Title
Field Study of Capitol Area East End Complex (CAEEC) Sacramento, California

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Field Study of Capitol Area East End Complex (CAEEC)
Sacramento, California

Final Report
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The earlier stages of this work was also partially supported by the California Energy Commission Public Interest Energy Research (PIER) Buildings Program under Contract 500-10-048 (CIEE sub-award POEF01-B05). We would like to thank Chris Scruton, former project manager from the Energy Commission PIER Buildings Team.

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1 EXECUTIVE SUMMARY

The energy and comfort performance of buildings using underfloor air distribution (UFAD) has been of interest, with some contention, in the building industry for many years. It is not often that an opportunity to address that question directly appears. This project represented such an opportunity to compare and contrast two similarly designed buildings in the same climate and co-located near one another, both occupied by California state employees, one with a UFAD system (B225) and the other with an overhead (OH) variable air volume (VAV) system (B172). At the outset there was hope that we could settle the question definitively due to the highly instrumented systems in these buildings that afforded an opportunity to use measured data for the comparison. This report contains a detailed description of the measured data and simulated analyses used to compare the energy performance of UFAD vs. OH systems, and a summary of the post occupancy evaluations (POE) used to study and compare the occupant satisfaction and indoor environmental quality (IEQ) of both buildings. In addition, we report on field measurements conducted in B225 to investigate two key performance issues with UFAD systems: (1) room air stratification and (2) temperature gain in underfloor plenums.

The key findings from the study are listed here:

- The measured energy performance data indicates improved efficiency for the UFAD system (B225) vs. the OH system (B172), as annual cooling energy is 31% higher and total annual fan energy is 50% higher for B172 compared to B225.
- To account for all major design and operating differences between the buildings, we developed an alternative analysis method based on estimating the impact on B172 energy performance as if it was configured and equipped with central system equipment similar to B225; aka “apples to apples” comparison. When this “apples to apples” comparison method was applied, the total annual HVAC energy use (including cooling, heating, and fans) for OH (B172) is 20% higher than UFAD (B225) and total annual whole building energy use for B172 is 8% higher than B225.
- Based on the calculated Energy Star ratings, both B225 and B172 demonstrate excellent energy performance overall. B225 showed a very high site Energy Star rating of 98 and the Energy Star rating for the B171-174 complex (B172 could not be calculated separately) was 91, both well above the 75 required to receive the Energy Star label.
- The final POE surveys conducted during October 2007 in the two buildings found that the satisfaction ratings were generally positive and very nearly the same for most of the categories. An important lesson learned from the repeated surveys in B225 between 2003 and 2007 was the value of continuous commissioning of a building’s HVAC system. Efforts by building operations staff and the research team led to an improved understanding of the unique features of the UFAD system, and as a result, greater occupant satisfaction with the quality of the indoor environment in B225.

1.1 BUILDING DESCRIPTIONS

Block 225 is a six-story, 479,000 ft^2 (gross) office building in which UFAD is used exclusively on the top five floors. Conventional overhead air distribution is used on the ground floor. The first floor is comprised of many facilities, including the entrance lobby, postal service, conference room, and child care center while the second through sixth floors are primarily open plan offices for the state employees. The central HVAC system (air handling units (AHU), chillers, and cooling towers) is mounted in the 6th floor penthouse and serves floors two through six.

Block 172 is a six-story, 189,632 ft^2 (gross) office building equipped with a conventional overhead HVAC system with chilled and hot water supplied by the complex's central district heating and cooling plants. Similar to B225, the first floor contains a variety of spaces, including lobby, theater, and classrooms. Floors two through six largely feature open plan offices of a similar design and layout as B225. Three packaged air-handling units are mounted on the roof and each is equipped with an evaporative cooling unit at the outside air intake.

The analysis techniques employed for this comparative study were aimed at overcoming the following challenges due to the fundamental differences between the two buildings.

- Building configuration – B172, despite having an almost identical façade, lighting and furniture systems, has a far different configuration; long and narrow as opposed to almost square for B225. This has an impact on occupancy density and many other aspects of performance since the thermal loads (perimeter and interior) are significantly affected.
- HVAC plant and equipment – B172 does not have an onsite plant (chillers and boilers) as does B225. It draws cooling and heating from a central district plant servicing all four buildings of the 17x complex. B225 has an engineered built-up system while B172 has rooftop packaged air handling units. This results in large differences in equipment performance specifications; e.g., supply fan efficiency for B225 is significantly greater than B172.
- Controls – The building management system (BMS) for B225 is much more sophisticated and comprehensive than B172, which resulted in less detailed data being available for B172. As a result, a new set of power meters had to be installed in B172 to measure lighting and plug loads. On the other hand, the UFAD system required non-standard approaches to controlling the system at the zone level. This fact was responsible for long delays in getting the system to operate in a reliable and consistent manner and required a number of changes delays to occur in the earlier stages of this project.

1.2 ENERGY PERFORMANCE STUDY

We completed an extensive comparison of the energy performance of B225 and B172 in the Capitol Area East End Complex. We used a variety of methods and metrics, covering a range that included "as measured" data, Energy Star rating, and a modeling approach in which we attempted to adjust the various components and features of B172 to create a building that is as equivalent as possible to B225, with the exception of the HVAC system. In this way, we have estimated to our best ability the true difference in energy performance between a UFAD system in B225 vs. an overhead VAV system in an equivalent building.

The energy analysis methods relied on the following assumptions and techniques to estimate the impacts of the differences in performance of the HVAC system types, the main objective of the study: (1) employ a limited set of data that is most likely to cover consistent operation between the two buildings: e.g., occupied hours for weekdays only after significant commissioning had been complete; i.e., 2007-2008; and (2) use modeling techniques and estimated performance adjustments to revise B172 performance as if it included all the central

HVAC system characteristics of B225 (e.g., same on-site chilled water system, outdoor air system, air handler fans, equipment efficiencies, etc.), the same building configuration, and the same internal loads (occupancy, lighting, plug loads). A detailed description of these analyses are contained in Section 5 of this report.

Note that in all of the comparisons presented below, we use the energy performance of B225 as the reference or base case because of the much more detailed and higher quality trend data available for that building. Differences are reported as B172 compared to B225. Our major findings for each type of comparison made are summarized below.

1.2.1 Comparisons without heating

Due to the fact that the four B17x buildings in CAEEC (171, 172, 173, 174) are served by a district heating and cooling plant, we could not obtain boiler data for B172. In addition, secondary hot water flow was not instrumented at the building level making isolating heating energy measurements for B172 impossible**.** For this reason, we did not include heating energy in our comparison for "as measured" data collected from the two buildings. We also performed some modeling analysis to adjust B172 to be equivalent to B225 ("apples to apples" comparison) that in the first stages did not include heating. Heating was added to our modeling analysis towards the end and our findings are summarized below in Section 5.6.2.

- **As measured**: Based on monitored secondary cooling and fan energy use, the measurement data indicates improved efficiency for the UFAD system vs. the OH system, as cooling energy is 31% higher and total fan energy is 50% higher for B172 compared to B225. Total annual HVAC energy is 31% higher for B172 compared to B225, despite the fact that total internal load energy demand (lights and small power) is 13% less for B172 relative to B225. When HVAC and internal loads are combined, the total annual building electrical energy use for B172 is only 14% higher than B225.
- **Modeled equivalent central plant and fans**: In this first step towards our full "apples to apples" comparison, we estimated the impact of equalizing the components of the central plant and AHU of B172 with those of B225. Total annual building energy use for B172 is now 5% less than B225 while HVAC energy use for B172 is still estimated to be 9% higher than B225. These results indicate that the HVAC system in B225 performs better than in B172. Despite having lower internal loads (13% lower, same as in "as measured" above), B172 (with its overhead air distribution system) uses more HVAC energy compared to the UFAD system in B225, even when the central systems are equivalent.
- **"Apples to apples" without heating**: In this next step towards a full "apples to apples" comparison, we identified all major design and operating differences between the buildings, B225 vs. B172, and the HVAC systems, UFAD vs. OH. These factors included building configuration, occupancy, lighting and plug loads, thermostat setpoints, supply air temperature, and system type. When all of these additional adjustments to B172 were made, total annual HVAC energy use is 21% higher for B172 compared to B225, representing a sizeable difference. With the equivalent internal loads applied for this comparison, total annual building energy use is 7% higher for B172 compared to B225.

1.2.2 Comparisons with heating

Although we had unreliable heating data for B172 (see Appendix B), heating has been shown to be an important consideration for the performance of UFAD systems. In this section we present two comparisons between B225 and B172 that include heating. The first is our full “apples to apples” modeled comparison and the second is the Energy Star Rating.

- **“Apples to apples” with heating**: Due to the fact that UFAD typically has no heating in interior zones and there is less reheat than for OH, we have attempted to estimate its impact in order to provide a more complete comparison between the two systems. We derived heating energy (as described in Appendixes B and C) from “as measured” data for both buildings. However, this does not include the effects of configuration changes shown to be 31% in Table 5-4 for heating. When we apply this correction, B172 heating EUI for the “apples to apples” case is 14% greater than B225; total HVAC EUI including heating is 20% greater for B172 when it has a configuration like B225. Total annual building energy use is 8% higher for B172 compared to B225.
- **Energy Star rating**: Based on the Energy Star results, both B225 and B172 show excellent energy performance overall. B225 showed a site Energy Star rating of 98, well above 75 required to receive the Energy Star label; the associated site and source energy use intensities (EUI) are 43 kBtu/ft^2·yr and 130 kBtu/ft^2·yr, respectively. This is 38% better than of the national average EUI for buildings of this type and represents a very energy efficient building based on this metric of whole-building energy performance. Energy Star data for B172 could not be independently obtained since it is not separately metered from the B171-174 complex which is served by a central district heating and cooling system. The Energy Star rating for the ***entire complex*** was 91, which is close to the B225 score of 98. However, the site EUI is 83% greater for the B17x complex (61% greater on a source basis). The fact that the two ratings are so close together is a result of the Energy Star methodology and the substantial differences between B225 and the B17x complex.

1.3 OCCUPANT SATISFACTION

An important part of the field study methodology was to assess the building occupants’ opinions about the quality of their indoor working environment. To accomplish this, the research team conducted periodic surveys using the CBE web-based occupant satisfaction survey. Eight separate surveys were conducted over the course of the project, as follows: (1) B-225 – one baseline survey (prior to occupancy in their previous buildings) and four post-occupancy evaluations (POEs); and (2) B-172 – one baseline survey and two POEs. Each survey took approximately two weeks to complete with response rates near 50% for B-225 and 40% for B-172

As reported in Section 6, the two final POE surveys conducted during October 2007 in the two buildings found that the satisfaction ratings were generally positive and very nearly the same for most of the categories, indicating that occupants in both buildings had a similar response to their building and its indoor environment. While the research team had hoped to observe differences between the two buildings with their two different air distribution systems (UFAD and overhead), this did not prove to be the case for these survey questions. Given that all buildings in the Capitol Area East End Complex followed a standardized interior open plan office design criteria, and all occupants are State employees, it is not that surprising to see such similar results. B-225 did rate slightly lower for two categories: office layout and acoustic quality. We suspect that this difference was due to the higher occupant density in B-225 compared to B-172, which generally gave less space to each occupant and therefore reduced satisfaction with acoustic privacy in B-225. B-225 did demonstrate greater occupant satisfaction with cleanliness and maintenance.

Although the occupant surveys did not identify clear differences between B-225, the UFAD building, and B-172, the conventional overhead air distribution building, an important lesson learned from the repeated surveys between 2003 and 2007 is the value of continuous commissioning of a building's HVAC system. In the case of B-225, efforts by building operations staff and the research team led to an improved understanding of the unique features of the underfloor air distribution system, representing a new building technology in California State buildings, and as a result, greater satisfaction on the part of the building occupants with the quality of the indoor environment in B-225.

2 INTRODUCTION

Figure 2-1. Street view of Block 225

2.1 OBJECTIVE

The goal of this project was to study and compare the positive and negative impacts of underfloor vs. conventional air distribution for a range of whole-building performance metrics, including:

- energy use
- indoor environmental quality
- occupant satisfaction and comfort

The original scope of work was to conduct a field study of two office buildings, located in a large four-square block area directly east of Capitol Park in Sacramento, California, known as the Capitol Area East End Complex (CAEEC). At the outset of this project, the CAEEC contained five new office buildings that had been developed by the California State Department of General Services (DGS). The primary building of interest is a 6-story, 479,000-ft^2 gross floor area (336,000-ft^2 usable floor area) building on Block 225 (shown in Figure 2-1) that is using underfloor air distribution (UFAD) exclusively on the top five stories of the building. Conventional overhead air distribution is used on the ground floor. A second office building within the Capitol Area East End Complex, Block 172, uses a conventional overhead air distribution system throughout and was selected for comparison. Construction was completed and occupancy began in August 2002 for Block 225. Block 172, as well as the other three new buildings (Blocks 171, 173, and 174), were completed in March 2003. In the original field study plan, all occupants for both Blocks 225 and 172 were to be from the California Department of Education (CDE). However, due to the State budget crisis, the planned occupancy of Block 172 by CDE was reconsidered, and in early October 2003, it was learned that the Department of Health Services (DHS) would be the new occupant of Block 172. (Hereafter in this report Block 172 and 225 will be referred to as B172 and B225, respectively.)

2.2 ORGANIZATION OF FINAL REPORT

The following is a summary of the material contained in the sections of this final report.

Section 1, Executive Summary, provides an overall summary of the final report.

Section 2, Introduction, presents the objective and organization of the final report.

Section 3, Building Descriptions, presents a general description of the design and layout of the two buildings studied in this project.

Section 4, Project Timeline and Building Performance Measurements, summarizes a chronology of the project activities and describes instrumentation, methods and results from several field measurement studies to investigate room air stratification and temperature distribution in the underfloor plenum in B225.

Section 5, Whole-Building Energy Analysis, presents a detailed comparison of the energy use for B225 with its UFAD system vs. B172 with its overhead (OH) VAV air distribution system. The comparison is based on both measured data and modeled components and factors to account for key differences in design and operation between the two buildings.

Section 6, Occupant Satisfaction Survey, presents results from the two baseline surveys (one for each building) and subsequent post-occupancy evaluation (POE) surveys, four in B225 and two in B172.

Section 7, Summary and Conclusions, provides overall conclusions for the project. Also included are lessons learned about UFAD systems from our experiences in B225, and a set of recommendations for the design and operation of future UFAD projects based on this field study and the authors experience.

The following is a summary of the material contained in the appendixes, which are included in a separate document to this final report.

Appendix A, Cx Cart Hardware and Specifications, provides a description of the portable measurement cart that was used by CBE researchers during commissioning related activities.

Appendix B, Data Processing and Component Modeling, describes the methods used to manage the large amounts of building performance trend data collected from the building management systems (BMS) from both buildings. This involved cleaning up erroneous data and filling in missing values so that the data could be properly applied to our detailed analyses. It also describes the models used to simulate HVAC equipment at B172 which were provided by the 17x complex central plant.

Appendix C, "Apples to Apples" Methodology, describes the methods employed to estimate the adjustment factors we used to bring the design and operation of B172 into compliance to B225 so that an "apples to apples" comparison can be made between UFAD and OH systems.

Appendix D, Energy Star Rating Data Sheets for B225 and B172, presents copies of the detailed data sheets describing the Energy Star ratings for both buildings as presented in Section 5.5.

Appendix E, Taylor Engineering Final Punch List, presents a copy of the final punch list from Taylor Engineering at the end of the project in 2007.

Appendix F, Response from Operators, presents a copy of the final list of known responses by the building operators at the end of the project in 2007.

3 BUILDING DESCRIPTIONS

3.1 GENERAL OVERVIEW

Figure 3-1 shows an overview of the CAEEC project with the subject buildings highlighted. Table 3-1 and Table 3-2 provide basic information about the two buildings. For Block 225, underfloor air distribution (UFAD) is used exclusively on the top five floors of the 6-story building. Conventional overhead air distribution is used on the ground floor. The central HVAC system (air handlers (AHU), chillers, and cooling towers) is mounted in the 6th floor penthouse. The first floor is comprised of many facilities, including the entrance lobby, postal service, conference room, and child care center while the second through sixth floors are primarily open plan offices for CDE employees. Figure 3-2 is a photo of the front entrance and Figure 3-3 is an illustration of Block 225. In January 2003, Block 225 was certified by the U.S. Green Building Council (USGBC) as Leadership in Energy and Environmental Design (LEED™) Gold 2.0 for its sustainability features, such as energy efficient operation, selection of sustainable building materials, and good indoor air quality. The building received 43 documented and approved points to achieve this LEED certification. A detailed summary of the many sustainability features are contained in an article in ASHRAE's High Performing Buildings magazine [Fentress et al. 2009]. Table 3-3 provides a list of the awards received by Block 225 during the period 2001-2003.

Block 172 is equipped with a conventional overhead HVAC system with chilled and hot water supplied by the complex's central district heating and cooling plants. Two modular air-handling units are mounted on the roof and each is equipped with an evaporative cooling unit at the outside air intake.

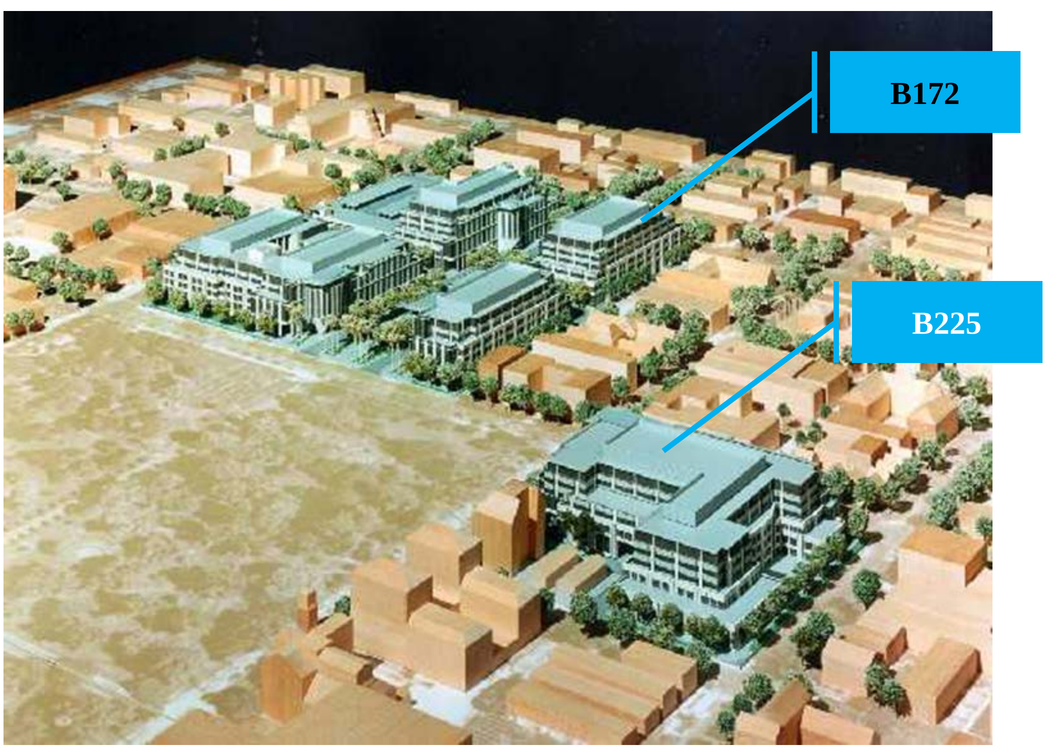

Figure 3-1. Project overview

Table 3-1. Description of Block 225 building

Project Name	Capital Area East End Complex, Block 225
Location	1430 N Street, Sacramento, California 95814
Building Type	Office building, with day care, restaurant, & parking
Floor Area	479,000 ft^2 gross (usable building floor area: 336,000 ft^2)
Number of Stories	6 above grade, 1 below grade
Owner	Department of General Services, State of California
Occupant	Department of Education, State of California
General Contractor	Hensel Phelps Construction Company
Architect	Fentress Bradburn Architects
Commissioning Agent	SMWM
Mechanical/UFAD Design Builder	Critchfield Mechanical, Inc.
Energy Systems Mechanical Designer	Taylor Engineering
Mechanical Controls	Yamas/Controlco Controls, Inc.
Construction Period	26 months

Table 3-2. Description of Block 172 building

Project Name	Capital Area East End Complex, Block 172
Location	1500 Capitol Avenue, Sacramento, California 95814
Building Type	Office building, retail and parking
Floor Area	189,632 ft^2 gross (usable building floor area: 122,692 ft^2)
Number of Stories	6 above grade, 1 below grade
Owner	Department of General Services, State of California
Occupant	Department of Health Services, State of California
General Contractor	Hensel Phelps Construction Company
Architect	Fentress Bradburn Architects
Commissioning Agent	SMWM
Mechanical/UFAD Design Builder	WSP Flack and Kurtz
Energy Systems Mechanical Designer	WSP Flack and Kurtz
Mechanical Controls	Honeywell Controls, Inc.
Construction Period	26 months

Table 3-3. Awards list of Block 225

CAPITOL AREA EAST END COMPLEX BLOCK 225	
Year	Award
December 1, 2003	Contracting Business Magazine 2003 Design/Build Awards - New Construction over $2 million Category
November 17, 2003	CAL EPA Governor's Environmental and Economic Leadership Awards (GEELA) - Sustainable Facilities Category
October 9, 2003	Design-Build Institute of America (DBIA) Public Sector Building over $15 million Design-Build Excellence Award
2003	Building Design & Construction (BD&C) Building Team Project of the Year Award

	2003 Merit Award Institutional Category
April 5, 2003	The Associated General Contractors (AGC) California Constructor Award Innovation in Construction Techniques or Materials
January 28, 2003	US Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) Gold Certification
2003	Pacific Coast Builder's Conference Gold Nugget Merit Award Best Office/Professional Building - 60,000 ft^2 and Over
2003	Pacific Coast Builder's Conference Gold Nugget Merit Award Sustainable Non-Residential Project
December 2002	California Construction Link Best of California 2002
December 20, 2002	Western Council of Construction Consumers Distinguished Project Awards Program
April 2001	Disabled Veteran Business Enterprises (DVBE Participation) The John K. Lopez Award Keeping the Promise

3.2 BUILDING DESIGN AND LAYOUT

Figure 3-2. B225 entrance photo

Figure 3-3. Illustration of B225

3.2.1 Floor plans and layouts

Figure 3-4 and Figure 3-5 show typical floor layouts for B225 and B172, respectively. Note the distribution "air highway" ductwork for the underfloor system in Figure 3-4. This represents an array of large ducts located in the underfloor plenum that are used to help distribute the supply air from the three central air handlers more uniformly across the floorplate of the building. Also indicated in Figure 3-4 are zone thermostat locations and underfloor pressure sensor locations. For comparison, one can see in Figure 3-5 the extensive and complicated arrays of overhead ductwork (in blue) that deliver supply air to all zones across the floorplate in B172.

