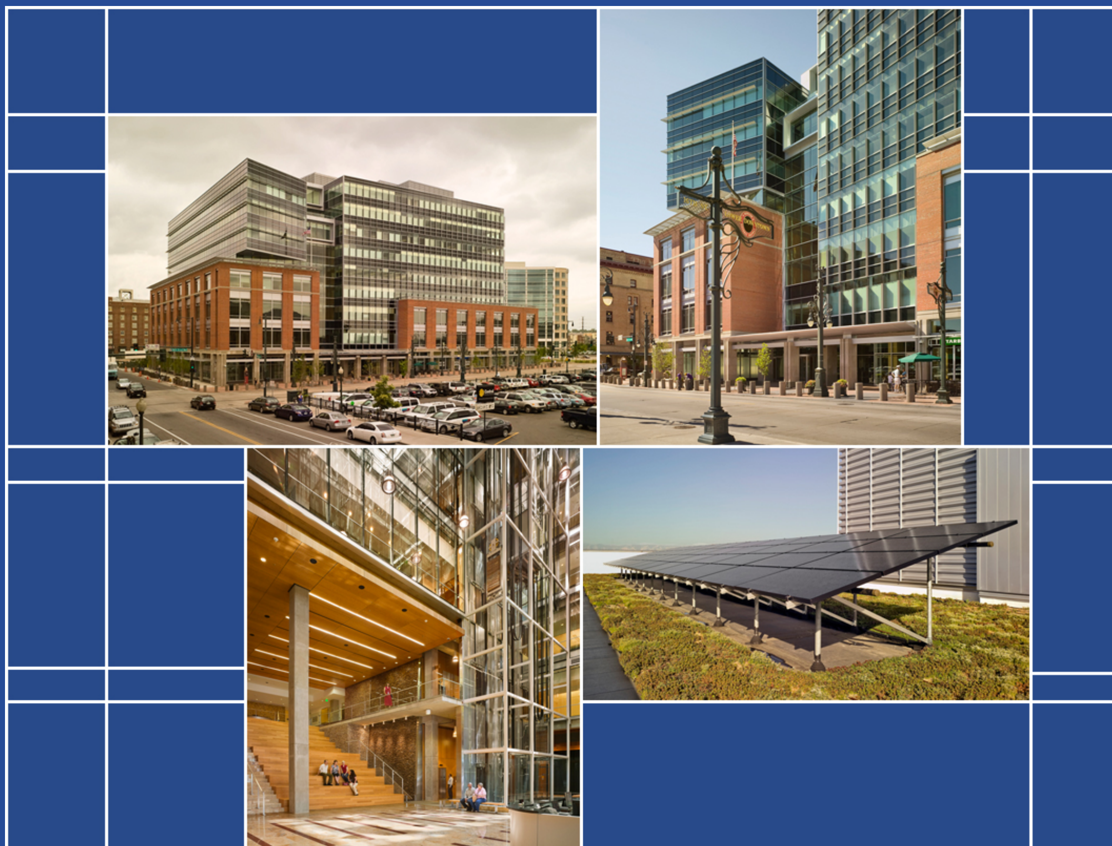
Title

Case study of environmental protection agency (EPA) region 8 headquarters building

Authors
Webster, Tom
Bauman, Fred
Dickerhoff, Darryl J
et al.

Publication Date
2008

Peer reviewed



CASE STUDY OF ENVIRONMENTAL PROTECTION AGENCY (EPA) REGION 8 HEADQUARTERS BUILDING DENVER, COLORADO

Final Report: September 2008

ACKNOWLEDGMENTS

This report would not have been possible without cooperation of and information provided by many collaborators. In particular, we are grateful for the support and information provided by the following: Jim Blackledge and Charlie Johnson from EIG; Amy Smith and Ryan Wilcoxen from Opus NW Management; Joni Teter and Kate Gregory from EPA. We sincerely appreciate the support and guidance of Kevin Powell, Director of Research, Michael Atkinson, and David Marciniak from GSA.

We would also like to acknowledge David Lehrer, CBE Director of Partner Relations for his assistance with report layout and formatting. We express our appreciation to John Goins and graduate student researcher Lindsay Baker for their invaluable contributions to this project.

The Center for the Built Environment (CBE) was established in May 1997 at the University of California, Berkeley, to provide timely unbiased information on promising new building technologies and design strategies. The Center's work is supported by the National Science Foundation and CBE's Industry Partners, a consortium of corporations and organizations committed to improving the design and operation of commercial buildings.

Underfloor Air Distribution (UFAD) Case Studies Project
Contract Number: GS-00P-06-CY-C-0295

Tom Webster, Fred Bauman, Darryl Dickerhoff, and Yoon Soo Lee
Center for the Built Environment (CBE)
University of California, Berkeley

Sponsored by:
US General Services Administration
Office of Applied Science
Kevin Powell, Director of Research

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report summarizes the major findings from a field study of the Region 8 Headquarters building for the Environmental Protection Agency (EPA) in Denver CO. This report constitutes one of three case studies we are conducting.

The overall goal of these studies is to collect whole-building performance data from selected operational buildings that are using underfloor air distribution (UFAD) as their primary means of space conditioning. By conducting a series of field investigations, the overall performance of underfloor air distribution (UFAD) buildings can be assessed with a consistent protocol that includes collecting data from utility-bills, occupant surveys, performance data from an advanced portable measurement cart, plus other available information on design, commissioning, operations, and lessons learned from conditions in the field. To conduct such case studies, CBE developed a performance assessment protocol [Bauman 2008] that includes the approaches that are briefly described below; the respective key findings accompany each discussion. A glossary of the UFAD terms used in this report is included in Appendix C.

ASSESSMENT PROTOCOL RESULTS

Our overall conclusions from this study are:

- The Region 8 EPA building is a good example of a well performing building in terms of energy, IEQ, and occupant satisfaction.
- The UFAD system is performing well and both occupants and operators are satisfied with it.

These conclusions are based on the results from the following three components of our assessment.

ENERGY STAR RATING

- This building achieved an Energy Star rating of 86, well above the threshold of 75 to qualify for an Energy Star label.
- The weather normalized site energy utilization intensity (EUI) was 71 kBtu-sf/yr.

The rating was based on utility bill data for electricity, steam, and water from June 2007 – May 2008.

PORTABLE UFAD CART MEASUREMENTS

From portable cart measurements we found the following:

- In most UFAD areas the average occupied zone temperatures were within, but at the lower end of, the comfort range calculated by ASHRAE procedures.

  The fact that these temperatures are at the lower end of the comfort range is dictated, primarily, by room setpoints in the range of 72-74°F. The thermal comfort survey responses appear to corroborate the short term cart measurements showing that the interior zone temperatures are reasonably well controlled despite there being no interior thermostats.
- Stratification in the occupied zone (head/foot temperature difference) was generally low at 1-2°F except in some private office spaces where it ranged up to 3-4°F; we consider the latter to be a normal range for UFAD systems.

- Supply plenum temperatures on the 7th floor ranged from 62 to 71°F but the average was consistently near 67°F. Overall thermal decay in the supply plenum was ~5°F.

  A range for average temperatures of 65-67°F is typical for well operated systems. Thermal decay is low compared to other projects we have studied. Low thermal decay improves economizer performance (in dry climates like Denver) by allowing the air handlers to operate at higher supply temperatures (i.e., 62°F).

These measurements were made during a 3-day site visit with the UFAD cart in May 2008. The results are based on representative room air stratification and plenum temperature distribution data we collected on four of the six floors served by the UFAD system.

CBE Occupant Satisfaction Survey

The following are major findings from the CBE occupant survey that was administered in March 2008.

General results

- Virtually all survey categories received consistently high scores when compared to the CBE benchmark database (i.e., greater than a 70% percentile ranking)
- Overall results were high for general building and workspace satisfaction as shown in Figure 1.

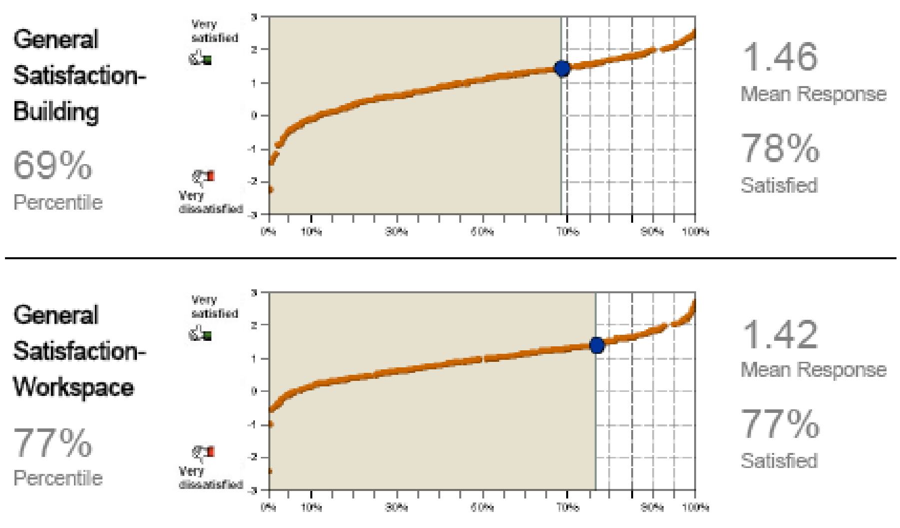


Figure 1: EPA building overall satisfaction rankings

- Results for acoustics with a percentile ranking of 71% were notably higher than most in the CBE database. We believe this may be attributed to the active sound masking system being used.
- Lighting was one of two categories that failed to achieve a high ranking compared to the CBE benchmark. Although the lighting overall score was reasonable at 1.08, occupants' comments suggest that there are many problems with the dimming controls as well as the operation of the blinds; this may explain the low relative ranking.

