Title

Hype vs. reality: new research findings on underfloor air distribution systems

Permalink

Authors

Lehrer, D.
Bauman, F.

Publication Date

2003-11-01

Hype Vs. Reality: New Research Findings on Underfloor Air Distribution Systems

David R. Lehrer, RA[1]
Fred S. Bauman, PE[2]

[1]Director of Partner Relations and Communications, Center for the Built Environment (CBE)
Phone: 510 642-4950. Fax: 510 643-5571. Email: lehrer@uclink.berkeley.edu
[2]Research Specialist, Center for the Built Environment (CBE)
Phone: 510 642-7848. Fax: 510 643-5571. Email: fbauman@uclink.berkeley.edu

1. INTRODUCTION

People frequently cite a number of benefits related to underfloor air distribution (UFAD) systems—more flexibility, better indoor air quality, comfort, energy efficiency, and reduced life-cycle costs. These benefits may be realized in practice, however much depends on the system design, building use, climate, and other factors. The focus of this paper is to describe each of these benefits briefly, discuss what is required to take advantage of these potential benefits, and note what is commonly observed in current practice.

1.1 Acknowledgments

This paper is based on research conducted at the Center for the Built Environment (CBE) at the University of California, Berkeley, with the assistance of Research Specialist Tom Webster, numerous graduate students, and CBE's industry partners. Many of CBE's findings have been compiled in the *Underfloor Air Distribution (UFAD) Design Guide*, which will be published by ASHRAE in late 2003. The approach to this topic, "hype vs. reality," is borrowed from a series of training seminars prepared for the Pacific Gas & Electric Company by Allan Daly and Steve Taylor of Taylor Engineering, and CBE staff.

2. BACKGROUND

The application of UFAD technology in new office buildings showed a great deal of growth in North America during the 1990s. Market data showed that by the end of the decade approximately 8% of new office buildings were built with raised floors. Of these buildings with raised floors, about 20-25% used UFAD systems. Growth of this technology is continuing and today it is estimated that approximately 12% of new office buildings have raised floors, and around 40% of these include UFAD (Reynolds 2003). The decision to include a UFAD system is typically not based solely on the obvious benefits of cable management and flexibility. Frequently, occupant comfort, improved IAQ, or other expected benefits are cited as key considerations. For some building designers and owners, having a UFAD system is required to provide state-of-the-art system integration and operational capability.

3. BENEFITS

The following benefits commonly associated with UFAD buildings will be discussed in this paper: (1) improved flexibility for building services; (2) improved ventilation efficiency and indoor air quality; (3) improved occupant comfort, productivity and health; (4) reduced energy use; (5) reduced life-cycle building costs; and (6) reduced floor-to-floor height in new construction.

In almost every case, the realization of these benefits is a function of several factors. While design teams may count on some easily achieved system advantages, other benefits are achieved through careful coordination during the design process and proper operation after occupancy.

3.1 Flexibility for Change and Churn

The first potential benefit of UFAD systems we will explore is the improved flexibility for building services provided by the raised floor itself. Properly designed UFAD systems are integrated solutions that provide a great deal of flexibility, allowing for fast and inexpensive reconfigurations to accommodate the high churn rates common in many industries (Bauman et. al., 2000). The floor systems themselves consist of 24” x 24” composite steel and concrete floor panels fastened to supporting pedestals. The pedestals, typically with integrated leveling devices, are bonded to the slab with adhesive. Building services are located in the space below the floor, accessed by lifting the floor panels. Diffusers and electrical boxes are typically installed in one quadrant of each tile, so their locations can be fine tuned by rotating tiles.

Figure 1 Raised floor installation, above ductwork and cabling in place. (Image: D. Lehrer)

In practice, cable management flexibility is a UFAD benefit that can be taken advantage of with very little specialized knowledge. A number of manufacturers now provide modular systems for cabling, allowing for “plug-and-play” capability. Combined power/voice/data boxes may be mounted in the raised floor, connected with modular cables to secondary distribution boxes below that accommodate a number of floor boxes, allowing most reconfigurations to be made by in-house maintenance staff. An additional advantage of underfloor power and data systems is that they easily accommodate freestanding furniture; there is no need to core through floor slabs as with overhead systems.