Figure 3-4. B225 4th floor plan

Figure 3-5. B172 4th floor plan

3.2.2 Interiors

Both Block 225 and Block 172 have virtually identical interior designs and layouts, albeit with different floor plate sizes and aspect ratios. These are open plan arrangements with some private offices and conferences rooms. Workstations are typical "pod" configurations with powered furniture partitions. Overhead lighting is direct-indirect suspended fixtures supplemented by workstation task lighting. Figure 3-6 through Figure 3-10 show typical interior details of B225; open plan and perimeter offices are similar for B172.

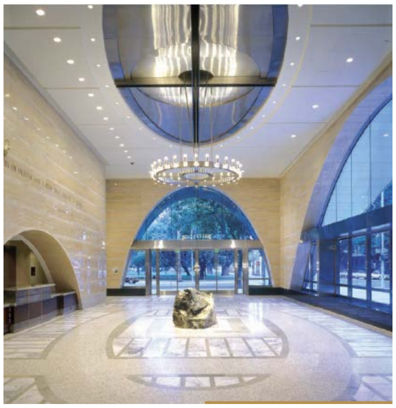

Figure 3-6. B225 lobby; image courtesy of High Performing Buildings

Figure 3-7. Typical open plan layout for both Block 225 and 172

Figure 3-8. Typical interior workstation

Figure 3-9. Typical perimeter workstation

Figure 3-10. Typical interior cubical layout

3.2.3 HVAC

As noted previously, the HVAC systems are different between B225 and B172. B172 uses a conventional overhead (OH) variable air volume (VAV) system with zone VAV boxes supplied from two penthouse packaged air handling units (AHU). Chilled and hot water are supplied from a district heating and cooling system that supplies the four buildings in the 17x complex. The penthouse units outside air system are equipped with evaporative cooling units.

B225 on the other hand, is a UFAD system with swirl floor diffusers (by Nailor) in interior zones supplied and controlled by varying the pressure in the underfloor plenum in response to interior zone thermostats. The plenum pressure is controlled by spin-in dampers mounted at approximate 30-ft intervals along the sidewalls of an air highway distribution system (see Figure 3-11 and Figure 3-12). Perimeter zones are supplied by variable speed fan coil units (by Greenheck) that draw air from the supply plenum and discharge through sill mounted diffusers (by Titus) mounted at the windows. Figure 3-13 is a photo during construction of B225 showing one of the perimeter fan-coil units connected by ductwork up through the exterior wall to the window sill diffusers. Cooling and heating are provided by central plant chillers and boilers located in a penthouse above the 6th floor; air is supplied by three AHUs that provide air at three core locations connected to the air highway system. A detailed accounting of the differences between these systems is presented and discussed in Section 5.

Figure 3-11. Photos of typical spin-in dampers mounted in air highway walls

Figure 3-12. Spin in damper

Figure 3-13. Perimeter fan-coil unit connected to window sill diffusers

3.2.4 Building Management Systems (BMS)

Both buildings are equipped with direct digital control building management systems comprised of digital controls down to the zone level, lighting control systems (including diming capability in B225), and card access systems. B225 uses an Invensys system based on Tridium; the Invensys system was upgraded to a Controlco Vykon system in 2007. B172 uses a Honeywell Excel 1000 system. Figure 3- and Figure 3- shows a screen shot of the frontend workstation for B225.

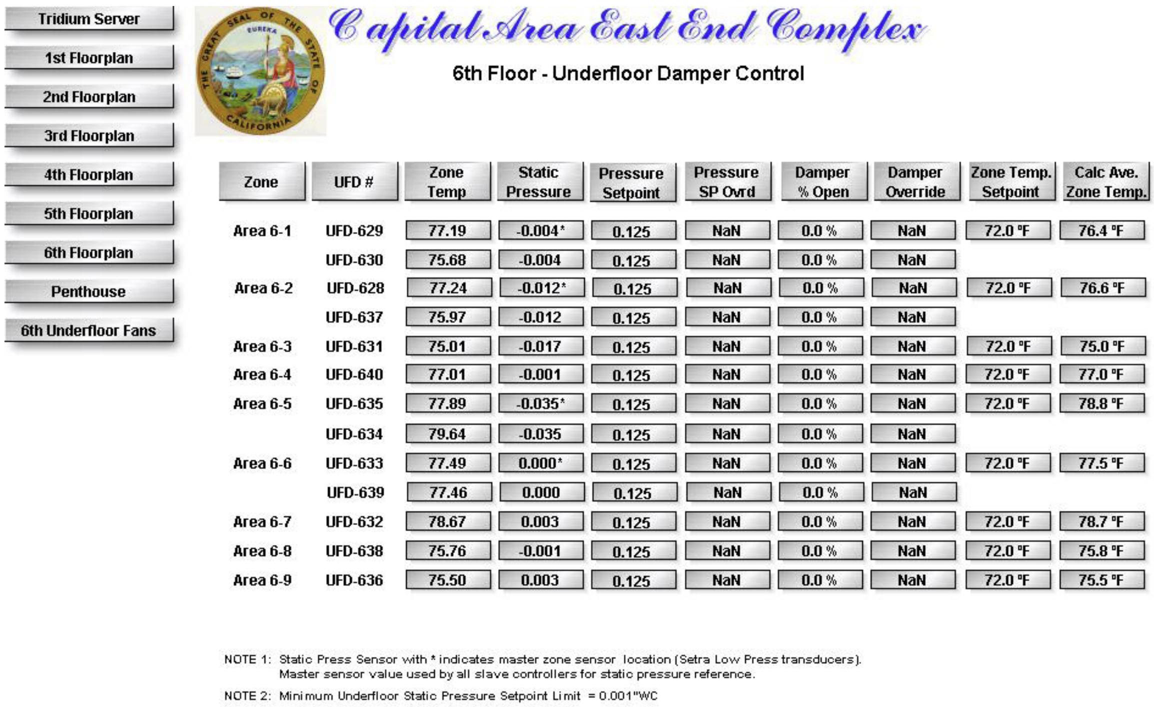

Figure 3-14. Screen shot of B225 BMS frontend showing an example of zone operation data for the 6th floor

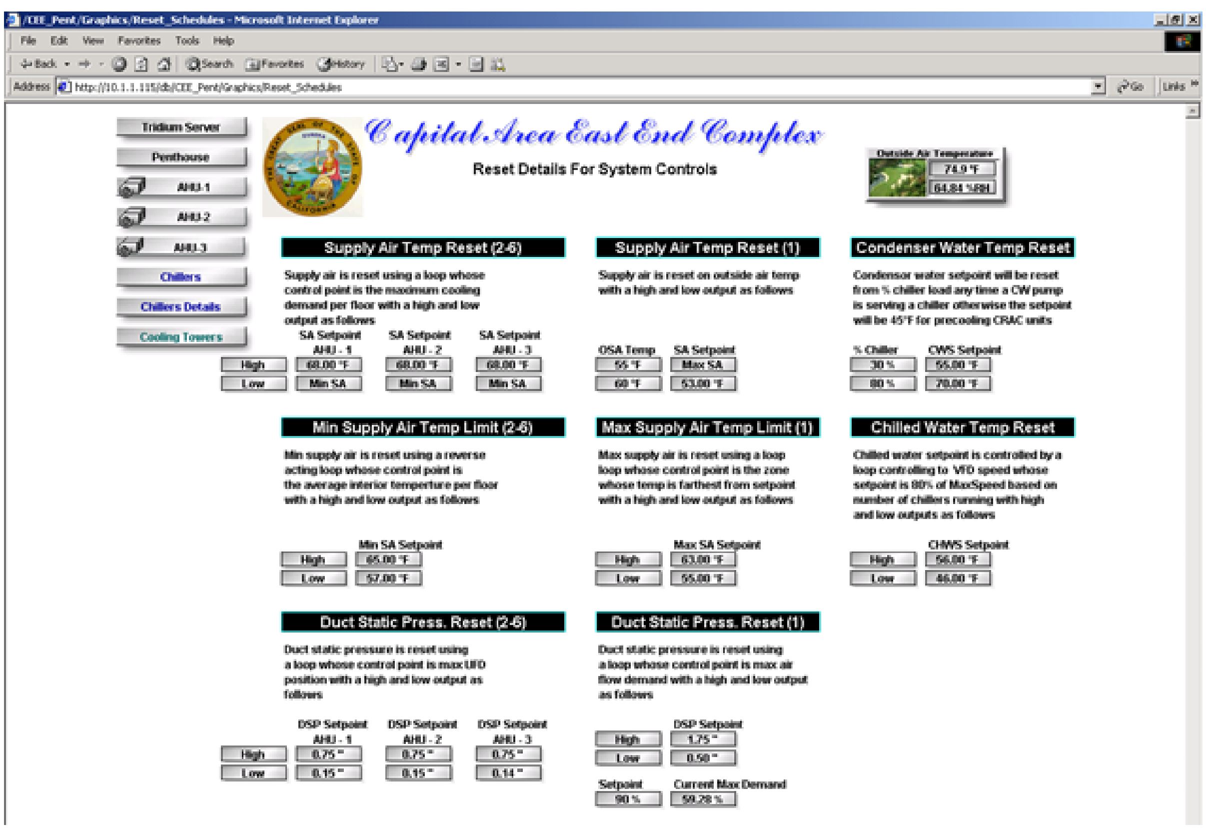

Figure 3-15. Screen shot of B225 BMS frontend showing central system operational data

4 PROJECT TIMELINE AND BUILDING PERFORMANCE MEASUREMENTS

4.1 PROJECT ACTIVITIES SUMMARY

Spanning several years from the date of occupancy (July 2002), this project encountered numerous commissioning (Cx) related issues that required on-going support from CBE to conduct the assessment contained in this report. A timeline of the major project activities is shown in Table 4-1. Included is a summary of HVAC upgrades, occupancy changes, occupant survey instances, Cx activities, and field measurement activities.

Table 4-1. Project timeline for East End field study

Date	Code*	Description	Notes
October 2001	Adm	Project start	CBE contract with DGS
January/February 2002	Surv	B-225 baseline survey	Surveyed Calif. Dept. of Education (CDE) workers in 6 existing buildings who will move into B-225
June 2002	Meas	Acoustical study of baseline buildings	Acoustical testing in open plan workstations
July 2002	Occ	B-225 occupancy Deploy Hobo data logger strings to measure stratification	Approximately 1,100 CDE employees moved into B-225
September 2002	Surv	2nd B-225 baseline survey	Surveyed CDE workers in 5 existing buildings who will move into B-225. Originally, these people were targeted to move into B-172, but changed to B-225.
October 2002	Adm	Project extension	CBE contract with DGS
November 2002	Meas	B-225 plenum thermal decay study	40 HOBO temperature loggers in 4th floor underfloor plenum
January/February 2003	Surv	1st B-225 POE	1st post-occupancy evaluation (POE) survey of CDE workers in B-225
July – September 2003	Cx	Installed underfloor ductwork at selected locations and completed programming of full set of trend logs	Ductwork was installed to address thermal decay at key perimeter zone conference rooms
October 2003	Adm	Project extension	CBE contract with DGS
August 2003 – March 2004	Meas	B-225 plenum thermal decay study	83 HOBO temperature loggers in 4th floor underfloor plenum

November 2003	Surv	B-172 baseline survey	Surveyed Calif. Dept. of Health Services (DHS) workers in 2 existing buildings who will move into B-172
December 2003	Occ	B-172 occupancy	Approximately 530 DHS employees moved into B-172
December 2003	Occ	B-225 move-in	Approximately 250 additional CDE employees moved into B-225
February 2004	Surv	2nd B-225 POE	2nd post-occupancy evaluation (POE) survey of CDE workers in B-225
September 2004	Cx	B-225 – Installed new pressure sensors (all floors) and updated controls (4th floor)	New pressure sensors allowed improved control at low plenum pressures.
October 2004	Adm	Project extension	CBE contract with DGS
April 2005	Surv	Thermostat comfort survey in B-225	Short-term comfort survey of 3rd and 4th floor occupants in response to thermostat setpoint changes
October 2005	Adm	Project extension	CBE contract with DGS
October 2005	Surv	3rd B-225 POE	3rd post-occupancy evaluation (POE) survey of CDE workers in B-225
October 2005	Surv	1st B-172 POE	1st post-occupancy evaluation (POE) survey of DHS workers in B-172
May 2006	Cx	B-225 – Updated control software for selected UFFs and UFDs on 4th floor	Tried to address overheating in perimeter conference rooms by opening nearby dampers (UFDs) on call for cooling by perimeter fan unit (UFF)
August 2006	Cx	B-225 and B-172 – new web server, control software and trend log programming	Trend logs of all desired measurement points were finally accessible via the web server
August 2007	Cx	B-225 – Installed plenum dividers and updated controls and raise cooling setpoints to 74°F	New plenum dividers created smaller controls zones within plenum. Some new pressure sensors, thermostats, and

			control logic were added to allow control of these zones.
September 2007	Meas	B-225 – measured room air stratification and underfloor plenum performance using mobile measurement cart	Commissioning cart measurements were taken to evaluate the impact of recently installed plenum dividers on system operation
October 2007	Surv	4th B-225 POE	4th post-occupancy evaluation (POE) survey of CDE workers in B-225
October 2007	Surv	2nd B-172 POE	2nd post-occupancy evaluation (POE) survey of DHS workers in B-172

*Adm = project administration; Cx = commissioning; Meas = field measurements; Occ = building occupancy changes; Surv = occupant satisfaction survey

4.1.1 Taylor engineering commissioning studies

Taylor Engineering served as the commissioning consultant for energy performance analysis. Several studies were conducted to analyze building operation and diagnose problems related to energy performance. Appendix E contains the final punch list for outstanding items as of July 2007.

4.2 BUILDING PERFORMANCE MONITORING

4.2.1 Trend log data from building management systems (BMS)

Several sources of data (besides the occupant surveys) are used for the energy comparison analysis. For B225, extensive trends logs were available due to the detailed monitoring system embedded in the BMS and made available by the Vykon monitoring system. This data included detailed end-use monitoring data. CBE supplemented this data using Hobo data loggers and the commissioning cart (see below).

B172 data was available via the Honeywell system, but the number of monitored points were significantly fewer than for B225. For example, not all of the VAV boxes were monitored, only those considered “representative,” and for these, no setpoints were logged. Additional power meters were installed to capture lighting and plug loads. Plant end-use data was not useful since the central district heating and cooling plant supplied four buildings concurrently. However, secondary chilled water was available due to water flow measurements on the chilled water supply to the building.

Utility data was available for both buildings and was used primarily for the Energy Star reports, but for the 17x complex, it was only available for the central plant serving all four buildings.

4.2.2 Early hobo tests of plenum and stratification thermal performance

In July of 2002, measurements using strings of Hobo data loggers provided early information about stratification and plenum thermal distribution.

4.2.2.1 Stratification

Figure 4-1 through Figure 4-4 show photos of how each stratification string was positioned in the office space. Figure 4-5 plots the locations of the strings on the floorplate illustration (as well as results of selected diffuser temperature measurements as measured by Hobos placed in the diffusers).

Figure 4-1. Red string in interior

Figure 4-2. Blue string in perimeter

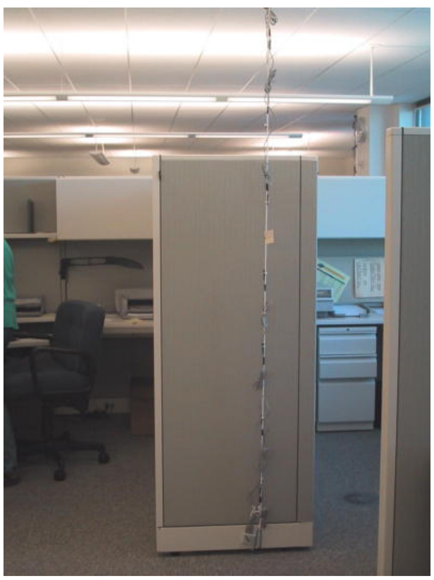

Figure 4-3. Green string in perimeter

Figure 4-4. Yellow string in conference room

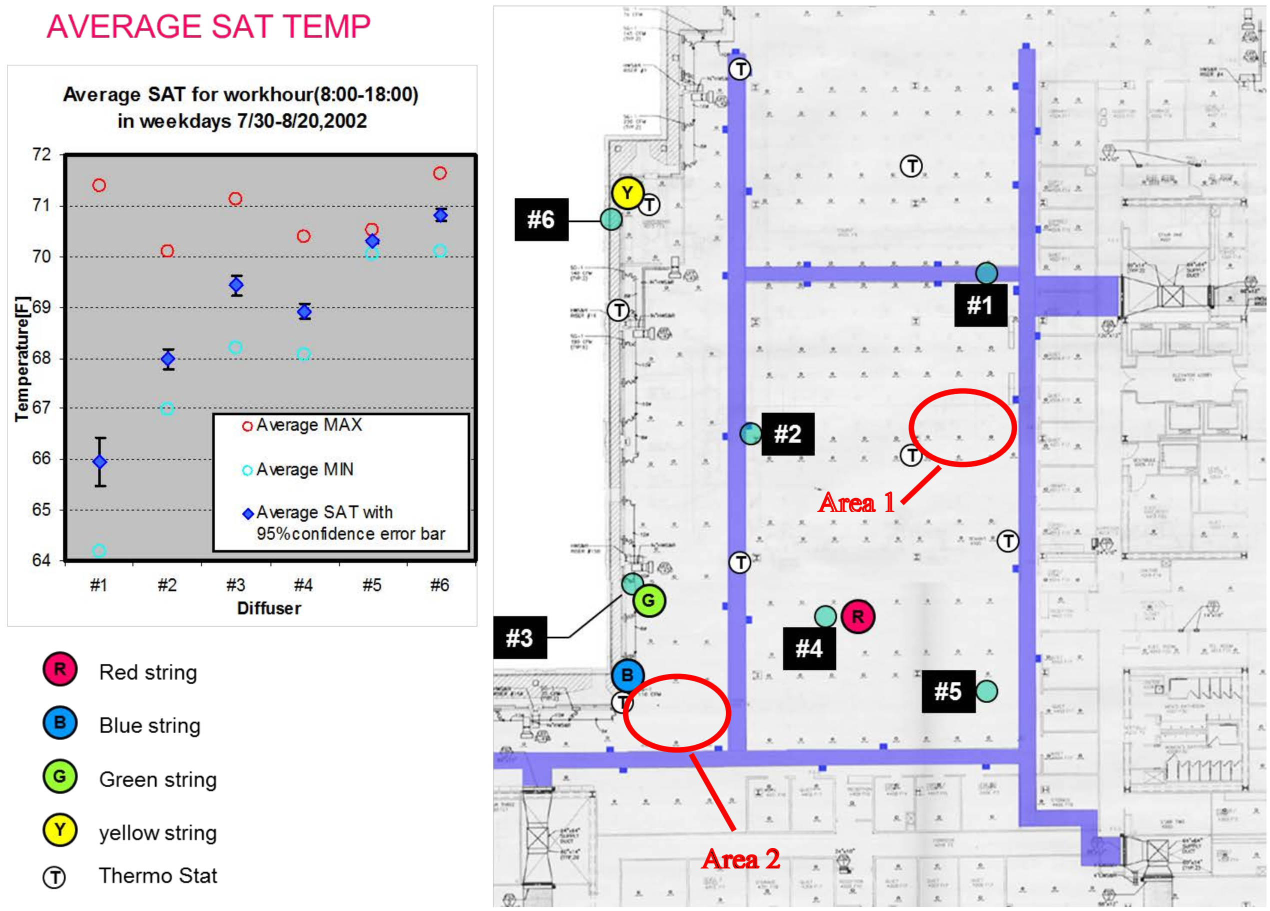

Figure 4-5. Hobo plenum and stratification logger locations

Figures 4-6 through 4-8 show results of stratification measurements for interior, perimeter, and perimeter conference room, respectively. Note that stratification is very low.

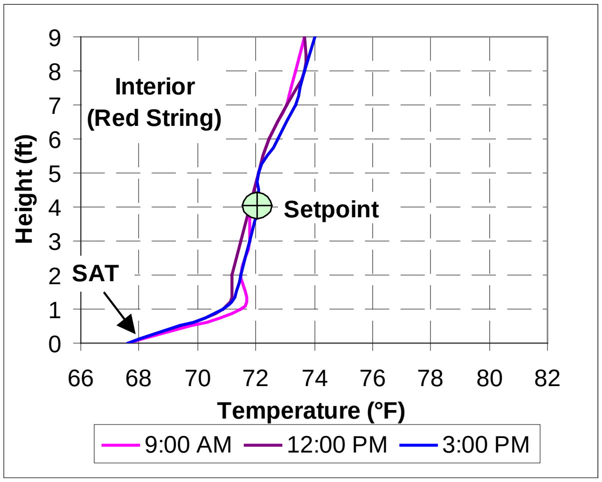

Figure 4-6. Typical interior zone

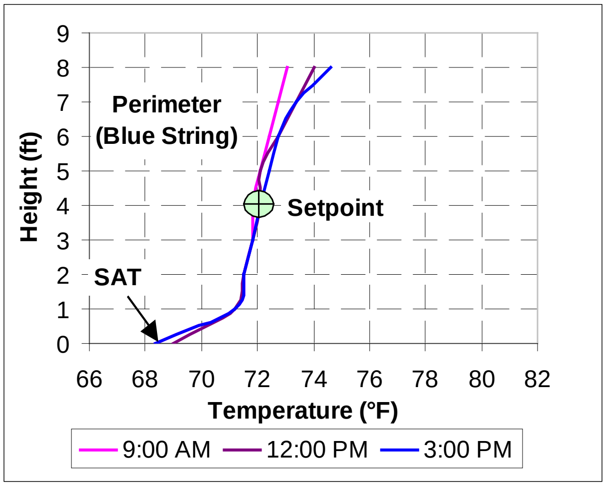

Figure 4-7. Typical perimeter zone

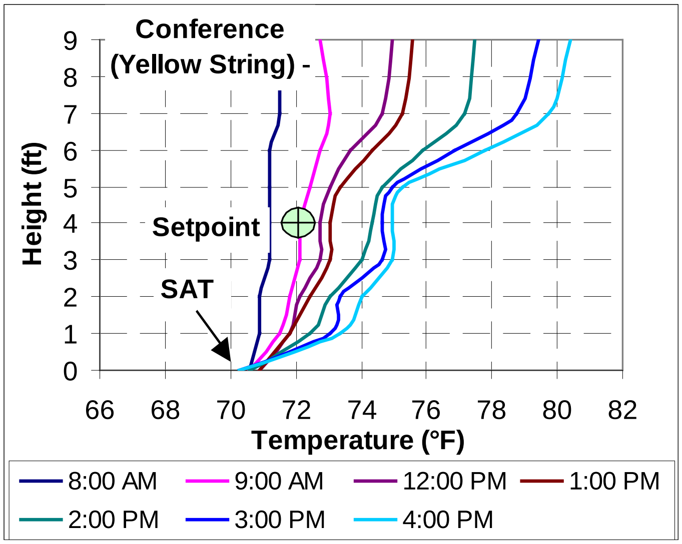

Figure 4-8. Typical conference room-west zone, unoccupied

The conference room results shown in Figure 4-8 above illustrate how the stratification can change with time of day (i.e., load conditions). In this west conference room zone, there was considerable afternoon gain causing the airflow to increase, but contrary to what we expect, the stratification also increases. This is most likely due to the fact that air is supplied only via swirl diffusers. Since the throw of these diffusers is much lower than linear bar grilles, mixing is reduced and higher stratification results; in the afternoon it reaches levels of 5-6°F. These results are consistent with those from Cx cart measurements (see Figure 4-13 through Figure 4-15), except for the unusual (i.e., swirl diffusers in perimeter zone) case of the perimeter conference room.

