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.

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ABSTRACT

California’s call for radical improvements in building energy efficiency requirements is prompting an integrated approach to designing the indoor environment. This approach implements new technologies; new ways of operating buildings; new tools for design, commissioning, and monitoring; and a new understanding of what comprises a comfortable and productive indoor environment. This project focused on two promising space conditioning technologies—personal comfort systems and radiant heating and cooling. Both systems, parts of a previous California Energy Commission project by UC Berkeley’s Center for the Built Environment, showed significant potential in improving traditional levels of energy efficiency and increasing occupant satisfaction and thermal comfort.

The research generated these findings and recommendations:

- Four field demonstration studies with personal comfort systems technologies, including chairs providing heating and cooling, leg warming devices and small desk fans displayed reduced zone heating energy and a dramatic improvement in occupant comfort. The personal comfort systems performed well enough for commercial market introduction.

- The research team gathered building energy performance data, gave occupant satisfaction assessments, and studied two successful and well-performing radiant slab office buildings. They also developed an online map of buildings using radiant technologies to provide resources to building stakeholders interested in their implementation.

- 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.

- Two energy simulation studies were completed. One showed that the David Brower Center’s 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. The second study demonstrated the potential impact of more accurately specifying internal mass (furniture and contents) 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.
# TABLE OF CONTENTS

Acknowledgements ................................................................................................................................. i

PREFACE ................................................................................................................................................ iii

ABSTRACT ............................................................................................................................................... iv

TABLE OF CONTENTS ........................................................................................................................... vi

LIST OF FIGURES ................................................................................................................................ ix

LIST OF TABLES ................................................................................................................................... xiii

EXECUTIVE SUMMARY ................................................................................................................... 1

Introduction ........................................................................................................................................ 1

Project Purpose .................................................................................................................................. 1

Project Process .................................................................................................................................... 2

Project Results ..................................................................................................................................... 2

Project Benefits ................................................................................................................................... 7

CHAPTER 1: Personal Comfort Systems .............................................................................................. 9

1.1 Bancroft Library Doe Annex ........................................................................................................ 11

1.1.1 Overview ................................................................................................................................ 11

1.1.2 Building, Equipment, and Climate .......................................................................................... 11

1.1.3 Experimental Methodology .................................................................................................. 15

1.1.4 Results From Comfort Surveys ............................................................................................ 18

1.1.5 Energy Calculations ................................................................................................................ 22

1.1.6 Exit Interviews ....................................................................................................................... 26

1.1.7 Comfort Model Analysis ......................................................................................................... 26

1.1.8 Discussion ................................................................................................................................. 27

1.2 Cesar Chavez Student Union Field Study .................................................................................... 27

1.2.1 Overview ................................................................................................................................ 27

1.2.2 Objective .................................................................................................................................. 27

1.2.3 Approach ................................................................................................................................... 27

1.2.4 Results ................................................................................................................................... 33
CHAPTER 2: Space Conditioning in Near Zero-Net-Energy Buildings

2.1 Online Map of Buildings Using Radiant Technologies

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

2.2.1 CBE Occupant Satisfaction Survey

2.2.2 Energy Star Rating

2.2.3 Field Measurements of Radiant Slab Performance

2.2.4 Building Energy Simulations

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

2.3.1 Field Measurements and Building Management System Trend Data

2.3.2 CBE Occupant Satisfaction Survey

2.3.3 Acoustic Measurements

2.4 Laboratory Testing

2.4.1 References

2.5 Radiant Systems Energy Simulation Report

2.5.1 Application of the David Brower Center Design to Different California Climates

2.5.2 Dynamic Energy Impacts of Thermal Mass

2.6 Presentation material for ZNE Building Performance Seminar

CHAPTER 3: Technology Transfer

3.1 ASHRAE Standard 55 and Technical Committee TC 2.1

3.1.1 ASHRAE Committee Work

3.1.2 Thermal Comfort Web-Tool

3.1.3 Solar Radiation Calculation Procedure

3.1.4 Stratification Limit in ASHRAE Standard 55

3.1.5 Air Speed Provisions

3.1.6 Clothing Model

3.1.7 ASHRAE Standard 55 Users’ Manual

3.1.8 ASHRAE Comfort Database II Development

3.2 ASHRAE Technical Committee TC 4.1
3.2.1 Cooling Load Differences Between Radiant and Air Systems ........................................ 120
3.2.2 Cooling Load Differences Between UFAD and Conventional Mixing Air Systems .... 121

3.3 ASHRAE Technical Committee TC 5.3 ............................................................................. 121
  3.3.1 Publication of Revised ASHRAE UFAD Design Guide ........................................... 121
  3.3.2 Development of Work Statement on Active Chilled Beams .................................... 122
  3.3.3 Development of Work Statement on Passive Chilled Beams .................................. 122

3.4 ASHRAE Technical Committee TC 6.5 ............................................................................. 122

REFERENCES .......................................................................................................................... 123
GLOSSARY ............................................................................................................................... 124
APPENDICES ........................................................................................................................... 127

LIST OF FIGURES

Figure 1: Bancroft Library and Office Layout ......................................................................... 11
Figure 2: Fan/Foot Warmer PCS ............................................................................................ 12
Figure 3: Doe Annex Office Floor Plan ................................................................................... 12
Figure 4: HVAC System Schematic Diagram ......................................................................... 13
Figure 5: Temperature Control Zone Plan in Doe Annex ....................................................... 14
Figure 6: Airflow Calibration Process and Measured Airflow Values ..................................... 14
Figure 7: Heating and Cooling Degree-Days at Oakland International Airport ....................... 15
Figure 8: Typical Hourly Temperatures and Relative Humidity at Oakland International Air-Port .......................................................... 15
Figure 9: Physical Data Logged for Energy Calculations ......................................................... 16
Figure 10: Timeline Showing Temperature Set Points During Study Period .......................... 17
Figure 11: Daily Perimeter and Core Temperatures During Occupied Hours ........................ 17
Figure 12: Daily Average Perimeter and Core Temperatures During Occupied Hours .......... 18
Figure 13: Average Temperatures During Study Periods ....................................................... 18
Figure 14: Online ‘Just Now’ Survey ...................................................................................... 19
Figure 15: Structure of a Boxplot ........................................................................................... 20
Figure 16: Overall Thermal Acceptability .............................................................................. 20
Figure 44: Floor Plan of Study Areas in Stanley Hall; Second Floor (Top), Third Floor (Bottom)44
Figure 45: Participants in Stanley Hall are Oriented to PCS Equipment.............................................45
Figure 46: Participants in Stanley Hall with PCS Equipment Installed .............................................46
Figure 47: Pre-Condition Survey ...........................................................................................................47
Figure 48: Post-Condition Survey ..........................................................................................................48
Figure 49: Exit Survey Questionnaire....................................................................................................49
Figure 50: Showing Airflow and Discharge Air Temperature Fluctuations ......................................52
Figure 51: Airflow Room 306C December 2013 Until March 2014 (Top); Airflow Room 206C March 2014 Until June 2014 (Bottom) ....................................................................................................55
Figure 52: Airflow and Temperature, Room 306C and 206B, October 2013 to January 2015 ..........58
Figure 53: Detailed Temperature Plot for 306J and 206, Oct. 1-3, 2014 ..............................................59
Figure 54: Temperature Plot for 206, Open Space, October 2-4, 2014 ..............................................60
Figure 55: Thermal Comfort Survey Results ........................................................................................62
Figure 56: Thermal Sensation Survey Results ......................................................................................62
Figure 57: Use of PCS for Heating or Cooling Throughout the Study Period ..................................63
Figure 58: Ambient Thermal Preferences Throughout the Study Period ...........................................63
Figure 59: Total Heating Load and Temperature Set Points for 306 ....................................................65
Figure 60: 306 Heating Energy for 3 Control Regimes as Function of Outside Temperature ........67
Figure 61: 306 Cooling Load Under Different Control Regimes .......................................................68
Figure 62: 306 Cooling Load in Different Control Regimes as Function of Outside Temperature ....69
Figure 63: Airflow Reductions in 206 (Blue) and 306 (Red) ...............................................................74
Figure 64: IDeAs Building Exterior, Left, and Interior, Right ............................................................75
Figure 65: Workshop to Explain the Personal Comfort System .........................................................77
Figure 66: PCS Equipment Supplied: (L to R) Chairs, Foot Warmers, and Leg Warmers .............77
Figure 67: Measurement Devices and Locations .................................................................................79
Figure 68: Schematic Diagram of Electric Power System ....................................................................80
Figure 69: Occupant Survey Questionnaire .........................................................................................81
Figure 70: Measured Outdoor Temperatures During the Study Period .............................................82
Figure 71: Outdoor Temperatures From Nearby Weather Station ................................................... 83
Figure 72: Measured Indoor Temperatures During Study Period From Three Sensors .......... 83
Figure 73: Temperature Stratification Shown by Five Sensors .......................................................... 84
Figure 74: Thermal Acceptability ........................................................................................................... 84
Figure 75: Thermal Sensation ................................................................................................................. 85
Figure 76: Air Movement Acceptability ............................................................................................... 85
Figure 77: Perceived Air Quality ........................................................................................................... 86
Figure 78: Clothing Level ........................................................................................................................ 86
Figure 79: PCS Use ................................................................................................................................... 87
Figure 80: Chair Heating/Cooling vs. Temperature ............................................................................ 87
Figure 81: Thermal Sensation Preference ............................................................................................. 88
Figure 82: Common Responses to Questions, Quantified ................................................................. 88
Figure 83: Heating Water Valve Position and Air and Water Temperatures .................................. 90
Figure 84: Detailed Chart for One Day ................................................................................................. 91
Figure 85: Heating Water Valve Position and Air and Water Temperatures .................................. 91
Figure 86: HyperChair Features ............................................................................................................. 94
Figure 87: Company Business Card ...................................................................................................... 94
Figure 88: Screen Shot From KGO Television News ........................................................................... 95
Figure 89: Screen Shot from KGO Television News Showing Chair Controls ................................. 96
Figure 90: New Technology for Wireless Power Transfer ................................................................. 97
Figure 91: Examples of Comments From Exit Survey ........................................................................ 97
Figure 92: Radiant Leg Warmer ............................................................................................................. 98
Figure 93: Chart for ASHRAE Standard 55 Showing Comfort Zones for Two Levels of Clothing ................................................................................................................................. 99
Figure 94: Output From the CBE Comfort Tool ................................................................................ 100
Figure 95: Comfort Conditions in the Adaptive Comfort Model .................................................... 101
Figure 96: PCS Field Study Data Plotted on ACM Chart ................................................................. 102
Figure 97: Field Study Points Plotted on ASHRAE Air Movement Guide .................................... 102
Figure 98: Temperature Range Over Which PCS Provided Comfort in Field Studies .......... 103
LIST OF TABLES