"UFAD related" results. The categories most related to UFAD system performance are thermal comfort, air quality, floor diffusers and to a lesser extent, acoustics and cleanliness and maintenance. Major findings derived from these survey results are:

- All of the UFAD related categories except floor diffusers had high percentile rankings ranging from 73% for thermal comfort to 87% for air quality.
- Thermal comfort satisfaction at a percentile ranking of 73% and low dissatisfaction scores at ~31% reinforced by portable cart measurements indicate that the occupied areas are operating within comfort standards overall.
- Air quality scores are very high with an 87% percentile ranking and dissatisfaction scores ranging from 9-11%.
- The building operator's response to 13 questions concerning problems that have been conjectured to be inherent to UFAD systems were positive overall. Excluding the neutral scores for occupant control, thermal decay, and stratification, all responses were +2 and above on a -3 to +3 scale, where +3 represents "No problem."
- Occupants' comments and the detailed responses from the UFAD diffuser section of the survey indicated low dissatisfaction with UFAD (~25% dissatisfied each for diffusers overall, their location, or impact on job performance). For those dissatisfied with diffusers complaints centered on noise, drafts, interferences with chairs, and problems with adjustments.

EPA REGION 8 HEADQUARTERS BUILDING

The new EPA Region 8 Headquarters building was a collaborative effort between, the U.S. General Services Administration, EPA, Opus Northwest Management, LLC, and Zimmer Gunsul Frasca Partnership. Unlike other GSA projects we have studied, the EPA headquarters building is privately owned and leased to EPA. It was designed to be a high-performance, environmentally responsible, and secure working space. The building received a LEED Gold certification in 2007.

The EPA building (Figure 2) is a 9 story structure with an area listed as 418,300 Gft^2. Completed and occupied in December 2006, the building includes 292,000 Gft^2 of non-retail office space, 56,000 ft^2 of ground-level retail, and 104,100 ft^2 of underground parking. It has approximately 800 EPA employees and contractors occupying the office space.

The first three floors of the building are served by an overhead air distribution system, while floors 4-9 are conditioned by an underfloor air distribution (UFAD) system. However, the 2nd floor is mostly conference rooms and the 3rd floor is dedicated predominantly to the IT department; occupancy of these two floors is estimated to be 13 and 62, respectively.

Figure 2: EPA Region 8 Headquarters, Denver, CO

The building design incorporates a "double-L" floor plan wrapped around a central 9-story atrium space, allowing views to either the outside or central atrium from most locations of the predominantly open plan office space.[1]

[1] Data from the occupant survey indicate that the building is about 20% private office, is populated by technical and professional personnel 50% of whom are 50 years and older.

TYPICAL UFAD FLOOR CONFIGURATION

The interior zones of the floor plate are served by swirl diffusers located in workstations and aisle ways. There are roughly 240 of these diffusers on a typical floor plate such as the 7th floor. Airflow from these diffusers is controlled by the pressure setting in the supply plenum. Occupants have some degree of control by manually adjusting the diffuser opening. In this building the plenum pressure is controlled to a constant value resulting in a semi-constant air volume system for the interior; i.e., normally with constant pressure in the plenum the interior airflow would be constant, however when occupants adjust diffusers the overall airflow rate will change since the pressure does not change.

Figure 3 shows a schematic plan of the 6th floor. This and the nearly identical 7th floor each have approximately 29,239 Gft^2 of floor area. The diagram shows the atrium centrally located on the north half of the floor plate. Also shown are two HVAC supply shafts, each serving four air highways that deliver and direct supply air into central regions of the open plenum. These shafts and air highways are shown in yellow on either side of the larger central return air shaft (shown in yellow). There are eight pressure sensors (small green circles) located in the large open underfloor plenum, each controlling the volume of air delivered by one of the eight supply air highways, as indicated, to maintain the desired plenum pressure setpoint. Each of these supply ducts contains an airflow measurement station.

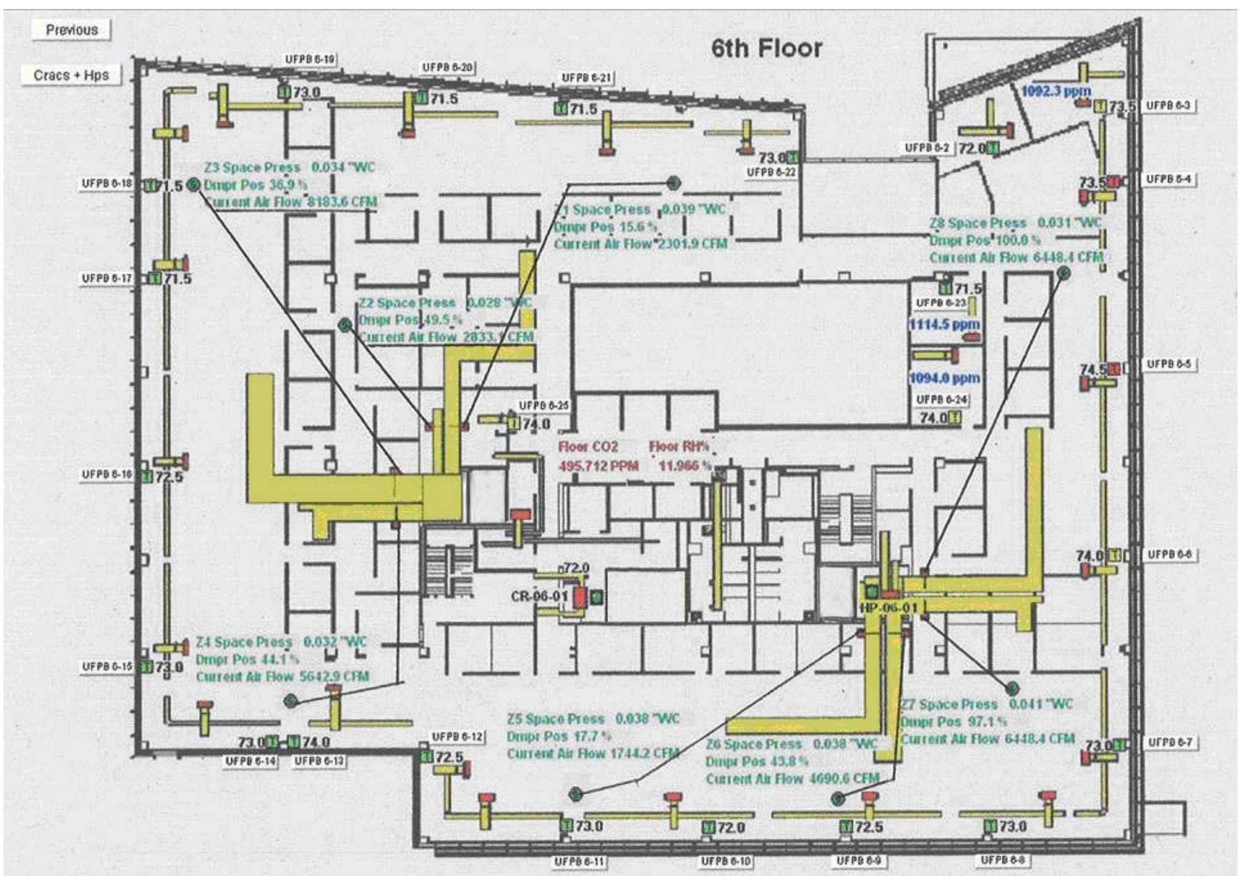


Figure 3: Schematic 6th floor plan taken from building automation system screenshot

Figure 3 also illustrates the design of the perimeter cooling and heating system. On the 7th floor, this consists of 21 underfloor fan-coil units, which are ducted to a series of linear grilles located in the window sills of the building. Each fan unit serves approximately 6-10 sill diffusers, depending on exposure and layout. The variable-speed underfloor fan boxes draw air directly from the plenum and use variable-air-volume (VAV) control to maintain the nearby perimeter thermostat at setpoint. During heating mode, a reheat coil provides warm air to the space. Figure 4 is a photo showing the layout of the perimeter sill diffusers.

Figure 4: Typical perimeter sill diffusers for UFAD floors

ASSESSMENT RESULTS

ENERGY STAR RATING

The Energy Star rating is based on metered energy use for the non-retail portion of the building. The Facility Summary Report in Figure 5 shows a site Energy Star rating of 86, well above that required to receive the Energy Star label, and the site energy use intensity (EUI) is 71 kBtu/ft^2•yr.

Figure 6 shows the actual electricity and steam use, and Figure 7 the water consumption data for the Denver EPA Headquarters, for the one-year period, June 2007 – May 2008. As mentioned above, the non-retail portion of the building, dedicated to EPA offices, represents 292,000 Gft^2 of which floors 4 through 9 are served by a UFAD system with two dedicated AHUs. Since the lower two non-retail floors have low occupancy (but are conditioned) resource utilization is predominantly due to the UFAD portion of the building floor area.

Statement of Energy Performance
FACILITY SUMMARY REPORT
EPA HQ

For 12-month Period Ending: May 31, 2008
Date Generated: June 30, 2008

This document was generated using EPA's Portfolio Manager system. All information shown is based on data provided by the Portfolio Manager account holder. Depending on the use of the SEP Facility Summary, building owners or managers may want to have a professional engineer (PE) verify that the underlying data is accurate. Blank space has been left intentionally on the SEP Facility Summary for a PE stamp.