4.2.2.2 Plenum temperature distribution

1. First field measurements: November 2002

Initial measurements of plenum thermal distribution were made with Hobo loggers in November 2002 on the west side of the fourth floor. Data were analyzed for work hours (8:00 am to 6:00 pm) and work days (Monday through Friday) only. Table 4-2 summarizes the major findings. The results indicate that sizeable temperature variations do occur at certain times. Under typical operating conditions, the largest measured variations within the plenum (~5°F) usually occurred in the mid-afternoon (3-5 pm). Also, it was observed that the warmest plenum temperatures were typically encountered at certain locations within the interior zone, while the coolest plenum temperatures were usually found in the perimeter zone and/or near a plenum inlet location. Figure 4-9 presents a color contour plot of the temperature distribution within the plenum on the day (November 21 at 4:00 pm) when the maximum temperature difference was observed. The two locations having the maximum and minimum temperatures are indicated in Figure 4-5 as Areas 1 and 2, respectively.

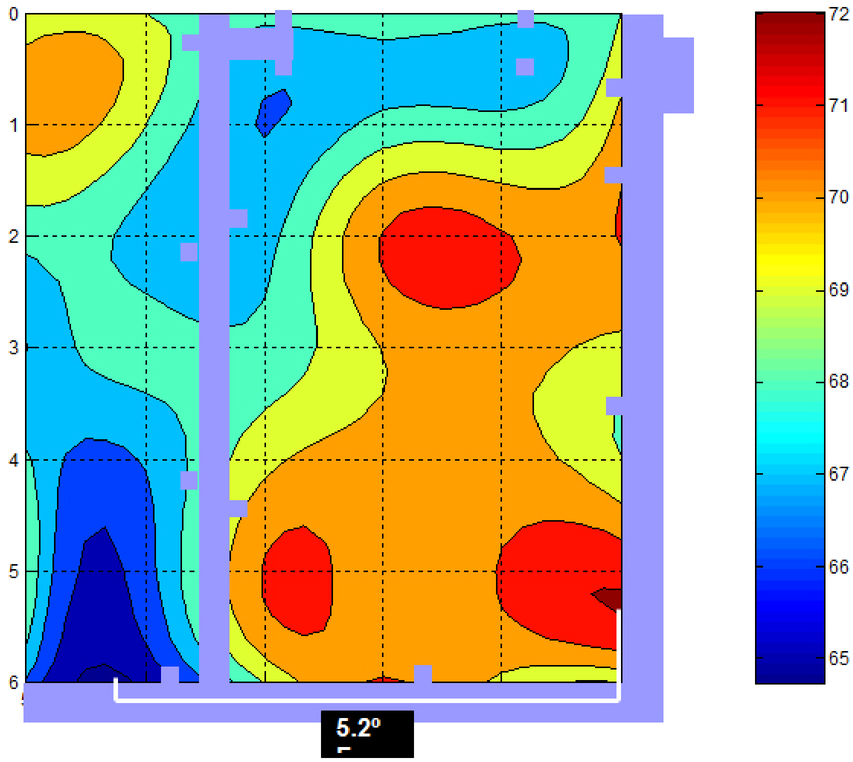

Figure 4-9. Image of plenum thermal distribution

Table 4-2. Plenum thermal distribution example characteristics

Measured Variable	
Plenum Temperature	Average over the period: 69.5°F [coldest day: 68.18°F , warmest day: 70.7°F]
Maximum temperature difference within the plenum	5.2°F (see Figure 4-9)
Supply Air 1 operation	Average : 67.4°F [Min : 63.5°F , Max : 70.0°F]
Supply Air 2 operation	Average : 66.3°F [Min : 63.2°F , Max : 71.8°F]
Outside air temperature	42.9°F < 52.0°F < 61.1°F

2. Second field measurements: August 2003

On August 29, 2003, we deployed 83 Hobo temperature loggers at selected locations within the underfloor plenum all over the 4th floor of Block 225. The purpose of these measurements was to record the temperature variations that occurred within the plenum during normal operation. The plenum area monitored included both interior and perimeter zones. These Hobos were kept in place over several months. Periodically, CBE researcher visited the building to download data and re-start the Hobos since their data capacity is set to 55 days.

The measurements were conducted on the 4th floor of Block 225 (as shown in Figure 4-10). Green dots indicate Hobo placement within the plenum. Each Hobo was placed on the slab. Plenum inlet temperatures were also measured at selected locations along the air highways (indicated as red dots) by placing Hobos into the damper-controlled stub-outs that supplied air from the air handlers into the plenum.

Measurements were conducted during three periods shown in Table 4-3.

Table 4-3. Plenum temperature measurement periods

Period	Dates
1st	Aug. 29 to Sept. 30, 2003
2nd	Oct. 3 to Nov. 23, 2003
3rd	Dec. 11, 2003 to Feb. 3, 2004

Figure 4-10. Plenum temperature measurement locations: Block 225, 4th floor

Table 4-4 summarizes the major findings for each of the three monitoring periods. The results indicate that sizeable temperature variations do occur at certain times. Under typical operating conditions, the largest measured variations within the plenum (around 8 to 9°F) usually occurred near lunchtime (12:00 pm –1:00 pm). On some occasions, the temperature difference within the plenum exceeded 10°F (often observed in the early morning at 8:00 am). The highest measured plenum temperatures typically occurred at the northeast corner near a large conference room that often experienced overheating problems. The coolest plenum temperatures were often measured at the opposite southwest corner of the building in the vicinity of the plenum supply inlet locations. Other than these two locations, the temperature difference observed in the plenum remains in the range of 4 to 7°F. Figure 4-11 presents a series of color contour plots showing the progression of plenum temperature distributions during the course of the day from 8 am to 6 pm in 2 hour intervals. One Thursday was selected from each of the three different monitoring periods (September, November, and January) to be consistent and comparable. Please refer to the temperature scale shown on the right-hand side of Figure 4-11 to read these plots. The plots show plenum temperature distributions for the warm season (September) and cold season (other three months). In September the plenum is kept cool below 67°F most of the time, to handle the higher cooling load in the building during the warm weather. Plenum temperatures during the other months are warmer, with most temperatures above 68°F.

One other observation has to do with the relatively warm temperatures that were measured on average in the plenum. As shown in Table 4-4, the average supply air and plenum temperatures were often higher than those that are commonly specified during design for UFAD buildings (e.g., 61-65°F). Given the cool space temperatures that were measured and the number of occupant comments about cool conditions obtained in the surveys, this suggests that the cooling load in the space is quite low. The energy efficient building façade and efforts to minimize internal loads (e.g., efficient lighting design) may have contributed to this result.

Table 4-4. Results of plenum temperature analysis [8:00am to 6:00pm, Workdays]

Measured Variable	1st 8/29 to 9/30 2003	2nd 10/3 to11/23 2003	3rd 12/11 to 2/3 2004
Average plenum temperature	67.8°F	68.4°F	68.5°F
Warmest measured temperature	77.3°F	78.7°F	77.3°F
Coldest measured temperature	59.4°F	56.0°F	62.2°F
Highest average	72.8°F	75.0°F	71.1°F
Lowest average	66.0°F	65.6°F	65.3°F
Temperature difference within the plenum	Average : 7.5°F [Max : 13.7°F, Min : 3.4°F]	Average : 6.4°F [Max : 14.4°F, Min : 1.4°F]	Average : 5.6°F [Max : 13.8°F, Min : 2.7°F]
Warmest supply air temperature	Average : 68.5°F [Max : 73.2°F, Min : 60.8°F]	Average : 69.1°F [Max : 73.8°F , Min : 62.9°F]	Average : 68.7°F [Max : 71.1°F , Min : 64.2°F]
Coldest supply air temperature	Average : 63.8°F [Max : 74.5°F, Min : 60.8°F]	Average : 65.3°F [Max : 77.3°F, Min : 60.1°F]	Average : 66.1°F [Max : 70.4°F, Min : 62.2°Fv]

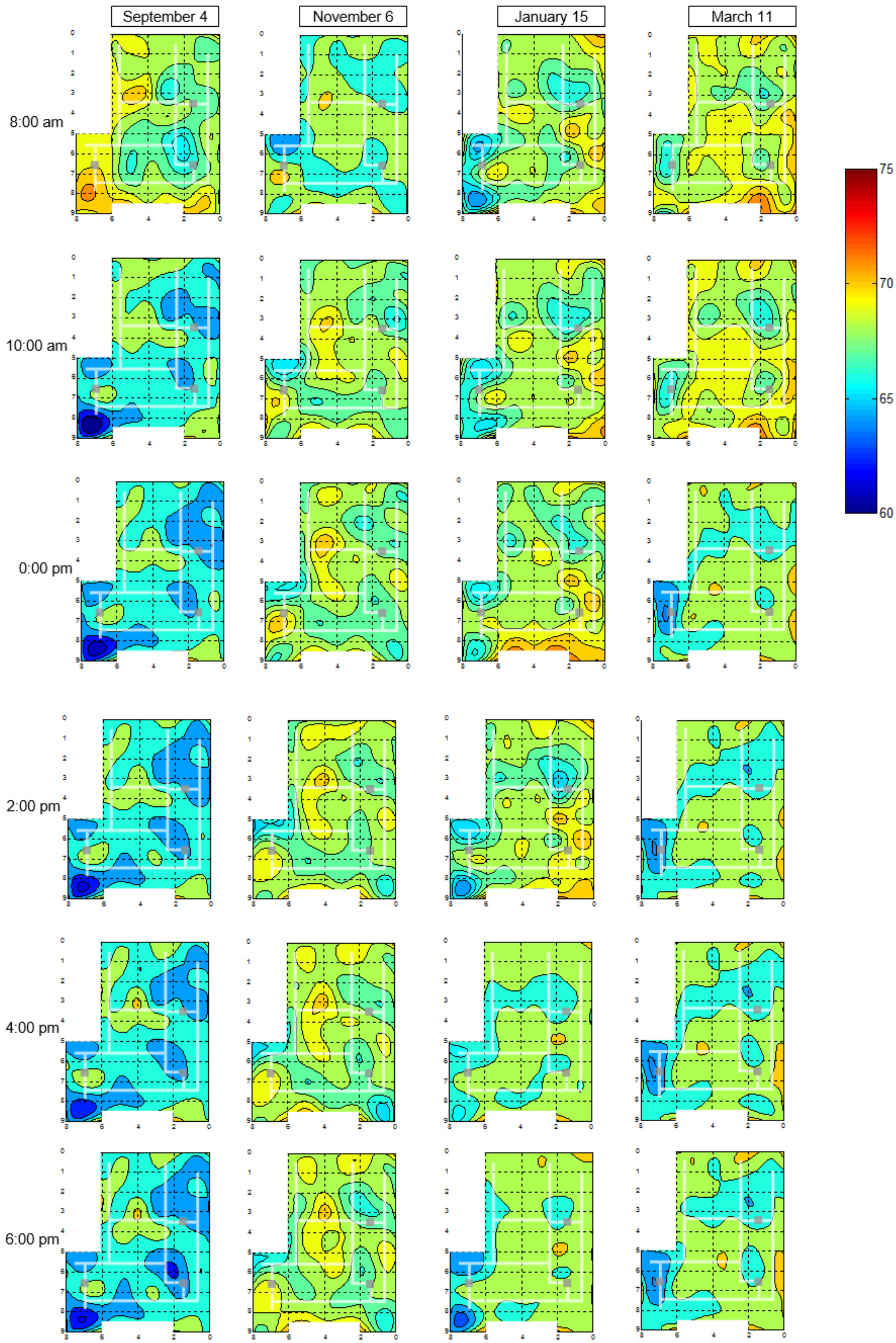

Figure 4-11. Plenum Temperature Contour Maps every 2 hour from 8:00am to 6:00pm

4.2.3 UFAD commissioning (Cx) cart measurements

In the latter stages of the project (~2007) stratification and plenum distribution measurements were greatly facilitated by using the UFAD commissioning cart developed by CBE under contract to the New York Times. A detailed description of the cart is contained in Appendix A. Photos shown in Figure 4- show the cart being used in B225.

Figure 4-12. Cx cart in use

4.2.3.1 Stratification

Figure 4- through Figure 4- show typical stratification profiles measured by the Cx Cart on the 4th floor in September 2007. Each figure contains a number of profiles measured over a certain area ~10 minutes apart. The thick white line shows the average of all the profiles measured for the given area. Interior zones, which use swirl diffusers, are consistent across the floorplate. The greatest variation occurs in the perimeter zone where in some cases the throw from the diffuser is so high that it strikes the ceiling causing the profile to bend backwards at the top. This is a common occurrence for profiles from linear bar grilles. Little stratification (i.e., the temperature difference between 4 and 67 inches from the floor) is developed in any of these cases, ~1-2°F. “Good” stratification is considered to be in the range of 3-5°F.

Note one difference between these profiles and those from the earlier Hobo loggers is the change in setpoint (i.e., temperature at 48 inches). In August 2007 the cooling setpoints were increased from 72 to 74°F.[1] This is reflected when the Hobo logger figures (see Figure 4-1 above) are compared to the Cx Cart figures; the occupied zone temperatures are greater in 2007. Since increasing the setpoint tends to lower the airflow, we would expect the stratification to increase, but this is not the case; stratification is in the range of 1-2°F in both cases.

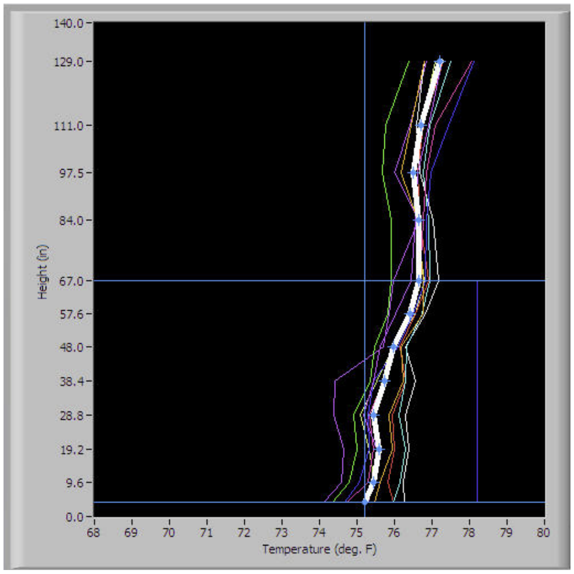

Figure 4-13. North interior

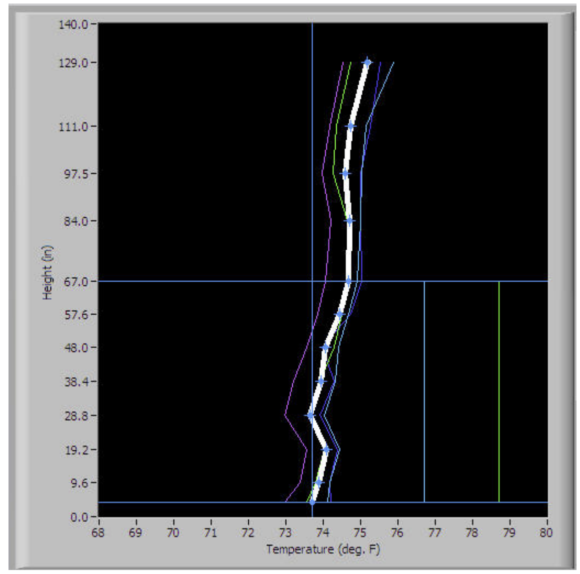

Figure 4-14. South interior

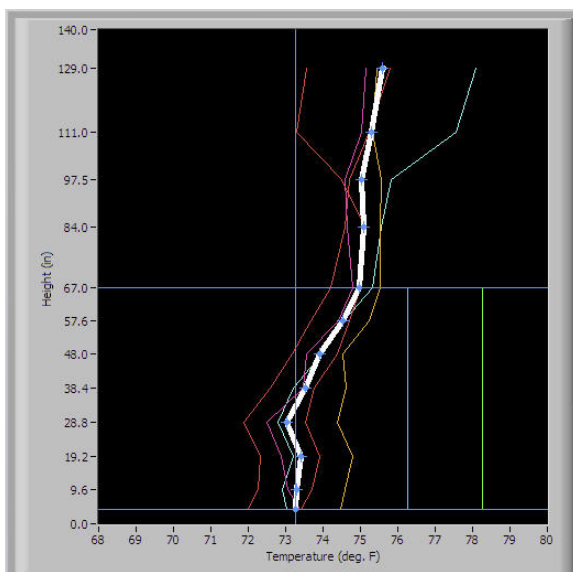

Figure 4-15. South perimeter

4.2.3.2 Plenum distribution

As discussed above, measurements during the first few years of occupancy revealed significant temperature gain to the supply air as it traveled through the underfloor plenum. The

[1] Although a year later in September 2008 many of the setpoints had been changed back to 72°F so that the average over the building was virtually the same as it was in pre-August 2007.

commissioning team attributed this in part to the absence of underfloor partitions at strategic locations to divide the plenum into manageable-sized control zones. In the original design, the entire outer ring of perimeter space in the building was a single open, connected plenum zone, which likely increased the travel distances of supply air before reaching a floor diffuser, thereby increasing temperature gain. In August 2007, four plenum dividers were installed on each floor, as shown in Figure 4-16 for the fourth floor, creating four separate perimeter plenum zones. While not eliminating all thermal decay, this retrofit greatly improved the UFAD system controllability by reducing the size of each control zone and aligning them with the different building exposures. The modification and improved control also resulted in higher occupant satisfaction (see survey results discussed below in Section 6).

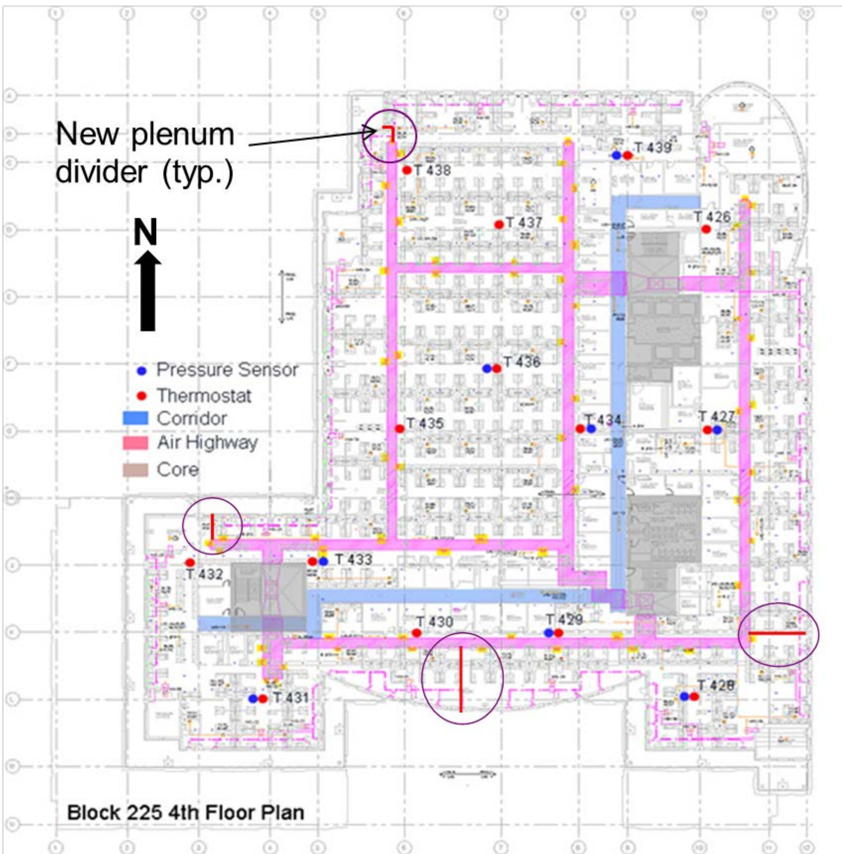

Figure 4-16. Plan view showing installation of plenum dividers at four locations

In September 2007, the CBE Cx Cart was used to take measurements in the southwest perimeter zone on the 4th floor of B-225 to evaluate the impact of the new plenum dividers. Figure 4-17 shows the distribution of diffuser discharge temperatures across this southwest zone in the later afternoon on Sept. 20, 2007. The temperatures of the colored dots (representing the measured supply air temperature at one diffuser) can be read from the legend on the right hand side. The coldest temperature was 57.3°F, measured at a location directly in line with one of the damper controlled supply air stub-outs on the air highways. The warmest measured plenum temperature was 70°F, with an overall average in this southwest zone of 66.5°F.