There are a few design considerations worth noting for getting maximum flexibility from a UFAD system. Although the general intent of raised floor systems is to allow for unlimited space planning options, designers must plan on providing appropriate access for servicing HVAC equipment, and attempt to locate them in areas not likely to be covered with systems furniture. While it is never possible to anticipate all possible space plans during the design phase, engineers and designers should make efforts to reduce future conflicts.

The selection of floor finish will also affect the ease with which reconfigurations are completed. Carpet tiles are the standard for flexibility, allowing for the best access to the floor panels. Carpet tiles are available in 18" and 24" standard sizes. Using 24" tiles aligned with the floor tiles provides the best flexibility, this one-to-one relationship reduces the number of carpet tiles that must be cut when diffusers and floor boxes are relocated. One manufacturer provides indexed tabs that keep carpet tiles aligned with the floor tiles. Carpet tiles that are 18" square are also available, these are typically installed in a non-aligned fashion, which will require more cutting and carpet waste during changes. However the non-aligned installation method provides one advantage that may balance this concern. The non-aligned carpet tiles can significantly reduce the air leakage from the pressurized plenum compared to installations with aligned carpet. If floor plenums allow too much leakage, it may be difficult to provide effective control of the UFAD system. In laboratory tests for air leakage conducted by CBE, it was found that when compared to aligned carpet tiles, the non-aligned carpet tiles reduced the leakage by approximately 50% (Bauman, 2003).

It should be added that we have seen a number of projects with floor tiles left bare for aesthetic reasons. This is not recommended as a standard practice, or as a minimum the effect of leakage must be considered in the design of the system. Laboratory tests found leakage from the gaps between uncarpeted tiles from one manufacturer to be 0.68 cfm/ft^2 with a typical plenum pressure of 0.05 in. H_20. Leakage rates for bare tiles from other manufacturers may be higher. (This amount of leakage is roughly equivalent to the airflow rates required in a typical interior zone. If a raised floor were left with no finish, it might be possible to have adequate airflow with no diffusers installed.)

When floor finishes besides carpet are required, special consideration must be taken in order not to impact the system's flexibility. Several UFAD buildings designed for a client in San Francisco required wood flooring in circulation corridors and in executive areas. Although the width of circulation corridors was limited to allow for cable management, when the time came for significant reconfiguration, the work was slowed by the need to remove adhered wood flooring from the raised floor. In the case of an executive area with larger areas of wood finish flooring, underfloor HVAC units were located in closets wherever possible. When this was not possible the interior architects provided special panels in the floor system to provide access for maintenance (O'Sullivan, 2003). However such installations should generally be avoided to take advantage of the flexibility offered by UFAD systems. When properly designed, UFAD systems also have the potential to reduce churn costs, as noted in the section on life-cycle costs, below.

3.2 Ventilation Efficiency and Indoor Air Quality

Another commonly cited benefit of UFAD systems is that ventilation efficiency and indoor air quality (IAQ) are improved in comparison to overhead systems. Overhead systems supply cooled air that is mixed uniformly in the space to create a comfortable temperature. Any pollutants in the air are also mixed evenly in the space, and there is a concern that supply air can "short circuit," escaping to return registers without adequately mixing in the space, and worsening air quality. This may be of special concern during heating operation with warm supply air that may tend to remain at the top of a space.

To explain the ventilation characteristics with underfloor air delivery, it is first important to understand the difference between UFAD systems and displacement ventilation (DV) systems, used for cooling only. In a true DV system, 100% outside air is supplied at low level with very slow velocity, just slightly cooler than a comfortable temperature. The extremely low velocity allows the thermal buoyancy from heat sources in the space to drive a steady flow upwards, carrying pollutants to return grilles near the ceiling where they are exhausted from the space. Research has determined that true DV systems improve ventilation effectiveness. Consequently the new version of ASHRAE Standard 62 (currently undergoing final review) will allow designers of DV systems to assume a 20% ventilation improvement over traditional overhead systems.

