Underfloor Air Report

ENERGY SAVINGS POTENTIAL OF FLEXIBLE AND ADAPTIVE HVAC DISTRIBUTION SYSTEMS FOR OFFICE BUILDINGS

Final Report
June 2002

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LIST OF ABBREVIATIONS

ABSIC	Advanced Building Systems Integration Consortium
AET	Advanced Ergonomic Technologies Ltd.
AHU	Air Handling Unit
ARTI	Air-Conditioning and Refrigeration Technology Institute
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
AWL	Adaptable Workplace Laboratory
B to C	"Business to Consumer"
BOMA	Building Owners and Managers' Association
CBE	Center for the Built Environment, University of California at Berkeley
CBPD	Center for Building Performance and Diagnostics, Carnegie Mellon University
CFM	Cubic Feet per Minute
DDC	Direct Digital Controls
FSS™	Flexible Space System (AET)
FTU™	Floor Terminal Unit (AET)
HVAC	Heating, Ventilating, and Air-Conditioning
IAQ	Indoor Air Quality
IFMA	International Facilities Management Association
IW	Intelligent Workplace
JIT	"Just in Time"
LBNL	Lawrence Berkeley National Laboratory
MIT™	Modular Integrated Terminal™ (York)
OA	Outside Air
ORNL	Oak Ridge National Laboratory
PEM™	Personal Environmental Module (Johnson Controls)
PIU	Powered Induction Unit
RH	Relative Humidity
RPI	Rensselaer Polytechnic Institute
SBS	Sick Building Syndrome
TAM™	Task Air Module™ (Tate)
UFA	Underfloor Air
UV	UltraViolet
VAV	Variable Air Volume
VOC	Volatile Organic Compound
WG	Water Guage

GLOSSARY OF TERMINOLOGY

Churn: Churn can be defined as the number of times per year that furniture, technology and environmental infrastructures are modified or relocated to meet the changing needs of the occupants. These changes can range from simple "box moves" of occupants' files and belongings to furniture reconfiguration, partition wall relocation or densification, to completely modified layouts for organizational reengineering to gut rehab.

Connectivity: Connection to power, voice, and data infrastructures

Displacement Ventilation (DV): A DV system relies on low supply-air velocities of 0.10-0.2 m/s combined with low temperature differentials 1-3°C (Int-Hout 2000), and is used mainly for ventilation. The low volumes (as a result of low velocities) are suitable for loads from 40-50 W/m^2 and may require separate air- or water-based thermal conditioning systems.

Underfloor Air: For the typical underfloor air system, the supply-air velocity is in the range of 2.0 – 2.5 m/s. These systems are used for cooling, heating, and ventilation purposes.

Ventilation Effectiveness: The ventilation effectiveness is defined by the fraction of the outdoor air delivered to the space that reaches the occupied space.

Vertical Riser/ Plenum Inlet: The vertical shaft through which supply air is fed to the floor.

Energy Savings Potential of Flexible and Adaptive HVAC Distribution Systems for Office Buildings

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EXECUTIVE SUMMARY

June 2002

Abstract

Energy efficient office buildings must be easily reconfigurable, including their mechanical and electrical infrastructures, to maintain maximum occupant productivity in an increasingly competitive global market for office space. There have been several innovations in engineering practice towards delivering flexible, user-based services for air quality, thermal comfort, lighting comfort and network access, predominantly using raised floors to move beyond "embedded" technologies in buildings to end-user technologies. The goal of this research effort is to document the state-of-the-knowledge, engineering diversity, and performance of recent developments in flexible and adaptive distribution systems in office buildings. Despite the need to resolve the inevitable field errors of innovative components and assemblies, the introduction of flexible and adaptive HVAC systems such as underfloor air, is approaching 10% of the new construction market (see Figure 1), and will continue to grow because of performance gains, including: equal or lower first costs, significant churn savings, measured thermal comfort and indoor air quality gains, and 20-35% energy savings.

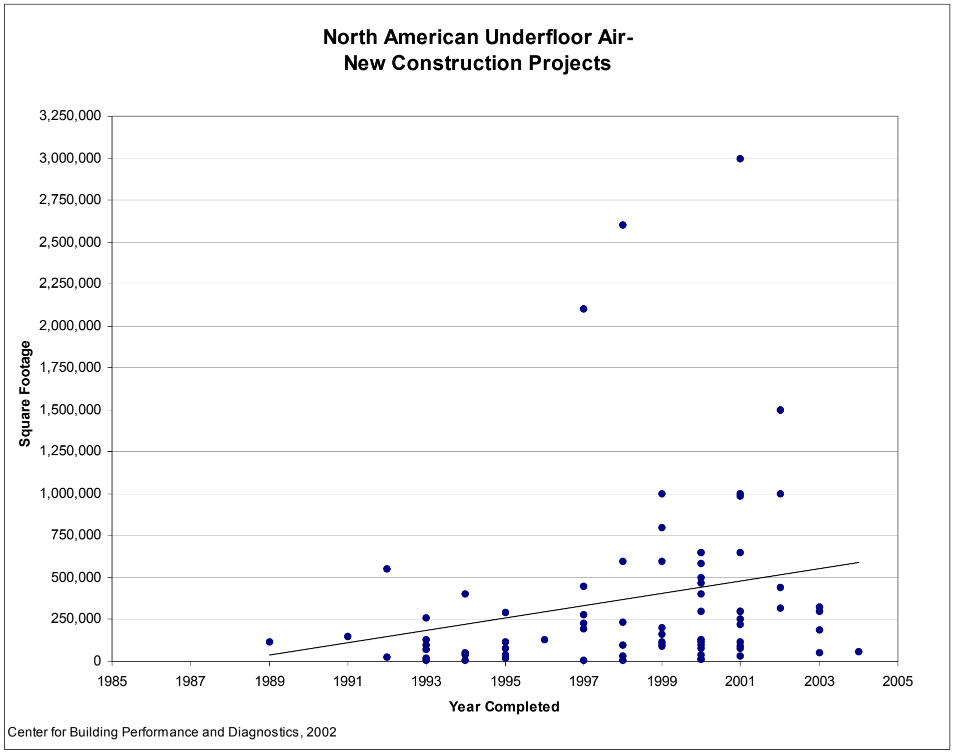


Figure 1: Increasing trend of underfloor air in new construction projects.

Chapter 1: Introduction

The six-person research team at the Center for Building Performance and Diagnostics (CBPD) and Oak Ridge National Laboratory (ORNL) identified over 140 references worldwide, including journal and conference articles, 300+ case studies, over 30 manufactured products and assemblies, and completed ten professional interviews for this state-of-the art report on flexible and adaptive HVAC distribution systems. The team identified key design issues in flexible and adaptive HVAC systems such as underfloor air, and their importance to cost and performance, forging the eight distinct chapters in the report: 1) system types; 2) plenum design alternatives; 3) diffuser design alternatives; 4) individual control alternatives; 5) central system issues; 6) systems integration and process issues; 7) performance concerns; 8) performance gains.

The report that follows describes the range of flexible HVAC distribution approaches documented in available literature, the frequency of their occurrence, and the range of their recorded performance. The document includes figures and tables of the quantitative and qualitative performance indices available, as well as illustrations of products and integrated systems. Key design or performance conclusions have been highlighted throughout the report, as well as the barriers and opportunities to the widespread adoption of innovative HVAC distribution approaches. Key recommendations for future field study or laboratory research efforts are included throughout the report. While the research team is reasonably confident that they have a comprehensive overview in relation to North

American references, the international practices would benefit from further study by a European, South-African and Asian-based research team.

Chapter 2: Flexible and Adaptive HVAC System Types

Defining the range of flexible and adaptive system types will enable the differences in performance data to be effectively recorded and long term research needs to be more fully defined. After reviewing over 140 papers and interviewing key engineers, the research team has identified at least four drivers that influence the categorization of system types: pressurization (push vs. pull), unducted vs. ducted, combined or separate ventilation and thermal conditioning systems, and floor versus ceiling locations. These four drivers have resulted in at least 15 significant system variations around the world worthy of comparative study (Figures 2a, 2b). The authors of this study have grouped these variations into four distinguishing factors: central-fan driven underfloor air (UFA) systems (push/ pressurized plenums); distributed-fan supported underfloor air (pull systems); separate ventilation and thermal conditioning systems including displacement ventilation (DV) systems; and ceiling-based flexible and adaptive systems.

Pressurized or ‘Push’ Underfloor Air Flexible and Adaptive Systems for Ventilation and Thermal Conditioning

- unducted or partially ducted UFA pressurized plenums
- fully ducted UFA pressurized delivery

Distributed Fans or ‘Pull’ Underfloor Air Flexible and Adaptive Systems for Ventilation and Thermal Conditioning

- Distributed floor fans and UFA plenums
- Distributed desk fans and UFA plenums
- Distributed underfloor fans in UFA plenums, ducted to desk
- Distributed fans with fully ducted UFA

Underfloor Ventilation and Separate Thermal Conditioning

- Displacement ventilation (DV) with separate thermal conditioning
- Underfloor ventilation air with distributed floor fans (pull) and separate thermal conditioning (heat pumps or fan coils)
- Underfloor pressurized ventilation with underfloor thermal conditioning
- Underfloor pressurized ventilation with thermal conditioning above the floor
- Underfloor pressurized ventilation with ceiling-based VAV cooling

Ceiling-based Flexible and Adaptive Systems

- Ceiling ventilation only, separate thermal above floor
- Separate ceiling ventilation and ceiling thermal air supply with mixing diffusers
- Individually controllable micro-zones
- Ceiling diffusers with flexible locations and individual control

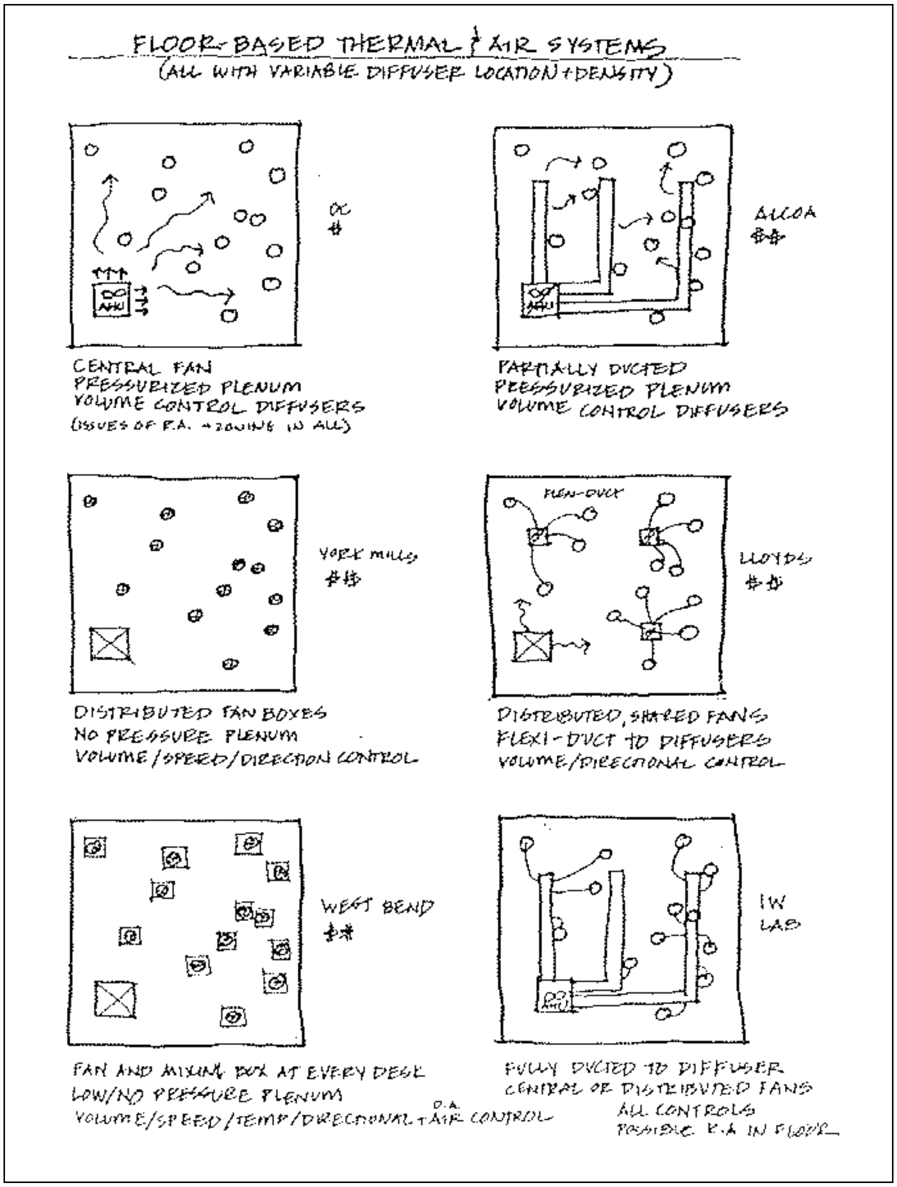


Figure 2a: Six system configurations for underfloor air systems.

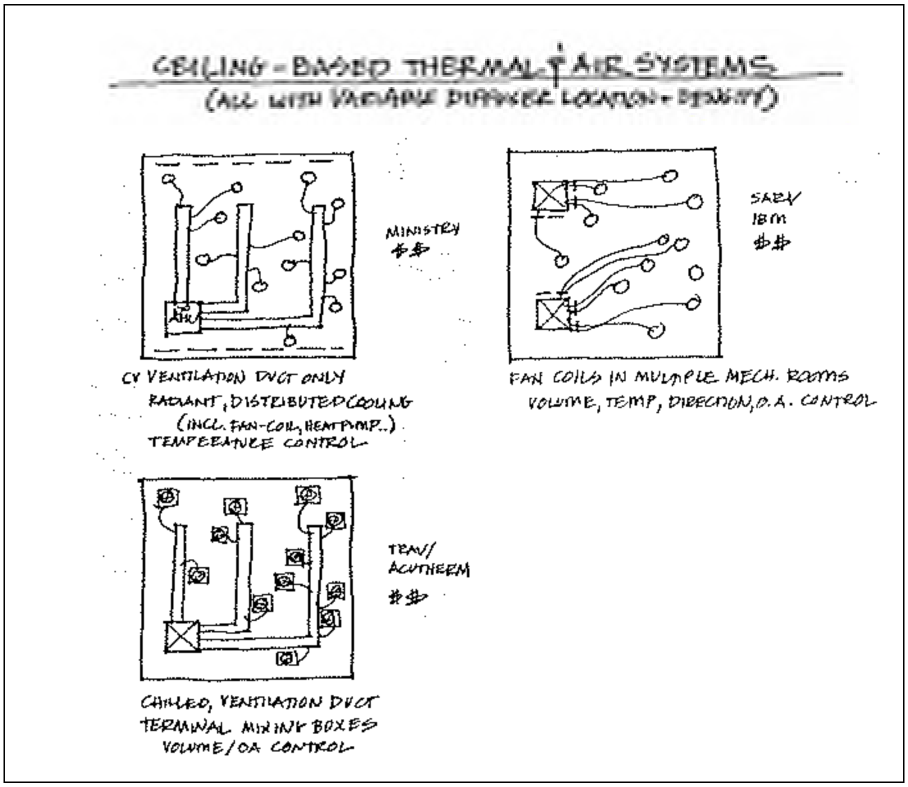


Figure 2b: Three system configurations for flexible and adaptive ceiling-based air systems.

Chapter 3: Plenum Design Alternatives

The major plenum design alternatives for flexible and adaptive HVAC systems include; plenum height, distance from a vertical riser or plenum inlet, pressurization and tightness, plenum subdivisions and ducting, as well as plenum material selection and access. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

- Effective plenum heights for underfloor air are pervasively set at 12 to 18 inches (Figure 3), with no penalty for even higher plenums. Some engineers recommend that 18 inches or more are preferable to support partial ducting and other underfloor infrastructures (Yates 2000). Some engineers/ researchers argue that floor plenums can be less than 12” with effective underfloor air, and possibly even as low as 7 inch clear for retrofit applications (Bauman et. al. 1999). Higher plenum heights do not automatically result in higher floor-to-floor heights, and indeed underfloor air HVAC could actually reduce floor-to-floor heights or support increased ceiling heights in the occupied space (Figure 4).

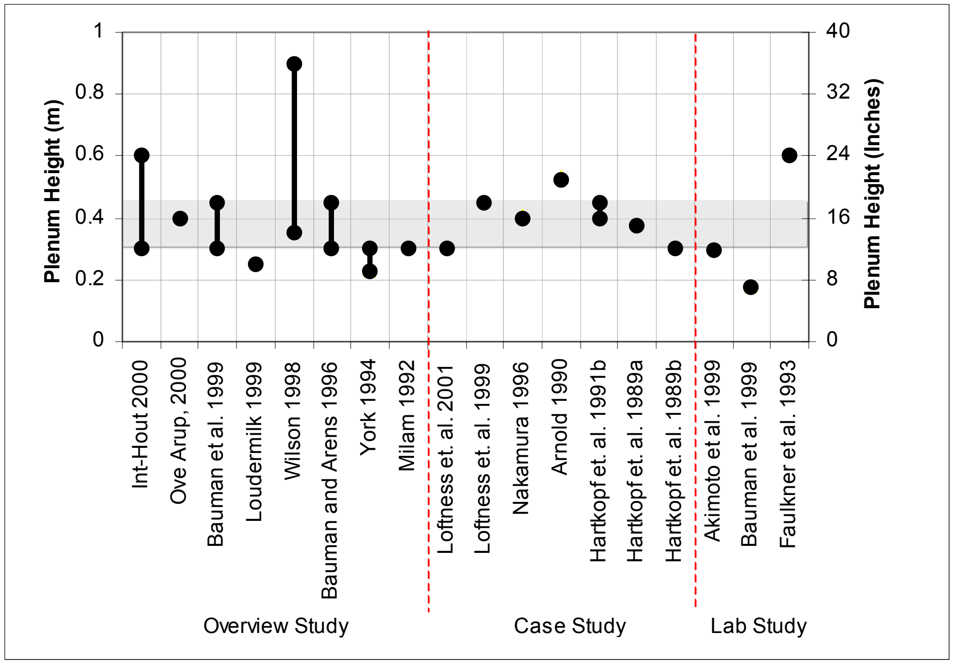


Figure 3: Range of plenum height reported in various studies (Typical range 0.3 to 0.45 m) (Center for Building Performance and Diagnostics, 2002).

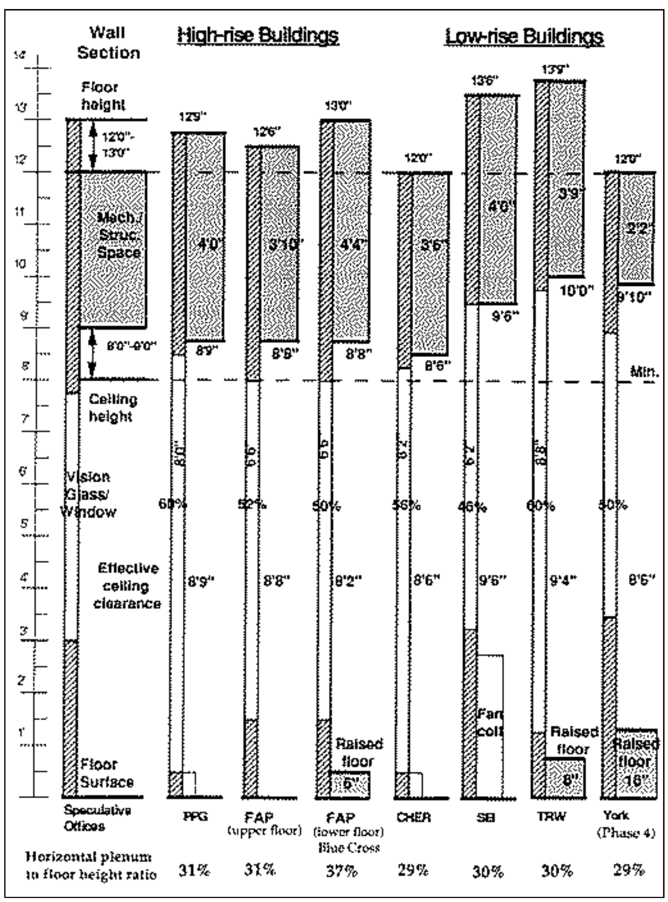


Figure 4: Effect of a raised floor on building floor-to-floor height (Chiu, 1991).

- Distances from the vertical riser/air supply can be as long as 80 feet; however, 30–40 feet are preferable to ensure no thermal decay and controllable pressure conditions.

- For delivering combined cooling and ventilation in office environments, at least a dozen references stipulated 0.1 in WG (25 Pa) static pressure for plenum underfloor air system (Figure 5).

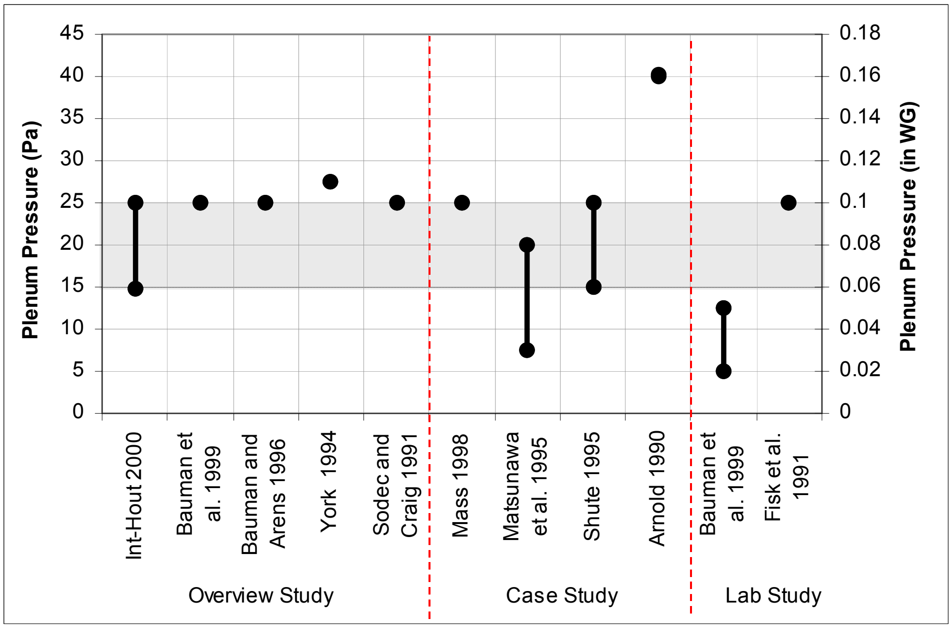


Figure 5: Range of plenum pressures in underfloor air systems (collected from multiple references) – typical range: 15 – 25 Pa (Center for Building Performance and Diagnostics, 2002).