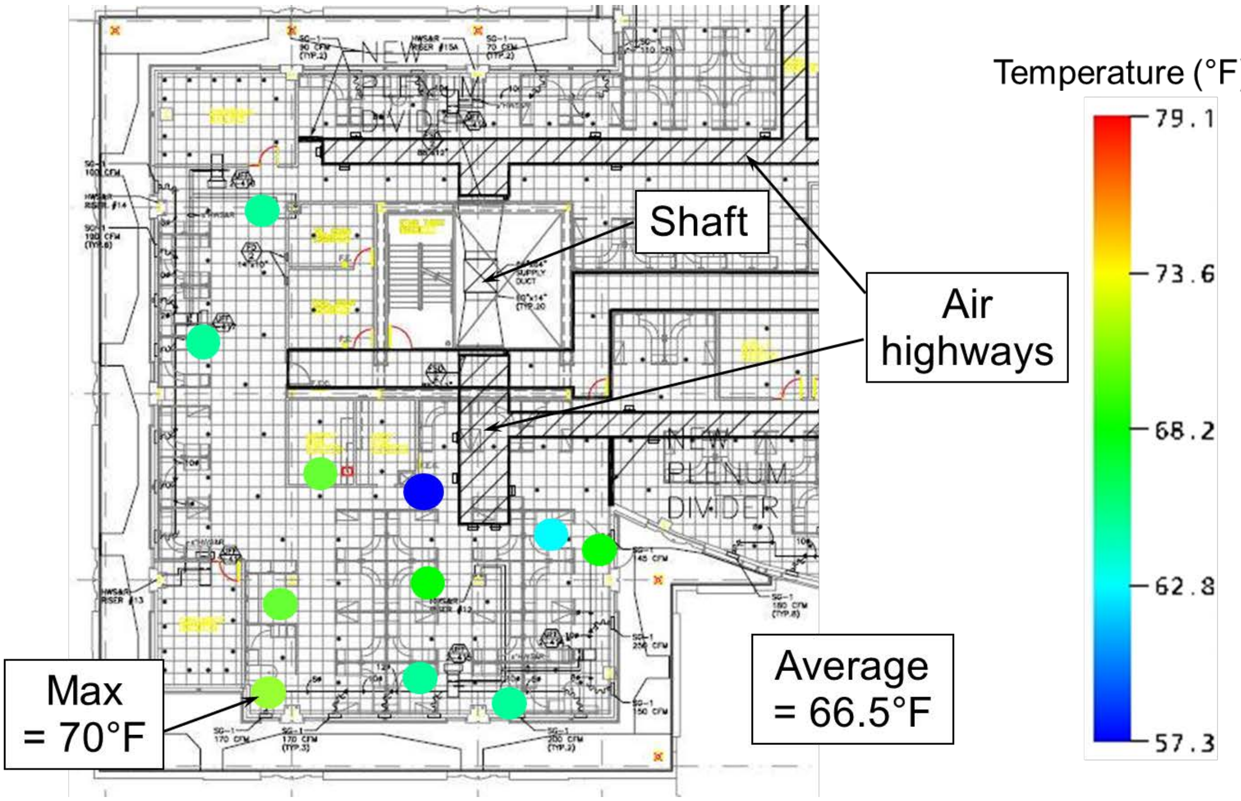

Figure 4-17. Diffuser discharge air temperatures: B-225, southwest zone, 4th floor, 9/20/2013

Although there is more than a 10°F temperature difference between the maximum and minimum plenum temperatures, the overall average of 66.5°F is quite reasonable for good UFAD system and stratification performance. This larger temperature gain would be expected because the recent increase in zone setpoint temperatures from 72°F to 74°F would cause the supply airflow rate to decrease, hence naturally increasing the temperature gain in the plenum.

The results from the installation of the plenum barriers and subsequent improved system performance were an important lesson learned from this field study and have contributed to new guidance now included in the revised ASHRAE UFAD design guide [ASHRAE 2013]. In addition, local energy and/or fire codes may limit the maximum size of any single plenum zone. In larger buildings, this may require plenum dividers to be installed for this purpose. It is recommended to limit the size of plenum zones in order to help manage supply air temperature rise, and more importantly, improve the controllability of the building zone.

5 WHOLE-BUILDING ENERGY ANALYSIS

5.1 INTRODUCTION

In Section 5, we present a detailed comparison of the energy use for B225 with its UFAD system vs. B172 with its overhead (OH) VAV air distribution system. Based on actual measured data obtained from BMS trends logs, these results are presented in three ways:

1. “As measured” to show how each building performs without consideration of some of the key fundamental differences between the two buildings, and
2. “Apples to apples” comparison in which we estimate the impact of several fundamental differences in design and operation using a technique we call “equivalent building analysis.” This entails accounting for the building differences by creating a model of B172 that is “equivalent” to that of B225 for all aspects of design, loads, operation, and central equipment with the one exception of the HVAC distribution system type itself (UFAD vs. OH). Through this detailed analysis, we attempt to demonstrate what the true energy impacts of using a UFAD system would be in comparison to an identical building with an OH system. We estimate the performance of B172 *as if it was equivalent* to B225 in overall design and operation as well as containing central system components *equivalent* in performance to those of B225 (e.g., including high efficient air handling units (AHUs), outdoor economizer, and a chilled water system like B225). The results shown below include impacts at both the whole-building and HVAC level.
3. Energy Star rating to apply an alternative, but widely used, metric to compare whole-building energy use.

In the following sections we proceed as follows:

Section 5.2: Illustrate differences in “as measured” energy performance based on raw data. This comparison focuses on cooling energy use and other monitored electricity consumption (e.g., lighting and plug loads) because we had access to much higher quality cooling energy data. Heating energy use was not included in this “as measured” comparison for the following reasons: (1) B225 boiler energy use was only available from monthly utility gas meter bills and was considered the least accurate measurement of energy use. (2) Comparable boiler data for B172 could not be obtained because hot water is supplied by the central district heating and cooling plant system which includes gas use for domestic hot water and gas fired chillers for all four B17x buildings. Likewise, secondary hot water flow was not instrumented at the building level making isolating heating energy measurements for B172 impossible**.**

Section 5.3: Provide overview of “apples to apples” analysis methods used to derive the data for comparing the two buildings while accounting for their differences. Full details of the data processing and analysis methodology are provided in Appendixes B and C.

Section 5.4: Present “apples to apples” comparison analysis and results for B225 and B172. We used a modified form of *electrical* energy use intensities (EUIs) to assemble whole-building end use breakdowns that clearly identify differences at the level of components, and how these components change once the estimated impacts due to the major differences between buildings B225 and B172 are applied. After accounting for the key differences in design and operation and their estimated impact on cooling energy use, we also attempt to estimate the heating energy use differences between the two buildings in Section 5.4.4 to provide a more complete comparison.

Section 5.5: Present a comparison of the Energy Star rating for B225 vs. B172. This method provides an alternative metric for comparing building energy use as it is based on more general whole-building utility data that includes key electrical loads, such as outside lighting, elevators, server rooms and for B225 first floor loads. In our detailed "apples to apples" comparison, we dropped the first floor or B225, since it is served by a separate OH air distribution system.

Section 5.6: Summarize energy analysis conclusions.

5.2 "AS MEASURED" END USE ENERGY CONSUMPTION

In Figure 5-1 we show the overall results for electric energy consumption and heat extraction for the two buildings . Each component shown in this figure is the total annual energy use for that component normalized by building floor area (excluding first floor of B225) in units of kBtu/gross square foot. These were derived from measured data to give 15-minute power measurements but are shown only for occupied hours (6am-6pm) of *weekdays* excluding holidays.[2] The breakdown for cooling energy shows *secondary cooling* (i.e., heat extraction) [3] because the cooling at 172 was provided by a central plant and its electric energy consumption was unknown, but the amount of secondary cooling was determined by the measured flow and temperature differences.

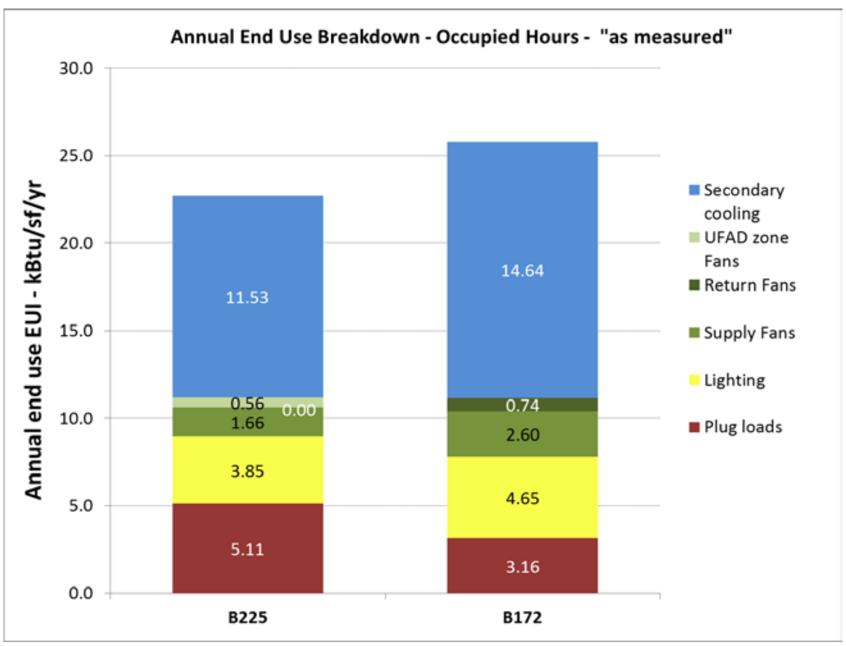

Figure 5-1. Annual occupied hours building end use energy breakdown for "as measured" (using secondary cooling)

[2] These results were calculated by averaging the power over the occupied hours and multiplying by 5 days/week * 52 weeks/yr*12 hours/day. (see Appendix B.)

[3] i.e., without including chiller COPs since performance data for the district cooling system that provides cooling for B172 was not available

Figure 5-2 shows results for monthly performance of electrical end use breakdown in units of W/square foot for both buildings and their average for a year.

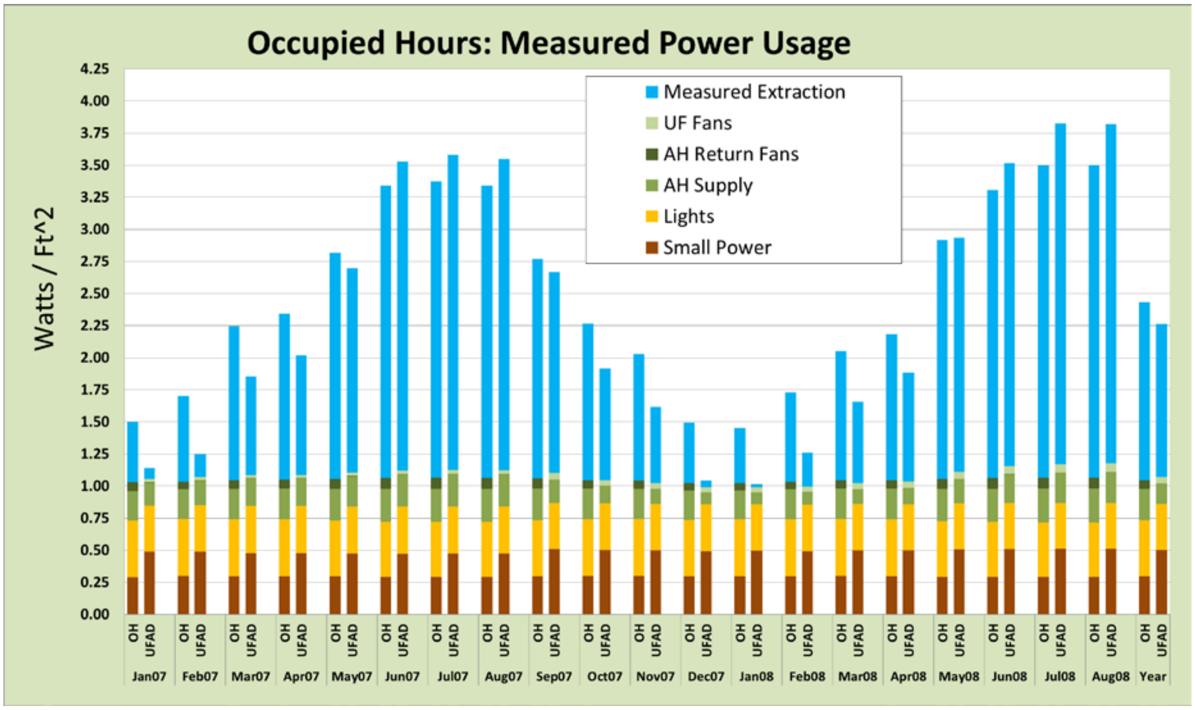

Figure 5-2. Monthly and annual electric energy end use breakdown for occupied hours for "as measured" using secondary cooling (Yearly = Sep 2007- Aug 2008)

The measurement data indicates improved efficiency for the UFAD system vs. the OH system, as cooling energy is 31% higher and total fan energy is 50% higher for B172 compared to B225. Table 5-1 shows annual results drawn from the data in Figure 5-1 for HVAC electric components (except heating) as well as internal loads, which are the sum of lighting and small power loads (but does not include occupancy). The results indicate that the "as measured" annual HVAC EUI is 31% higher for the overhead system (B172) compared to the UFAD system (B225). This significant difference occurs despite the fact that total internal load energy demand (lights and small power) is 13% less for B172 relative to B225. The internal load difference is actually greater due to an estimated 8% greater occupancy density for B225 (discussed further in Section 5.4). When combined, this results in the total "as measured" annual building energy use for B172 being only 14% higher than B225.

Table 5-1. "As measured" annual energy use summary, occupied hours, no heating

	Annual average electric energy use* (EUI)		**B172 relative to B225**
	B225	B172	
	kBtu/Gsf/yr		
Whole Building	22.7	25.8	+14%
HVAC	13.7	18.0	+31%
Internal loads	9.0	7.8	-13%

*Building and HVAC totals include secondary cooling for both buildings, no heating

5.3 “APPLES TO APPLES” METHODS

5.3.1 Overview

The following is an overview of methods used to derive the data for comparing the two buildings while accounting for their differences.

- **Equivalent modeled central plant and fans comparison** – These methods constitute a preliminary step employed for the “apples to apples” analysis. As summarized below, in this first stage of analysis, we estimated the impact of equalizing the components of the central plant of B172 with those of B225. The results of this analysis are presented in Section 5.4.1.
  - **Cooling energy** - Cooling energy was developed from the application of three models to normalize the design and operation of the two systems: (1) an outside air model based on the measured operation of B225 was applied to the measured airside extraction rate of B172 (airside and water side extraction rates were found to be virtually identical); (2) a chiller COP performance model based on measured data from B225 was applied to the B172 (outside air modeled) secondary chilled water extraction rate to correct for the fact that B172 is actually supplied from a central plant; and (3) a pump and cooling tower model derived from B225 measured performance. See details in Appendix C.
  - **Fan energy** - Air handler energy is subdivided into central supply, return fan, and perimeter fan coil unit energy (B225). Fan coil unit power for B225 was derived from a speed vs. power correlation based on manufacturers data and measured speed for each unit. Design data for both buildings were used to construct a correction factor for the B172 supply fans to account for the performance differences between the two fan designs. Adjustments to fan energy are discussed beginning in Section 5.4.2.
- **Heating** – For B225 boiler energy from monthly utility gas meter data was collected; it is the least accurate measurement used due to its lack of detail. Comparable boiler data for B172 could not be obtained because hot water is supplied by the district central plant system which includes gas use for domestic hot water and gas fired chillers for all four B17x buildings. Likewise, secondary hot water flow was not instrumented at the building level making isolating heating energy measurements for B172 impossible**.** For this first stage comparison, we did not include boiler energy. Further below in Section 5.4.4, we estimate the heating energy use differences between the two buildings to provide a more complete comparison.
- **PV Arrays** – Both buildings are equipped with photovoltaic arrays (see **Error! Reference source not found.**) on the penthouse enclosure walls on the roofs. Since these arrays are of similar size and geometry and provide less than 10% of the annual energy they were ignored in these analyses.

Figure 5-3. Photo of PV array on B225

5.3.2 Summary of building differences

There are additional differences in building configuration, system design, and operation that impact performance differences between the two buildings, apart from the significant differences represented by HVAC system type. These may include differences in solar gain due to the differences in orientation and aspect ratio despite the fact that the façade specifications are virtually identical. Table 5-2 contains a brief outline of the fundamental differences that we evaluated between the two buildings that affect their energy and comfort performance. Details of each of these factors are discussed in Appendix C, as identified in Table 5-2.

Table 5-2 – Summary of building design and operation differences

Item	Appendix section	Description
Building design and configuration	C1, C2	Despite the fact that the main design features of the two buildings are virtually identical, there still are notable differences that may impact energy use. Chief among these are aspect ratio, floor area, orientation and interior spaces.
Lighting and plug internal loads	C3, C5	Lighting and plug load levels are each different between the two buildings.
Occupancy	C4, C5	Occupancy levels
Room temperature setpoints	C6	Room setpoints are nominally different, but in practice turned out to be similar after adjustments in B225 during commissioning.
HVAC system design and operation	C7	Apart from the distribution system differences (B172 OH VAV and B225 UFAD) the central systems are not the same: B172 is equipped with packaged VAV AHUs and cooling and heating water are supplied by a central/district system that services all four B17x buildings. Although, in common practice the supply air temperatures are different between the two systems, in operation they were only 2.5°F apart.
Air handlers and outside air systems	C8	B225 has an engineered central system including relief fans, and common economizer all with high performance components; while B172 was designed with an evaporative cooling outside air system.
Cooling and chiller performance	C9	A model of the building B225 central system was applied to B172 to achieve “equivalent” performance, other than the distribution system types.

5.4 “APPLES TO APPLES” ANALYSIS

As discussed above, besides the differences in HVAC systems type, the major differences between energy related aspects of the two buildings are building configuration, internal loads, room set points, and system efficiencies. These factors have counterbalancing and asymmetric effects. If the impact of these factors could be accurately analyzed together, the HVAC system types could be compared on an equal basis. However, this would require more advanced analysis methods such as calibrated simulations that are outside the scope of this project. We developed an alternative analysis based on estimating the impact on B172 performance as if it was configured and equipped with central system equipment similar to B225; aka “Apples to Apples” comparison.

5.4.1 Equivalent modeled central plant and fans comparison

In this section we show the initial step for the “apples to apples” comparison by estimating the impact of equalizing central system components. This primarily includes adjusting B172 as if it contained an outside air system, central system components and air handler fans equivalent to those of B225.

Figure 5-4 shows the comparison of annual end use energy between B225 and B172 broken down by major HVAC components, lighting, and plug loads. The results are shown as side-by-side bars to highlight the differences between HVAC and internal loads, and are also shown for occupied hours only, similar to what is presented in Figure 5-1. The main change from Figure 5-1 is that we are now using models to estimate the performance of an equivalent central HVAC system for B172 that is based on equivalent outside air fraction, chilled water system models, and air handler fans, not including underfloor perimeter fans, of B225 equipment. The modeled equivalent central plant for B272 impacts the cooling (chiller) and pumps & cooling tower categories reported in Figure 5-4. As described in section 5.3.1, because our cooling energy predictions are based on a chiller COP model from B225, the reported EUI for cooling is lower than in Figure 5-1 for both B225 and B172. These values represent the amount of energy that must be provided to the buildings.

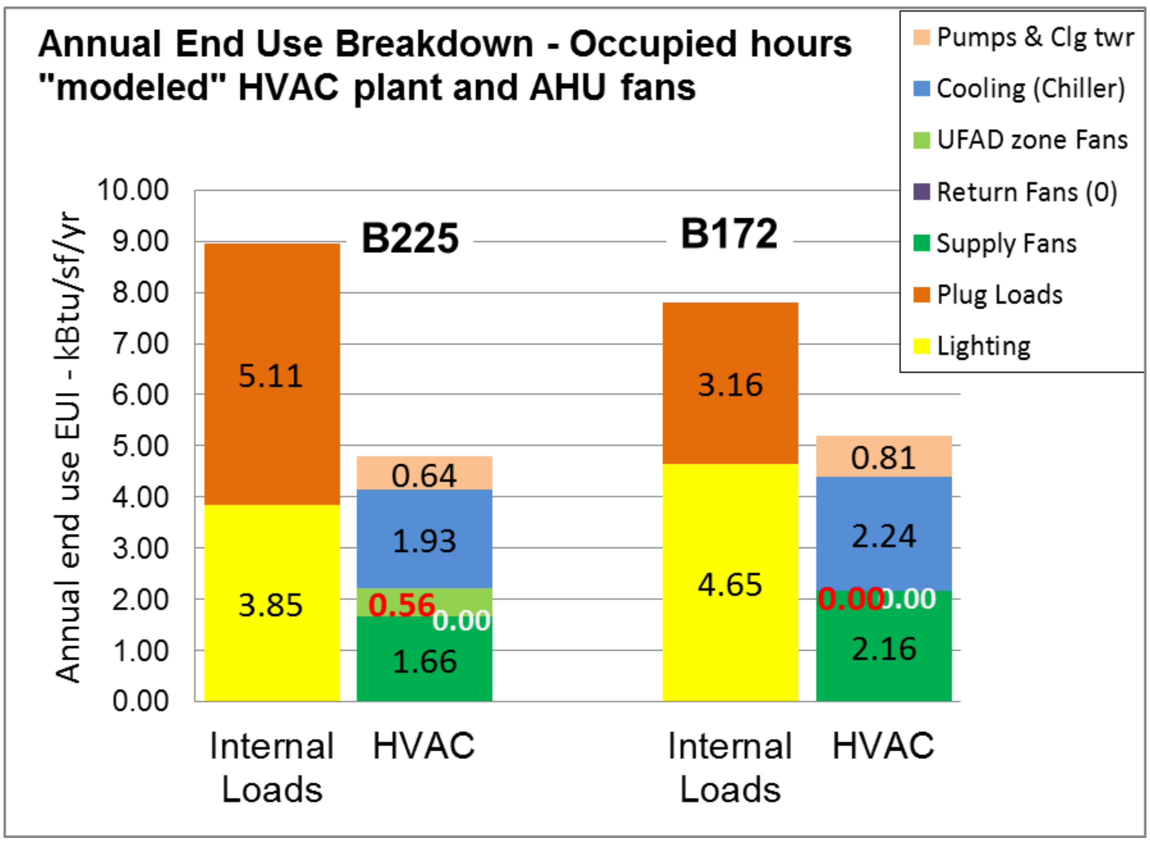

Figure 5-4: Annual end use breakdown for occupied hours (no heating); B225 and equivalent central plant cooling and air handler models applied to B172; showing internal loads vs. HVAC energy

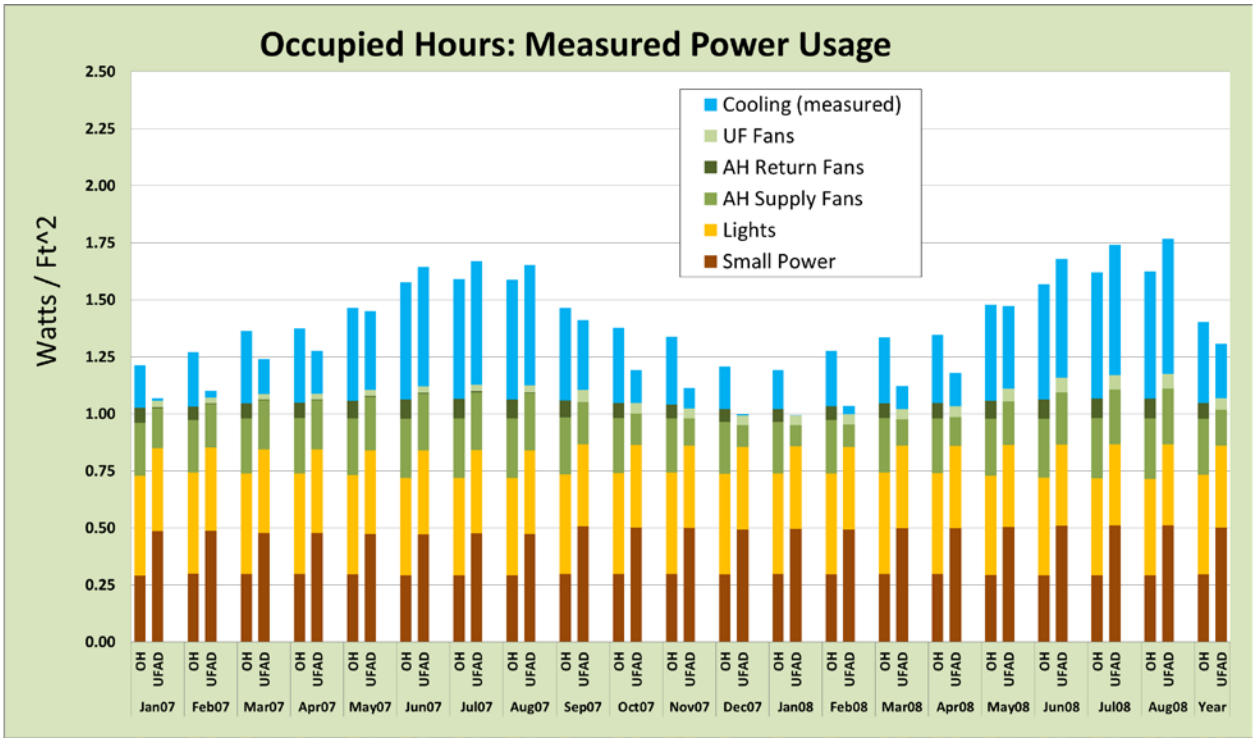

Figure 5-5: Monthly and annual electric energy end use breakdown (no heating) for occupied hours for B225 and equivalent central plant cooling models applied to B172 (Yearly = Sep 2007-Aug 2008)

Overall comparison results based on end use component average annual energy demand (W/sf) are shown in the monthly stacked column summary in Figure 5-5. Shown are the measured average electrical demands for all end use components (except heating) by month for an 18-month period covering 2007 and 2008 for both B172 (OH) and B225 (UFAD). Annual results are included for the period of September 2007 through August 2008. These results represent weekday occupied hours (6am to 6pm) of operation only to narrow the scope of the analysis to just the occupied hours where much of the energy is consumed and where the operations between the two buildings are most consistent; e.g., removes nighttime operation from the comparison.