Table 1: Pre-Existing Temperature Set Points in the Study Rooms ........................................... 50
Table 2: VAV Airflow Set Points on Third Floor Implemented Feb-Mar 2014 ......................... 53
Table 3: Airflow Set Points on Second Floor ............................................................................. 54
Table 4: Project Timeline ................................................................................................................. 56
Table 5: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction, 306 .... 70
Table 6: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction .......... 71
Table 7: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction .......... 72
Table 8: Energy Saving Corresponding to Temperature Set Point Reduction ......................... 73
Table 9: Measurements and Devices .............................................................................................. 78
Table 10: Survey Schedule ............................................................................................................ 81
EXECUTIVE SUMMARY

Introduction
When California’s Title 24 Building Energy Efficiency Standards (California Code of Regulations, Chapter 10, Part 6) were published in 2013, California Energy Commission staff estimated that the standards might reduce statewide annual electricity consumption by approximately 613 gigawatt-hours, annual electrical peak demand by 195 megawatts, and annual natural gas consumption by 10 million therms per year. Meeting these efficiency goals requires an integrated approach to building design that involves developing new design tools and technologies; new ways of operating, commissioning, and monitoring buildings; and a new understanding of what comprises a comfortable and productive indoor environment.

Project Purpose
This project supported the building industry by investigating solutions for making both new and existing buildings energy efficient with high indoor environmental quality. Researchers focused on two advanced and innovative technologies, the Personal Comfort System (PCS) and the Space Conditioning in Near Zero-Net-Energy (ZNE) Buildings, both concentrating on radiant heating and cooling systems.

Designers and engineers expect modern buildings to provide satisfactory comfort for at least 80 percent of their occupants; some buildings exceed this expectation, but many are still below the required minimum comfort level. One difficulty for gauging the standard of comfort is that most occupants have different preferences about conditions like temperature and air movement; another difficulty is that occupants may have different preferences at various times of the day.

The PCS concept remedies these difficulties by allowing individuals to alter their personal environment to their liking at any given time. With PCS, potentially 100 percent of the people in a building can be comfortable. Currently, the PCS components consist of chairs providing both heating and cooling, foot warming devices, leg warming devices, and small desk fans.

Radiant cooling and heating systems can also provide significant energy savings, peak demand reduction, load shifting, and thermal comfort improvements compared to conventional all-air systems. Installing these systems has increased in recent years, particularly in ZNE and other advanced high-performance buildings. A status report by New Buildings Institute 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. A recent article reported on a large side-by-side comparison study 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 square foot (ft²) 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 was reported that the radiant system used 34 percent less energy compared to the VAV system, and the results of an occupant satisfaction survey also
indicated greater satisfaction with thermal comfort for the radiant half of the building (63 percent satisfaction rate for radiant versus 45 percent satisfaction rate for VAV system).

Both the personal comfort systems and radiant cooling and heating systems demonstrated dramatic improvements in energy efficiency and also increased occupant satisfaction and thermal comfort. The work was performed in collaboration with a broad consortium of building industry partners and the deliverables support the energy-efficiency goals prescribed for buildings statewide.

Project Process

Researchers demonstrated the energy and comfort impacts of PCS in different types of buildings, both conventional and energy-efficient; demonstrated how PCS should be integrated with existing building controls to harvest the energy-savings made possible by PCS, made presentations to the building industry; and provided specifications for clients and standards organizations to influence manufacturing future PCS.

The professional design community was also provided with new and improved information, guidance, and tools for designing and operating near ZNE buildings using radiant heating and cooling systems. Researchers conducted two case studies of existing near ZNE buildings using radiant systems. In addition to performance data and occupant satisfaction survey results from the case studies, a series of fundamental laboratory experiments improved understanding of optimized control strategies for radiant slab systems. 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.

Project Results

**Personal Comfort Systems (PCS)**

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. The studies also provided invaluable feedback for improving these components, and for assessing their effectiveness. Although further development is necessary, PCS have reached a level of performance that supports commercial market introduction.

Currently, the PCS components consist of chairs that provide heating and cooling, foot warming devices, leg warming devices, and small desk fans; additional components are still under consideration. Current devices are in active development at CBE and at a startup firm licensing the technology.

Results From Field Studies

Two field studies under this contract were carried out, one at Stanley Hall on the University of California, Berkeley campus and the other at the Integrated Design Associates (IDeAs) Z2 Design Facility in San Jose. Two more studies were also completed at buildings on the Berkeley campus - the Bancroft Library and the Cesar Chavez Student Union; these studies were funded
separately and reported by the California Institute for Energy and the Environment (CIEE) State Partnership for Energy Efficient Demonstrations (SPEED). The researchers included them as part of this report because they were an essential part of PCS development and testing, used the same researchers, and occurred during the same time frame as this contract.

The field study in Stanley Hall, a nearly new laboratory building on the Berkeley campus, took place over 16 months. Stanley Hall is both a large energy consumer and a source of comfort complaints stemming from uncomfortable temperature swings. PCSs successfully mitigated and improved comfort issues while the heating, ventilating, and air conditioning (HVAC) system was adjusted. The PCS increased the average satisfaction rate from 56 percent to more than 80 percent under all test conditions. Zone energy savings were also high, 60 percent in heating and 40 percent in cooling.

The IDeAs Z2 Design Facility in San Jose, California is an advanced, radiantly heated and cooled building that 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 approximately three weeks, testing the limits of the comfort that PCS chairs could provide in colder conditions.

The Bancroft Library study began with a week-long baseline comfort survey of the sixteen participants, then the research team installed foot warmers and desk fans in their vicinities. The surveys following installation indicated an immediate improvement of comfort. During the six-month winter season, the heating set point was lowered in 1 degree Fahrenheit (°F) increments from 70°F (21.1 degrees Celsius [°C]) to 66°F (18.9°C). Good comfort was maintained until the lowest set point, during which cold sensation began to affect comfort. The temperature was then 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 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 Cesar Chavez Student Union is a mechanically conditioned building has ventilation and heating but lacks cooling, making it an ideal location to demonstrate of the effectiveness of PCSs in a space that might be uncomfortable in warm weather. The study included 18 participants; 14 used PCS chairs and four used fans and foot warmers continuing for six months during a heating and cooling season. Results indicated more than 80 percent comfort rate with PCS between 68°F and 80°F (20 and 26.7°C); without the PCS, the average satisfaction rate was around 50 percent, with no period more than 70 percent. The energy savings in this study were modest due to temperature set backs because the building is so efficient to begin with. The PCS, as usual, substantially improved comfort.