Given this low pressure and limited distances from risers, air tightness is not a major issue, however carpet tiles could be offset 50% over access floor tiles to support air tightness of the plenum. Whether offset or super-imposed, carpet tiles should be the same dimension as the access floor tiles to support ease of relocating diffusers and outlet boxes in the dynamic office without carpet waste.

- The prevailing underfloor air systems in the U.S. are unducted, plenum air supply. Perimeter conditioning, however, is typically ducted, and plenum subdivisions are common to service different tenants or high demand spaces such as conference rooms. Plenum duct dividers are often locally built of sheet metal or duct board. The lack of prefabricated plenum dividers that can be reconfigured as occupant layouts change is a serious annoyance to professionals and should be addressed by raised floor manufacturers. The Europeans have predominantly relied on ducted underfloor (UFA) air systems and ducted displacement ventilation (DV) systems to ensure the air quality of ventilation air.

- A number of professionals argue that thermal mass can be effective for cooling in an unducted/ plenum underfloor air system, but is "like dancing with an elephant" and requires careful monitoring and control.

- Ideally, return air should be ducted at ceiling level to ensure vertical air flow patterns from floor diffusers for pollution removal and stratification benefits.

Whether the servicing plenum is above the ceiling or under the floor, the necessity for better systems integration is critical to ensure the long term performance of each building sub-system in the face of dynamic work environments. The Center for Building Performance and Diagnostics argues for a one-day early design workshop to include all disciplines who have components they intend to introduce into the plenum and its surface interfaces – HVAC, networking, fire, structure, and interior system designers. The challenge is for each of these disciplinary experts to bring the physical components that they intend to introduce – 3-dimensional elements, not line drawings and specs – to ensure full debate about the cross-sectional integration and the surface integration of all building systems. In this "plenum real estate challenge" charrette, the maximum performance of each system should be sought, with first cost, constructability and life cycle maintenance and reconfigurability fully addressed to ensure the value of the systems integration effort.

Chapter 4: Diffuser Design Alternatives

The major diffuser design alternatives for flexible and adaptive HVAC systems include: floor diffuser density; diffuser design and capacity; displacement flow diffusers; fan air diffusers; desk, wall and ceiling diffuser design; diffuser material specifications; and return air diffuser design. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

- Diffuser density should be no less than 1-2 per person or 1 per 100 ft^2 (10 m2) with diffusers to be at least 2.5 ft (0.8 m) from the occupants. Additional diffusers are required for ambient conditioning of circulation areas.
- To ensure effective thermal mixing and maintain stratification for energy conservation, swirl diffusers are preferable to jet diffusers for the turbulent mixed flow of supply air and room air in underfloor air systems.
- With induction diffusers and swirl distribution, up to 100 cfm can be supplied per diffuser, especially with the larger 8" diffuser. Otherwise, between 25-75 cfm would be maximum allowable and greater diffuser densities would be required.
- Diffuser slots should be inclined to effectively diffuse the air and generate a swirl for induction, with an industry preference between 36-38 degree incline from the vertical (Kim et al 2001).
- Many diffuser manufacturers assume air delivery of 50-150 cfm (23-71 l/s) at 0.05-0.25 in WG (12.5 Pa – 60 Pa) with velocities of 50-150 fpm (0.254 – 0.726 m/sec) depending on diffuser size and mixing capabilities.
- Fan-powered floor air diffusers must be designed to ensure effective room air mixing and horizontal distribution patterns to eliminate drafts and thermal discomfort. Fan-powered floor boxes are valuable for high thermal load areas such as conference rooms, however, the combination of passive and fan-powered diffusers must be studied in relation to short circuiting.
- For desktop fan-powered diffusers, 150-180 cfm is possible, however volume,

direction, and speed controls should be considered. Larger face dimensions of the desktop air diffusers increase thermal comfort (Bauman et al 1993).

Chapter 5: Individual Control Alternatives

The major control alternatives for flexible and adaptive HVAC systems include: dynamic zone sizing, micro-zoning or split task and ambient systems; control of location and density of diffusers; direction of airflow; volume of airflow; speed of airflow; temperature control; air filtration; and control over outside air quantity. Before both first cost and market readiness decide the future of user controls in underfloor air, each of these user control alternatives should be studied in both laboratory and field research as to their cost-benefits for improved human comfort and health, reduced energy and churn/asset costs, as well as in relation to individual and organizational productivity over time. Until that time, based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

- To ensure comfort and energy efficiency in dynamic office environments, HVAC systems must be designed to allow for a continuous reconfiguration of thermal zones and controllers, or with micro-zoning (one zone per workstation) that can be dynamically grouped and regrouped with control.
- User controls improve user satisfaction with thermal comfort despite the finding that "a majority of the volume controls of floor air diffusers seem to be set once and left, possibly because of lack of discomfort or lack of awareness (Hedge et al, 1993)."
- The ability to easily relocate diffusers is critical to churn/ reconfiguration cost savings, and all systems should be coordinated to make this possible (carpet, outlets, diffusers, tethers). Changing the density and location of diffusers is the central strategy of underfloor air systems to effectively deliver breathing air and cooling to the range of functions and layouts that occur in the dynamic workplace environment.
- Digital volume controls with local thermostats could be a benefit if they do not eliminate individual user control or limit the relocatability of the diffusers.
- Fan controls are required for conference rooms, and possibly additional water-based cooling (e.g. fan-coil) controls.
- Directional control is a benefit for higher velocity and non-swirl diffusers where supply air streams of 65°F (18.3°C) could be uncomfortable on the lower body.
- There are at least three strategies for temperature control in underfloor air systems: 1) separate thermal conditioning and ventilation systems, 2) mixing control of cool supply air with warmer room air, and 3) additional water or air-based heating or cooling components.
- Replacing pressurized buildings with the natural stratification distribution of conditioned air, (rising from an underfloor air system to a ceiling return) allows for local opening of windows without compromising ventilation effectiveness.

- There is a significant need for further development of both manual and digital controls that are easily understandable by the occupant. This includes easy recognition of the percent of aperture that is open in volume control, and the direction of airflow, fan-speed, and real temperature indications for warmer and cooler settings.
- There is a significant need for further development of modular, 'plug-and-play' local air conditioning units that are quiet, energy efficient and easily controllable to address the rapidly changing space layouts and densities in modern office buildings.

Chapter 6: Central System Issues

The major central system issues for flexible and adaptive HVAC systems include: the separation of thermal conditioning and ventilation systems (air/air and water/air); the separation of ambient and task conditioning; the sizing of the air handlers for ventilation and effective pressurization; the sizing of the cooling and heating sources for temperature and humidity control of supply air; perimeter conditioning systems; dehumidification; and central system control responses. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

- Most North American underfloor air (UFA) systems utilize air for both cooling and ventilation. Most European underfloor air and displacement ventilation (DV) systems combine air for ventilation with water-based thermal conditioning.
- Based on climate, perimeter conditioning will be separate, unless the enclosure is very well designed. Three strategies have emerged for perimeter conditioning in flexible and adaptive HVAC systems: sub-divided air only systems; split air and water systems; and high performance enclosures where the load has been eliminated or neutralized (for example air flow windows).
- Supply air temperatures are higher in underfloor air systems than conventional ceiling VAV, ranging from 62^oF to 68^oF instead of 52^oF to 58^oF. As a result, underfloor air systems often use higher percentages of outside air or 'economizer'.
- Chiller capacity can also be reduced in underfloor air systems because of higher supply temperatures, and the chiller operates at a slightly higher efficiency.
- Cooling coil sizing can be 80% of coil sizes for conventional ceiling VAV, because of the benefits of stratification that eliminate some of the impact of equipment loads.
- Underfloor air systems can handle up to 300 W/m^2 while displacement ventilation can handle 40 W/m^2 - 120 W/m^2.
- Relative humidity control is critical, especially in humid climates. Either hyper-cooling the outside air and mixing this with return air, or additional desiccant cooling is typically necessary.
- Underfloor air systems can support natural ventilation as a mixed-mode conditioning in which the mechanical systems are shut down seasonally.

Improved building design can allow over 50% of the year to be naturally conditioned in many climates.

Chapter 7: Systems Integration and Delivery Process Issues

Both systems integration and improved delivery process are critical to ensure high performance flexible and adaptive HVAC systems. In addition to multi-disciplinary decisionmaking to address the "plenum real estate challenge," the design team needs to integrate: the HVAC assembly itself, and the flexible and adaptive HVAC system with: enclosure; massing, structure and vertical cores; connectivity; raised floor, carpet and outlet/diffuser components; and interior systems. There is also a need for new industrial partnerships dedicated to performance delivery rather than product delivery, with innovations in the building delivery process. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

Figure 6: Power, voice, data floor box

HVAC Industry:

- The performance of installed HVAC systems is continuously compromised by the fragmented delivery of hot and cold water generators, air handlers, piping and valves, ducting and dampers, mixing boxes and fan coils, diffusers, sensors and controllers and building automation system. It is past time for the major players in the HVAC manufacturing community – central system manufacturers or control companies – to develop regional solutions to flexible and adaptive but fully integrated HVAC systems – to be delivered as performance contracts directly from business to customer.

Figure 7: Grid of service

Data/Power/Voice Networking Industry (Figures 6 – 9)

- Coordinate strategies for the horizontal distribution and relocatable nodes for the underfloor HVAC and power/data/voice and controls wiring should be prototyped, tested for performance, priced and installed with performance guarantees.
- Floor outlets for data, voice, power, video, and environmental controls need further development for: ease of relocation with quick-connect/ tethers as well as the ability to reconfigure the number and types of outlets.
- Desktop outlets need further development for: ease of relocation (clip-on to desk, easy-connect underfloor), reconfigurable numbers and types of outlets (data, voice, power, video, environmental controls), and for general elegance or fun as a desktop object.

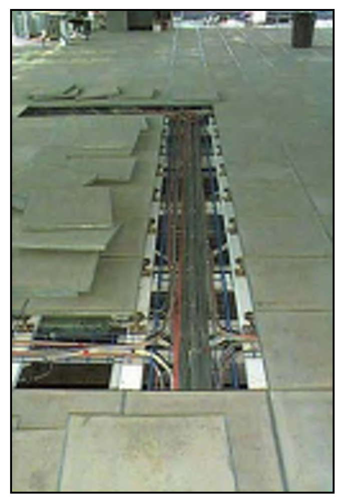


Figure 8: Underfloor cable-tray

Raised Floor Industry

- Raised floor manufacturers need to actively market underfloor air as part of the package.
- Need for underfloor partitioning system in the raised floor "kit of parts." Dimpled floor tiles are difficult to seal to a duct board or sheet metal partition on the site.
- Well before construction, the raised floor pedestal configuration must be resolved in dimensioned drawings in relation to columns, exterior walls and all underfloor infrastructures.

Figure 9: Satellite closets

- Cutouts in the raised floor for outlet boxes or cabling should be coordinated with cutouts for the air diffusers. If outlet boxes will be in partitions or desks instead of the floor, cutouts for diffusers and cabling could be the same dimension for maximum flexibility.

Carpet Industry

- Diffuser and outlet cutouts should be in locations that allow the easy reconfiguration of systems without carpet waste. Indeed, carpet tiles should be identical in size to access floor tiles, so that cutouts are continuously re-usable, although they can be offset 50% to reduce leakage from the plenum. Carpets should be selected for benign materials with benign adhesives (low VOC emitting) that support relocations, and should not “pill” or release carpet fragments into the diffuser baskets.

Fire and Human Safety Industry

- Fire issues vary by location. In some locations, sprinklers are required if a plenum is over 16” deep, and in other locations, wiring must be in conduit or plenum rated cables. Some codes may require that diffusers are of fire resistant material, though others contest the necessity of this. Large unducted plenums must have plenum dividers for smoke and fire control. The first UFA project in a region seems to establish the code/standard rules for future projects.
- While underfloor air systems must be carefully designed in seismic zones, the elimination of the traditional penetrations in the structural floor slab for networking and power improves the structural integrity of buildings.

Ceiling Industry

- Ceiling manufacturers need to explore the opportunities of non-flat, non-continuous forms to take advantage of UFA work environments, while resolving acoustics, up lighting and possibly return air and sprinkler system integrations.
- The elimination of a hung ceiling that must be positioned below the lowest beam and duct combination can increase ceiling height in the occupied space. However, acoustics must be resolved through floating acoustic ceilings and improved wall and floor absorption. In addition, the designs of lighting, sprinklers, and return air need to be resolved in new ways.

Architectural/Interior Design Team

- An extremely well designed building enclosure can support the elimination of a separate perimeter thermal conditioning system, with the significant cost savings available for improving the facade.
- The architects and interior designers must be given a set of drawings highlighting the maximum possible location of air terminal units and outlet boxes, given possible underfloor obstructions (Shute 1992a).

Construction Team

- A simple construction sequencing video on-line or hands-on training of the construction crew can ensure the construction time and cost savings possible with underfloor infrastructures (see Cost Savings in Chapter 9).

Chapter 8: The Performance Concerns

The major performance concerns for flexible and adaptive HVAC systems include: higher first costs; thermal comfort control in relation to widely varying interior functions; maintaining humidity control and the air quality of the underfloor air; and fire and security protection in the plenum. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

First Costs (Figure 10)

- Increases in first costs are almost completely attributable to the cost of the raised floor, that is often charged to the underfloor air system despite the fact that the plenum also serves networking installation and modification cost-savings.
- In retrofit projects, the 5-20% increase in first costs for underfloor air systems are typically due to modifications required to ramp or rebuild elevator cores, fire stairs and bathrooms to the raised floor height.

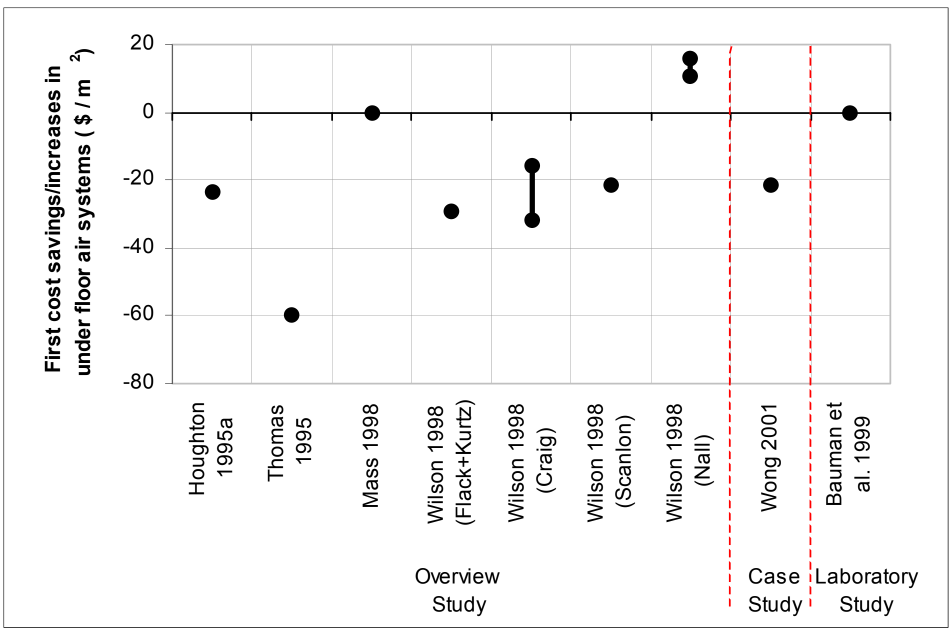


Figure 10: First cost savings/increases in underfloor air systems, collected from various references (Center for Building Performance and Diagnostics, 2002).

Thermal Comfort

- Due to the higher supply air temperatures and lower velocities in underfloor air systems, there are concerns that the maximum cooling capacitance of the HVAC system will be lower than ceiling based systems. The need to provide greater levels of cooling in conference rooms has led to a number of field modifications, including: adding fan-powered diffusers, dedicated ducting to create conference room zones, and additional water-based cooling components. Concerns about thermal decay in the air stream of a plenum supply UFA system (due to the capacitance of the slab and floor tiles) has resulted in recommendations for shorter distances from the vertical risers or partial ducting.

- One research team, Melikov and Nielsen (1989), found that 33% of measured locations had higher than 15% dissatisfied people due to draft conditions. These concerns have led to a consistent recommendation for relocatable, swirl diffusers.
- Melikov and Nielsen (1989) also found that 40% of the occupied locations had a temperature difference between the head and feet larger than 5^{o}F (3^{o}C), the limit defined by ANSI/ASHRAE Standard 55-1992 on Thermal Conditions for Human Occupancy.

Air Quality

- Three indoor air quality concerns have been raised in the literature or by practicing engineers in relation to plenum underfloor air systems: 1) the inability to fully dehumidify and control relative humidity given higher supply air temperatures; 2) potential condensation in the plenum; and 3) dust and debris accumulation in the plenum. At the same time, some manufacturers argue that the plenum "duct" can be most effectively monitored and vacuumed for the highest IAQ.
- One additional IAQ concern that has been raised in relation to UFA systems is the possibility that an excessive number of air diffusers would be dampered closed by the occupants, compromising the delivery of ventilation air. Early air diffusers were introduced without minimum air settings, and early diffuser densities were set without separating task and ambient conditioning solutions.

Fire & Security

- Plenum dividers need to be further developed to ensure that HVAC modifications can be made with spatial change while still providing both security and smoke separation in the plenum for various tenants. The requirements for sprinklers or plenum rated cabling should be resolved on a national scale so that professionals do not have to negotiate each project.

Chapter 9: The Performance Gains

This research effort identified a significantly greater number of performance gains than concerns for flexible and adaptive HVAC systems including: first cost savings, organizational and technological 'churn' cost savings, thermal comfort gains, indoor air quality gains, energy cost savings, and individual productivity gains. Based on the cross section of studies, papers, and interviews, the following conclusions can be drawn:

First Cost Savings (Figure 11)

- In new construction, first costs of underfloor air systems are equal to or lower than ceiling HVAC systems. Once a raised floor has been cost-justified for connectivity, the introduction of underfloor air should be cost neutral or a cost savings. The full list of variables that have resulted in lower first costs for numerous underfloor air systems include:

- Reduction in HVAC construction sequencing and installation costs
- Reduction in power, data/voice networking installation costs
- Reduced ductwork, lighter duct materials
- Reduction in HVAC controls
- Lower horsepower fans
- Smaller chillers
- Building height reduction
- Construction time and materials cost savings

- Floor-to-floor height does not need to be increased in underfloor air projects, and can in fact be decreased due to the more deliberate systems integration efforts within the plenum.

First Cost Savings with Access Floors		
Description	*Standard HVAC* (overhead mixing)	*Access Floor* (underfl. air dist.)
BUILDING SHELL & CORE SYSTEMS		
Steel beam duct penetrations	$8,000	$0
Floor stop at core/ tenant space transition	$0	$4,200
TENANT FIT-OUT		
Drywall partitions allowance (to struct. floor)	$75,000	$82,000
Drywall furring of cols./ext. wall to 10 ft.	$38,620	$42,372
Raised flooring (incl. floor-mounted diffusers)	$0	$400,000
Acoustical and/ or drywall ceilings	$150,000	$150,000
Carpeting (rolled goods vs. tile)*	$111,128	$12,600
Fire sprinklers	$12.500	$12,500
HVAC		
Main duct**	$115,500	$0
Branch ducts to VAV terminals	$31,500	$16,000
Branch ducts to diffusers	$66,000	$0
Diffusers**	$46,876	$0
Ceiling registers	$31,260	$1,000
Duct insulation	$30,000	$0
Hot water reheat piping	$45,000	$45,000
VAV boxes	$76,600	$75,000
ELECTRICAL		
Power distribution	$100,000	$75,000
Receptacles	$34,725	$11,250
Data/ communication devices	$16,650	$0
Data/ communications cabling allowance	$200,000	$150,000
Cable tray vs. hard floor "routing"	$26,000	$3,000
Light fixtures	$156,500	$156,500
Low-voltage systems/ security/ video allow.	$100,000	$100,000
TOTAL	$1,471,859	$1,336,422
Cost per square foot	$29	$26
Cost per square meter	$316	$287

Data from 50,000 sq. ft. (4,650 sq. m) office building in California.
** Access flooring system included finished surface*
*** Main duct and diffusers included in cost of access floor*
Source Data provided by Flack & Kurtz Consulting Engineers and E Source Inc.; adapted by EBN to reflect more common practice.

Figure 11: First cost savings with access floors (Wilson, 1998).

Churn Cost Savings (Figure 12) – Organizational Effectiveness

- Every organization that has tracked the cost of churn is finding significant cost savings with raised floor systems that include HVAC and networking components designed for modification. Churn cost savings - for relocating a mix of furniture, walls and people - can be from $100 to $500 per person moved. The greatest cost savings occur at tenant roll-over.
- Flexible and adaptive HVAC systems reduce material and component waste that is often necessary in mechanical and electrical system modifications, and allow for "just-in-time" purchasing of diffusers and outlet boxes to accommodate increasing occupant densities.
- The San Francisco market has demonstrated an increase in the ability to attract tenants and a potential for higher rental rates for underfloor air systems due to the ease of churn and improved comfort in dynamic spaces.

Square Foot Costs of Conventional Mechanical and Electrical Systems vs. Raised Floor Systems

	Tenant Fitout			Estimated First Churn Costs		
	Conventional Systems	*Raised Floor Systems*	*Savings*	*Overhead Systems*	*Raised Floor Systems*	*Savings*
Electrical Power						
Labor	0.98	0.28	0.70	0.98	0.28	0.70
Material	1.67	1.26	0.41	0.85	0.00	0.85
Subtotal	2.65	1.54	1.11	1.83	0.28	1.55
Telephone/Data						
Labor	0.56	0.32	0.24	0.56	0.32	0.24
Material	0.94	0.55	0.39	0.53	0.00	0.51
Subtotal	1.50	0.87	0.63	1.07	0.32	0.75
Mechanical HVAC						
Labor	1.15	0.10	1.05	1.15	0.09	1.06
Material	2.69	0.72	1.97	1.30	0.00	1.30
Subtotal	3.84	0.82	3.02	2.45	0.09	2.36
TOTAL	7.99	3.23	**$4.76**	5.35	0.69	**$4.66**

Figure 12: Soffer Tech office building cost comparisons (Loftness et. al. 1999).

Thermal Comfort Gains

- Measured studies show that thermal comfort is greater in underfloor air systems if air velocities are low and diffusers are designed for effective mixing without drafts, given measurements of predicted mean vote (PMV) and percentage people dissatisfied (PPD). Reductions in facility complaints have also been recorded, down to less than 10 calls per 1000 employees per year (1%).