Table 5-3 shows annual results drawn from the data in Figure 5-4. This represents the two buildings as they are configured (with their individual differences), but with B172 modeled for outside air fraction, air handler fans, and cooling system equivalent to B225. Contrary to the "as measured" results shown in Figure 5-1, total building energy use is 5% less for B172 while HVAC energy use for B172 is 8.7% higher than B225. Total internal load energy demand (lights and small power only) is 13% less for B172 relative to B225; this is the same result as in the "as measured" case. These results indicate that the HVAC system in B225 performs better than in B172. Despite having lower internal loads, B172 (with its overhead air distribution system) uses more HVAC energy compared to the UFAD system in B225, even when the central systems are equivalent. But there are still important differences that affect this conclusion as will be discussed in more detail in Sections 5.4.2 and 5.4.3.

Table 5-3. Annual energy use summary, occupied hours, no heating: Equivalent modeled central plant cooling and air handler fan system applied to B172

	Annual average electric energy (EUI)		**B172 relative to B225**
	B225	B172	
	kBtu/Gsf/yr		
Whole Building	13.8	13.0	-5.3%
HVAC	4.8	5.2	8.7%
Internal loads	9.0	7.8	-13%

5.4.2 Estimated HVAC electric load impacts of building differences

Taking the next step in our "apples to apples" comparison, Table 5-4 summarizes all the identified design and operating factor differences between UFAD and OH with a rough estimate of the relative energy impact on the category EUI. As Table 5-4 outlines, we are considering the following additional factors in our energy performance comparison between B225 and B172: building configuration, occupancy, lighting and plug loads, thermostat setpoints, air handling unit (AHU) system, supply air temperature, heating, and system type. Table 5-4 also lists differences due to cooling system and AHU fans, but these factors were already partially accounted for in our first-step analysis in which we modeled an equivalent central plant cooling system and AHU for B172 based on B225 (described in Section 5.4.1).

Table 5-4. Summary of impact of design and operating differences; effect on B172 if designed like B225

<table>
<tr><th>Building design and operating characteristic</th><th>Contributes to building and/or HVAC energy</th><th>Estimated impact
(increase or decrease in B172 energy relative to B225)[4]</th></tr>
<tr><td rowspan="2">Building configuration</td><td>HVAC + Building</td><td>-5% cooling system
-6% AHU
-31% heating</td></tr>
<tr><td colspan="2">Simulation study indicates the main driver for this difference is heating; this is likely due to the fact that B225 has a 30% greater perimeter area than B172.</td></tr>
<tr><td rowspan="2">Occupancy</td><td>Building[5]</td><td>+26% plug loads</td></tr>
<tr><td colspan="2">Based on gross area B172 has a 27% lower occupant density than B225 which would increase internal loads and HVAC for an equivalent B172. We assume that increased occupancy would also increase plug loads in the same proportion.

The impact of occupancy on HVAC energy is factored into the internal load differences below.</td></tr>
<tr><td rowspan="2">Lighting & plug loads</td><td>HVAC + Building</td><td>+15% cooling system
+19% AHU
-17% lighting
+62% plug loads</td></tr>
<tr><td colspan="2">These internal loads contribute to both building level loads and HVAC loads; the impact on HVAC is difficult to estimate. These estimates were derived by a simulation study that determines the overall impact on system cooling and AHU energy in proportion to the combined total of lighting, plug loads, and occupancy. (See Appendix C)</td></tr>
</table>

[4] Impact on B172 EUI if it was configured with the same building and load characteristics of B225 and had an equivalent HVAC central system. These are very rough estimates, based on engineering judgment. These percentages apply only to the change in component energy, not building or HVAC EUI (i.e., the overall effect would have to be weighted by the component EUIs as we have attempted to do in Table 5-5)

[5] HVAC impacts of occupancy differences are included in internal loads estimates

Thermostat setpoints	HVAC - cooling	~~-10%~~[6]
	If setpoints for B172 were increased to those of B225, cooling and fan energy would be decreased. However, the lower setpoints for B172 are assumed to be representative of the state of practice for OH systems of this vintage so this credit was not applied.	
AHU system	HVAC - AHU	~ -10% on average over operating range
	The more efficient fans, use of relief fan vs. return fan, and better part load performance for B225 AHUs would decrease AHU energy for B172 if they were employed in B172. These factors are embodied in the adjustments made below, in which the difference in fan efficiency is applied to the B172 fan energy. (See Appendix C, for more detail of this modeling procedure). Note also, that return fan energy is also not included for the adjusted B172 AHU system on the assumption that it would reflect the minimal amount found in B225. Fan energy for B172 does not include underfloor terminal unit fan energy, one of the major differences between the two system types. This and use of lower VAV box minimum airflows consistent with B225 operation would also decrease fan energy but these factors are part of the differences between system types that remain intact in the analysis. The effect of economizer differences are included in the “equivalent central plant cooling” analysis, which includes models of the outside air and chiller system of B225.	

[6] Strikeouts indicate items not included explicitly in final analysis, shown for reference purposes only, see table text

Supply air temperature (increase to B225 level)	HVAC cooling + AHU	~~-4% cooling~~ ~~+5% AHU~~
	Higher SAT for B225 reduces cooling by allowing more economizer hours, but this effect is small in this case since the average SAT temperatures differ by only 2.5°F. Studies indicate that this would result in about a 4% decrease in cooling energy, and about 5% increase in fan energy. However, the difference in these temperatures are characteristic of the system differences we are trying to analyze, therefore to prevent double accounting, they are not explicitly included in Table 5-5.	
Cooling system	HVAC - Cooling	
	Cooling energy impacts were included in the “equivalent central plant cooling” analysis by employing outside air and chilled water models based on B225.	
Heating	HVAC - heating	NA
	Heating differences are discussed in the building configuration section; other reductions in heating would be related to system type. Heating was not included in the HVAC electricity comparison due to lack of B172 data, but is discussed further in Section 5.4.4.	
System type	HVAC all	(see Table 5-5)
	UFAD vs. OH; UFAD has lower minimum volumes at terminal units, lower static pressures, but these are offset by overall fan energy increases due to terminal fan coil units (assuming all design specifications are equivalent). [Webster et al. 2012]. Ideally, stratification should lower cooling and fan energy but the lack of significant stratification in B225 would mitigate against this advantage. A significant amount of reheat can be eliminated with UFAD. See further discussion of heating impacts in Section 5.4.4.	

5.4.2.1 Potential errors

Shown in Table 5-5 is a summary of the individual impacts on B172 end use EUIs if the building and HVAC system components were designed and operated like B225. This analysis is based on the end use breakdown shown in
Figure 5-1. Note that the estimates shown in Table 5-4 and Table 5-5 represent the impact of each factor alone, not in combination with the others. There may be counter-balancing effects when these factors all are considered together in combination. This requires a more sophisticated analysis such as a simulation study (preferably based on a calibrated model of each building) to be able to ascertain the overall impact of these factors operating in combination. However, several of these factors were arrived at by targeted simulations, which is likely to reduce potential errors by not doing all in combination.

In addition, there are errors in the analysis due to instrumentation and measurement inaccuracies as well as missing data and the consequential propagation of these types of errors in the energy modeling techniques we used in this study. We expect errors to be relatively low for measured power readings (~10%), and relatively high for model calculations (~15-25%). Still, a calibrated simulation would allow a more accurate evaluation of the impact of the UFAD system than we currently are able to do.

5.4.3 "Apples to apples" HVAC electric EUI comparison (without heating)

In this section we illustrate the process of applying the estimated impacts to the end use category EUIs for B172. These adjustments are then added to the whole building and HVAC baseline EUIs for B172 provided by the "equivalent modeled central plant and fan" results. Table 5-5 summarizes the results of applying these adjustments to the various electric end uses. These results do not include alternatives to HVAC system types that could be made (e.g., effect of increased stratification for UFAD[7]) and as such the results indicate the electrical energy differences between these two systems as they are actually configured (as discussed previously in this report), and without the impact of heating differences. Embedded in the results for B225 and B172 performance are most of the factors that are representative features of each of them; for example, SAT differences, temperature rise in the UFAD plenum, room setpoint differences, terminal units for UFAD and similar ones for OH (e.g., minimum air volumes of VAV boxes). The results in Table 5-5 show that when the estimated impacts for all end use categories are added to the modeled baseline energy use for B172, the total adjustments are an increase of 11% for HVAC energy and 13% for whole building energy.

[7] Although stratification can reduce cooling energy it appears to be minimal in B225

*Table 5-5. Summary of estimated impact on B172 EUI if designed like B225, occupied hours[8], **without heating***

		Building B172		
			Whole building	HVAC
		Baselines, Modeled	13.02	5.21
Building design & operating characteristics (end use category affected)	Estimated change (% change in B172 end use category)	Baseline End use category EUI, kBtu/sf/yr	Adjustment of whole building EUI, kBtu/sf/yr	Adjustment of HVAC EUI kBtu/sf/yr
Building configuration				
HVAC – cooling system	-5%	3.05[9]	-0.15	-0.15
HVAC - AHU	-6%	2.16	-0.13	-0.13
Occupancy				
Building – plug loads	Included in Internal loads adjustments			
HVAC – cooling & fan	Included in Internal loads adjustments			
Internal loads				
Building - Lighting	-17%	4.65	-0.80	
Building – Plug loads	+62%	3.16	+1.95	
HVAC – cooling system	+15%	3.05	+0.46	+0.46
HVAC - AHU	+19%	2.16	+0.41	+0.41
		Net change[10]	**+1.74**	**+0.59**
	Net change, % from baseline		**+13%**	**+11%**
	Revised EUI		**14.8**	**5.8**

[8] Occupied hours assumed to be 6am to 6pm schedule for 5 days per week without holidays

[9] Auxiliaries included

[10] Although the net total impact shown here derived by simple addition, to be more accurate these individual effects should be added up in combination as described in Section 5.4.2.1.

Figure 5-6 compares the annual energy use for B225 vs. the B172 equivalent building that has been adjusted according to Table 5-5. The stacked bar charts are broken down by HVAC components and internal loads. This represents our “apples to apples” comparison of the two buildings for all factors except heating. These results emphasize that when the buildings are configured the same way and have equivalent central systems and internal loads B172 would use 21% more total HVAC electric energy than B225. On a whole building basis, the difference is smaller (7%), as listed in Table 5-6.

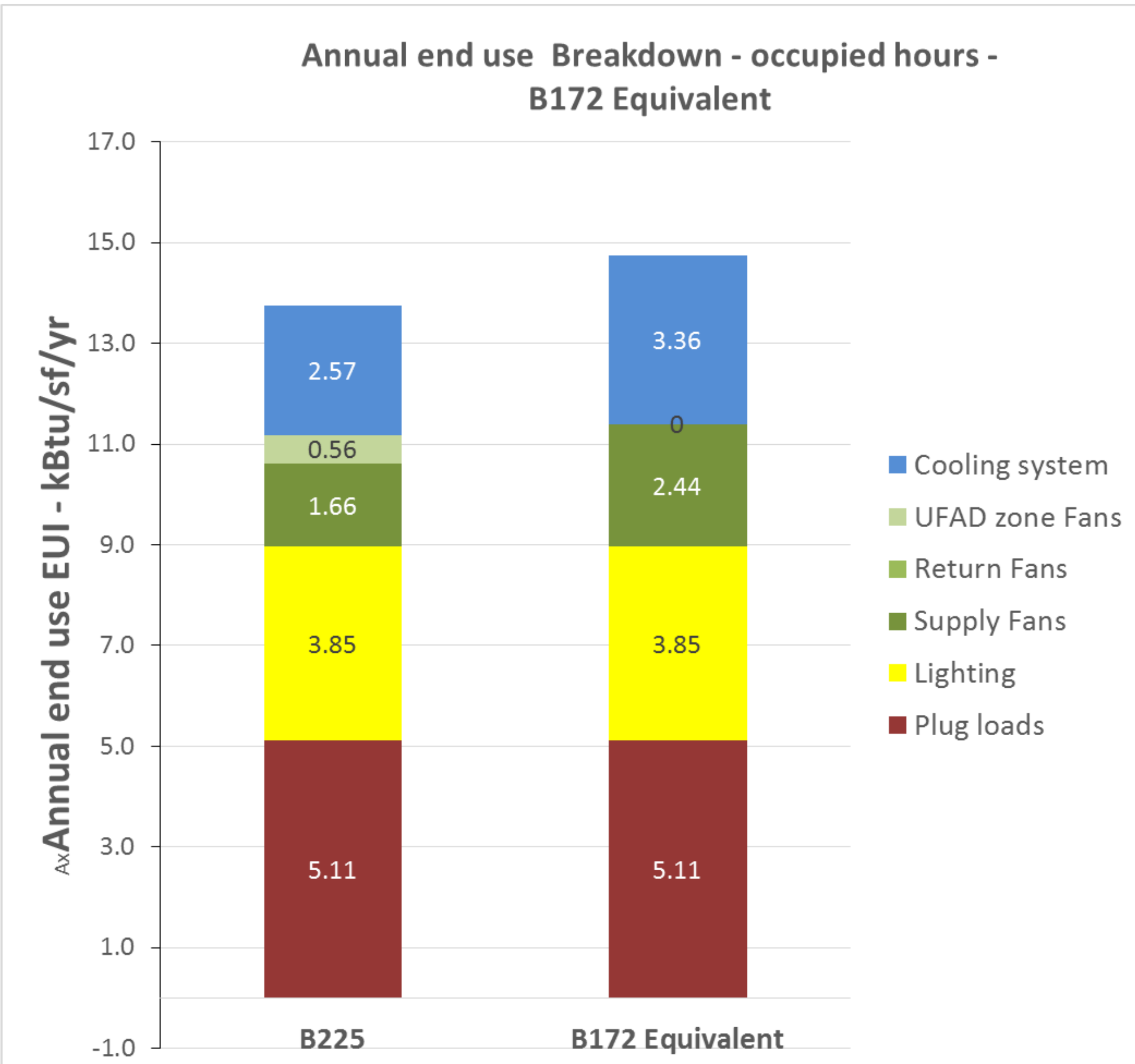

Figure 5-6. Annual energy end use breakdown, occupied hours, “B172 equivalent” (B172 “Modeled” adjusted for configuration and load differences), without heating

These findings are somewhat consistent (considering uncertainties in the results) with other UFAD studies the authors have done. In particular, using EnergyPlus simulations, Webster et al. (2012) showed that for an underfloor plenum configuration that was similar to that of B225 (i.e., series plenum) a typical state-of-the-art overhead VAV system HVAC electric usage is shown to be about 12% *lower* than UFAD, for the same building design and operating conditions in a Sacramento climate (see "Total HVAC savings" in Figure 5-7). However, Figure 5-7 also shows that total HVAC EUI for a UFAD system can be improved when a combination of alternative design and operating strategies are employed (last two categories in Figure 5-7), bringing the results without heating more in line with our findings of the current study.

Note that when heating is included, UFAD total HVAC energy use is significantly lower than the overhead (OH) system across all configurations; heating energy is consistently about 45% lower than OH. This suggests that if heating is included in our comparison analysis that the UFAD system total HVAC energy consumption would be considerably lower than OH as discussed in Section 5.4.4.

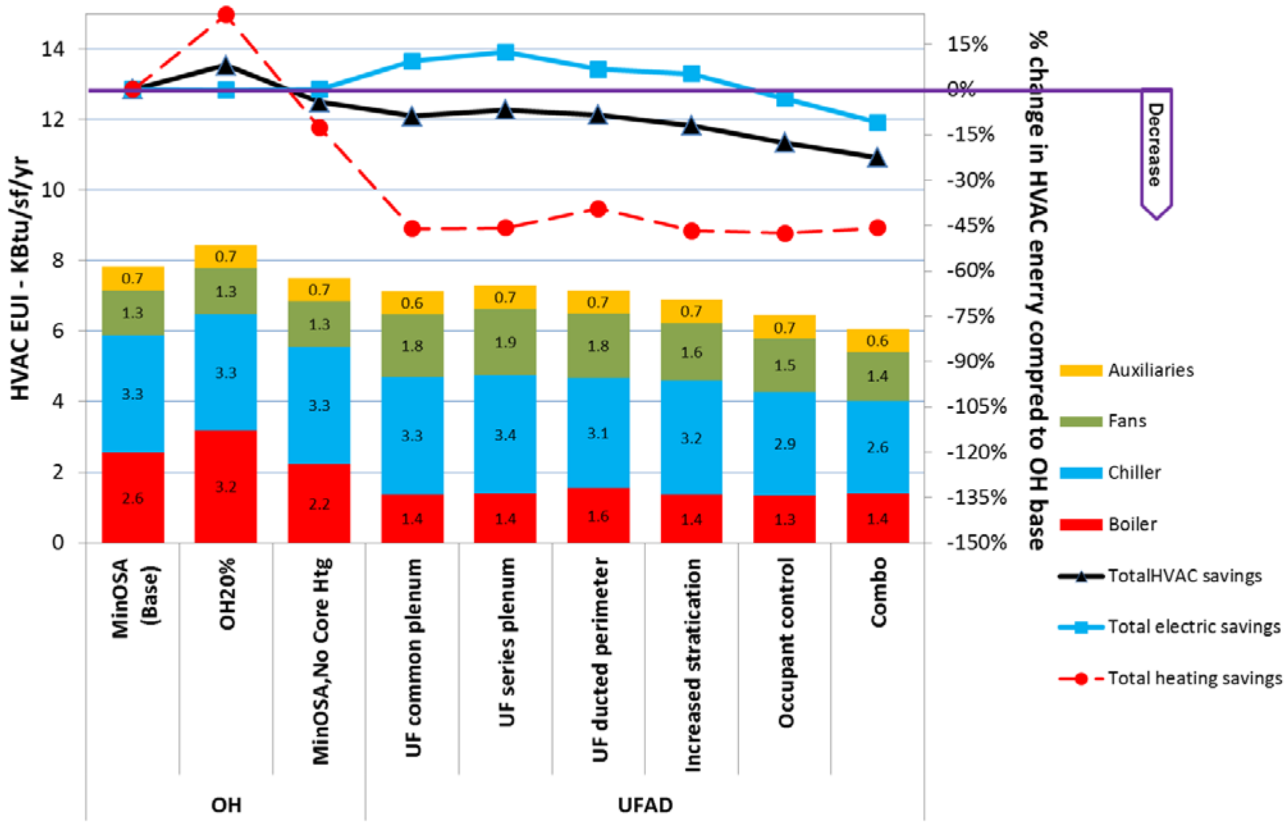

Figure 5-4. Results of UFAD vs OH simulation study [Webster et al. 2012]

5.4.4 Heating considerations

Heating has been shown to be an important consideration for UFAD systems given that UFAD typically has no heating in interior zones and there is less reheat than for OH. We have attempted to estimate its impact in order to provide a more complete comparison between the two systems.

We derived heating energy (as described in Appendixes B and C) from "as measured" data for both buildings. However, this does not include the effects of configuration changes shown to be 31% in Table 5-4 for heating. When we apply this correction, B172 heating EUI for the "apples to apples" case is 14% greater than B225; total HVAC EUI including heating is 20% greater for B172 when it has a configuration like B225. Total annual building energy use is 8% higher for B172 compared to B225.

