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Alternative Air Conditioning Technologies: Underfloor Air Distribution (UFAD)

An overview of UFAD technology and its potential in federal facilities

Introduction and Background

Recent trends in today's office environment make it increasingly more difficult for conventional centralized HVAC systems to satisfy the environmental preferences of individual office workers using the standardized approach of providing a single uniform thermal and ventilation environment. Since its original introduction in West Germany during the 1950s, the open plan office containing modular workstation furniture and partitions is now the norm. Thermostatically controlled zones in open plan offices typically encompass relatively large numbers of workstations in which a diverse work population having a wide range of preferred temperatures must be accommodated. Modern office

buildings are also being impacted by a large influx of heat-generating equipment (computers, printers, etc.) whose loads may vary considerably from workstation to workstation. Offices are often reconfigured during the building's lifetime to respond to changing tenant needs, affecting the distribution of within-space loads and the ventilation pathways among and over office partitions. Compounding this problem, there has been a growing awareness of the importance of the comfort, health, and productivity of individual office workers, giving rise to an increased demand among employers and employees for a high-quality work environment.

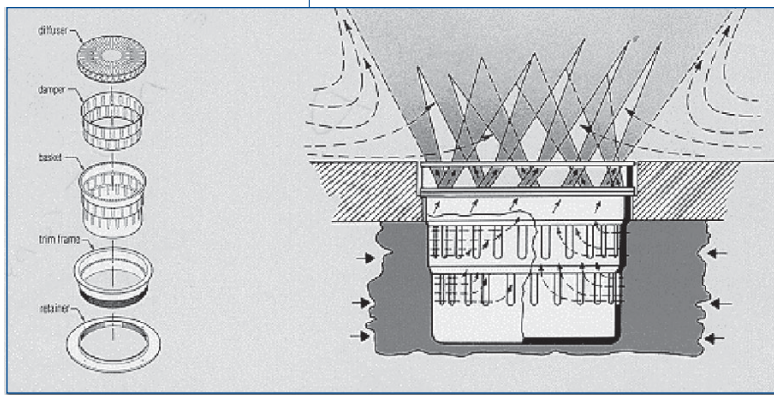


Illustration of typical swirl diffuser used in UFAD systems.

Task Ambient Conditioning

During recent years an increasing amount of attention has been paid to air distribution systems that individually condition the immediate environments of office workers within their workstations to address the issues outlined above. As with task/ambient lighting systems, the controls for the "task" components of these systems are partially or entirely decentralized and under the control of the occupants. Typically, the occupant has control over the speed and direction, and in some cases the temperature, of the incoming air supply. Variously called "task/ambient conditioning," "localized thermal distribution," and "personalized air conditioning" systems, these systems have been most commonly installed in open-plan office buildings in which they provide supply air and (in some cases) radiant heating directly into workstations. TAC systems can be classified into the following two major categories: 1) furniture-based, and 2) floor-based, underfloor air distribution (UFAD). A majority of these systems include a raised floor system with which underfloor plenums are used to deliver conditioned air to the space through floor grills, or in conjunction with the workstation furniture and partitions.

Underfloor Air Distribution

In the 1970s, underfloor air distribution was introduced into office buildings in West Germany as a solution to cable management and heat load removal issues caused by the proliferation of electronic equipment throughout the office [1]. In these buildings, the comfort of the office workers had to be considered, giving rise to the development of occupant-controlled localized supply diffusers to provide task conditioning. Some of the first UFAD systems in Europe used a combination of desktop outlets for personal comfort control and floor diffusers for ambient space control [2].

Prior to the 1990s, office installations using underfloor systems had been found primarily in South Africa, Germany, and other parts of Europe. The technology was not commonly used in North America prior to about 1995, in part due to the downturn in office building construction beginning in the mid-1980s. Japan did not experience this same downturn, and as a result, significant growth in UFAD technology was observed during this period. Between 1987 and 1995, more than 250,000 m² (2.7 million ft²) of office space in more than 90 buildings were installed with UFAD systems in Japan [3].

However, in the late 1990s growth for raised floor installations in the US was dramatic and designers and manufacturers predicted that 35% of new offices would use raised floors by 2004. Half of these installations were expected to incorporate UFAD technology. This rate of increase has slowed now (2003) due to the economic downturn and much reduced office construction.

The purpose of this technology review is to provide federal facilities managers an overview of the principles, features,

benefits, and limitations of this important innovation in building conditioning technology.