Indoor Air Quality (IAQ) Gains

- A number of studies reveal a ventilation effectiveness of 1.0-2.0 (Figure 13) as compared to typical field studies of overhead systems with a ventilation effectiveness of 0.5-1.0 (Milam 1992, Loudermilk 1999, Yuan et al. 1999a). These indoor air quality improvements are due to:

1) the ability to relocate and add diffusers to match use patterns and to eliminate stagnant air regardless of the height of partitions and the degree of workspace enclosure (Hedge et al. 1990);
2) the proximity of the diffusers to the individual's breathing zone; and
3) the elimination of ceiling diffuser air distribution patterns that force lateral mixing and dispersion of the more polluted air at the ceiling level into the occupied zone (Int-Hout 2000).

- The upward direction of air flow from underfloor air removes equipment contaminants and heat directly through ceiling return air systems, reducing the mixing and migration of indoor pollutants throughout the occupied space.

- The separation of ventilation from thermal conditioning (possible in a number of flexible and adaptive HVAC system approaches) can dramatically reduce the quantity of air ducted through buildings (to as low as 10%), with greater control of the quality of that air, and the effective delivery of the air to the individual occupant.

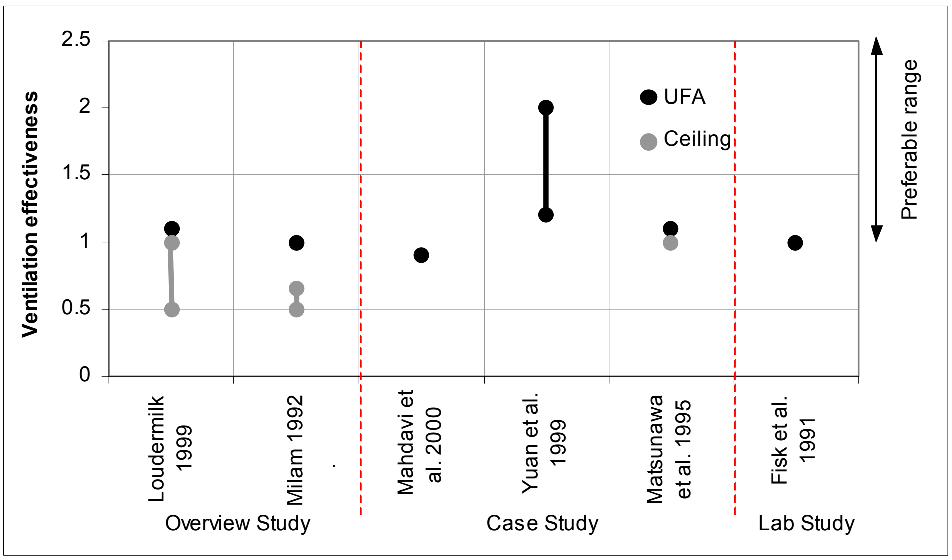


Figure 13: Range of ventilation effectiveness values reported in the literature (Center for Building Performance and Diagnostics, 2002).

Energy Cost Savings (Figure 14)

- Energy savings of underfloor air systems are between 20-35% due to improved ventilation effectiveness, stratification savings on fan power, higher supply temperatures (and the impact on central systems) (Figure 15), and increased use of outside air (extended economizer).

- The fan power energy savings have been estimated at 5-30% and attributed to reduced volume requirements for conditioned air resulting from the stratification benefits and to better ventilation effectiveness for heat and pollutant removal (Sodec and Craig 1990, Hu et al. 1999, Loudermilk 1999, Bauman et al. 1999, Mass 1998).

- The paired benefits of higher supply air temperatures possible in underfloor air delivery (60-68^{o}F) and reduced conditioned volume through stratification, allows a warmer cooling coil and warmer evaporator temperatures, resulting in reduced chiller capacitance (0.60 kW/ton to 0.37 kW/ton according to E-Source (Houghton 1995a), and 3-15% higher chiller efficiencies (Int-Hout 2000, Houghton 1995a, Loudermilk 1999).

- Because of higher supply air temperatures with chilled water temperatures of 10-12^{o}C (vs.5-6^{o}C), significantly extended economizer cycles and alternatives to CFC-based cooling are possible, including ground source or aquifer source heat pumps (cooling ponds).
- With the introduction of one or more diffusers in each workstation, and the willingness to separate task conditions from ambient conditions, underfloor air systems offer far greater capability to yield operational energy savings through partial conditioning based on zone and flex-time requirements (Heinemeier et al 1990, Sodec and Craig 1990, Bauman et al. 1997).

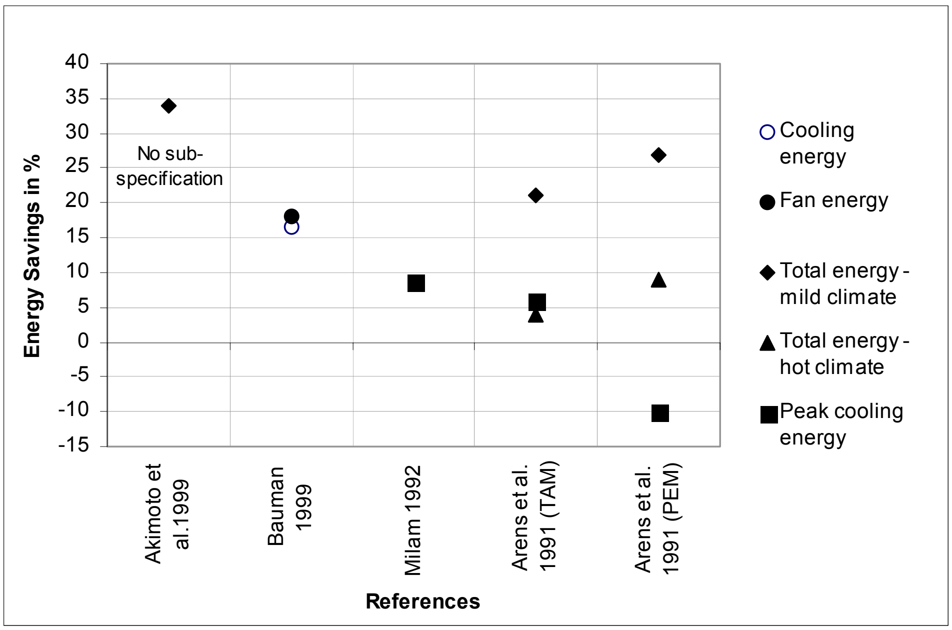


Figure 14: Energy savings due to underfloor air systems, from multiple references (Center for Building Performance and Diagnostics, 2002).

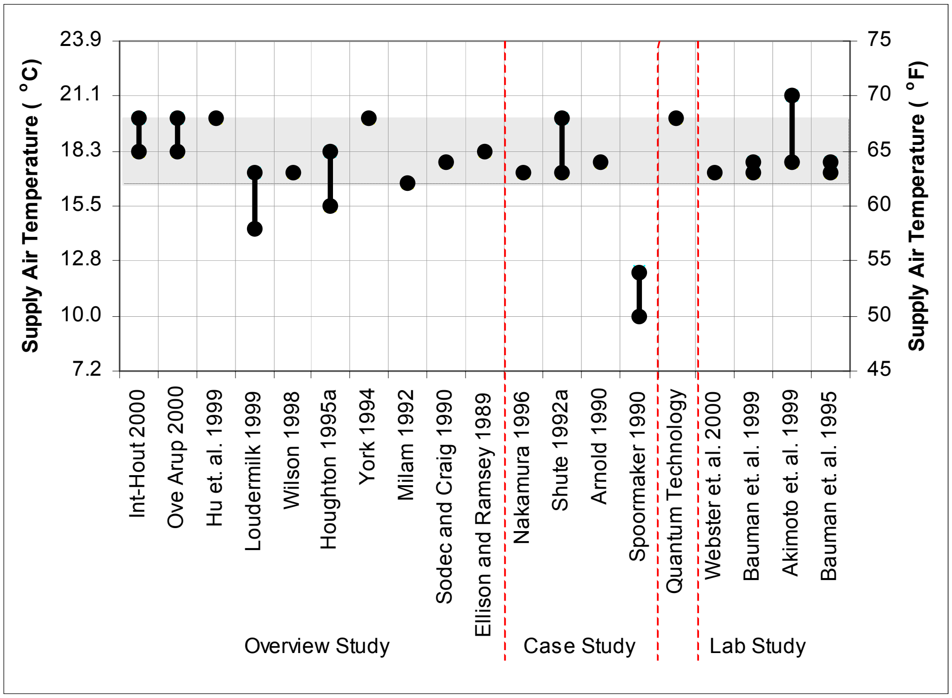


Figure 15: Range of supply air temperatures with underfloor air from various references, typical range: 62-68°F (Center for Building Performance and Diagnostics, 2002).

Individual Productivity Gains

- An RPI study of the West Bend Mutual Insurance Headquarters identified a 2.8% benefit in individual productivity (Figure 16) for those workers with operational task air systems (compared to 'dummy' systems) over a six-month period (Kroner et. al. 1992).

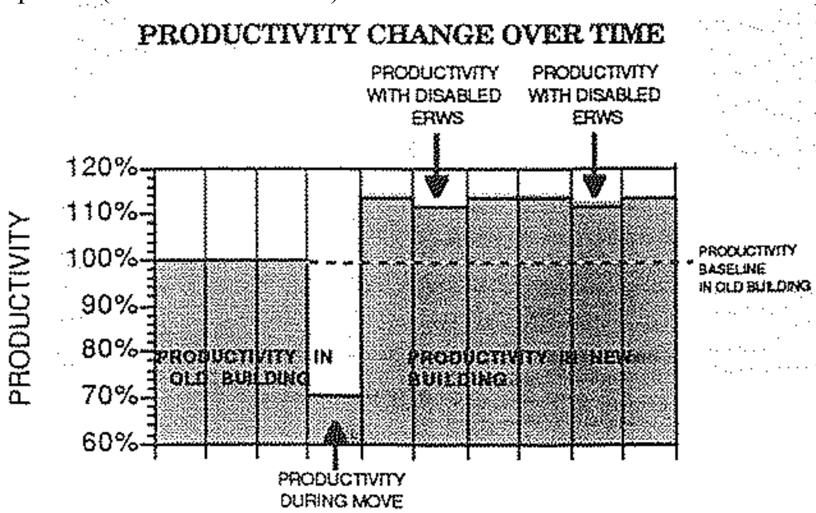


Figure 16: A study of the West Bend Mutual Insurance Headquarters identified a 2.8% benefit in individual productivity for those workers with operational task air systems (Kroner et al 1992).

Conclusion

It is becoming increasingly clear that flexible and adaptive HVAC systems, such as underfloor air: perform as well if not better than ceiling-based systems most notably because they support a greater level of spatial change. Leading engineers are active proponents of underfloor air after their first experience, and these flexible and adaptive systems are now more than 10% of the market, including many of the newest headquarters buildings and "green" building landmarks.

The performance concerns of flexible and adaptive HVAC systems should be fully addressed by the manufacturing industry to resolve: potential higher first costs especially in existing buildings; component and integrated system availability and robustness; thermal comfort control in relation to widely varying interior functions; maintaining humidity control and the air quality of the underfloor air; and fire and security protection in the plenum. Working collaboratively with research laboratories in different climates, system innovations should be explored towards the widespread introduction of energy efficient, flexible, user based HVAC for commercial buildings.

The significant number of performance gains of flexible and adaptive HVAC systems should be fully documented in detailed field studies, to irrefutably confirm the: first cost savings, organizational and technological 'churn' cost savings, thermal comfort gains, indoor air quality gains, energy cost savings, and individual productivity gains.

Given the increasing level of spatial and functional change in commercial buildings today, the importance of equally flexible and adaptive HVAC infrastructures has never been more important. The major types of flexible and adaptive HVAC systems identified in this Air-Conditioning and Refrigeration Technology Institute (ARTI) report offer significant opportunities to cost-effectively improve the quality of indoor environments for all building occupants, and sustain that improvement over time.

INTRODUCTION Chapter 1

1.1 Goals and Objectives

Energy efficient office buildings must be easily reconfigurable, including their mechanical and electrical infrastructures, to maintain maximum occupant productivity in an increasingly competitive global market for office space. There have been several innovations in engineering practice towards delivering flexible, user-based services for air quality, thermal comfort, lighting comfort and network access, predominantly using raised floors to move beyond "embedded" technologies in buildings to end-user technologies. The goal of this research effort is to document the state of the knowledge, engineering diversity, and performance of recent developments in flexible and adaptive distribution systems in office buildings.

1.2 Motivation: The Need for Flexible and Adaptive Systems

1.2.1 Embedded Infrastructures No Longer Meet the Needs of Dynamic Organizations

While modern organizations have become more organizationally and technologically dynamic, office buildings and their infrastructures remain rigidly fixed, designed to meet early space planning requirements. Buildings and infrastructures continue to be designed with the assumption that the facility needs of organizations do not differ significantly over time, and are designed to fit a particular floor plan, with rigid and idiosyncratic assemblies.

Class A office designations are assigned irrespective of the density, quality or reconfigurability of major heating, ventilating, and air-conditioning (HVAC), lighting or electrical systems. The resulting signs of a building's inability to respond to changing organizational and technological needs are clearly measurable, including inadequacies in lighting, thermal, and air quality, as well as connectivity. The HVAC systems in buildings, for example, often have inadequate cooling capacity, supply air volume and diffuser density to support the technological and organizational changes in offices today. Moreover, zone size (or the number of people sharing a thermostat) is unacceptably large for the dynamic office, with interior HVAC zones even larger than perimeter zones. The lighting is often inappropriate to support the changes underway. Field measurements in numerous Class A and B buildings reveal high connected lighting loads (>16 W/m^2 or 1.5 W/ft^2), high light fixture density, poor control of brightness and glare, and poor locational control (lighting the aisles and cabinet tops rather than work surfaces) (Tu 1997). Access to electric and telecommunications networks are also inadequate for the changing workplace, in density of service, location and type of outlet. The number of outlets provided averages at 7 per workstation (4 power, 2 data, 1 voice), less than the demand for connectivity (power/voice/data networks). Fixed outlets (poke-throughs and tombstones) are still prevalent, followed by furniture-based outlets, while raised floors and modular, relocatable outlets are still somewhat rare.

The interrelationships of all three building infrastructures (HVAC, lighting, and connectivity) reveal a serious level of mismatch with evolving workplace layouts (Figure 1.1). In both plan and section, there are signs of a lack of a systemic approach to coordinate and integrate various building services into a coherent service entity to meet workplace needs. The layered, 'idiosyncratic' and fixed solutions to introducing major building systems results in: inefficient system operation; difficulty in maintaining and modifying system components; poor individual and organizational satisfaction with service; and greater costs in the plenum 'real estate' due to inefficient plenum utilization.

It is important at this point to emphasize that the inflexible infrastructures leading to performance failures in the dynamic workplace are not confined to older buildings. Although new buildings often have greater central system capacity (cooling, power, telecommunications), the vertical risers, horizontal plenums, zone sizes and user interfaces in today's least-cost new buildings are just as embedded, inflexible, and idiosyncratic as their predecessors. Indeed, re-investment in beautifully crafted, historic buildings could ensure greater infrastructure flexibility to absorb today's rapid organizational and technological change than moving to newly built space in today's market (Loftness et al. 1996).

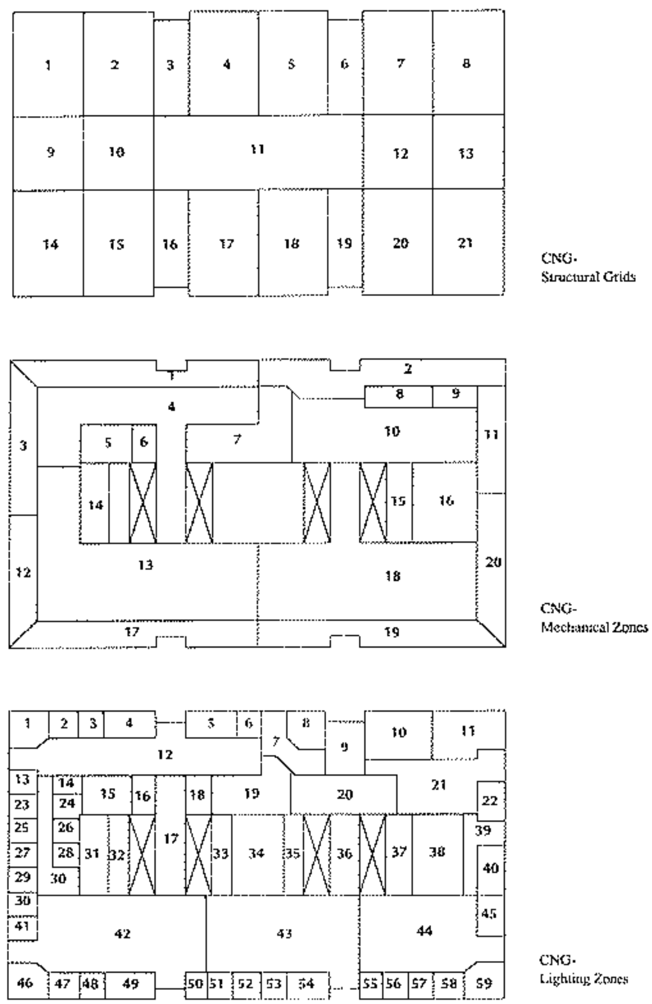


Figure 1.1: The interrelationships of building infrastructures reveal a serious level of mismatch with evolving workplace layouts (Tu, 1997).

1.2.2 Dynamic Organizations Require Flexible Infrastructures

To address the issues of long-term productivity and organizational effectiveness, it is time to move beyond definitions of code-compliant buildings and even "high tech" buildings to the creation of truly "motivational" buildings. Motivational buildings provide environmental performance at a level that consistently and reliably ensures health, comfort, security and financial effectiveness, while supporting high levels of productivity with continuing organizational and technological change. In contrast to present practice, motivational buildings rely on guarantees that every building occupant, at their individual workstation, will be supplied with critical services:

7 Basic Infrastructures Every Occupant/Workstation Needs Individually (CBPD)

- fresh air
- temperature control
- lighting control
- daylight and view, reduced isolation from outdoors
- privacy and working quiet
- network access (multiple data, power, voice connections)
- ergonomic furniture and environmentally appropriate finishes

By ensuring these seven mandates over time, "smart" or intelligent buildings can provide productive environments that attract the best workforce, offer personalized infrastructure and control, and support continuous change in organizational and technological configurations through infrastructure flexibility.

What is actually supplied at the workstation in old and new buildings, however, does not mirror this obvious list of environmental and technical needs for today's workers. Since the 1950's, we have been investing the minimum amount possible in our buildings' hidden infrastructures - from least-cost thermal zoning to minimum lighting control to idiosyncratic network connections.

What Every Occupant/Workstation Actually Gets Collectively (CBPD)

- variable air supply, dependent on thermal demand
- blanket supply of cooling, large zones for 15 people on average
- uniform, high-level lighting
- rare daylight and view, isolation from outdoors
- rare working quiet and privacy control
- one data connection, non relocatable
  2 power connections, non relocatable
  one voice connection, non relocatable
- non-ergonomic, pre-computers furniture and unmeasured indoor pollutant sources

The least-cost, "blanket" conditioning and networking offered in present day buildings emphatically cannot accommodate organizational and technological changes. The rapid increase in desktop technology requires multiple connections to data, power and voice networks, and increased cooling of equipment heat. The rapid exploration of new space planning concepts to reflect new organizational structures and "teaming" work approaches (which radically redistributes the density of workstations, equipment and space enclosures) requires new approaches to networking, HVAC, lighting and control systems.

Yet, both new technologies and new space planning concepts are often introduced into buildings without any modification of the buildings' base systems – heating, cooling, ventilation, lighting, networking, or ceiling/acoustics - with disastrous results. In corporate eagerness to try new organizational concepts, there is little corresponding discussion of the need for each workstation to sustain key independent services, with serious concerns and failures occurring with each spatial renovation or reconfiguration.

1.2.3 New Technologies and New Space Planning Concepts: Potential Stresses in Existing Subsystem and Service

1) Cooling and Thermal Quality:
   Capacity, Diffuser Grid Density and Location, Control
2) Ventilation and Air Quality:
   Zoning, Diffuser Grid Density and Location, Control
3) Acoustic Quality for Individual and Collective Work
4) Lighting and Visual Quality: Grid Density and Location, Control
5) Access to Window, Building Enclosure Control
6) Rank, Territoriality and Personalization
7) Voice Connectivity
8) Data Connectivity
9) Power Connectivity
10) Wall Systems, Spatial Modification and Material Reuse
11) Ceiling Systems and Closure, Acoustics and Light
12) Work Storage & Access

If fixed, open plan concepts such as "universal" or box/cubicle workstations are adequately serviced for each occupant at the outset (not a given), the potential stresses in relation to existing systems and services will be low. However, if dynamic workplace concepts are being considered, if an organization is intended to evolve in size, mission and structure, or if workspaces are being planned for changing tenant users and equipment densities, then major shifts in the selection of HVAC, lighting, enclosure, and networking subsystems and service must be pursued.

1.2.4 New Design Approaches to Absorb Change and Avoid Obsolescence:

Flexible Grid - Flexible Density - Flexible Closure Systems

To avoid frequent environmental quality failures and long term obsolescence, it is critical to invest in user-based infrastructures that are modular, reconfigurable, and expandable for all key services - ventilation air, thermal conditioning, lighting, data/voice and power networks. The dynamic reconfigurations of space and technology typical in buildings today cannot be accommodated through the existing service infrastructures - neither the "blanket systems" for uniform open-plan configurations nor the idiosyncratic systems for unique configurations. Instead, what is needed are flexible infrastructures capable of changing both location and density of services:

Flexible Grid - Flexible Density - Flexible Closure Systems are a constellation of building subsystems that permit each individual to set the location and density of HVAC, lighting, telecommunications, and furniture, and the level of workspace enclosure (CBPD 1995).

These services can be separate ambient and task systems where users set task requirements and the central system responds with the appropriate ambient conditions, or they can be fully relocatable, expandable task/ambient systems. The recent innovations in engineering practice towards delivering flexible, user-based services for air quality, thermal comfort, lighting comfort and network access, have not yet been captured in a comprehensive review of the literature. Since there is now a critical number of buildings with innovative, flexible and adaptive HVAC distribution systems, as well as an increasing number of laboratory studies on underfloor air (UFA) distribution systems, this state-of-the-art literature survey is critically needed.

The goal of this research effort is to document the breadth of references available and the design issues they address, the range of completed buildings with flexible and adaptable HVAC systems, the professional biases that are emerging, the size of the manufacturing industry, and research efforts that are still critically needed towards improving the performance of flexible and adaptive HVAC distribution systems.