UFAD systems differ from true DV systems in that the air is supplied from floor diffusers with some momentum, providing greater mixing of the supply air into the space. In a properly designed UFAD system, this mixing does not occur above the breathing zone, which extends from floor level to a height of 4-6 ft, as shown in Figure 2. Air in the space separates into two distinct zones divided by the stratification height (SH), and after air moves into the upper zone it does not remix with air in the breathing zone. The air above the breathing zone will be warmer and contain more pollutants than the lower zone. People and equipment in the space create heat, which rises in "plumes" that carry pollutants above the SH, drawing supply air where it is needed. In addition, in many climates UFAD systems may be operated with extended economizer cycle cooling, allowing for a higher percentage of outside air in the supply air volume. This is described in greater detail in the section on energy use, below.

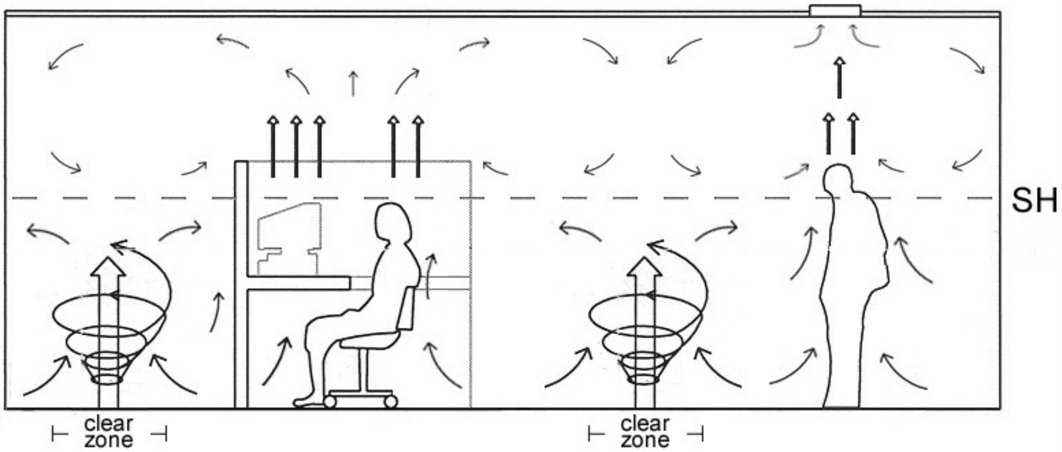

Figure 2 Diagram showing airflow patterns of UFAD systems. (Image: CBE)

A field study conducted in Japan found that underfloor systems provided slightly better air quality compared to overhead systems. In a building with both underfloor and overhead systems on different floors, it was found that airborne particulates were lower in the areas with the UFAD system (Oguro et. al., 1995). Another case study currently being conducted by CBE compares the occupant satisfaction of occupants that have moved from several buildings with overhead systems into a new building with an underfloor system. A survey of building occupants showed that the satisfaction rating for air quality in the underfloor building was significantly higher than in the overhead buildings, and the number of dissatisfied IAQ responses was cut in half (Shirai et.al., 2003).

Additional field or laboratory research is still needed to accurately determine the improvement in air quality provided by UFAD systems. However, field study research has shown that the perception of better air quality may have positive effects on building occupants. Building occupant satisfaction surveys conducted by CBE frequently reveal that occupants in buildings with overhead systems want more air movement to reduce the feeling of "stale air." It is reasonable to believe that when air is delivered from floor diffusers relatively close to occupants, they will have a perception of improved air quality.

3.3 Thermal Comfort, Productivity, and Health.

ASHRAE Standard 55-1992 is the standard by which occupant comfort in buildings is measured. It was based on laboratory studies in steady state conditions in which occupants had no control over their environment. These tests found that in any large population, at least 10% of people will not be satisfied, even in optimal conditions, due to individual preferences. When local sources of discomfort are factored in, this finding led to a standard that allows for up to 20% of building occupants to be dissatisfied.

However more recent research has shown that when occupants are given control of their environment, they are much more tolerant of a range of conditions. Two studies on individual occupant control, one with operable windows, (de Dear and Brager, 1998) and another looking at desktop controls, (Bauman et al., 1998) came to the same conclusions—occupants who were able to control their environment were approximately twice as tolerant to temperature variations. From a building management standpoint, this may result in fewer hot and cold complaints.