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

The CBE patented several aspects of the PCS concept through the University in anticipation for its marketability. A highly regarded building mechanical engineer is beginning to commercialize the PCS chair after learning about it through outreach at the CBE meetings. At least 50 of the heated and ventilated chairs have been manufactured to date under the license. The PCS chair also intrigued a local television news affiliate, which broadcasted and sponsored an informative segment about the chair.

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. A number of participants also mentioned that the foot warmer hit their shins or altered their posture, so further research on design alternatives is being done to resolve this issue. Additionally, a means to charge the chair battery without having to plug in, like a wireless power transfer, is being developed. Modifications to the fan design were also suggested, and these are under consideration and development.

Since it is evident that a building could use a much smaller HVAC system in conjunction with PCS and still provide superior comfort, standard operation of the PCS was considered. First-cost savings from this plan, plus the energy savings from operations, would easily recoup the cost of PCS. However, before this plan can be fulfilled, performance standards, technical development, and wider commercial deployment of PCS is needed.

Space Conditioning in Near Zero-Net-Energy Buildings

The research 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. The research has generated (1) an online map listing buildings using radiant systems to share information on radiant technologies and identify potential case study sites (the online map can be accessed at: http://bit.ly/RadiantBuildingsCBE), (2) occupant satisfaction survey results, energy use data, and valuable lessons learned from two case studies on the David Brower Center in Berkeley and the Sacramento Municipal Utility District (SMUD) East Campus Operations Center in Sacramento, (3) improved fundamental understanding 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.

Case Studies of Near ZNE Buildings Using Radiant Systems

In this task, the researchers 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 45,000ft² 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 through 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 through 4th floors of the building. A dedicated outdoor air system (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, performs 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 ft² 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 such as: 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, and advanced window blinds that redirect solar energy onto ceiling. 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 summer 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. The team’s attention was focused on the operation and control of the radiant slab system on one representative floor (level 2) of the six-story office building. When the research team first began monitoring the building, they found 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 reviewing the operation and control of the radiant slab system are listed.
• A preferred approach is to adjust the controls so that the slab is precooled during the night and 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 the above control adjustments were made, the building successfully maintained comfortable zone temperatures throughout hot summer days.

• 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°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, laboratory experiments were conducted comparing zone-level sensible cooling loads between radiant chilled ceiling and overhead air distribution systems to verify the differences observed during the 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, it was concluded 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.
Researchers carried out two simulation studies to investigate radiant system performance under different climate conditions, as well as the impact of furniture and internal thermal mass on building energy performance.

**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 (for example, thermally activated building systems [TABS], mixed-mode ventilation based on the combination of underfloor air distribution (UFAD) and natural ventilation, no chiller, evaporative cooling tower, high performance envelope, and exterior sun shading devices) to three California cities and climates: Oakland, Los Angeles, and Sacramento.

The researchers 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 American Society of Heating, Ventilating, and Air Conditioning Engineers (ASHRAE) Standard 55-2013 target of 80 percent satisfied was 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:** Researchers assessed the impact that furniture and contents (in other words, 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 their findings, the researchers recommend conducting an experimental study to answer outstanding questions regarding improved specification of internal mass parameters.

**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.

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

- PCS technology is suitable for different size office buildings and new or existing colleges. 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), the team assumed the average baseline temperature deadband of 71 to 73°F (21.7 to 22.8°C) could be broadened to 1°F below the lower end of the ASHRAE Standard 55-2013 (ASHRAE 2013) comfort zone (67°F [19.4°C]) and 1°F above the upper end of the comfort zone (80°F [26.7°C]). 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 68 cents per therm and 14 cents per kWh)
- 141,000 tons of carbon dioxide equivalent (CO2e) emissions per year avoided (at 11.7 pounds [lbs] per therm and 0.83 lbs per kWh)

**Radiant Heating And Cooling Systems**

Based on the outcomes of this project, the researchers estimated the following energy savings:

- 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:
  - Improved understanding of fundamentals leading to well-defined standards, more reliable systems, improved sizing methods, and detailed guidance regarding design considerations and limitations.
  - 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.
  - Improved understanding of operations and controls of radiant systems.

- 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).

The estimated savings across all California building types is 844 gigawatt hours per year (GWh/yr), $165 million per year, and 496 million pounds of CO2e per year by 2030. In addition to these savings, it was estimated a reduction in peak electricity demand of 104 MW, corresponding to an additional $46 million per year in TDV-weighted electricity costs.
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, and others prefer less. The same occupant may have different preferences at different times of day, such as 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 the 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 the California Institute for Energy and the Environment (CIEE) Deputy Director, Karl Brown. CIEE has been extremely helpful with arranging tests and demonstrations on University of California campuses, which contain a wide variety of building types with various 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, the studies are synergistic and complementary, terms that apply to much of the valuable work facilitated by SPEED.
These 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 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 testing. 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 systems, 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 PCS 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 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°F (21.1°C). 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°F (18.9°C), and then gradually raised back to 70°F (21.1°C) 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: 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 watts (W) of electrical power.

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 user’s 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 2.

**Figure 2: Fan/Foot Warmer PCS**

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 ft² of open plan office and 420 ft², total, in two private offices (Figure 3).

**Figure 3: Doe Annex Office Floor Plan**
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 4). The AHU supplies seven Variable Air Volume (VAV) air terminal units with air temperature maintained at a constant 56°F (13.3 °C) (Figure 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 4: HVAC System Schematic Diagram
Prior to data collection, airflow through the VAV boxes was calibrated at three flow settings using a laboratory-grade flow measurement hood (Figure 6). The airflows reported by the ALC system agreed to within 1.5 percent of the flow measurement hood.

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 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 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.
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 9 shows all the physical data that was logged and used in the energy calculations.

**Figure 9: Physical Data Logged for Energy Calculations**

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

Figure 10 shows the temperature set points for the study period, and Figures 11 and 12 show actual zone temperatures during the study period, which correspond well with set points. Figure 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 13.
Figure 10: Timeline Showing Temperature Set Points During Study Period

Figure 11: Daily Perimeter and Core Temperatures During Occupied Hours
1.1.4 Results From Comfort Surveys

Each of the 16 participants was reminded by email to take a 'Just Now’ survey three times daily, at 9 a.m., 11 a.m., and 2 p.m. 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 14 shows the on-line survey, which has 10 questions and normally takes about one minute.

The 16 subjects asked to return at least 10 surveys per week for 12 survey periods, totaling 1,920 surveys. In total 2,774 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 15).

Figure 14: Online ‘Just Now’ Survey

<table>
<thead>
<tr>
<th>1. TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right now, how acceptable is the temperature at your workspace?</td>
</tr>
<tr>
<td>Very acceptable</td>
</tr>
<tr>
<td>You feel (Please mark on the scale)?</td>
</tr>
<tr>
<td>Hot</td>
</tr>
<tr>
<td>You would prefer to be:</td>
</tr>
<tr>
<td>Cooler</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. AIR MOVEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right now, how acceptable is the air movement at your workspace?</td>
</tr>
<tr>
<td>Very acceptable</td>
</tr>
<tr>
<td>Right now, how do you feel the air movement?</td>
</tr>
<tr>
<td>No air movement (don't notice any)</td>
</tr>
<tr>
<td>You would prefer:</td>
</tr>
<tr>
<td>More air movement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. AIR QUALITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right now, how acceptable is the air quality at your workspace?</td>
</tr>
<tr>
<td>Very acceptable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. THE PERSONAL COMFORT SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right now, does the footwarmer provide enough heat?</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>Right now, does the desk fan provide enough cooling?</td>
</tr>
<tr>
<td>Yes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5. COMMENTS TO THE ENVIRONMENT PROVIDED BY THE PERSONAL COMFORT SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>If you have additional comments to your Personal Comfort System, click <a href="#">here</a></td>
</tr>
</tbody>
</table>
Figure 15: Structure of a Boxplot

- Outlier
- Highest datum within 1.5*IQR of upper quartile
- Upper quartile (75th percentile)
- Median
- Lower quartile (25th percentile)
- Lowest datum within 1.5*IQR of lower quartile
- Outlier

Figure 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.