Technology Description

A task/ambient conditioning system is defined as any space conditioning system that allows thermal conditions in small, localized zones (e.g., regularly occupied work locations) to be individually controlled by building occupants, while still automatically maintaining acceptable environmental conditions in the ambient space of the building (e.g., corridors, open-use space, and other areas outside of regularly occupied work space).

UFAD systems are uniquely characterized by their ability to allow individuals to have some degree of control over their local environment, without adversely affecting that of other nearby occupants.¹ Depending on the UFAD system design, ambient environmental control in non-work areas may be provided by additional local supply outlets, or by a separate space conditioning system, but in either case under automatic control.

The types of diffusers supported, active or passive, further distinguish UFAD systems from furniture-based TAC systems. Active diffusers (for purposes of this report) are defined as those with local means of volume adjustment (such as an integral variable speed fan or damper) that is amenable to automatic zone control (in addition to means for occupant control). Passive diffusers, although they may have means for occupant adjustment, are combined with terminal or system elements to achieve zone control. Systems designed with all fan-assisted active diffusers typically utilize zero-pressure plenums. Passive diffusers require pressurized plenums. The majority of UFAD systems currently being deployed

have pressurized plenums with either active or passive diffusers.

Principles of Operation

Figures 1 and 2 illustrate the fundamental differences between traditional overhead and furniture-based TAC and UFAD systems, respectively. As shown in Figure 1, overhead systems (in office buildings, these are predominately variable air volume [VAV] all-air distribution systems) employ an extensive array of ductwork and terminal devices to provide supply air through the ceiling-mounted diffusers. Often referred to as mixing ventilation systems, these systems are designed to promote complete mixing of supply air with room air, thereby maintaining the entire volume of air in the space at the desired temperature setpoint. Space air is typically returned to the AHU via an open ceiling plenum that also contains various other systems for lighting, electrical, communications, and fire protection. UFAD systems turn this concept upside down and have in common the following characteristics:

- Supply air, including at least the minimum required volume of outside air, is filtered and conditioned to the required temperature and humidity by a conventional AHU and passed through a minimum amount of ductwork to an underfloor plenum. The underfloor plenum is formed by installation of a raised floor system, typically consisting of 0.6 m x 0.6 m (2 ft x 2 ft) concrete-filled steel floor panels positioned 0.3–0.46 m (12–18 in.) above the concrete structural slab of the building. The raised floor system also allows all cable services, such as power and communication, to be located in the plenum and provides easy access for modifications and maintenance.

¹ In open plan settings there is less control due to airflow rate change associated with opening and closing floor diffusers than in private offices. Better occupant control is achieved by designs that allow the airflow to be directed toward the occupant.

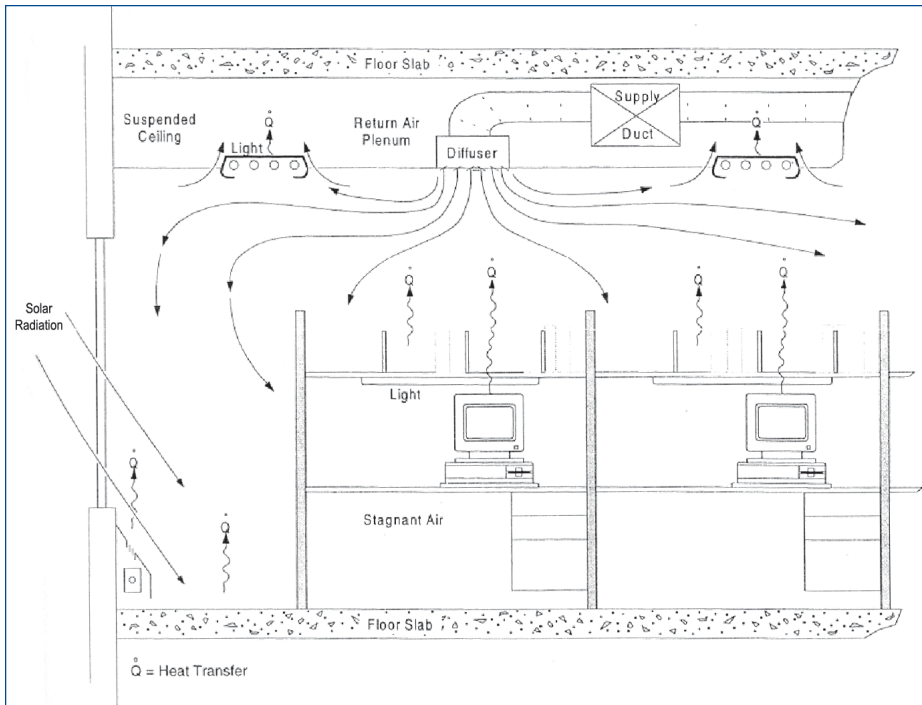


Figure 1. Overhead system.