1.3 Research Method

1.3.1 Overview

The six-person research team at the Center for Building Performance and Diagnostics (CBPD) and Oak Ridge National Laboratory (ORNL) sought references, journal and conference articles, manufacturers' materials, case studies, and professional interviews, worldwide, for this state-of-the art report on flexible and adaptive HVAC distribution systems. While the initial effort focused on underfloor air (UFA) approaches to infrastructure flexibility, further study identified a range of innovative floor and ceiling-based systems, as described in Chapter 2. In the detailed review of about more than 140 references, the team identified key design issues and their importance to cost and performance, forging the eight distinct chapters in the report: 1) System Types; 2) Plenum Design Alternatives; 3) Diffuser Design Alternatives; 4) Individual Control Alternatives; 5) Central System Issues; 6) Systems Integration and Process Issues; 7) Performance Concerns; 8) Performance Gains. The team also identified key figures from the references and generated new figures compiling distributed data and biases, and compiled a list of 300+ major buildings and about 30 manufactured products and assemblies. Finally, detailed interviews were conducted with ten engineers who have completed significant numbers of UFA projects, to capture up-to-date information about recommendable design details and system performance. Throughout the study, critical areas for research and product development, as well as important changes needed in the building delivery process were identified for advancing the opportunities for flexible and adaptive HVAC distribution systems.

1.3.2 Comprehensive Literature Survey

Building on an already significant compilation of 35 studies by the Center for Building Performance and Diagnostics (CBPD), the literature survey effort was expanded through the combined efforts of the CBPD and ORNL. The team has assembled conference papers and journal articles from professional, federal, international, university and industry sources in relation to all of the system variables and performance implications for flexible and adaptive HVAC distribution systems. After the review of the first papers, a comprehensive list of parameters that should be carefully studied was compiled into a literature review protocol that is attached as Appendix A5. These key parameters include: plenum configuration alternatives (floor, ceiling, ducted, unducted, pressurized, non-pressurized, of varying depths and subdivision); diffuser type and their flexibility in relation to location and density as well as level of control; the range of user controls (location, directional, air flow, temperature, and outside air control); as well as return air configurations relative to flexible and adaptive supply air approaches.

The team has assembled over 140 research papers (Appendix A1) from materials published in the last 20 years by ASHRAE, IEEE, IEA, ASTM, federal agencies, university research units (national and international), manufacturers' studies, and international case studies that have been documented in research publications, conferences and articles. While all of these papers cannot be put into an on-line database due to copyrights, they are available for review in notebooks at ARTI and at the Center for Building Performance and Diagnostics. The literature has been divided into the following categories – overview reports, laboratory studies, field studies, case studies, dissertations, and manufacturers' literature. 68 articles are cross-sectional in nature; 24 are laboratory studies; 11 are lab studies/field studies, 22 are case studies, 3 are PhD dissertations, and 10 are manufacturers' literature. Bauman and Arens, 1996 and Krepchin, 2001 have been identified as extremely valuable sources for more information on underfloor air systems.

The literature search also pursued studies that address the interfaces of flexible HVAC distribution systems with other building infrastructures, including structural, networking/connectivity, interior systems and fire systems. Special attention was given to identifying studies of split or separate thermal and ventilation approaches to flexible HVAC distribution systems, including air systems and air-water systems for thermal conditioning. This is a very important pursuit due to the potential of split systems to effectively address growing indoor air quality issues in buildings, and the increasing demands for air conditioning in European and developing nations due to increases in internal gains.

The literature search and the completed case studies enabled the research team to finalize the table of contents for this Report on The Energy Savings Potential of Flexible and Adaptive HVAC Distribution Systems for Office Buildings.

1.3.3 Case Studies

Given the rapid growth of underfloor air systems in new buildings in North America, one vehicle for identifying key advances in the design of flexible and adaptive HVAC systems is through case study databases and field studies. The

CBPD and Advanced Building Systems Integration Consortium (ABSIC), an industry-university cooperative research center, has completed 17 in-depth case studies with multi-disciplinary teams in buildings with flexible HVAC systems in Japan, Germany, France, the United Kingdom, the U.S. and Canada (Hartkopf et. al. 1989a, Hartkopf et. al. 1989b, Hartkopf et. al. 1991a, Hartkopf et. al. 1991b, Hartkopf et. al. 1991c). The U.S. Department of State identified over 80 recent buildings worldwide with underfloor air, and our engineering and manufacturers interviews, and extensive web searches added over 200 more to create a list of over 300 buildings with flexible and adaptive HVAC systems. The list of buildings with flexible and adaptable HVAC distribution systems, and the engineering and architectural firms involved in their design, are attached as Appendices A2 and A4. The research team anticipates that a second phase of this ARTI research effort will fully utilize field studies of selected building examples to further explore the design choices and performance differences of flexible and adaptive HVAC systems.

1.3.4 Manufacturers' Literature

The CBPD/ORNL research team pursued the manufacturers of products and systems as well as companies/partnerships who are involved in the design, development, and implementation of flexible and adaptable HVAC distribution systems. Nine mechanical system component manufacturers were identified, and 11 raised floor companies, as well as 4 product partnerships with a track record in flexible infrastructures. The marketing materials and detailed specifications from these manufacturers (see Appendix A3) were collected, and the team evaluated the range of products available and specifications given, in the development of this report.

1.3.5 Interviews of Engineers with "Track Records" in Flexible and Adaptive HVAC Systems

The evaluation of trends in flexible and adaptive HVAC systems reveals that the number of engineers committed to underfloor air and other flexible infrastructure approaches is rapidly growing. Nonetheless, there still are a discrete number of engineers or engineering firms with a portfolio of projects demonstrating a "track record" in engineering, constructing, commissioning, and field evaluation of flexible infrastructures. The research team decided to interview between 10 – 15 of these leading engineers to ensure up-to-date information on the design issues and performance of underfloor air and other flexible infrastructures. The research team developed an interview/case study profile for these discussions, based on many of the issues identified in the literature review protocol. Ten engineers were interviewed (see Appendix A4), with the summaries included in the literature database, and referenced where relevant in the chapters. The team has found these interview conclusions invaluable in clarifying non-recorded field knowledge of critical details, barriers and opportunities for the accelerated use of flexible and adaptive HVAC distribution systems.

1.3.6 Interview, Literature, and Data Evaluations

The data gathered through the literature studies, case studies, manufacturers' literature, and interviews was evaluated in three broad areas – 1) the physical characteristics of and the various approaches to flexible and adaptable systems, 2) the performance characteristics of these systems, and 3) interface with other systems and delivery process issues.

The physical characteristics of the systems were evaluated to address:

- Classification of flexible HVAC distribution system variations in relation to plenum location, pressurization, and configuration,
- Plenum design alternatives
- Diffuser design alternatives
- Individual control alternatives
- Central system issues

The performance characteristics of the systems were evaluated to address:

- First costs of components and systems
- Energy performance, peak and annual
- Thermal comfort performance
- Air quality performance
- Facility management performance
- Individual and organizational productivity indices, including churn cost-benefits

The systems integration and the delivery process issues were evaluated to address:

- Innovations in the building delivery process
- Emerging industrial partnerships
- Systems integration issues for the HVAC package; the connectivity package; the enclosure package; the raised floor and the interior systems package.

The report that follows describes the range of flexible HVAC distribution approaches documented in available literature, the frequency of their occurrence, and the range of their recorded performance. The document includes figures and tables of the quantitative and qualitative performance indices available, as well as illustrations of products and integrated systems. Key design and performance conclusions have been highlighted throughout the report. Finally, the research team begins to identify the barriers and opportunities to the widespread adoption of innovative HVAC distribution approaches, as well as key recommendations for future field study or laboratory research efforts. While the research team is reasonably confident that they have a comprehensive overview in relation to North American references, the international practices would bear further effort by European, Australian, South-African and Asian-based research teams.

FLEXIBLE AND ADAPTIVE HVAC SYSTEM TYPES

There may be significant advantage to defining the range of flexible and adaptive system types so that differences in performance data can be effectively recorded, and long term research needs can be defined. After reviewing over 140 papers and interviewing key engineers, the research team has identified at least four drivers that influence the categorization of system types: pressurization (push vs. pull), unducted vs. ducted, combined or separate ventilation and thermal conditioning, and floor vs. ceiling locations. These four drivers have resulted in at least 15 significant system variations around the world (Figures 2.1a and b), worthy of comparative study. The authors of this study have grouped these variations into four distinguishing factors: central fan driven underfloor air (UFA) systems (push/pressurized plenums), distributed fan supported underfloor air (pull systems), separate ventilation and thermal conditioning systems including displacement ventilation (DV) systems, and ceiling-based flexible and adaptive systems

Pressurized or 'Push' Underfloor Air

- unducted or partially ducted UFA pressurized plenums
  (e.g. Owens Corning HQ, Toledo, OH; Alcoa World HQ, Pittsburgh, PA)
- fully ducted UFA pressurized delivery

Distributed Fans or 'Pull' Underfloor Air

- Distributed floor fans and UFA plenums (e.g. York Mills Center, Toronto, Canada)
- Distributed desk fans and UFA plenums
  (e.g. West Bend Mutual HQ, West Bend, WI)
- Distributed underfloor fans in UFA plenums, ducted to desk
  (e.g. Lloyds of London, London, England)
- Distributed fans with fully ducted UFA
  (e.g. Intelligent Workplace south end, Pittsburgh, PA)

Underfloor Ventilation and Separate Thermal Conditioning

- Displacement ventilation (DV) with separate thermal conditioning
  (e.g. Intelligent Workplace north end, Pittsburgh, PA; Gartner HQ, Gundelfingen, Germany)
- Underfloor ventilation air with distributed floor fans (pull) and separate thermal conditioning (heat pumps or fan coils) (e.g. AET-FSS)
- Underfloor pressurized ventilation with underfloor thermal conditioning
  (e.g. Nixdorf Building, Koln, Germany)
- Underfloor pressurized ventilation with thermal conditioning above the floor
  (e.g. Adaptable Workplace Laboratory, Washington, D.C.)
- Underfloor pressurized ventilation with ceiling-based VAV cooling
  (e.g. PNC Firstside Bank, Pittsburgh, PA)

Ceiling-Based Flexible and Adaptive Systems

- Ceiling ventilation only, separate thermal conditioning above floor
  (e.g. Ministry of Finance and Budget, Paris, France)
- Separate ceiling ventilation and ceiling thermal air supply with mixing diffusers
  (e.g. Acutherm^{TM}, TRAV)
- Individually controllable micro-zones
  (e.g. Umeda Center, Osaka, Japan: 3.2m x 3.2m modules)
- Ceiling diffusers with flexible locations and individual control
  (e.g. IBM France by SARI)

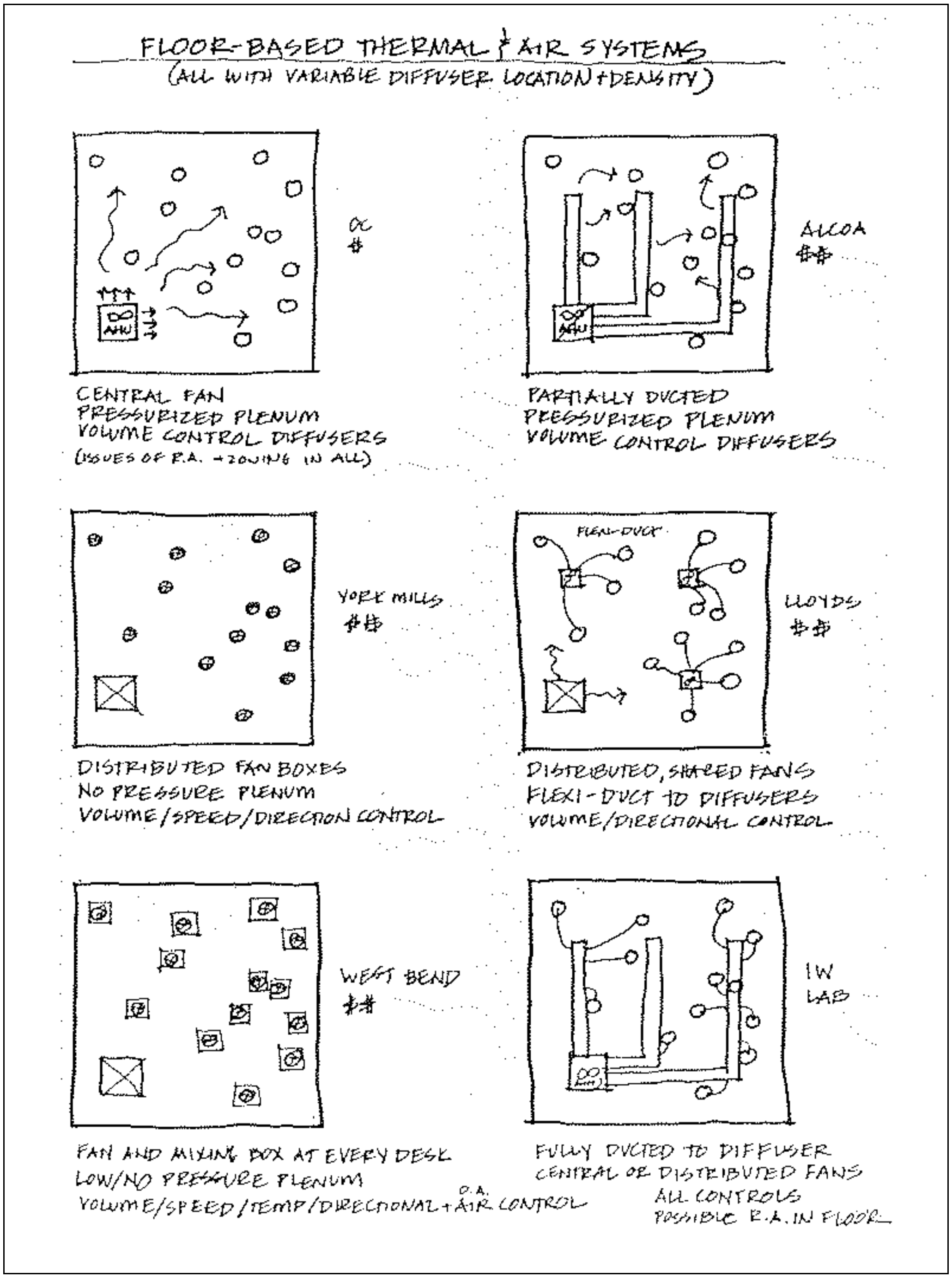


Figure 2.1a: Six system configurations for underfloor air systems (CBPD).

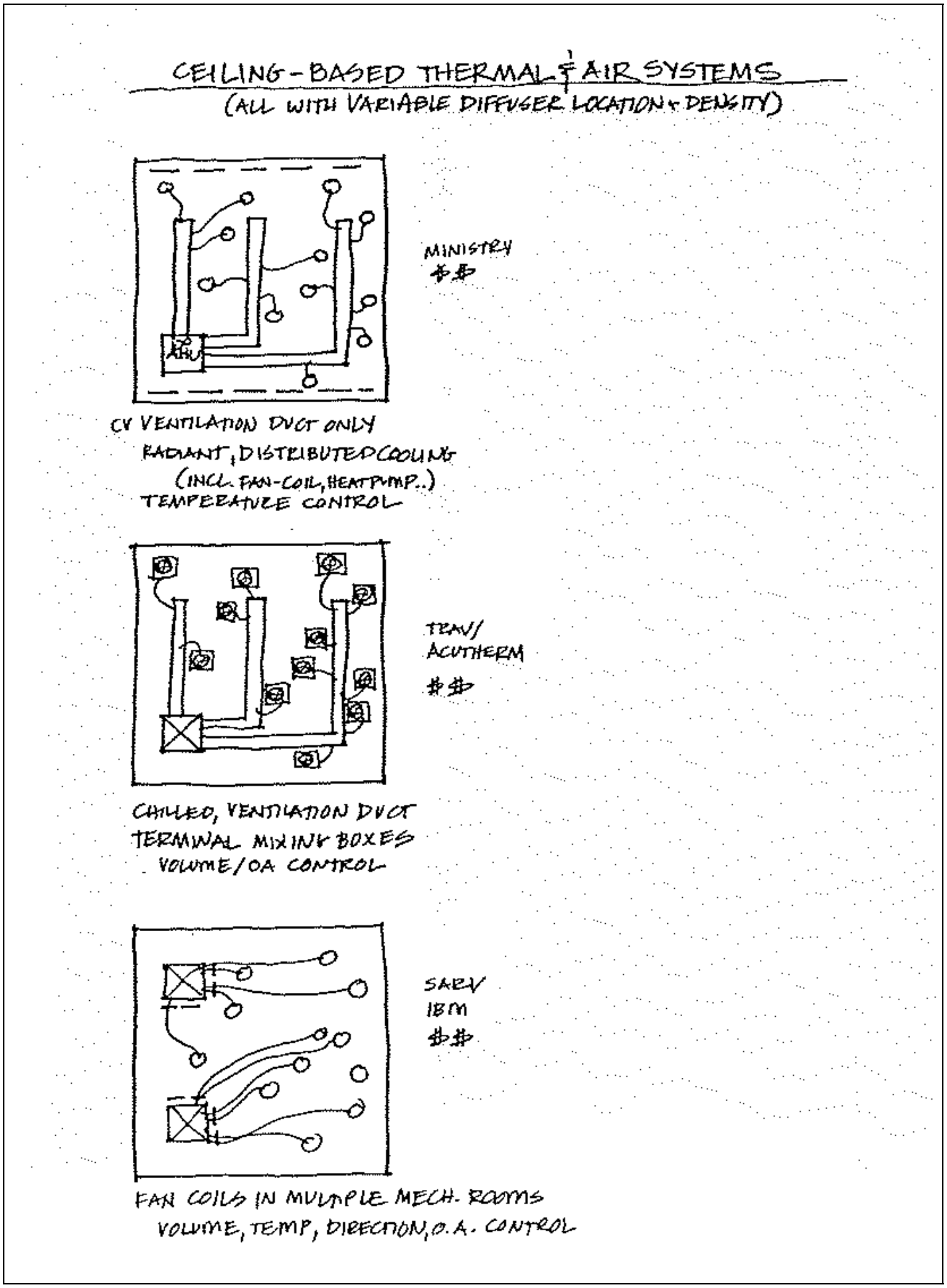


Figure 2.1b: Three system configurations for flexible and adaptive ceiling-based air systems (CBPD).

2.1 Pressurized or 'Push' Underfloor Air (UFA) Flexible and Adaptive Systems for Ventilation and Thermal Conditioning

One of the major distinguishing characteristics of underfloor flexible and adaptive systems is the decision to use central fans to provide full pressurization for underfloor air distribution (push mode), or to use distributed, individual fans to assist in air distribution (pull mode). The use of central fans (whole building or floor by floor) to provide combined ventilation and thermal conditioning in pressurized plenums is the most prevalent flexible and adaptive HVAC system discussed in this report. The only significant variation in this dominant form of underfloor air is the introduction of ducting or partial ducting to address the stated concerns of some engineers about zone control, thermal decay, pressure loss, or smoke/fire separation.

2.1.1 Unducted and Partially Ducted, Pressurized Plenums

A majority of underfloor air HVAC systems in the U.S. rely on pressurized plenums with either unducted distribution of cooling and ventilation air from risers, or partially ducted distribution of air, supporting changing densities and locations of floor air diffusers with centralized, variable speed fans. Similar to the Owens Corning World Headquarters in Toledo, Ohio, engineered by Cosentini Associates, most of the new underfloor air projects utilize an unducted plenum with passive diffusers than can be manually relocated or dampered by the facilities personnel or the occupants for local comfort. A number of manufacturers are developing active diffusers with DDC controllers to vary the volume of air supply based on local thermostats, such that UFA systems resemble ceiling systems in their central control (see Chapter 5). The importance of occupant control and ease of diffuser relocation, as well as the ability to rapidly modify "zone" dimensions must still be carefully studied.

In order to ensure that thermal decay or pressure loss does not affect the delivery of thermal conditioning to the furthest diffusers, maximum distances from the vertical riser or point of feed for pressurized, unducted plenums are typically set at 30-70 feet.

Some pressurized plenum configurations rely on partial ducting to avoid the potential thermal decay of cooling air, or to avoid obstructions in the plenum, or to help subdivide large floor plenums into zones. The Alcoa World Headquarters in Pittsburgh, PA demonstrates a partially ducted plenum supply feeding changing densities and locations of floor air diffusers. In this case, the floor diffusers are actively dampered by direct digital controls (DDC), and maximum distances from the point of feed are less than 9 m (30 ft). Construction sequencing is a major issue for partially ducted plenums because the movement of materials requires open floor areas for the critical period of time until the underfloor infrastructures are completely installed.

2.1.2 Fully Ducted Underfloor Pressurized Delivery

Due predominantly to air quality concerns in relation to the plenum materials and maintenance over time (Roth 2001), a number of European underfloor air systems rely on a fully ducted configuration under the floor. In the Intelligent

Workplace (IW) in Pittsburgh, PA, this supply air ducting is divided into a fixed armature of sheet metal ducts (grid of service) with multiple flexible duct connections feeding changing densities and locations of floor air diffusers (nodes of service) (Loftness in Teicholz 2001). While increasing the first cost and setting minimum plenum heights for duct clearance, the fully ducted systems will ensure that air quality and fire integrity are not in anyway compromised by an open plenum. Sodec and Craig contend that fully ducted systems offer faster temperature control and lower cooling losses to the thermal mass of the floor, which is especially important at the perimeter due to quickly changing cooling loads (Sodec and Craig 1990).

2.2 Distributed Fans or 'Pull' Underfloor Air Flexible and Adaptive Systems for Ventilation and Thermal Conditioning

2.2.1 Distributed Floor Fans and UFA Plenums

A third system configuration for underfloor air is the design of neutral or low-pressure plenums with distributed floor fan air diffusers. A number of companies (AET-FSS, Protek, Tate, and Titus) manufacture floor fan air boxes and/or diffusers that 'pull' the air from the plenum to ensure ventilation and thermal delivery to directly meet demands. The advantages of fan air diffusers include the ability to deliver higher volumes of combined cooling and breathing air to conference spaces – wherever they have 'migrated' to – and to diminish central system fan-power. Distributed fan air diffusers also allow for the use of fewer diffusers per unit area to meet the same flow requirements (Wong 2001).

Many of the fan diffusers use induction units to mix room air with plenum supply air for some level of local temperature control. (See Chapter 4 – Diffuser Design Alternatives). To improve the performance of "mixing" diffusers, a number of projects use furred out columns to feed ceiling return air to the underfloor. The York Mills Center in Toronto, Canada by The Mitchell Partnership supported the comparative study of fully pressurized plenums and the neutral plenums with individual Tate Task Air Modules (TAM's™). Bob Shute of The Mitchell Partnership argues that maximum distance from discharge should be kept at 9-12 m (30-40 ft) to avoid thermal decay of the cool supply air moving across exposed concrete surfaces (Shute 2001). He concluded that neutral plenums with individually controllable fan air diffusers offered higher thermal comfort in the face of spatial change and greater user satisfaction than pressurized plenums (Shute 1992b).