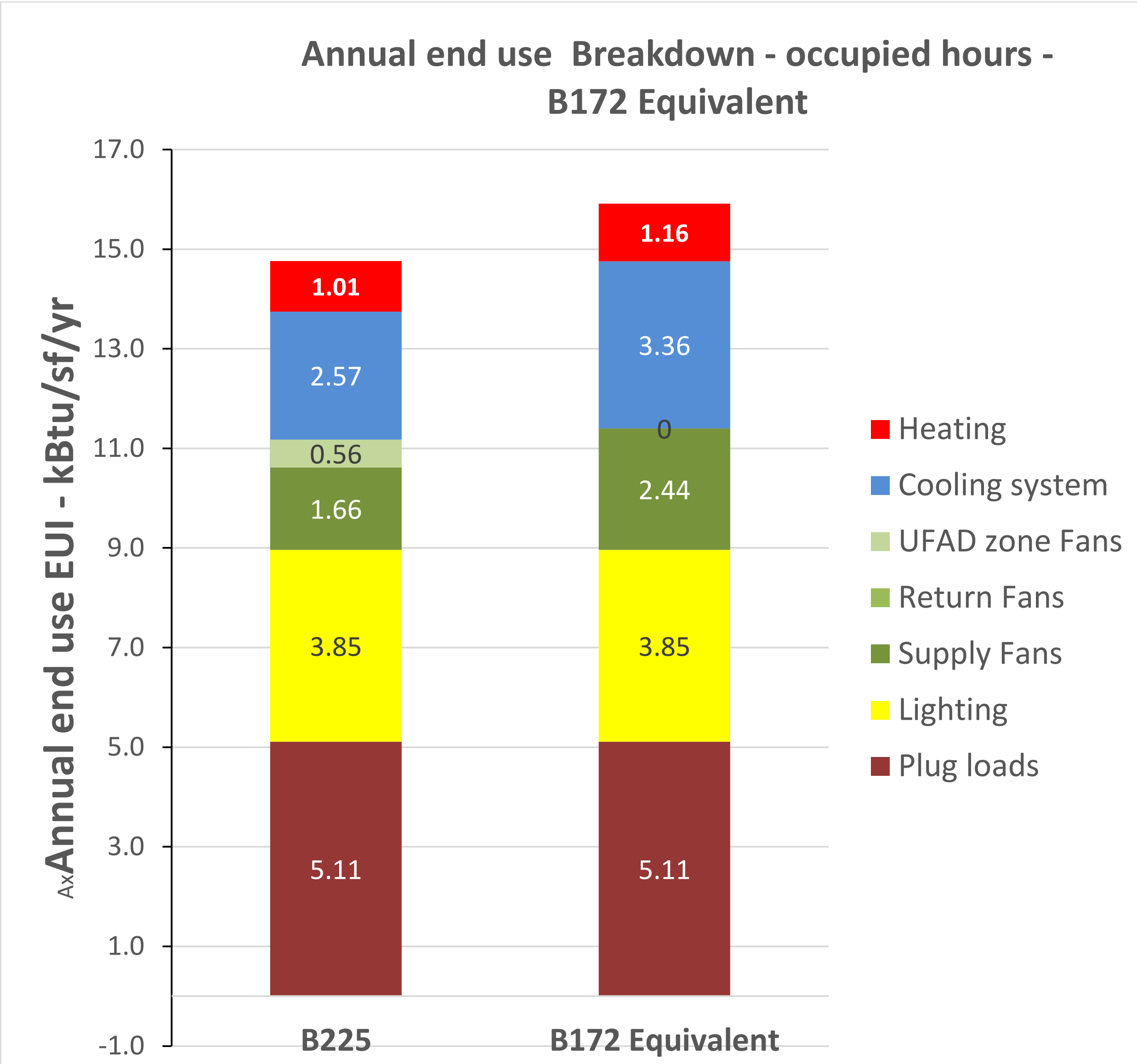

Figure 5-8. Annual end use breakdown, occupied hours, "B172 equivalent" (B172 "Modeled" adjusted for configuration and load differences) with estimated B172 heating

Table 5-6. HVAC and whole building EUI summary comparison

	B225 EUI kBtu/sf/yr	Revised B172 EUI kBtu/sf/yr	Percent difference (B172 vs B225)
Total HVAC EUI, *without* heating	4.8	5.8	21%
Total HVAC EUI, *with* estimated heating	5.8	7.0	20%
Total Building EUI, *without* heating	13.8	14.8	7%
Total Building EUI, *with* estimated heating	14.8	15.9	8%

5.5 ENERGY STAR COMPARISON

The Energy Star rating is based on metered energy use for the non-retail portion of the buildings. Summary results presented in Table 5-7 for B225 shows a site Energy Star rating of 98, well above 75 required to receive the Energy Star label; the associated site and source energy use intensities (EUI) are 43 kBtu/ft^2·yr and 130 kBtu/ft^2·yr, respectively. This is 38% better than of the national average EUI for buildings of this type and represents a very energy efficient building based on this metric of whole-building energy performance.

A profile of monthly gas and electricity use presented in Figure 5-9 shows higher gas usage in winter for 2008. Electricity use is higher only in the second half of 2008 [Fentress et al. 2009].

Energy Star data for B172 could not be independently obtained since it is not separately metered from the B171-174 complex which is served by a central district heating and cooling system. Table 5-8 shows Energy Star performance for the ***entire complex*** and provides only a rough comparison to B225. Although the Energy Star rating of 91 is close to the B225 score of 98, the site EUI is 83% greater for the B17x complex (61% greater on a source basis). The fact that the two ratings are so close together is a result of the Energy Star methodology and the substantial differences between B225 and the B17x complex. For example, the parking area for B17x is ~40% of the total facility floor area where for B225 it is ~20%. Other differences are in the number and size of server rooms, configuration differences, retail/restaurants, and the fact that B17x has a central district heating and cooling system.

Note also that the rating actually decreased for B17x from a baseline of 97 in 2003 to a rating of 91 for 2009 while there was a slight increase for B225. This most likely results from the ongoing commissioning of B225 during the period after the baseline and possible deterioration of B17x performance. For example, the evaporative cooling system and possibly fans running at night, were conditions we knew only for B172. Unknown is how representative these conditions are for the other buildings in the complex. The B172 EUI is most likely under-represented by these results since it is the smallest of the four buildings included (e.g., B171 is ~432 gsf); and the net to gross ratio differences caused by the auditorium in B172. Energy Star data regressions show that smaller buildings tend to have larger EUIs. Data sheets for the two complexes are included in Appendix D.

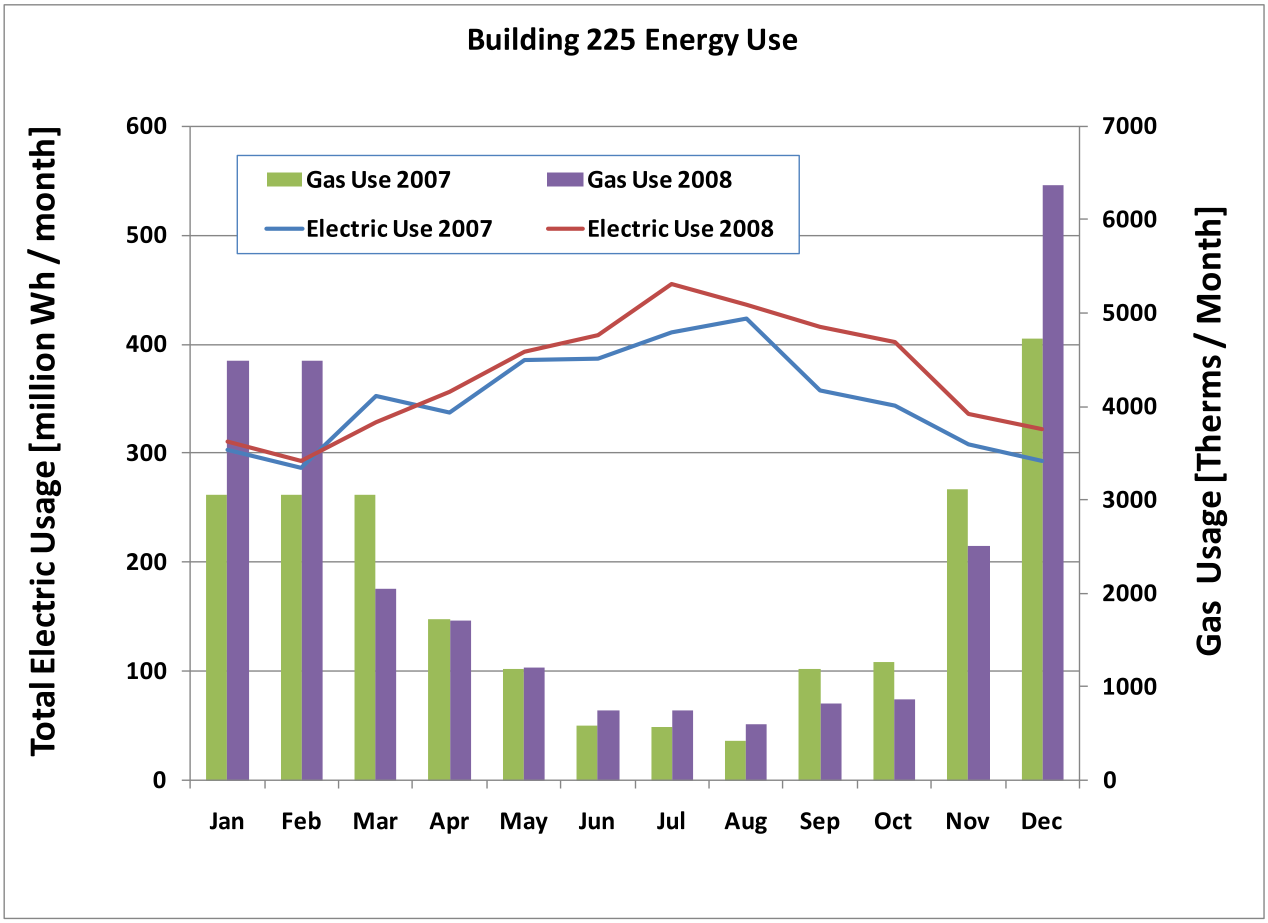

Figure 5-9. B225 monthly utility data for 2007 and 2008

EPA developed the Energy Star rating system to evaluate the energy performance of an individual building. By rating its energy performance on a scale of 1 to 100 it can be compared to similar buildings nationwide. This rating system was developed using statistical analysis of the Department of Energy's Commercial Building Energy Consumption Survey (CBECS) database comparing certain key building characteristics with source energy use. A building is rated by inputting key independent variables (e.g., gross area, number of occupants) and the monthly energy (and water) use for the past year. After weather normalizing, this data is passed through the EPA regression models [EPA 2008] to arrive at a percentile ranking relative to the comparison population. Buildings that rate 75 or greater may qualify for the Energy Star label. In addition, those Energy Star partners who demonstrate continuous improvement or top performance organization-wide may qualify for recognition as Energy Star Leaders.

Note that the EUIs listed in the Energy Star tables are a useful indicator of overall building efficiency even though it masks the reasons for differences. Given differences in building and system design and operating conditions as well as unaccounted for external and service core loads, it is not surprising that the Energy Star results are somewhat different from those of our detailed measurements and modeling analysis, as discussed above in Section 5.

Table 5-7. B225 Energy Star rating summary

Performance Metrics	Current (Ending Date 03/31/2009)	Baseline (Ending Date 12/31/2003)	Energy Star Label	National Average
Energy Performance Rating	98	97	75	50
Energy Use Intensity				
Site (kBtu/ft^2)	43	51	83	110
Source (kBtu/ft^2)	130	144	247	330
Energy Cost				
$/year	$466,751	$408,215	$886,656	$1,184,392
$/ft^2/year	$1.11	$0.97	$2.11	$2.82
Greenhouse Gas Emissions				
MtCO$_2$e/year	1,649	1,875	3,132	4,184
kgCO$_2$e/ft^2/year	4	4	8	10

Table 5-8. B171-174 complex Energy Star rating summary

Performance Metrics	Current (Ending Date 03/31/2009)	Baseline (Ending Date 12/31/2003)	Energy Star Label	National Average
Energy Performance Rating	91	97	75	50
Energy Use Intensity				
Site (kBtu/ft^2)	79	64	107	141
Source (kBtu/ft^2)	209	166	280	370
Energy Cost				
$/year	$1,889,518	$1,367,467	$2,539,345	$3,352,877
$/ft^2/year	$1.74	$1.27	$2.34	$3.09
Greenhouse Gas Emissions				
MtCO$_2$e/year	7,154	5,740	9,614	12,695
kgCO$_2$e/ft^2/year	7	5	9	12

5.6 ENERGY ANALYSIS CONCLUSIONS

We have completed an extensive comparison of the energy performance of B225 and B172 in the Capitol Area East End Complex. We used a variety of methods and metrics, covering a range that included “as measured” data, Energy Star rating, and a modeling approach in which we attempted to adjust the various components and features of B172 to create a building that is as equivalent as possible to B225, with the exception of the HVAC system. In this way, we have estimated to our best ability the true difference in energy performance between a UFAD system in B225 vs. an overhead VAV system in an equivalent building. Note that in all of the comparisons presented below, we use the energy performance of B225 as the reference or base case because of the much more detailed and higher quality trend data available for that building. Difference are reported as B172 compared to B225. Our major findings for each type of comparison made are summarized below.

5.6.1 Comparisons without heating

Due to the fact that the four B17x buildings in CAEEC (171, 172, 173, 174) are served by a district heating and cooling plant, we could not obtain boiler data for B172. In addition, secondary hot water flow was not instrumented at the building level making isolating heating energy measurements for B172 impossible**.** For this reason, we did not include heating energy in our comparison for "as measured" data collected from the two buildings. We also performed some modeling analysis to adjust B172 to be equivalent to B225 ("apples to apples" comparison) that in the first stages did not include heating. Heating was added to our modeling analysis towards the end and our findings are summarized below in Section 5.6.2.

- **As measured**: Based on monitored secondary cooling and fan energy use, the measurement data indicates improved efficiency for the UFAD system vs. the OH system, as cooling energy is 31% higher and total fan energy is 50% higher for B172 compared to B225. Total annual HVAC energy is 31% higher for B172 compared to B225, despite the fact that total internal load energy demand (lights and small power) is 13% less for B172 relative to B225. When HVAC and internal loads are combined, the total annual building electrical energy use for B172 is only 14% higher than B225.
- **Modeled equivalent central plant and fans**: In this first step towards our full "apples to apples" comparison, we estimated the impact of equalizing the components of the central plant and AHU of B172 with those of B225. Total annual building energy use for B172 is now 5% less than B225 while HVAC energy use for B172 is still estimated to be 9% higher than B225. These results indicate that the HVAC system in B225 performs better than in B172. Despite having lower internal loads (13% lower, same as in "as measured" above), B172 (with its overhead air distribution system) uses more HVAC energy compared to the UFAD system in B225, even when the central systems are equivalent.
- **"Apples to apples" without heating**: In this next step towards a full "apples to apples" comparison, we identified all major design and operating differences between the buildings, B225 vs. B172, and the HVAC systems, UFAD vs. OH. These factors included building configuration, occupancy, lighting and plug loads, thermostat setpoints, supply air temperature, and system type. When all of these additional adjustments to B172 were made, total annual HVAC energy use is 21% higher for B172 compared to B225, representing a sizeable difference. With the equivalent internal loads applied for this comparison, total annual building energy use is 7% higher for B172 compared to B225.

5.6.2 Comparisons with heating

Although we had unreliable heating data for B172 (see Appendix B), heating has been shown to be an important consideration for the performance of UFAD systems. In this section we present two comparisons between B225 and B172 that include heating. The first is our full "apples to apples" modeled comparison and the second is the Energy Star Rating.

"Apples to apples" with heating: Due to the fact that UFAD typically has no heating in interior zones and there is less reheat than for OH, we have attempted to estimate its impact in order to provide a more complete comparison between the two systems. We derived heating energy (as described in Appendixes B and C) from "as measured" data for both buildings. However, this does not include the effects of configuration changes shown to be 31% in Table 5-4 for heating. When we apply this correction, B172 heating EUI for the “apples to apples” case is 14% greater than B225; total HVAC EUI including heating is 20% greater for B172 when it has a configuration like B225. Total annual building energy use is 8% higher for B172 compared to B225.

Energy Star rating: Based on the Energy Star results, both B225 and B172 show excellent energy performance overall. B225 showed a site Energy Star rating of 98, well above 75 required to receive the Energy Star label; the associated site and source energy use intensities (EUI) are 43 kBtu/ft^2·yr and 130 kBtu/ft^2·yr, respectively. This is 38% better than of the national average EUI for buildings of this type and represents a very energy efficient building based on this metric of whole-building energy performance.

Energy Star data for B172 could not be independently obtained since it is not separately metered from the B171-174 complex, which is served by a central district heating and cooling system. The Energy Star rating for the ***entire complex*** was 91, which is close to the B225 score of 98. However, the site EUI is 83% greater for the B17x complex (61% greater on a source basis). The fact that the two ratings are so close together is a result of the Energy Star methodology and the substantial differences between B225 and the B17x complex.

6 OCCUPANT SATISFACTION SURVEY

An important part of the field study methodology was to assess the building occupants' opinions about the quality of their indoor working environment. To accomplish this, the research team conducted periodic surveys using the CBE web-based occupant satisfaction survey [CBE 2015]. Figure 6-1 shows a timeline of the surveys (referred to as post-occupancy evaluations, or POEs) conducted in both B225 and B172. The surveys that were completed include the following: (1) Baseline Field Study of Block 225 [Douglas et al. 2002]; (2) Baseline Field Study of Block 172 [Shirai and Bauman 2003] (Note, this baseline survey of Department of Education (CDE) employees who were scheduled to move into Block 172, instead served as additional baseline data for Block 225 – it was decided that all CDE employees would move into Block 225) ; (3) First POE of Block 225 [Shirai et al. 2003], (4) Baseline Field Study of Block 172 – Dept. of Health Services (DHS) [Shirai et al. 2004] (Note, this second baseline survey was conducted on the DHS employees who subsequently moved into Block 172); (5) Second POE of Block 225 [Shirai and Bauman 2004]; (6) Third POE of Block 225 and 1st POE of Block 172 [Bauman and Lukaschek 2006]; and (7) Fourth POE of Block 225 and Second POE of Block 172. Table 6-1 and Table 6-2 provide summaries of the survey periods and response rates.

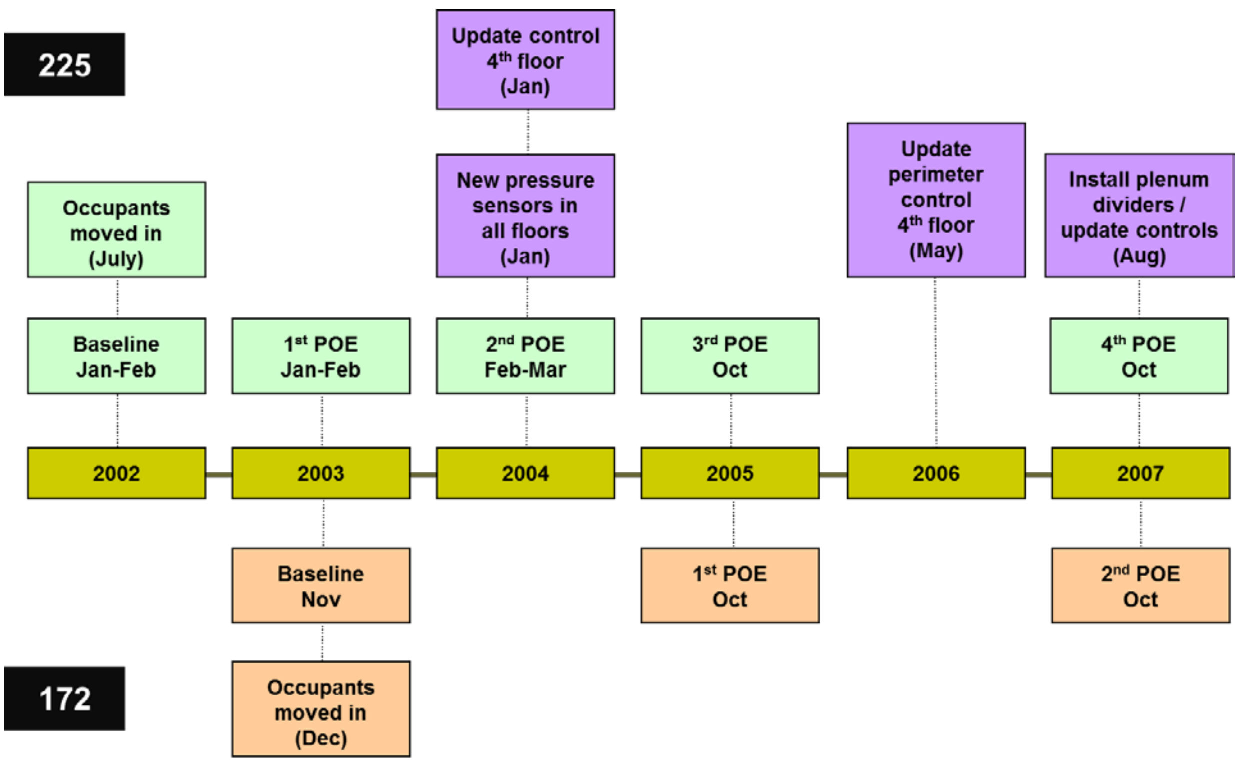

Figure 6-1. Timeline of occupant satisfaction surveys (POEs) in B225 and B172. Legend: green – B225; orange – B172; purple – controls

6.1 FIRST POST-OCCUPANCY EVALUATION OF BLOCK 225

The first post-occupancy evaluation survey conducted Jan. 21 – Feb. 7, 2003, allowed occupant satisfaction results approximately six months after occupancy in the new B -225 building to be compared with results from the baseline survey conducted in buildings prior to the move into B-225. As shown in Table 6-1, survey responses were obtained from 516 employees out of a total number of 1,106 who were asked to participate, representing a 47% response rate. For purposes of comparing the B-225 POE #1 survey results with those from the B-225 Baseline survey, we analyzed the data from the 334 occupants who took both surveys.

Figure 6-2 compares average occupant satisfaction ratings for each of the seven different environmental categories addressed by the survey, as well as the two questions about general satisfaction with the building and personal workspace. The scores are presented in terms of the 7-point satisfaction scale used in the survey, ranging from –3 (very dissatisfied) to +3 (very satisfied) with 0 being neutral. Results shown for each category represent the average score for the 2-4 questions that were asked pertaining to that category.