1595 Wynkoop St.
Denver, CO 80222

Year Built: 2007
Gross Floor Area: (ft²) 292,000

Facility Space Use Summary

Office

Space Name	Gross Floor Area (ft2)	Operating Hours/Week	Workers on Main Shift	Number of PCs	Office Air-Conditioned	Office Heated
Whole Building	292,000	68	922	922	50% or more	50% or more

Energy Performance Comparison

Results	Current (05/31/2008)	Baseline (05/31/2008)	Delta	Target	Industry Average	ENERGY STAR
Energy Performance Rating	**86**	**86**	**0**		**50**	**75**
Energy Intensity (kBtu/ft2)						
Site	71	71	0		118	87
Source	189	189	0		312	230
Energy Cost						
$/year	455564	455564	0		751454	555766
$/ft2/year	1.56	1.56	0.00		2.57	1.90
CO_2 Emissions (tons/year)	4598	4598	0		7584	5609

More than 50% of your building is defined as Office. Please note that your rating accounts for all of the spaces listed. If you cannot see a rating, you will be compared to the national average of Office.

Figure 5: EPA Energy Star Facility Summary Report for EPA Denver

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.

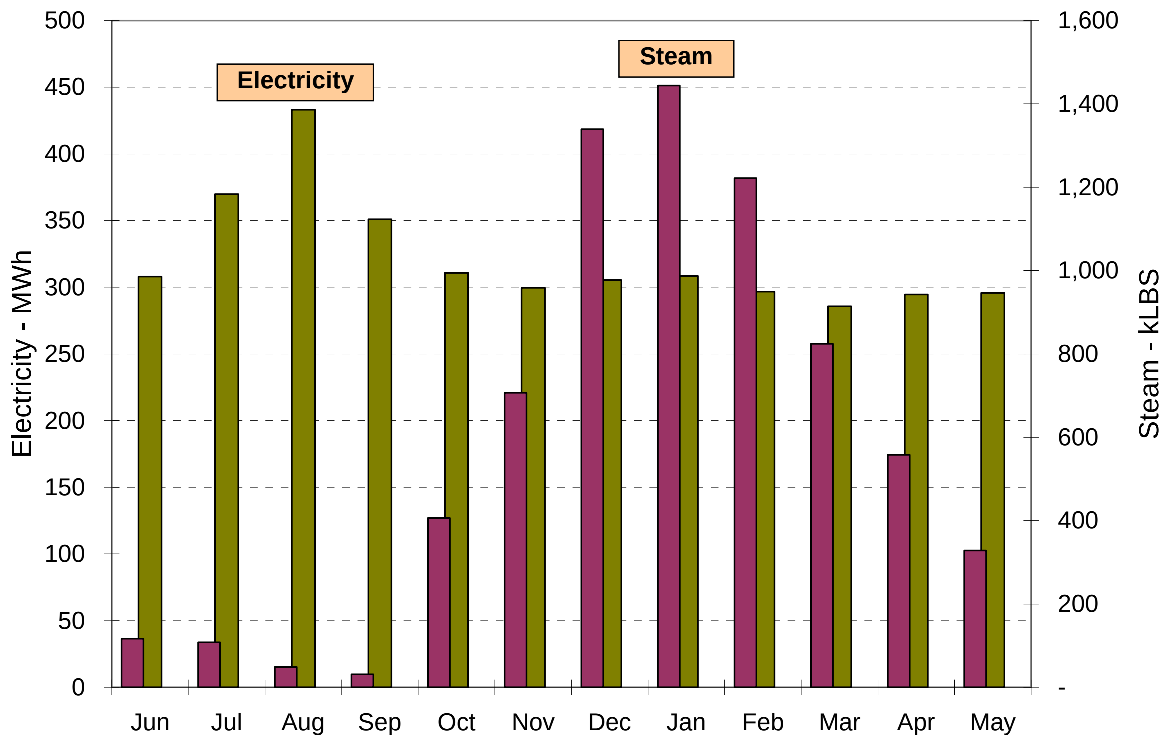


Figure 6: Monthly electricity and steam usage (MWh and kLbs) for June 2007 – May 2008

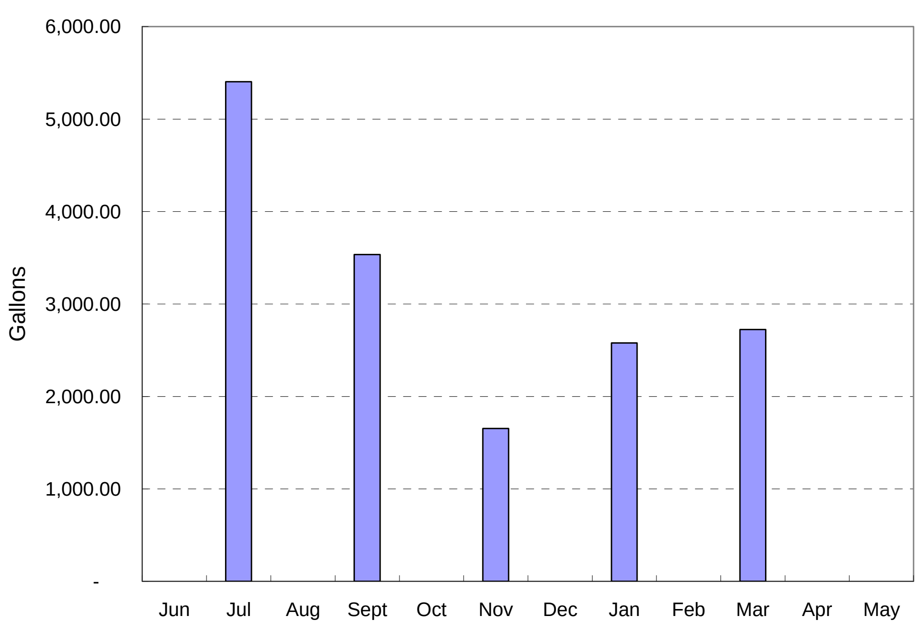


Figure 7: Bi-monthly water consumption (gallons) for June 2007 – May 2008

PORTABLE CART MEASUREMENTS

The CBE portable measurement cart shown in Figure 8 and described in more detail in Appendix B is a valuable tool for assessing UFAD system performance. It helps us determine the following:

- Variability of profile shapes over a given area of the building
- Floor-to-floor temperature differences
- Supply plenum operation from temperature and pressure measurements
- Degree of stratification in relation to location and operating conditions
- Difference in operation of interior vs. perimeter zones. This is especially important for the EPA building since interior zones are controlled as a constant volume system.
- In conjunction with the survey results, to ascertain the overall comfort level of the occupants
- Provide some insight into energy performance

Although we collected space temperature profiles on UFAD floors 5 through 9, we collected more detailed measurements on floor 7 using 15 temperature sensing "motes" (i.e., wireless data sensors) that were placed in widely dispersed diffusers in four measurement zones[2] (see Figures 8 and 9). These help us determine the temperature distribution in the supply plenum.

We conducted a total of 86 tests most of which were on the 7th floor (48). Generally, we took measurements at about the time the area should have been under peak load as we "followed the sun" around the floor plate area-to-area. Since we obtained these measurements at various times during the day, they only provide a "snapshot" of the overall performance over a short time for each area.

Figure 8: Portable measurement cart shown in perimeter zone

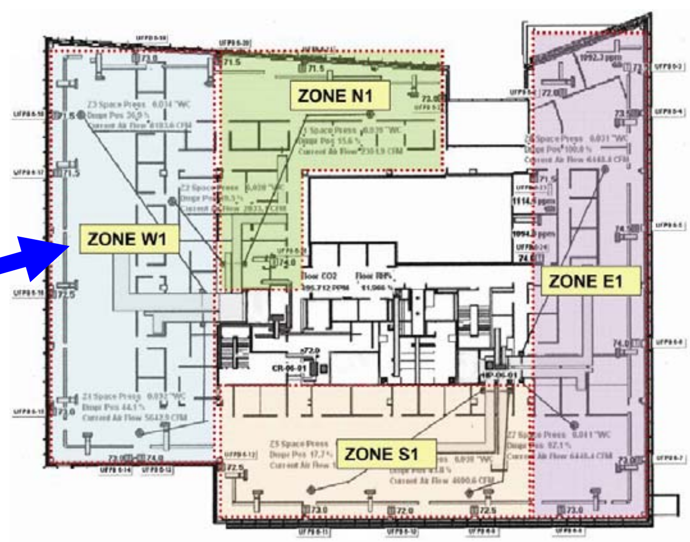


Figure 9: 7th floor layout showing designations for cart measurement areas/zones

[2] For tracking purposes we identified measurement areas by assigning a label roughly (since the building is oriented about 45° from North) consistent with the various exposures of the perimeter zones; we labeled these four zones as N, E, W, S. These zones are not HVAC zone designations used by the operators.

UFAD Room Temperature Performance

Typical temperature profiles

The magnitude of stratification that occurs during fully occupied operation was measured to assess the level of comfort and identify opportunities for saving energy. The trends are shown by Figures 10 and 11.