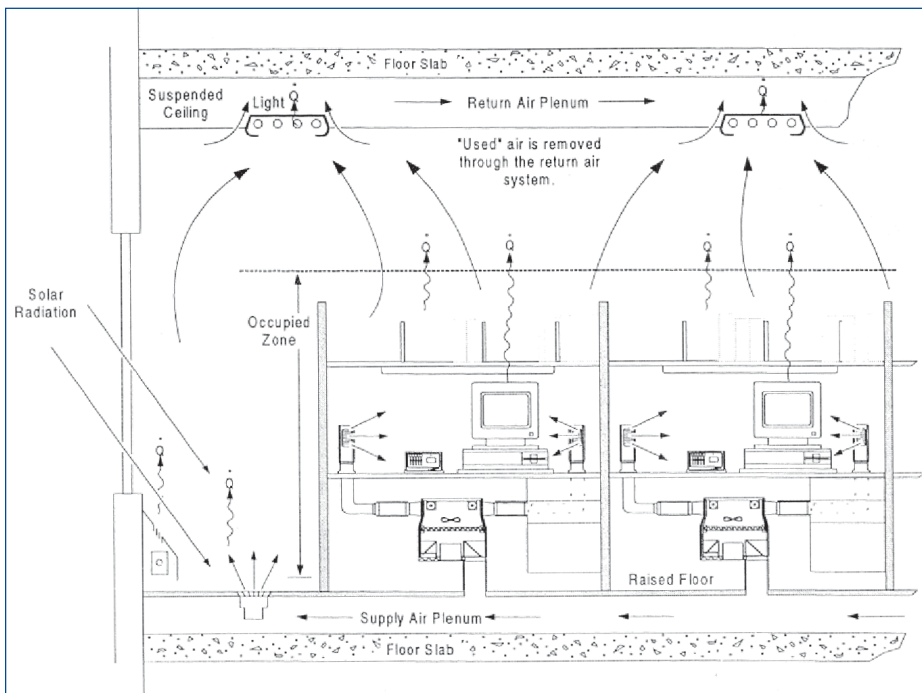


Figure 2. TAC system.

- Individual office workers can control their local thermal environment over a relatively wide range (typically by adjusting the volume and/or

trajectory of the supply air entering the space), giving them the opportunity to fine-tune the thermal conditions in their workstation to their

personal comfort preferences. Different supply outlet configurations may be used depending on the conditioning requirements for a particular zone of the building, as discussed below.

- UFAD systems benefit from a floor-to-ceiling airflow pattern that takes advantage of the natural buoyancy produced by heat sources in the office to efficiently remove heat loads and contaminants from the space. Air is returned from the room at ceiling level through recessed lighting fixtures and return grilles via a conventional ceiling return plenum or return grilles located high in the space when a return plenum is not used.
- Because the air is supplied directly into the occupied zone (up to 6 ft (1.8 m) height), supply outlet temperatures are generally maintained above 17 to 18°C (63 to 64°F) to avoid uncomfortably cool conditions for the nearby occupants and to minimize cool temperatures near the floor.

There are a wide variety of approaches being used to provide a combination of individual and automatic zone control for UFAD systems.² (See reference [4]). Typically, these systems use variable-air-volume (VAV) or constant-air-volume (CAV) methods for general zone control (i.e., overall zone control other than local occupant control).

- Six types of diffusers are currently being offered;
 1. Fan-assisted, active
 2. Variable area, active
 3. Swirl, passive
 4. Swirl, active
 5. Linear bar grille, passive
 6. Linear bar grille, active

² The author has identified over a dozen variations of these systems.

- The heating and cooling loads of perimeter zones are handled by fan-powered constant volume or variable volume terminal reheater units located in the underfloor plenum (similar to those shown in Figure 3). Passive or active diffusers are located in occupied areas of the zone normally within about 4.5 m (15 ft) from the exterior walls. Passive diffusers are generally supplied by a (series) fan powered mixing box or fan coil unit, or a VAV box either connected to the diffuser by ducting or by supplying air to a partitioned area of the plenum where the diffusers are located.
- Interior zones are generally large zones each controlled by one thermostat, but with diffusers located near the occupants within or close to their workstations.