A number of projects combine central fans for pressurized plenums (push) with distributed floor fans for increasing local delivery of conditioned air, especially in conference rooms (pull). It is unclear to what extent this will cause short-circuiting as the fan diffusers pull air down into the plenum through the passive diffusers. The importance of clearly designing either a pressurized plenum or a neutral plenum with distributed fans must be carefully studied.

2.2.2 Distributed Desk or Partition Fan Diffusers and UFA Plenums

Neutral or low-pressure plenums can also be combined with desk-based fan diffusers for the delivery of conditioned air directly to the occupant's breathing zone. The use of furniture-based fan diffusers will definitely yield different performance characteristics for neutral plenum system types.

Several companies (AET-FSS Climadesk, Johnson Controls, Argon, Centercore, Inscape) manufacture desk or partition-based fan diffusers, often with user control for fan speed, as well as volume and direction of airflow. In the case of the Personal Environmental Module^{TM} (PEM^{TM}) by Johnson Controls, the desk-based fans are mixing boxes, allowing the end user to set mixed air temperatures in addition to fan-speed and air direction control.

Further comparative study of floor and furniture-based fan diffusers is needed to understand the physiological consequences of different design specifications for effective conditioned air delivery. The delivery of conditioned air at the occupant's waist is cited as the best for thermal comfort and minimizing drafts and eye dryness (Wyon 1991). Larger face areas for desktop diffusers are cited as the best for thermal comfort (Bauman et. al. 1993).

While the central system must be sized for the maximum draw, with variable supply based on demand, the energy savings in operation can be substantial for distributed, individual fan system types. Due to standard desk vacancy rates, occupancy sensors can allow task air to be shut down or off for significant energy savings, as demonstrated in the West Bend Mutual Insurance HQ by the Zimmerman Design Group (Kroner et. al. 1992) and Johnson Wax installations by HOK. Moreover, user surveys in the West Bend Mutual building identified that desk-based air systems provided a 33% higher overall satisfaction as compared to conventional ceiling systems (Kroner et. al. 1992).

2.2.3 Distributed Underfloor Fans in UFA Plenums, Flexi-ducted to Floor and Desk Diffusers

One of the earliest flexible and adaptive underfloor air systems is in the Lloyds of London building. In this very dynamic building, Ove Arup introduced a variation on underfloor air delivery that has allowed them to meet the rapidly changing loads and configurations of this building. Through the introduction of underfloor fans in regular locations throughout the facility, the HVAC system pulls air from the risers to different locations underfloor, with multiple flexi-duct connections feeding floor and desk air diffusers (Figure 2.2). These fans significantly reduce central system demands and allow rapid delivery of additional cooling and breathing air to groups of trading desks. Field studies have shown that this UFA system can effectively absorb the population changes on the trading floor - from 0 to 6,000 occupants in less than an hour - with no more than a 6 - 7^{o}F temperature rise (Hartkopf et. al. 1989b).

2.2.4 Distributed Floor or Desk Fans with Fully Ducted UFA

The fully ducted underfloor system, often preferred in Europe due to air quality concerns, can be designed to combine highly pressurized ducts with passive diffusers (ducted, push UFA) or low pressure ducts with distributed floor or desk fans (ducted, pull UFA). In the south end of the Intelligent Workplace at Carnegie Mellon, a fully ducted UFA distribution has been combined with Personal Environmental Modules™ by Johnson Controls to “pull” conditioned ventilation air to each desk as needed, allowing for local mixing of room air, as well as air speed and air direction control. Some manufacturers offer both floor fan air diffusers and passive diffusers with duct “boots” that can allow the engineer to decide if the ducted underfloor air system will be centrally pressurized or neutral. Although there may be a comparative study of the performance of these two fully ducted variations, this report could not locate measured comparisons.

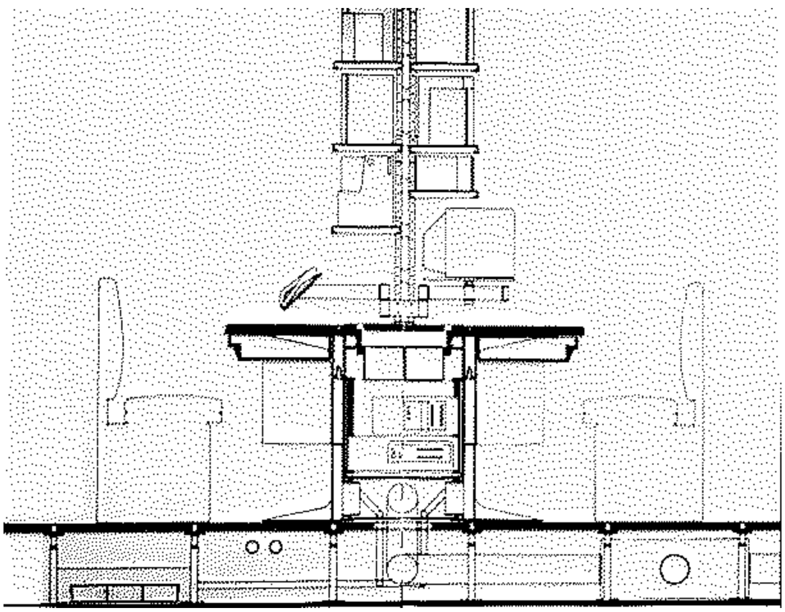


Figure 2.2: Lloyds of London relies on both underfloor fan powered distribution boxes and desktop diffusers.

2.3 Underfloor Ventilation and Separate Thermal Conditioning

Repace (Repace 1988) states that "the delivery of thermal conditioning should be divorced from the delivery of breathing air". There are many reasons to support this argument.

First of all, the widespread use of Variable Air Volume (VAV) systems, in which the supply of any air (recirculated or outdoor air) is dependent on thermal demand, has led to numerous failures in swing seasons, and inadequacies in multiple spaces that are tied to a single sensor/controller. Although minimum air settings on VAV are of some benefit, a 20% minimum setting of the 20% outside air content promises only 4% "fresh air", with even less delivered to the nose due to the mixing patterns with existing air in the space. In addition, the ventilation "effectiveness" of the entire duct distribution system is in question, with a 20% minimum setting at the air handler not correlating to a 20% outside air contribution at the diffuser. Ventilation effectiveness is significantly more reliable with independent ventilation systems.

There are also energy efficiency advantages to separating thermal conditioning from ventilation/breathing air supply, in both central and task-air systems. With a constant volume of 100% outside air for ventilation requirements alone (conditioned to appropriate temperature and humidity as needed), much smaller ducts can be utilized with a guarantee of adequate volume of outside air regardless of season and internal thermal loads. Since air is a very inefficient thermal transport medium compared to water, the constant volume ventilation system can be coupled with a wider range of energy efficient thermal conditioning options (beyond the traditional all-air systems), such as water based heat pumps, fan-coils, radiant heating and radiant cooling systems. Moreover, individual occupants can modulate, redirect or shut off thermal conditioning systems while still guaranteeing ventilation delivery, allowing conditions to meet individual comfort requirements or be shut down when the space is unoccupied.

A third advantage of splitting ventilation and thermal conditioning, is the viable use of room carbon dioxide (CO_2) sensors and other air quality technologies to actually control the filtration and supply of ventilation air. When air quality is monitored by room CO_2 or other pollutant sensors, ventilation rates can be increased proportionally to need without awaiting thermal demand. Strindehag and Norell (Strindehag 1991) state that ventilation systems that employ CO_2 sensors are best suited for buildings in which occupant and equipment load vary widely and unpredictably over time - an appropriate description of the modern office. The smaller quantities of air that are distributed through the building for ventilation only can also be more effectively filtered and monitored to ensure indoor air quality, protecting the occupants from external pollutants and allergens as well as possible toxic ‘agents.’

Finally, the separation of ventilation air from thermal conditioning enables operable windows to be re-introduced into office buildings. While a dedicated constant volume ventilation system guarantees the levels of outside air at the desk, in spite of changeable wind conditions, the separate thermal conditioning system can be shut off to avoid simultaneous heating and cooling. In the Ministry of Finance and Budget building in Paris, France, a constant volume supply of 100% outside air (conditioned) ensures ventilation requirements regardless of the outdoor wind conditions. When occupants open windows to cope with local overheating and pollution build-up, or to enjoy a perfect day, the perimeter fan coil units (for thermal conditioning only) will shut off to avoid energy waste, while the constant volume ventilation air supply continues. A split system offers significant gains for ensuring thermal comfort and air quality, increasing energy efficiency through zoning and load matching, as well as reopening the opportunities for operable windows in the workplace - critical to both perceived and actual comfort and air quality.

2.3.1 Displacement Ventilation with Separate Thermal Conditioning

Since separating ventilation from thermal conditioning will allow very low velocity air systems, it is important to differentiate displacement ventilation (DV) from other underfloor air (UFA) systems at this point. Displacement ventilation is a variation on floor-based supply air dedicated primarily for ventilation, typically in conjunction with secondary chilled water systems for handling excess thermal loads (Brown 2000, Int-Hout 2000). Displacement ventilation systems are typically differentiated from UFA by their lower air velocity and commensurate lower cooling capacity, and their reliance on the "thermal plumes" around heat sources for fresh air distribution (in lieu of forced air distribution). Michael Brown of Lincolne Scott Engineers in Australia summarizes, "Displacement air distribution, in contrast to mixed flow systems, introduces supply air usually at low level and low velocity with almost no indication and mixing of room air…The mechanism involved in displacement air distribution is that of thermal buoyancy, wherein a relatively thin pool of conditioned air spreads across the floor and rises around a heat source such as a person or an item of equipment and then rises under buoyancy and convective air currents to return air locations at ceiling level." (Brown 2000).

Displacement ventilation is predominantly used to meet breathing requirements, not cooling loads, although some cooling requirements can be met by displacement systems. The use of floor or perimeter/ sidewall displacement air diffusers (LTG, Trox) will take advantage of thermal buoyancy to ensure ventilation delivery to every "heat island" – predominantly humans and equipment – without the requirement for universal distribution of breathing air.

According to Brown (Brown 2000) and Int-Hout (Int-Hout 2000),
"displacement ventilation relies on low velocities of 0.15-0.2 m/s (30-40 fpm) combined with low temperature differentials 1-3^{o}C (2-6^{o}F) with thermal buoyancy ensuring effective distribution around heat sources in the conditioned spaces. Displacement ventilation also allows for a reduction in total supply air volume as the higher levels of stratification and greater space differentials are allowed. These low volumes, however, may only be suitable for loads from 40-50 W/m2 (4-5 W/ft2) and may require the design of separate thermal conditioning systems. Displacement ventilation functions best with higher ceiling heights (greater stratification and no downward mixing) and return air grilles should be uniformly spaced to ensure plume stability".

Since displacement ventilation systems introduce conditioned air at very low velocities but high volumes near the floor, return air is typically at the ceiling level for measurable air quality gains (see Performance Gains Chapter 9). The upward movement of air in the space is driven by natural convection from the internal heat sources, which induce thermal stratification. The reliance on this stratification, if properly controlled, can lead to reductions in the space cooling load by as much as 15% compared to conventional well-mixed systems (Shute 1992b).

Defining Characteristics:
Ceiling Systems, Underfloor Air, and Displacement Ventilation

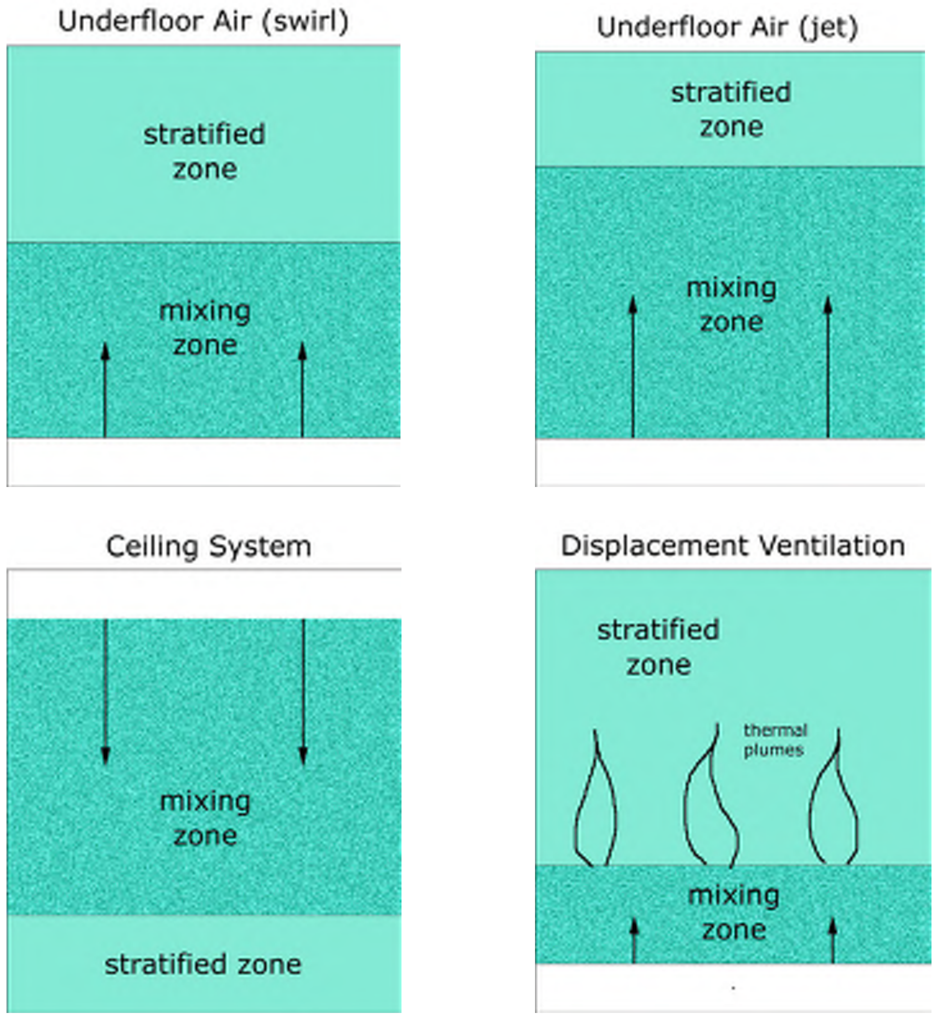


Figure 2.3: There are distinct differences in the size and location of the "mixed" or conditioned layer in ceiling systems, underfloor air with jet diffusers, underfloor air with swirl diffusers, and displacement ventilation.

	ΔT (supply to room)	Velocity	Volume	Cooling Capacity
Ceiling System	6-10 °C (10.8-18°F)	2.5 m/s (492 fpm)	94 L/s (200 cfm)	300 W/m^2 (95 Btu/h/sf)
Underfloor Air	4-5 °C (7.2-9°F)	2.5 m/s (492 fpm)	38-47 L/s (12-105 cfm)	300 W/m^2 (95 Btu/h/sf)
Displacement Ventilation	1-3 °C (1.8-5.4°F)	0.1-0.2 m/s (30-40 fpm)	9.4 L/s (20 cfm)	40-50 W/m^2 (13 Btu/h/sf)

References: Brown 2000; Int-Hout 2000; Seppanen et al 1989; Yuan et al 1999c

With a commitment to separating thermal conditioning and ventilation, many European underfloor air systems use the underfloor plenum for ventilation alone – relying on this displacement ventilation (DV) for energy effective distribution of breathing air. The 100% outside air is filtered, conditioned and fed in high volumes at low velocity to an unducted or ducted plenum for distribution. Combined with perimeter and/or floor diffusers, the conditioned air "pours" across the floor and around obstructions (flowing like water) until it finds a "thermal plume" such as a person or piece of equipment. In this way, fresh air and some cooling is delivered where it is needed most, in a natural upflow, significantly improving indoor air quality (Milam 1992, Loudermilk 1999, Seppanen et. al. 1989, Burnley 1993, Yuan et. al. 1999b, Yuan et. al. 1999c) and energy efficiency (Hu et. al. 1999, Loudermilk 1999, Kim and Homma 1992). Perimeter heating and cooling, as well as concentrated cooling loads in the building, are met by a separate HVAC system, typically water-based radiant systems, fan-coils, or heat pumps.

In the headquarters building at the Gartner Company in Gundelfingen, Germany (Germany's largest enclosure/curtainwall manufacturer), a constant volume displacement ventilation system is bundled with a variety of water based thermal conditioning systems (water flow mullions, radiant ceilings, and water cooled equipment systems) for thermal comfort and air quality, as well as energy efficiency, load balancing and user control. The conditioned outside air is introduced in large volume, low velocity ducts in the floor plenums to provide silent delivery of conditioned breathing air around the entire building perimeter, with opportunities for flexible duct connections to isolated central spaces.

2.3.2 Underfloor Ventilation Air with Distributed Floor Fans (Pull) with Thermal Conditioning Above the Floor

Just as combined ventilation and thermal conditioning systems can utilize pressurized plenums (push) or distributed fans (pull), dedicated ventilation systems can also utilize low/no pressure plenums combined with distributed fan boxes. One of the most developed under floor ventilation systems manufactured by AET-FSS™, combines relocatable fan-boxes with a plenum air supply for ventilation and modest cooling. Additional cooling requirements are met by supplemental in-floor or floor-standing fan coils to provide for local/ on-demand thermal zoning and control. The ability to increase the density of fan diffusers ensures that changes in layout densities or meeting spaces can be met with increased ventilation rates, with the plug-in fan-coils to meet the additional cooling loads.

2.3.3 Underfloor Pressurized Ventilation with Underfloor Heat Pumps or Fan Coils

In a series of fully integrated office buildings in Europe, Nixdorf combined underfloor ventilation (pressurized plenums) with underfloor heat pumps for delivering air quality and thermal comfort in dynamic office environments (Hartkopf et. al. 1989a). Functioning like a terminal "mixing box" and heat exchanger, the heat pumps allow for individualized temperature settings as well as increased ventilation air rates as needed for workstations and meeting spaces. The heat pumps were specially designed to fit in the 18" raised floor plenum beneath the networking distribution. Quick connections allow the heat pumps to be relocated, added, or removed for maintenance. The heat pumps were selected for their ease of control, ease of maintenance, energy efficiency and low noise.

2.3.4 Underfloor Pressurized Ventilation with Thermal Conditioning Above the Floor

In the Adaptable Workplace Laboratory (AWL) at the General Services Administration in Washington DC, underfloor air is supplied through a pressurized plenum with cooling and heating provided by perimeter heat pumps, because it is a narrow section historic building. The underfloor air offers quiet, efficient delivery of ventilation air and some cooling (or heating) capacity. However, two concerns have been raised that should be further studied for pressurized plenum systems (both separate and combined thermal/ ventilation systems). First, the air velocity is so low that users often cannot tell if the system is on, with no convective airflow felt at the diffuser. Despite effective ventilation at every workstation, the system does not give the occupant the ‘feel’ of air movement, which is often used as a cue that the system is working. Second, the open plenum can be a source of migrating pollutants from unsealed risers or of local air quality concerns such as dust and water accumulation. As with any ventilation system, the maintenance of the ‘duct’ path is critical to its long-term success (Loftness et. al. 2001).

2.3.5 Underfloor Pressurized Ventilation with Ceiling-based VAV Cooling

In the PNC Bank Firstside operations center in Pittsburgh, PA, L.D. Astorino engineers introduced both an underfloor pressurized plenum for ventilation and partial cooling load conditioning, combined with ceiling VAV for supplemental cooling. The unducted, pressurized plenum with passively dampered diffusers was sized to meet all of the ventilation loads for the high density check processing center, as well as approximately 60% of the cooling load, with easy relocatability of diffusers for churn. A ceiling based, conventional DDC-controlled VAV system was then designed to meet the remaining 40% of the cooling load. The first costs for the separate floor and ceiling HVAC systems were actually lower (~12%) than conventional overhead systems, with far fewer control points required. The engineering team is confident that operational costs - both energy and facilities management costs – will also be lower. In addition, facility management costs will be reduced with greater occupant satisfaction in the high density, dynamic work environment (Wong 2001).

2.4 Ceiling-Based Flexible and Adaptive Systems

Although this study focuses primarily on underfloor flexible and adaptive HVAC systems, and plenum systems most prominently, there are a number of ceiling based approaches to “flexible grid - flexible density - flexible closure” HVAC – with dramatically increased zoning flexibility and individual control.

2.4.1 Ceiling Ventilation Only; Separate Thermal Above the Floor

In many parts of Europe, the introduction of ventilation systems for commercial office spaces is far more critical to cope with increased densities than cooling. As a consequence, numerous buildings demonstrate the use of a constant volume supply of fresh air throughout the work environment from ducted diffusers in the ceiling, with water-based or radiant systems for task cooling and heating. The flexibility of these systems is driven by the ability to add or relocate the thermal conditioning units, as well as to locally control the thermal conditioning units - temperature and/or air speed and direction.

In the Ministry of Finance and Budget in Paris, France, over 12,000 workers highly rate the air quality and thermal performance of their constant-volume ceiling ventilation system combined with the perimeter fan coil units which fully support the opening of windows in offices (Hartkopf et al. 1991b). For energy efficiency, the perimeter fan coils (in heating or cooling modes) automatically shut off whenever the adjacent windows are opened, with the constant volume ventilation system continuing as a guarantee of ventilation effectiveness.

2.4.2 Ceiling Ventilation and Ceiling Thermal Air Supply with Mixing Diffusers

In the U.S., where all-air HVAC systems are prevalent, there have been three developments in flexible and adaptive HVAC strategies that separate ventilation from thermal conditioning control. Pursuing an all-air approach, the Hines Development Interests have introduced a two-duct system in their Texas tenant office building projects. By combining a small, constant volume ventilation duct throughout the buildings with large cooling ducts, very local decisions can be made about ventilation rates and temperatures to guarantee long term air quality, system reliability, and improved energy efficiencies. The Hines Partnership is convinced that the modest increases in first cost of these separate thermal and ventilation systems contribute significantly to their 97% occupancy rates.

Acutherm™ also has developed a two-duct system, with each diffuser acting as a terminal mixing box. Again, the small ventilation duct runs alongside the large cooling duct with individual controllers determining the mix for thermal comfort and air quality.

The Hartman Company has been developing a mixing diffuser that allows individuals to vary the quantity of primary chilled ventilation air and the room air mix. Most appropriate in milder climates where cooling loads can be managed by ventilation air rates, the Hartman TRAV™ diffuser requires only a single duct for air delivery, since room air is used for thermal mixing. This product is not yet commercially available, but offers significant opportunity for existing buildings to use their now-undersized ductwork to supply conditioned ventilation air to terminal mixing boxes.

2.4.3 Individually Controllable Ceiling-Based Micro-Zones

There are a few buildings that demonstrate fixed-grid, fixed-density micro-zoning to provide individual control of thermal conditions regardless of space function or closure (from open to fully closed). This micro-zoning relies on a very high density of supply and return air diffusers as well as water-based cooling and heating coils to support continuous changes in thermal zone control.