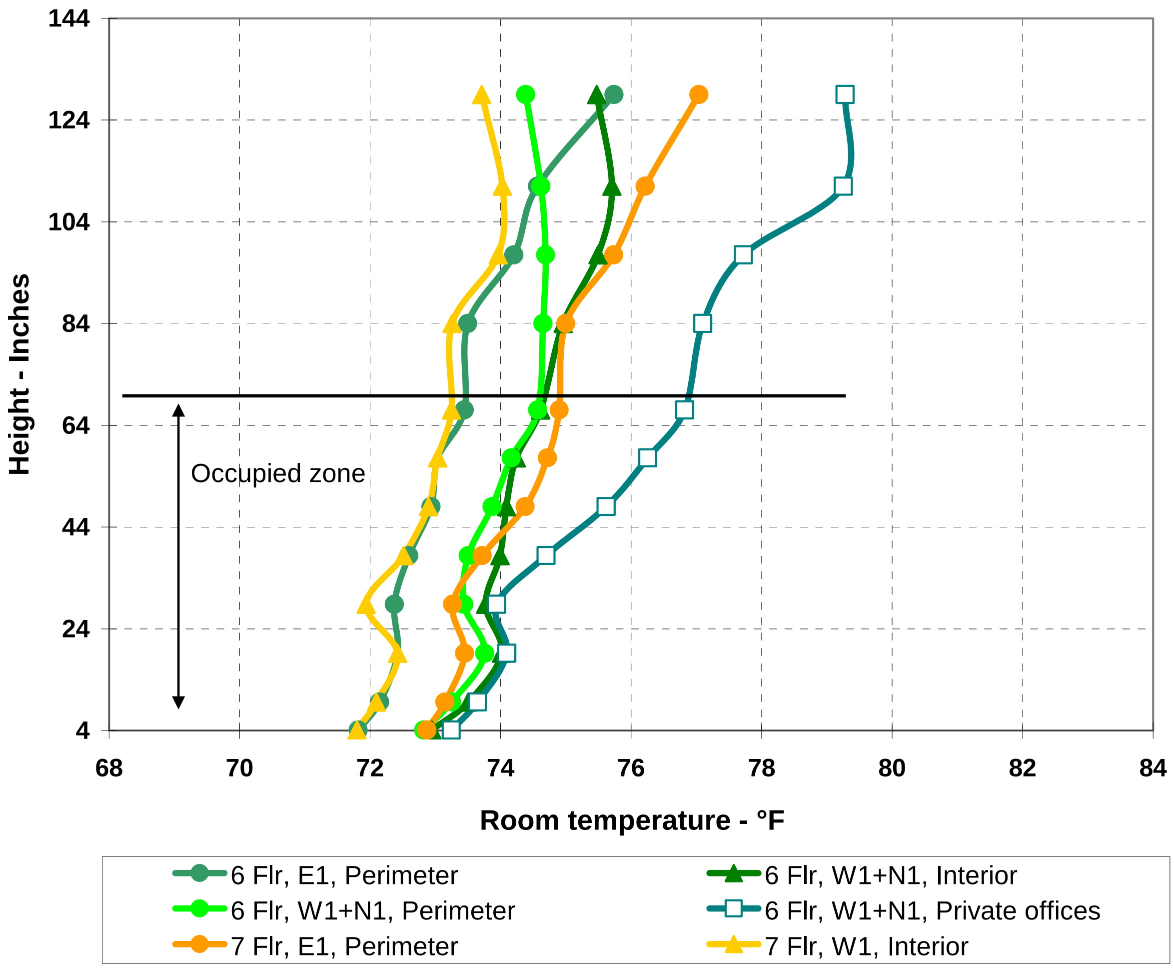


Figure 10: Typical stratification profiles, 6th and 7th floor zones

UFAD systems are commonly controlled using a thermostat mounted at a 4 ft height. If significant stratification develops the occupied zone ((OZ) defined as the vertical region from 4 inches to 67 inches from the floor) may end up being too cool and cause discomfort.

The degree of stratification is gauged by the difference between the temperatures at 67 and 4 inches. We generally consider stratification optimal when it is in the range of 2 to 4°F. Figure 10 shows typical profiles for perimeter, interior, and interior private office areas of the 6th and 7th floor measurement zones.

UFAD Room temperature performance summary

Figure 11 shows summarized results of cart measurements for room air stratification for each floor studied. Note that for each floor there are two horizontal lines of data, one for interior spaces and one for perimeter spaces. Each dot represents the average of all available readings for the specified measurement zone. Note also that the results on the left show the average for the occupied zone.

The left side of Figure 11 shows how these averages compare to an ASHRAE Standard 55 “comfort zone” that can be determined from operational and occupant parameters. In this case we determined the comfort zone by assuming a **Met**abolic value = 1.2 , **Clo**thing value = 0.6, **R**elative **H**umidity = 50%, and **V**elocity at the occupant <50 fpm.

Likewise, the data on the right shows the degree of stratification expressed as the temperature difference between the measurements at head and ankle heights. The ASHRAE Standard 55 upper limit for this temperature difference (5°F) is indicated on the chart. From this figure, we can observe the following:

- Based on the West zone results, it appears that floor-to-floor differences are relatively minor
- The 7th floor indicates that all perimeter zones are operating within 2°F of each other.[3]
- Virtually all the zones operate at the lower end of the comfort zone which is a result of controlling to room setpoints of 72-74°F
- The interior zones, despite being operated in constant volume mode, are being controlled to roughly the same temperature as the perimeter zones and overall are slightly cooler.
- The range of stratification is predominately between about 1.5°F to 3°F and is mostly well below the ASHRAE upper limit. The highest stratification occurs in private offices.

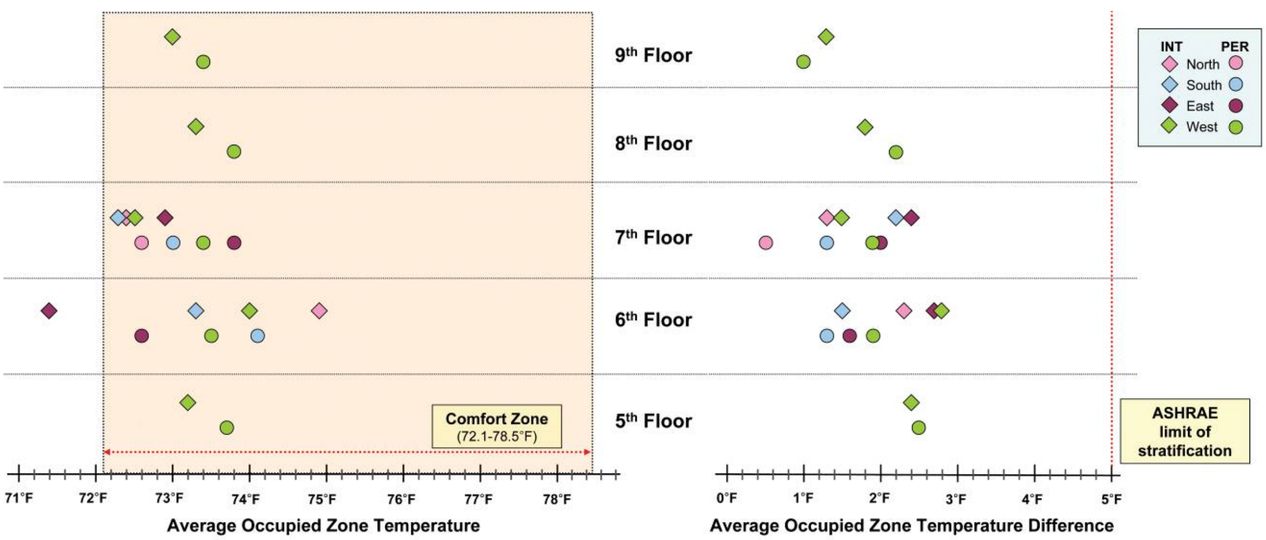


Figure 11: Cart measurement results for all floors

[3] The one outlier occurs in a private office with diffusers (mistakenly) located in the air highway.

Floor and ceiling temperatures

The portable cart instrumentation includes infrared temperature sensors pointed at the floor (carpet) and the ceiling. We reviewed the collected floor and ceiling temperature data to see whether the generally cooler floor temperatures and expected warmer ceiling temperatures encountered in a UFAD system might impact comfort. The results indicated an average floor surface temperature of 70.6°F with an average room temperature at a height of 48 inches of 73.8°F (note, the average occupied zone temperatures shown in Figure 11 are slightly cooler that this). Over the same set of measurements, the average recorded ceiling temperature was surprisingly only 72°F. These cooler ceiling temperatures will require further investigation, but provide further evidence that higher overall airflow rates being used in the EPA building are reducing stratification.

Using the Berkeley Thermal Comfort model, we investigated the potential impact of a cool floor surface temperature on comfort and thermal sensation. The model predicted that for a floor temperature that is up to 4°F below the average occupied zone temperature, the influence on both thermal sensation and overall comfort is very small. The magnitude of this impact will increase only slightly when the occupied zone temperature is near the edges of the comfort zone (e.g., cool local discomfort may be increased under slightly cool room conditions, and overall comfort may be improved under slightly warm room conditions). A quick check with ASHRAE Standard 55-2004 also indicates floor temperatures in the range that we measured are not expected to cause significant local discomfort with percent dissatisfied well below 10%.

UFAD Plenum Temperature Distribution/Decay

We determined the supply plenum temperature distribution from mote measurements taken on the 7th floor; Figure 12 shows how a mote is positioned in a diffuser. Each data point represents an average for a given mote of all the tests conducted in that zone.[4] Since the layout and operation of all floors are very similar to each other, we assume that these distributions are typical of those throughout the building.

Figure 12: Mote placement in diffusers

[4] For each cart location, a set of mote temperatures is obtained.