The amount of individual control that occupants have with underfloor systems varies depending on the type of diffusers installed. With commonly used passive swirl diffusers, individuals can reach down and control air flow by rotating the face of the diffuser, or by changing the position of paired nested baskets (commonly referred to as "salad spinners"). Floor mounted diffusers that incorporate variable air volume (VAV) boxes utilize thermostats to control airflow. In this case individuals may be able to adjust the direction of airflow in their workspace, but not the amount of airflow. The degree to which occupants will actually sense air movement, and benefit from these adjustments will depend on the location of the diffuser. Installation guidelines for UFAD systems call for a clear zone (~ 3 ft. diameter) to be defined around diffusers to prevent excessive airflow on occupants, as shown in Figure 2. Allowing people to move diffusers closer to their location when desired, should provide greater comfort.

The degree to which UFAD systems provide occupant comfort was studied in a field study conducted by CBE at the Teledesic Broadband Center, in Bellevue, WA. This field study included physical measurements in the building during both warm and cool seasons, and a Web-based survey of the building occupants. The study concluded that the thermal qualities in the space were very good, and that the systems worked well both in heating and cooling modes. The survey revealed that occupants were very satisfied with the UFAD system, and a large majority, 88%, preferred it to an overhead system. Only 36% of the people surveyed understood that they could adjust the diffusers, and few did in practice (Webster et. al., 2002a). The low adjustment rate may be a result of building operators that did not educate building occupants about the proper use of the diffusers. This observation has been confirmed in other field studies, occupants appreciate the benefit of having control even if they do not take advantage of it frequently.

Although there was no available metric for employee productivity in the Teledesic study (as is often the case in office environments) we did ask occupants about "self-reported" productivity. Fifty percent of the building occupants felt that the floor diffusers enhanced their ability to do their work, 39% gave a neutral response, and only 11% thought that it interfered with their work. Similar results have been observed in occupant survey results in other buildings. Certainly additional research on this topic would be needed to show productivity gains as a direct result of UFAD systems. However UFAD systems show great potential for improved thermal comfort and perceived air quality, factors which have a significant effect on building occupant productivity.

3.4 Energy Use.

Improved energy efficiency is another commonly cited benefit of UFAD systems. Unfortunately no energy modeling software available allows for an accurate comparison of whole building energy performance between UFAD and overhead systems. To address this information gap, a team of researchers from CBE, Lawrence Berkeley National Laboratory, UC San Diego, and York International are currently developing UFAD modeling capability for EnergyPlus, the energy simulation software developed by the Department of Energy. (For more information on this research project visit www.cbe.berkeley.edu/research/briefs-ufadmodel.htm.) Although we can not yet model all of the combined effects of underfloor systems, there are several independent factors that can make underfloor systems highly energy efficient.

3.4.1 Extended Economizer Cycle. One potential for energy savings results from the higher supply air temperatures used in UFAD systems, allowing for extended economizer cycle operation. (Economizer cycle cooling is the use of outside air for cooling with no or reduced chiller operation.) While overhead systems typically use a supply air temperature (SAT) of 55-57º F, underfloor systems supply air at 63-65º F. With higher supply air temperatures 100% economizer cycle cooling may be extended during times of the year in which the outside air temperature is in the range of 56º-65º F. The degree to which this can be used as an energy saving strategy will vary depending on climate variables, with the greatest opportunity in cool and dry climates. Figure 3 shows the hourly temperature data for San Francisco, with vertical bars indicating the number of hours of occurrence annually for each degree Fahrenheit. The bracketed area represents the range of temperatures between 56º F and 65º F. The bars in this range represent the portion of the year (2217 hours) that an underfloor system could run on 100% economizer cycle, when compared to an overhead system, in this climate. As noted earlier, the increased use of outside air for cooling provides an additional benefit of improved indoor air quality. In addition, the extended economizer hours can be a benefit for buildings with operable windows, for it is during economizer hours that windows can be opened to provide occupant control and ventilation with no energy consequence.

