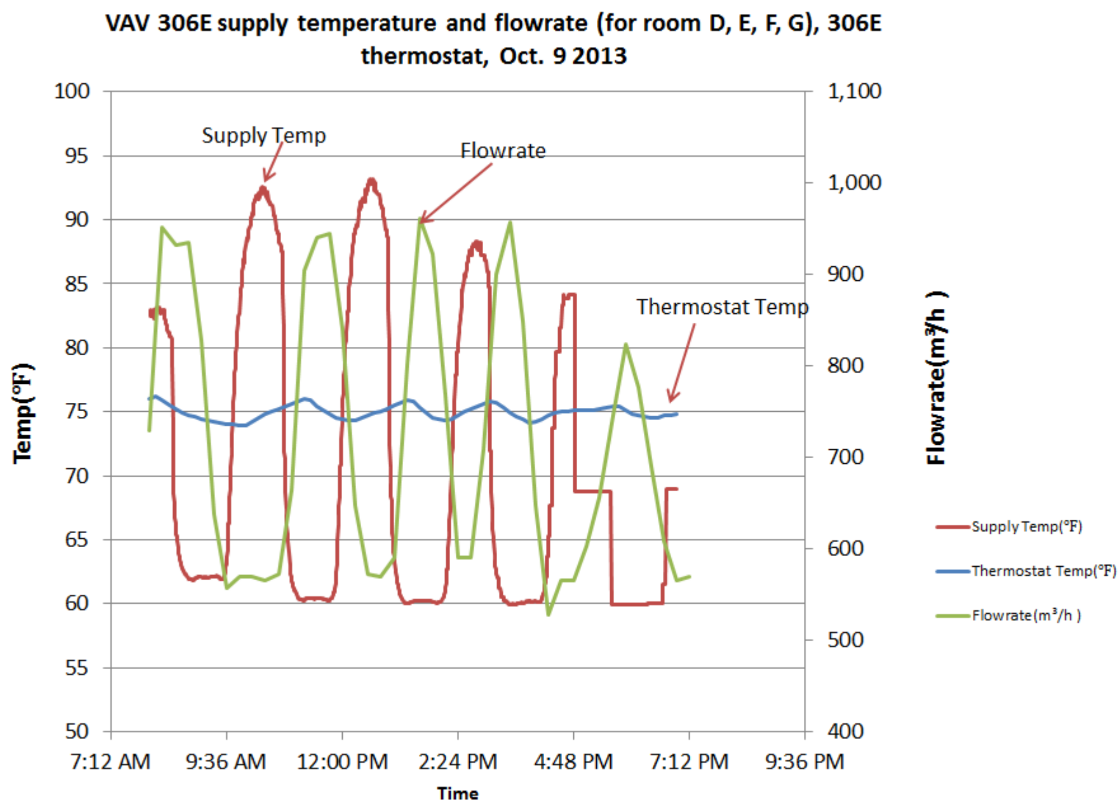
After the PCS units were installed, the researchers conducted a 2-week long thermal comfort survey. The post-condition survey included several questions specific to the PCS, as shown in Figure 1.3-7 above. The HVAC system control conditions were kept the same as the base-case condition.

Once occupants began using the PCS, comfort improved significantly, with the percent satisfied with the thermal comfort rising from 56 percent in the pre-PCS survey period to 77 percent in the post-PCS survey period. 80 percent satisfied is considered as the target for functional building designs, so adding the PCS essentially brought building comfort to a level considered acceptable. At this point the researchers began to investigate why the spaces had so many comfort complaints to begin with.

1.3.6.1 Existing airflow rate, supply and room temperature fluctuations

To find the reasons for the cool complaints, the researchers examined airflow rate, supply air temperature, heating valve operation, and thermostat temperatures in several offices where cool complaints were high. They identified problems with the existing operation of the building's HVAC system. Specifically, the VAV system was not maintaining a steady airflow rate (green line in Figure 1.3-9) or discharge air temperature (red line). Instead, they fluctuated widely between its maximum and minimum set points, in a cycle with a period of about 2.5 hours. During this cycle, while the airflow was at the maximum, the supply air temperature switched from heating mode (maximum around 90 degrees F) to cooling model (minimum around 60 degrees F), as shown in Figure 1.3-9. These spaces are very over-ventilated (described later under flow rate and temperature reductions), so the sudden transition in the supply temperature drop with maximum flow rate caused cool discomfort complaints. These fluctuations are further discussed in the discussion section. It could be partially caused by the single set point, and partially caused by improper control strategy.

Figure 1.3-9: Showing airflow and discharge air temperature fluctuations



1.3.6.2 Airflow rate reduction

The CBE researchers worked with the building and campus personnel responsible for controlling Stanley Hall's HVAC system. The Barrington control system uses a single temperature set point for heating and cooling, at least in the Stanley Hall implementation. Sometimes advanced control parameters are not accessible to building operators. The researchers approached the problem using one avenue they had available: the minimum and maximum airflow set points for the VAV boxes could be adjusted.

The researchers gradually reduced maximum and minimum airflow rates. Because the initial minimum airflow set points were greatly in excess of what was needed to provide sufficient ventilation, there was considerable scope to make these adjustments, which would also save on fan, heating, and cooling energy.

The first steps were taken in room 306, where the minimum airflow set points were reduced as a first step. At the beginning of the study, during the airflow rate sensor validation period, the team found that below certain levels, the valve positions could not be recorded accurately (appeared as zero frequently), so the newly reduced low minimum airflow rate could not be lower than those minimum valve positions, although the airflow rates were still far above the ventilation requirement (see table 1.3-2 below). For example, for a one person room, the minimum airflow rate is 15 cfm for ventilation purposes; here the lowest minimum airflow rate for one person room is still 75 cfm. After the minimum airflow rate reduction, the maximum set points were reduced in two steps between January and March 2015 to equal the minimum airflow rate levels

The researchers actively monitored temperatures in the third floor area through March of 2014 to make sure comfort could be maintained. When they were satisfied that conditions were acceptable, they began to reduce the air volumes in the rooms on the second floor, as shown in the lower graph in Figure 1.3-10. The same procedure applied: they first lowered the minimum airflow rate, then lowered the maximum airflow rate to the minimum airflow rate. The maximum airflow rates for all the VAV boxes for the 2nd and 3rd floors are presented in Tables 1.3-2 and 1.3-3. On average, the minimum airflow rate was reduced to about 30 percent of the original values on the 3rd floor, and 50 percent on the 2nd floor. The maximum airflow rate was reduced to between 50 and 75 percent of the original values on both floors.

Table 1.3-2: VAV airflow set points on third floor implemented Feb-Mar 2014

VAV reheat unit	Area description	Minimum Airflow Setpoint (cfm)		New maximum airflow setpoint		
		Original: as of 1/13/2014	New	Original: as of 2/24/2014	Step 1 (cfm) (2/24/14)	Step 2 (cfm) (3/3/14)
VAV 306B	Private office 306B, 1 occupant	125	Desired = 75 cfm	225 cfm	Desired = 150	Desired = 75
VAV 306C	Private office 306C, 1 occupant	150	Desired = 75 cfm	375 cfm	Desired = 225	Desired = 75
VAV 306E	Private offices 306D, 306E, 306F, 306G, 7 occupant	600	Desired = 400 cfm	1200 cfm	Desired = 800	Desired = 400
VAV 306H	Private office 306H, 1 occupant	275	Desired = 175 cfm	575 cfm	Desired = 375	Desired = 175
VAV 306J	Private offices 306J (1 occupant), 306K	325	Desired = 225 cfm	650 cfm	Desired = 440	Desired = 225
VAV 306L	Open plan 306A, kitchen 306L	300	Desired = 200 cfm	525 cfm	Desired = 365	Desired = 200

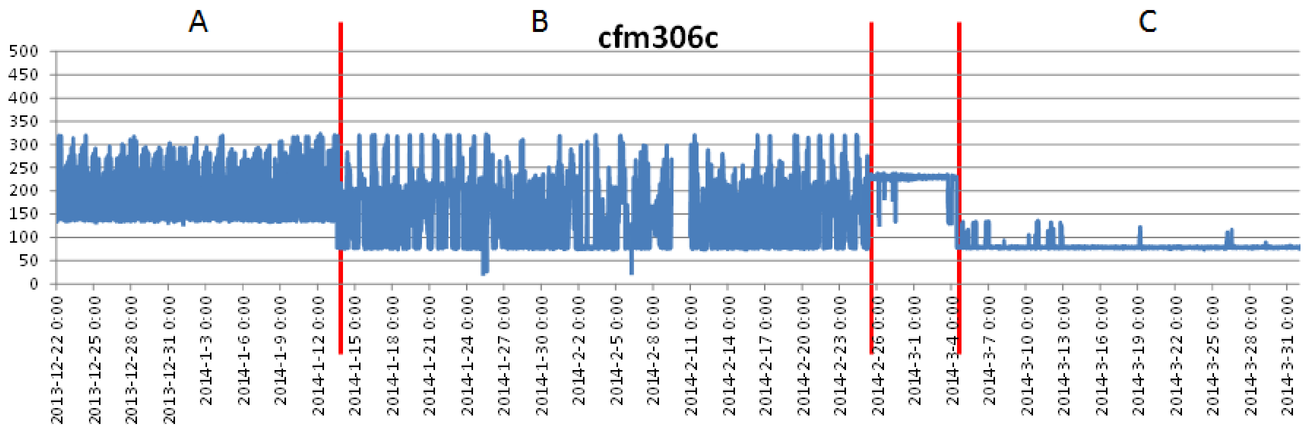
Table 1.3-3: Airflow set points on second floor

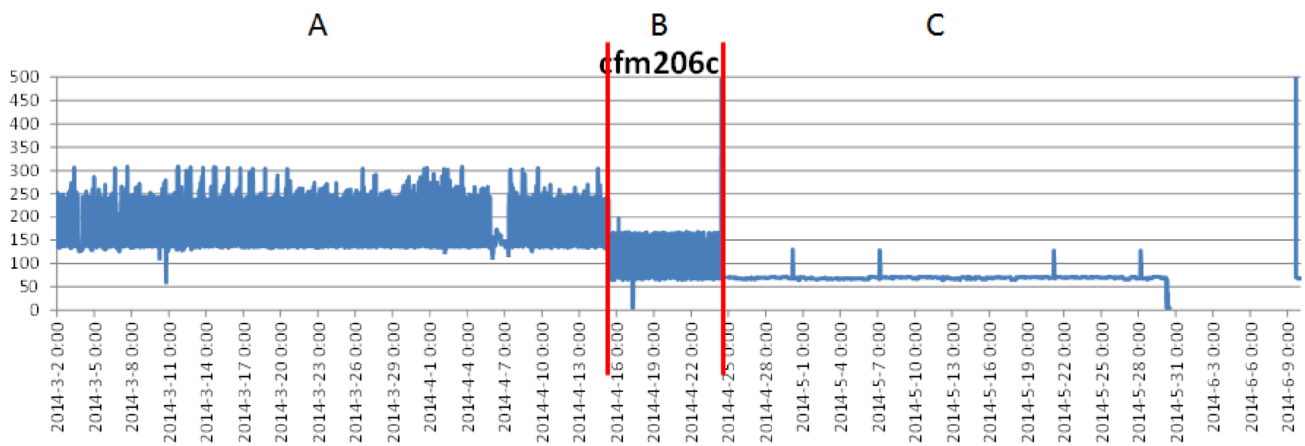
VAV reheat unit	Area description	Minimum Airflow Setpoint (cfm)		Maximum Airflow Setpoint (cfm)		
		as of 4/11/2014	New	as of 4/11/2014	New-Step 1	New-Step 2
206-1	Open plan; interior diffusers	300	Desired = 150	600	Desired = 375	Desired = 150; BMS = 179
206-2	Open plan; perimeter diffusers	450	Desired = 250	900	Desired =575	Desired = 250; BMS = 249
206B	Private office 206B, 2 occupants	150	Desired = 75	300	Desired = 190	Desired = 75; BMS = 89
206C	Private office 206C, 1 occupants	150	Desired = 75	270	Desired = 175	Desired = 75; BMS = 109
206D	Private office 206D, 2 occupants	150	Desired = 75	375	Desired = 225	Desired = 75; BMS = 101

The graph of room 306C in Figure 1.3-10 indicates the changes that were made over a period of 3 months on the 3rd floor: Period A is the baseline condition. The minimum airflow was reduced in period B to 75 cfm. After period B, we planned to reduce the maximum airflow rate Step I level as shown in Table 1.3-2. However, due to a miscommunication, the building operator also increased minimum airflow rate to the maximum airflow rate simultaneously. As a result, the total airflow rate was increased instead of reduced. Since operation during this period was a mistake, this period is not included in the data analysis later. In period C the maximum was set to the same lower minimum airflow rate, 75 cfm. Setting the minimum and the maximum to the same number eliminates the large swings in volume, but it also eliminated the ability of the VAV box to actively control temperature in cooling mode.

The graph of room 206C in Figure 1.3-10 shows the changes in April on the second floor. Again, period A is the baseline condition. The minimum airflow was reduced in period B, and the maximum airflow rate was reduced about half towards the minimum of 175 cfm. In period C the maximum was set equal to the minimum at 75 cfm.

Figure 1.3-10: Airflow room 306C December 2013 until March 2014 (top); Airflow room 206C March 2014 until June 2014 (bottom)





1.3.6.3 Temperature set point reduction

After the airflow rate reduction, in winter season (Nov. 2014 to Jan. 2015), we started to lower the temperature set points 1 degree F at a time until they were 5 degrees F lower than the beginning set points shown in Table 1.3-1. The timeline of the airflow rate and temperature set point changes are presented in Table 1.3-4

Table 1.3-4: Project timeline

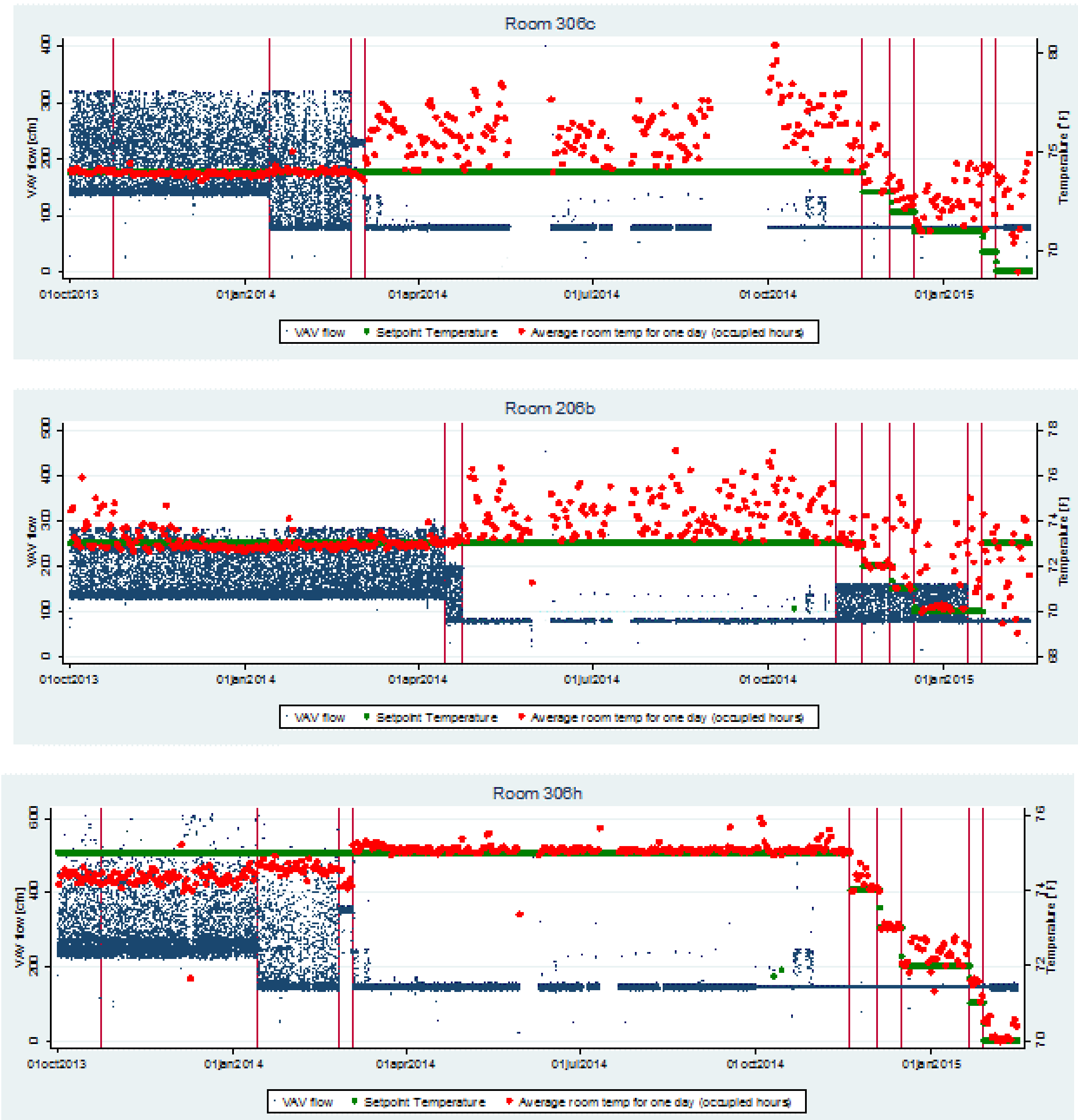
Task	Date		Description
T1	Pre	2013 Oct. 14 - 25	Pre-survey started
T2	2013 Oct. 24		Deliver PCS
T3	Post1	2013 Oct28-Nov26	Post survey started, no change of HVAC control
T4	2014 Jan. 13 3:40PM		R306 min Flowrate (q) reduction
T5	2014 Feb. 25 5:11PM		R306 Max q reduction (Step I)
T6	2014 Mar. 4 11:40AM		R306 Max q reduction (Step II)
T7	2014 Apr. 15 11:44AM		R206 Min q reduction, Max q reduction (Step I)
T8	2014 Apr. 24		R206 Max q reduction (Step II)
T9	Post2	2014 May 12 - 21	Survey under warm weather
T10	Post2	2014 August 4 - 12	Survey under warm weather
T11	Post2	2014 Sept. 4 - 23	Survey under warm weather
T12	Post2	2014 Oct. 1 - 18	Survey under warm weather
T13	2014 Nov. 5th 4:20PM,		Increased Max q for the second floor
T14	Post3	2014 Nov. 12 - 20	Base-case with higher flow rate on the 2nd floor
T15	2014 Nov. 19, 4:17PM,		-1F lowering
T16	Post4	2014 Nov20-Dec2	Survey 1F lowering
T17	2014 Dec. 4, 4PM		-2F lowering
T18	Post5	Dec. 8 - 15	Survey 2F lowering
T19	2014 Dec. 16, 9:18AM		-3F lowering
T20	Post6	2014 Dec. 16 - 23	Survey 3F lowering
T21	Post6	2015 Jan. 5 - 12	Survey 3F lowering
T22	2015 Jan. 13, 9:33AM		Flow rate 2nd floor reduced back to minimum
T23	Post 7	2015 Jan. 13 - 20	Survey 3F lowering
T24	2015 Jan. 21, 8:26AM		– 4F lowering
T25	Post 8	2015 Jan. 21 - 27	Survey 4F lowering
T26	2015 Jan. 28, 9:25AM		– 5F lowering
T27	Post 9	2015 Jan 28-Feb 4	Survey 5F lowering

1.3.6.4 Ambient temperature float in summer and winter

The reduction of airflow rates not only improved rapid fluctuations in zone airflow rate and supply temperature, they also let the room temperature float in an expected range in warm weather (see the top two charts in Figure 1.3-11 for two examples, 306C on the 3rd floor and 206B on the 2nd floor). The red dots in the figures represent the average daily temperatures for the two spaces. There are rooms (as shown in the third chart 306H in Figure 1.3-11) in which the temperatures didn't float as much, however, the room temperatures fluctuated less, as shown in Figure 1.3-9, so the room temperature in general was warmer. These changes allowed the team to examine PCS comfort under warm conditions.

As the season changed and outside temperatures began to drop, the study transitioned into heating mode. From T15 (November 2014) until T27 (January 2015) the temperature set points were reduced in 5 steps. The effects of this on rooms 306C and 306H are shown in Figures 1.3-15 and 1.3-16, respectively. In room 306C internal loads are enough to keep the room temperature from following the set point reductions, while in room 306H the average daily temperature tracks well with the set point change.

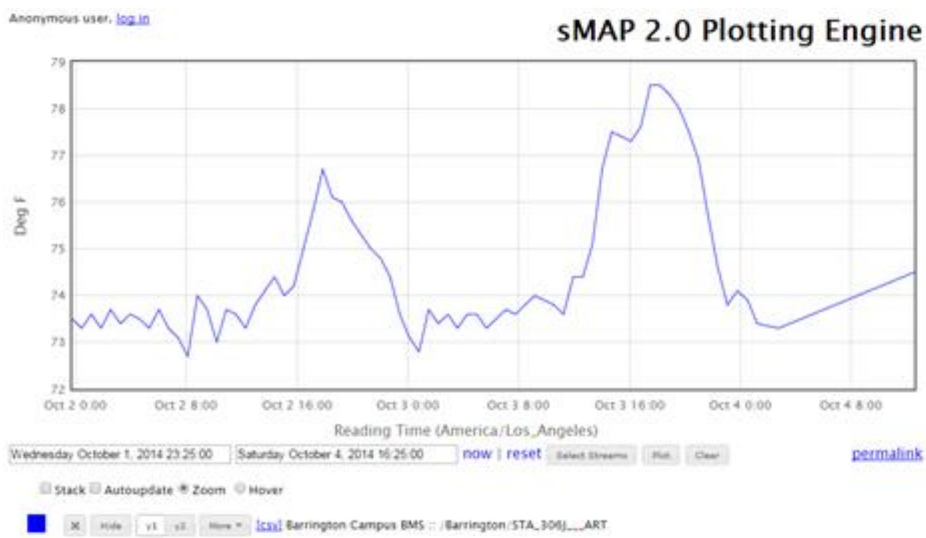
Figure 1.3-11: Airflow and temperature, Room 306C and 206B, October 2013 to January 2015



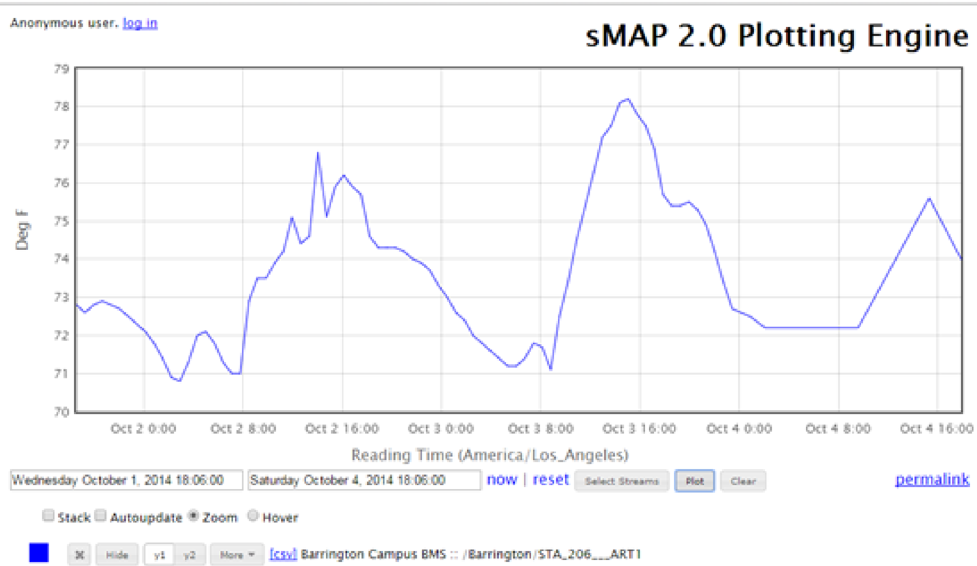
The two charts in Figure 1.3-12 show the detailed temperature changes over a few days during warm weather (October) on the two floors. In zone 306J, the heating valve may be able to maintain control when the zone temperature tends to fall below the set point of 73.5, but when the temperature tends to rise above, the VAV box cannot respond with more cooling air, so the temperatures drift upward. They reach over 77F for three or four hours in the afternoon.

In the second floor 206 open space, the zone temperature floats as high as 78 during the day, falling to around 71 in early morning.