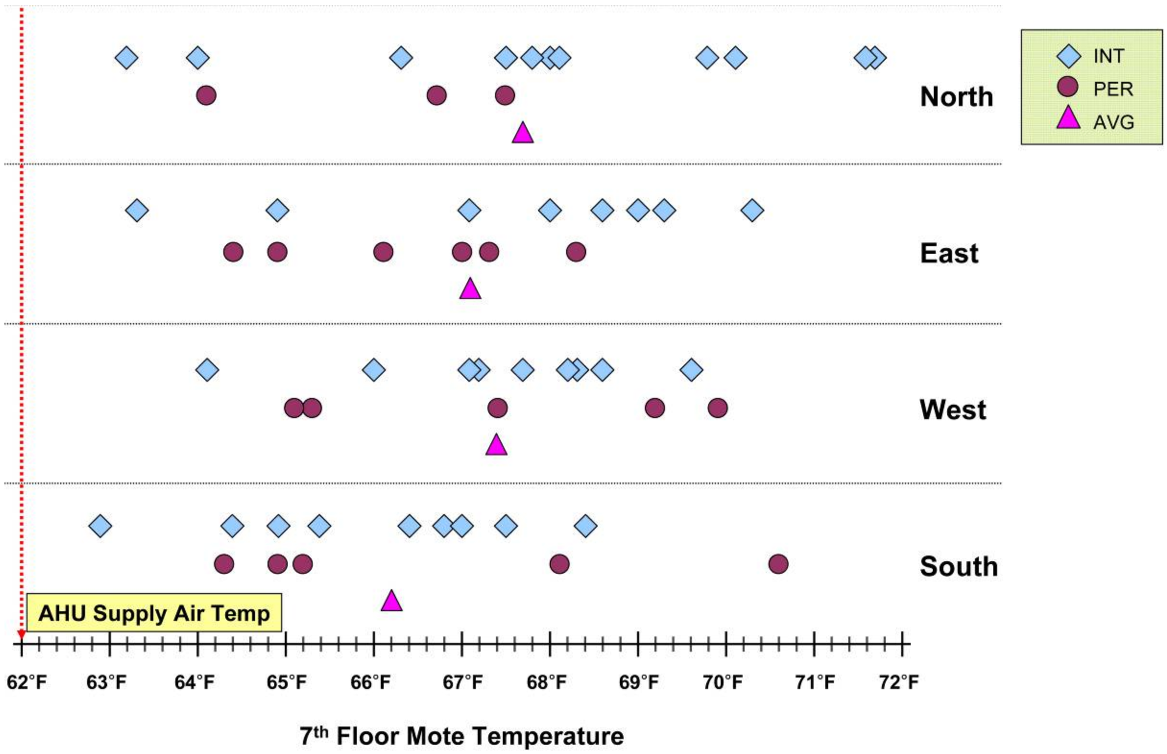


Figure 13: Supply plenum temperature distribution, 7th floor (INT = interior sensors, PER = perimeter sensors, AVG = measurement area overall average (perimeter + interior))

Figure 13 is a summary of plenum temperature measurements taken on the 7th floor with the interior and perimeter readings shown separately. The average for the entire measurement zone is indicated by the triangle. From this figure, we can observe the following:

- Average plenum temperatures for all zones are in the range of 66 to 68°F
- Minimum temperatures are around 63-64°F and maximums near 70°F.

As shown in Figure 13, the air handler (AHU) supply temperature at the time of the tests was about 62°F. From this we determined an average thermal decay (difference between supply to the plenum and average plenum temperature) of about 5°F.

Thermal decay depends on airflow rate and temperature distribution caused by how the supply airflow is delivered to the plenum. In the EPA building, a combination of air highways (Figure 3) delivers the supply air into the underfloor plenum at eight different locations. This partially ducted configuration establishes a rather complex airflow pattern within the plenum, so temperatures are dictated by how long the air has to travel (while picking up heat) to a particular location. Since there is no clear directionality to the temperature gain (e.g., temperature gain vs. distance) we can only describe thermal decay in an overall sense based on plenum average and plenum supply temperatures.

During the testing period the total airflow for the 7th floor varied between 40,000 and 46,000 cfm (average ~ 1.5 cfm/ft^2). This is about equal to the floor design airflow. However, weather conditions in Chicago during this same period were fairly mild for the summer (high temperatures near 80°F). Higher airflows will reduce thermal decay which is why we observed this relatively low level of thermal decay while the building was experiencing less than design load conditions.

CBE OCCUPANT SATISFACTION SURVEY

The CBE web-based survey addresses occupant satisfaction for seven different environmental categories (core), as well as two questions about overall satisfaction with the building and personal workspace. Eight hundred thirty invitations were distributed via e-mail to the building occupants and 422 valid survey responses were received for a response rate of 50%, which exceeds the preferred rate of about 40%.

The version of the survey administered at the EPA building included the core survey questions, as well as additional questions about floor diffusers (UFAD module). Normally for these case studies, a modified version of the core survey is administered that includes questions requested by GSA – this version is called the GSA SPOT survey; it was NOT implemented in the EPA building. More about the survey and an example of the questions can be found on the CBE website. [CBE 2008]

BUILDING INDOOR ENVIRONMENTAL QUALITY (IEQ)

Figure 14 presents average occupant satisfaction ratings for each environmental category addressed by the survey. This chart shows only the average score for each category based on the standard -3 to +3 scale used in the survey. For comparison, also shown for the core survey categories are the results from the large CBE benchmark database.[5] A full set of detailed occupant satisfaction results from the survey are presented in Appendix A. As shown, the EPA building scored better than the benchmark in virtually all categories.

Figures 15 and 16 show the mean response and percent satisfied as well as percentile ranking for EPA as compared to the CBE benchmark. The figures show that except for lighting, the rankings are all greater than ~70%.

[5] As of May 2008 (N=45,824); ~450 buildings

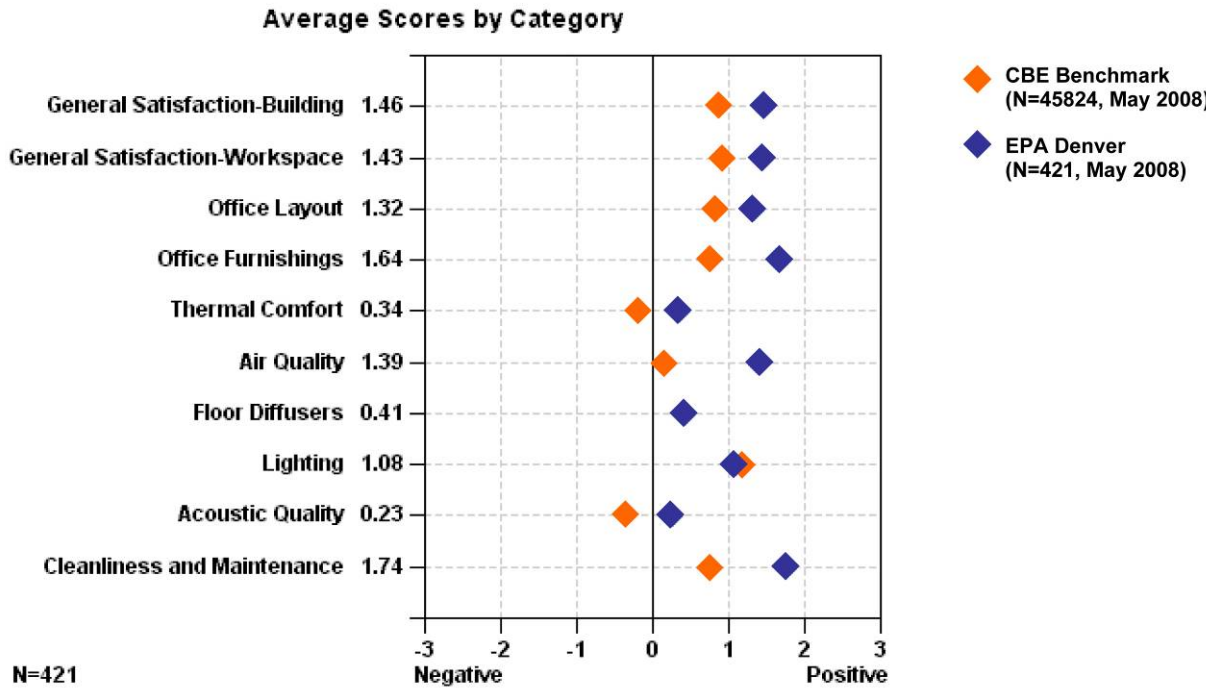


Figure 14: Average satisfaction ratings of indoor environmental quality by category for EPA Denver HQs compared to CBE benchmark database.