**Figure 16: Overall Thermal Acceptability**

Figure 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 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 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 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.
1.1.5 Energy Calculations

HVAC heating energy was calculated based on the amount of heat added to 56°F (13.3°C) supply air in order to maintain space temperature. The formula used to calculate this energy is shown below:

\[
\text{Reheat Power (kW)} = \text{Q} \times \Delta T_f \times k
\]

Where:
\[
\text{Q} = \text{Airflow in cubic feet per minute (cfm)}
\]
\[
\Delta T_f = [\text{Discharge Air Temperature (F)}] - [\text{Supply Air Temperature (F)}]
\]
\[
k = \text{conversion factor} = 0.0003176 \text{ kW/cfm} - T_f/9
\]

Where:
\[
\text{cfm} = 0.000472 \text{ m}^3/\text{s}
\]
\[
T_x = 5 \text{ F}/9
\]
\[
\rho_{\text{air}} = \text{density of air} = 1.204 \text{ kg/m}^3
\]
\[
C_p = \text{specific heat capacity of air} = 1006 \text{ Joules/kg-T_k}
\]
\[
k = (\text{m}^3/35.31\text{ft}^3)(\text{min/60sec})(1.204\text{kg/m}^3\text{air})(5T_x/9 T_x)(1006\text{J/kg-T_k})(\text{sec-kW/1000J})
\]

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 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.
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 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 22 and 23 show the aggregate energy use was quite low, because of the limited amount of time they were actually in use.
By adding the power of the foot warmers to the HVAC power used over a period and dividing by the number of workstations, the heating energy used per workstation can be calculated during each zone temperature regime. This is shown for two bins of outdoor air temperatures (OAT) in Figure 24. Note that HVAC heating energy use is significantly higher when outdoor air temperatures are lower.
Based on energy use for a 70°F (21.1°C) set point at similar outdoor air temperatures, as shown by previous Figure 20, the energy savings from reduced zone temperatures combined with foot warmers are significant, as shown in Figure 25. Figure 26 shows energy normalized for area (heating density).

**Figure 25: Heating Energy Use and Savings From Foot Warmers vs. Zone Temperatures**

<table>
<thead>
<tr>
<th></th>
<th>Setpoint 66F</th>
<th>Setpoint 67F</th>
<th>Setpoint 68F</th>
<th>Setpoint 70F</th>
<th>Setpoint 70F (no PCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Power Density (W/sf) (OAT 55 – 60)</td>
<td>0.12</td>
<td>0.17</td>
<td>0.13</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>Heating Power Density (W/sf) (OAT 52 – 57)</td>
<td>0.11</td>
<td>0.24</td>
<td>0.25</td>
<td>0.50</td>
<td>0.47</td>
</tr>
</tbody>
</table>

**Figure 26: Heating Energy Use and Savings vs. Zone Temperature Normalized for Area**

<table>
<thead>
<tr>
<th></th>
<th>Setpoint 66F</th>
<th>Setpoint 67F</th>
<th>Setpoint 68F</th>
<th>Setpoint 70F</th>
<th>Setpoint 70F (no PCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footwarmer Power (W) (OAT 55 – 60)</td>
<td>12</td>
<td>8</td>
<td>7</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Heating Power (W) (OAT 55 – 60)</td>
<td>133</td>
<td>195</td>
<td>145</td>
<td>332</td>
<td>328</td>
</tr>
<tr>
<td>Percent Savings (from 70F no PCS) (OAT 55 – 60)</td>
<td>56%</td>
<td>38%</td>
<td>54%</td>
<td>-2%</td>
<td>NA</td>
</tr>
<tr>
<td>Footwarmer Power (W) (OAT 52 – 57)</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Heating Power (W) (OAT 52 – 57)</td>
<td>119</td>
<td>265</td>
<td>281</td>
<td>567</td>
<td>532</td>
</tr>
<tr>
<td>Percent Savings (from 70F no PCS) (OAT 52 – 57)</td>
<td>75%</td>
<td>49%</td>
<td>46%</td>
<td>-7%</td>
<td>NA</td>
</tr>
</tbody>
</table>
1.1.6 Exit Interviews

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

**Figure 27: Summary of Exit Interviews**

<table>
<thead>
<tr>
<th>Workstation Number</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x x x x</td>
</tr>
<tr>
<td>2</td>
<td>x x x x</td>
</tr>
<tr>
<td>3</td>
<td>x x x x</td>
</tr>
<tr>
<td>4</td>
<td>x x x x</td>
</tr>
<tr>
<td>5</td>
<td>x x x x</td>
</tr>
<tr>
<td>6</td>
<td>x x x x</td>
</tr>
<tr>
<td>7</td>
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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 assumed. 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°F (10°C) 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 'Predicted 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 66°F (18.9°C) than a reference building operated at a set point of 70°F (21.1°C) 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.

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 (Figure 28). 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 two to four 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 28: Heated and Cooled Chair and Fan Used in Cesar Chavez Student Union

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 (Figure 28). 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 28: Foot Warmer and Fan Developed by CBE**

![Foot Warmer and Fan Diagram](image)

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 (Figure 29). 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.
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 30 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.
An initial survey was conducted before the PCS were distributed, over the course of two weeks, during the warm season (Sept. 25 through 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, the PCS each occupant chose was distributed. The ‘post’ surveys covering warm (Oct. 14 through Nov. 17, 2013) and cool (Feb. 6 through 21, 2014) seasons were conducted.

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

Occupant’s Satisfaction Survey Questions

Fatigue caused by long survey questions is known to affect the accuracy of responses. 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 31. The questions cover three areas, thermal comfort, air movement satisfaction, and perceived air quality. There are six questions total.
For the post-survey, another group of questions regarding use of the PCS were added. The additional questions are shown in Figure 32.
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 33. 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.)
1.2.4.1 Comparisons of Thermal Comfort Acceptability and Sensation With and Without PCS in Summer Season

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. The subjective comfort votes were first matched with the simultaneously measured ambient air temperatures.

Figure 34 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 to 82°F (23.3 to 27.8°C). There were not as many low (74 to 76°F [23.3 to 24.4°C]) temperatures during the pre-survey period as higher (77 to 82°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.
In warm weather, the PCS is able to keep occupants comfortable within and up to 80°F (26.7°C), with acceptability above 80 percent except for one temperature bin. Beyond 80°F, the acceptability rates are significantly decreased, even with the PCSs.

For the ambient air temperature range between 74 to 80°F (23.3 to 26.7°C) 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 to 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 35) shows that within this ambient air temperature range 74 to 80°F (23.3 to 26.7°C), 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).
With Chair Only

For the ambient air temperature range between 74 to 80°F (23.3 to 26.7°C), the acceptability rates considering chairs only increased to 72 to 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°F (26.7°C), the acceptability rates are significantly lower, even with the PCS chairs (Figure 36).
Again, the thermal sensation values with chairs are all very close to zero (neutral sensation) for ambient air temperature between 74 to 80°F (23.3 to 26.7°C) (Figure 37), see median values – lines, and mean values – open circles inside the dark grey bars).
1.2.4.2 Thermal Comfort Ranges and Sensation With PCS in Both Summer and Winter
With Both Types of the PCS

This section shows the thermal comfort ranges with both types of the PCS. Figures 38-40 show that PCS provides occupants’ comfort over a range of 68 to 80°F (20 to 26.7°C), with acceptability above 80 percent except for one temperature bin. The number-of-vote weighted average acceptability rate is 86 percent.

**Figure 38: Comfortable Ambient Temperature Range With PCS in Summer and Winter Seasons**

**Figure 39: Comfortable Ambient Temperature Range With PCS Chairs Only in All 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°F (26.7°C). 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 (Figure 41). After the Pre-survey and delivery of the PCS however before the Post-survey was started (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, the team 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 to 80°F (20 to 26.7°C). In cool ambient conditions (between 68 to 72°F [20 and 22.2°C]), the PCS can maintain occupants’ thermal sensation votes between “slightly cool” and “neutral.” In neutral to warm ambient conditions (73 to 80°F [22.8 to 26.7°C]), the PCS can maintain occupants’ thermal sensation votes near ‘neutral’.