Figure 1.3-12: Detailed temperature plot for 306J and 206, Oct. 1-3, 2014



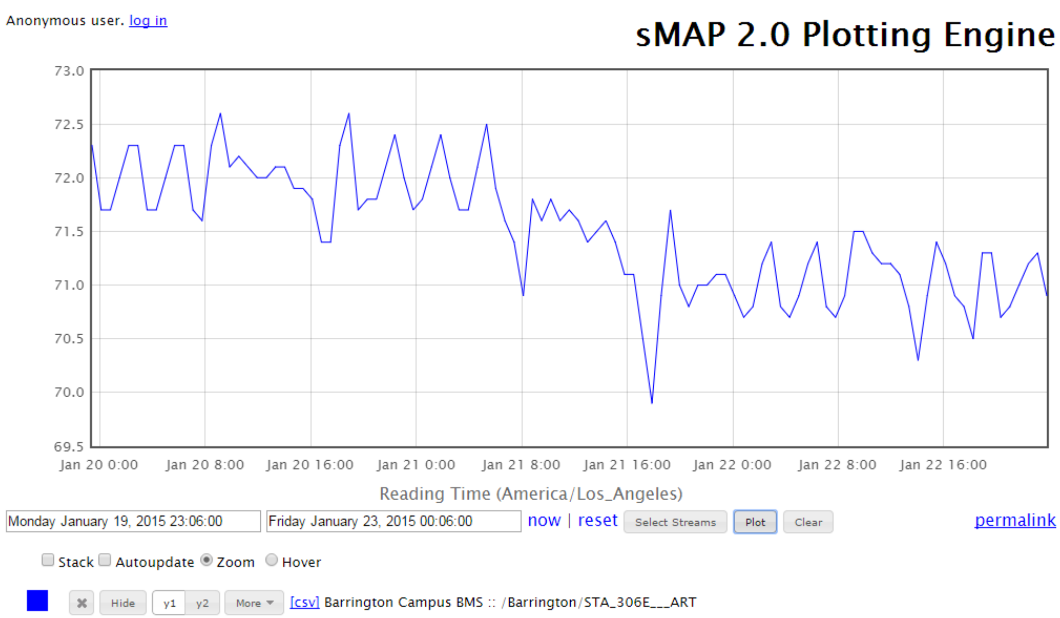
306J

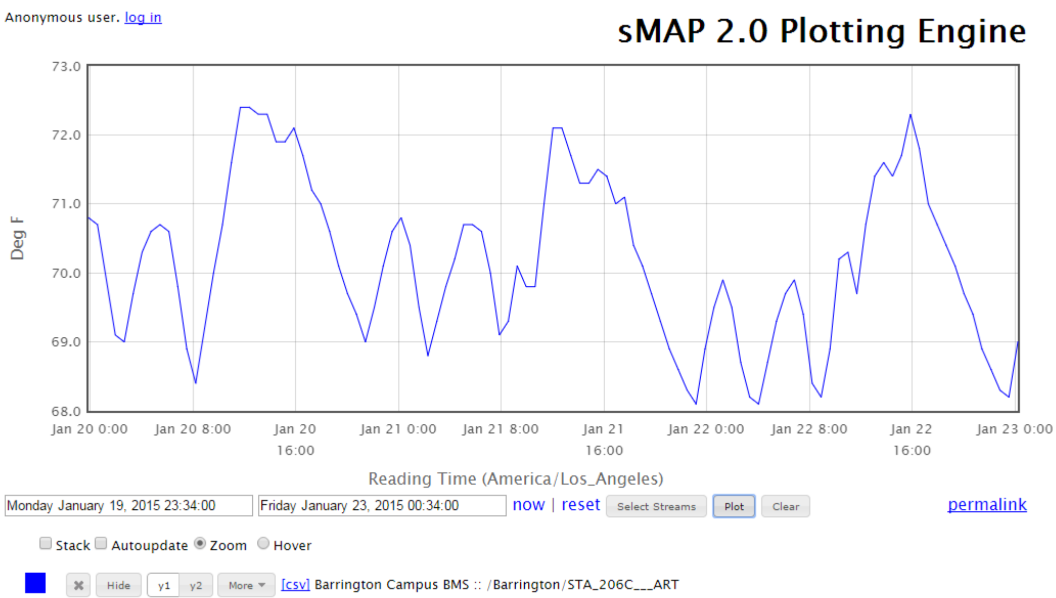


206

The two charts in Figure 1.3-13 show the detailed temperature changes over a few days in the cool season (January) on the two floors. The set point reduction happened in January 21, from a 3 degree F reduction (timeline T23) to a 4 degree F reduction (T24). In zone 306E, the set point changed from 72 degrees F to 71 degrees F, and the ambient temperature basically followed the set points. In zone 206C, the set point changed from 70 degrees F to 69 degrees F, but after about 10 AM each day, the ambient temperature could not reach the set points, which were about 1-2 degrees F higher. The problem is caused by the constant airflow rate, which could not meet the cooling load requirements. The advanced control parameters are not accessible to building operators due to the difficulty with the Barrington control, so proper ambient temperatures could not be maintained.

Figure 1.3-13: Temperature plot for 206, open space, October 2-4, 2014

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Jan 23 0:00
Reading Time (America/Los_Angeles)
Monday January 19, 2015 23:34:00
Friday January 23, 2015 00:34:00
now | reset
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Plot
Clear
permalink
Stack
Autoupdate
Zoom
Hover
Hide
y1
y2
More
[csv] Barrington Campus BMS :: /Barrington/STA_206C___ART

1.3.7 Results

1.3.7.1 Occupant satisfaction survey

From Figures 1.3-11 to 1.3-13, we can see that the team successfully increased ambient temperatures during warm weather. Most of the ambient temperatures in the study spaces reached 77 degrees F to 78 degrees F several hours each day. During cool weather, when the temperature set points were lowered by 1 degree F to 3 degrees F, the zone temperature was close to the set points. When the set points were lowered further by 4 degrees F and 5 degrees F, zone temperatures in most rooms did not fall further.

During all these zone temperature changes, the reported comfort was quite acceptable. The box chart in Figure 1.3-14 shows the acceptability for each survey period represented in Table 1.3-4 (timeline). The first two boxes show the comparison with and without the PCS without any changes in ambient condition set points: the red box represents the baseline condition without PCS, and the blue with the PCS. The acceptability was increased significantly from 56 percent without PCS to 77 percent with the PCS.

The blue boxes (May, August, Sept., Oct.) represent warm condition survey results. The acceptability is all around or near 80 percent. The blue box for November represents transitional outdoor conditions. The zone temperature float was not as high as in the previous months in summer. The acceptability rate is higher than the warm months at 84 percent.

The 5 green boxes present the survey results in the cool season when the ambient set point was reduced by 1 degree F to 5 degrees F. The acceptability is all well above 80 percent.

The thermal sensation in the base case was slightly cool (Figure 1.3-14). Although PCS were able to increase the baseline acceptability rate from 56 to 77 percent as described above (the red and the first blue boxes), the sensation was not warmer with PCS, it was still slightly cool. The author's hypothesis is that the transient cooling, during the maximum airflow rate and lowest supply air temperature, dominated the occupants' cool sensation, even with the PCS chair. During warm conditions (May, August, Sept., Oct.), the thermal sensation was near neutral. This is an indication that the PCS was able to maintain comfort in an otherwise warm environment.

As the set points were lowered in the cool season (green boxes), the ambient temperature became cooler, and occupants' thermal sensation was cooler. The levels of cool sensation were similar to the level under the base case condition, close to "slightly cool", although the acceptability was much higher than the base case condition (Figure 1.3-15). The survey indicates that thermal sensations are slightly cool, but comfort remains quite acceptable for the cool season when the set point was lowered.

Figure 1.3-14: Thermal comfort survey results

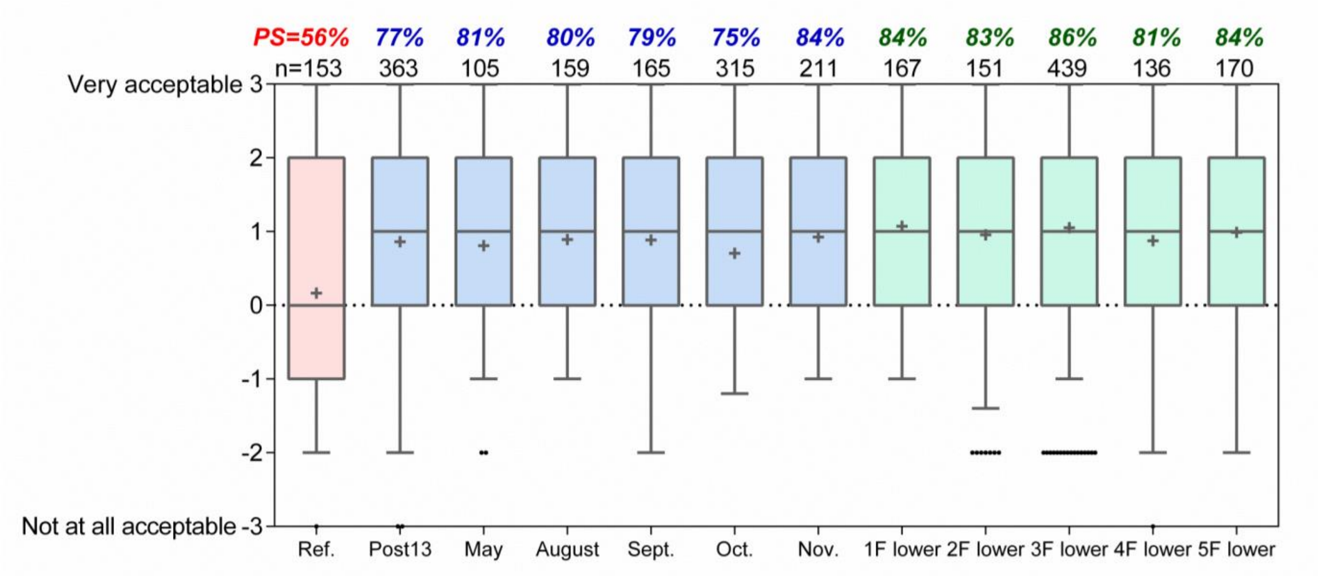
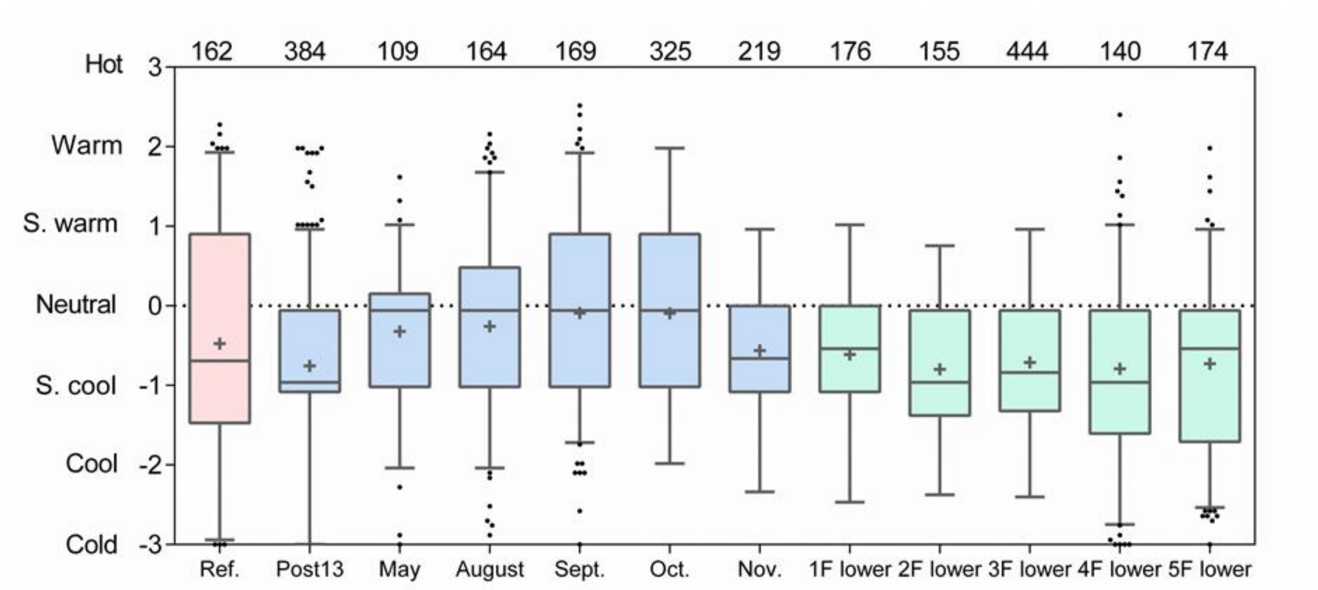


Figure 1.3-15: Thermal sensation survey results



1.3.7.2 How Participants Used PCS

Figure 1.3-16 shows how people used their PCS throughout the study period, according to the survey, and Figure 1.3-17 shows preferences for ambient temperatures. The diversity of responses makes clear that there is no one ambient temperature that will satisfy everyone, and giving people some control over their own thermal settings results in higher satisfaction, regardless of ambient temperature.

Figure 1.3-16: Use of PCS for heating or cooling throughout the study period

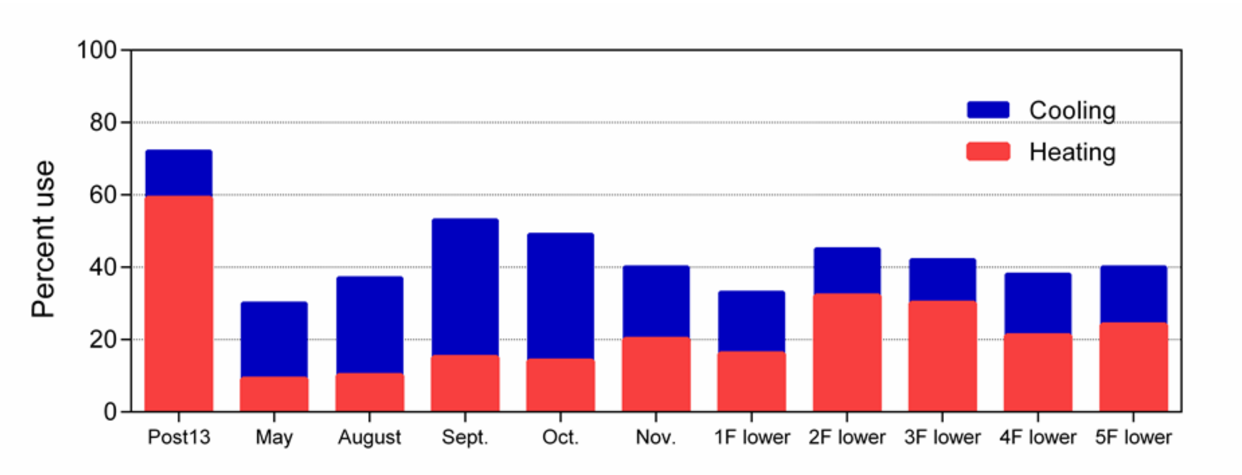
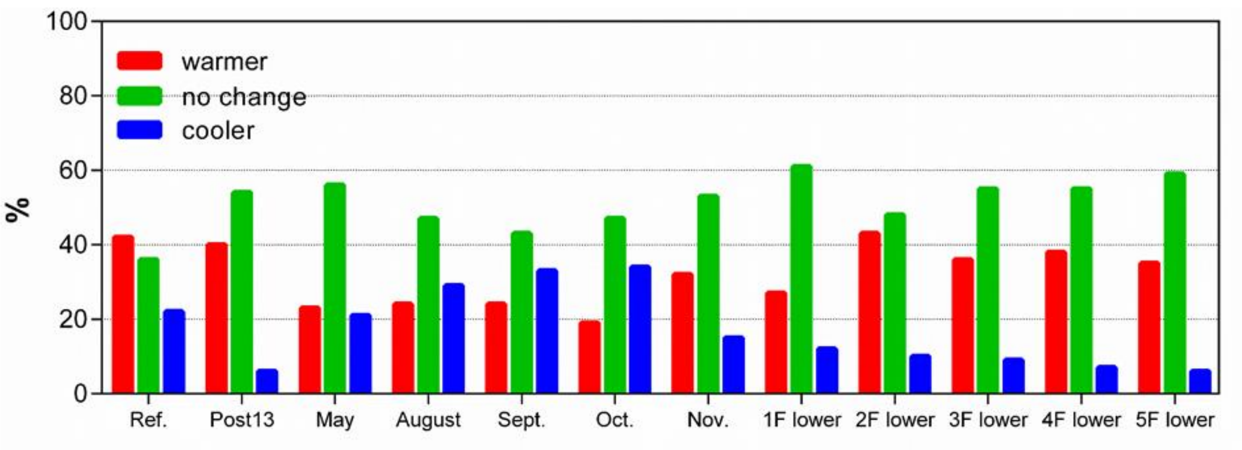


Figure 1.3-17: Ambient thermal preferences throughout the study period



1.3.7.3 Exit survey

Twelve participants took the exit survey, representing 12 chair users, 2 foot warmer users, and one legwarmer user.

Ten people liked the PCS, and said that the PCS provides relief from cold and warm discomfort. Two people could not use the chairs, one was due to her very small body size, one complained of back pain, and needed a very specific chair.

Regarding whether there is any specific time when the PCS is needed, 11 participants said there was no particular time, but one mentioned that she appreciated it most in the afternoon, when the vent above her workstation was blowing cold air.

As for improvements to the PCS equipment, one mentioned that the maximum level of chair heating is not high enough, and the heating is difficult to control adequately. Two people mentioned that the charging cable was not convenient, and one mentioned that the heating to the back and bottom should be separately controlled. She found that sometimes she wished the back to be warmed, but not the bottom. She had to sit more forward in the chair to reduce the bottom heating. One mentioned that once, after not using the chair for a while, when she turned on the cooling fan, dust was blown up.

One of the foot warmer users mentioned that she liked her foot warmer, but it did not warm the upper body. Half way into the study, she wished that she had selected the chair instead of a foot warmer. The legwarmer user mentioned that it needs to accommodate longer legs.

As for the aesthetics of the PCS, three of 12 people commented on the back of the chair; one said it was “a bit chunky”, one mentioned that the silver color does not look good and should be covered with some good looking material, and another said that the silver color made it look “like a NASA chair”. One mentioned that the range of motion of armrests should be greater.

1.3.8 Energy Results

It is clear that despite many confusing difficulties with controlling the temperature in Stanley Hall, the addition of PCS greatly improved thermal comfort satisfaction, and enabled the experimentation with airflow and temperature set points.

But what is the effect on energy use?

The PCS itself does add an electrical load, but small. A study described in Chapter 1 in the Bancroft DOE Annex Library showed that on average, the foot warmer electrical power is 20W/person. The electrical power use is nearly negligible in the case of small fans and heated/cooled chairs. The PCS chairs run on batteries that would normally be charged at night.

The major energy impact therefore is the reduction of heating, cooling and ventilating energy by the installed HVAC system. We will examine each of these in turn.

1.3.8.1 Heating Energy

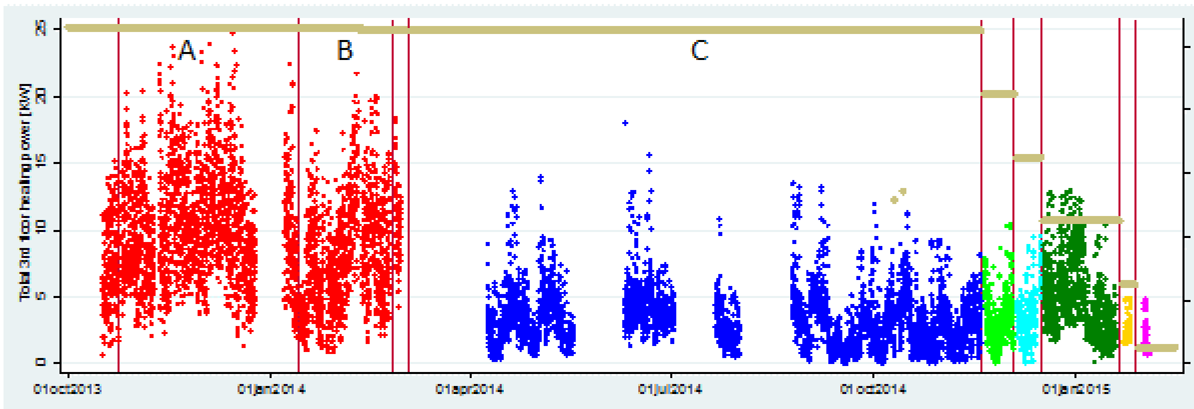
A primary contributor to reduction in central system heating energy is reduction of zone temperature, which reduces heat loss by conduction through walls and by mass transfer through loss of warm exhaust air and building air leaks. This heating energy is strongly affected by seasonal factors, rising in cold weather. A second contributor is reduction of reheat energy, by reduction of the volume of air needing reheat. A third contributor is eliminating fluctuations in airflow, which led to the oscillating behavior observed in Figure 1.3-9. This is a completely unnecessary energy use, functionally equivalent to simultaneous heating and cooling, but even worse because it also causes discomfort. This energy loss should not be encountered in a well-tuned building. While the savings can not be attributed to the addition of the PCS, the PCS clearly made an observable improvement in the occupant comfort.

Figure 1.3-18 illustrates the heating load for the 306 office complex (top chart) and the 206 office complex (lower chart). The corresponding air flow rate changes are indicated by letters "A"-original, "B"-minimum airflow rate reduction, and "C"-maximum airflow rate reduction, as also marked in Figure 1.3-11. We can see the heating load reduction in Period "B", when the minimum flow rate was reduced. The main observable reduction is when the maximum airflow set points were reduced to the same level as the minimum set points, Period "C".

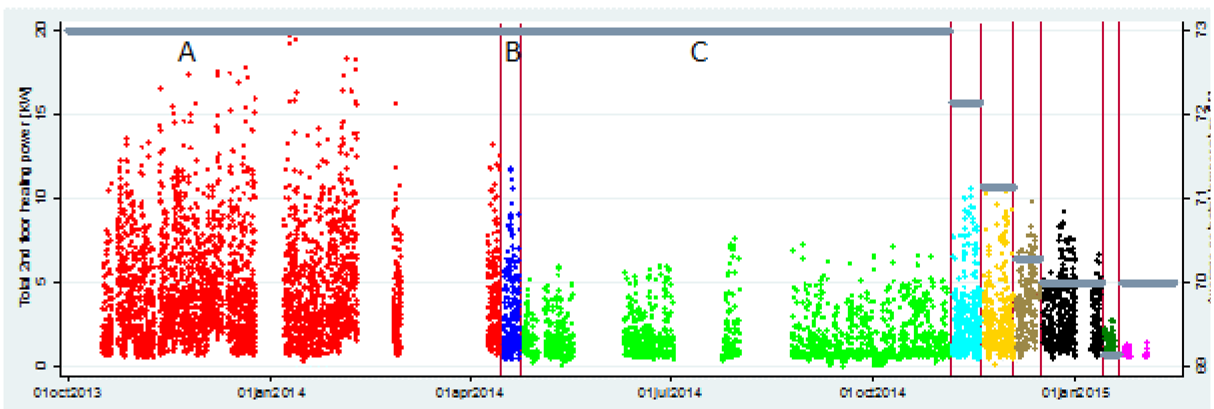
The savings are coming from all three contributors of savings: seasonal factors, reheat, and reduced fluctuations. The tan line in the upper chart and the grey line in the lower chart illustrate the temperature set point over the period. During the heating season, the temperature set point was reduced, but while the heating energy is reduced on the 2nd floor, it remains roughly constant or rises slightly on the 3rd floor due to the outdoor temperature reduction during that period. The outdoor temperature created more effect on the 3rd floor than the 2nd floor, because internal load is much higher on the 2nd floor than the 3rd floor.

The initial phase, after the introduction of PCS but before the airflow set point changes also illustrates that the PCS by themselves do not save energy, instead, they *enable* energy savings by maintaining excellent comfort while allowing set point changes and experimentation for maximum energy savings.

Figure 1.3-18: Total heating load and temperature set points for 306



3rd floor total heating load and temperature set point represented by the tan line



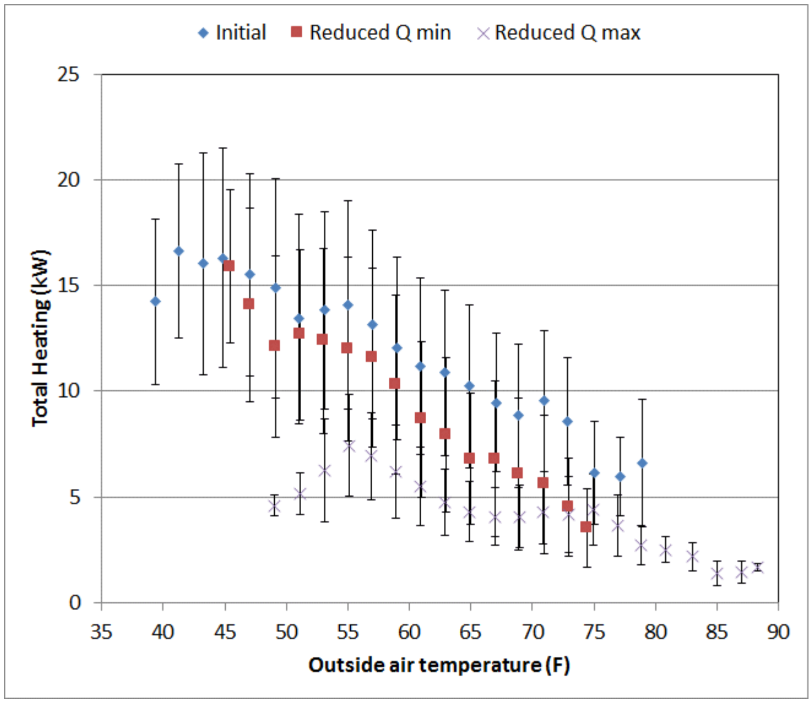
2nd floor total heating load and temperature set point represented by the grey line

Figure 1.3-19 illustrates how heating energy responded to the airflow changes as a function of outside air temperature in office complex 306 (top chart) and 206 (bottom chart), normalized for outside air temperature. This standardizes the three approaches with respect to seasonal factors, the lower airflow rates are saving as much as 65 percent of heating energy at 45 degrees F outside air temperature.