In the Umeda Center by Takenaka Construction Company in Osaka, Japan, a “cell body” of 10 ft by 10 ft (3.2 m by 3.2 m) was established as a minimum workspace size. Each cell body (whether open or closed) has a dedicated supply air diffuser with constant volume outside air supply, a dedicated return air diffuser, and a negotiated thermal control capability via distributed fan-coil units (Hartkopf et. al. 1991a).

2.4.4 Ceiling Diffusers with Flexible Locations and Individual Control

Finally, reconfigurable ceiling-based HVAC systems have also been developed, in which ceiling diffusers can be relocated and added or subtracted (with flexi-duct connections) to meet the local demands of a diverse configuration of people and equipment.

In IBM Paris, a speculative tenant building, SARI Development and Carrier France introduced one fan coil unit per workstation, giving each individual the control of air on/off and temperature settings. Bundled in two mechanical rooms per floor, the outside air supply to each fan-coil in the mechanical room can be modified to respond to local needs. The conditioned air is fed through a flexi-duct to two linear ceiling diffusers per workstation, which can be relocated as needed. An Acutherm™ controller shifts the air throw pattern from winter to summer to avoid drafts, and end users can modify supply air temperature +/- 2^{o}C as desired, while maintaining a constant volume of ventilation. Since the ceiling air supply and thermal conditioning systems are only turned on by occupant command (with staged shut-off at 6, 7 and 8 pm), the energy demands of this building are the lowest for all of IBM France, and the occupant satisfaction with air freshness and thermal conditions are the highest (Hartkopf et. al 1991b).

2.5 Conclusion

In Heinemeier, Schiller and Benton's words (Heinemeier et. al. 1990), "If conditions are allowed to vary over time and space, and if the occupants can control the conditions in which they work, it may become possible to 1) make a larger percentage of the population comfortable; 2) adapt conditioning to work areas with non-uniform heat loads and isolating partitions; 3) offer a broader menu of conditions from which to pick, many of which have the potential to save energy."

The four significantly different system configurations outlined and the 15 variations that have been identified from over 300 buildings worldwide, have all yielded measurable performance gains for the owners and end-users. The need remains, however, to fully study the cost/benefits of these system types, by region and building function, to improve the next generation of flexible and adaptive HVAC systems.

3.1 Plenum Height

More than 20 references identify effective plenum heights for underfloor air is pervasively set at 12 to 18 inches, with no penalty for even higher plenums (Figure 3.1). Several variables influence the identification of optimums:

1) distance from vertical riser to furthest point;
2) introduction of HVAC ducting for supply and/or return
3) introduction of HVAC fans, piping and coils units.
4) depth of relocatable diffusers and outlet boxes
5) telecommunications and fire system components
6) thermal mass of slab and floor tile
7) cleaning and management strategies.

Effective plenum heights for underfloor air are pervasively set at 12 to 18 inches (0.3-0.45 m), with no penalty for even higher plenums.

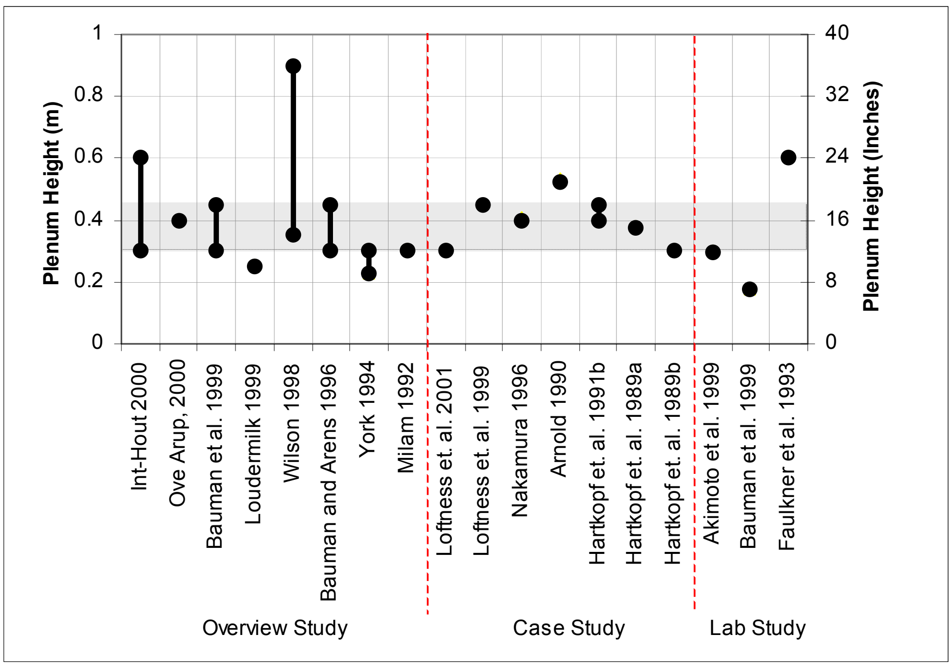
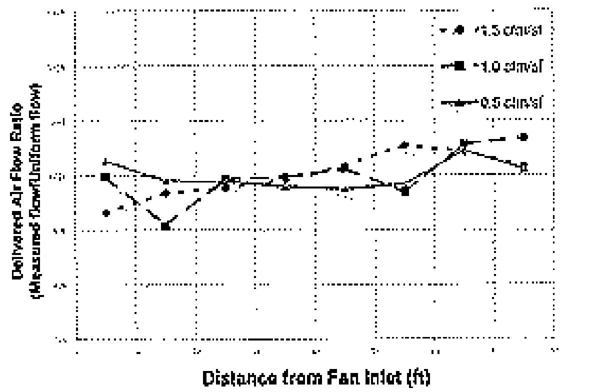
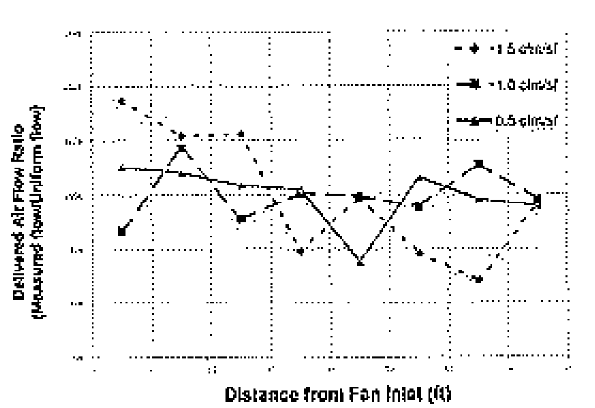


Figure 3.1 Range of plenum heights reported in various references (Center for Building Performance and Diagnostics, 2002).

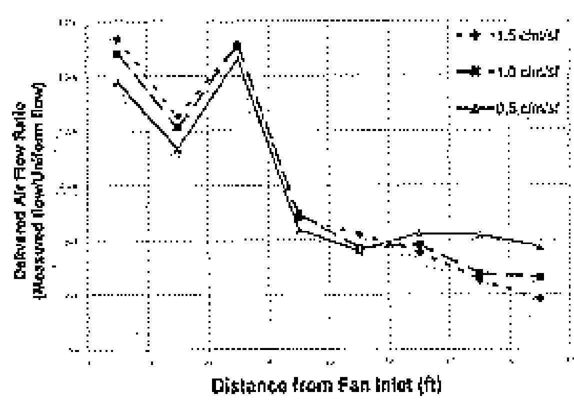
A study by the Center for the Built Environment (Bauman et. al. 1999) found that a nominal 8-inch (7-inches of clear space) plenum provided uniform air flow performance across a 3,200 ft^2 plenum. The study recommended that, "on average, at least 3 inches of clear space for air flow be provided in addition to the height required for other factors." This study was aimed at retrofit applications where limiting plenum heights may be an important consideration. In new construction one would typically have the freedom to use higher plenums without penalty (Figure 3.2). Several references argued for more than 18" clear to support effective systems integration and easy maintenance and reconfiguration (Yates 2000,).



Air flow ratio comparison
for 7-inch plenum



Air flow ratio comparison
for 3-inch plenum



Air flow ratio comparison
for 2-inch plenum

Figure 3.2: The Center for the Built Environment tested the air flow performance of low-height underfloor plenums (Bauman et. al. 1999).

Higher plenum heights do not automatically result in higher floor-to-floor heights, and indeed under floor air HVAC could actually reduce floor-to-floor heights or support increased ceiling heights in the occupied space. Indeed, underfloor air and networking systems often relieve the need for deep ceiling plenums that are clear of both structure and ducting. A number of underfloor air projects have greater than 9 foot ceiling heights, supporting indirect lighting in the occupied space, without increased floor-to-floor heights. Chiu (Chiu 1991) illustrated that floor-to-floor height of a range of projects is independent of the introduction of a raised floor for networking or HVAC (Figure 3.3).

Higher plenum heights do not automatically result in higher floor-to-floor heights, and indeed under floor air HVAC could actually reduce floor-to-floor heights or support increased ceiling heights in the occupied space.

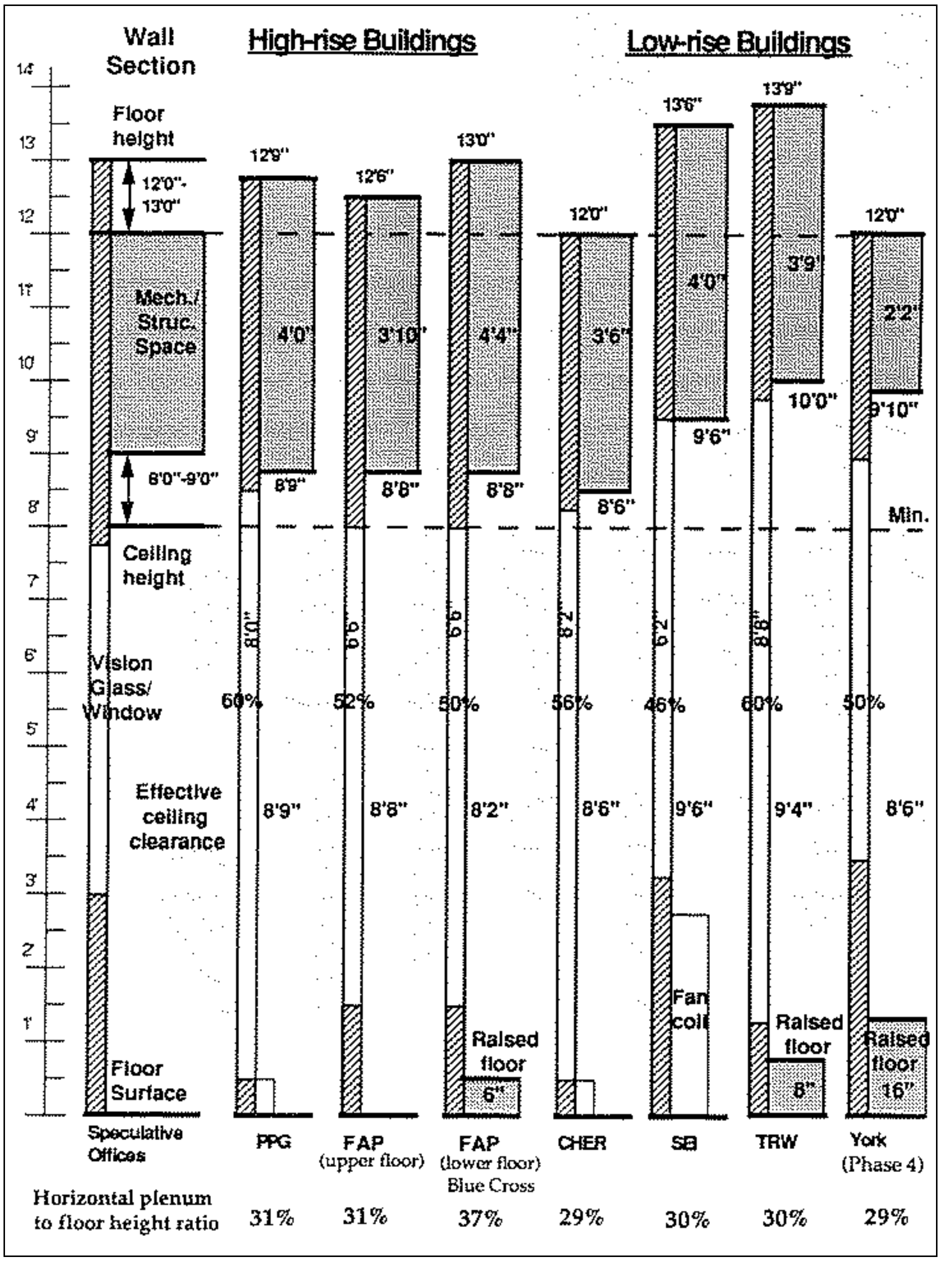


Figure 3.3: Effect of a raised floor on building floor-to-floor height (Chiu, 1991).

3.2 Distance from Vertical Riser

Distances from the vertical riser/air supply can be as long as 80 feet; however, 30–40 feet are preferable to ensure no thermal decay and controllable pressure conditions.

As floor plate sizes increase, the question of distance from a vertical riser to the furthest air diffuser becomes more important for both thermal comfort and indoor air quality. Shute (Shute 2001) identified thermal decay in concrete plenums when distances from the point of feed exceeded 30 feet. To avoid the discomfort that would occur as a result of this decay, either ducted feeds or an increased number of vertical risers would be recommended. Given the variations in thermal loads and zone sizes that can occur in the dynamic office, maintaining distances from the vertical riser at less than 30-40 ft (9-12 m) is recommended. A few engineers interviewed felt that air quality can be achieved at distribution distances as high as 70 feet, especially if separate cooling provisions are designed for local thermal demands (e.g. Distributed fan coils, radiant cooling, ceiling based VAV).

Distances from the vertical riser/air supply can be as long as 80 feet; however, 30–40 feet are preferable to ensure no thermal decay and controllable pressure conditions. With a clear height of 8-12 in (200 - 300 mm), and a discharge velocity not higher than 500 fpm (2.5m/s), Bauman et. al. 1999, Shute 2001). Engineer Val Lehr states that distances from the vertical riser/air supply can be as high as 75-100 ft (25-33 m); however, 40 ft (13 m) is preferable to ensure no thermal decay and pressure inconsistencies (Lehr 2001).

3.3 Pressurization and Tightness

For delivering combined cooling and ventilation in office environments, at least a dozen references stipulated 0.1 in WG (25 Pa) static pressure for plenum underfloor air systems.

For delivering combined cooling and ventilation in office environments, at least a dozen references stipulated 0.1 in WG (25 Pa) static pressure for plenum under floor air systems (Figure 3.4). Sodec and Craig (Sodec and Craig 1990), further identified that up to 3000 ft^2 (300 m^2) can be easily pressurized from one free discharge supply air duct into a pressurized plenum with a clear height of 12 in (300 mm). Given discharge velocities of not higher than 500 fpm (2.5 m/s), supply air will be uniformly distributed to the air outlets (Sodec and Craig 1990). Clark Bisel at Flack & Kurtz designs systems to deliver air at a pressure of less than 0.1 inWG (Thomas 1995). A few engineers argued that 0.15 - 0.2 inWG static pressure might be preferable to ensure adequate cooling in high-density work areas and to provide building occupants with the feeling of air movement that they often associate with effective HVAC delivery of air quality and comfort. Indeed, a major drawback of underfloor air systems designed to deliver ventilation air predominantly is that the very low pressures required cannot be easily felt by the human hand – perceived by occupants as a failure in the HVAC system.

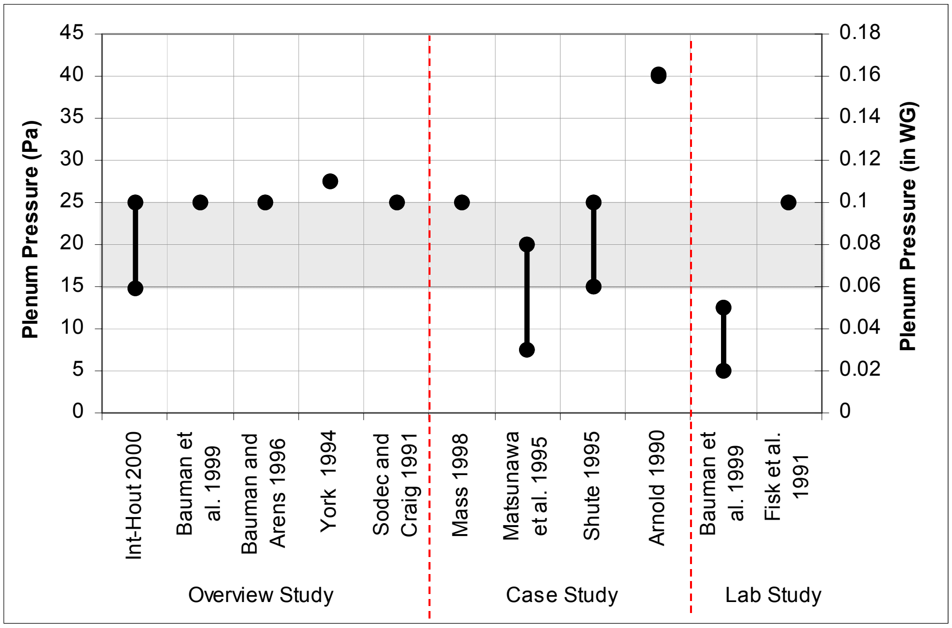


Figure 3.4: Range of plenum pressures in underfloor air systems collected from multiple references (Center for Building Performance and Diagnostics, 2002).

The fan pressure requirement for ducted systems would be slightly higher than that for pressurized plenums, by about 25% (Webster et. al. 2000), to compensate for friction losses in the duct assembly. In both ducted and unducted pressurized systems, the distribution fans must be variable frequency drives to adequately feed conditioned air to the varying density and aperture of diffusers throughout the space. In contrast to these "push" distribution approaches, the "pull" fan diffusers in the floor, desk, or wall can rely on non-pressurized plenums or distribution ducts.

Given the low pressures of less than 0.2 inches of water static pressure in underfloor air systems, most references argued that leakage through the floor/carpet assembly is not significant. Moreover, Sodec and Craig (Sodec and Craig 1990) state "given the low water static pressure, the partitioning of zones and penetrations for cabling do not have to be airtight, since leakage will amount to less than 0.7% of volume floor rate. Again due to low pressure, we have experienced about a 3% leakage rate for non-carpeted installation and less than 1% for carpeted. Unlike an overhead system where leakage is lost to the occupied zone, underfloor systems benefit the occupants. Segregation of zones is important (for conference rooms and perimeter loads) but can be accomplished by the installation of a simple underfloor partition form the floor slab to the underside of the raised floor."

3.4 Plenum Subdivisions and Ducting

Bauman and Arens (Bauman and Arens 1996) argue that,"It is not necessary to partition the underfloor plenum into zones and doing so can make future office layout changes more difficult." However, "Because of the special heating and cooling requirements of the perimeter of the building, it may be necessary to create a perimeter zone in the underfloor plenum to run a separate perimeter system."

A dominant number of US projects demonstrate open plenum distribution systems with separately ducted or water based perimeter systems. A number of engineers are actively pursuing innovative building facades that can neutralize climatic loading and allow the underfloor pressurized plenum to meet the cooling and ventilation loads of the entire building. However, a number of references illustrate continued thermal load differentials that cannot be met by diffuser densities or fan powered diffusers alone, requiring plenum subdivisions to support zone control. Sodec and Craig (Sodec and Craig 1990) argue that, "Faster temperature control and lower cooling losses due to thermal storage, are especially important at the perimeter due to quickly changing heat loads."

In both perimeter zones and specialized core zones such as conference rooms, zoning control is often handled by partitioning the underfloor plenum to correspond to the building zones having unique load requirements. These partitions are typically custom fabricated on-site, since only a few raised floor manufacturers have modular components for underfloor partitioning. Shute (Shute 2001) developed custom solutions that, "consider the use of three-sided ductwork with the open side against the structural floor to avoid penetrations by pedestals, and the need for escutcheon seals. An angle frame system allows ducts to be spanned by two or more modules of the raised floors."

Sodec and Craig (Sodec and Craig 1990) also mention that given the 0.08 in of water static pressure, the partitioning of zones and penetrations for cabling do not have to be airtight. Their calculations for a zone of 2000 ft^2 (200 m^2) show that the leakage will amount to less than 0.7% of volume flow rate. Custom partitioning for zoning underfloor air is typically made of sheet metal or drywall cut to fit around pedestals and the horizontal distribution of HVAC, fire or networking components. Several raised floor systems make underfloor partitioning difficult by eliminating the flat face on the underside of the floor for structural or material reasons, or introducing unwieldy pedestals, making simple partition shapes unusable. The lack of prefabricated plenum dividers that can be reconfigured as occupant layouts change is a serious annoyance to professionals and should be addressed by raised floor manufacturers.

3.5 Raised Floor and Plenum Materials

The selection of raised floor materials is typically determined by cost, structural integrity, and ease of assembly/disassembly. Early raised floors had unacceptable reputations for vibration, squeaking and drumming noises and many engineers formed long-term opinions against the use of raised floors in general office space. However, raised floors today can be as robust as structural slabs, with the careful selection of access floor tiles and pedestals for structural integrity – given both static and rolling loads.

In addition to structural integrity, however, the ease of assembly and disassembly of the raised floor is critical, with a number of details that can determine the ease with which end users can access and modify the service infrastructures under the floor. A number of raised floors use screws at each corner of the tile to ensure floor tightness. These screws can be difficult to remove if a floor tile and its diffuser or outlet box are to be relocated. If the screws do not have a catch at the tip to keep them with the tile, the screws are often misplaced, and lighter floor tiles can then begin to squeak. In heavier gravity-laid tiles or those with pedestal "seats" for the tiles that do not require corner screws for tightness, the ability to lift the tile must be tested for ease of access and reconfiguration.

Third, the structural framing of the tiles and the infill materials will impact the number, shape and location of penetrations that can be introduced for air or networking faceplates. Some floor tiles offer four quadrants for penetration in each 2 ft by 2 ft or 60 cm by 60 cm tile, with maximum diameters for diffusers or boxes at 8 in or 20 cm. Other floor tiles offer one central area for penetrations or two off-center locations. Since the rotation of tiles may be critical to relocating a diffuser in today's very small workstation areas (less than 48 ft^2 [4.5 m^2] at times), access floor tiles should be selected for their options in number, size and location of penetrations.