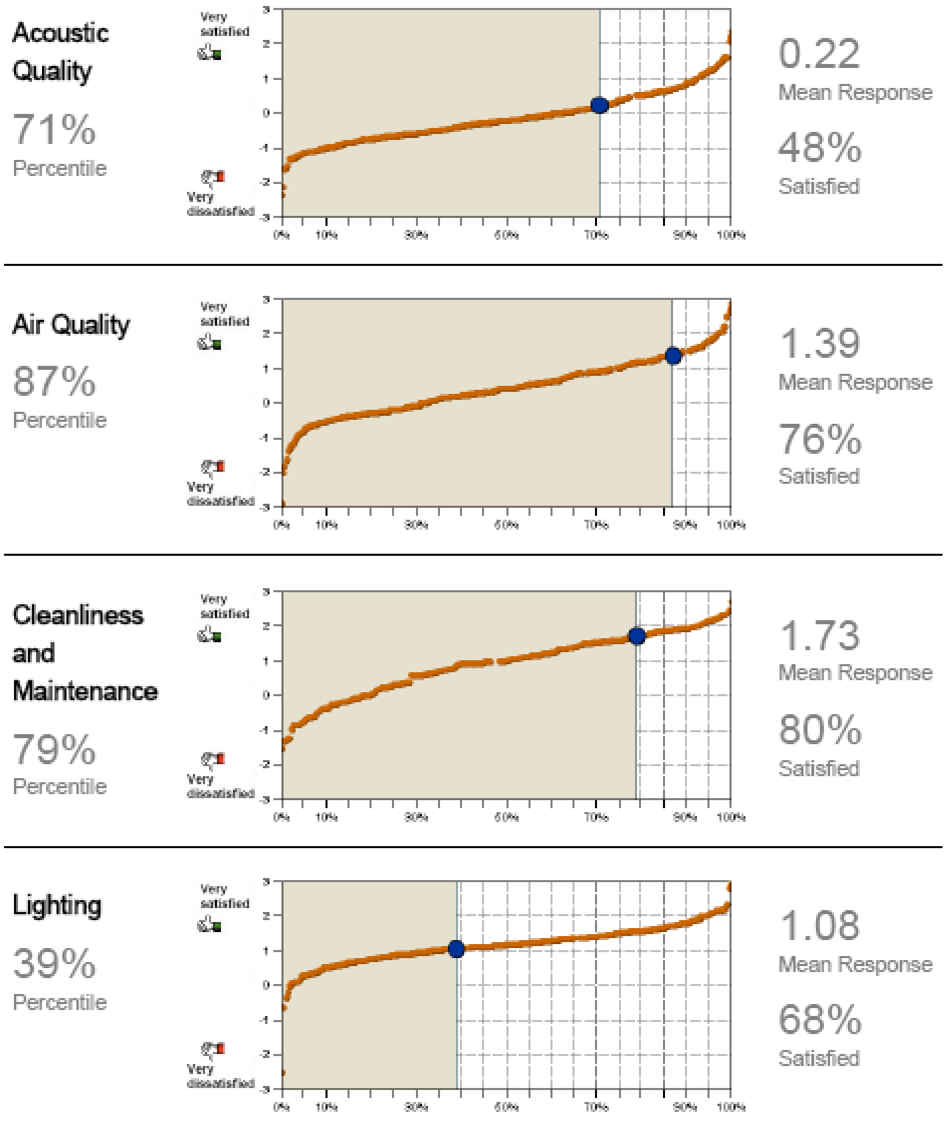


Figure 15: Occupant satisfaction survey category rankings relative to CBE benchmark database

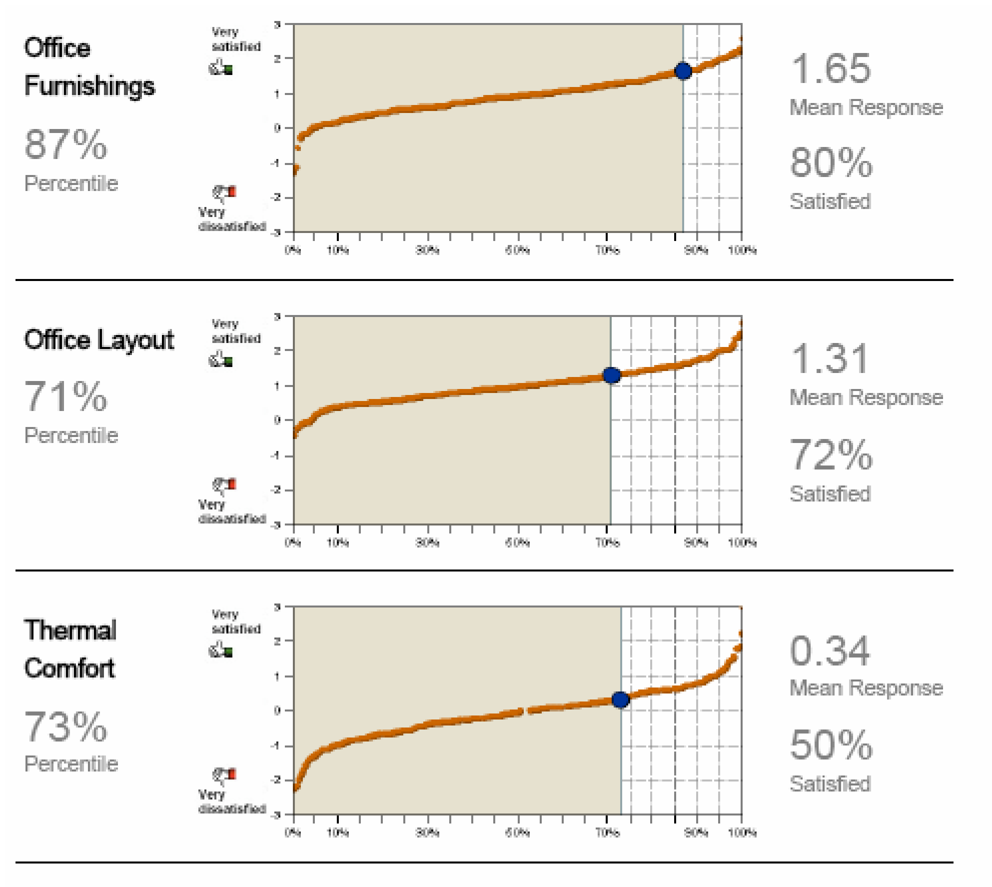


Figure 16: Occupant satisfaction survey category rankings relative to CBE benchmark database

Thermal Comfort and Air Quality

Thermal comfort results are particularly interesting for this building. Although Figure 16 shows a modest satisfaction score of 50%, when we look at the detailed thermal comfort questions we find that *dissatisfaction* with temperature in the workspace, and how thermal comfort impacts self assessed work performance, only ~32% of occupants are dissatisfied.

Based on the cart measurements and anecdotal comments we received during our visit we would not expect this result; i.e., we would expect greater dissatisfaction. Furthermore, since the interior zones are not actively controlled (there are no thermostats in the interior) we assumed that temperature performance over time would be mixed at best. The survey results imply that these perceptions are incorrect.

Air quality received some of the highest satisfaction scores we have seen. Moreover, dissatisfaction scores (N=411) with overall air quality and with impact on work performance were exceptionally low at 11% and 9%, respectively.

UFAD Floor Diffusers

Floor diffusers refer to the swirl diffusers located near or in each workstation. They generally control the interior temperature as discussed in the building description section above. They also can be considered a "user interface" to the system since they can be adjusted by the user to vary the airflow.

They can also be moved to different positions within or near the occupant. These two features offer a limited degree of personal control to fine tune an individual's personal comfort.

Results from responses to questions about diffusers are shown in Figures 17 (overall satisfaction) and 18 (responses to drill down questions for those not satisfied). From these and other anecdotal information we observe the following:

- Occupant dissatisfaction with floor diffusers is low, only ~25% of respondents were dissatisfied with (each) diffusers overall, their location, and their impact on work. In the standard output report shown in Figure 17 only *satisfaction* is shown which does not include the neutral responses. When we look at *dissatisfaction* we see a different perspective.
- Dissatisfaction with diffusers centered on noise, drafts, interferences with chairs, and problems with adjustments
- The complaints breakdown closely reflects comments occupants wrote in the survey as well as those we collected in our visit.

Note that comparisons to other UFAD buildings are limited by the relative lack of UFAD building data in the CBE database (N=11); i.e., the UFAD specific dataset is too small to be considered representative of UFAD buildings in general so the percentile rankings are not a significant indicator.

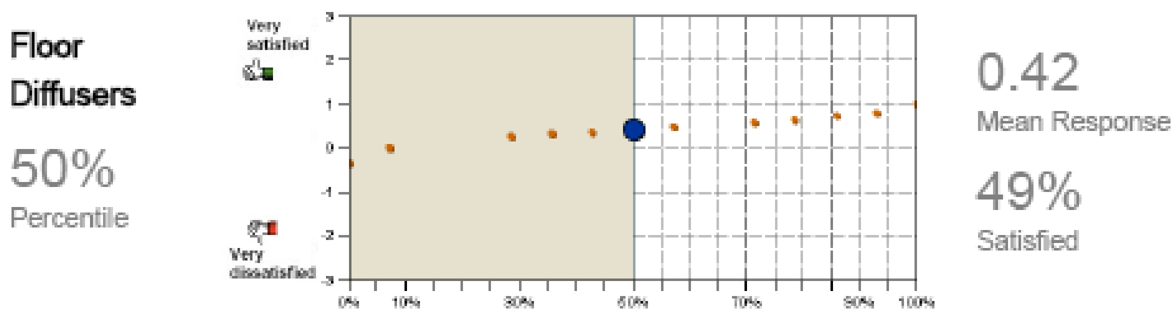


Figure 17: Occupant satisfaction with floor diffusers

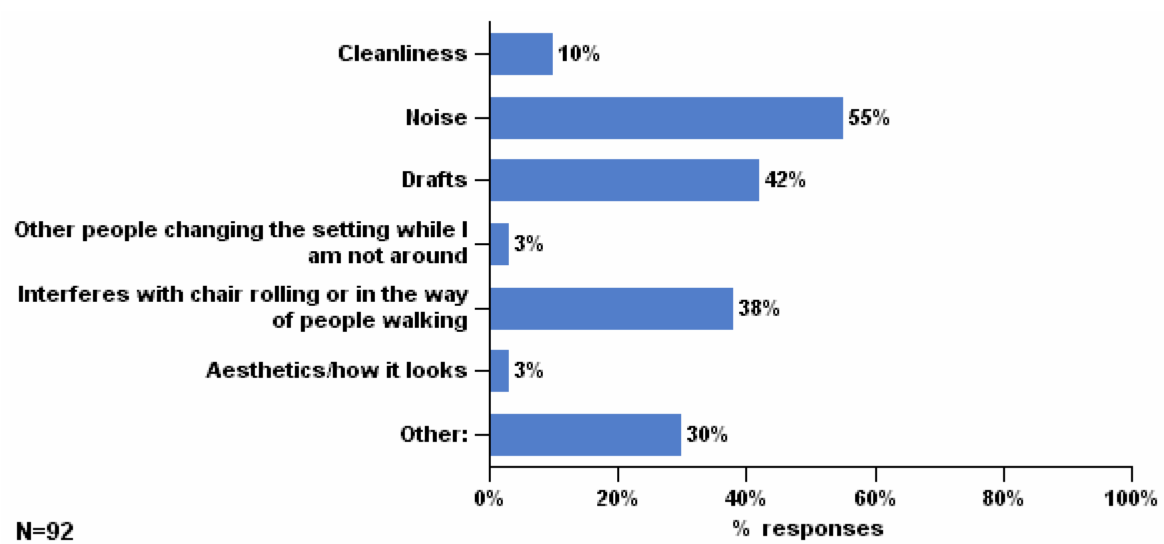


Figure 18: Dissatisfaction with diffusers

Other survey data from the UFAD module (not shown here) indicate the following about floor diffusers:

- Many occupants do not know how to use the diffusers. (42% percent have not been instructed on how to operate them)
- Few occupants know about or have requested diffusers to be relocated (only 23% of occupants have requested to have a diffuser relocated)
- Occupants are about evenly divided on the issue of whether the floor diffusers improve comfort or not (N=375)
- Most occupants are too close to their diffusers (87% of responses indicate a diffuser is within 3-4 feet)
- Most occupants like UFAD systems as opposed to overhead ones despite complaints (75% of respondents (N=362) prefer UFAD)

During our three days in the building, we noted a significant number of floor diffusers that were located too close to the occupants permanent work location (sometimes almost directly underneath the chair). When the occupant is within the "clear zone" (~3-4 feet) they are subject to higher velocities that can exacerbate comfort problems. The building operator confirmed that they had already relocated about 200 diffusers since the building was first occupied. It appears from this situation that there was not adequate coordination between diffuser and furniture placement during the design process.

We also observed problems with adjusting the diffusers; they tend to stick so that they cannot be easily closed even though they appear to be closed mechanically.

The excessive noise that many occupants noted may be related to a mistaken perception that the noise from the diffusers is HVAC noise when in fact it is from the sound masking system.

UFAD Operator's Observations

Recently, as part of an upgrade to the building characteristics component of the occupant survey, we added questions to obtain the operating engineers view about UFAD system operation. This module was used in previous work to systematically gather operators opinions about ancillary characteristics of UFAD systems that have been cited as potential problems or barriers to implementation. The operator is asked to register on a 7 point scale his perceptions as to the seriousness of these issues. Table 1 summarizes the results for these questions for the EPA building. These responses are representative of those found in our previous work.

These results indicate that problems associated with the issues listed are not as serious as is sometimes conjectured.

Table 1: Operators perspective on UFAD system performance

Based on your knowledge of how the UFAD system has been operating, how the occupants have responded on average, and your experience in other non-UFAD/ conventional buildings, how much better or worse is this UFAD building than conventional buildings with respect to the following:	***-3 Much worse +3 Much better***
Hot and cold complaints	+3
Quality of ventilation	+2
Energy use	+2

Problems with zone equipment	+2
Effort and cost of maintenance	+2
Making changes to tenant space	+2
Occupant control: ability of occupant to influence local environment to increase comfort	0 (neutral)
Overall performance of the UFAD system	+2
Based on your experience with this building, indicate how serious of a problem the following have been (in terms of interruptions to operations, cost, occupant comfort, etc.)	***-3 Serious problem +3 No Problem***
Dust and dirt in the underfloor plenum (i.e., does dust from the plenum blow onto desks, cause mold or other hazards?)	+3
Moisture in the supply plenum	+3
Air leakage from supply plenum	+2
Underfloor plenum air distribution and temperature decay	+1
Temperature stratification in the occupied spaces (i.e., UFAD systems are supposed to have some stratification-- has there been too much or too little?)	0 (neutral)

ADDITIONAL OBSERVATIONS

Although not part of the scope of this study, we made several other observations that we consider worth reporting.

1. Especially noteworthy are the air quality results. The ranking of 87% may indicate that the UFAD system is contributing to high perceived ventilation effectiveness. Further research could help determine reasons for this high rating and possibly what differences there are between UFAD and OH areas.
2. Just prior to our assessment work we conducted a study to measure leakage rates for one floor of the EPA building. The results are shown in Table 2 and indicate that Category 1 leakage is very low and Category 2 is also very reasonable.
3. Overall the stratification is minimal and the airflows are high, it appears to us that changes in the operation of the system could yield even better energy performance.
4. We found 30% of the floor diffusers on the 7th floor were closed, and 21% were partially open. We encountered a number of sticky diffusers, received comments from occupants both pro and con about the temperature control issues, noise from the diffusers etc. Further research could provide valuable information for owners and operators on how to improve system performance and occupant comfort
5. The overhead lighting controls appeared to work well; there were many instances where the overhead lights were off due either to occupancy sensors or day lighting controls. This can lead to load variations in interior zones greater than is generally assumed since both occupants and their associated lighting and computers might be turned off for periods of time. However, the low satisfaction ratings for the lighting system indicate problems with lighting and blinds controls beyond their impact on loads.
6. The acoustics rating from the survey deserves to be explored further. This building is equipped with a sound masking system that generates “pink noise” to replicate HVAC noise that serves to reduce the impact on occupants from nearby conversations. However, based on our experience at the site

and reviewing the comments from the survey it appears that this rating could be even higher if the sound masking system was tuned up.

Table 2: Summary of Air Leakage Test Results, 7th Floor, EPA Region 8 Headquarters based on multi-path method (Assumptions: 7th floor area = 29,239 ft^2, plenum pressure = 0.05 iwc, design airflow = 1.5 cfm/ft^2)

Description	Flow (cfm)	cfm/ft^2	% of Design	Comments
Category 1 leakage	440	0.015	1.1	Construction quality leakage
Category 2 leakage	4,720	0.16	10.7	Floor leakage
Total leakage	5,160	0.18	11.7	Actual total leakage

SUMMARY AND CONCLUSIONS

BUILDING PERFORMANCE

The Region 8 EPA building is a good example of a well performing building. How well a building performs is a function of many factors but chief among those are overall energy performance, HVAC system performance and how well occupant spaces are controlled, and the satisfaction of its occupants. Summarized below are the results of these three components for the EPA building.

ENERGY PERFORMANCE

The calculated Energy Star rating for the building was 86 and the weather normalized site energy utilization intensity (EUI) was 71 kBtu-sf/yr. Since the rating is above 75, the building qualifies for an EnergyStar label.

UFAD SYSTEM PERFORMANCE

In terms of effectively conditioning the EPA building the UFAD system appears to operate very well. This conclusion is supported by the following findings.

Findings based on CBE Occupant Satisfaction Survey

- *Occupant satisfaction with the UFAD system is positive.*
  All of the categories of the CBE occupant satisfaction survey relevant to UFAD system performance (thermal comfort, air quality, floor diffusers and to a lesser extent, acoustics and cleanliness and maintenance), had high percentile rankings relative to the CBE database benchmark ranging from 73% for thermal comfort to 87% for air quality.

  For questions about diffusers (overall satisfaction, location, and impact on their work) only ~25% of respondents were dissatisfied. For those dissatisfied with diffusers complaints centered on noise, drafts, interferences with chairs, and problems with adjustments.

  Dissatisfaction with thermal comfort was very low at ~32%. Dissatisfaction with air quality was extremely low at 9-11%.

- *Occupants prefer UFAD over traditional systems*
  75% of respondents preferred UFAD
- *Operators did not perceive any major issues with 13 items that have been cited as potential problem areas for UFAD systems.*
  Other than for occupant control, thermal decay, and stratification that all scored neutral, all responses were +2 and above on a -3 to +3 scale.

Findings based on Portable UFAD Cart Measurements

During a 3-day site visit with the UFAD cart in May 2008, we were able to collect representative room air stratification and plenum temperature distribution data on four of the six floors served by the UFAD system.

- *Room temperature is within ASHRAE standards.*
  In most of the UFAD areas the average occupied zone temperatures were within, but at the lower end of, the comfort range predicted by ASHRAE procedures. This appears to apply to the interior zones as well which are not actively controlled. These low temperatures were primarily attributed to the relatively low controls settings being used (72-74°F).
- *Stratification performance is acceptable although lower than optimal.*
  Results from cart measurements revealed that stratification was generally low at 1-2°F except in private office spaces where it ranged up to 3-4°F.
- *Supply plenum performance is satisfactory.*
  The 7^{th} floor measurements showed that temperatures ranged from 62 to 71°F but the average was consistently near 67°F which yields an average thermal decay of ~5°F (based on the AHU supply temperature of 62°F); this is relatively low based on our experience with other projects. Low thermal decay improves economizer performance by allowing the air handlers to operate at higher supply temperatures (i.e., 62°F).

Findings from leakage testing

- *Supply plenum leakage is low.*
  Comprehensive testing that we conducted before the site visit showed Category 1 leakage to be negligible and Category 2 leakage (i.e., leakage to room) to be ~10% of floor peak design airflow.

OCCUPANT SATISFACTION WITH THE BUILDING

The CBE web-based survey including core and a UFAD specific module was completed in March 2008. The survey captures occupant's responses in 7 categories related to indoor environmental quality.