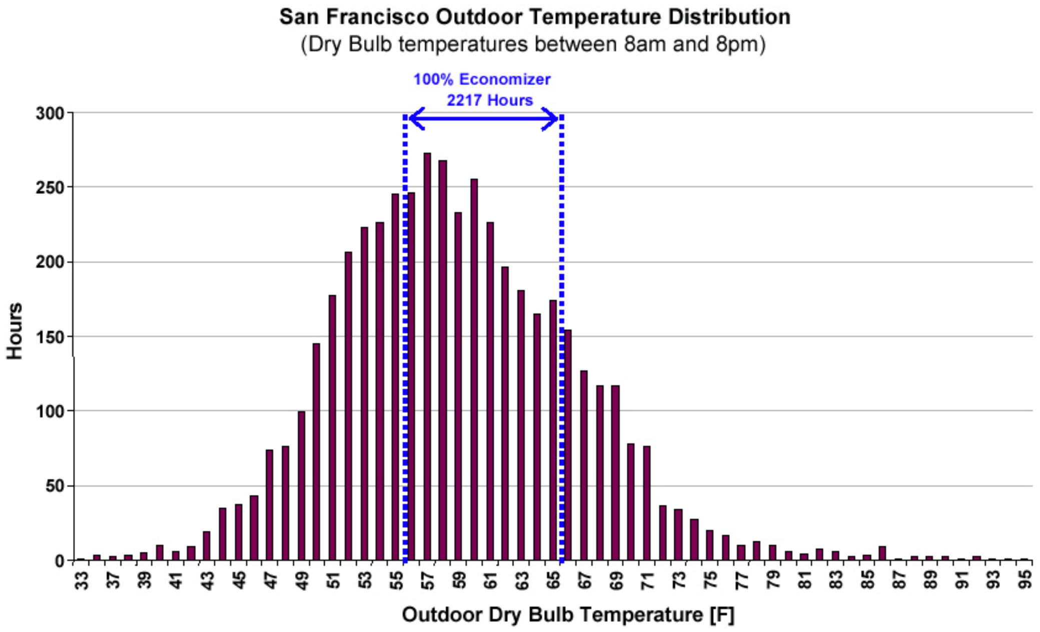

Figure 3 Hourly temperature distribution for San Francisco. The bracketed hours represent extended 100% economizer cycle potential with underfloor systems. (Chart: Taylor Engineering)

The use of economizer cycle cooling is highly climate dependent, and the example in San Francisco is close to an ideal climate for this UFAD strategy. In climates in which air must be cooled for humidity control, it may not be possible to use an economizer strategy extensively. However in many temperate zones of North America and Europe there are months during the year when the higher supply air temperature of a UFAD system could provide significant energy savings.

3.4.2 Room Air Stratification. It is also believed that UFAD can provide an opportunity for energy savings through careful optimization of the stratification of air temperatures within the conditioned spaces. (Stratification is the degree to which the air temperature varies from the floor to the ceiling level.) Laboratory tests conducted by CBE and York International have shown that for a constant heat input (heat from occupants, computers, solar gain, etc.) stratification increases as supply air volume is reduced. Figure 4 shows temperature profiles developed from laboratory testing under a constant heat input. The highest airflow rate is represented by the line for 1.0 cfm/ft^2, which would produce close to a well mixed condition similar to an overhead system, with little temperature stratification. When the supply air volume is reduced to 0.6 cfm/ft^2, the stratification is increased. This represents a 40% reduction in airflow and significant energy savings, however the temperature in the occupied zone is still within a reasonable range for comfort. The temperature profile that represents 0.3 cfm/ft^2 would result in occupant discomfort, as the stratification level has dropped down into the occupied part of the space (Webster et. al., 2002b).