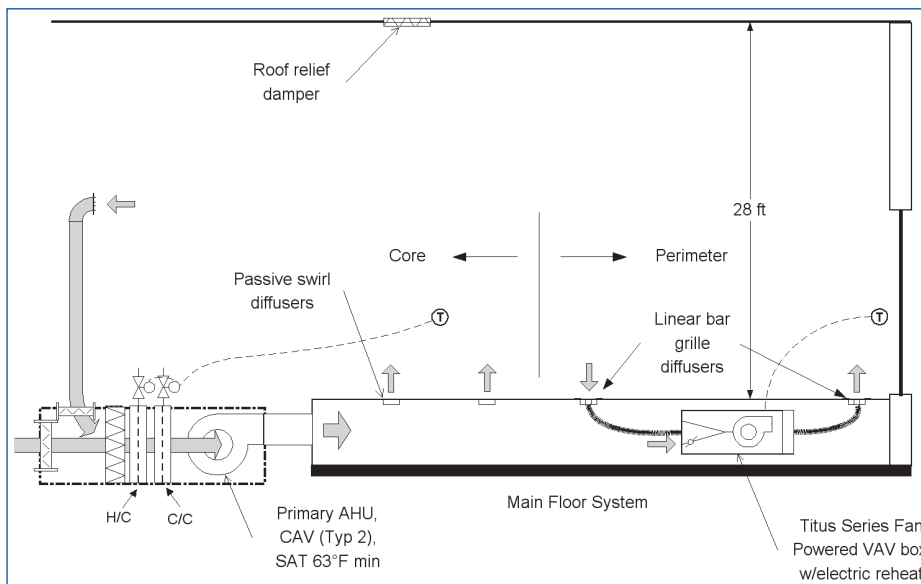


Figure 3. Pressurized plenum UFAD system.



Figure 4. Typical interior swirl diffuser layout.

Figure 3 shows a schematic diagram and Figure 4 a typical diffuser layout for a pressurized plenum UFAD system. This system is being commonly applied to office buildings due to its simplicity and cost savings. Although this floor-based air distribution system provides somewhat limited individual comfort control for occupants, it still affords many of the same flexibility and energy-saving benefits associated with the others.

Potential of UFAD Applications

Benefits

Improved thermal comfort for individual occupants – Occupant thermal comfort is perhaps the area of greatest potential improvement in that UFAD systems

can accommodate individual differences. In today’s work environment, there can be significant variations in individual comfort preferences due to differences in clothing and activity level (metabolic rate) as well as differences in the local heat gains and losses. By allowing personal control of the local thermal environment, UFAD systems could satisfy virtually all occupants, including those out of thermal equilibrium with their surrounding ambient environment, as compared to the 80% satisfaction quota targeted in practice by existing thermal comfort standards [5].

Improved air movement and ventilation effectiveness; cleaner environment – Some amount of improvement over conventional uniformly-mixed systems is expected by delivering the fresh supply air near the occupant and at the floor.

Improved occupant satisfaction and increased worker productivity – UFAD systems have the potential to increase the satisfaction and productivity of occupants as a result of their having the ability to individually control their workspace environments. The financial implications of such improvements can be extremely large as salary costs typically make up at least 90% of all costs (including construction, operation, and maintenance) over the lifetime of a building.

Energy Savings – Energy savings over conventional overhead systems are predominately associated with two factors: cooling energy savings from economizer operation and increased chiller COP, and fan energy savings. Details of how these savings are achieved can be found in [6].

Limitations

Among the items that limit the widespread acceptance and application of UFAD technology are the following:

New and unfamiliar technology – For the majority of U.S. building owners,

developers, architects, engineers, and equipment manufacturers, UFAD systems still represent a relatively new and unfamiliar technology. The decision to select a UFAD system will initially require changes in common practice, including new procedures and skills in the design, construction, and operation of such systems as well as changes in responsibilities of the various installation trades. This situation creates some amount of perceived risk to designers and building owners.

Perceived higher costs – An industry survey found the perceived higher cost of UFAD systems to be one of the two top reasons that UFAD technology is not used more widely by the industry today.

Many designers immediately eliminate underfloor UFAD systems from consideration out of concern for higher first costs of the raised flooring. However, as described above, there are many factors associated with raised floor systems that contribute to reduced life-cycle costs in comparison to traditional air distribution systems. In UFAD systems using fan-powered supply diffusers, the additional cost of installing and maintaining many small units must be balanced against the benefits of providing personal environmental control (reduced occupant complaints) and reducing the size of other system components (e.g., central fan).