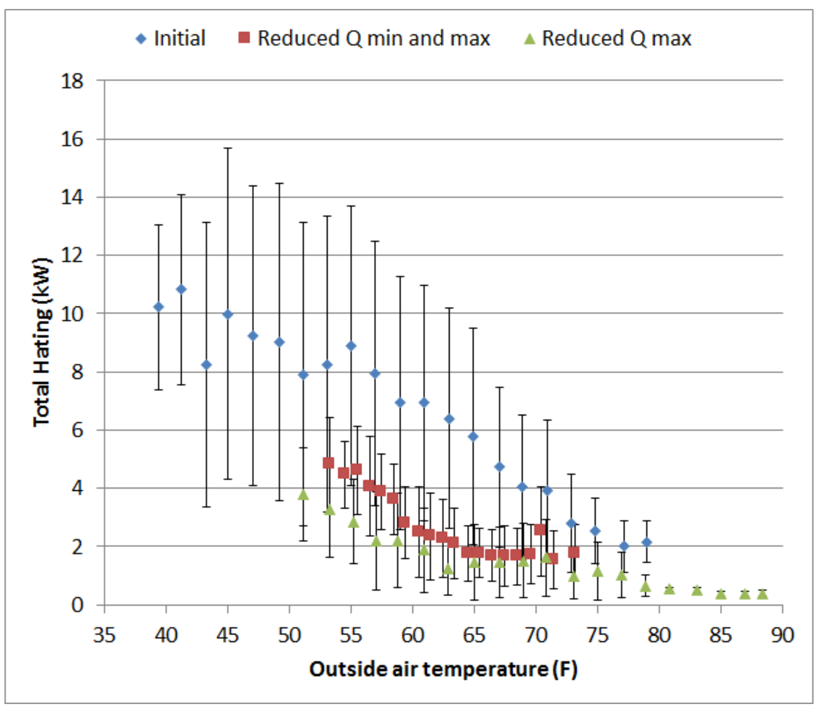
The savings in Period "B" for space 206 is higher than for space 306. The reason is that in addition to reducing the minimum flow rate, the maximum flow rate was also reduced (See Figure 43 bottom chart).

The energy saving with the temperature set point lowering in cool season is presented later in Table 1.3-5 through 1.3-8.

Figure 1.3-19: 306 heating energy for 3 control regimes as function of outside temperature



306 total heating energy saving with air flow rate reductions



206 total heating energy saving with air flow rate reductions

1.3.8.2 Cooling Energy

Cooling energy has many of the same contributors as heating energy: conduction and mass transfer, which are strongly affected by temperature set point and seasonal factors, airflow volumes and consequent reheat, and also the fluctuations due to improper control parameters, which simultaneously increase cooling loads and discomfort. Virtually all loads in the building contribute to cooling loads: people, equipment, conduction and leakage when the weather is warm, and the HVAC equipment itself, through fan energy and reheat.

Figure 1.3-20 shows how the cooling load dropped during various phases of the project. It's remarkable that the cooling load in August of 2014 is lower than the cooling load in January 2013, after the flow rate was reduced. The cooling load was further lowered as the set point was reduced in the cool season.

Figure 1.3-20: 306 cooling load under different control regimes

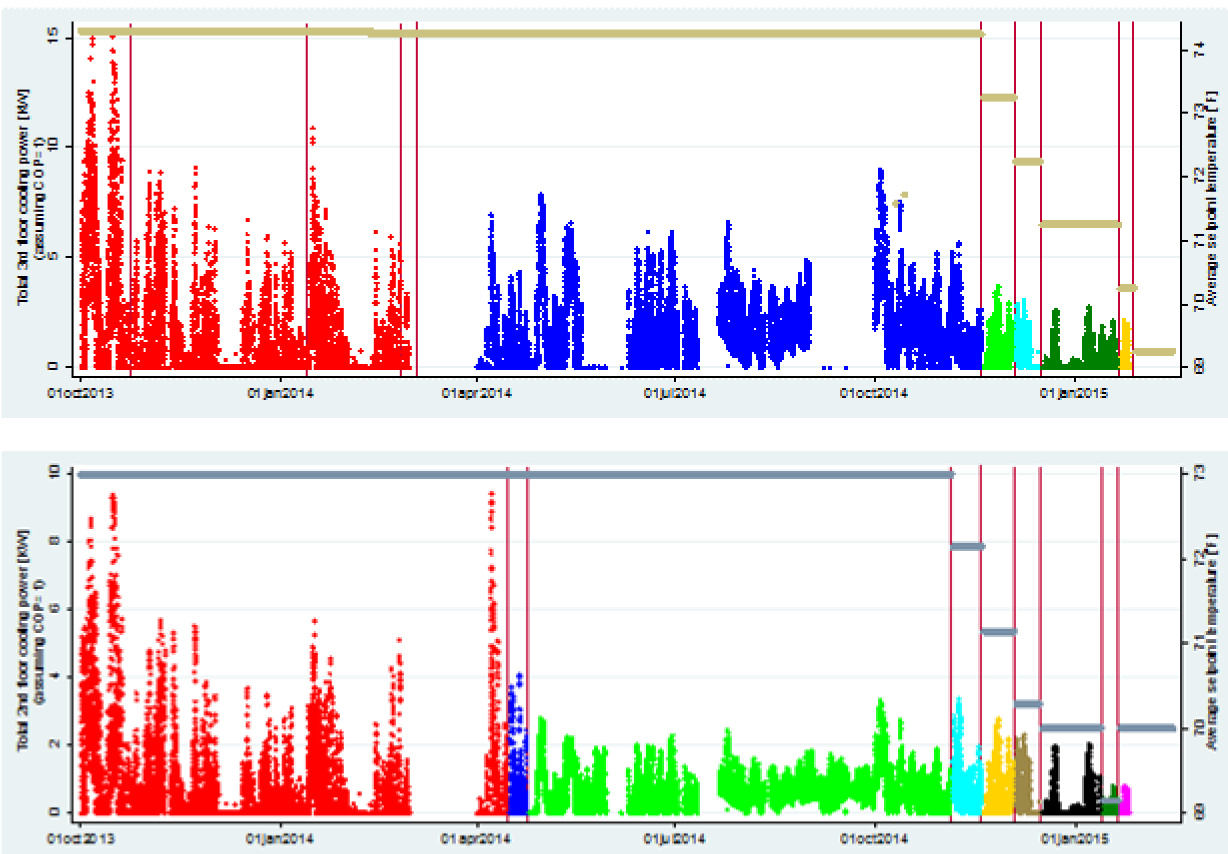
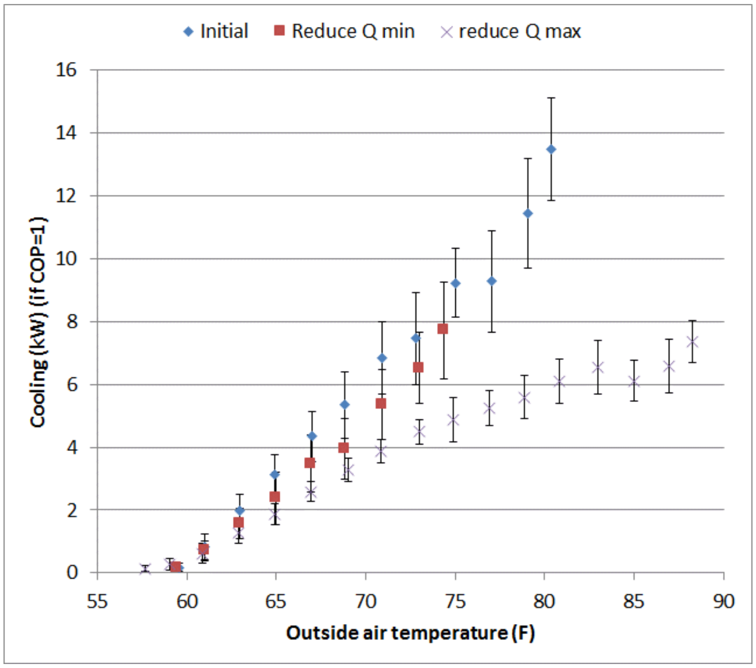


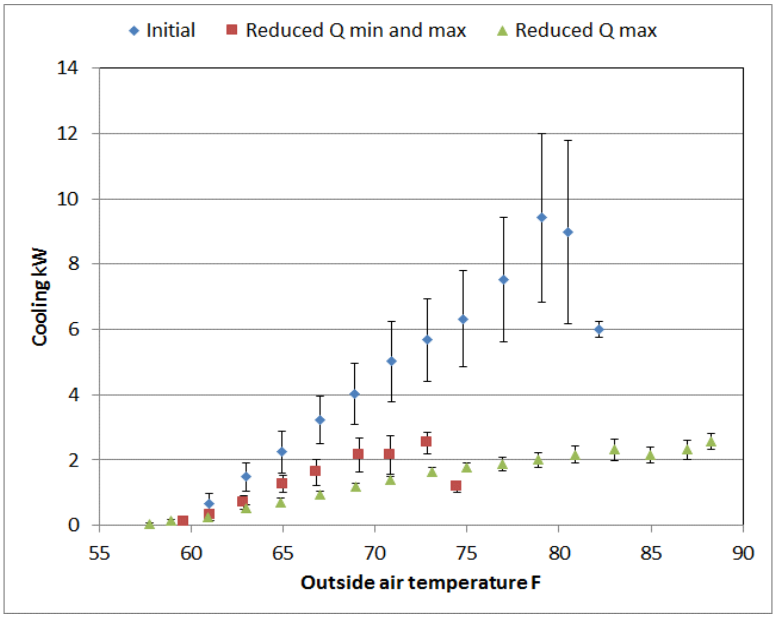
Figure 1.3-21 shows the effect of different control regimes, actually the reduction of airflows and elimination of fluctuations, normalized for outside air temperatures for both floors. During warmer temperatures (e.g. 80 degree F outdoor temperature), the energy used in cooling was less than half of what it had been previously, and the PCS resulted in substantially improved

comfort levels. Second floor results were even lower, at 80 degrees F outdoor temperature the cooling load was only about 30 percent of what it had been previously.

Figure 1.3-21: 306 cooling load in different control regimes as function of outside temperature



306 cooling energy saving with air flow rate reductions



206 cooling energy saving with air flow rate reductions

As the temperature set point was reduced, the heating and cooling energy was further saved. Tables 1.3-5 through 1.3-8 show the heating and cooling energy savings for spaces 306 and 206, for each step during the flow rate and temperature set point reductions. Unlike Figures 1.3-19 and 1.3-21, which show the energy savings corresponding to outdoor temperature, Tables 1.3-5 through 1.3-8 show energy savings corresponding to each test period (marked by the timeline). The weather conditions varied between these test periods, so the energy savings vary with the weather.

Table 1.3-5 presents the heating and cooling energy saving associated with minimum flow rate reduction (T4), maximum flow rate reduction (T6), from (T1, reference condition). Reducing the minimum flow rate reduced the heating energy use by 4 percent, and cooling energy use by 24 percent. With the maximum flow rate reduction, the heating energy was reduced 51 percent, and cooling energy 47 percent. The magnitude of the minimum and maximum flow rate levels for T1, T4, and T6 are shown in Table 1.3-2 (3rd floor) and Table 1.3-3 (2nd floor).

Table 1.3-5: Heating and cooling energy saving corresponding to flow rate reduction, 306

3rd floor time line			**Data from 9 AM to 5 PM only (no weekend setbacks)**						
		Start date	**Flow average [cfm]**	**Flow max (95th %tile)**	**Flow min (5th %tile)**	**Average Temperature setpoint**	**Average zone temperature**	**Estimated yearly average heating power [kw]**	**Estimated yearly average cooling power [kw] (COP=1)**
T1 (ref)	As found	01oct2013	2081	2454	1741	74.3	74.0	**7.91**	**2.46**
T4	Min flow reduced	14jan2014	1643	2175	1211	74.25	74.1	7.62 **(4%)**	1.87 **(24%)**
T6	Flow max reduced more	05mar2014	1096	1115	1072	74.25	74.7	4.02 **(51%)**	1.31 **(47%)**

Table 1.3-6 shows the heating and cooling energy savings associated with reducing zone temperature set points.

Lowering temperature set point mainly saves heating energy. We used the T6 (before the set point was lowered 1 degree F) as the reference condition to calculate energy savings. When the set point was reduced from 1 degree F to 3 degrees F, the heating energy saving was between 5 – 17 percent. The big energy savings happened when the zone temperature set point was reduced 4 degrees F and 5 degrees F. The reason for the big saving is that the weather was warm during these two periods. When the weather is mild, with the set point lowered, the need for heating is significantly reduced, therefore, a big saving was shown.

Cooling energy was small, around 5 percent for lowering the set point 1 degree F to 3 degrees F, 13 percent for lowering the set point 4 degrees F. There are times the savings are too small to be measured accurately, so the savings were not available.

Table 1.3-6: Heating and cooling energy saving corresponding to flow rate reduction

3rd floor time line			**Data from 9 AM to 5 PM only (no weekend setbacks)**						
		Start date	**Flow average [cfm]**	**Flow max (95th %tile)**	**Flow min (5th %tile)**	**Average Temperature setpoint**	**Average zone temperature**	**Estimated yearly average heating power [kw]**	**Estimated yearly average cooling power [kw] (COP=1)**
T6 (ref)	Flow max reduced more	05mar2014	1096	1115	1072	74.25	74.7	**4.02**	**1.31**
T15	-1F lower	20nov2014	1092	1112	1082	73.25	73.6	3.84 **(5%)**	1.27 **(3%)**
T17	-2F lower	05dec2014	1094	1109	1078	72.25	72.4	3.33 **(17%)**	1.26 **(4%)**
T19	-3F lower	17dec2014	1095	1110	1078	71.25	71.7	3.63 **(10%)**	1.25 **(5%)**
T24	-4F lower	22jan2015	1097	1114	1082	70.25	71.2	2.69 **(33%)**	1.14 **(13%)**
T26	-5F lower	29jan2015	1098	1119	1078	69.25	70.5	1.56 **(61%)**	n/a

The heating and cooling energy savings for the second floor associated with flow rate reductions are presented in Table 1.3-7. The minimum flow rate reduction corresponds to about 25 percent heating and cooling energy reduction, and maximum flow rate reduction corresponds to about 60 percent heating and cooling energy reduction.

Table 1.3-7: Heating and cooling energy saving corresponding to flow rate reduction

2nd floor time line		Data from 9 AM to 5 PM only (no weekend setbacks)							
		Start date	**Flow average [cfm]**	**Flow max (95th %tile)**	**Flow min (5th %tile)**	**Average Temperature set point**	**Average zone temperature**	**Estimated yearly average heating power [kw]**	**Estimated yearly average cooling power [kw] (COP=1)**
T1 (ref)	As found	01oct2013	1056	1512	678	72.2	72.4	**4.17**	**1.27**
T7	Flow max/min reduced	16apr2014	761	1092	382	72.2	72.4	3.18 **(24%)**	0.93 **(27%)**
T8	Flow max reduced to min	25apr2014	395	408	374	72.2	73.7	1.70 **(59%)**	0.48 **(62%)**
T13	Flow max increased	06nov2014	665	836	396	72.2	72.4	3.04 **(27%)**	0.74 **(42%)**

Again, we took the period before the temperature set point lowering (T13) as the reference case to calculate the energy savings associated with lowering the temperature set point. Very similar to the energy savings on the 3rd floor, we saw heating energy savings from 7 – 30 percent as the temperature set point was lowered from 1 degrees F to 3 degrees F. Significant heating energy was saved in periods T24 and T26, when the outdoor temperature was warm.

The cooling energy saving is very small, because the 2nd floor is internal load dominant.

Table 1.3-8: Energy saving corresponding to temperature set point reduction

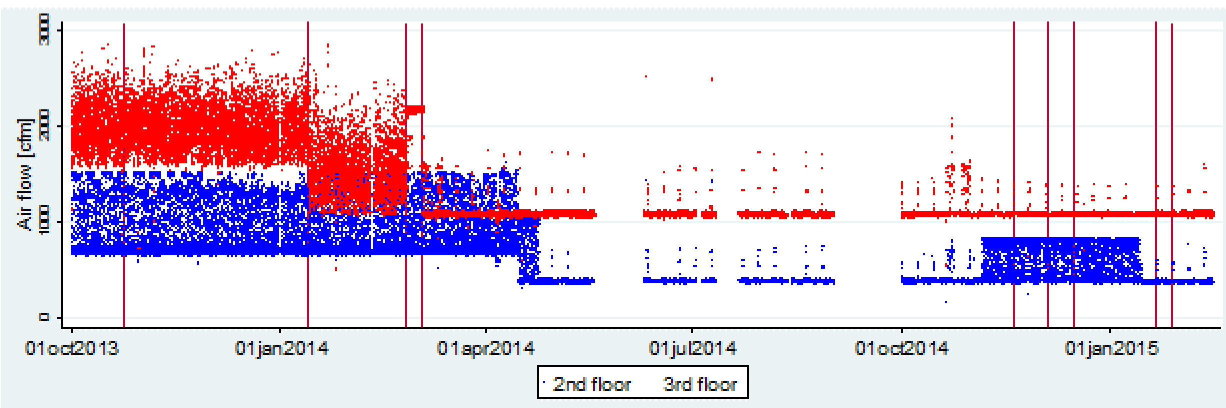
2nd floor time line			**Data from 9 AM to 5 PM only (no weekend setbacks)**						
		Start date	**Flow average [cfm]**	**Flow max (95th %tile)**	**Flow min (5th %tile)**	**Average Temperature set point**	**Average zone temperature**	**Estimated yearly average heating power [kw]**	**Estimated yearly average cooling power [kw] (COP=1)**
T13 (ref)	Flow max increased	06nov2014	665	836	396	72.2	72.4	**3.04**	**0.74**
T15	-1F lower	20nov2014	702	836	390	71.2	71.6	2.84 **(7%)**	0.85 (NA)
T17	-2F lower	05dec2014	738	837	399	70.4	70.9	3.42 (NA)	0.89 (NA)
T19	-3F lower	17dec2014	713	835	393	70.0	70.0	2.12 **(30%)**	0.93 (NA)
T24	Flow max lowered to min, -4F lower	14jan2015	386	405	371	69.2	71.6	0.94 **(69%)**	0.40 **(46%)**
T26	Various Setpoints	22jan2015	390	405	374	70.4	71.5	0.77 **(75%)**	0.40 **(46%)**

1.3.8.3 Ventilation Energy

Because the fans serving 206 and 306 also provide ventilation for other areas, it would not be meaningful to use measured fan energy data. Fan energy reductions are nonetheless very significant, and also contribute to cooling energy reductions, because fan energy ultimately expresses itself as heat. Figure 1.3-22 illustrates airflow reductions on the second and third floors in blue and red, respectively. The airflows can be conservatively estimated to have been cut by more than 50 percent. (Note: the sporadic weekly increase airflows are due to periodic fire alarm testing, when the HVAC system enters a 'purge' mode used to exhaust smoke.)

Engineering fan laws indicate that power scales as the cube of volume air flow in a simple fan system. A VAV system may depart from this characteristic, because the fan is varied to maintain a constant static pressure. The duct system itself will follow laws of static pressure loss, which indicate that pressure loss will be proportional to the square of volume flow rate. Assuming, as a rough estimate, that the fan laws apply, a 50 percent reduction in volume flow through the duct system will reduce fan energy by 87 percent. Obviously, this is a significant energy savings.

Figure 1.3-22: Airflow reductions in 206 (blue) and 306 (red)



1.3.9 Discussion and Conclusion

Stanley Hall is not an unusual building, in the sense that most modern buildings are not working nearly as efficiently as they might. All the advanced technology does little to save energy if it is not commissioned and functioning properly. Laboratory buildings like Stanley are especially susceptible to high energy use, because they embody many factors of safety and have high ventilation rates.

The researchers in this study were confronted with a building that was both uncomfortable in sections and using large amounts of energy, reportedly as much as 20 percent of the entire Berkeley campus. Proprietary control systems are often made difficult to understand and program in order to guarantee service contracts for the companies who supply and install them. Often onsite building operators have no access to training that would allow them to master these systems.

From the data collected, it is obvious that at least some parts of Stanley Hall were not properly commissioned by the controls contractor who installed the system. This is not unusual, in fact, it's more the rule than the exception. HVAC systems are complex and take time and expertise to master. Controls contractors typically don't have enough time to do the job properly. Commissioning also benefits from having the building fully occupied and operating. This often is not the case for some brand new buildings. Ideally, facilities engineers would be trained in how to tune these systems, but unfortunately, controls contractors often prefer to keep their secrets in order to guarantee future work. Oftentimes facilities staff have little time or budget for training, anyway. Unfortunately, the penalty is a high price in both energy and discomfort, leading to energy expense and loss of productivity.

The PCS clearly offers a partial solution. The comfort provided is substantial and immediate. It also gives operators an opportunity to reduce the building energy use, as was done in this case. PCS can be installed incrementally, provided to employees who indicate comfort problems. The diversity of use indicated by Figures 1.3-15 and 1.3-16 demonstrates that there is no one environmental state which is ideal for everyone, but the increases in satisfaction shows that giving occupants some ability to choose and control their own environment leads to much higher satisfaction, even in ambient conditions that would normally be considered unacceptable. The Stanley Hall field study is a great example of the multiple benefits this new approach to creating comfort brings.

1.4 IDeAs Building Case Study

1.4.1 Overview

The IDeAs Z^2 Design Facility building is the San Jose office of Integral Group, Inc. Integral Group is an innovative engineering firm offering advanced solutions in lighting design, electrical and mechanical engineering, and building performance analytics in the United States, Canada, and the United Kingdom.

The IDeAs building is located at 1084 Foxworthy Avenue (Suite 150) in San Jose, California. It was formerly a two-story, windowless, massive concrete tilt-up type structure of 7200 ft^2 used as a bank branch office. In 2005 the building was purchased by lighting engineer David Kaneda with the aim of renovating it to the highest LEED rating of Platinum, as an office for his firm, IDeAs. Kaneda engaged Scott Shell of EHDD Architects in San Francisco to help design the facility, and Shell convinced him to go beyond LEED Platinum and do something practically unheard of, to construct a building with zero net energy use.

The building was completed and occupied in 2007, and employs skylights, low-e and electrochromic windows for natural lighting, radiant heating and cooling using slab-embedded tubing driven by a ground-source heat pump, ultra-efficient electric lighting with advanced controls, carefully selected computers and office equipment, and about 30 (kilowatt) kW of rooftop photovoltaic panels. The building was certified as zero-net energy in 2012. About half of the ground floor is used as the Integral Group office, and is usually occupied by 24 people.

Figure 1.4-1: IDeAS building exterior, left, and interior, right

Photo Credit: Center for the Built Environment

1.4.2 Objective

Radiant floors and ceilings can be effective and energy efficient space conditioning techniques. However, heat transfer is dependent on the temperature of a massive concrete slab, and changing that slab temperature takes a good deal of time.

Personal Comfort Systems, by contrast, can respond nearly instantly to users individual thermal preferences. This suggests that they may be good complements to the slow-moving radiant slabs. The objective of this field study is to evaluate the performance of PCS in a building with radiant slabs. The research team set out to measure how comfort was affected by the addition of the PCS, and how much energy could be saved when heating set points were lowered and cooling set points were raised in the radiant zones.

1.4.3 Approach

As with other PCS field studies, the team first provided a workshop to familiarize the participants in the building with the Personal Comfort Systems. This took place in October 2014. All 24 occupants participated in the study.