Over the full temperature range, comfort acceptability was improved from 30 to 71 percent (average 44 percent) acceptability under the base-case condition to 72 to 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 41: 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 ft² 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 42).

![Figure 42: 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°F (12.8°C) at all times, which is a common strategy, though not optimal for energy efficiency (Figure 43).

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°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 55°F supply air set point, the economizer dampers will modulate, mixing outside air with return air so as to maintain the 55°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°F at the minimum outside air fraction, then the heating valve modulates open to allow hot water to flow through a heating coil, to maintain the supply air temperature at its 55°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 43: Installing Wireless Sensors (Left); Typical Air Handler Schematic Diagram (Right)**

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 required, 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. $O_t = O_{pb} + \sum_{t=1}^{n}(O_{pb} / IC)$. 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 44.
Figure 44: Floor Plan of Study Areas in Stanley Hall; Second Floor (Top), Third Floor (Bottom)

Source: 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 45), which they felt would be most beneficial. In total they chose 18 heated and cooled chairs, four legwarmers, and four foot warmers. The occupants were also taught to take the comfort surveys. The survey tool was identical to the one described for the Student Union study in Chapter 2.

Figure 45: Participants in Stanley Hall are Oriented to PCS Equipment

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 46).
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. 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 10 a.m. and 3 p.m., 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 47 and 48. Because the survey asks for people’s perceptions at the moment when they’re taking the survey, it is called the ‘right-now’ survey.
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 48: Post-Condition Survey

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:
   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.
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 49 shows the exit survey questions.

**Figure 49: Exit Survey Questionnaire**
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. Using 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 25, 2013 before PCS were delivered, to establish a baseline for comfort. Table 1 shows the pre-existing temperature set points, which varied between 71°F and 75°F in the zones studied.

<table>
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<td>206C</td>
<td>73</td>
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<td>71</td>
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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 24, 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. 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 50) 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°F[32.2°C]) to cooling model (minimum around 60°F [15.6°C]), as shown in Figure 50. 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.
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 (Table 2). 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 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 5. 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 2 and 3 floors are presented in Table 3. On average, the minimum airflow rate was reduced to about 30 percent of the original values on the 3 floor, and 50 percent on the 2 floor. The maximum airflow rate was reduced to between 50 and 75 percent of the original values on both floors.

Table 2: VAV Airflow Set Points on Third Floor Implemented Feb-Mar 2014

<table>
<thead>
<tr>
<th>VAV reheat unit</th>
<th>Area description</th>
<th>Minimum Airflow Setpoint (cfm)</th>
<th>New maximum airflow setpoint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Original: as of 1/13/2014</td>
<td>Original: as of 2/24/2014</td>
</tr>
<tr>
<td>VAV 306B</td>
<td>Private office 306B, 1 occupant</td>
<td>125 Desired = 75 cfm</td>
<td>225 cfm Desired = 150</td>
</tr>
<tr>
<td>VAV 306C</td>
<td>Private office 306C, 1 occupant</td>
<td>150 Desired = 75 cfm</td>
<td>375 cfm Desired = 225</td>
</tr>
<tr>
<td>VAV 306H</td>
<td>Private office 306H, 1 occupant</td>
<td>275 Desired = 175 cfm</td>
<td>575 cfm Desired = 375</td>
</tr>
<tr>
<td>VAV 306J</td>
<td>Private offices 306J (1 occupant), 306K</td>
<td>325 Desired = 225 cfm</td>
<td>650 cfm Desired = 440</td>
</tr>
<tr>
<td>VAV 306L</td>
<td>Open plan 306A, kitchen 306L</td>
<td>300 Desired = 200 cfm</td>
<td>525 cfm Desired = 365</td>
</tr>
</tbody>
</table>
Table 3: Airflow Set Points on Second Floor

<table>
<thead>
<tr>
<th>VAV reheat unit</th>
<th>Area description</th>
<th>Minimum Airflow Setpoint (cfm)</th>
<th>Maximum Airflow Setpoint (cfm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>206-1</td>
<td>Open plan; interior diffusers</td>
<td>300</td>
<td>Desired = 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>206-2</td>
<td>Open plan; perimeter diffusers</td>
<td>450</td>
<td>Desired = 250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>900</td>
</tr>
<tr>
<td>206B</td>
<td>Private office 206B, 2</td>
<td>150</td>
<td>Desired = 75</td>
</tr>
<tr>
<td></td>
<td>occupants</td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>206C</td>
<td>Private office 206C, 1</td>
<td>150</td>
<td>Desired = 75</td>
</tr>
<tr>
<td></td>
<td>occupants</td>
<td></td>
<td>270</td>
</tr>
<tr>
<td>206D</td>
<td>Private office 206D, 2</td>
<td>150</td>
<td>Desired = 75</td>
</tr>
<tr>
<td></td>
<td>occupants</td>
<td></td>
<td>375</td>
</tr>
</tbody>
</table>

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, it 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 51 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.
1.3.6.3 Temperature Set Point Reduction

After the airflow rate reduction, in winter season (Nov. 2014 to Jan. 2015), the temperature set points were lowered 1°F at a time until they were 5°F lower than the beginning set points shown in Table 3. The timeline of the airflow rate and temperature set point changes are presented in Table 4.
<table>
<thead>
<tr>
<th>Task</th>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Pre</td>
<td>2013 Oct. 14 - 25</td>
</tr>
<tr>
<td>T2</td>
<td>2013 Oct. 24</td>
<td>Deliver PCS</td>
</tr>
<tr>
<td>T3</td>
<td>Post1</td>
<td>2013 Oct28-Nov26</td>
</tr>
<tr>
<td>T4</td>
<td>2014 Jan. 13 3:40PM</td>
<td>R306 min Flowrate (Q) reduction</td>
</tr>
<tr>
<td>T5</td>
<td>2014 Feb. 25 5:11PM</td>
<td>R306 Max q reduction (Step I)</td>
</tr>
<tr>
<td>T6</td>
<td>2014 Mar. 4 11:40AM</td>
<td>R306 Max q reduction (Step II)</td>
</tr>
<tr>
<td>T7</td>
<td>2014 Apr. 15 11:44AM</td>
<td>R206 Min q reduction, Max q reduction (Step I)</td>
</tr>
<tr>
<td>T8</td>
<td>2014 Apr. 24</td>
<td>R206 Max q reduction (Step II)</td>
</tr>
<tr>
<td>T9</td>
<td>Post2</td>
<td>2014 May 12 - 21</td>
</tr>
<tr>
<td>T10</td>
<td>Post2</td>
<td>2014 August 4 - 12</td>
</tr>
<tr>
<td>T11</td>
<td>Post2</td>
<td>2014 Sept. 4 - 23</td>
</tr>
<tr>
<td>T12</td>
<td>Post2</td>
<td>2014 Oct. 1 - 18</td>
</tr>
<tr>
<td>T13</td>
<td>2014 Nov. 5 th 4:20PM,</td>
<td>Increased Max q for the second floor</td>
</tr>
<tr>
<td>T14</td>
<td>Post3</td>
<td>2014 Nov. 12 - 20</td>
</tr>
<tr>
<td>T15</td>
<td>2014 Nov. 19, 4:17PM,</td>
<td>-1°F (-0.6°C) lowering</td>
</tr>
<tr>
<td>T16</td>
<td>Post4</td>
<td>2014 Nov20-Dec2</td>
</tr>
<tr>
<td>T17</td>
<td>2014 Dec. 4, 4PM</td>
<td>-2°F (-1.1°C) lowering</td>
</tr>
<tr>
<td>T18</td>
<td>Post5</td>
<td>Dec. 8 - 15</td>
</tr>
<tr>
<td>T19</td>
<td>2014 Dec. 16, 9:18AM</td>
<td>-3°F (-1.7°C) lowering</td>
</tr>
<tr>
<td>T20</td>
<td>Post6</td>
<td>2014 Dec. 16 - 23</td>
</tr>
<tr>
<td>T21</td>
<td>Post6</td>
<td>2015 Jan. 5 - 12</td>
</tr>
<tr>
<td>T22</td>
<td>2015 Jan. 13, 9:33AM</td>
<td>Flow rate 2nd floor reduced back to minimum</td>
</tr>
<tr>
<td>T23</td>
<td>Post 7</td>
<td>2015 Jan. 13 - 20</td>
</tr>
<tr>
<td>T24</td>
<td>2015 Jan. 21, 8:26AM</td>
<td>- 4°F (-2.2°C) lowering</td>
</tr>
<tr>
<td>T25</td>
<td>Post 8</td>
<td>2015 Jan. 21 - 27</td>
</tr>
<tr>
<td>T26</td>
<td>2015 Jan. 28, 9:25AM</td>
<td>- 5°F (-2.8°C) lowering</td>
</tr>
<tr>
<td>T27</td>
<td>Post 9</td>
<td>2015 Jan 28-Feb 4</td>
</tr>
</tbody>
</table>
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 (top two charts in Figure 52 for two examples, 306C on the third floor and 206B on the second floor). The red dots in the figures represent the average daily temperatures for the two spaces. There are rooms in which the temperatures didn’t float as much, however, the room temperatures fluctuated less, 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 five steps. The effects of this on rooms 306C and 306H are shown in Figure 52, 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 52: Airflow and Temperature, Room 306C and 206B, October 2013 to January 2015
The two charts in Figure 53 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 °F (23.1°C), 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 77°F (25°C) for three or four hours in the afternoon.