Finally, the raised floor materials can be significant for their contribution to thermal mass for nighttime or flywheel cooling. Blowing air through the concrete "duct" of a raised floor over a structural slab offers the opportunity for providing 30% of the building cooling load (Shute 1995). Shute clarifies "to realize the benefits of mass storage in a plenum system, pre-cast or concrete filled metal sandwich panels are needed. Lightweight wood core are not suitable." A number of professionals argue that thermal mass can be effective for cooling in an unducted/ plenum underfloor air system, but is "like dancing with an elephant" and requires careful monitoring and control. A number of underfloor air buildings have effectively used plenum underfloor air systems to provide low-energy flywheel cooling to offset refrigerant cooling loads. Lloyds of London, for example, has used nighttime flushing of the plenum for over 16 years, to pre-cool the mass of the floor and the exposed waffle slab ceiling, with fan only or chilled air, for the high rise trading and office building. The pre-cooled mass capacitance in this building can absorb population shifts from 0 to 6,000 people in the space of an hour on the trading floor at opening. The operators of the building, Johnson Controls, keep critical watch on dewpoint temperatures, however, with thermocouples on the underfloor slab ensuring that the slab is never cooled below dewpoint so no condensation is possible (Hartkopf et al 1989b). The possibility of condensation due to high humidity and low temperatures must be avoided in air distribution plenums so that air quality can be ensured. In addition, the concrete slab and floor tile materials should be selected for their material integrity – designed to eliminate outgassing or concrete dust or other pollutant sources in the airstream. Careful cleaning of the construction site, sealing of the slab, and provisions for ongoing maintenance is especially critical in unducted, plenum air supply system types. The ability to easily access the plenum for visual inspection and cleaning, however, is an

A number of professionals argue that thermal mass can be effective for cooling in an unducted/ plenum under floor air system, but is "like dancing with an elephant" and requires careful monitoring and control.

important benefit of underfloor air systems that is not typically offered by ceiling systems.

3.6 Module and Carpet Tiles

Raised floor tile modules are typically set at 60 cm by 60 cm in metric countries and 2 ft by 2 ft in inch-pound countries. Given building structural dimensions and the weight of the individual tiles, there will probably be little variation in raised floor modules. If workstation sizes continue to get smaller, however, there may be a need for access floor tiles to get smaller as well, since partitions and storage elements may make opening and relocating floor tiles more difficult. As previously described, the modular options for penetrating each floor tile do vary (from 1-4 punch-out locations of differing sizes), and will be significant for infrastructure flexibility to match spatial dynamics.

The dimensions of the carpet tile should be equal to the access floor tiles, whether located directly on top of the tile or at a 50% offset.

At the same time, carpet tile modules and connections to the floor tile must be selected for ease of reconfiguring HVAC and networking interfaces for the dynamic workplace. Carpet tiles are a critical part of the underfloor air system, and should be selected for their appearance, maintainability, life cycle, and their recognition of indoor air quality and sustainability concerns. The dimensions of the carpet tile should be equal to the access floor tiles, whether located directly on top of the tile or at a 50% offset. Whether offset or super-imposed, carpet tiles should be the same dimension as the access floor tiles to support ease of relocating diffusers and outlet boxes in the dynamic office without carpet waste. Some manufacturers and engineers prefer a 50% offset of carpet tiles to cover the joints in the access floor for both smoothness of walking surface and tighter plenums. In that case, since four carpet tiles must be lifted to move or open one floor tile, the benefits of the offset may not be adequate to offset the inconvenience.

The carpet tile must be attached to the raised floor in such a way to ensure access to the underfloor infrastructures. A choice between "dimpled weights" that position the tile, a light and benign adhesive on every tile, or frames of adhesive that keep the remaining tiles in place by friction – all seem to be equally popular. Carpet tiles that are permanently adhered to the floor tile should not be pursued because of the inability to easily replace and recycle the surface materials.

3.7 "The Plenum Real Estate Challenge"- Systems Integration

Some of the worst examples of non-collaborative design/engineering may be above the ceilings in American buildings. Between three and five feet (1 to 1.5 meters) of plenum space is dedicated to linear, non-integrated decision-making, guaranteeing poor access, poor flexibility, and in most cases poor performance. Systems are totally idiosyncratic, tangled, and designed to serve a specific floor plan at a specific point in time - quickly obsolete. As a result, air quality and thermal complaints abound. The density of service nodes (air diffusers, controllers, outlet boxes, lights) is entirely inadequate for the occupant and equipment densities common in today's workplace. Moreover, abandoned wiring in plenums and slabs has made many U.S. buildings a greater potential source of copper than copper mines.

A number of advanced buildings today demonstrate that floor-based servicing may more effectively support the dynamic workplace. Since the intention is to deliver networking, ventilation and thermal conditioning to each workstation, services at floor level or at desktop offer a greater ease of reconfiguration (York 1993). In addition, electrical and telecommunication cabling and outlet density can be continuously updated to meet changing needs.

Whether the building infrastructure plenum is above the ceiling or under the floor, the necessity for better systems integration to ensure the long-term performance of the system in dynamic work environments is critical. The Center for Building Performance and Diagnostics (CBPD) argues that a critical step should be introduced early in the design process – entitled "the plenum real estate challenge." This one-day design charrette would require the presence of all disciplines who have components they intend to introduce into the plenum and its surface interfaces:

1) HVAC supply and return ducts, zone boxes, diffusers, sensor/controllers
   HVAC piping, terminal units; separation of ventilation and thermal conditioning
2) Lighting conduit, fixtures, controllers
3) Data, power, voice conduit, trays/baskets, poles/partitions, and boxes
4) Fire piping, pressure valves, sprinklers, sensors/ controllers, smoke separations
5) Structural components, columns, beams, trusses, openings
6) Flooring components
7) Ceiling components and acoustic materials

The challenge is for each of these disciplinary experts to bring the physical components that they intend to introduce – 3-dimensional elements, not line drawings and specs – to ensure full debate about the cross-sectional integration and the surface integration of all building systems. The maximum performance of each system should be sought with first cost, constructability, life cycle maintenance and reconfigurability as the added value of the systems integration effort.

To the benefit of overall performance, underfloor air (UFA) infrastructures have been forced to initiate these collaborative design efforts in an effort to keep down plenum heights while maintaining the maximum choice in locating diffusers and outlet boxes without hitting underfloor distribution system infrastructure. Today, a number of industry partnerships (Tate/ York/ Honeywell and InterfaceAR/ Titus/ Carrier) have formed to offer collaborative solutions to flexible infrastructures - floors, data/voice, power, thermal conditioning and ventilation. Moreover, with these modular, floor-based services, the ceiling can become more playful and elegant - as a light and acoustic diffuser - defining working groups, 'neighborhoods' and landmarks.

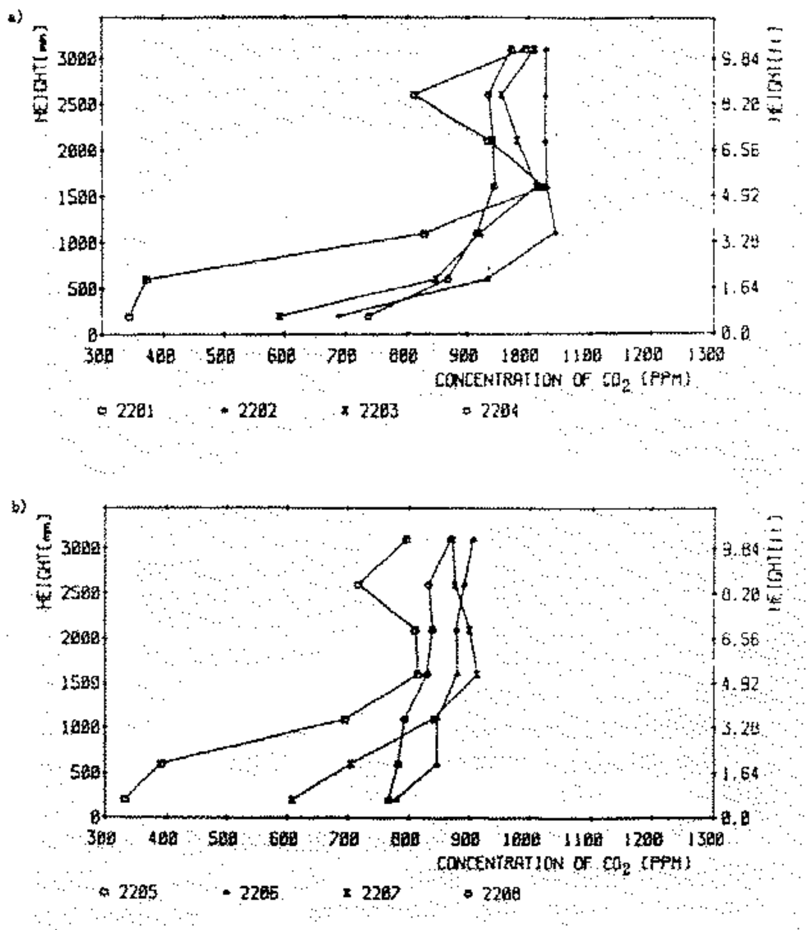
Flexible and adaptive HVAC systems assume that diffuser locations and densities will undergo continuous change and will need to anticipate significant variations in thermal conditioning loads. In addition, floor and desk based HVAC systems introduce air very close to the building occupants and rely on thermal buoyancy and stratification for effective conditioning, requiring careful design for ensuring thermal comfort and the use of stratification.

4.1 Diffuser Locations – Floor, Desk, Partition, Ceiling

Flexible and adaptive HVAC systems have employed a wide range of locations for the terminal units, from floor to freestanding to desk to partition to ceiling locations (see Figures 4.1-4.26). The most significant debate of the last few years has been the performance advantage of floor and desktop supply air locations over conventional ceiling based systems.

The specifications of the diffusers in flexible and adaptive HVAC systems will be very important, as will material performance specifications and systems integration.

A wide range of authors from Sweden, Germany, Japan, and the U.S. have data revealing the improved thermal and air quality performance of floor and desktop (task) air supply locations over ceiling task-ambient system locations (see Performance Gains Chapter 9). Fitzner (Fitzner 1980) argues that the concentration level of contaminants in the occupied zone is lower with an underfloor and desk (upward flow) air supply than with an overhead (downward flow) air supply. Experimental studies demonstrate that upward flow ventilation systems continually purge contaminants from the occupied zone to the stratified zone above head level, where they can be extracted by the return air system and filtered (Figure 4.27). Kim and Homma (Kim and Homma 1992) demonstrate that ventilation requirements could actually be reduced with an upward ventilation system (to about 11.8 cfm per person (5.6 l/s)), without exceeding CO_2 concentrations of 1000 ppm in the breathing zone of a traditional system. CBE and LBNL researchers also found that floor-based supply air, with the air stream directed towards the occupant, typically yielded an age of air at the occupant's breathing level that was 15-25% younger than the age at breathing-level locations with ceiling air diffusers (Bauman et. al. 1991, Fisk et. al. 1991a).



Vertical distribution of CO_2 concentration at the end of occupancy (T = 60 min).
(a) Ventilation rate of 23.5 cfm (11.1 L/s)
(b) Ventilation rate of 35.3 cfm (16.7 L/s)

Figure 4.27: Vertical distribution of CO_2 concentration with upward flow ventilation (Kim and Homma, 1992).

Now the question remains; what are the variations in diffuser design criteria that should be applied to maximize performance in each of these locations for flexible and adaptive systems – floor, desk, wall and ceiling? The following section clearly illustrates that design guidelines are emerging for floor diffusers, but that diffuser design for desk, partition and ceiling-based flexible and adaptive systems need to be fully evaluated.

Floor: Passive Swirl Diffusers

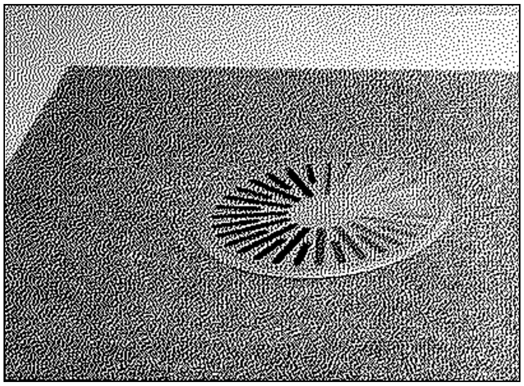


Figure 4.1

Kranz Komponenten –
Floor Twist Outlet

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

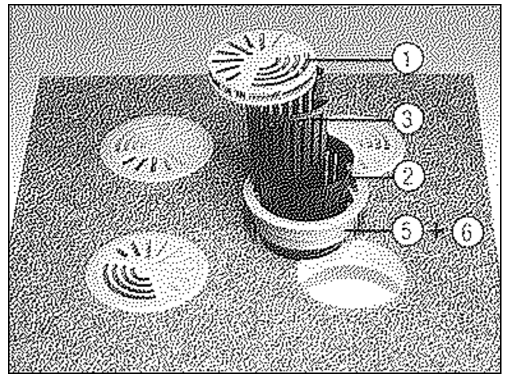


Figure 4.2

Kranz Komponenten –
Rotary Floor Twist Outlet

user control of:

- ● location and density
- ● air direction
- ● air volume
- ○ air speed
- ○ air temperature

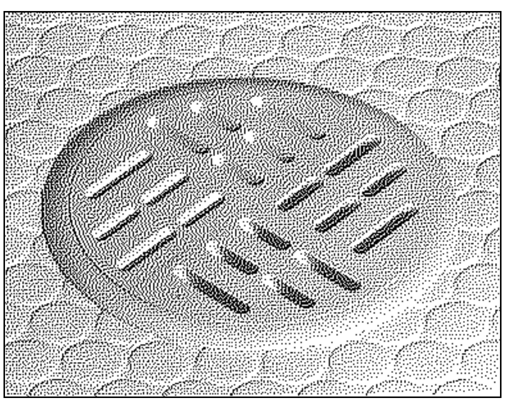


Figure 4.3

LTG Air Engineering–
BLA Air Diffuser

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

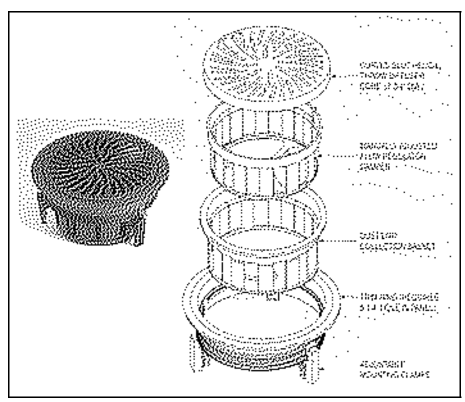


Figure 4.4

Tate Access Floors Inc. –
Tate Diffuser

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

Floor: Passive Swirl Diffusers cont.

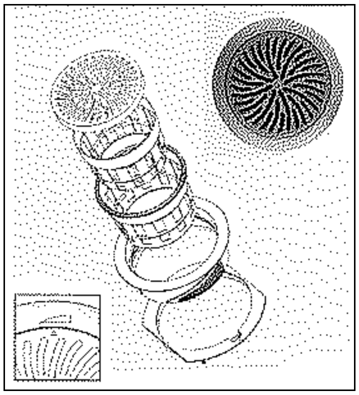


Figure 4.5

Titus –
TAF-R Diffuser

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

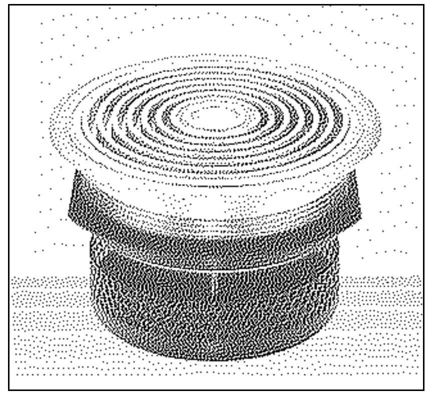


Figure 4.6

Trox Technik –
FB Series Floor Diffusers

user control of:

- ● location and density
- ● air direction
- ● air volume
- ○ air speed
- ○ air temperature

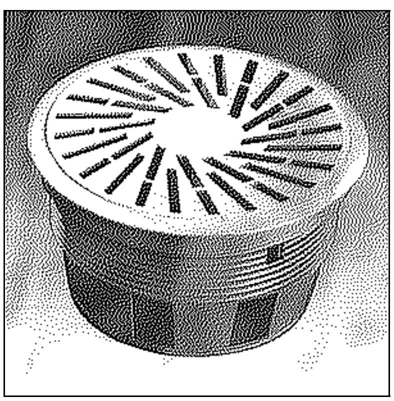


Figure 4.7

Waterloo Air Management–
WFO Aircell Floor Diffuser

user control of:

- ● location and density
- ● air direction
- ● air volume
- ○ air speed
- ○ air temperature

Floor: Passive Vertical Flow Diffusers

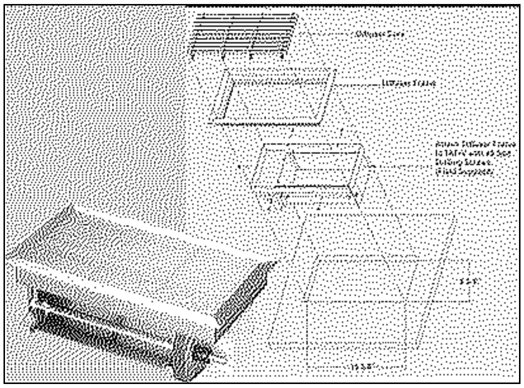


Figure 4.8

Titus–
TAF-V Diffuser

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

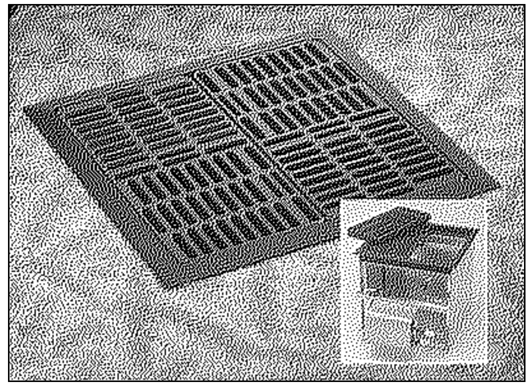


Figure 4.9

York International –
Modular Integrated Terminal (MIT)

user control of:

- ● location and density
- ● air direction
- ● air volume
- ○ air speed
- ● air temperature

Floor: Passive Swirl & Vertical Flow Diffuser

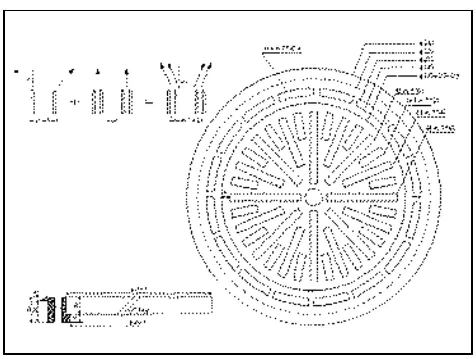


Figure 4.10

Experimental Diffuser –
Kim et. al. 2001, Thermal/ Flow Control
Research Center, Korea Inst. Of Science and Technology

user control of:

- ● location and density
- ● air direction
- ● air volume
- ○ air speed
- ○ air temperature

Floor: Passive Displacement Diffusers

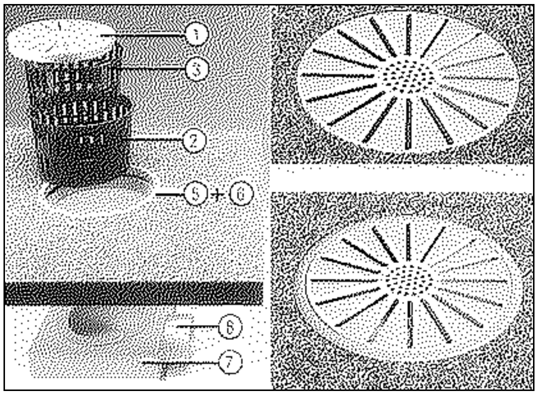


Figure 4.11

Kranz Komponenten –
Floor Displacement Outlet

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

Figure 4.12

LTG Air Enginnering –
BLQ Series

user control of:

- ● location and density
- ○ air direction
- ○ air volume
- ○ air speed
- ○ air temperature

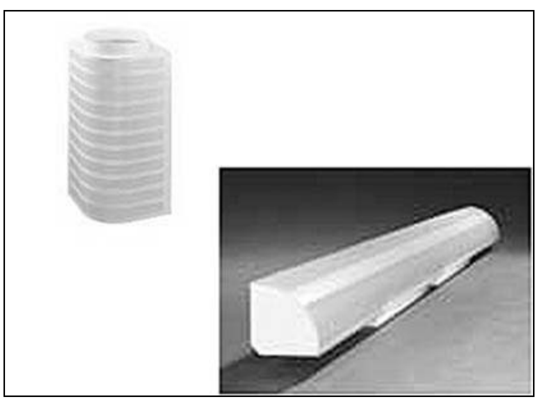


Figure 4.13

Trox Technik–
Displacement Flow Diffusers

user control of:

- ○ location and density
- ○ air direction
- ○ air volume
- ○ air speed
- ○ air temperature

Floor: Fan Diffusers

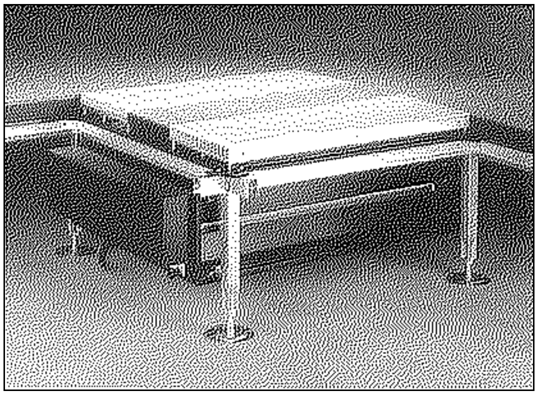


Figure 4.14

Advanced Ergonomic Technologies –
Floor Terminal Unit (FTU)

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ● air speed
- ● air temperature

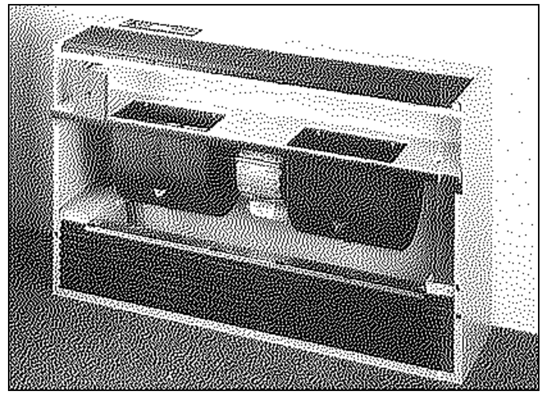


Figure 4.15

Advanced Ergonomic Technologies –
Console Terminal Unit (CTU)

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ● air speed
- ● air temperature

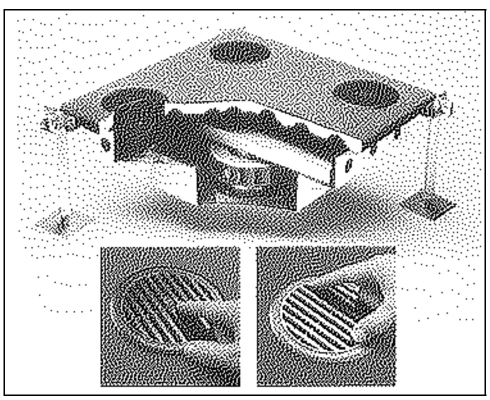


Figure 4.16

Tate Access Floors Inc –
Task Air Module^{TM}

user control of:

- ● location and density
- ● air direction
- ● air volume
- ● air speed
- ○ air temperature

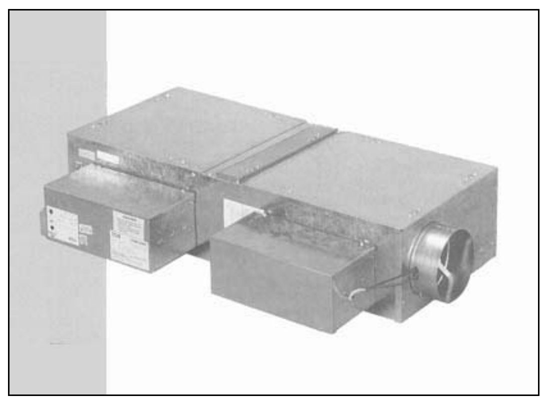


Figure 4.17

Titus –
Fan Powered Box (to supply diffusers)

user control of:

- ○ location and density
- ○ air direction
- ● air volume
- ● air speed
- ○ air temperature

Floor: Fan Diffusers cont.