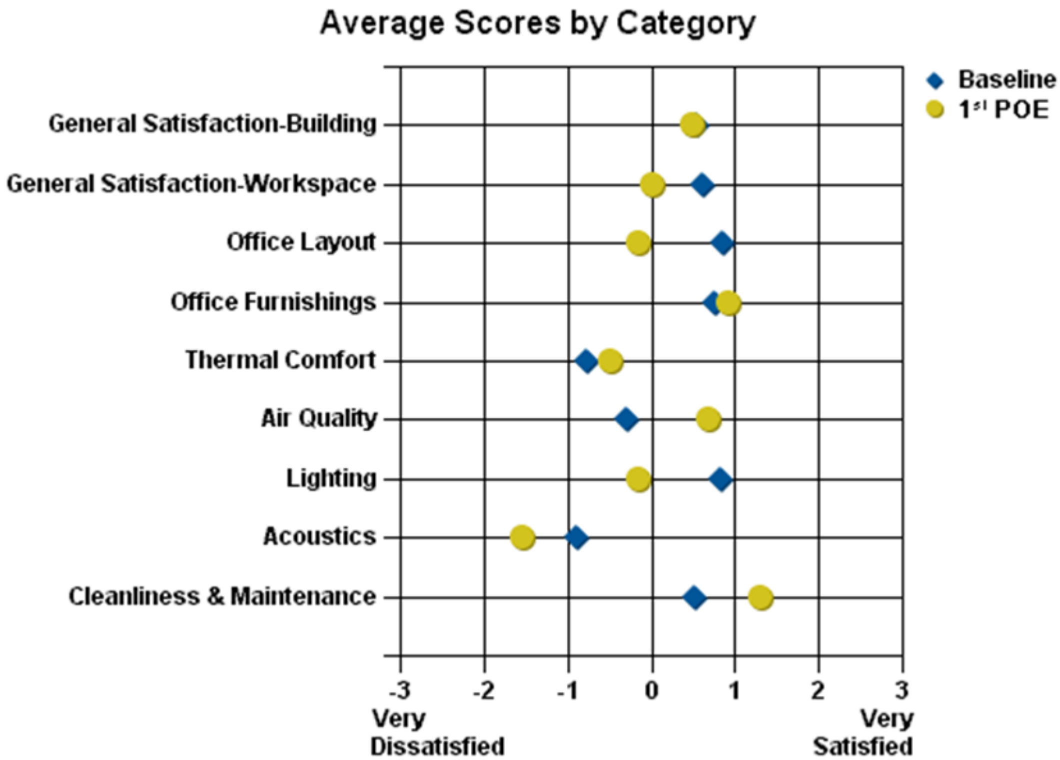

Figure 6-2. Average satisfaction ratings by category from Baseline and 1st POE surveys of Block 225

Table 6-1. Summary of Block 225 Survey Periods and Response Rates

	Baseline	1st POE	2nd POE	3rd POE	4th POE
Survey period	Jan. 22 – Feb. 6, 2002	Jan. 21 – Feb. 7, 2003	Feb. 23 – Mar. 12, 2004	Oct. 3-14, 2005	Oct. 10-26, 2007
Invitations	1083	1106	1353	1316	1316
Valid responses	610	517	711	638	653
Response rate	56%	47%	53%	48%	50%

Table 6-2. Summary of Block 172 Survey Periods and Response Rates

	Baseline	**1st POE**	**2nd POE**
Survey period	Nov. 4-26, 2003	Oct. 3-14, 2005	Oct. 10-26, 2007
Invitations	533	609	609
Valid responses	211	249	217
Response rate	40%	41%	36%

General satisfaction with Block 225 was found to be nearly identical to that for the Block 225 baseline buildings. General satisfaction with their personal workspace, however, was noticeably lower for respondents in Block 225 compared to their previous responses in the baseline buildings. Given that Block 225 was a brand new building that had been recently certified by the U.S. Green Building Council as LEED Gold 2.0, this was, at first appearance, a surprising result. A review of the survey responses for the seven environmental categories (some higher and some lower than the corresponding baseline data) helps to explain the reasons behind these findings. The major survey results for the seven environmental categories from the first POE of Block 225 are summarized below.

OFFICE LAYOUT. All four questions in the office layout category (amount of space, visual privacy, ease of interaction with co-workers, and impact on job performance) were rated significantly lower than the results from the baseline survey. After discussions with DGS staff, it was learned that workers in the baseline buildings were allocated workstations of a variety of sizes, many of which were larger than the standard 8 ft by 8 ft cubicles in open plan office space in Block 225. In addition, there were more private offices in the baseline buildings. It was therefore understandable that occupant satisfaction was lower with the smaller workstations in Block 225. Many comments from the survey indicated concern about the lack of space and privacy.

OFFICE FURNISHINGS. The overall satisfaction rating for the office furnishings category (comfort of chair, adjustability of furniture, colors and textures, impact on job performance) was nearly identical to that obtained from the baseline survey. On the 7-point satisfaction scale, the overall rating for this category was just below +1.

THERMAL COMFORT. The overall satisfaction rating for the thermal comfort category (temperature, humidity, air movement, and impact on job performance) was very close to zero (neutral) and only slightly higher than the result from the baseline survey. With the installation of a sophisticated UFAD system in Block 225 giving individuals some amount of control over their local thermal conditions, greater satisfaction with temperature had been anticipated, especially compared to the baseline buildings constructed in the 1950s and 1970s. One of the most common complaints was that the building was too cold during the January (winter) survey period with thermostat setpoints set at 72°F. Temperature measurements and discussions with the facility management staff demonstrated that lack of familiarity with UFAD technology may have led to the use of some design and operating strategies that needed to be adjusted and refined during the commissioning process. These adjustments were still underway at the time of the first POE.

AIR QUALITY. The overall satisfaction rating for the air quality category (air quality, impact on job performance) exhibited a significant increase over the baseline rating, the greatest such increase for any one category. It is believed that the floor supply UFAD system contributed to this perception by improving air movement in the occupied zone (air movement, from thermal comfort category, was rated significantly higher than the baseline survey, too) and providing improved ventilation effectiveness. Another important factor is the low emission building materials used in this LEED Gold building. Indoor air quality measurements conducted during the first year of occupancy in B-225 reported significantly lower concentrations of chemical pollutants.

LIGHTING. The overall satisfaction rating for the lighting category (amount of light, lighting quality, impact on job performance) was less than zero (neutral) and significantly less than the corresponding rating from the baseline survey. Given the attention that had been paid to the task/ambient lighting system design in Block 225, this was a surprising result. However, a review of the survey comments indicated quite clearly that the lighting problems were largely due to the task light, which had too harsh of a bulb and did not illuminate enough of the work surface. The suspended indirect ambient lighting system, which is controlled in response to available daylight, appeared to be working properly. This information was passed on to building management in May 2003 and corrective actions were underway.

ACOUSTIC QUALITY. The overall satisfaction rating for the acoustic quality category (noise level, sound privacy, impact on job performance) was by far the worst rating of any category on the survey, and significantly worse than the result from the baseline survey. In particular, sound privacy received a rating of –2 compared to the already poor baseline rating of –1.45. As discussed previously under office layout, open plan offices are typically characterized by a lack of sound privacy. In the case of Block 225, the dissatisfaction with the small cubicles probably contributed to the severe dissatisfaction with acoustic quality. Many survey comments described the lack of sound privacy, distraction from conversations in nearby cubicles, and difficulty of conducting confidential meetings.

CLEANLINESS AND MAINTENANCE. The overall satisfaction rating for the cleanliness and maintenance category (general cleanliness, cleaning service, general maintenance, impact on job performance) received the highest rating of any category and was significantly higher than the baseline survey result. This was an expected result as the building was brand new and had been well maintained since occupancy began.

6.2 OTHER SURVEY RESULTS

In this section we provide an overview of other survey results that were obtained during the project. Figure 6-3 presents results for the last two POE surveys conducted in B-225 (POE 3 and POE 4) in comparison to the large CBE benchmark database, containing 37,309 individual survey responses collected from several hundred buildings as of April 2008. This shows the trend in occupant satisfaction in B-225 over the last two years of the project with POE 3 done in October 2005 and POE 4 done in October 2007. For nearly every category, occupant satisfaction is equal or higher for POE 4 compared to POE 3, so the trend was definitely upward over this period in B-225. It is very likely that this positive trend is in part due to the commissioning, controls and operational improvements that the B-225 building operators implemented during the years of this study. The overall results, however, were not significantly different from the CBE benchmark. In comparison to the CBE benchmark, POE 4 shows some improvement for general building satisfaction, thermal comfort, air quality, and cleanliness, but still rates below for general workspace satisfaction, office layout, lighting, and acoustic quality. In most cases, these lower ratings are likely due to the primary office configuration in B-225: small cubicle workstations in an open plan office.

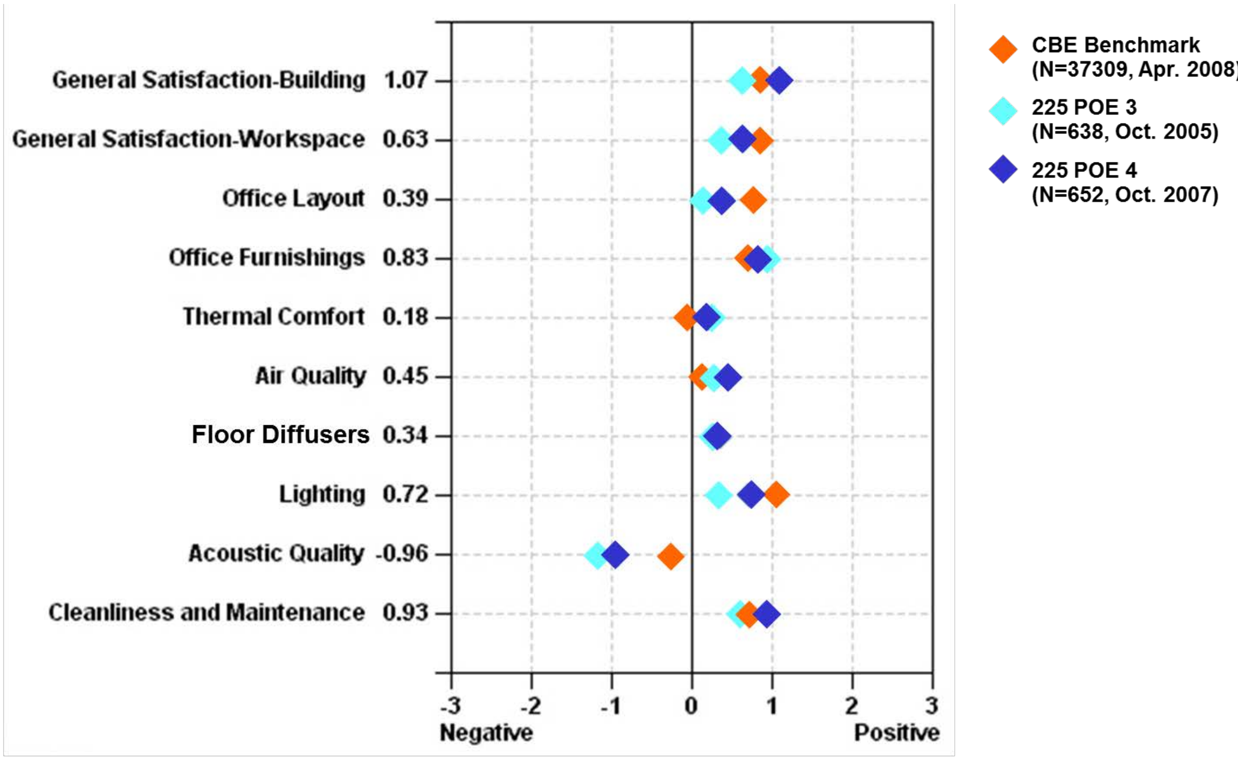

Figure 6-3. Average satisfaction ratings for 3rd and 4th POE surveys of Block 225 vs. CBE benchmark

Figure 6-4 presents results for the last two POE surveys conducted in B-172 (POE 1 and POE 2) in comparison to the large CBE benchmark database. We conducted these two surveys at the same times as POE 3 and POE 4 in B-225, so they represent the trend during the last two years of the project. In the case of B-172, for nearly every category, occupant satisfaction is equal or lower for POE 2 in relation to POE 1, demonstrating the opposite trend over this period compared to B-225. Unlike B-225, the building operations staff did not take any specific extra commissioning or control actions in B-172 during this period. A gradual decrease in occupant satisfaction over time represents a more typical response in buildings that we have surveyed over the years at CBE. For most categories, the results are fairly close to the CBE benchmark database. In comparison to the CBE benchmark, POE 2 shows some improvement for general building satisfaction, thermal comfort, and air quality, but rates slightly below for lighting, acoustic quality, and cleanliness.

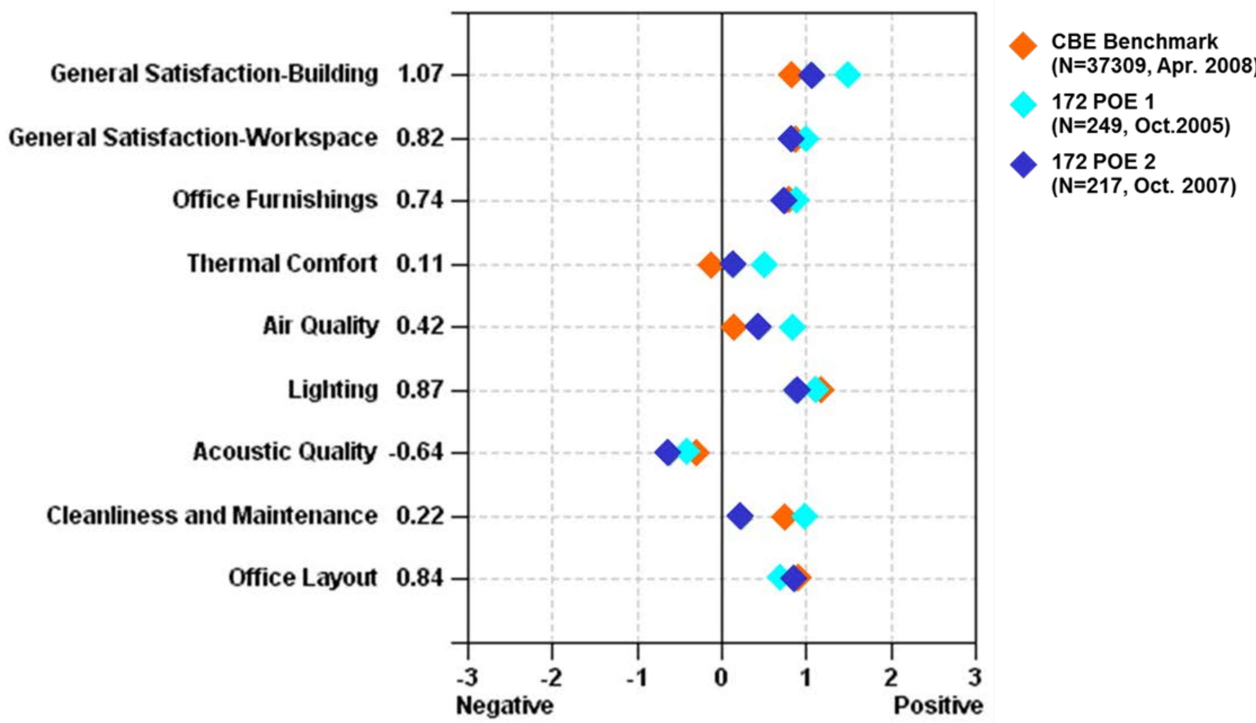

Figure 6-4. Average satisfaction ratings for 1st and 2rd POE surveys of Block 172 vs. CBE benchmark

Figure 6-5 compares results for the two final POE surveys conducted during October 2007 in the two buildings: POE 4 in B-225 and POE 2 in B-172. The satisfaction ratings are generally positive and very nearly the same for most of the categories, which indicates that occupants in both buildings had a similar response to their building and its indoor environment. While the research team had hoped to observe differences between the two buildings with their two different air distribution systems (UFAD and overhead), this did not prove to be the case for these survey questions. Given that all buildings in the Capitol Area East End Complex followed a standardized interior open plan office design criteria, and all occupants are State employees, it is not that surprising to see such similar results. B-225 did rate slightly lower for two categories: office layout and acoustic quality. We suspect that this difference was due to the higher occupant density in B-225 compared to B-172, which generally gave less space to each occupant and therefore reduced satisfaction with acoustic privacy in B-225. B-225 did demonstrate greater occupant satisfaction with cleanliness and maintenance.

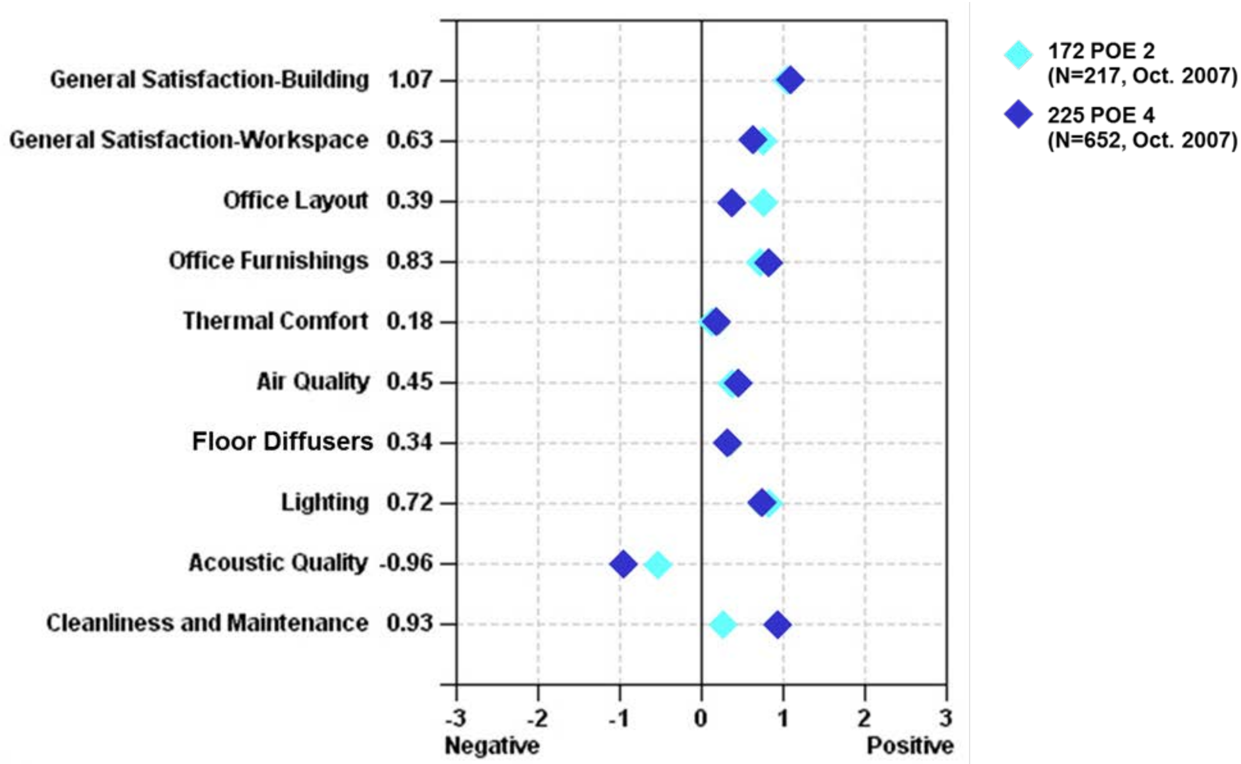

Figure 6-5. Average satisfaction ratings for 2rd POE survey of Block 172 vs. 4th POE survey of Block 225

Figure 6-6 presents results for the first (POE 1) and last (POE 4) surveys conducted in B-225 in comparison to the large CBE benchmark database. This figure was previously reported by Fentress et al. (2009). At the time of this analysis, the benchmark database included 430 buildings and 47,929 individual surveys. The survey results are generally positive, considering that Block-225 is a large open plan office building. A key observation from Figure 6-6 is that the results for POE 4 indicate that, in most categories, occupant satisfaction has increased significantly since the first POE. Three categories (general building, thermal comfort, air quality) were likely influenced by the existence of the UFAD system and the efforts of recommissioning and tuning-up the building's HVAC operation during the course of the project period. Floor diffusers give occupants a sense of personal control while increasing air movement and available fresh air.

All categories were rated above zero except acoustic quality in POE 4. The low acoustic quality rating is not surprising for a large open plan cubicle layout and is a contributing factor to the average or below average ratings for general workspace, office layout, and office furnishings. Improvements to the task lighting resulted in a large increase in satisfaction with lighting quality. The decline in satisfaction with cleanliness/maintenance and, to some extent, air quality since the first POE is likely due to the building's increasing age.

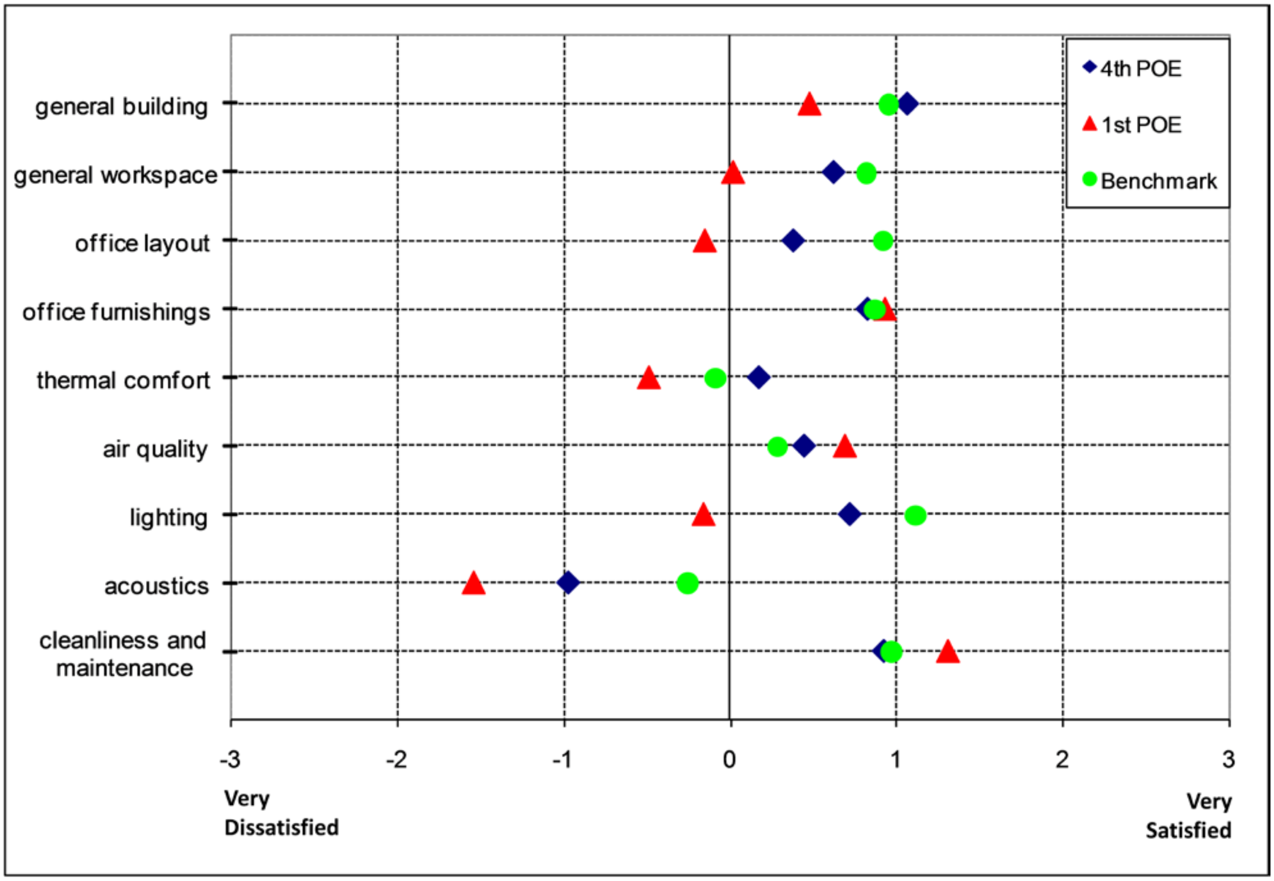

Figure 6-6. Average satisfaction ratings for 1st and 4th POE surveys of Block 225 vs. CBE benchmark

In conclusion, although the occupant surveys did not identify clear differences between B-225, the UFAD building, and B-172, the conventional overhead air distribution building, an important lesson learned from the repeated surveys between 2003 and 2007 is the value of continuous commissioning of a building's HVAC system. In the case of B-225, efforts by building operations staff and the research team led to an improved understanding of the unique features of the underfloor air distribution system, representing a new building technology in California State buildings, and as a result, greater satisfaction on the part of the building occupants with the quality of the indoor environment in B-225.