In the second floor 206 open space, the zone temperature floats as high as 78°F (25.6°C) during the day, falling to around 71°F (21.7°C) in early morning.

**Figure 53: Detailed Temperature Plot for 306J and 206, Oct. 1-3, 2014**
The two charts in Figure 54 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°F-reduction (timeline T23) to a 4°F-reduction (T24). In zone 306E, the set point changed from 72°F to 71°F (22.2 to 21.7°C), and the ambient temperature basically followed the set points. In zone 206C, the set point changed from 70°F to 69°F (21.1 to 20.6°C), but after about 10 a.m. each day, the ambient temperature could not reach the set points, which were about 1 to 2°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 54: Temperature Plot for 206, Open Space, October 2-4, 2014
1.3.7 Results

1.3.7.1 Occupant Satisfaction Survey

The team successfully increased ambient temperatures during warm weather. Most of the ambient temperatures in the study spaces reached 77°F to 78°F (25 to 25.6°C) several hours each day. During cool weather, when the temperature set points were lowered by 1 to 3°F (0.6 to 1.7°C), the zone temperature was close to the set points. When the set points were lowered further by 4 and 5°F (2.2 to 2.8°C), 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 55 shows the acceptability for each survey period represented in 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, September, October) 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 five green boxes present the survey results in the cool season when the ambient set point was reduced by 1 to 5°F (0.6 to 2.8°C). The acceptability is all well above 80 percent.

The thermal sensation in the base case was slightly cool. 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, September, October), 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 56). 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 55: Thermal Comfort Survey Results

Figure 56: Thermal Sensation Survey Results
1.3.7.2 How Participants Used PCS

Figure 57 shows how people used their PCS throughout the study period, according to the survey, and Figure 58 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 57: Use of PCS for Heating or Cooling Throughout the Study Period](image1)

![Figure 58: Ambient Thermal Preferences Throughout the Study Period](image2)

1.3.7.3 Exit Survey

Twelve participants took the exit survey, representing 12 chair users, two 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 required a 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 and examined 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. 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 59 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. The heating load is reduced 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 come 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 second floor, it remains roughly constant or rises slightly on the third floor due to the outdoor temperature reduction during that period. The outdoor temperature created more effect on the third floor than the second floor, because internal load is much higher on the second floor than the third 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 59: Total Heating Load and Temperature Set Points for 306**

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

Second floor total heating load and temperature set point represented by the grey line
Figure 60 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°F (7.2°C) 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.
Figure 60: 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 61 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 61: 306 Cooling Load Under Different Control Regimes](image)

Figure 62 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 (for example, 80°F [26.7°C] 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°F (26.7°C) outdoor temperature the cooling load was only about 30 percent of what it had been previously.

Figure 62: 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 5 through 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 the previous figures, which show the energy savings corresponding to outdoor temperature, these tables 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 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 these tables.

**Table 5: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction, 306**

<table>
<thead>
<tr>
<th>3rd floor time line</th>
<th>Start date</th>
<th>Flow average [cfm]</th>
<th>Flow max (95(^{th}) %tile)</th>
<th>Flow min (5(^{th}) %tile)</th>
<th>Average Temperature setpoint</th>
<th>Average zone temperature</th>
<th>Estimated yearly average heating power [kw] (Coefficient of Performance [COP]=1)</th>
<th>Estimated yearly average cooling power [kw] (Coefficient of Performance [COP]=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 (ref)</td>
<td>As found</td>
<td>01oct2013</td>
<td>2081</td>
<td>2454</td>
<td>1741</td>
<td>74.3</td>
<td>74.0</td>
<td>7.91</td>
</tr>
<tr>
<td>T4</td>
<td>Min flow reduced</td>
<td>14jan2014</td>
<td>1643</td>
<td>2175</td>
<td>1211</td>
<td>74.25</td>
<td>74.1</td>
<td>7.62 (4%)</td>
</tr>
<tr>
<td>T6</td>
<td>Flow max reduced more</td>
<td>05mar2014</td>
<td>1096</td>
<td>1115</td>
<td>1072</td>
<td>74.25</td>
<td>74.7</td>
<td>4.02 (51%)</td>
</tr>
</tbody>
</table>
Table 6 shows the heating and cooling energy savings associated with reducing zone temperature set points.

Lowering temperature set point mainly saves heating energy. T6 (before the set point was lowered 1°F [0.6°C]) was used as the reference condition to calculate energy savings. When the set point was reduced by 1 to 3°F (0.6 to 1.7°C), the heating energy saving was between 5 to 17 percent. The big energy savings happened when the zone temperature set point was reduced by 4 and 5°F (2.2 and 2.8°C). 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 demand for heating is significantly reduced, shown significant savings.

Cooling energy was small, around 5 percent for lowering the set point by 1 to 3°F (0.6 to 1.7°C), 13 percent for lowering the set point by 4°F (2.2°C). There are times the savings are too small to be measured accurately, so the savings were not available.

Table 6: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction

<table>
<thead>
<tr>
<th>3rd floor time line</th>
<th>Data from 9 AM to 5 PM only (no weekend setbacks)</th>
<th>Estimated yearly average heating power [kw]</th>
<th>Estimated yearly average cooling power [kw] (COP=1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start date</td>
<td>Flow average [cfm]</td>
<td>Flow max (95th %tile)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flow average [cfm]</td>
<td>Flow max (95th %tile)</td>
</tr>
<tr>
<td>T6 (ref)</td>
<td>Flow max reduced more</td>
<td>05mar2014</td>
<td>1096</td>
</tr>
<tr>
<td>T15</td>
<td>-1°F (-0.6°C) lower</td>
<td>20nov2014</td>
<td>1092</td>
</tr>
<tr>
<td></td>
<td></td>
<td>05dec2014</td>
<td>1094</td>
</tr>
<tr>
<td>T17</td>
<td>-2°F (-1.1°C) lower</td>
<td>17dec2014</td>
<td>1095</td>
</tr>
<tr>
<td>T19</td>
<td>-3°F (-1.7°C) lower</td>
<td>22jan2015</td>
<td>1097</td>
</tr>
<tr>
<td>T24</td>
<td>-4°F (-2.2°C) lower</td>
<td>29jan2015</td>
<td>1098</td>
</tr>
</tbody>
</table>
The heating and cooling energy savings for the second floor associated with flow rate reductions are presented in Table 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 7: Heating and Cooling Energy Saving Corresponding to Flow Rate Reduction

<table>
<thead>
<tr>
<th>2nd floor timeline</th>
<th>Data from 9 AM to 5 PM only (no weekend setbacks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start date</td>
</tr>
<tr>
<td>T1 (ref)</td>
<td>As found</td>
</tr>
<tr>
<td>T7</td>
<td>Flow max/min reduced</td>
</tr>
<tr>
<td>T8</td>
<td>Flow max reduced to min</td>
</tr>
<tr>
<td>T13</td>
<td>Flow max increased</td>
</tr>
</tbody>
</table>

Again, the period before the temperature set point lowering (T13) was used as the reference case to calculate the energy savings associated with lowering the temperature set point. Very similar to the energy savings on the third floor, heating energy savings increased from 7-30 percent as the temperature set point was lowered from 1-3°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 second floor is internal load dominant.
Table 8: Energy Saving Corresponding to Temperature Set Point Reduction

<table>
<thead>
<tr>
<th>2nd floor timeline</th>
<th>Data from 9 AM to 5 PM only (no weekend setbacks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start date</td>
</tr>
<tr>
<td>T13 (ref)</td>
<td>06nov2014</td>
</tr>
<tr>
<td>T15</td>
<td>20nov2014</td>
</tr>
<tr>
<td>T17</td>
<td>05dec2014</td>
</tr>
<tr>
<td>T19</td>
<td>17dec2014</td>
</tr>
<tr>
<td>T24</td>
<td>14jan2015</td>
</tr>
<tr>
<td>T26</td>
<td>22jan2015</td>
</tr>
</tbody>
</table>

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 63 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, a significant energy savings.
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 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 Z² 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 7,200 ft² 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 (Figure 64).