Limited applicability to retrofits and certain building types/areas – The installation of UFAD systems and the advantages that they offer are most easily achieved in new construction. Some of the key system features are not always suitable for retrofit applications (e.g., access floors cannot be installed in existing buildings with limited floor-to-floor heights). Although widely applicable, there are building types and areas within buildings where access floors and underfloor air distribution are not

appropriate. These areas are generally those in which spillage has the potential to occur, including bathrooms, laboratories, cafeterias, and shop areas.

Lack of information, design guidelines, and evaluation methods – Although in recent years there have been an increased number of publications on UFAD technology (see References), there is still not a complete understanding of some fundamental fluid mechanics and thermal issues and no standardized design methods exist yet. System operating sequences and control techniques are likewise under development.

Earlier versions of ASHRAE Standard 55 [7] were based on the assumption of a well-mixed and uniformly conditioned environment. UFAD systems, however, usually involve greater variability of thermal conditions over both space and time. The effect of providing occupant-control has not been fully taken into account, although it is well established that occupants will tolerate greater fluctuations in environmental conditions if they have control over them. The current version of the standard (55-92) was revised (see Figure 3 of the standard) to allow higher air velocities than the previous version, if the occupant has control over the local air speed.

ASHRAE Standard 113-90 [8] is the only currently available building standard for evaluating the air diffusion performance of an air distribution system. The current version of Standard 113, however, is based on the assumption of a single uniformly mixed indoor environment, as provided by a conventional overhead air distribution system. This assumption is not necessarily appropriate for evaluating the performance of UFAD systems that deliver conditioned air directly into the occupied zone of the building through supply outlets that are

in close proximity to and under the control of the building occupants.

Potential for higher building energy use – As with any space conditioning system, a poorly designed and operated UFAD system has the potential to use more energy than that used by a well-designed conventional system. For example, the energy use of UFAD systems using large numbers of small local fans³ may increase due to the relatively poor fan and motor efficiencies in these units.

Thermal discomfort – UFAD systems are perceived by some to produce a cold floor, and because of the close proximity of supply outlets to the occupants, the increased possibility of excessive draft exists. Some systems appear to be designed and operated in such a manner that they produce hot and cold complaints similar to existing conventional systems despite the potential to achieve better comfort performance.

Problems unique to underfloor plenums – In UFAD systems, concern is sometimes expressed about the increased probability of spillage and dirt entering directly into the underfloor supply air stream, and therefore being more widely distributed throughout the occupied space. There is also some concern about improperly dehumidified air being delivered to the plenum where condensation could occur on cool structural slab surfaces.

Virtually all of the issues listed above are actively being researched [9] or addressed by design and construction professionals and equipment vendors in response to market demand. Some of these issues (e.g., plenum dirt and moisture) have not been shown to be problems in projects installed to date. Many of the problems that do occur can be traced to inadequate design and operating strategies that have resulted from lack of knowledge and experience

³ Either integral to the floor diffuser or in terminal units.

typically associated with early installations of any nascent technology.

Cost-Effectiveness

Cost considerations will be different depending on whether the installation represents new or retrofit construction. Total first costs (shell and core plus tenant improvement) for UFAD systems utilizing raised flooring will likely be somewhat higher than those for a conventional system. Preliminary results from research studies [9] have shown total building first costs of pressurized UFAD systems in new construction (including raised floor and structural differences) to be about 4-6% greater than conventional. However, if a raised floor system has already been justified for other reasons, such as improved cable management, the cost differential is often eliminated altogether. In new construction, UFAD can lead to reduced floor-to-floor heights thus reducing structural costs. Furniture-based and active diffuser based systems will generally cost more than other solutions.

Operating costs can be reduced in accordance with the energy-saving strategies discussed above. With the improved thermal comfort and individual control provided by UFAD systems, occupant complaints requiring response by facility staff can be minimized. UFAD systems using raised flooring provide maximum flexibility and significantly lower costs associated with reconfiguring building services (when changes are being made in the office layout) due to churn—and thus reduce life-cycle costs substantially.

First cost for retrofits, generally the bulk of construction activity is most likely greater than those for new construction. And as indicated previously, some facilities are not amenable to retrofit by UFAD systems.

To determine total life cycle cost differences between UFAD systems and conventional designs the following factors must be considered in addition to first cost:

Churn – This is the cost associated with relocating personnel and is defined as the ratio of total workplace moves in a year to the total number of building occupants. These figures vary widely by industry type and building activities. Results of a study by IFMA [10] are shown in Table 1.