7 SUMMARY AND CONCLUSIONS

7.1 OVERALL ASSESSMENT OF BUILDING PERFORMANCE

7.1.1 Energy performance

We have completed an extensive comparison of the energy performance of B225 and B172 in the Capitol Area East End Complex. We used a variety of methods and metrics, covering a range that included "as measured" data, Energy Star rating, and a modeling approach in which we attempted to adjust the various components and features of B172 to create a building that is as equivalent as possible to B225, with the exception of the HVAC system. In this way, we have estimated to our best ability the true difference in energy performance between a UFAD system in B225 vs. an overhead VAV system in an equivalent building. Note that in all of the comparisons presented below, we use the energy performance of B225 as the reference or base case because of the much more detailed and higher quality trend data available for that building. Difference are reported as B172 compared to B225. Our major findings for each type of comparison made are summarized below.

7.1.1.1 Comparisons without heating

Due to the fact that the four B17x buildings in CAEEC (171, 172, 173, 174) are served by a district heating and cooling plant, we could not obtain boiler data for B172. In addition, secondary hot water flow was not instrumented at the building level making isolating heating energy measurements for B172 impossible**.** For this reason, we did not include heating energy in our comparison for "as measured" data collected from the two buildings. We also performed some modeling analysis to adjust B172 to be equivalent to B225 ("apples to apples" comparison) that in the first stages did not include heating. Heating was added to our modeling analysis towards the end and our findings are summarized below in Section 5.6.2.

- **As measured**: Based on monitored secondary cooling and fan energy use, the measurement data indicates improved efficiency for the UFAD system vs. the OH system, as cooling energy is 31% higher and total fan energy is 50% higher for B172 compared to B225. Total annual HVAC energy is 31% higher for B172 compared to B225, despite the fact that total internal load energy demand (lights and small power) is 13% less for B172 relative to B225. When HVAC and internal loads are combined, the total annual building electrical energy use for B172 is only 14% higher than B225.
- **Modeled equivalent central plant and fans**: In this first step towards our full "apples to apples" comparison, we estimated the impact of equalizing the components of the central plant and AHU of B172 with those of B225. Total annual building energy use for B172 is now 5% less than B225 while HVAC energy use for B172 is still estimated to be 9% higher than B225. These results indicate that the HVAC system in B225 performs better than in B172. Despite having lower internal loads (13% lower, same as in "as measured" above), B172 (with its overhead air distribution system) uses more HVAC energy compared to the UFAD system in B225, even when the central systems are equivalent.
- **"Apples to apples" without heating**: In this next step towards a full "apples to apples" comparison, we identified all major design and operating differences between the buildings, B225 vs. B172, and the HVAC systems, UFAD vs. OH. These factors included building configuration, occupancy, lighting and plug loads, thermostat setpoints, supply air temperature, and system type. When all of these additional adjustments to B172 were made, total annual HVAC energy use is 21% higher for B172 compared to B225,

representing a sizeable difference. With the equivalent internal loads applied for this comparison, total annual building energy use is 7% higher for B172 compared to B225.

7.1.1.2 Comparisons with heating

Although we had unreliable heating data for B172 (see Appendix B), heating has been shown to be an important consideration for the performance of UFAD systems. In this section we present two comparisons between B225 and B172 that include heating. The first is our full "apples to apples" modeled comparison and the second is the Energy Star Rating.

- **"Apples to apples" with heating**: Due to the fact that UFAD typically has no heating in interior zones and there is less reheat than for OH, we have attempted to estimate its impact in order to provide a more complete comparison between the two systems. We derived heating energy (as described in Appendixes B and C) from "as measured" data for both buildings. However, this does not include the effects of configuration changes shown to be 31% in Table 5-4 for heating. When we apply this correction, B172 heating EUI for the "apples to apples" case is 14% greater than B225; total HVAC EUI including heating is 20% greater for B172 when it has a configuration like B225. Total annual building energy use is 8% higher for B172 compared to B225.

- **Energy Star rating**: Based on the Energy Star results, both B225 and B172 show excellent energy performance overall. B225 showed a site Energy Star rating of 98, well above 75 required to receive the Energy Star label; the associated site and source energy use intensities (EUI) are 43 kBtu/ft^2·yr and 130 kBtu/ft^2·yr, respectively. This is 38% better than of the national average EUI for buildings of this type and represents a very energy efficient building based on this metric of whole-building energy performance.
  Energy Star data for B172 could not be independently obtained since it is not separately metered from the B171-174 complex which is served by a central district heating and cooling system. The Energy Star rating for the ***entire complex*** was 91, which is close to the B225 score of 98. However, the site EUI is 83% greater for the B17x complex (61% greater on a source basis). The fact that the two ratings are so close together is a result of the Energy Star methodology and the substantial differences between B225 and the B17x complex.

7.1.2 Occupant satisfaction

The two final POE surveys conducted during October 2007 in the two buildings found that the satisfaction ratings were generally positive and very nearly the same for most of the categories, indicating that occupants in both buildings had a similar response to their building and its indoor environment. While the research team had hoped to observe differences between the two buildings with their two different air distribution systems (UFAD and overhead), this did not prove to be the case for these survey questions. Given that all buildings in the Capitol Area East End Complex followed a standardized interior open plan office design criteria, and all occupants are State employees, it is not that surprising to see such similar results. B-225 did rate slightly lower for two categories: office layout and acoustic quality. We suspect that this difference was due to the higher occupant density in B-225 compared to B-172, which generally gave less space to each occupant and therefore reduced satisfaction with acoustic privacy in B-225. B-225 did demonstrate greater occupant satisfaction with cleanliness and maintenance.

Although the occupant surveys did not identify clear differences between B-225, the UFAD building, and B-172, the conventional overhead air distribution building, an important lesson learned from the repeated surveys between 2003 and 2007 is the value of continuous commissioning of a building's HVAC system. In the case of B-225, efforts by building operations staff and the research team led to an improved understanding of the unique features of the underfloor air distribution system, representing a new building technology in California State buildings, and as a result, greater satisfaction on the part of the building occupants with the quality of the indoor environment in B-225.

7.2 LESSON LEARNED FOR B225

Listed below are key lessons learned during our extended field study and experiences with B225. Some of these topics were presented by Fentress et al. (2009).

- Thermal decay – Temperature gain (thermal decay) to the supply air in the underfloor plenum was larger than expected in this 50,000-ft^2 floor plate building. The control of thermal decay was improved by dividing the plenum into smaller-sized zones (using plenum dividers or other means), particularly along different exposures of the perimeter zone. Nevertheless, there still exists some amount of temperature gain within the underfloor plenum. This is a normal and expected outcome with UFAD systems and must be accounted for in the design and operation of the building (see recommendations in Section 7.3).
- UFAD system control – It is important to remember that each separate underfloor plenum zone (created when the plenum is divided up as described above) will operate at very nearly the same uniform pressure. To prevent pressure control instabilities, each plenum zone and the interior conditioned space above it must be controlled based on a single average interior space thermostat (if more than one exist), a single plenum pressure setpoint (based on one or more pressure transducers), and a single control damper signal serving all VAV supply dampers in that plenum zone. Each plenum zone should have one high quality and properly sized pressure sensor that can measure and control plenum pressures down to zero (preferred range: ±0.15 in. H_2O).
- Reset strategies – Since heating is provided only in the perimeter zones, supply air temperature reset strategies must be carefully considered in plenum zones serving both interior and perimeter spaces. During periods of peak cooling demand at the perimeter, reducing the supply air temperature entering the plenum (to address perimeter loads) must be traded off against overcooling occupants in the interior.
- Perimeter sill grilles – While perimeter sill grilles are attractive architecturally, it is preferred to install perimeter diffusers at floor level to reduce the vertical projection (mixing) of supply air in the room, thereby improving stratification and energy performance in the perimeter zones.
- The extensive network of air highways in B225 appears to have leakage problems due to faulty design, fabrication, and lack of continued maintenance since the building opened. The integrity of well-sealed air highways and the underfloor plenum must be preserved over the life of the building.
- Technical, BMS trend logs – BMS problems, and lack of controls commissioning at the beginning of the project caused significant delays and problems with collecting monitoring data and complicated the commissioning and monitoring process.
- Building commissioning and operations – An important lesson learned from the repeated surveys between 2003 and 2007 is the value of continuous commissioning of a building's HVAC system. In the case of B-225, efforts by building operations staff and the research team

led to an improved understanding of the unique features of the underfloor air distribution system, representing a new building technology in California State buildings, and as a result, greater satisfaction on the part of the building occupants with the quality of the indoor environment in B-225.

7.3 RECOMMENDATIONS FOR DESIGN AND OPERATION OF FUTURE UFAD PROJECTS

Based on this project and the authors experience, the following are factors that we recommend be considered for future UFAD projects. Much can be learned from the newest version of the ASHRAE UFAD design guide [ASHRAE 2013].

7.3.1 General guidelines

7.3.1.1 System design

There are multiple ways to design UFAD systems; B225 represents only one of them, albeit currently a popular one. The new ASHRAE UFAD Guide shows examples of many of these in Chapter 5. The main factors are plenum design and configuration, and the associated air distribution methods; perimeter system design; and diffuser type and number. All of these factors should be carefully considered to address the primary issues of plenum temperature rise, perimeter system supply temperature, perimeter system fan energy use, and room air stratification. We generally recommend configurations that deliver lower supply temperature to the perimeter system, and maximize stratification (within reasonable limits).

7.3.1.2 HVAC equipment selection

As has been demonstrated in this project, high efficiency equipment is a minimum requirement for these systems since it has a significant effect on overall performance. Fans, chillers, and boilers should all be specified with the highest possible efficiency ratings. Proper outside air systems are also important, in particular powered exhaust systems are recommended over return fans. Condensing boilers are recommended due to their high efficiency and turndown ability.

Also demonstrated by this (and other UFAD projects) is that the low overall efficiency (~15%) of fan coil units for perimeter zones may have significant impacts on overall fan energy use. Future UFAD applications should investigate opportunities for perimeter design solutions that eliminate underfloor fan coil units, if possible, as described by Taylor (2016).

7.3.1.3 Floor diffuser selection

The goal of diffuser selection is to ensure adequate room air stratification in all spaces while maintaining thermal comfort (see below for more discussion of stratification). Linear diffusers, which are capable of delivering larger volumes of air, are typically used only in perimeter zones. These diffusers are known to have high vertical throws, which can cause high mixing and therefore limited stratification. This is something to be aware of – look for newer units on the market that might reduce the amount of mixing (for example, adjustable vanes and other design features that produce a lower vertical throw). In general, alternatives to standard linear bar grilles should be considered.

For interior spaces, it is recommended to install smaller diffusers that may be located in the near vicinity of occupants. In open plan offices, a good strategy is to install one diffuser per permanent occupant so that each person has a sense of personal control. There are a wide variety of smaller floor diffusers on the market, including the common round swirl diffuser, a variable-air-volume square diffuser, and many others (some manually-adjustable and others automatic). One relatively newer model is the horizontal discharge/low throw diffuser, similar in size and appearance to the standard swirl diffuser. This diffuser delivers supply air with a very low vertical throw, thereby reducing the amount of mixing and ensuring higher amounts of stratification in the space. A recent laboratory study demonstrated that these diffusers produce stratification that resembles that of a displacement ventilation system [Raftery et al. 2015].

An important benefit of UFAD systems is to recognize that smaller "personal" diffusers should be easily adjustable so that occupants can control them to satisfy their own personal preferences. The ability to have personal control has been shown to dramatically improve satisfaction with thermal comfort, and depending on how effective it is, may lead to significant reductions in cooling energy use by allowing increased thermostat cooling setpoints.

7.3.2 Room air stratification

Under cooling operation of a UFAD system, the floor-to-ceiling airflow pattern supports the rising thermal plumes from heat sources to create stratification. When pollutants are associated with heat sources (e.g., body odor) the pollutants will also tend to stratify in the space with warmer and more polluted conditions near the ceiling and cooler and fresher conditions in the occupied zone. Stratification requires that the assumption of a uniform, well-mixed space is not used when making operational changes to maintain comfort, ventilation, and energy performance of the UFAD system.

7.3.2.1 Airflow and room air stratification

The goal of a high performing UFAD system (under cooling operation) is to maintain comfortable conditions while minimizing energy use. As shown in chapter 2 of the new ASHRAE UFAD Guide [ASHRAE 2013], the amount of stratification is primarily determined by the room supply air volume relative to cooling load plus the impact of mixing caused by diffuser vertical throw height. Higher airflow rates will tend to reduce stratification (greater mixing) and produce higher fan energy usage. It is therefore important to specify and maintain a room supply airflow rate that produces a reasonable amount of stratification (3-4°F between head and ankle heights for a standing occupant is recommended). Experience with UFAD systems has shown that the average airflow rate should be about equal or slightly higher than that of a typical overhead mixing system.

7.3.2.2 Thermal comfort and room air stratification

In a stratified space, it is important to keep in mind that controlling comfort based on a single thermostat reading at 4-ft height will not be the same thing as controlling a well-mixed overhead air distribution system. Temperatures near the floor will be cooler, so it may be necessary to raise the 4-ft thermostat setpoint to provide overall comfort. The primary operating parameters to adjust are the thermostat setpoint temperature, supply air temperature, and plenum pressure setpoint. Thermostat and plenum pressure setpoints are often linked in the UFAD system control strategy. Raising the 4-ft setpoint temperature will decrease the airflow rate (reducing fan energy) in a VAV system. The approach for achieving comfort in the occupied zone is to maintain an average temperature (between head and ankle level) that is equivalent to the setpoint for an overhead mixing system and to aim for a head-ankle temperature difference of about 3-4°F. Too little stratification implies higher than necessary airflow rates, and correspondingly higher than necessary fan energy usage. Too extreme stratification (>7°F between head and ankle heights for a standing occupant) will lead to occupant discomfort, as specified by ASHRAE Standard 55 [ASHRAE 2013a].

7.3.3 Underfloor air supply plenums

The use of the space under a raised access floor system (referred to as the underfloor plenum) to deliver conditioned air directly into the occupied zone of the building is the key design feature that distinguishes UFAD systems from conventional ducted overhead air distribution systems. The most common approach for distributing air in a UFAD system is to operate the plenum as a pressurized air supply plenum (this was used in B225). In pressurized plenums, one or more air-handling units (AHU) are controlled to maintain a small, but positive pressure in the underfloor plenum relative to the conditioned space (room). Typical plenum pressures at design airflow rates fall in the range of 0.05 - 0.1 in. H_2O (12.5 - 25 Pa). There are three key issues to be aware of in the design and operation of pressurized underfloor plenums: (1) air leakage, (2) airflow and pressure distribution, and (3) supply air temperature rise.

7.3.3.1 Underfloor plenum leakage

Uncontrolled air flowing into the occupied space, to the return path or even out of the envelope must be minimized in pressurized underfloor plenum designs. There are two primary types of uncontrolled air leakage from a pressurized underfloor plenum.

- Category 1: Construction Quality Leakage -- The most detrimental to system performance is leakage to unconditioned spaces such as wall cavities (leading to increased risk of condensation), columns, and other short-circuiting pathways to the return plenum, outside the building, or back to the return of the floor below via fire stops or other unsealed floor slab penetrations. These leaks represent air loss that is detrimental to the operation of the system, causing an increase in fan power and possible loss of ability to condition the space properly causing occupant discomfort.
- Category 2: Floor Leakage -- Leakage from the plenum into the occupied space is a class of leakage that has varying consequences depending on a number of factors. In general, this leakage is not necessarily detrimental to the operation of the system. However, if the leakage rate is large, or if it occurs at the wrong place it may cause comfort problems. These leaks occur through floor panel gaps, electrical outlets, through closed diffusers and other floor openings, and joints at the edges of the floor and around columns.

It is important that proper attention be given to the sealing of edge details all around the underfloor plenum, including window-wall connections to the slab, interior walls, along pipe chases, stair landings, elevators, and HVAC shaft walls during the construction phase of the project. Even if this is done, the integrity of a “well-sealed” underfloor plenum must be preserved over the lifetime of the building, as subsequent work (for example, running IT cabling) can easily lead to new penetrations. If this is not done carefully, these types of leaks will be the most difficult to locate and fix later in the project. See the ASHRAE *UFAD Guide* for further discussion of recommendations for sealing details [ASHRAE 2013].

7.3.3.2 Airflow and pressure distribution

The primary goal of acceptable airflow performance in underfloor plenums is to deliver the required amount and temperature of air to every location on the floor plate served by the plenum. In pressurized plenums this translates to maintaining, as close as possible, a uniform air pressure throughout the plenum equal to the pressure setpoint. A full-scale experimental study conducted in 1999 showed that uniform pressure and airflow distribution is achievable with plenum heights as low as four inches (100 mm) [Bauman et al. 1999]. When this type of uniform pressure control is maintained, every pressure dependent diffuser served by the plenum will deliver the same volume of air as other diffusers of the same type and opening setting. In perimeter zones and other areas where fan-driven diffusers are often employed, airflow delivery will be controlled by the local fan and will not be significantly impacted by the pressure maintained in the plenum.

7.3.3.3 Supply air temperature rise

Supply air temperature rise is defined as the difference between the temperature of the primary supply air entering the underfloor plenum through plenum inlets and the temperature of the air leaving the plenum through floor diffusers, or other terminal devices such as fan-coil units. In all practical applications of UFAD systems in commercial buildings, the supply plenum is operated in cooling mode, meaning that the underfloor plenum creates a relatively cool reservoir of air extending across the entire building floorplate, establishing large-area pathways for heat to enter the supply plenum. As reported in the new ASHRAE UFAD Guide [ASHRAE 2013], extensive research involving simulation, laboratory, and field studies (including measurements in B225) has demonstrated that the amount of heat gain entering the underfloor plenum, and leading to supply air temperature rise, can be substantial.

One of the most commonly observed operational challenges resulting directly from plenum supply air temperature rise is the following scenario encountered in an open plenum serving both interior and perimeter spaces, but with all plenum inlets located in the interior: building operators frequently decrease the supply air temperature from the air handler entering the plenum (in the interior zone) to offset supply air temperature rise and provide adequate cooling in the perimeter zone. However, if this supply temperature reset is not done carefully, overly cool diffuser discharge temperatures in the interior zone will increase the likelihood of complaints of overcooling by occupants sitting in the interior. The following recommendations are provided to help manage and minimize supply air temperature rise in underfloor plenums.

- The best strategy is to try to provide most, if not all, of the supply air for both perimeter and interior zones directly into perimeter plenum zones. This approach allows the coolest supply air to be delivered in the near vicinity of perimeter fan-coil units, diffusers and other supply outlets, thereby reducing the amount of temperature rise. As the supply air in the plenum flows back toward the interior zones of the building, the normal temperature rise that occurs will provide a warmer and more comfortable supply air temperature for occupants in the interior. Possible ways to accomplish this include the following:
    - Use ductwork (flexible, textile, or rigid) to deliver air to/towards the perimeter. In some cases, they may be directly ducted to the perimeter outlet devices.
    - Direct plenum inlets (if further away from the perimeter) with higher velocity toward the perimeter.
    - Consider placing primary inlet locations (shafts) in or near the perimeter where possible.
- Increasing the overall airflow rate will reduce supply air temperature rise, although there is a tradeoff with increased fan energy.
- On larger floor plates (> 25,000 ft^2 [2,300 m^2]), consider adding plenum dividers to create more plenum control zones. This was done in B225.

Please refer to the ASHRAE UFAD Guide for additional information and guidance on managing supply air temperature rise in underfloor plenums [ASHRAE 2013]. Very recently, a new article was published in ASHRAE Journal in which the author describes a new ducted perimeter design for UFAD systems that he hopes will successfully address this issue [Taylor 2016].

7.3.4 Operation and controls

Control systems and sequences can have a major impact on performance and the ability to properly monitor and maintain these systems. UFAD systems are complex enough that sophisticated building management systems are warranted. These should include sub-metering for end use components so energy performance can be tracked. Other recommendations are:

- AHU Reset strategies – AHU control using supply *pressure* reset and supply *temperature* reset should be specified using load monitoring schemes as opposed to simple outside air control.
- Perimeter unit dual max control – Dual max controls (as specified in Title 24) optimize both cooling and heating performance.
- Interior zone control – Care should be exercised with the design and specification of the interior temperature control system. This includes cascaded reset strategies where plenum supply pressure is reset based on interior zone thermostat demand, including provision for zero plenum pressure at minimum conditions to mitigate overcooling in the interior zones.
- Thermostat settings – With proper stratification, thermostat cooling setpoints can be set higher (generally 75-77°F) than is normal practice for mixed overhead systems, and even higher if good occupant control is provided.

7.3.4.1 Building operators

One key factor that was demonstrated in this project was the lack of consistent training for system operators on UFAD technology. UFAD systems are markedly different in a few important ways (e.g., stratification, leakage and temperature gain in underfloor plenums, perimeter vs. interior control) that operators need to recognize so they can properly operate and maintain these systems. It is recommended that building operators in a building with UFAD are either properly trained about the unique characteristics of these systems, or have direct experience with UFAD systems.

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9 ACRONYMS

Acronym	Definition
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BMS	Building Management System
C	Celsius
CAEEC	Capitol Area East End Complex
CBE	Center for the Built Environment, UC Berkeley
CBECS	Department of Energy's Commercial Building Energy Consumption Survey
CDE	California Department of Education
CIEE	California Institute for Energy and Environment
Cx	Commissioning
DGS	California State Department of General Services
DHS	California State Department of Health Services
Energy Commission	California Energy Commission
Energy Star	United States Environmental Protection Agency building energy rating system
EPA	United States Environmental Protection Agency
EUI	Energy Utilization Intensity
F	Fahrenheit
HVAC	Heating, ventilating, and air-conditioning
IEQ	Indoor Environmental Quality
kBTU/ft^2	Thousand British Thermal Units per square foot
kBTU/ft^2/yr	Thousand British Thermal Units per square foot per year
LEED	Leadership in Energy and Environmental Design
OH	Overhead
Pa	Pascals
PIER	Public Interest Energy Research, administered by California Energy Commission
POE	Post-Occupancy Evaluation
PV	Photovoltaic
SAT	Supply Air Temperature
UCB	University of California, Berkeley
UFAD	Underfloor Air Distribution
USGBC	U.S. Green Building Council
VAV	Variable Air Volume
Vs.	Versus
W	Watts
W/sf, ft^2	Watts per square foot (of floor area)