Figure 1.4-2 Workshop to explain the Personal Comfort System

Photo Credit: Center for the Built Environment

Figure 1.4-3: PCS equipment supplied: (L to R) Chairs, foot warmers, and leg warmer

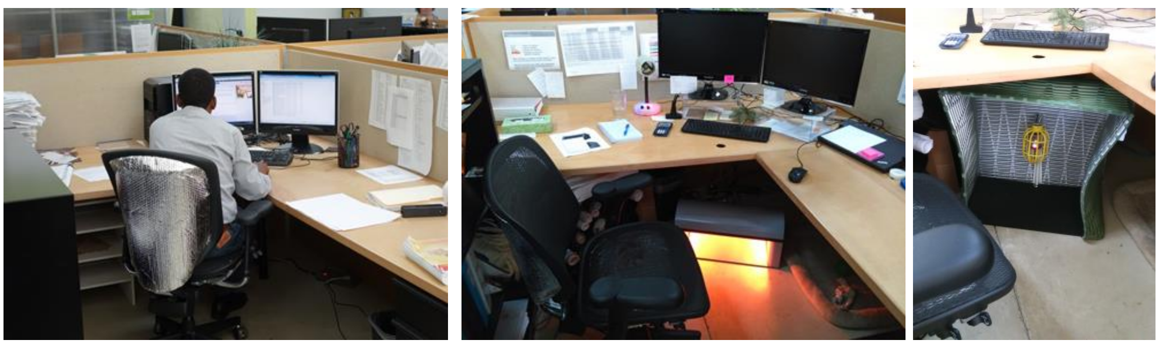


Photo Credit: Center for the Built Environment

1.4.3.1 Data Collection

Due to the nature of radiant floors, globe temperature, the assessment of the combined effects of radiation, air temperature and air velocity on human comfort, is more relevant than air temperature. Stratification is also important to measure, because the cooled and heated floor might affect that. The researchers also monitored energy use, HVAC system performance, and indoor environmental conditions. The details are described below.

Table 1.4-1: Measurements and devices

Physical parameters	Devices	Accuracy	Point
Room T, RH/outdoor	OnSet Hobo U12-013	Temperature: ± 0.35°C RH: ±2.5%	Eight points in the building
Globe (MRT) temperature	OnSet TMC1-HD external temperature sensor	±0.25°C	Seven points
Floor Surface temperature			Two points
Stratification			One point

OnSet Hobo ambient air temperature and relative humidity sensors, accurate to ± 0.35 degrees Celsius (C) and ±2.5 percent rehative humidity (RH), measured room temperature and RH, and OnSet TMC1-HD external globe temperature sensors, accurate to ±0.25 degrees C, measured globe temperature at seven places in the open plan workspace and private offices.

External temperature sensors and Hobo data loggers measured and recorded floor temperatures in two locations. Room temperature stratification was also measured at two locations, at 0.1meter (m), 0.3m, 0.6m, 1.1m, 1.7m heights above the floor, and 0.1m beneath the ceiling height. A Hobo located in a bush right outside of the building measured outdoor temperature. A nearby weather station provided independent weather data for comparison.

There are 3 zones in the building (Figure 1.2-4). Zone 1 is the open-plan office space (blue area), Zone 2 is the conference room (green area), and Zone 3 is the private office area (pink area). Sensor locations are also presented in Figure 2.4-4.

Figure 1.4-4: Measurement devices and locations

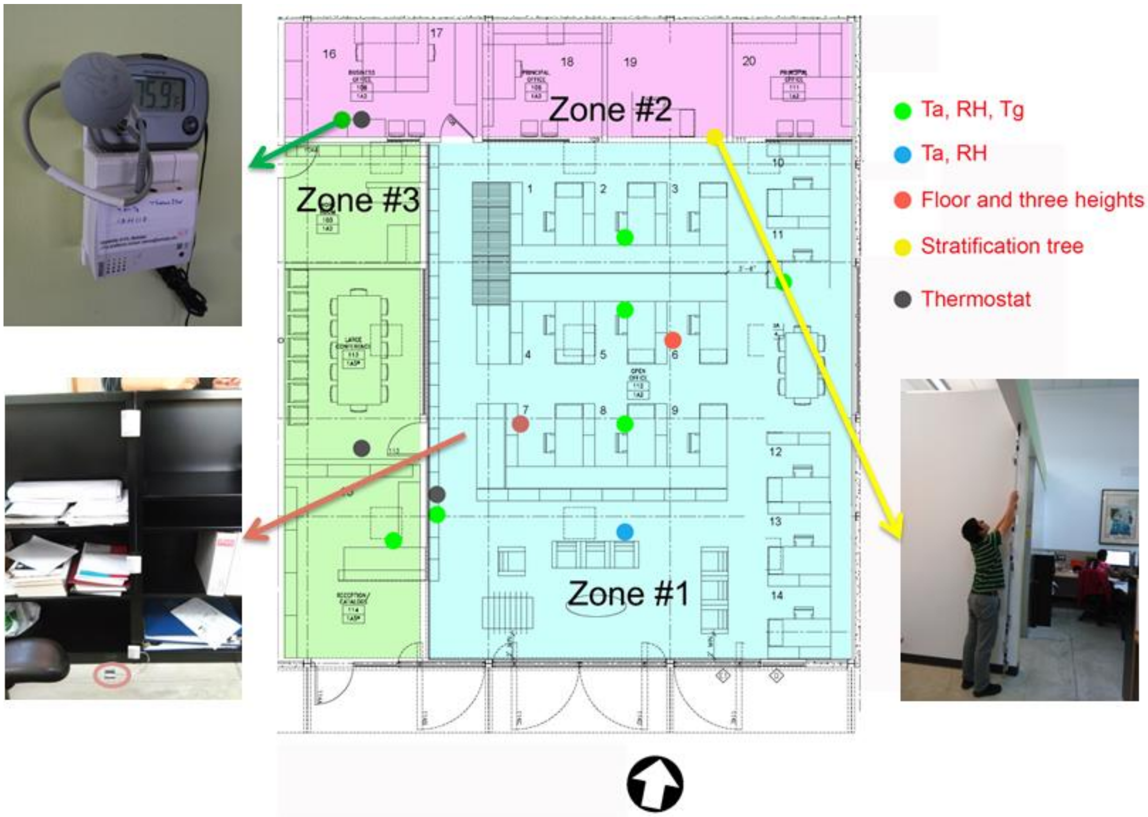


Photo Credit: Center for the Built Environment

1.4.3.2 Sensor calibration

The researchers calibrated the HOBO U12 data loggers in a climate-controlled chamber at 20 degrees C, 25 degrees C and 30 degrees C, and the TMC1-HD external sensors using a warm bath at the same three temperatures. All except one sensor measured temperature within 0.250 degrees C of the set point.

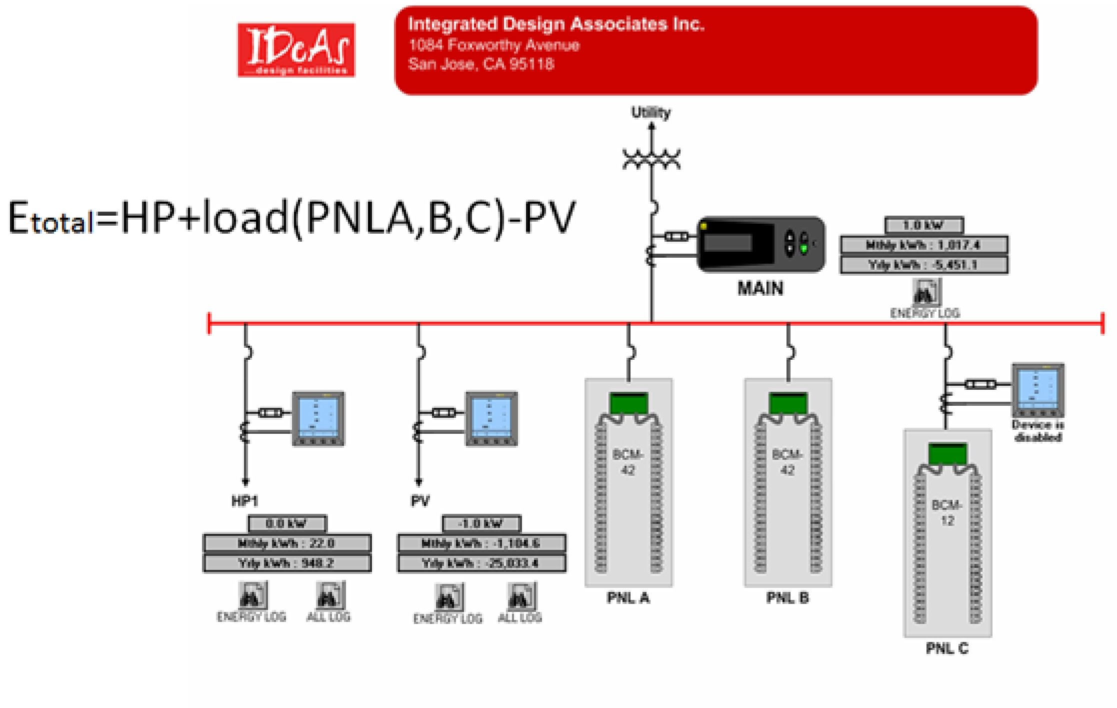
1.4.3.3 HVAC data collection

The researchers remotely connected to the building Building Management System computer and continuously downloaded the HVAC trend data, including zone temperature at each thermostat, slab temperature, heating/cooling water temperature from the heat pump, valve positions, and outdoor air temperature.

1.4.3.4 Power data

The researchers primarily examined data from the heat pump, solar panel electrical energy generation, and whole building electricity bills. They calculated HVAC energy by calculated by adding solar panel generation and subtracting plug load and lighting energy from the total energy bill (Figure 1.4-5).

Figure 1.4-5: Schematic diagram of electric power system



1.4.3.5 Occupant Surveys

The researchers surveyed occupants according to the schedule below. The survey questions are in Figure 1.4-8. The study was designed to evaluate PCS performance in winter season. The team conducted a survey from October 16 to 22 under preexisting condition, without PCS, to establish a comfort baseline. (Base survey). They delivered the PCS chairs October 23 and after a period for the participants to gain familiarity, surveyed comfort again from November 3 through 19. (T1 survey).

The team intended to adjust temperature set points through 2-steps: first from the original 71degrees F heating – 75 degrees F cooling, to 69.5 degrees F heating – 76.5 degrees F cooling, and again 68 degrees F heating – 78 degrees F cooling. Unfortunately, during the first set point adjustment, from December 15 to 17, many cold complaints led to the discovery that floor heating had been inadvertently shut off completely (T2-F survey).

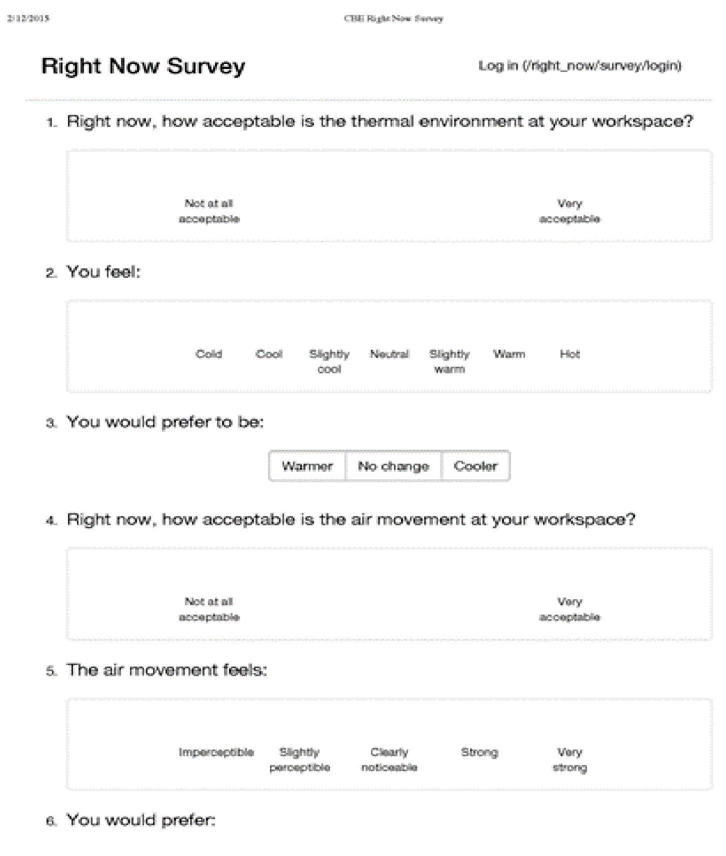
The researchers reset the experiment, going back to the initial set points from January 12 to 16 (T3 survey), then the first set point change from January 20 to February 2 (T4 survey). After January 20, a number of people complained of cold feet, so foot warmers and leg warmers were offered. Six chose foot warmers and one chose a leg warmer, which were delivered February 2.

Survey T5 was conducted until February 10, and then set points were changed to 67degrees F heating and 78 degrees F cooling, until February 20 (T6 survey)

Table 1.4-2: Survey schedule

Year	Date	SetpointT(F)	PCS	Phase	Notes
2014	Oct 16-22	71-75	none	Base	
2014	Nov 3-19	71-75	Chair	T1	Chair delivered on Oct. 23
2014	Dec 15-17	69.5-76.5	Chair	T2-F	Floor heating failed
2015	Jan 12-16	71-75	Chair	T3	Setpoint temperature changed back
2015	Jan 20-Feb 1	69.5-76.5	Chair	T4	Setpoint temperature 3F expanded
2015	Feb 2-10	69.5-76.5	Chair + footwarmer	T5	Footwarmer delivered on Feb.2
2015	Feb 11 - 20	67-78	Chair + footwarmer	T6	Setpoint temperature 6F expanded

Figure 1.4-6: Occupant survey questionnaire



2/12/2015 CBE Right Now Survey

Right Now Survey

Log in (/right_now/survey/login)

1. Right now, how acceptable is the thermal environment at your workspace?

Not at all acceptable … Very acceptable

2. You feel:

Cold | Cool | Slightly cool | Neutral | Slightly warm | Warm | Hot

3. You would prefer to be:

Warmer | No change | Cooler

4. Right now, how acceptable is the air movement at your workspace?

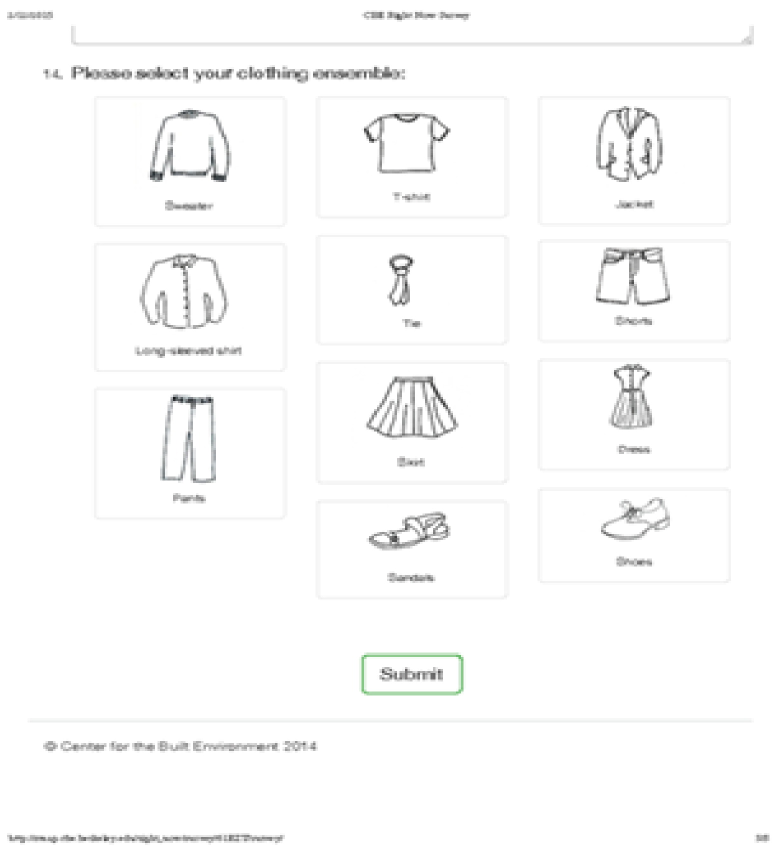
Not at all acceptable … Very acceptable

5. The air movement feels:

Imperceptible | Slightly perceptible | Clearly noticeable | Strong | Very strong

6. You would prefer:

1/3



1.4.4 Results

1.4.4.1 Outdoor and indoor air temperatures

Measured outdoor temperatures are close to the temperatures from a nearby weather station.

Figure 1.4-7: Measured outdoor temperatures during the study period

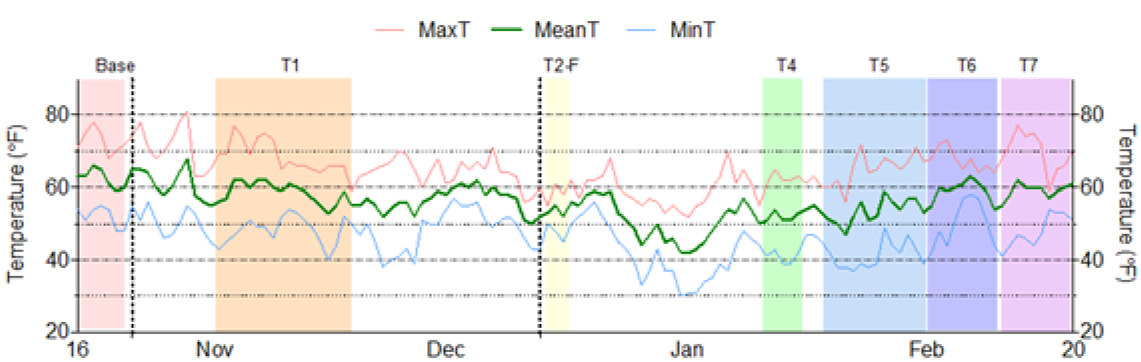


Figure 1.4-8: Outdoor temperatures from nearby weather station

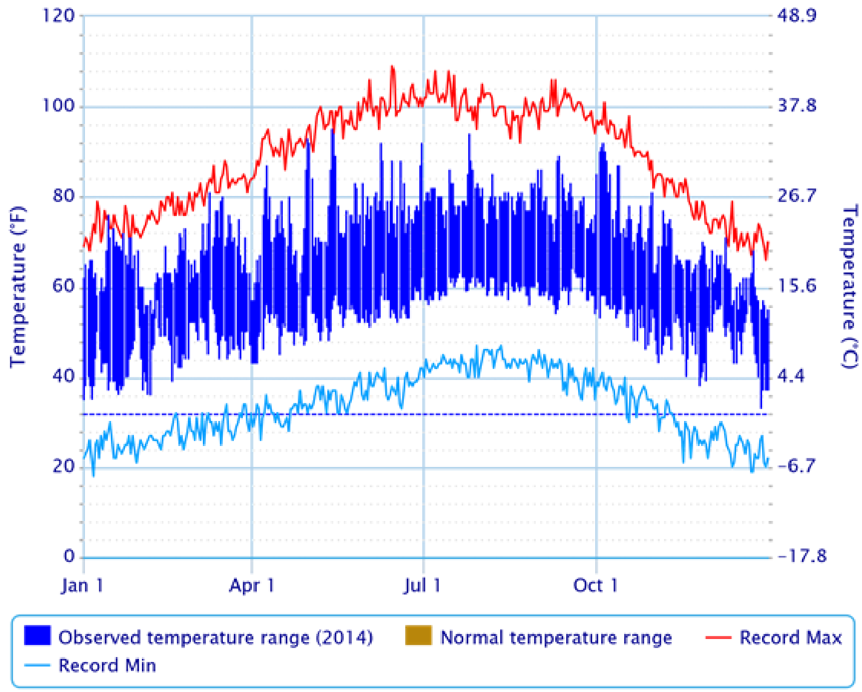
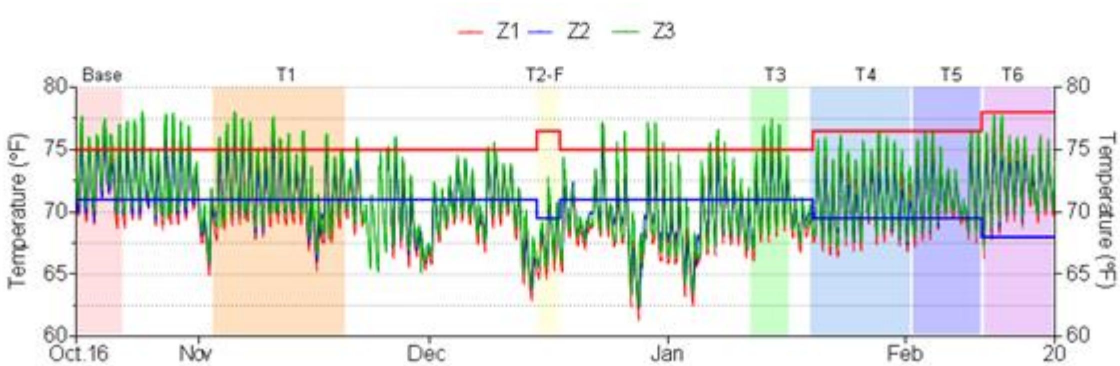


Figure 1.4-9 shows measured indoor temperatures from three different sensors during the study period. Intervals when temperatures remained below heating set point tended to be weekends, when the system was not operated, except for the extended period when the heating system was been shut off, denoted by T2-F.

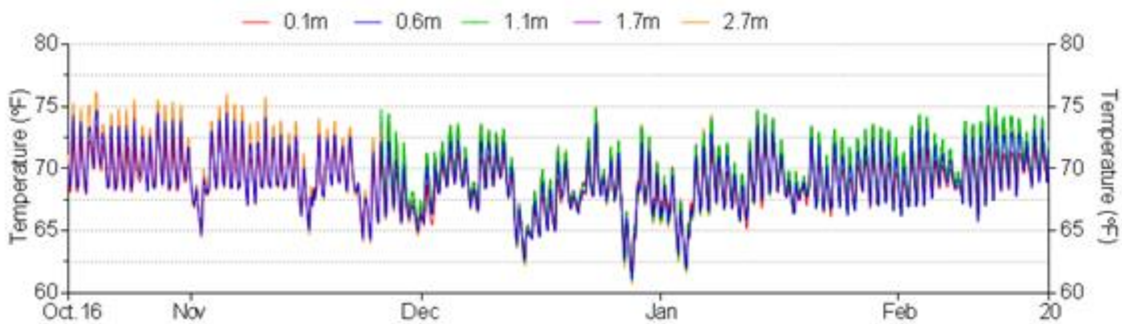
Figure 1.4-9: Measured indoor temperatures during study period from 3 sensors



1.4.4.2 Air temperature stratifications

The stratification appears quite small throughout the period (Figure 1.4-10).

Figure 1.4-10: Temperature stratification shown by 5 sensors



1.4.4.3 Survey results

Comfort levels were generally high, with the one exception of T2-F, when the heating was valved off. Occupants showed high levels of satisfaction. Levels did improve after introduction of PCS, and remained so, even as temperatures were allowed to drift. By period T6, even though temperature heating set points was reduced, the temperature inside the space was increasing. Increasing solar gain could have been a factor.

Figure 1.4-11: Thermal acceptability

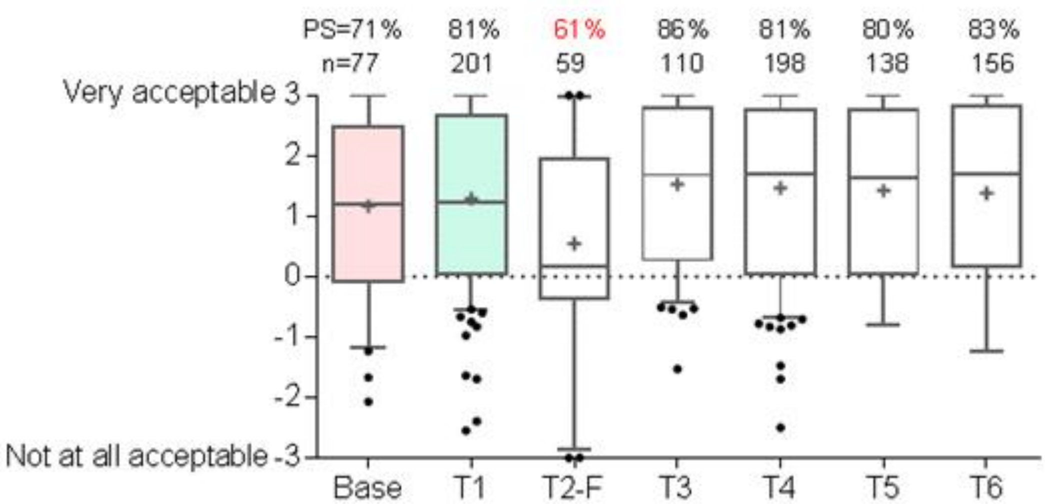
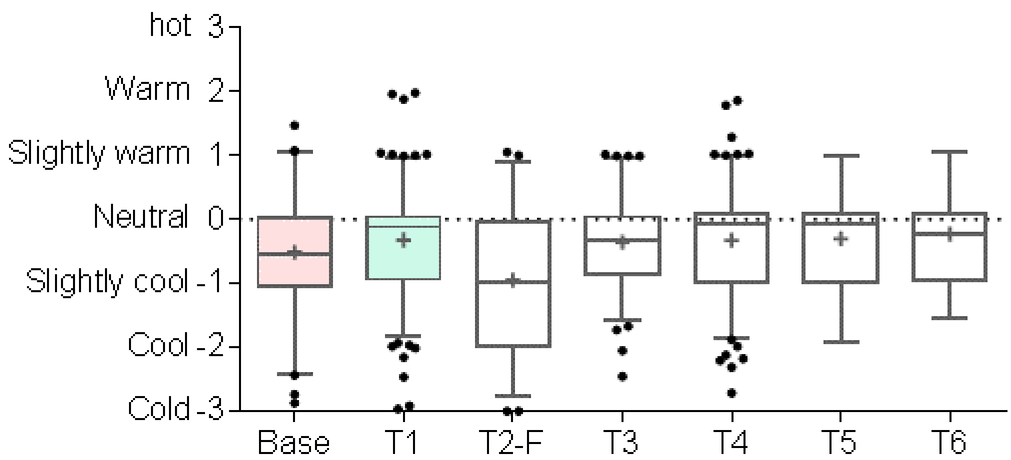


Figure 1.4-12: Thermal sensation



Thermal sensation markedly improved to near neutral with the addition of PCS (Figure 1.4-12). Air movement acceptability is hardly changed, perhaps because the test was done in heating season rather than cooling season (Figure 1.4-13).