- *Occupants are satisfied with the EPA building overall*
  Responses were consistently high for virtually all survey categories (percentile rankings all greater than 70%) when compared to the CBE benchmark database. Likewise, overall results for building and workspace satisfaction were ranked 69% and 77%, respectively.
- *Acoustical performance is better than most buildings in this class*
  Percentile ranking for the acoustics category at 71% was notably higher than most in the CBE database, particularly for a large open plan office building like the EPA building. We believe this may be largely attributed to the active sound masking system being used.

- *Lighting system performance received mixed reviews*
  Lighting was one of two categories that failed to achieve a high ranking; occupants' comments suggest that there are many problems with the dimming controls as well as the operation of the blinds.

OTHER ISSUES

Some issues of concern that do not seem to materially impact the overall operation but could beneficially improve IEQ, energy performance and satisfaction are:

- *Occupied zone average temperatures are at the low end of the comfort range and stratification levels are low.*
  Addressing these issues present opportunities for improving thermal comfort and energy performance. Simply raising the room temperature setpoints and implementing control for the interior zones are two obvious improvements.

- *Dissatisfaction with diffusers could be further reduced*
  Despite low dissatisfaction with diffusers, improvements could be made that would likely ameliorate occupant complaints and lead to better overall IEQ performance. Occupant's comments and the detailed responses from the UFAD diffuser section of the survey indicated low dissatisfaction with UFAD (~25% dissatisfied with diffusers overall, their location or impact on their work). For those dissatisfied with diffusers, complaints centered on noise, drafts, interferences with chairs, and problems with adjustments.

REFERENCES

EPA. 2008. "Energy Star Portfolio Manager." Environmental Protection Agency, (https://www.energystar.gov

Bauman, F. and Tom Webster. 2008. "UFAD Building Performance Assessment Protocol." Center for the Built Environment (CBE), University of California, Berkeley, CA August.

Bauman, F, T. Webster, D. Dickerhoff. 2008. "Air Leakage Test Report: EPA Region 8 Headquarters, Denver, CO." Center for the Built Environment (CBE), University of California, Berkeley CA August.

NIBS. 2006. "PBS Standard for Raised Floor Systems With and Without Underfloor Air Distribution." The National Institute Of Building Sciences (NIBS), Washington, D.C.

CBE. 2008. "CBE Occupant Satisfaction Survey." Demonstration version, http://www.cbesurvey.org/cbesurvey/survey1003/welcome.asp?

APPENDIX A: EPA DENVER HEADQUARTERS BUILDING SCORECARD

See attached report.

APPENDIX B: PORTABLE MEASUREMENT CART

The portable measurement cart is a self-contained highly instrumented mobile monitoring platform. It was originally designed to support commissioning of UFAD systems, most notably the New York Times headquarters building.

CART DESCRIPTION

The major elements of the cart are as follows; the various elements are shown in Figure B1:

- *Computer:* Laptop computer with software visualization and data processing software and a database to store results for further review and analysis.
- *Stratification profile tree:* A series of rapid response thermocouples on a telescoping pole can extend to 13 feet, with thermo-couples in increments of 9 or 12 inches, and 4 inches from the floor and ceiling.
- *Wireless temperature sensor network:* Up to 70 wireless temperature sensors (motes) may be installed in UFAD floor diffusers, air highways, and at thermostat locations.
- *UFAD pressure:* The underfloor pressure at the diffuser nearest the cart can be measured.

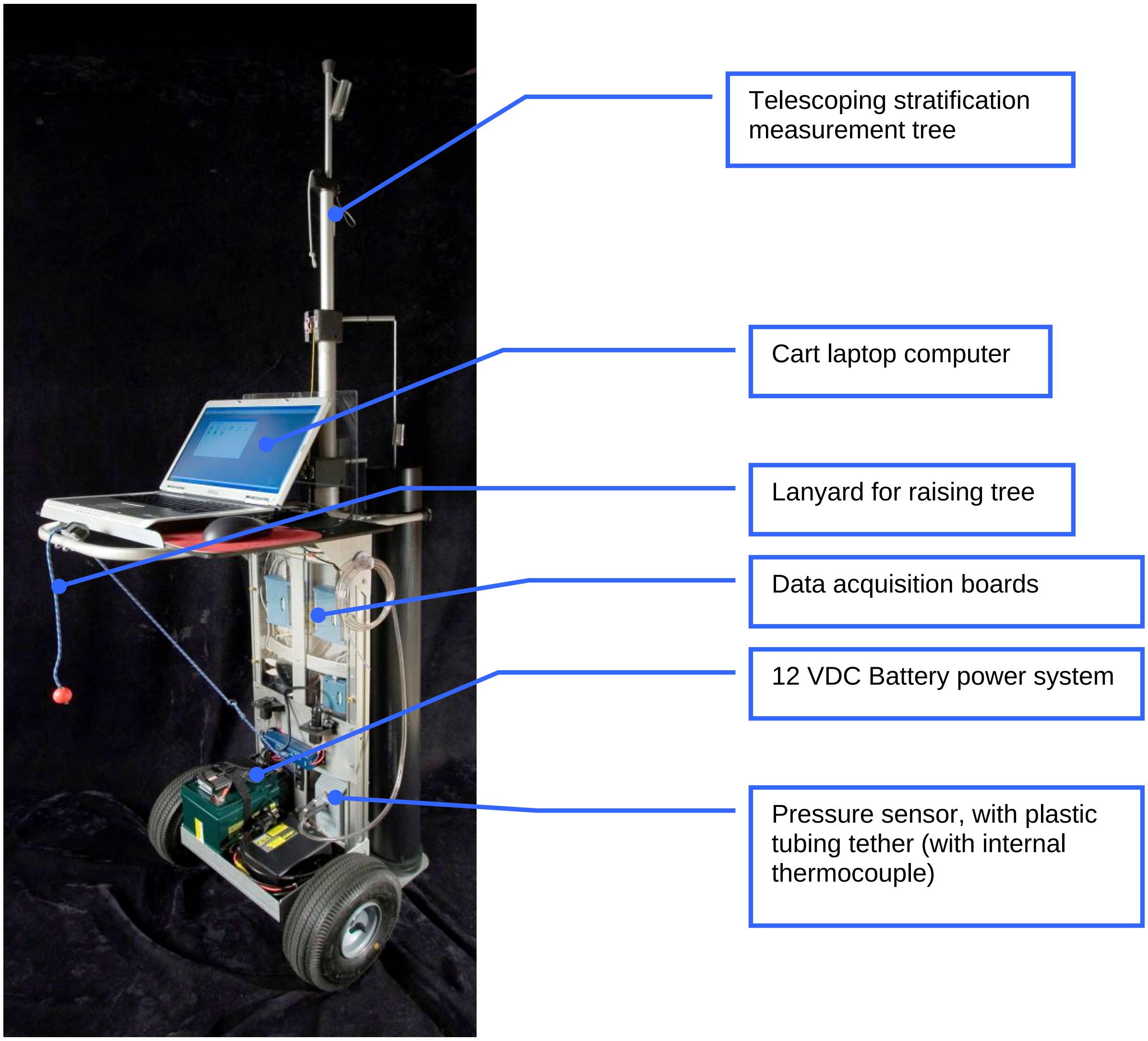


Figure B1. Portable measurement cart

Wireless Sensor System

Motes are small devices that use a new wireless technology called mesh networks to communicate data collected from on-board sensors back to a base station that communicates to the cart laptop via WiFi. The cart hardware (and software) system supports data acquisition of up to 70 motes that can be deployed over a broad area in the building. While these can be deployed in many places they are primarily designed to measure and report the following parameters:

- Zone temperatures at thermostat locations
- Diffuser supply temperature in air super highway
- Diffuser supply temperature in low pressure plenum
- Perimeter diffuser temperature at the linear bar grilles

APPENDIX C: GLOSSARY OF UFAD TERMS

1. Floor Diffusers – Floor diffusers are mounted in the raised floor and are responsible for introducing conditioned air into the occupied space. Depending on the design, these may have some degree of occupant control via adjustment of direction, volume, and velocity of the entering air.

2. Thermal Decay – Generally denotes temperature increase in the supply plenum due to the combined impact of heat transfer through the floor slab below and the raised floor above. As used in this report, it refers to a simplified overall measure of thermal decay, the difference between the plenum average temperature and the AHU supply temperature. By and large, the plenum temperature distribution is not uniform due to the impact of supply methods and obstructions from underfloor equipment.

3. Stratification – A measure of temperature increase with height in a room defined by the temperature difference between 67" (head height) and 4" (feet level). Generally, we consider differences in the range of 3-4°F to be optimal; the ASHRAE Standard 55 upper limit is 5°F.

4. Occupied zone temperatures – Due to stratification the temperature near the occupants (i.e., between 4" and 67") is lower than that above. We use the average of the temperatures measured in this region as an indicator of thermal comfort. We assume that the comfort impact of this average is virtually equivalent to the thermostat temperature in mixed systems.

5. Supply Plenum – The space below the raised floor bounded by the floor slab that serves as a supply air distribution "duct".

6. Air Quality – This refers to the impact of the complex interaction between a number of factors such as CO2, humidity, particle concentrations from out gassing and odor sources, as well as air movement. It is generally related to the amount of outside air circulating in the building. In this report we refer to occupants perceptions of air quality as opposed to objective measures of it.

7. Thermal Comfort – Thermal comfort refers to the complex interaction between air temperature, relatively humidity, air velocity and radiation as they impact an individual occupant. In this report we rely on both some objective measures and occupants perception of their thermal satisfaction.

8. AHU – Air handling unit; refers to the main air handlers in a commercial building