Table 1. Churn rates.

Group	Churn %	Office plan (% office/open/bullpen)
Services	37	35/55/10
Manufacturing	40	34/58/8
Institutional/Government ⁴	23	67/20/13

As shown government facilities have significantly lower churn than other industries, which is also reflected in the much lower percentage of open plan space. This indicates that the benefits of reduced churn costs in federal facilities may be limited. It should be noted that the cost of churn can vary considerably depending on the extent of the reconfiguration; i.e., simply moving to a new cubicle is much different than reconfiguring the layout of cubicles and/or offices. The high proportion of offices in government facilities could drive these costs significantly if the reconfiguration involves more than office to office moves.

O&M – This item includes the costs of facility management and energy. While energy savings estimates are limited due to the lack of appropriate capabilities in energy simulation programs and data

from monitored projects, indications are that savings in annual HVAC system energy can be in the range of 10-20% depending on system design and weather conditions. Maintenance costs are expected to be less than conventional systems due to the ease of access to the distribution system. However, commissioning/startup costs may be greater since the location and operation of the diffusers may require fine-tuning to optimize the occupant interaction benefits.

Productivity and health – The savings associated with productivity and health benefits are difficult to measure and require considerably more research. However, recent studies [11] indicate that work performance improvements of 0.5 to 5% may be possible when the indoor environmental quality is improved.

Federal-Sector Potential

The potential for deployment of UFAD technology in the federal sector will depend on cost-effectiveness and availability of suitable buildings. Each project must be considered on its own merits. Overall the federal government owns and operates over 500,000⁵ residential and non-residential buildings totaling about 3 billion ft² [12]. The floor space is broken down between agencies as shown in Table 2.

Table 2. Federal building floorspace.

Agency	% of Floor space
Defense	65.4
Postal	10.7
GSA	6.1
VA	5.0
DOE	2.6
Other	10.2

⁴ This study did not distinguish between various types of government facilities (i.e., state, local, federal) so it is unclear as to how representative these figures are for federal facilities.

⁵ About 85% of these buildings are military housing.

There are roughly 76,000 existing *non-residential* federal buildings [13] comprising 1.7 billion ft² of floor space. Of this floor space, 51% (7% health care, 23% mercantile services, and 21% offices) is suitable for the application of UFAD. Assuming a rate of growth in federal floor space roughly equivalent to the private sector at 2%⁶ per year, and assuming that the ultimate penetration of UFAD technology could reach that of VAV systems in new construction (i.e., 75%) then about 13 million ft² per year of new construction could be considered for a UFAD solution. Likewise, using the same criteria, about 650 million ft² of existing facilities could be considered for UFAD retrofits.

Summary and Conclusions

UFAD systems have significant potential advantages compared with traditional VAV systems. Rarely has there been a space conditioning technology that promises the combined benefits of improved thermal comfort, energy efficiency, and productivity and health improvement. While this technology has seen significant adoption in other countries, its use in the United States has only been notable since 1995. UFAD technology, like all nascent technologies, is being advanced both in theory and practice by researchers, designers, manufacturers, and “early adopter” owners who are working to bring the design, operation, and costs

to the point where it can be more easily and reliably applied. UFAD technology may someday displace overhead VAV as the “system of choice” for space conditioning.

While the use of UFAD systems in particular is becoming more common in the private commercial sector, the overall potential for UFAD in federal facilities may be limited by low churn that reduces life-cycle cost benefits. In addition, the overall federal building stock is not as amenable to UFAD installations as the private sector due to the higher cost of retrofits (i.e., a greater ratio of fixed private offices) and less overall applicable building types (51% of the federal building floor space versus 62% for private commercial).

However, in those situations where it is appropriate there are many compelling reasons to consider UFAD for the space conditioning solution.

Acknowledgment

Much of the material for this report has been derived from the work of Fred Bauman at the Center for the Built Environment (CBE) at the University of California, Berkeley. The author would like to gratefully acknowledge the support of Mr. Bauman, CBE and its industry partners, CBE sponsor the National Science Foundation (NSF), and the Regents of the University of California.

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⁶ This also assumes that the rate of growth in the three most applicable building types is equal to the nominal rate.

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Produced for the U.S. Department
of Energy, Energy Efficiency and
Renewable Energy, by the Lawrence
Berkeley National Laboratory

DOE/EE-0295

March 2004