Figure 1.4-13: Air movement acceptability

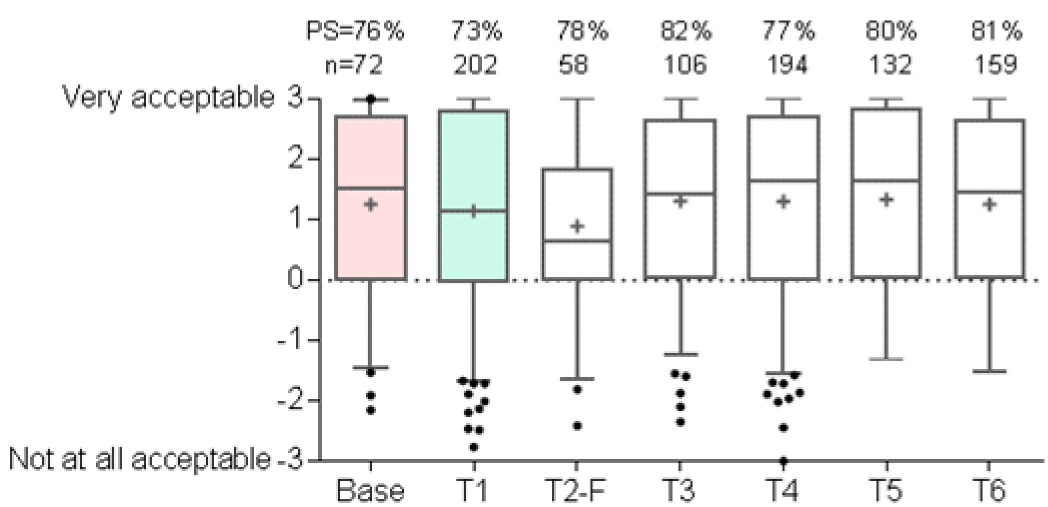
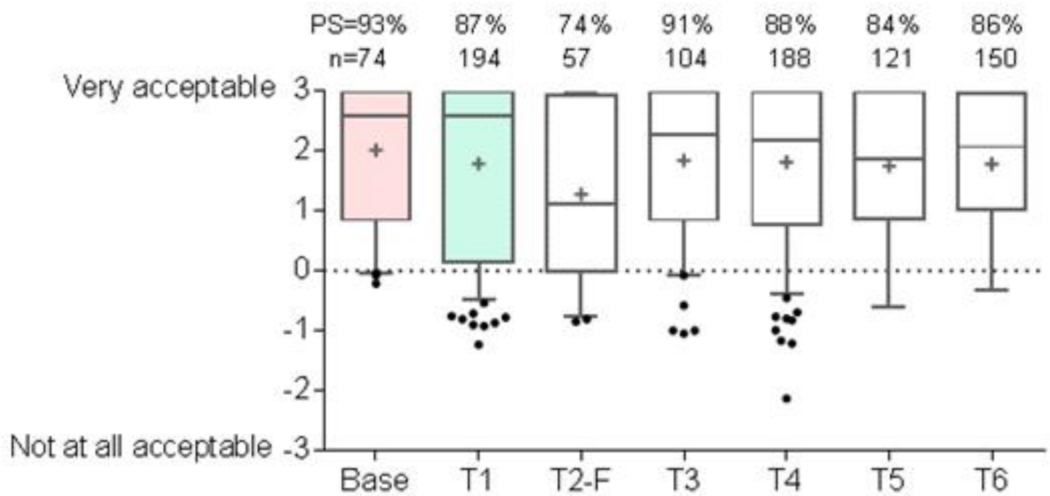


Figure 1.4-14: Perceived air quality



Perceived air quality actually fell slightly, especially during the failure period, from which it never quite recovered, though it was quite high throughout (Figure 1.4-14). This is difficult to explain, though again, improvements might become evident during cooling season. There could have been seasonal factors at work too, for example, smells of wood smoke in the air.

Clothing level seemed to follow seasonal factors, and responded to the heating failure at T2-F, perhaps some people were wearing sweaters or heavier clothing (Figure 1.4-15).

Figure 1.4-15: Clothing level

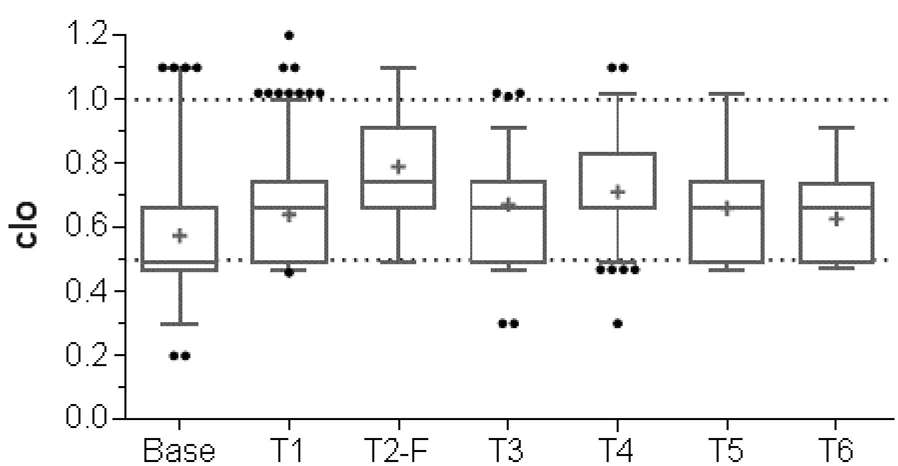


Figure 1.4-16: PCS use

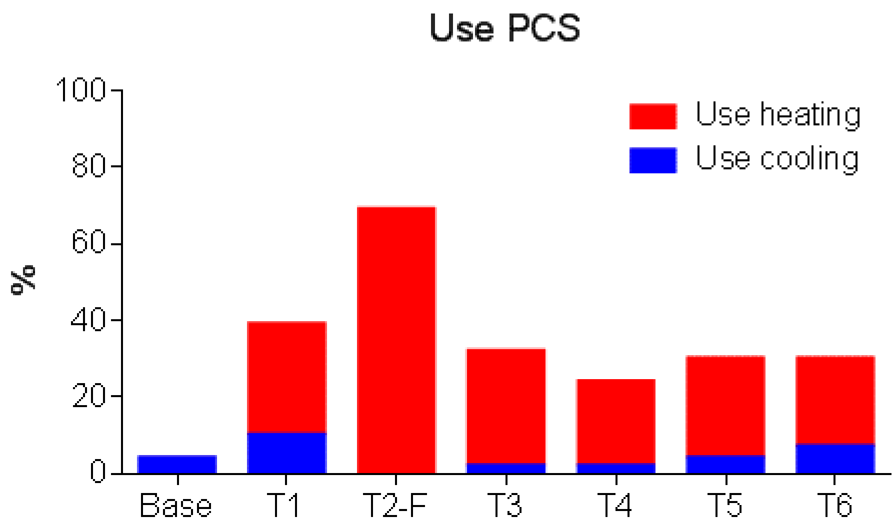


Figure 1.4-16 reminds us that the study was done during heating season, and also that only between one half and one third of the people were using the conditioning at all. There could have been a temporal factor at work here, for example, many people may have been using the chair for heating in the morning and not been using any conditioning in the afternoon when it is warmer in the building (Figure 1.4-16). Figure 1.4-17 demonstrates that people used the heating feature more when it was cold inside, and the cooling feature use rose with temperature.

Figure 1.4-17: Chair heating/cooling vs. Temperature

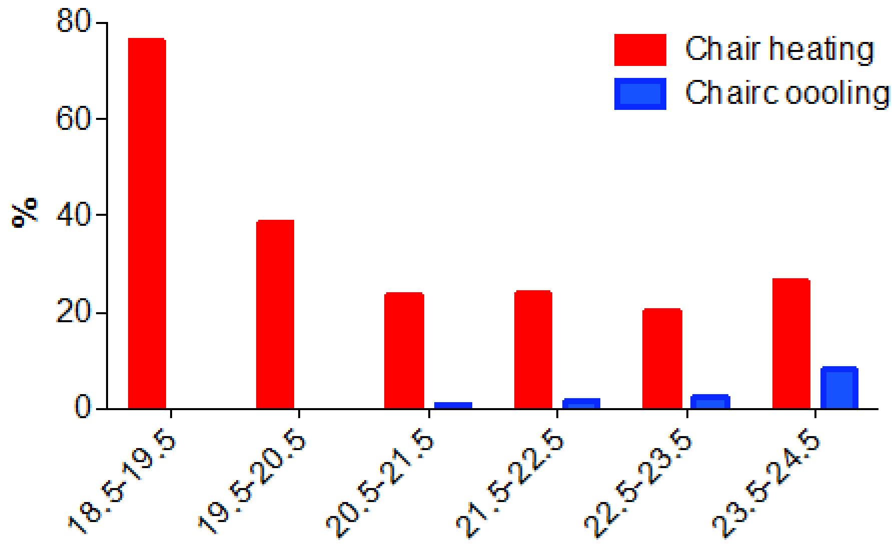


Figure 1.4-18: Thermal sensation preference

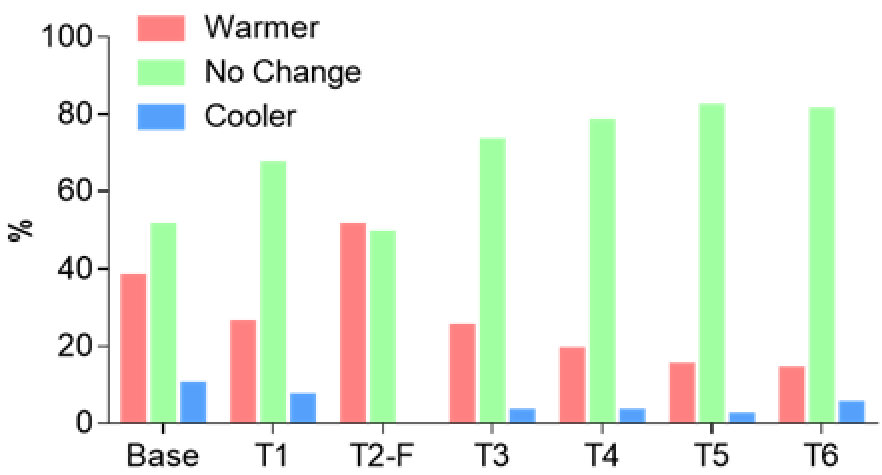
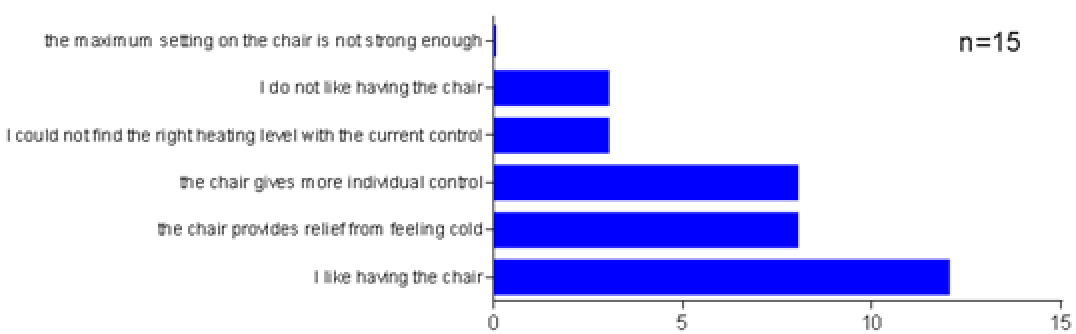


Figure 1.4-18 reflects the generally high level of thermal satisfaction in the building; people were generally comfortable in this building.

1.4.4.4 Exit survey

The exit survey reveals what people do and don't like about the PCS. The exit survey is a powerful tool for discovering ways to improve these devices, and reveal the diversity of opinions present. Figure 1.4-19 shows us that most people were happy to have the chair for some heating, though a few were not quite satisfied with it.

Figure 1.4-19: Common responses to questions, quantified



Reasons why some people do not like the chair

These responses focus on the reasons why some people do not like the chair:

- I was quite indifferent to the chair. I really didn't use the heating or cooling function of the chair.
- The chair isn't very comfortable.
- I do not like that the back of the seat angles down. It makes my back uncomfortable. If the seat were concave instead of convex, I think I would have liked the cooling for the summer time.

Were there specific or regular times in which the chair did not keep you warm enough at your workstation?

- Yes- 2 (13 percent), No-13 (87 percent).

Reason for your answer:

- I only used the cooling feature on it.
- I rarely ever get cold in California. And if I do, I would use a sweater over the heated chair.

Suggestions for improvements to how the chair operates

- Chair does not lean, arm rest needed to go down more.
- I would have used the warm feature on it if it just warmed slightly - too hot, even on the lowest setting.
- More granular heating and cooling control and a single on-off switch for both.
- The LED light for the 'heating' part of my chair went bad so since it doesn't light up it is difficult to know if the chair has drained its battery or not. I then have to switch to cooling for a few seconds to check the status of the battery. It would be nice to have a more long lasting LED light.
- Need a lower setting for the heat. Sometimes I just wanted a little heat and the lowest setting was too much.
- It would be better to have the battery pack on the front. I kept rolling over the chord of the charger when I needed to plug it in.
- Finer heating controls would be good. The chair was generally useful, but may not provide sufficient heating around rest of body if it’s too cold inside.
- Way to radiate the heat, fan + heat.

Suggestions on how chair looks

- The chair is a little uncomfortable after long sitting periods. Softer seating area.
- Arms that can slide under the desk.
- Height adjustment was the biggest problem for me.
- Just needs to be more comfortable and VOC free.
- I would like the back of the chair to be lower on the lumbar section. Too open at the hips.
- Hide the mylar bubble wrap.
- Concave seat.

1.4.4.5 HVAC system monitoring results

Figure 1.4-20 and Figure 1.4-21 show the zone, slab, and outdoor temperatures, and the valve opening positions for ambient thermostat setpoint range 71– 75 degrees F. In the morning, about 6:00 – 8:00 AM, the valve opened and supplied heat to the floor. The floor temperature increased about 1 degree F with valve opening. The duration of the opening is different, depending on the room ambient temperature; the cooler the temperature, the longer of the duration of the valve opening. There were days when the valve didn't open, because the ambient temperature was higher than 71 degrees F (e.g. morning of January 16 2015).

The ambient temperature changed between 71 – 77 degrees F, slightly higher than the warm temperature of the setpoint range.

Figure 1.4-20: Heating water valve position and air and water temperatures

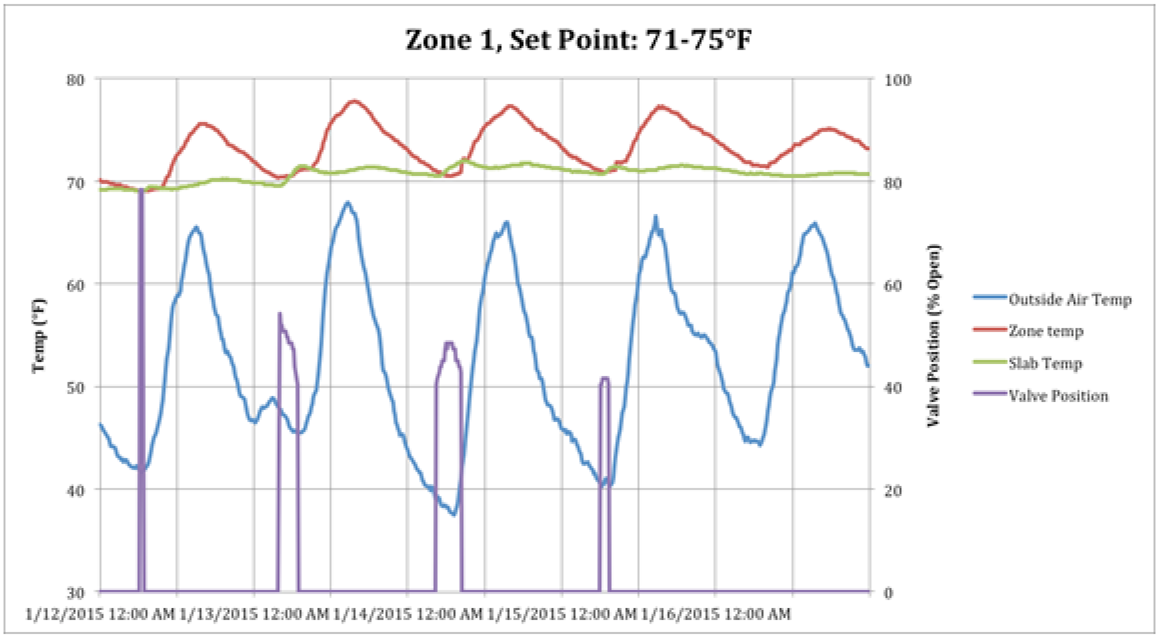
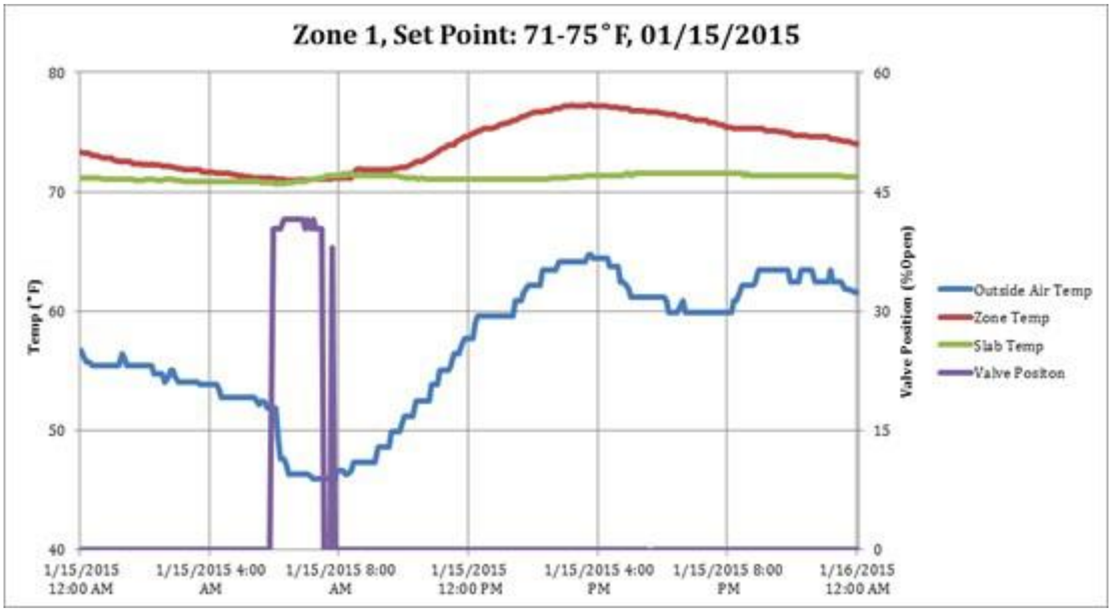


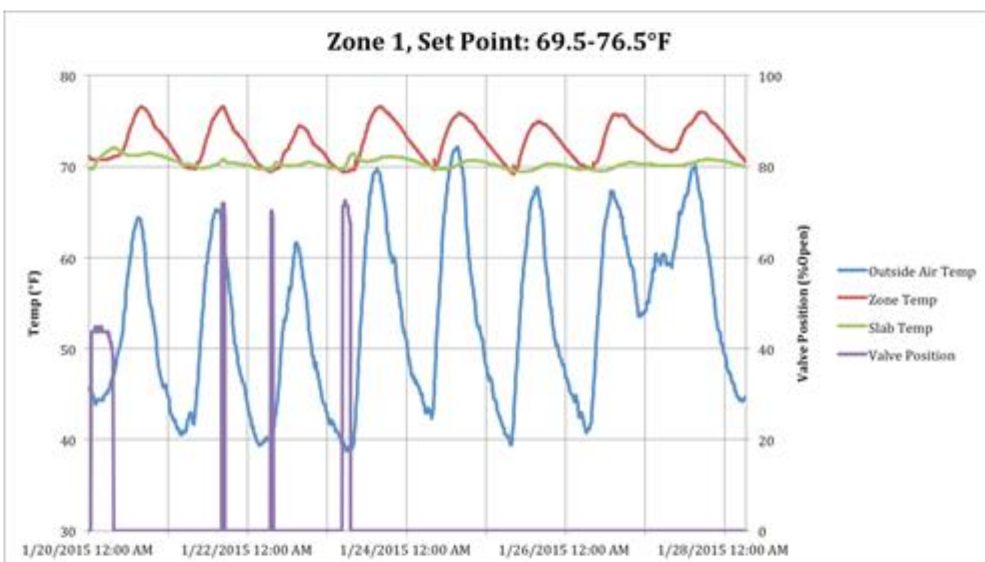
Figure 1.4-21: Detailed chart for one day



Valve opening as heating temperature set point is reduced

The duration of the valve opening is shorter when the heating set point was reduced, but the magnitude (percent open) is higher. The weather conditions were not exactly the same. Choosing two similar outdoor conditions, January 15 and January 23, the calculated daily valve opening ratios are 6.9 percent (original set point, 71 – 75 degrees F) and 3.8 percent (69.5 – 76.5 degrees F) respectively, but the valve opened wider in the expanded set point condition.

Figure 1.4-22: Heating water valve position and air and water temperatures



1.4.5 Discussion and Conclusion

The measurements and surveys show an improvement of average comfort using the PCS. From the exit survey responses, we may infer that most people liked the PCS chairs, with a few suggested improvements. The heating was an issue for a number of people: they desired a lower setting, or at least finer granularity of control. Several suggested the chairs could be more comfortable, softer seats, different angles on the back and other refinements. Most, however, liked the chair and appreciated its features.

The surveys reveal another truism: even when most people are comfortable, there are some who are too warm, some too cold, and perhaps some have comfort issues with their feet or hands. For these people, various parts of the PCS have particular value. Even though a well-designed building may make about 80 percent of its occupants comfortable, there is always that 20 percent who are not. For them, the PCS can provide a lot of value.

Had the test period extended into the cooling season, additional observations would have been possible. Because the testing only occurred during heating season, even with raised cooling set points, the building temperature rarely rose to a point many would feel uncomfortable.

This raises another point about the building; it was generally very comfortable, and so the marginal improvement of the PCS chairs was less than would be the case in a building with more comfort issues. The only significant departure from fairly good comfort conditions was in mid December when the heating was turned off completely, and the building became very cold. In this case, even the added benefit of the chairs was not sufficient to provide adequate comfort.

1.5 Personal Comfort Systems Commercialization

1.5.1 Introduction

After developing initial PCS prototypes and deploying them for years in a research context to collect performance data, the research team took several specific steps to move potential PCS products into commercialization. These steps included filing a patent application, market research, coordinating the launch of a start-up company, media outreach, wireless power transfer, and product improvements based on user feedback.

1.5.2 Results

1.5.2.1 Patent filed

In coordination with the UCB, Office of Intellectual Property and Industry Research Alliances (IPIRA), CBE personnel filed a patent application in August 2014 entitled “Energy Efficient Personal Thermal Comfort Chair for Commercial Workspaces, Auditoriums and Vehicles” [application number 20140217785].