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 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 64: 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 (Figure 65). This took place in October 2014. All 24 occupants participated in the study and were provided chairs, leg and foot warmers (Figure 66).
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 (Table 9).
OnSet Hobo ambient air temperature and relative humidity sensors, accurate to ±0.63°F (± 0.35 degrees Celsius [°C]) and ±2.5 percent relative humidity (RH), measured room temperature and RH, and OnSet TMC1-HD external globe temperature sensors, accurate to ±0.45°F (±0.25°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 0.1 meter (m), 0.3 m, 0.6 m, 1.1 m, 1.7 m heights above the floor, and 0.1 m beneath the ceiling height. A Hobo datalogger located in a bush right outside of the building measured outdoor temperature. A nearby weather station provided independent weather data for comparison.

There are three zones in the building (Figure 67). 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 shown.
1.4.3.2 Sensor Calibration
The researchers calibrated the HOBO U12 data loggers in a climate-controlled chamber at 20°C, 25°C, and 30°C (68°F, 77°F, 86°F) and the TMC1-HD external sensors using a warm bath at the same three temperatures. All except one sensor measured temperature within 0.45°F (0.250°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 68).
1.4.3.5 Occupant Surveys

The researchers surveyed occupants according to the schedule (Table 10) and the survey questions (Figure 6). 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 Two-steps: first from the original 71°F heating to 75°F cooling (21.7°C heating to 23.9°C cooling), to 69.5°F heating to 76.5°F cooling (20.8°C heating to 24.7°C cooling), and again 68°F heating to 78°F cooling (20°C heating to 25.6°C 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 67°F heating and 78°F cooling (19.4°C heating to 25.6°C cooling), until February 20 (T6 survey).
Table 10: Survey Schedule

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

Figure 69: Occupant Survey Questionnaire

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

2. You feel:

3. You would prefer to be:

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

5. The air movement feels:

6. You would prefer:
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 70) and outdoor temperatures from nearby weather station (Figure 71).

**Figure 70: Measured Outdoor Temperatures During the Study Period**
Figure 71: Outdoor Temperatures From Nearby Weather Station

Figure 72 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 72: Measured Indoor Temperatures During Study Period From Three Sensors
1.4.4.2 Air Temperature Stratifications
The stratification appears quite small throughout the period (Figure 73).

Figure 73: Temperature Stratification Shown by Five 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 (Figure 74). Levels did improve after introducing 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.

Thermal sensation markedly improved to near neutral with the addition of PCS (Figure 75). Air movement acceptability is hardly changed, perhaps because the test was done in heating season rather than cooling season (Figure 76).

Figure 74: Thermal Acceptability
Perceived air quality actually fell slightly, especially during the failure period, from which it never quite recovered, though it was quite high throughout (Figure 77). 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 78).

Figure 78: Clothing Level
Figure 79 shows 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. Results showed people used the heating feature more when it was cold inside, and the cooling feature use increased with temperature (Figure 80).

**Figure 79: PCS Use**

![Use PCS](chart1.png)

**Figure 80: Chair Heating/Cooling vs. Temperature**

![Chair Heating/Cooling](chart2.png)
Figure 81 reflects the generally high level of thermal satisfaction in the building; people were generally comfortable in this building.

**Figure 81: Thermal Sensation Preference**

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 82 shows that most people were happy to have the chair for some heating, though a few were not quite satisfied with it.

**Figure 82: Common Responses to Questions, Quantified**

- I do not like having the chair: n=15
- I could not find the right heating level with the current control:
- The chair gives more individual control:
- The chair provides relief from feeling cold:
- I like having the chair:
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

Figures 83 and 84 show the zone, slab, and outdoor temperatures, and the valve opening positions for ambient thermostat setpoint range 71 to 75°F (21.7 to 23.9°C). Between 6-8 a.m., the valve opened and supplied heat to the floor. The floor temperature increased about 1°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°F (21.7°C) (for example, morning of January 16, 2015).

The ambient temperature changed between 71 to 77°F (21.7 to 25°C), slightly higher than the warm temperature of the setpoint range.

Figure 83: Heating Water Valve Position and Air and Water Temperatures
Valve opening as heating temperature set point is reduced

The duration of the valve opening is shorter when the heating set point was reduced, however 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 to 75°F [21.7°C to 23.9°C]) and 3.8 percent (69.5 to 76.5°F [20.8 to 24.7°C]) respectively, but the valve opened wider in the expanded set point condition (Figure 85).

Figure 85: 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, it may be inferred 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 (15.8 and 28.1°C). 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 United States 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 United States 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.” (Figure 86). "The Hyper Chair featuring
integrated user-controlled heating & cooling that can lower building HVAC energy usage up to 50 percent.”

**Figure 86: HyperChair Features**

![HyperChair Features](image)

Photo Credit: Center for the Built Environment

Personal Comfort Systems is currently involved in the production of the Hyper Chair version 2 (Figure 87) and has been promised the rights to the patent once it has been approved by the United States Patent Office.

**Figure 87: Company Business Card**

![Company Business Card](image)

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.” (Figure 88).

*Figure 88: Screen Shot From KGO Television News*

The piece was aired on December 4, 2013 and shows CBE researchers demonstrating and commenting on the chair. (Figure 89)

“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.
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 desks, 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 90).
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 in Figure 91.

**Figure 91: Examples of Comments From Exit Survey**

- "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 (Figure 92). An early model was tested in the iDeAs field study. This and other innovative equipment will continue to be developed and tested.
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 93 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.
Researchers at UCB, CBE developed a more accurate and specific computer-based model for Standard 55 and is available on-line at http://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 mean radiant temperature (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 94.
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, 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 downsized or eliminated. A chart of the ACM is shown in Figure 95. 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.
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 96 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.
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 97 plots the field study data points on an ASHRAE air movement guide. Here again comfort is indicated at points beyond what might be expected from the ASHRAE guide.

*There is no upper limit to air speed when occupants have local control.*
Finally, Figure 98 shows the entire temperature range, over which the PCS provided comfort in the present field studies.

### Figure 98: Temperature Range Over Which PCS Provided Comfort in Field Studies

<table>
<thead>
<tr>
<th>PCS heating (CP 8K)</th>
<th>HVAC</th>
<th>0.3-0.6 m/s (CP-3K)</th>
<th>0.6-1 m/s (CP-5K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-running</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Operative temperature (°C)](image)

#### 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 this will be known.
1.6.4 References


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 between 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, California, and the SMUD East Campus Operations Center, Sacramento, California. 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, the team 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, California

The David Brower Center is a four-story 45,000-ft² office building located in downtown Berkeley, California (Figure 99). 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 second through fourth 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 second through fourth 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 seven times more efficient), the building cooling energy savings are attained by using a cooling tower, instead of a chiller, to make cooling supply water.

Figure 99: David Brower Center, Berkeley, California
The overall conclusions from this case study are:

- The Brower Center is a good example of a high performing building in terms of energy, 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 this 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 summer 2014, the team wanted to learn about occupant’s satisfaction five 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 100.

- 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 about 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 100: 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 thousand British thermal units per square foot per year (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 p.m. to 6 a.m. as part of a pre-cooling strategy. Pre-cooling is triggered during warm weather when the outside air temperature reaches 84°F (28.9°C). 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 one office floor of DBC was modeled using the whole-building energy simulation program, EnergyPlus, for three cities (climates) in California: Oakland, Los Angeles and Sacramento.

The DBC design and HVAC strategy presented 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, California

The SMUD East Campus Operations Center is a 200,000 ft² LEED Platinum certified office building (Figure 101). The building was designed by Stantec (Architecture and MEP) and includes a great number of energy efficient technologies and design strategies such as: TABS, radiant embedded surface ceiling system, chilled beams, geothermal exchange, thermal energy storage tanks, heat recovery wheel, ceiling fans, high thermal mass, and advanced window blinds that redirect solar energy onto ceiling. 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 summer 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 101: SMUD East Campus Operations Center, Sacramento, California

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. The team focused their attention on the operation and control of the radiant slab system on one representative floor (level 2) of the six-story office building. Their efforts were supported by regular conference calls with the SMUD building operators as the team 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 the SMUD building field study:

- 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, California.