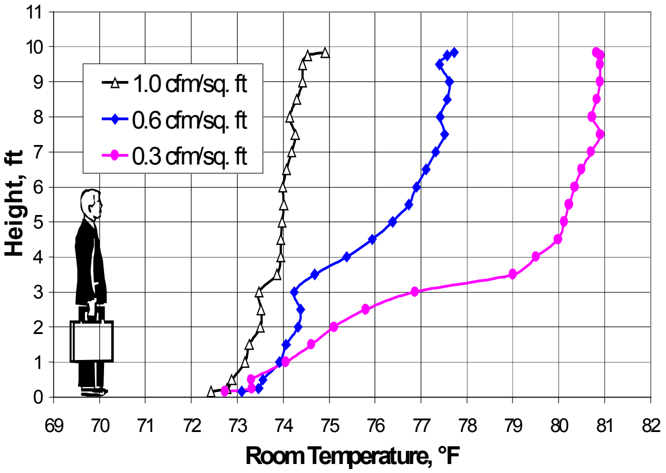

Figure 4 Room air temperature stratification profiles for three supply air volumes with constant heat input. (Chart: Tom Webster)

These laboratory tests clearly demonstrate the potential for energy savings by controlling temperature stratification. However operating systems in occupied buildings present variables that are far more complex than a lab setting. CBE field studies of a small number of buildings have found that in some spaces stratification is properly controlled, and in others it is not (Webster 2003). Additional research in a larger number of buildings is still needed to determine what is occurring generally in practice.

3.4.3 Thermal Mass Storage. Another energy saving potential for UFAD systems results from the fact that supply air is in direct contact with the structural slab's thermal mass. During the warm season, nighttime ventilation can precool the concrete slab, allowing the cooled thermal mass to act as a heat sink, extending the economizer cycle. An additional benefit is that this strategy utilizes off peak power. The Lloyd's Building in London, engineered by Arup, is an early example of a UFAD building that implemented nighttime ventilation. The Gap 901 Cherry building in San Bruno, California, also by Arup, represents a more recent application of this strategy. In addition, the 901 Cherry design team successfully applied to the local utility for an energy efficiency rebate, arguing that the UFAD system provided the same benefit as thermal ice storage equipment, but without purchasing equipment. Nighttime cooling can also be effective in multi-story buildings where the heat from the stratified air below fully penetrates the floor slab during the day (McGregor, 2003).

There are several factors that will determine whether nighttime cooling is appropriate for a particular building. Climate is a key factor, with the greatest potential existing in climates with mild summer temperatures, a significant diurnal swing, and low humidity. Design engineers also need to consider the increase in fan energy due to nighttime operation, insuring that net energy use is reduced. Another challenge occurs in buildings that require some morning heating, in which case system control becomes a key factor. Data from the Lloyd's Building showed that when the night ventilation was stopped an hour before occupancy, the air temperature would increase slightly due to background heat loads (from computers, equipment, etc.). This control sequence provides comfortable air temperatures when occupants arrive in the morning, but keeps the slab cool and able to absorb heat as the building heats up during the day. This operational strategy must be understood by building operators, who should not respond to cold complaints in the morning by turning on the heat, as this makes the strategy ineffective (McGregor, 2003). Again, additional research is needed to determine the effectiveness of this strategy in a greater number of buildings.

3.4.4 Primary Fan Power. One final additional energy efficiency benefit commonly ascribed to UFAD systems is the potential to reduce primary fan power through the reduction of ductwork. Because UFAD systems distribute air through the underfloor plenum, there is much less ductwork than an overhead system, and less pressure is required to force air through the system. However many UFAD systems rely on terminal fan powered boxes, particularly in perimeter zones, and this must be factored into calculations for total fan power (Webster et. al., 2000c).

We have discussed four potential strategies for designing underfloor systems for greater energy efficiency. There are other UFAD energy strategies that can create additional minor savings, but these are beyond the scope of this paper. All of these strategies rely on climate and careful system design. However until UFAD modeling capabilities are available with EnergyPlus, it will be difficult to accurately determine the combined effects of these design options independently or in comparison to overhead systems.

3.5 Potential for Reduced First Costs and Life-Cycle Costs

First cost factors continue to drive the design of non-residential buildings. Although owners may give high importance to energy and maintenance costs, construction budgets are rarely expanded to provide for long term savings. As a result, project design and development teams are eager to have reliable tools for predicting system costs. CBE has worked with its industry partners on a pilot cost study to compare UFAD and overhead systems, and is currently conducting detailed research on this topic funded by the U.S. General Services Administration. The research team is studying alternative building and system designs to build a detailed cost model, using data from industry professionals with extensive UFAD experience. Later, CBE will gather information related to life-cycle cost—commissioning, startup, operations, energy, churn, and potential tax benefits—and incorporate it into the cost model for life-cycle cost analysis.