The patent application highlights the construction and functional features of the chair namely: this “rechargeable chair consists of mesh seating coverage, reflective surfaces, air plenum chambers and spot heating functionality. The technology exploits the concept of alliesthesia operating spatially across the skin surface. Localized resistance heating is woven into the mesh fabric in key contact areas in the seat and back. Radiant heat loss from the body to the environment is redirected to conserve energy. Cooling of the body is achieved by increasing convective heat and moisture exchange across the underside and backside surfaces of the mesh. This contrasts sharply with traditional ventilation approaches that push or pull air through the seat surface. Comfort conditions can be maintained for individual users occupying the same space between 60.5 and 82.5 F. The battery-powered chair has a 4-day operation capacity and switches off when unoccupied."

The patent application also discusses the following specific advantages of the PCS chair:

- Ability to create user-adjustable local thermal environments for individuals close by.
- Convective cooling produces superior comfort effect without local cold spots on the skin.
- Uses less energy than comparable systems, energy use: 11 W heating, 3.5 W cooling.
- System has less pressure drop and higher efficiency than conventional ventilated seats.
- Ease of deployment, cost savings and quietness compared to building thermal/AC systems and stand-alone heaters/fans.

1.5.2.2 Market Research

In late 2012, CBE supported the efforts of a team of students from the UCB Haas School of Business to do basic market research in the area of PCS. Some of the findings from this market research project include:

1. An economic analysis showed a large variance in payback period between sample US cities, with San Francisco having the fastest payback period of 2.6 years, and Miami the least attractive at 6.2 years. Complimenting this work with expert interviews, according to which, the de-facto industry standard for minimum payback period was considered to be three years.

2. The team concluded that while PCS could certainly offer an attractive payback, the inherent variation caused by the indirect savings mechanism of raising the cooling set point and/or lowering the heating set point of the space encompassing the PCS could prove a significant barrier to adoption and require large amounts of real-world data to be collected in order to convince the counterparties making the investment.

3. Following an extensive analysis of alternative use-cases and market segments, it was concluded that the target first customer should be commercial office buildings in California. California represents the most attractive market place in the US both in terms of payback periods, external sources of value, supportive regulatory environment/trends, and company profiles (likelihood of willing early adopters).

1.5.2.3 Start-up Company

Needing a commercial entity with both energy efficiency experience and scalable manufacturing capability, CBE looked to its partners in industry and coordinated the formation by AccuTherm, Inc. and Peter Rumsey of a new company called Personal Comfort Systems to manufacture and distribute the "Hyper Chair." "The Hyper Chair featuring integrated user-controlled heating & cooling that can lower building HVAC energy usage up to 50 percent." Personal Comfort Systems is currently involved in the production of the Hyper Chair version 2 (see Figure 1.5-2 below) and has been promised the rights to the patent once it has been approved by the US Patent Office.

Figure 1.5-1: Company business card

Figure 1.5-2: HyperChair features

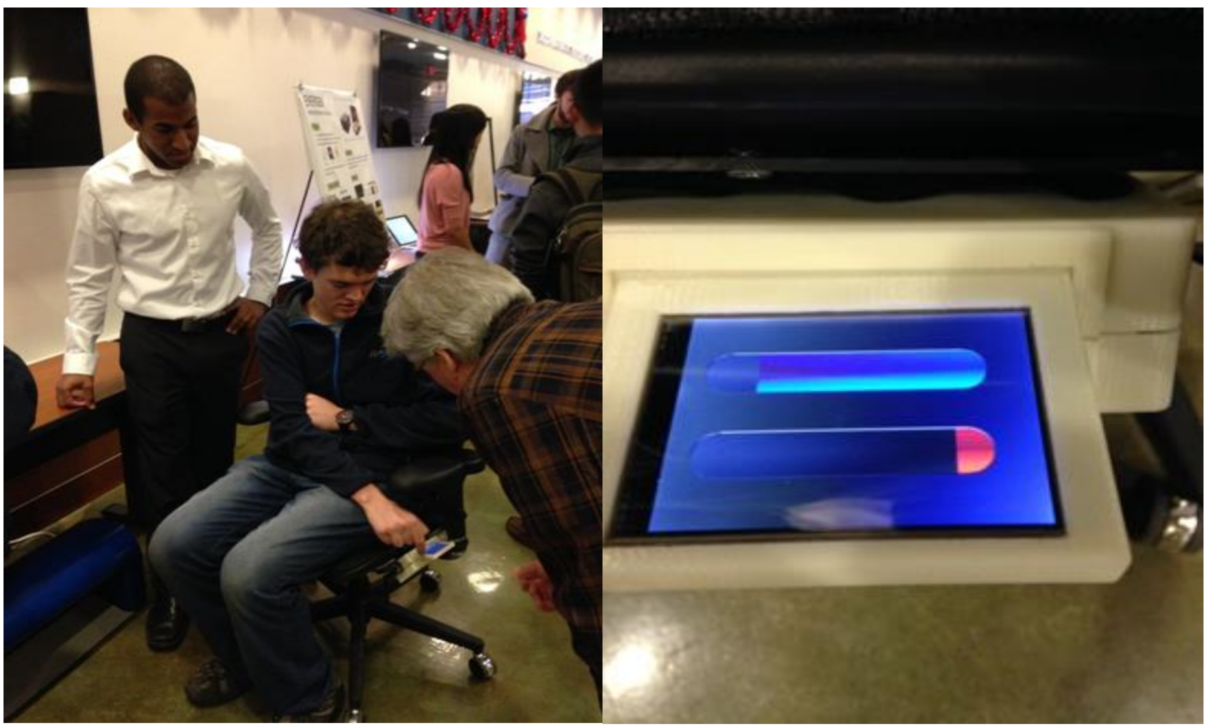


Photo Credit: Center for the Built Environment

1.5.2.4 Media Outreach

KGO television news, the local San Francisco Bay area ABC affiliate, did a piece on the PCS chair with the title “New chair lets users decide the temperature” and byline, “Researchers at UC Berkeley think they've found a way to keep you warm, without having to heat the entire room.”

The piece was aired on December 4, 2013 and shows CBE researchers demonstrating and commenting on the chair.

"When people have control, they always perceive that the environment is better," says Dr. H. Zhang, CBE.

"They have found out that heating and cooling people is a lot more efficient than heating and cooling a building," says Reporter Jonathan Bloom, KGO.

"We were able to cut the energy use by 50 percent during a period when we gave people these chairs," says Dr. Ed Arens, CBE.

Figure 1.5-3: Screen shot from KGO Television News

Figure 1.5-4: Screen shot from KGO Television News showing chair controls

A link to the news report is below:

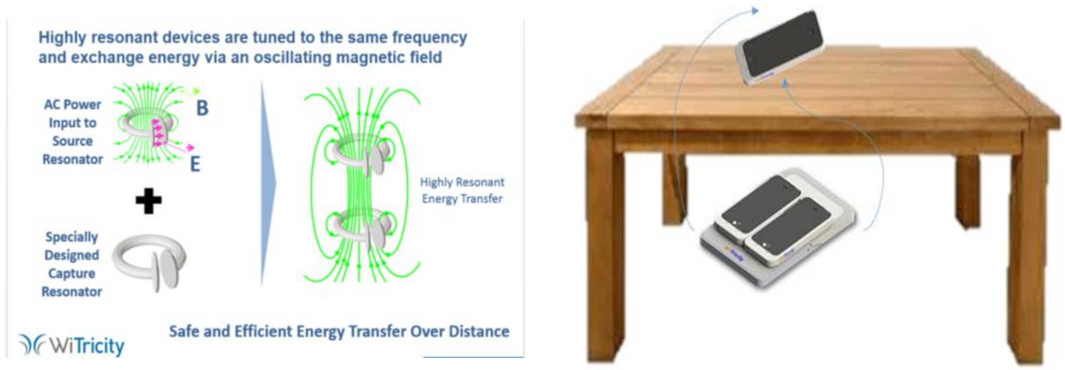
http://abclocal.go.com/kgo/video?id=9349203&pid=9348081

1.5.2.5 Improvements to the PCS Design

Although most users were very pleased with the various components of the PCS, exit interviews with those who participated in the field tests revealed some consistent themes, which led the researchers to improving the designs. With the foot warmer, many people observed that it affected their posture when sitting at their desk, others complained that the foot warmer box hit their shins.

The researchers have taken a new approach based on this feedback, and also on new technology now available. It includes a heated insole, which can slip inside the shoe. Power for the insole is supplied by a new technology, which allows wireless power transfer through a significant distance. This technology, developed by a company called WiTricity, will also facilitate wireless charging of the PCS chair, eliminating the need to plug it in to charge the battery, and wireless operation of the desk fan.

Figure 1.5-5: New technology for wireless power transfer



Other comments included the desire for finer granularity in adjusting the heat settings for the chair, a greater range of height adjustments, more fan power, and the ability to change fan occupancy behavior. These comments are included in more detail in the field study chapters, and some brief examples are listed below.

Figure 1.5-6: Examples of comments from exit survey

6. What suggestions do you have in terms of the operation and/or functionality of the chair?

- "Height adjustable more"
- "I would love a high chair with foot rests"
- "It would be nice to have a chair that can be raised higher"
- "an indicator of low battery"
- "The highest heat setting is too hot!"
- "It would be nice to have more in between levels of heating/cooling. 5 would be more ideal."

Comments about the foot warmer contact and desire for greater heating capacity led to the development of a radiant leg warmer. An early model was tested in the iDeAs field study. This and other innovative equipment will continue to be developed and tested.

Figure 1.5-7: Radiant leg warmer

Photo Credit: Center for the Built Environment

1.5.3 Conclusion

The PCS is emerging as an approach that can provide substantial comfort improvements at the same time it enables energy savings. It is a relatively low cost and low disruption approach to providing thermal comfort in problematic situations, or for those with special needs. Components can be added incrementally as needed. For these reasons commercial entrepreneurs have begun to see the potential in PCS as a business opportunity. The authors expect to see many more developments of PCS in the future.

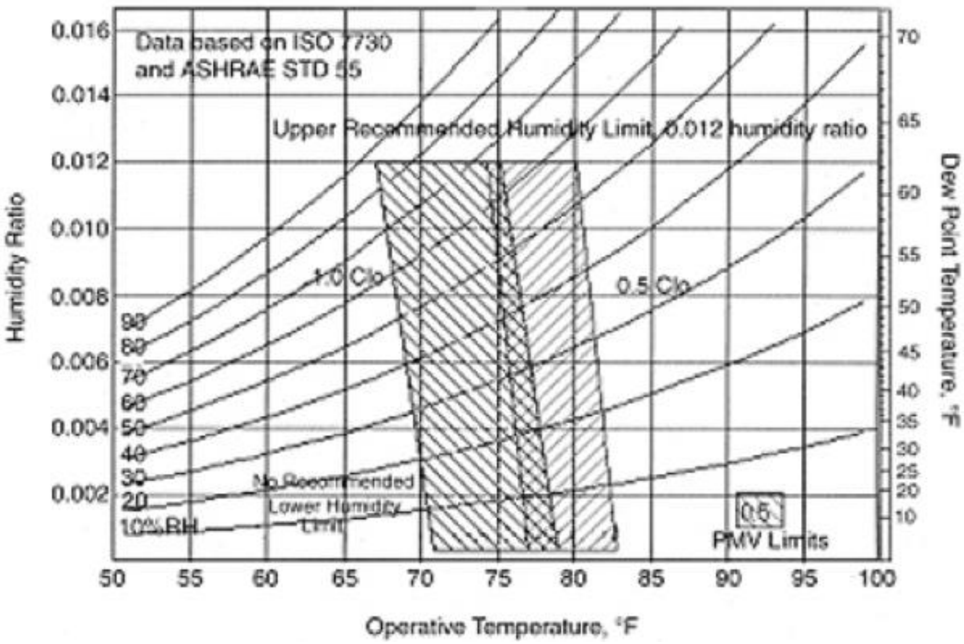
1.6 Personal Comfort Systems and the ASHRAE Thermal Comfort Standard

1.6.1 Overview

Modern office buildings are expected to maintain levels of comfort that are acceptable to at least 80 percent of the occupants. Just what these conditions are is defined in ASHRAE Standard 55.

The main parameters determining what comfort conditions will be in the standard implementation of ASHRAE 55 are temperature, humidity, metabolic rate, and clothing level, abbreviated as 'Clo'. Figure 1.6-1 shows a traditional chart of comfort conditions as defined in Standard 55, with two levels of clothing shown. The areas darkened with diagonal hatching within parallelograms indicate conditions presumed to be comfortable for 80 percent of the occupants.

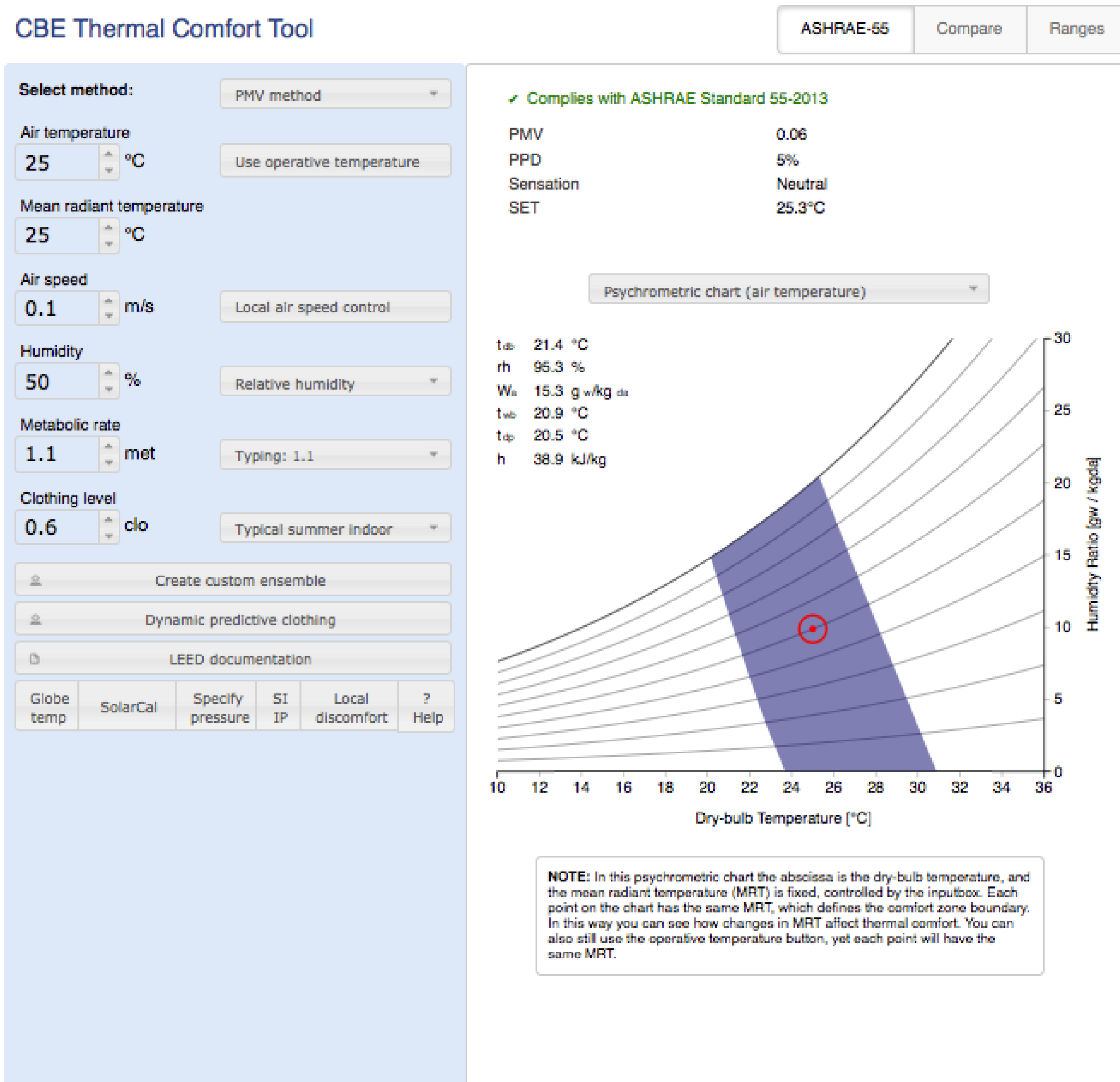
Figure 1.6-1: A chart for ASHRAE Standard 55 showing comfort zones for two levels of clothing



Researchers at UCB, CBE developed a more accurate and specific computer-based model for Standard 55. It is available on-line athttp://smap.cbe.berkeley.edu/comforttool.

This tool is more sophisticated than traditional charts and allows input of additional relevant variables, including metabolic rate (Met), air speed, and MRT. MRT is important in environments with non-uniform radiant conditions, where occupants, for example, may be near cold windows or warm radiators that produce additional thermal sensations. The CBE tool is able to accurately integrate all these additional inputs. A screen shot of the tool is shown for reference in Figure 1.6-2.

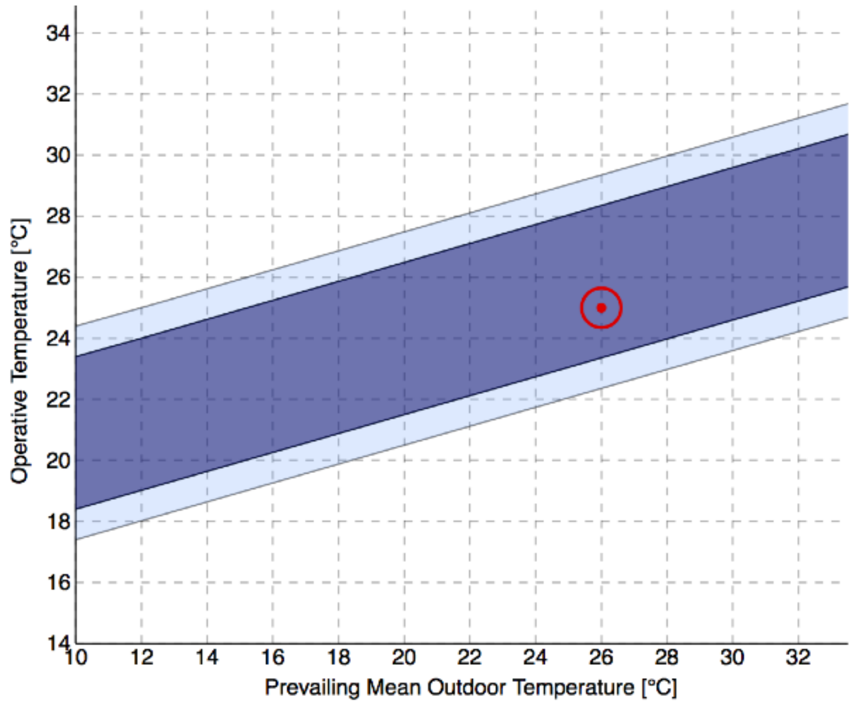
Figure 1.6-2: Output from the CBE Comfort Tool



More recently, researchers at CBE and University of New South Wales, Australia, demonstrated that when people were given access to windows that they could open, in buildings that did not have air conditioning, they expressed comfort satisfaction over a wider range of conditions than would be expected from traditional methods in Standard 55. This resulted in a new model for these situations known as the Adaptive Comfort Model (ACM).

The ACM also depends upon the prevailing mean outdoor temperature, based on the observation that people acclimate to cooler temperatures in winter and warmer temperatures in summer, and so indoor temperatures can also be cooler in winter and warmer in summer. Allowing wider indoor temperature ranges has the benefit of saving a lot of energy and capital investment, because heating and cooling equipment can be down sized or eliminated. A chart of the ACM is shown in Figure 1.6-3. The darker zone in the center of the range shows the zone of 90 percent satisfaction and the lighter zone slightly outside shows the range of 80 percent satisfaction.

Figure 1.6-3: Comfort conditions in the Adaptive Comfort Model

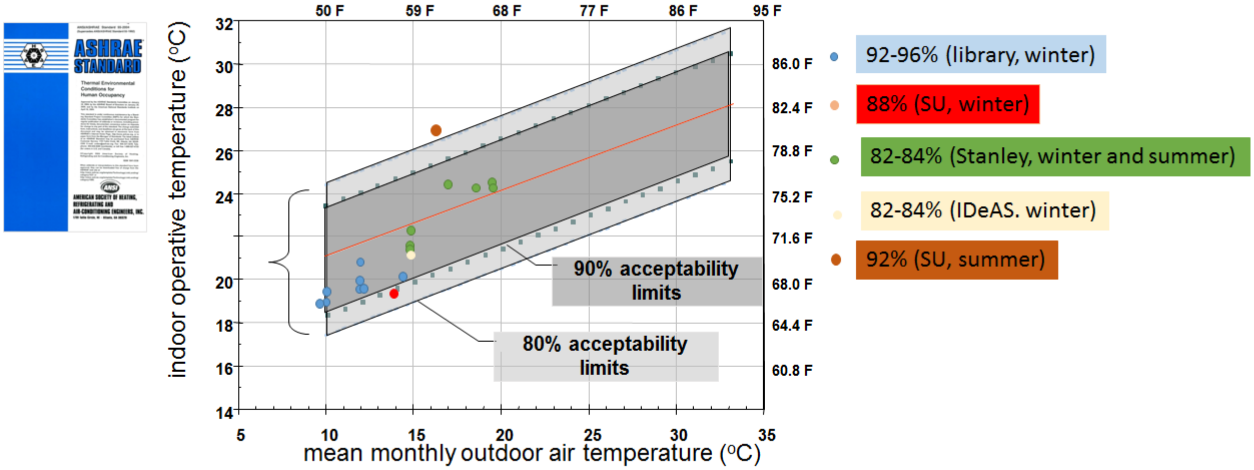


The data that led to the ACM was from buildings with operable and accessible windows and that lacked any means of mechanical cooling. If heating was available, it was not in use. Whether the model is applicable to mixed-mode buildings, which combine air conditioning with operable windows, or those which use their air conditioning only to avoid extremes of indoor temperature, and otherwise rely on natural ventilation, is a topic of active research.

1.6.2 Results

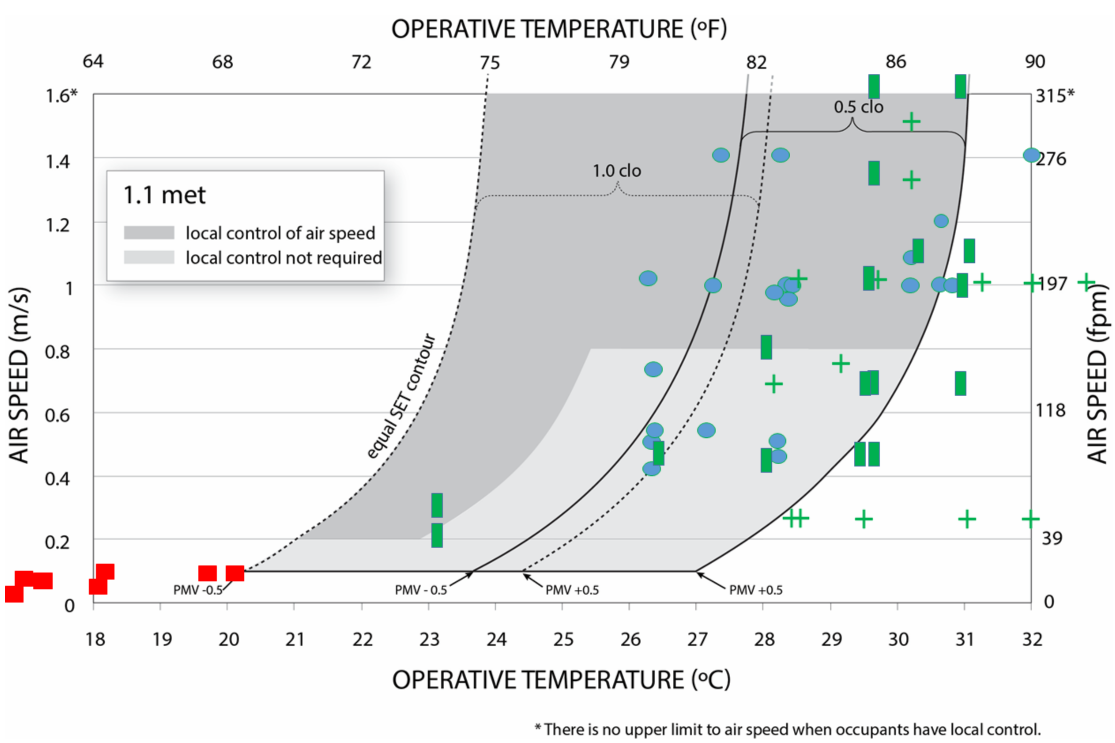
Even at the time of ACM development around the turn of the millennium, the question of whether PCS, also known as Personal Environmental Controls and Task Ambient Controls, could provide a similar widening of acceptable indoor temperatures was an open question. The data from the field studies in this project suggest that is the case. Figure 1.6-4 shows data points from the four projects at various satisfaction levels superimposed on the ACM. They generally indicate a high level of satisfaction, even when near the extremes of the ACM, and even in Stanley Hall, which has independent comfort issues related to rather wildly fluctuating discharge air temperatures and volumes.