2.3.1 Field Measurements and Building Management System Trend Data

When the research team first began monitoring the building, 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 reviewing 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°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 second level for the SMUD building on December 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, laboratory experiments were conducted comparing zone-level sensible cooling loads between radiant chilled ceiling and overhead air distribution systems to verify the differences observed during the 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 the team 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 to 21 percent higher instantaneous cooling rates compared to the air system, and 75 to 82 percent of total heat gains were removed, while for the air system only 61 to 63 percent were removed. Based on the study, it was 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, the team 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


2.5 Radiant Systems Energy Simulation Report

Two simulation studies were carried out to improve the team’s understanding of radiant system performance under different climate conditions and to investigate the impact of furniture and internal thermal mass on building energy performance.

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 (for example, TABS, mixed-mode ventilation based on the combination of UFAD and natural ventilation, no chiller, evaporative cooling tower, high performance envelope, and 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. One middle floor of the DBC was modeled using the whole-building energy simulation program EnergyPlus.

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 the ongoing energy simulation studies of advanced low-energy HVAC systems, including radiant and underfloor air distribution, the team became 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 aspect of 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 assessed the impact that furniture and contents (internal mass) have on zone peak cooling loads using a perimeter zone model in EnergyPlus across 5,400 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. A new internal mass modeling method was also evaluated, which models direct solar radiation on the internal mass surface, an effect that is missing in current methods. It was shown 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 $-2.28\%$ ($-5.45\%$ and $-0.67\%$ 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 the team recommended conducting an experimental study to answer outstanding questions regarding improved specification of internal mass parameters.

In 2014, a peer-reviewed journal article was published describing full details of this simulation study of internal mass [Raftery et al. 2014] (Appendix 2.5.2).

2.5.2.1 References

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. The team was 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 must 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:


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:


### 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°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.


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, almost 10 times the data of Database I has been collected 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 (Figures 101 and 102). 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:


**Figure 101: Screenshot of the Probit Analysis Tool**

This example shows comfort and acceptability probit curves over real thermal sensation votes.
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 this work indicating differences in cooling loads for both UFAD and radiant systems compared 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 (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


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.

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


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 this 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.
REFERENCES


<table>
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<tr>
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<tbody>
<tr>
<td>/yr</td>
<td>Per year</td>
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<tr>
<td>ACM</td>
<td>Adaptive Comfort Model</td>
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<td>Air Handling Unit</td>
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<td>Automated Logic Corporation</td>
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<td>American Society of Heating Refrigerating and Air Conditioning Engineers</td>
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<td>BMS</td>
<td>Building Management System</td>
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<td>°C</td>
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<td>CBE</td>
<td>Center for the Built Environment, University of California, Berkeley</td>
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<tr>
<td>CEUS</td>
<td>Commercial End-Use Survey</td>
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<tr>
<td>CFM or cfm</td>
<td>Cubic Feet per Minute</td>
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<td>CIEE</td>
<td>California Institute for Energy and Environment</td>
</tr>
<tr>
<td>clo</td>
<td>Clothing insulation value</td>
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<tr>
<td>CO2e</td>
<td>Carbon dioxide equivalent</td>
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<tr>
<td>COP</td>
<td>Coefficient of performance</td>
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<td>$c_p$</td>
<td>Specific heat capacity</td>
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<td>CV</td>
<td>Controlled variable</td>
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<td>DBC</td>
<td>David Brower Center</td>
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<tr>
<td>DOAS</td>
<td>Dedicated outdoor air system</td>
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<tr>
<td>Energy Commission</td>
<td>California Energy Commission</td>
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<tr>
<td>EUI</td>
<td>Energy Utilization Intensity</td>
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<tr>
<td>°F</td>
<td>Degrees Fahrenheit</td>
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<td>FPM or fpm</td>
<td>Feet per minute</td>
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<td>ft²</td>
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<td>Gigawatt-hours per year</td>
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<td><strong>Definition</strong></td>
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<td>----------</td>
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<tr>
<td>HVAC</td>
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<td>Integrated Design Associates</td>
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<td>IEQ</td>
<td>Indoor Environmental Quality</td>
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<td>IQR</td>
<td>Interquartile Range</td>
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<td><strong>k</strong></td>
<td>Conversion factor equal to 0.0003176 kw/ cfm-(T_F)</td>
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<td><strong>K</strong></td>
<td>Kelvin</td>
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<tr>
<td>kBtu-ft(^2)/yr</td>
<td>Thousands of British thermal units per square foot per year</td>
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<tr>
<td>m(^3)</td>
<td>Cubic meters</td>
</tr>
<tr>
<td>m/s</td>
<td>Meters per second</td>
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<tr>
<td>MEP</td>
<td>Mechanical, electrical and plumbing</td>
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<td>Met</td>
<td>Metabolic rate</td>
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<td>Mean radiant temperature</td>
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<td>NSF</td>
<td>National Science Foundation</td>
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<tr>
<td>O(_{\phi})</td>
<td>Proportional controller output signal</td>
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<td>OAT</td>
<td>Outdoor air temperature</td>
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<td>PCS</td>
<td>Personal Comfort Systems</td>
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<td>PEX</td>
<td>Crosslinked polyethylene</td>
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<tr>
<td>PIER</td>
<td>Public Interest Energy Research, administered by California Energy Commission</td>
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<tr>
<td>PMV</td>
<td>Predicted Mean Vote</td>
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<tr>
<td>Q</td>
<td>Airflow rate in cubic feet per minute</td>
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<td>RAC</td>
<td>ASHRAE Research Administration Committee</td>
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<tr>
<td>RD&amp;D</td>
<td>Research, development and demonstration</td>
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<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>$\rho_{\text{air}}$</td>
<td>Density of air</td>
</tr>
<tr>
<td>sMAP</td>
<td>Simple Monitoring and Actuation Protocol</td>
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<td>SMUD</td>
<td>Sacramento Municipal Utility District</td>
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<td>Universal Serial Bus</td>
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<td>Variable Air Volume</td>
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<td>W</td>
<td>Watt</td>
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<td>ZNE</td>
<td>Zero-net-energy</td>
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APPENDICES

Appendices for this report as available as separate volumes.

Appendix A - 1.1.1: Using Footwarmers in Offices For Thermal Comfort And Energy Savings
Publication Number: CEC-500-2016-068-APA

Appendix B - 1.7.1 April 2013 Human Comfort Research Program Presentation
Publication Number: CEC-500-2016-068-APB

Appendix C - 1.7.2 October 2013 Human Comfort Research Program Presentation
Publication Number: CEC-500-2016-068-APC

Appendix D - 1.7.3 April 2014 Human Comfort Research Program Presentation
Publication Number: CEC-500-2016-068-APD

Appendix E - 1.7.4 October 2014 Human Comfort Research Program Presentation
Publication Number: CEC-500-2016-068-APE

Appendix F – 2.1.1 Online Map of Buildings Using Radiant Technologies
Publication Number: CEC-500-2016-068-APF

Appendix G – 2.2.1 Case Study of David Brower Center, Berkeley, California
Publication Number: CEC-500-2016-068-APG

Appendix H – 2.3.1 Sacramento Municipal Utility District (Smud) East Campus Operations Center, Sacramento, California
Publication Number: CEC-500-2016-068-APH

Appendix I – 2.4.1 Cooling Load Calculations for Radiant Systems
Publication Number: CEC-500-2016-068-API

Appendix J – 2.4.2 Experimental Comparison of Zone Cooling Load Between Radiant and Air Systems
Publication Number: CEC-500-2016-068-APJ

Appendix K – 2.5.1 David Brower Center - Building Performance Simulation
Publication Number: CEC-500-2016-068-APK

Appendix L – 2.5.2 Effects of Furniture and Contents on Peak Cooling Load
Publication Number: CEC-500-2016-068-APL

Appendix M – 2.6.1 Radiant Slab Systems for Zero-Net-Energy (ZNE) Buildings: Advantages and Differences From Air Systems
Publication Number: CEC-500-2016-068-APM

Appendix N – 3.1.3 Modeling the Comfort Effects of Short-Wave Solar Radiation Indoors
Publication Number: CEC-500-2016-068-APN