3.5.1 First Cost Factors The distinct features of UFAD buildings result in certain elements that increase costs, and others that reduce costs, in comparison to overhead systems. (A detailed matrix of added and reduced cost factors will be available when the *Underfloor Air Distribution (UFAD) Design Guide* is published at the end of 2003. See references.) The raised floor system is the primary cost addition in UFAD systems. Other cost adding elements include raised slabs typically used in core areas where underfloor is not desired, and physically sealing the plenum at the connections between the building skin and the slab, at cores, and other penetrations. Generally a floor plenum need not be treated differently from a ceiling plenum with respect to code regulations, however local code officials may make demands based on their own interpretations. In some cases, code officials have requested that plenum dividers and/or smoke detectors be installed under the raised floor, resulting in added costs. (Possibly in rare instances, sprinklers might be required by a code official.) To avoid unanticipated costs, project teams should consult local building codes and officials early in the design process.

On the other hand, there are several opportunities for potential cost savings for underfloor systems. Well designed underfloor systems allow for the elimination of overhead ductwork, downsized HVAC equipment, and savings by reducing the floor-to-floor height, as discussed below. Modular "plug-and-play" power and voce/data systems incorporated into UFAD systems allow for the elimination of electrified furniture systems and potentially reduced costs. However the number of options for furniture, power, and data management systems makes this a highly complex cost issue. Preliminary findings show overlapping ranges for the sums of added and saved costs, indicating that UFAD systems may cost more or less than overhead systems, depending on the design options under consideration. Anecdotal project information shows that through careful integration with other building systems (and cooperation of code officials) UFAD solutions may in some cases have lower first costs. For example, cost estimates for the California State University (CSU) Monterey Bay Library show a UFAD system with a concrete structure costing approximately \$5-\$6/sf^2 less than an overhead system with either a concrete or steel structure. The primary cost saving factors include the reduction in overhead ductwork, HVAC zoning, and lower floor-to-floor heights (Shell, 2003).

3.5.2 Life-Cycle Cost Factors The decision to go with a UFAD system will also affect the life-cycle costs of a building. As noted above, energy use may be reduced in well designed UFAD buildings and result in year to year cost savings. Accurately predicting energy savings with UFAD will be facilitated when a UFAD module for EnergyPlus is available. There are also potential cost savings from reduced building costs related to churn, defined as the percentage of building occupants annually that move from one workstation to another. The flexibility provided by the access floor and an integrated design solution can reduce the costs associated with employee moves and reconfigurations. A study by Carnegie Mellon University of the Owens Corning Headquarters reported savings of \$300 per employee move with UFAD, equivalent to annual savings of \$0.45/ft^2 for a building with a 30% churn (Hartkopf and Loftness, 1997). Preliminary findings by CBE found similar results, it was estimated that the flexibility provided by a UFAD system can save between \$0.26/ft^2 to \$1.82/ft^2 annually for a building with a churn rate of 41%, the average identified by the IFMA Research 1997 Benchmarks Report. Again, additional research is needed, a task made difficult by the fact that churn costs are typically not tracked by building operators in any consistent manner.

3.6 Potential for Reduced Floor-to-Floor Heights.

A number of articles have noted the possibility of reducing floor-to-floor heights in buildings with UFAD systems, creating cost savings in structural and facade systems. It is true that laboratory testing has shown that even an 8" raised floor height provides uniform air distribution in an underfloor plenum (Bauman et. al., 1999). However in practice, raised floor heights are driven by two factors, the size of underfloor equipment and the size of the floor area. Manufacturers have developed lower height equipment (VAV boxes, dampers, etc.) for underfloor applications, however smaller sized units may increase the unit quantity, increasing costs. Larger floor areas requiring larger main supply ducts increase raised floor heights due to the physical constraints of integrating the main horizontal supply ducts with floor pedestals and/or vertical ducts in the building core.