Figure 1.6-4: PCS field study data plotted on ACM chart



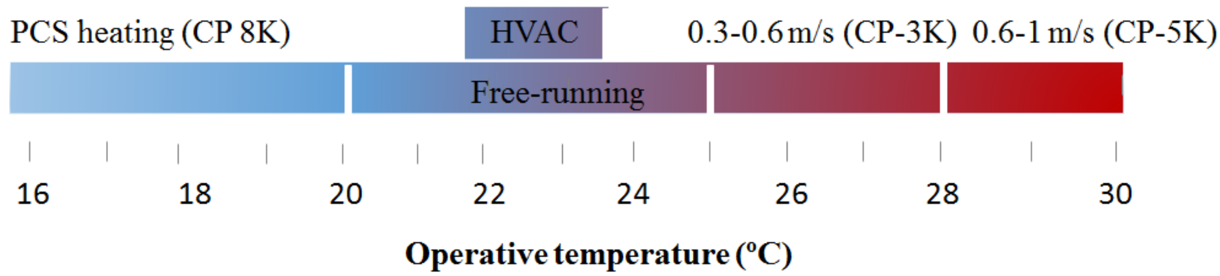
Since a component of the PCS uses airflow for cooling, it might be useful to compare comfort as measured by the PCS field studies to the ASHRAE model for air movements. Figure 1.6-5 plots the field study data points in Figure 1.6-4 on an ASHRAE air movement guide. Here again comfort is indicated at points beyond what might be expected from the ASHRAE guide.

Figure 1.6-5: Field study points plotted on ASHRAE air movement guide



Finally, Figure 1.6-6 shows the entire temperature range, over which the PCS provided comfort in the present field studies.

Figure 1.6-6: Temperature range over which PCS provided comfort in field studies



1.6.3 Discussion and Conclusion

It is obvious from the results that the PCS can provide comfort in temperatures which are at or beyond those of the ACM. Does that mean that designers could relax building design criteria or building operational criteria if PCS are in use? The field studies suggest that they could, but additional questions are raised:

If PCS other than those tested were used, what outcome would be expected?

This question suggests that some means of a standardized rating for the effectiveness of PCS is needed. These ratings could be based on laboratory or field studies, or in some cases, perhaps on the expert judgment of people with experience with similar equipment and applications. It is quite likely that as PCS continue to be further developed, thermal conditions well beyond those tested in these studies may be acceptable.

Is a PCS method of testing needed?

Certainly, if PCS came to be much more widely used and relied upon, a standard method of test for rating their effectiveness could be very useful.

How much of the effectiveness of PCS comes from their individual control?

This is a question that needs much more research. Perhaps the ability to provide individual control simply allows the user to accommodate different levels of metabolic rate or clothing. For example, if a person has just come in from a walk outside in very hot conditions, perhaps they would want more air movement for a while, and later would prefer less. Certainly changes in clothing could result in changes in desired settings, from cool to warm. Even times of day might make a difference in a given individual's preference. Some of the benefit of individual control of PCS comes from being to respond to these ever changing preferences.

Finally, does the simple addition of user control in and of itself provide a perceived benefit?

This is an interesting question raising psychological issues: does giving a person control result in higher satisfaction, even in a situation where some automatic means could give them the same choice they would have made for themselves? Perhaps some day we will know.

1.6.4 References

[1] ASHRAE Standard 55-2013. Thermal environmental conditions for human occupancy. Atlanta: American society of heating, refrigerating and air conditioning engineers, 2013.

[2] Zhang, H., E. Arens, Y. Zhai, 2015, A review of the corrective power of personal comfort systems in non-neutral ambient environments. Accepted by Building and Environment for publication.

[3] Zhang, H., E. Arens, M. Taub, D. Dickerhoff, F. Bauman, M. Fountain, W. Pasut, D. Fannon, Y. Zhai, and M. Pigman. Using footwarmers in offices for thermal comfort and energy savings. *Energy and Buildings.*

1.7 Personal Comfort Systems Presentation Materials

Over the past two years, CBE has developed and presented updates on PCS at the semi-annual CBE Industry Advisory Board Conference, which is attended by CBE industry partners and guests. They are as follows:

- April 2013 (attached as Appendix 1.7.1)
- October 2013 (attached as Appendix 1.7.2)
- April 2014 (attached as Appendix 1.7.3)
- October 2014 (attached as Appendix 1.7.4)

CHAPTER 2: Space Conditioning in Near Zero-Net-Energy Buildings

The goal of Task 6.0 is to provide to the professional design community new and improved information, guidance, and tools for designing and operating near ZNE buildings using radiant heating and cooling systems. This will be accomplished by conducting two thorough case studies of existing near ZNE buildings using radiant systems. The two buildings to be studied will be selected from a list of candidate buildings with radiant systems based on information provided by CBE industry partners and from other sources. The case studies will provide occupant satisfaction survey results, energy use data, and valuable lessons learned from monitored performance data of the radiant slab systems. In addition, improved understanding of cooling load differences betwee radiant and air systems will be developed through a series of laboratory experiments in the Hydronic Test Chamber at Price Industries in Winnipeg, Manitoba. Findings from the case studies and laboratory testing will be supplemented with whole-building energy simulations using EnergyPlus, allowing a sensitivity analysis of climate and control strategies.

Results for this task on space conditioning in near ZNE buildings with radiant systems are presented in the following sections. Section 2.1 describes an online map listing buildings using radiant systems to support the exchange of information on radiant technologies and help identify potential case study sites. Sections 2.2 and 2.3 present two case study reports on the David Brower Center, Berkeley, CA, and the SMUD East Campus Operations Center, Sacramento, CA. Section 2.4 presents the results of a full-scale laboratory experiment to investigate cooling load differences between radiant and air systems. Section 2.5 describes two simulation studies: application of the David Brower Center design to different California climates, and dynamic energy impacts of thermal mass. Section 2.6 describes the development of presentation material on the design and control of radiant slab systems for use in near ZNE buildings.

2.1 Online Map of Buildings Using Radiant Technologies

Radiant heating and cooling systems are regarded as energy efficient, particularly with renewable sources, due to the relatively small temperature difference needed and the efficiency of using water as a distribution fluid. This makes them attractive to consider for ZNE Buildings. However, while radiant system are more commonly adopted in central Europe, their design and application are still considered in early adoption in North America, especially for cooling applications. Besides this disparity, the various types of radiant systems (embedded surface systems, thermally activated building systems and radiant panels) are not evenly popular. Web mapping applications are powerful tools to visualize and summarize data. In this task, we developed an online map of buildings using radiant technologies to provide resources to building stakeholders who are interested in their implementation. The collected information was also helpful in selecting case study sites for this project. A paper about the online map was presented at the Indoor Air 2014 Conference in Hong Kong, July 7-12, and is attached as Appendix 2.1.1. The map can be accessed at: http://bit.ly/RadiantBuildingsCBE.

2.2 Case Study #1: David Brower Center, Berkeley, CA

The David Brower Center (DBC) is a 4-story 45,000-ft^2 office building located in downtown Berkeley, California (Figure 2.2-1). The building was completed and first occupied in May 2009. It contains lobby and public meeting space on the first floor and open plan office spaces on the 2nd – 4th floors that primarily house non-profit environmental activist organizations. Integral Group (formerly Rumsey Engineers) was the mechanical design engineer on the project and, working with the architect (Solomon E.T.C.–WRT) and other design specialists, put together a design promoting low energy consumption.

The goal of a low energy building was achieved through an integrated design process that combined thermal mass, shading, and insulation into an efficient building envelope, implemented daylighting and efficient lighting control strategies, and used a low energy HVAC system. The primary space conditioning subsystem is hydronic in-slab radiant cooling and heating that is installed in the exposed ceiling slab of the 2nd – 4th floors of the building. Due to their larger surface area and high thermal mass, slab integrated radiant systems use relatively warmer chilled water temperatures, making them well-matched with non-compressor-based cooling, such as cooling towers. In addition to the improved efficiency of transporting thermal energy with water vs. air (about 7 times more efficient), the building cooling energy savings are attained through the utilization of a cooling tower, instead of a chiller, to make cooling supply water.

Figure 2.2-1: David Brower Center, Berkeley, CA

The overall conclusions from this case study are:

- The Brower Center is a good example of a high performing building in terms of energy, indoor environmental quality (IEQ), and occupant satisfaction.
- The building demonstrated exceptional energy performance, achieving an Energy Star rating of 99, well above the threshold of 75 to qualify for an Energy Star label. The rating was based on utility bill data for electricity, steam, and water from calendar year 2014.
- The radiant slab system, in combination with advanced shading, underfloor air distribution, operable windows, thermally massive concrete structure and other design features, is performing well. Although there have been instances when inside temperatures during warm weather have reached higher levels, overall the advance integrated design and mild Berkeley weather have produced an indoor environmental quality that the occupants are quite satisfied with, as reported by the occupant survey. The building operator also expressed satisfaction with the building.
- The results of a whole-building energy simulation study demonstrate that the radiant system design and control strategy used in the Brower Center could be successfully implemented in other Californian cities/climates such as Los Angeles and Sacramento.

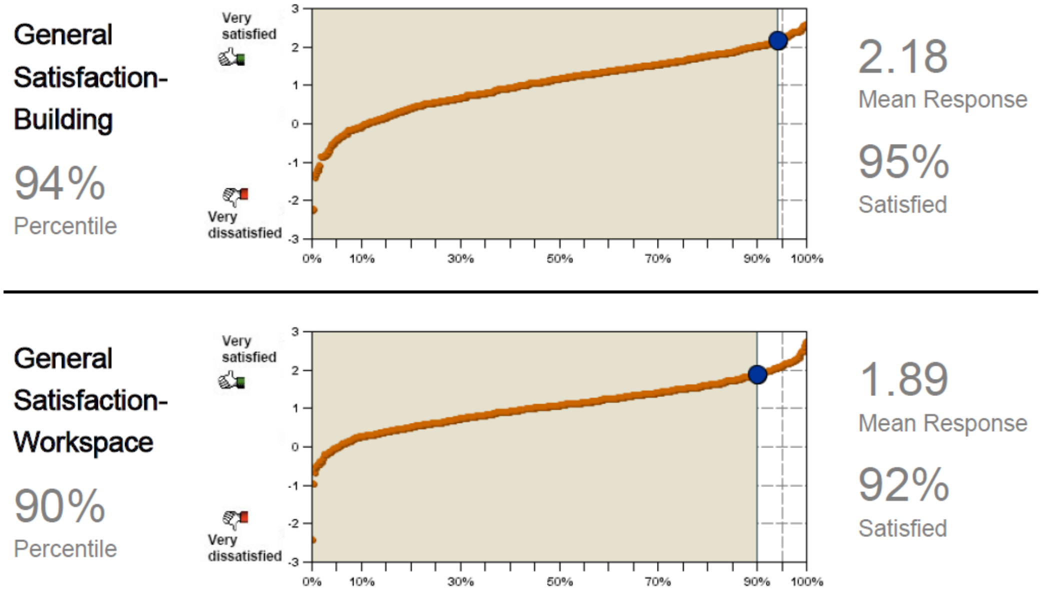
These conclusions are based on the results from the following four components of our assessment. Full details of the case study are provided in Appendix 2.2.1: Case Study of David Brower Center, Berkeley, CA.

2.2.1 CBE Occupant Satisfaction Survey

DBC was original surveyed in 2010, one year after its completion. With this second survey completed during the summer of 2014, we wanted to learn about occupant's satisfaction 5 years after its completion and after earlier operational issues had been addressed.

- From a general standpoint, all survey categories of DBC 2014 received consistently high scores when compared to the CBE benchmark database: 94 percent percentile for overall building satisfaction and 90 percent percentile for workplace satisfaction as shown in Figure 2.2-2.
- Results from 2014 were higher than the results from 2010 for all categories.
- Occupants were extremely satisfied with cleanliness and maintenance (98 percent percentile) and with lighting (93 percent percentile).
- The DBC is outperforming the benchmark in air quality, lighting, daylighting and thermal comfort. All these categories show percentile rankings greater than ~84 percent.
- Thermal comfort satisfaction is at a percentile ranking of 91 percent. This indicates that the occupied areas are operating within relatively high comfort standards.
- While acoustic quality satisfaction remained the weakest category, it is noted that the David Brower Center substantially increased its satisfaction score (from -1.2 in 2010 to -0.2 in 2014).

Figure 2.2-2: David Brower Center overall satisfaction rankings (June 2014)



2.2.2 Energy Star Rating

This building achieved an Energy Star rating of 99, well above the threshold of 75 to qualify for an Energy Star label. The site energy utilization intensity (EUI) was 46 kBtu.ft2/yr and the source energy EUI was 70.4 kBtu.ft2/yr. The rating was based on utility bill data for electricity, steam, and water from calendar year 2014.

2.2.3 Field Measurements of Radiant Slab Performance

Analysis of collected trend data from 2011 found the following patterns of use for cooling and heating with the radiant slab system.

Active cooling of the radiant slabs occurs only at nighttime between 10 pm – 6 am as part of a pre-cooling strategy. Pre-cooling is triggered during warm weather when the outside air temperature reaches 84°F. The advanced integrated design of the Brower Center combined with the mild climate of Berkeley provide comfortable temperatures in the building without the need for active cooling by the radiant slab for most of the time. During 2011, only 16 instances of pre-cooling occurred.

Because of cool nighttime temperatures in Berkeley, calls for heating occur much more frequently in the Brower Center. Trend data shows that the radiant slab is heated primarily during nighttime, early morning, and evening hours. Due to the efficient building envelope combined with internal loads, very little heating is used during the middle of the day.

2.2.4 Building Energy Simulations

For this study we modeled one office floor of DBC using the whole-building energy simulation program, EnergyPlus, for three cities (climates) in California: Oakland, Los Angeles and Sacramento.

We learned that the DBC design and HVAC strategy present a viable design option in terms of predicted energy use and thermal comfort for these three cities. Overall energy consumption is low and quite typical for an energy efficient building. The ASHRAE 55-2013 target of 80 percent satisfied is reached for over 90 percent of the time (weighted by occupancy) for the three cities. This supports the idea that using evaporative cooling sources (cooling tower) only, without the need for a chiller, is an appropriate HVAC design approach in the three tested Californian climates (Oakland, Los Angeles and Sacramento).

2.3 Case Study #2: SMUD East Campus Operations Center, Sacramento, CA

The SMUD East Campus Operations Center is a 200,000 ft^2 LEED Platinum certified office building (see Figure 2.3-1). The building was designed by Stantec (Architecture and MEP) and includes a great number of energy efficient technologies and design strategies: TABS, radiant embedded surface ceiling system, chilled beams, geothermal exchange, thermal energy storage tanks, heat recovery wheel, ceiling fans, high thermal mass, advanced window blinds that redirect solar energy onto ceiling, etc. The site also integrates a large area of solar photovoltaic panels that enable the whole campus (five buildings in total) to approach ZNE. The SMUD building was completed and occupied during the summer of 2013. The building uses an exposed radiant ceiling slab for primary space conditioning in combination with an overhead DOAS for ventilation and latent load control.

Figure 2.3-1: SMUD East Campus Operations Center, Sacramento, CA

Image courtesy HRGA Architecture.

In this field study the research team had a unique opportunity to conduct a detailed review and analysis of the building's performance through access to a full set of trend log data from the BMS in combination with additional data from an array of about 50 wireless sensors installed by the research team. We focused our attention on the operation and control of the radiant slab system on one representative floor (level 2) of the 6-story office building. Our efforts were supported by regular conference calls with the SMUD building operators during which we reviewed observations, discussed possible adjustment and improvements, and in some cases were able to study the impact of changes that were implemented. The results provided valuable lessons learned about controlling the radiant slab system.

The following additional assessment methods were used during our field study of the SMUD building:

- A web-based survey of occupant satisfaction for seven different indoor environmental categories (thermal comfort, air quality, lighting, acoustics, cleanliness & maintenance, office layout, and office furnishings), as well as two questions about overall satisfaction with the building and personal workspace.
- A series of on-site portable noise level measurements were made to assess acoustic quality throughout the second floor study area.
- Although of interest to the study, detailed energy use data are not yet available as the overall energy performance of the building is quite complex due to the multiple sub-systems. Future work will investigate the energy use patterns of the office building and campus.

Full details of the case study are provided in Appendix 2.3.1: Case Study of SMUD East Campus Operations Center, Sacramento, CA.

2.3.1 Field measurements and building management system trend data

When the research team first began monitoring the building, we found that many of the control settings for the radiant slab system were more representative of how a quick-response all-air system would be controlled. Key observations and findings derived from our review of the operation and control of the radiant slab system are listed below.

- A preferred approach is to adjust the controls so that the slab is precooled in the early morning, thereby avoiding the need for active cooling during the middle of the day and shifting system cooling loads to more efficient and cost-effective nighttime hours.
- After control adjustments were made following the above strategy, the building was able to successfully maintain comfortable zone temperatures throughout hot summer days by precooling the radiant slab during the night.
- Changes were made to the original heating and cooling setpoint schedule for the radiant slab zones that widened the deadband and added nighttime and weekend setbacks. After implementation, heating and cooling activity in all zones was significantly reduced. This represents a control strategy that is more energy efficient, reduces wear and tear on the hydronic system, and recognizes that radiant slab systems require some sort of anticipatory control.
- It was observed that perimeter zone thermostats, embedded in the exterior wall, were unsealed and exposed to airflow in the wall cavity (when the air distribution system was turned off at night), thereby causing the thermostats to measure nighttime temperatures during winter months that were about 5 degrees F cooler than the actual zone air temperatures. After sealing and insulating the thermostats, this pattern was eliminated, which helped to reduce unnecessary heating by the radiant slab system during the night. It is important to ensure that thermostats used for radiant system control are representative of zone temperatures, since slab systems often operate at night.

2.3.2 CBE Occupant Satisfaction Survey

The CBE occupant satisfaction survey was conducted from November 18 to December 5, 2014. Two hundred ninety eight invitations were distributed via e-mail to the building occupants and 134 valid survey responses were received for a response rate of 45 percent, which is a very representative sample.

The survey results indicate a comparable satisfaction as the large CBE benchmark database (more than 50,000 survey responses) for building overall satisfaction and workspace overall satisfaction. Responses for thermal comfort and air quality were close to neutral satisfaction and are slightly above the benchmark. Acoustics and lighting are slightly below the benchmark. Given the status of the SMUD building as a new building with many advanced and less familiar technologies, it is not surprising that the survey results indicate lower satisfaction rates for some categories. The findings can be helpful in identifying categories that are candidates for improvement.

2.3.3 Acoustic measurements

On-site noise level measurements were taken on the 2nd level for the SMUD building on Dec. 12, 2013. It was found that the ducted ventilation system provides the loudest noise sources in the areas tested. In particular, supply and exhaust locations in the central corridors were identified as producing the most noise. Adjacent open plan office areas on the north and south sides of the building experienced some of these same elevated noise levels. Enclosed meeting rooms in core and north sides of the building had the lowest sound level measurements, which were quite acceptable.

2.4 Laboratory Testing

Radiant cooling systems work fundamentally differently from air systems by taking advantage of both radiant and convective heat transfer to remove space heat. However, in current practice, the same design cooling load calculation methods for radiant systems are used as the convection-only-based air systems. In 2013, we conducted laboratory experiments comparing zone-level sensible cooling loads between radiant chilled ceiling and overhead air distribution systems to verify the differences observed during our previous simulation studies [Feng et al. 2013].

Cooling load calculations are a crucial step in designing and sizing any HVAC system. Compared to air systems, the presence of an actively cooled surface changes the heat transfer dynamics in a zone of a building. The chilled surface is able to instantaneously remove radiant heat (long and short wave) from any external (solar) or internal heat source, as well as interior surface (almost all will be warmer than the active surface) within its line-of-sight view. This means that radiant cooling systems may impact zone cooling loads in several ways: (1) heat is removed from the zone through an additional heat transfer pathway (radiant heat transfer) compared to air systems, which rely on convective heat transfer only; (2) by cooling the inside surface temperatures of non-active exterior building walls, higher heat gain through the building envelope may result; and (3) radiant heat exchange with non-active surfaces also reduces heat accumulation in building mass, thereby affecting peak cooling loads. Using simulations we previously demonstrated that dynamic responses of rooms when conditioned by radiant cooled surface(s) are significantly different from the case of air systems and consequently the cooling loads for system sizing are also drastically different (in fact, often higher for the studied cases) [Feng et al. 2013]. Thus, current cooling load calculation and modeling methods may not be applicable for radiant systems.

The experiments were conducted in the Hydronic Test Chamber at CBE partner Price Industries in Winnipeg, Manitoba. Four tests with two heat gain profiles were carried out in the full-scale climatic chamber. For each profile, two separate tests were carried out to maintain a constant operative temperature: one with radiant chilled ceiling panels; and a second with an overhead mixing air distribution system. The experiments show that, during the periods the heat gain was on, the radiant system has on average 18–21 percent higher instantaneous cooling rates compared to the air system, and 75–82 percent of total heat gains were removed, while for the air system only 61–63 percent were removed. Based on the study, we conclude that a new definition must be used for radiant system cooling load. Peak cooling loads for radiant systems may be higher or lower than those for air systems, depending on how the systems are configured and operated.

During the past year, we summarized and published the results of this laboratory study in two publications, which are attached. Appendix 2.4.1 provides a practitioner-based article describing the differences between cooling load calculations for radiant vs. air systems [Bauman et al. 2013]. Appendix 2.4.2 is a peer-reviewed journal article describing full details of the laboratory experiments [Feng et al. 2014].

2.4.1 References

Bauman, F., J. Feng, and S. Schiavon. 2013. Cooling load calculations for radiant systems: Are they the same as traditional methods? *ASHRAE Journal*, 55(12), 20-27, December.

Feng, J., F. Bauman, and S. Schiavon. 2014. Experimental comparison of zone cooling load between radiant and air systems. *Energy and Buildings*, 84, 152-159.

Feng, J., S. Schiavon, and F. Bauman. 2013. Cooling load differences between radiant and air systems. *Energy and Buildings*, 65, 310-321. http://escholarship.org/uc/item/7jh6m9sx.

2.5 Radiant Systems Energy Simulation Report

Two simulation studies were carried out to improve our understanding of radiant system performance under different climate conditions and to investigate the impact of furniture and internal thermal mass on building energy performance, as described below.

2.5.1 Application of the David Brower Center design to different California climates

The case study of DBC described in Section 2.2 concluded that DBC is a good example of a high performing building in terms of energy, IEQ, and occupant satisfaction. The radiant slab system, in combination with other advanced integrated design features was able to achieve extremely high energy efficiency (Energy Star rating of 99) as well as very positive occupant satisfaction ratings as measured by the CBE Occupant Satisfaction Survey. Although these results are very promising, the research team was interested in investigating how well this same building design would perform in climates more severe than the relatively mild Berkeley climate.

The goal of this simulation study was to evaluate the applicability of the main features of the DBC design and HVAC strategies (e.g., TABS, mixed-mode ventilation based on the combination of underfloor air distribution systems (UFAD) and natural ventilation, no chiller, evaporative cooling tower, high performance envelope, exterior sun shading devices) to three California cities/climates: Oakland, Los Angeles and Sacramento. These three cities were chosen because: (1) They represent places in California that have the largest portion of the population; and (2) They represent different climatic conditions ranging from mild and wet winters to hot and dry summers. We modeled one middle floor of the DBC using the whole-building energy simulation program EnergyPlus.

We learned that the DBC design and HVAC strategy present a viable design option in terms of predicted energy use and thermal comfort for these three cities. Overall energy consumption is low and quite typical for an energy efficient building. The ASHRAE 55-2013 target of 80 percent satisfied is reached for over 90 percent of the time (weighted by occupancy) for the three cities. This supports the idea that a radiant slab system using a pre-cooling strategy based on evaporative cooling sources (cooling tower) only, without the need for a chiller, is an appropriate HVAC design approach in the three tested California climates (Oakland, Los Angeles and Sacramento).

Full details of the simulation study of the David Brower Center model are presented in Appendix 2.5.1: David Brower Center Simulation Report.

2.5.2 Dynamic energy impacts of thermal mass

In our ongoing energy simulation studies of advanced low-energy HVAC systems, including radiant and underfloor air distribution, we have become aware of the importance of thermal mass in the building, particularly when illuminated by direct solar radiation. This simulation study focused on the effect that internal mass has on cooling loads, and how current simulation tools model these effects. There is considerable debate whether current practices yield sufficiently accurate instantaneous peak cooling load estimates. This also applies to heating loads, but is less critical because heating energy costs are not as time and peak sensitive as cooling energy costs.

Whole-building energy simulation is a widely used method to design and evaluate the energy performance of a building. The peak cooling load in each thermal zone in the model is often a key aspectof design, as it determines the size of the HVAC equipment needed to cool the zone sufficiently, which affects energy performance throughout the year. It also influences the peak demand of the building.

A wide range of factors affect the peak cooling load in a thermal zone, such as:

- Solar radiation through fenestration;
- Transient conduction through zone surfaces;
- Internal gains (convective and radiant) from occupants, lights and equipment;
- Infiltration;
- The capacitive effects of the zone air volume;
- The HVAC system used to reject heat from the zone;
- The thermal inertia of the furniture and contents (internal mass).

In this study we assessed the impact that furniture and contents (i.e., internal mass) have on zone peak cooling loads using a perimeter zone model in EnergyPlus across 5400 parametric simulation runs. The zone parameters were HVAC system type (overhead, underfloor, and TABS), orientation, window to wall ratio, and building envelope mass. The internal mass parameters were the amount, area, and the material type used. We also evaluated a new internal mass modeling method, which models direct solar radiation on the internal mass surface, an effect that is missing in current methods. We show how each of these parameters affect peak cooling load, highlighting previously unpublished effects. Overall, adding internal mass changed peak cooling load by a median value of −2.28 percent (−5.45 percent and −0.67 percent lower and upper quartiles respectively) across the studied parameter space. Though the median is quite low, this study highlights the range of effects that internal mass can have on peak cooling loads depending on the parameters used, and the discussion highlights the lack of guidance on selecting reasonable values for internal mass parameters. Based on this we recommend conducting an experimental study to answer outstanding questions regarding improved specification of internal mass parameters.

During 2014, we published a peer-reviewed journal article describing full details of this simulation study of internal mass [Raftery et al. 2014] and it is attached as Appendix 2.5.2.

2.5.2.1 References

Raftery, P., E. Lee, T. Webster, T. Hoyt, and F. Bauman. 2014. Effects of furniture and contents on peak cooling load. *Energy and Buildings*, 85, 445–457.

2.6 Presentation material for ZNE Building Performance Seminar

During the past six months, CBE has been developing a set of slides to introduce radiant systems to the professional design community. We were assisted in this effort by CBE Partner Viega LLC, manufacturer of PEX tubing for radiant slab systems (TABS). A slightly edited version of a presentation given by Fred Bauman at a Viega-sponsored seminar on Jan. 27, 2015 at the Air-Conditioning, Heating, Refrigerating (AHR) *Exposition in Chicago, IL, associated with the ASHRAE Winter Conference is attached as* Appendix 2.6.1. The presentation covered the following topics related to radiant slab systems for ZNE buildings:

- How radiant systems work with a focus on radiant slab (TABS) systems;
- Heat transfer fundamentals;
- Energy use;
- Thermal comfort in comparison to conventional all-air systems;
- Project examples;
- Design guidance.

CHAPTER 3: Technology Transfer

The goal of this task is to make the knowledge gained, experimental results and lessons learned available to key decision-makers. This will include encouraging that revisions to ASHRAE standards be done in an energy-conscious manner, reflecting the full range of design and technology choices available today.

Work will also be performed to assist ASHRAE in developing Handbook chapters, the revised UFAD Design Guide, Special Publications, and research projects that adequately reflect new technologies and advanced design concepts.

3.1 ASHRAE Standard 55 and Technical Committee TC 2.1

Various additional efforts were undertaken during the duration of research on personal comfort systems to transmit knowledge to the design profession. Most the effort involved activities related to upgrading the indoor environmental standard, ASHRAE Standard 55. This standard embodies the state of knowledge about indoor thermal environments, and although it does not involve energy in its scope, the nature of Standard 55 requirements have profound implications on building energy use. Standard 55 needs to address the full range of design and technology choices available today. This has not been the case in the recent past.

3.1.1 ASHRAE committee work

Edward Arens worked as a member of the Standing Standards Project Committee (SSPC) 55 in the large effort to convert Standard 55 into code language. This revision was completed in 2013, and several stages of addenda have subsequently been prepared and adopted by ASHRAE. The process is still underway.

Hui Zhang continues to serve as the research sub-committee chair of Technical Committee TC 2.1 (thermal physiology). She has overseen substantial research efforts on obtaining new clothing insulation data for comfort modeling. This effort is closely related to the needs of Standard 55.

3.1.2 Thermal comfort web-tool

CBE developed and is hosting an internet-based program to compute thermal comfort indices and visualize the results in ways useful to building designers. It was prepared by Tyler Hoyt and Stefano Schiavon. It was published last summer:

- Schiavon S, Hoyt T, Piccioli A. 2014. Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55. Building Simulation, Volume 7, Issue 4, 321-334. http://dx.doi.org/10.1007/s12273-013-0162-3; http://escholarship.org/uc/item/4db4q37h

The CBE tool is maintained in strict accordance with ASHRAE Standard 55, and is updated immediately as the Standard is upgraded with addenda (see below). As the CBE tool has become more accurate than the previous ASHRAE comfort software, ASHRAE has recently made an arrangement with CBE to adopt it as their official tool, branded with their logo and packaged with the standard. CBE will maintain it. Updates of their official tool will occur biannually as the paper version of the Standard is republished. The CBE tool will continue to be offered for free on the web, and will continue to incorporate new calculation and visualization options that might be proposed for future standards.

3.1.3 Solar radiation calculation procedure

Tyler Hoyt and Ed Arens prepared in 2013 a new procedure for Standard 55 to limit the amount of solar radiation on occupants in buildings. This has never been done before and has large energy implications for façade design. The procedure is based on a model (SolarCal) that has been included as an optional feature in the CBE comfort tool over the last year. Its widespread testing by design professionals has led to its consideration as a new addendum to the standard, and for its code to be incorporated as a normative appendix in Standard 55. The model has been published, and is attached as Appendix 3.1.3:

- Arens, E., T. Hoyt, X. Zhou, L. Huang, H. Zhang, S. Schiavon. 2014. Modeling the comfort effects of short-wave solar radiation indoors, *Building and Environment*, 2014.

3.1.4 Stratification limit in ASHRAE Standard 55

Hui Zhang and Ed Arens worked with the SSPC 55 committee to correct the air stratification limit in the Standard. The original research underlying the limit had tested sedentary subjects and established a 3 degree Kelvin (K) (6 degree F) maximum. Following some law of ever-ratcheting requirements, this 3K limit was then applied also to standing postures so that (interpolating by height) 2K suddenly became the new limit for sedentary subjects. This 2K limit is a problem, causing overcooling in buildings with displacement ventilation systems because over-ventilation is required in order to keep stratification within 2K. Hui Zhang conducted a careful literature study and showed that all the studies for sedentary subjects permit a stratification 3K or higher. There has been no study of standing subjects, so the 3K standing limit in the Standard has no factual basis. Normally when people have a higher metabolic level (as when you are standing), the thermal sensitivity for the environment is lower. CBE worked with the Standard 55 members and changed the stratification limit to 3K for seated and 4K for standing people. The changes have been adopted.

3.1.5 Air speed provisions

Ed Arens has worked with SSPC 55 to rework the entire elevated air movement section, to replace the lower velocity limit from 0.15 meters per second (m/s) to 0.2 m/s, and to revise the upper limits as well as a function of temperature and other factors. It is based on new research and practical considerations and empowers energy-efficient technologies such as within-space fans as an equal component of HVAC. The Adaptive Model for naturally ventilated buildings has also been revised with added air movement provisions for velocities above the base of 0.3 m/s, provided by Stefano Schiavon. CBE's Jessica Uhl prepared the graphics of the standard showing the changes—compelling graphics are key to having the new air speed provisions widely adopted in practice.

3.1.6 Clothing model

Stefano Schiavon and Ed Arens prepared a new clothing predictive model that has been added to Standard 55. It is based on outdoor temperature for simulation of comfort throughout the year. A paper describing the clothing model was published in 2012.

- Schiavon S, Lee KH. 2012. Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures. *Building and Environment. http://dx.doi.org/10.1016/j.buildenv.2012.08.024*

3.1.7 ASHRAE Standard 55 Users' Manual

Since Standard 55 has been rewritten in code compliant language, similar to Standards 62 (ventilation) and 90 (energy), it will have increased influence in the future. ASHRAE has funded the preparation of a users' guide for the Standard. CBE teamed up with TRC (formerly Heschong Mahone Group), Schoen Engineering, and Arup to work on this project. The goal of the manual is to improve the handling of comfort in design practice. An underlying theme is to make it possible that the mandated comfort can be provided in a variety of energy-efficient ways, and that indoor thermal environmental quality can be quantified using methods that are comparable to the energy required to provide it. The Guide includes many worked-out examples. It is scheduled for completion at the end of 2015.

3.1.8 ASHRAE Comfort Database II development

ASHRAE is partially funding this effort by CBE and the University of Sydney, Australia. The South Korean government is also contributing. The goal of Database II is to assemble into a widely usable format all field research data on human comfort that has been conducted since 1997 (when the ASHRAE Database I was assembled). Having this body of data compiled in a single database will be highly valuable to comfort researchers around the world. Meta-analyses of Database I were responsible for many of the improvements made to Standard 55 in the last decade, including the most recent ones described here. The field data is being voluntarily donated by a large international set of researchers, into a relational database designed by Tyler Hoyt and maintained at CBE. Data cleansing and formatting is being done at CBE, Sydney, and Seoul.

To organize the database and encourage the volunteering of data, Hui Zhang and Ed Arens worked with Richard de Dear from Sydney and Chunyoon Chun from Yonsei University, Korea, to organize two workshops. A technical meeting was held in Seoul in February 2013, followed by a large workshop at the Indoor Air Conference in Hong Kong in July. About 80 people participated in the workshop, and revival-style, most volunteered datasets. Since then, we have collected almost 10 times the data of Database I from a wide range of geographic locations.

Database II will include publicly accessible interactive visualization tools. CBE graduate student Margaret Pigman has developed two interactive visualization tools to give both practitioners and researchers an easy way to select subsets of thermal comfort field study databases that are interesting to them (see Figures 1 and 2 below). The tools are built with the statistical package R (a free software environment for statistical computing and graphics). The user interface has dropdown menus, sliders, and input fields that allow users to filter the overall database based on the building location, cooling strategy, and program. Users can choose various metrics for the graph axes, the width of bins, and the minimum number of votes that are required in a bin for it to be displayed. The screen then gives them immediate feedback, visualizing the results based on the input parameters and filters. In addition to the graph, there is a data table that indicates the sources of the data and the mean values of the basic physical and survey responses for each city that is included. A paper was published:

- Pigman, M; Zhang, H; Honnekeri, A; Arens, E; & Brager, G. (2014). Visualizing the results of thermal comfort field studies: putting publicly accessible data in the hands of practitioners. *Proceedings of 8th Windsor Conference: Counting the Cost of Comfort in a Changing World*. http://escholarship.org/uc/item/5s18p0sv

Figure 3.1-1: Screenshot of the probit analysis tool; this example shows comfort and acceptability probit curves over real thermal sensation votes

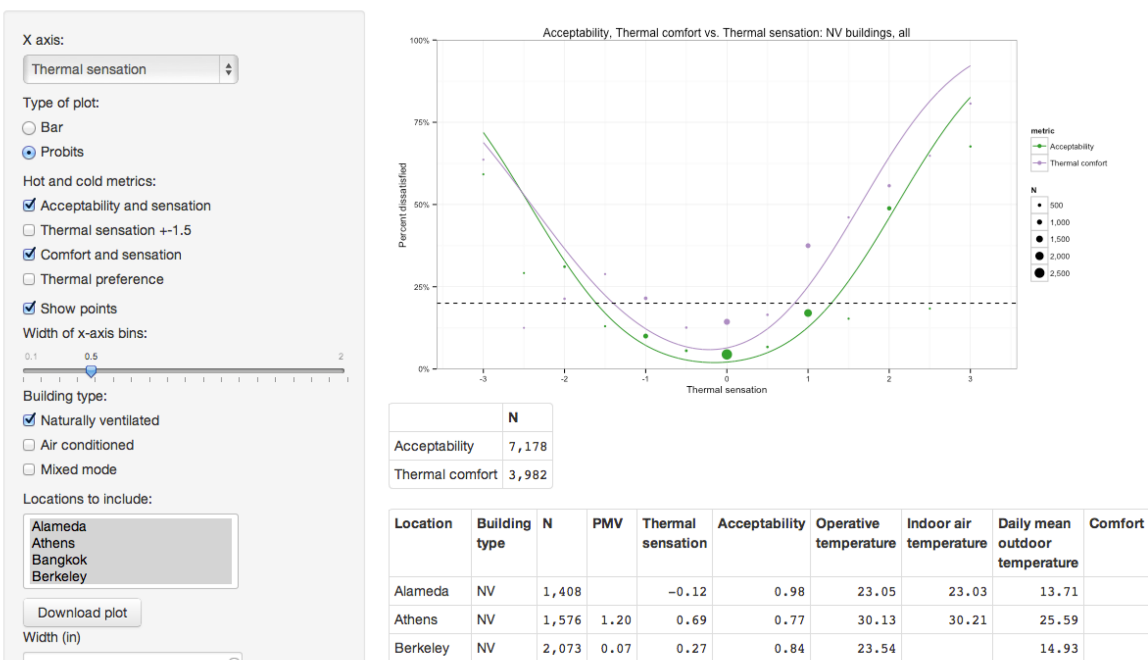
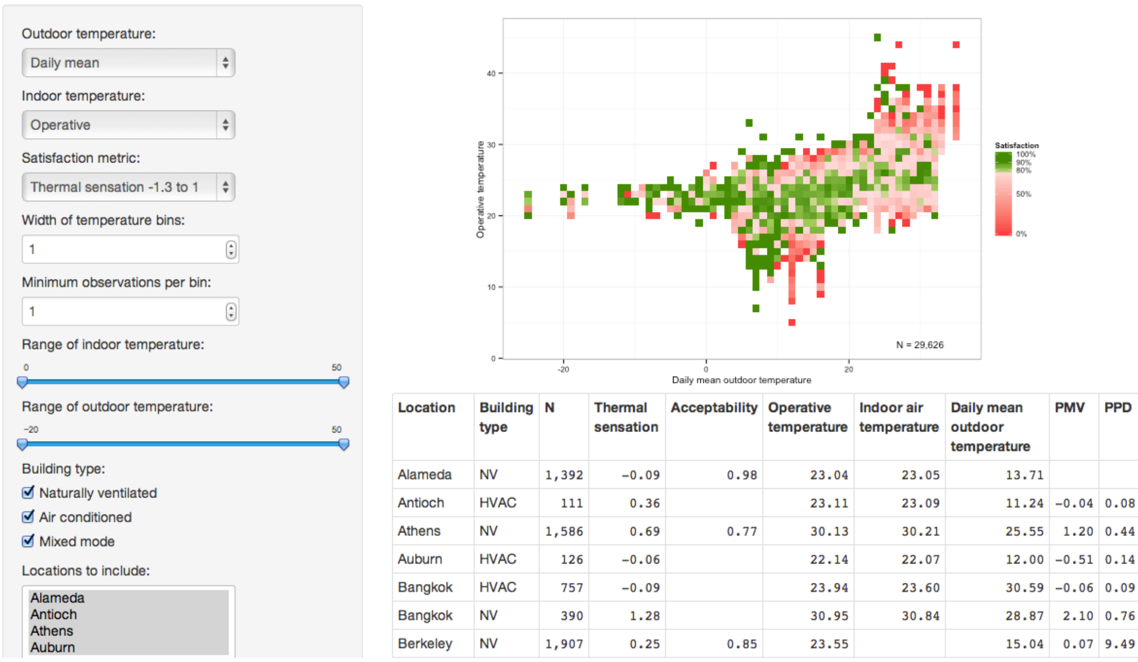


Figure 3.1-2: Mapping tool shows the satisfaction rates on the outdoor vs indoor air temperature map



Location	Building type	N	Thermal sensation	Acceptability	Operative temperature	Indoor air temperature	Daily mean outdoor temperature	PMV	PPD
Alameda	NV	1,392	-0.09	0.98	23.04	23.05	13.71		
Antioch	HVAC	111	0.36		23.11	23.09	11.24	-0.04	0.08
Athens	NV	1,586	0.69	0.77	30.13	30.21	25.55	1.20	0.44
Auburn	HVAC	126	-0.06		22.14	22.07	12.00	-0.51	0.14
Bangkok	HVAC	757	-0.09		23.94	23.60	30.59	-0.06	0.09
Bangkok	NV	390	1.28		30.95	30.84	28.87	2.10	0.76
Berkeley	NV	1,907	0.25	0.85	23.55		15.04	0.07	9.49

3.2 ASHRAE Technical Committee TC 4.1

Over the past five years, CBE researchers have become involved with ASHRAE TC 4.1 (Load Calculation Data and Procedures) due to research findings from our work indicating differences in cooling loads for both UFAD and radiant systems in comparion to all-air systems. Fred Bauman and former Ph.D. student, Dove Feng, now with CBE Partner Taylor Engineering, have both become corresponding members of TC 4.1.

3.2.1 Cooling load differences between radiant and air systems

Since the ASHRAE Summer Conference in June 2014, Dove Feng and Fred Bauman have been working with ASHRAE TC 4.1 to develop a work statement (1729-WS) entitled "Experimental Verification of Cooling Load Calculations for Radiant Systems." This proposed research project is based largely on the experiments conducted by Dove at Price Industries in 2013, as part of the current CEC PIER project (see Section 2.4). The goal of the proposed ASHRAE research project will be to conduct a more extensive series of laboratory experiments to verify and more accurately characterize the differences in cooling load between radiant and all-air systems. The information gained from such an experiment will provide updates and improvements to current guidance in ASHRAE Handbooks, as well as other available cooling load calculation procedures used by building design engineers. Currently, the work statement is under internal review by TC 4.1 and will be submitted for consideration by the ASHRAE Research Administration Committee (RAC) at the upcoming ASHRAE Annual Conference in June 2015.

3.2.2 Cooling load differences between UFAD and conventional mixing air systems

Previous PIER-sponsored research by CBE demonstrated that cooling loads are not the same between UFAD and conventional overhead mixing systems [Schiavon et al. 2010a]. It is believed that this is due to two major factors: (1) thermal storage effect of the lower-mass raised-floor UFAD panels vs. the greater mass of a structural floor slab for conventional systems; and (2) radiant cooling effect of the slightly lower floor surface temperature in a UFAD system caused by the cool supply air in the underfloor plenum. The radiant cooling effect is similar to that observed above for the cooling load differences between radiant and air systems. CBE researchers published several papers documenting these cooling differences and describing the development of a simplified online UFAD cooling load calculation tool [Bauman et al. 2010, Schiavon et al. 2010b]. Working with TC 4.1, Fred Bauman wrote a section on UFAD system that was added to Chapter 18 on cooling loads in the 2013 ASHRAE Handbook of Fundamentals [ASHRAE 2013].

3.2.2.1 References

ASHRAE. 2013. *2013 ASHRAE Handbook: Fundamentals*. Atlanta: ASHRAE.

Bauman, F., S. Schiavon, T. Webster, and K.H. Lee. 2010. Cooling Load Design Tool for UFAD Systems. *ASHRAE Journal* 52(9), pp. 62-71, Sept.; http://escholarship.org/uc/item/7hh1t2z4.

Schiavon S., K.H. Lee, F. Bauman and T. Webster, 2010a. Influence of Raised Floor on Zone Design Cooling Load in Commercial Buildings. *Energy and Buildings 42 (5);* http://escholarship.org/uc/item/7bf4g0k1.

Schiavon, S., K.H. Lee, F. Bauman, T. Webster, 2010b. Simplified Calculation Method for Design Cooling Loads in Underfloor Air Distribution (UFAD) Systems. *Energy and Buildings 43 (2-3),* 517-528; http://escholarship.org/uc/item/5w53c7kr.

3.3 ASHRAE Technical Committee TC 5.3

Fred Bauman has been a long-standing voting member of ASHRAE TC 5.3 (Room Air Distribution). Tech transfer activities within TC 5.3 are described below

3.3.1 Publication of revised ASHRAE UFAD design guide

Fred Bauman, along with CBE researchers, Tom Webster, Stefano, Schiavon, and Wilmer Pasut, participated for several years on ASHRAE Technical Resource Group TRG7-UFAD, formed by ASHRAE in 2007 to review and revise the original ASHRAE UFAD Design Guide [Bauman 2003]. TC 5.3 is the cognizant committee for TRG7-UFAD. CBE contributed significant material and research results that were incorporated into the new design guide, published by ASHRAE in 2013 [ASHRAE 2013]. The guide is available from the ASHRAE bookstore at http://www.techstreet.com/ashrae/products/1859223.

3.3.1.1 References

ASHRAE. 2013. *UFAD Guide: Design Construction and Operation of Underfloor Air Distribution Systems*. Atlanta: ASHRAE.

Bauman, F. 2003. *Underfloor Air Distribution (UFAD) Design Guide.* Atlanta: ASHRAE.

3.3.2 Development of work statement on active chilled beams

Fred Bauman, working with members of TC 5.3 authored a work statement (1629-WS) entitled "Testing and Modeling Energy Performance of Active Chilled Beam Systems." The goal of this research project is to test a representative number of active chilled beams from several manufacturers and compare measured beam capacity to the predicted beam capacity using available empirical models. Published results will assess the validity of active chilled beam models in building energy simulation programs and make recommendations for improvement where needed. The work statement was approved by ASHRAE RAC as Technical Research Project 1629-TRP in 2013. The project is now underway with University of Colorado at Boulder (John Zhai, Principal Investigator) as the contractor.

3.3.3 Development of work statement on passive chilled beams

Fred Bauman, working with members of TC 5.3 authored a work statement (1666-WS) entitled "Experimental Evaluation of the Thermal and Ventilation Performance of Stratified Air Distribution Systems Coupled with Passive Beams." The goal of this research project will be to test a representative number of passive beams from several manufacturers installed in a full-scale test facility using displacement ventilation. Computational fluid dynamics (CFD) modeling will be used to extend the applicability of the experimental results. The resulting experimental and numerical database obtained will be used to prepare practical design guidelines for combined stratified systems with passive chilled beams and specify the operating parameters necessary to achieve thermal comfort, energy efficiency, and improved ventilation performance. The work statement has been revised several times and most recently has been submitted for review and approval by ASHRAE RAC at the ASHRAE Annual Conference in June 2015.

3.4 ASHRAE Technical Committee TC 6.5

Over the past five years, CBE researchers have become more involved with ASHRAE TC 6.5 (Radiant Heating and Cooling) due to our active research program on radiant systems, in part sponsored by this project. Recently, Paul Raftery, Fred Bauman and former Ph.D. student, Dove Feng, became corresponding members of TC 6.5. Paul has volunteered to be the committee webmaster and also is contributing to revising the ASHRAE Handbooks on radiant systems. Currently, he is revising Chapter 6 (Panel Heating and Cooling) for the 2016 HVAC Systems and Equipment Handbook.

GLOSSARY

Term	Definition
/yr	Per year
ACM	Adaptive Comfort Model
AHU	Air Handling Unit
ALC	Automated Logic Corporation
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
BMS	Building Management System
C	Celsius
CBE	Center for the Built Environment, University of California, Berkeley
CFM	Cubic Feet per Minute
CIEE	California Institute for Energy and Environment
clo	Clothing insulation value
CO2e	Carbon dioxide equivalent
DBC	David Brower Center
DOAS	Dedicated outdoor air system
Energy Commission	California Energy Commission
EUI	Energy Utilization Intensity
F	Fahrenheit
HVAC	Heating, ventilating, and air-conditioning
IDeAs	Integrated Design Associates
IEQ	Indoor Environmental Quality
IQR	Interquartile Range
K	Kelvin
kW	Kilowatt
kWh	Kilowatt hour

Term	Definition
LBS	Pounds
LEED	Leadership in Energy and Environmental Design
m	Meter
m/s	Meters per second
MEP	Mechanical, electrical and plumbing
MRT	Mean radiant temperature
MW	Megawatt
NBI	New Buildings Institute
PCS	Personal Comfort Systems
PEX	Crosslinked polyethylene
PIER	Public Interest Energy Research, administered by California Energy Commission
PMV	Predicted Mean Vote
RAC	ASHRAE Research Administration Committee
RH	Relative Humidity
sMAP	Simple Monitoring and Actuation Protocol
SMUD	Sacramento Municipal Utility District
SPEED	CIEE State Partnership for Energy Efficient Demonstrations
SSPC	Standing Standards Project Committee
SU	Cesar Chavez Student Union
TABS	Thermally Activated Building Systems
TC	ASHRAE Technical Committee
TDV	Time Dependent Valuation
UCB	University of California, Berkeley
UFAD	Underfloor Air Distribution
USB	Universal Serial Bus
VAV	Variable Air Volume

Term	Definition
W	Watt
ZNE	Zero-net-energy