Many design teams are finding that that careful integration with the structure is critical for reducing floor-to-floor heights. Underfloor systems integrated with flat slab concrete structures have the greatest potential to reduce heights, with floor-to-floor height reductions of 6”-12” frequently possible. EHDD Architecture’s design team for the CSU Monterey Bay Library compared multiple options for steel vs. concrete structures, and overhead vs. underfloor systems. Although it is early in the design process, the most cost-effective proposal appears to be a concrete/underfloor solution with a typical floor-to-floor height of 13’-6”, significantly lower in height than other solutions but still providing the required 10’-6” floor to ceiling height (Shell 2003).

One common pitfall in the effort to reduce floor-to-floor heights results from the elimination of acoustical ceilings in exposed concrete structures. The naming convention for acoustical ceilings is not by chance, and these systems do more than conceal fireproofing and building systems. Several projects have been completed with insufficient regard for acoustic considerations, and in some cases the elimination of the suspended ceiling has resulted in acoustical problems in open plan areas and conference rooms.

4. CONCLUSION

UFAD systems offer a number of potential benefits as described above. The key factors to the success of UFAD design include the experience of the project team, the location and climate, design integration, HVAC control strategies, and sufficient training of building management staff. The technology has moved beyond early adopters, and is becoming well understood through a large number of completed case studies and research studies. However challenges still exist for teams doing their first underfloor application, and design strategies are still evolving. It is hoped that design resources now in development will fill soon these information gaps and lead to cost effective and high performing UFAD buildings.

5. REFERENCES

(Note: A number of papers on UFAD and related research are available from the publications page of CBE’s website, at www.cbe.berkeley.edu/research/research-pubs.htm.)

Bauman, F. 2003. *Underfloor Air Distribution (UFAD) Design Guide.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bauman, F., T. Webster, A. Lee, J. Lin, D. Lehrer, K. Powell, R. Bannon, and Q. Doan, 2000. “CBE underfloor air technology website,” www.cbe.berkeley.edu/underfloorair

Bauman, F., P. Pecora, and T. Webster. 1999. "How low can you go? Air flow performance of low-height underfloor plenums." Center for the Built Environment, University of California, Berkeley. October.

Bauman, F.S., T.G. Carter, A.V. Baughman, and E.A. Arens. 1998. “Field study of the impact of a desktop task/ambient conditioning system in office buildings.” *ASHRAE Transactions,* Vol 104 (1).

de Dear, R., and G.S. Brager. 1998. “Developing an adaptive model of thermal comfort and preference.” *ASHRAE Transactions*, Vol. 104 (1).

Hartkopf, V. and V. Loftness, 1997. “Systems integration for the owens corning headquarters.” Toledo.

McGregor, A. 2003. Personal correspondence with Arup, San Francisco, CA.

Oguro, M., H. Fukao, M. Ichihara, Y. Kobayashi, and N. Maehara. 1995. “Evaluation of a floor-based air-conditioning system performance in an office building.” *Proceedings, Pan Pacific Symposium on Building and Urban Environmental Conditioning in Asia.* Nagoya University, Nagoya, Japan, 16-18, March.

O’Sullivan, K. 2003. Personal communication. Former design consultant to Gensler, San Francisco, CA.

Reynolds, B. 2003. Personal communication. Tate Access Floors, Inc., Jessup, MD.

Shell, S. 2003. Personal communication. EHDD Architecture, San Francisco, CA.

Shirai, R., F. Bauman and L. Zagreus. 2003. “First post-occupancy evaluation (POE) of block 225: Capitol area east end complex.” Interim report to California State Department of General Services and California Energy Commission, Center for the Built Environment, University of California, Berkeley, August.

Webster, T., R. Bannon, and D. Lehrer. 2002a. “Teledesic Broadband Center.” Center for the Built Environment, University of California, Berkeley, April.

Webster, T., F. Bauman, J. Reese. 2002b. “Underfloor air distribution: thermal stratification,” *ASHRAE Journal*, May.

Webster, T., Bauman, F., and F. Ring. 2000c. "Supply fan energy use in pressurized underfloor air distribution systems." Center for the Built Environment, University of California, Berkeley, October.

Webster, T. 2003. Personal communication. Center for the Built Environment, University of California, Berkeley, CA.