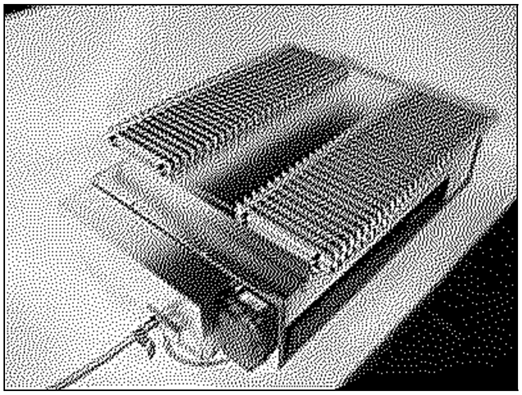


Figure 4.18

WM Protek AB–
RAG Unit

user control of:

- ● location and density
- ○ air direction
- ● air volume
- ● air speed
- ● air temperature

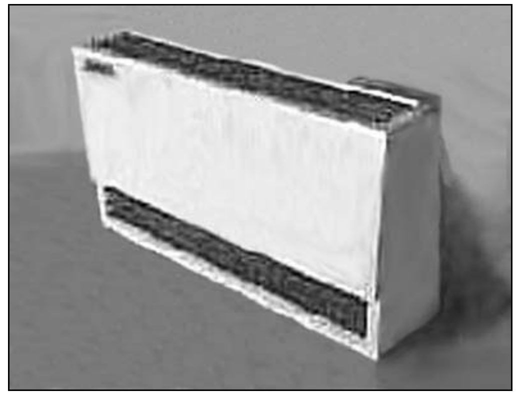


Figure 4.19

WM Protek AB–
RAS Unit

user control of:

- ○ location and density
- ○ air direction
- ● air volume
- ● air speed
- ● air temperature

Task/Desk Diffusers

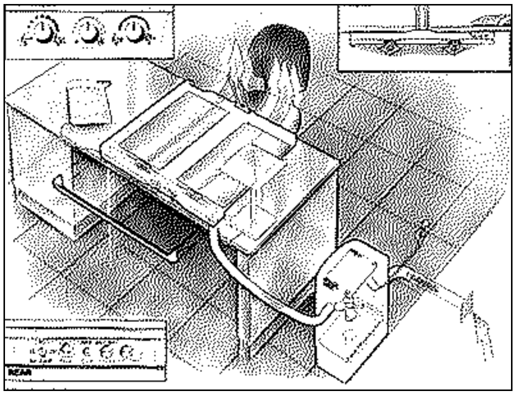


Figure 4.20

Advanced Ergonomic Technologies–
Mikroklimat Climadesk

user control of:

- ● location and density
- ● air direction
- ● air volume
- ● air speed
- ● air temperature

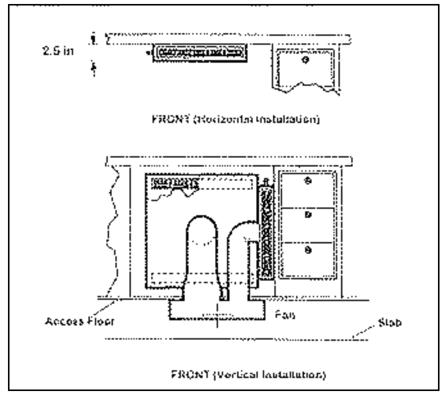


Figure 4.21

Argon Corporation –
Argon Personal Air Control System (APACS)

user control of:

- ● location and density
- ● air direction
- ● air volume
- ● air speed
- ○ air temperature

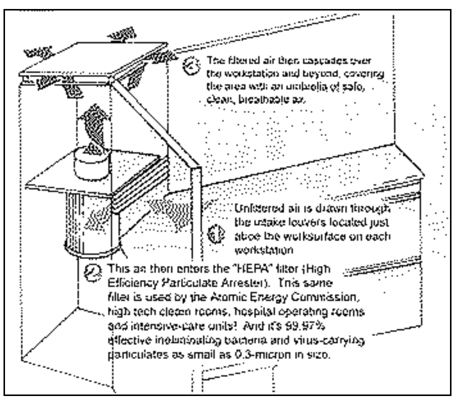


Figure 4.22

CenterCore –
Airflow 2000™

user control of:

- ○ location and density
- ○ air direction
- ○ air volume
- ○ air speed
- ○ air temperature

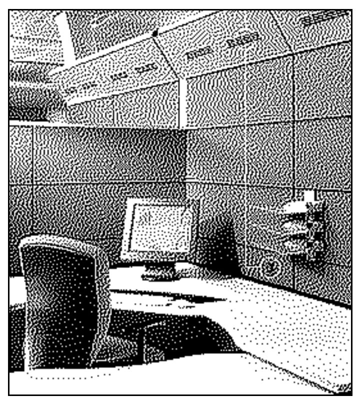


Figure 4.23

Inscape –
Platform Airstream™ HVAC System

user control of:

- ○ location and density
- ○ air direction
- ● air volume
- ○ air speed
- ○ air temperature

Task/Desk Diffusers cont.

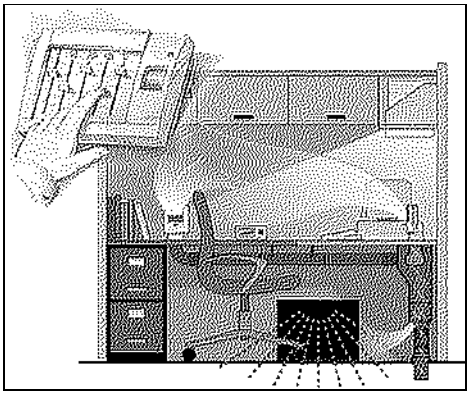


Figure 4.24

Johnson Controls, Inc. –
Personal Environmental Module (PEM)

user control of:

- ● location and density
- ● air direction
- ● air volume
- ● air speed
- ● air temperature

Flexible Ceiling Diffusers

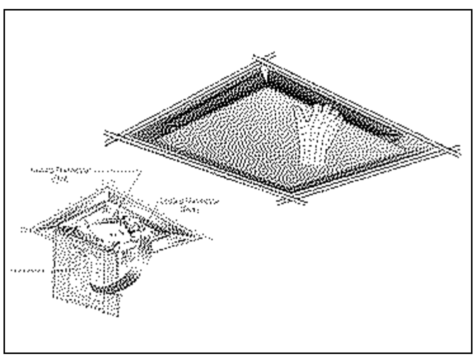


Figure 4.25

Acutherm™–
Therma-Fuser modular VAV system

user control of:

- ○ location and density
- ○ air direction
- ○ air volume
- ○ air speed
- ○ air temperature

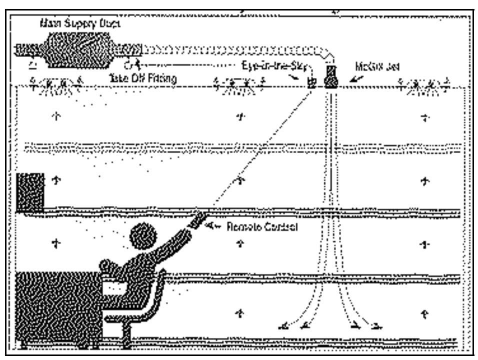


Figure 4.26

Zero Complaint System –
Zero Complaint Air Conditioning

user control of:

- ○ location and density
- ○ air direction
- ● air volume
- ● air speed
- ● air temperature

4.2 Floor Diffusers - Swirl vs. Linear/ Jet Diffusers

Most practitioners and researchers argue that a key to a successful underfloor air (UFA) system is the ability of the diffuser to rapidly mix room air into the supply air - at low velocities close to the floor - to ensure occupant comfort and to ensure the energy benefits of thermally stratified layers of air. To ensure effective thermal mixing and maintain stratification for energy conservation, swirl diffusers are preferable to jet diffusers for the turbulent mixed flow of supply air and room air in under floor air systems.

To ensure effective thermal mixing and maintain stratification for energy conservation, swirl diffusers are preferable to jet diffusers for the turbulent mixed flow of supply air and room air in under floor air systems.

Dan Int-Hout (Int-Hout 2000) further clarifies the value of swirl diffusers for providing the greatest occupant comfort by slowing the supply air down to 0.25 m/s (50 fpm) and warming it up to 23^{o}C (75^{o}F) as close to the diffuser face as possible. In his words, "A typical access floor diffuser should reach the 0.25 m/s (50 fpm) maximum air motion for cooling and the 23^{o}C point within 0.3 to 0.6 m (1-2 ft) from the center of the diffuser (to ensure useable floor space without discomfort). An increase from a 0.6 m radius to a 1.2 m radius decreases the usable space by almost 3.5m^2 per diffuser. The conventional wisdom is that diffusers should project air jet no further than 1.8 m (6') into the space, thus creating a stratification zone at the ceiling. In order for this to happen, rapid mixing is required, and a swirl pattern has been shown to be the best way to achieve this."

While a majority of the diffuser manufacturers (Kranz, LTG, Tate, Titus, Trox, Waterloo) offer swirl or twist diffusers predominantly, a few manufacturers (Titus, York) promote vertical flow or directional diffusers. Moog and Sodec (Moog and Sodec 1978) state that, "From the twist outlets with a higher degree of turbulence, a more intensive inductive effect of the outdoor air is better distributed into the occupied zone; the air jet is stable and less sensitive to cross-convections."

Hanzawa and Nagasawa (Hanzawa and Nagasawa 1990) characterize the preferred diffuser design specification: a highly turbulent mixing action, high rate of induction for high entrainment of air jet from the outlet, limited angle of spreading of the air jet, and a swirl diffusion pattern with movable vanes and dampers to minimize draft conditions. They conclude, "Swirl diffusers at the feet resulted in the lowest perception of draft with Ambient Temperature (AT) and Mean Radiant Temperature (MRT) at 26^{o}C."

With induction diffusers and swirl distribution, up to 100 cfm can be supplied per diffuser, especially with the larger 8" diffuser. Otherwise, between 25-75 cfm would be maximum allowable and greater diffuser densities would be required.

McCarry (McCarry 2001) and McGregor (McGregor 2001) strongly prefer swirl diffusers, which can support 100 cfm of cooling per diffuser without breaking through the stratified air layer above the occupant's head. With induction diffusers and swirl distribution, up to 100 cfm can be supplied per diffuser, especially with the larger 8" diffuser. Otherwise, between 25-75 cfm would be maximum allowable and greater diffuser densities would be required. With linear or jet diffusers, they argue that a maximum allowable air speed would be 25-75 cfm per diffuser- to avoid drafts and destratification - and greater diffuser densities would be required.

On the other hand, one reference proposed a low lateral air diffusion pattern, as opposed to the tight vertical jet or swirl diffusion patterns, as the best for ventilation effectiveness and thermal comfort, and a number of manufacturers offer linear and jet diffusers for UFA systems. To ensure thermal comfort in variable heating and cooling conditions, the York MIT™ terminal unit, which does not employ swirl diffusers, has diffuser grills that can be reconfigured in 16 air flow patterns from straight up to a 360^{o} flare.

A Korean team (Kim et. al 2001) has recently completed a study of a prototype diffuser that incorporates both a swirl flow and a vertical flow component (Figure 4.10). They found that, "In underfloor air systems…supply conditions (i.e. flow direction and swirl strength) need to be controlled for each condition (heating and cooling seasons)… it is advantageous to increase the discharge angle and swirl strength during heating. On the other hand, it is advantageous to supply air vertically during the cooling period." "If the edge section is fully closed, swirl strength and the discharge angle will be maximum. If the edge section is open, swirl strength and the discharge angle will be minimum."

Diffuser slots should be inclined to effectively diffuse the air and generate a swirl for induction, with an industry preference of a 36 to 38 degree incline from the vertical.

The team further concludes that diffuser slots should be inclined to effectively diffuse the air and generate a swirl for induction, with an industry preference of a 36 to 38 degree incline from the vertical (37.5 degree for the experimental diffuser). They assume that air velocities must be less than 0.2 m/s to avoid drafts, with low velocity swirl diffusers inducing room air to allow a large volumetric flow of air and keep foot to head temperature differences at less than 3^{o}C.

There appears to be no variation in floor diffuser designs for ducted as opposed to open plenum air supply systems. The assumption that ducted pressures will be similar to plenum pressures of less than 0.3 inWG seems to drive the diffuser design and the control options. Further study is definitely needed in relation to the configuration of the diffuser airflow patterns and mixing effectiveness at different thermal loads. Standards are needed to ensure that maximum air velocities and minimum temperatures are related to mixing and plume dimensions. In addition, the ability of the various diffusers to maintain the energy benefits of stratified air must be evaluated. Webster (Webster et. al. 2000) states, "Anecdotal accounts from designers indicate that floor diffuser performance has a significant impact on the amount of stratification achieved. In general, there is a dearth of information that verifies the stratification performance of various diffusers under different load conditions. Diffuser performance should be carefully analyzed when systems are designed."

4.3 Displacement Flow Floor Diffusers

It is again critical to distinguish between underfloor air (UFA) systems that are designed to ensure thermal conditioning and ventilation and pure displacement ventilation (DV) systems. Diffuser design for displacement airflow assumes lower velocities and lower temperature differentials, with apparently less importance placed on turbulent mixed flow.

While Fisk et. al. (Fisk et. al.1991a) argue that the mixing/swirl diffusers will act as effective displacement diffusers at the minimum airflows of 10-30 cfm (4-15 L/s), most manufacturers have dedicated diffuser designs for displacement ventilation. These diffusers vary from the mixing/swirl diffusers to include diffusers that have only 1/4 to 1/2 of the aperture area, to grill diffusers in the floor or wall plinth that are ducted for ensuring maximum air quality (see Figures 4.11-4.13). The critical factor is ensuring the widespread introduction of conditioned breathing air at the floor level, relying on the natural thermal plumes surrounding occupants and equipment to carry the required ventilation to a uniformly spaced ceiling return air system. According to Yuan et al. (Yuan et al. 1999b),

“The air velocity in the room with displacement ventilation is generally small – less then 40 fpm except in the thermal plumes and the flow near the floor and walls.”

4.4 Fan-Air Floor Diffusers

At least three manufacturers – AET-FSS, Protek, and Tate – market fan air diffusers for floor based HVAC, in addition to all of the desk and partition fan systems to be discussed later. Many of the engineers interviewed rely on these fan air diffusers to increase the delivery of ventilation air and cooling to conference rooms, replacing passive diffusers with floor tiles that incorporate the fan diffusers. AET-FSS and Protek also offer a standing fan air diffuser with potential for additional cooling or heating elements for local zone control of thermal conditions. The advantages of a “pull” underfloor air system with neutral or zero pressure plenums as compared to the “push” underfloor air has not been adequately studied – neither for thermal, ventilation, maintenance, user satisfaction or air quality. The additional cost of fan air diffusers over passive diffusers and the perception of maintenance and noise issues may have led most manufacturers and engineers away from the potential advantages of fan air diffusers (Shute 2001).

4.5 Floor Diffusers - Size, Volume, and Air Velocities

Most of the references argued strongly that fpm (speed) face velocities and cfm (volume) of air delivery must be controlled with floor air diffusers – to ensure thermal comfort of the occupants. Int-Hout (Int-Hout 2000) states, the optimum design speed for underfloor air is “38-47 L/s (80-100 cfm) when a 5.5^{o}C (10^{o}F) room/supply differential is used. At this point, the noise is negligible and the pressure required is less than 25 Pa (0.1 inWG).”

The optimum design speed for underfloor air is “38-47 L/s (80-100 cfm) when a 5.5^{o}C (10^{o}F) room/supply differential is used. At this point, the noise is negligible and the pressure required is less than 25 Pa (0.1 inWG).”

In addition, Int-Hout (Int-Hout 2000) argues that the distribution pattern or throw should be less than 6 ft (1.8 m). Testing shows that there is 100% mixing in the occupied zone under these conditions. Yuan et. al. (Yuan et al. 1999b) also state that for displacement ventilation systems, “The supply air velocity has an upper limit to avoid draft… with a maximum face velocity for a diffuser set at 40 fpm (0.2 m/s).”

Clearly, the mixing properties of the diffuser and the resulting supply air temperature will impact the maximum velocities acceptable to the occupants, although this design criteria does not seem to be clearly set.

Many diffuser manufacturers assume air delivery of 50-150 cfm (23-71 l/s) at 0.05-0.25 in WG (12.5 Pa – 60 Pa) with velocities of 50-150 fpm (0.254 – 0.726 m/sec) depending on diffuser size and mixing capabilities.

Many diffuser manufacturers assume air delivery of 50-150 cfm (23-71 l/s) at 0.05-0.25 in WG (12.5 Pa – 60 Pa) with velocities of 50-150 fpm (0.254 – 0.726 m/sec) depending on diffuser size and mixing capabilities. While passive or active dampers allow for the airflow to vary from a minimum to the maximum of 150 cfm (71 L/s), the cooling and ventilation capability of the diffusers will vary accordingly. Most diffusers have built-in settings for minimum openings to ensure that ventilation loads are met. Alternatively, the designer will need to introduce diffusers for ambient ventilation and thermal conditioning (which cannot be controlled by the end user) in addition to the user-controllable task diffusers.

Surprisingly, there is very little discussion in the literature of diffuser size or percent of aperture and its impact on cooling, ventilation and user satisfaction. Most manufacturers offer 5 – 6 inch floor air diffusers. Several manufacturers offer 8 and 10 in diffusers, and several manufacturers bundle two to four 6 in diffusers into one floor tile. Clearly, the cooling and ventilation capacitance will vary based on diffuser size, as will thermal comfort. Further study of the relationship of diffuser type (swirl, jet), diffuser size, and aperture area is needed in relation to the velocity and temperature of air for effective thermal comfort and air quality.

4.6 Floor Diffusers – Location and Densities

Both the research literature and the professional community provide insights into the appropriate locations and densities of diffusers for UFA systems.

Because drafts are a possibility even with the higher supply air temperatures and low velocities, most of the references argue for diffusers to be at least 2.5 ft (0.8 m) from the occupants. Sodec and Craig (Sodec and Craig 1990) suggest that floor diffusers should be located a minimum distance of 2.5 to 3.3 ft. (0.8 to 1 m) from the individual for outlets of 6 in diameter (150 mm) and 3.3 to 5 ft. (1 to 1.5 m) for outlets of 8 in diameter (200 mm), given diffusers with adequate velocity for cooling at 400-800 fpm or 2-4 m/s (Sodec and Craig 1990). Shute (Shute 1992b) argues for proper placement of the diffusers, generally to the side of the workstation, at 4 ft (1.2 m) from the individual - if the UFA is the primary cooling source. While there are some advantages to user control of air flow direction for direct, convective cooling of their bodies, untrained users must be fully aware of how to modify the direction of the flow (it should be visually apparent).

Diffuser density should be no less than 1-2 per person or 1 per 100 sq.ft (per 10 m2) with diffusers to be at least 2.5 ft (0.8 m) from the occupants. Additional diffusers are required for ambient conditioning of circulation areas.

Case studies and interviews reveal a consistent recommendation that diffuser density should be no less than 1-2 per person or 1 per 100 sq.ft (per 10 m2) with diffusers to be at least 2.5 ft (0.8 m) from the occupants. Additional diffusers are required for ambient conditioning of circulation areas. Diffuser densities in conference rooms and other meeting areas will be even higher to ensure thermal comfort and air quality for the high occupancies, or fan-diffusers will be required. While conference rooms can be effectively conditioned with UFA, additional cooling capacity with fan-coils is often introduced to augment the higher density of diffusers or fan-powered diffusers. There appears to be little comparative study of the impact of diffuser densities on thermal comfort and air quality and there are no published standards available.

4.7 Floor Diffuser Controls - Passive and Active

Controls for UFA systems will be more fully discussed in Chapter 5, including controls for air volume, air direction, air speed, air mixing, filtration, and thermal conditioning (heating and cooling). However, a number of variables will impact the design of the diffuser itself - the air distribution pattern, percent of aperture, velocity, and other characteristics.

The most common control for floor air diffusers is volume control, either passive control by manually closing inlets (through an additional basket in the outer basket) or active control with VAV dampers connected to local thermostats. The importance of this control to thermal comfort must be studied, as well as the impact of volume adjustments on system effectiveness. Again, almost all of the manufacturers have added a minimum setting for volume control to ensure that adequate ventilation air is delivered regardless of thermal demands.

The most significant complaint related to volume control is the illegibility of the control to the end-user. Most open/closed indicators are stamped into the rim of the diffuser, with no way to quickly identify the positions they are in. Active controllers are often even less useful to the end-users, since the driver is typically the building automation system for which the occupant has little if any control.

When fan-powered diffusers are introduced such as Tate's TAM™ or AET's FTU, "individual electronic controls on each supply unit enable the user to select a wide variety of air temperatures by varying the take-up of cooled air from the floor void." (Thomas 1995).

These diffusers also allow the end-user to adjust fan speed while ensuring energy efficiency from the motors and noise/vibration control.

Most of the manufacturers of floor air diffusers incorporate two details for sustained air quality. Diffuser slots are kept to a minimum (7 mm or less) to avoid objects falling or being caught in the slots (Kim et. al. 2001). And a dirt/dust receptacle to collect dust and carpet fibers is included in each floor air diffuser, easily removable for cleaning. Again, the performance of these details, and any requirements for additional details to ensure air quality, should be the subject of study.

Floor diffusers that incorporate coils for thermal conditioning, or electric resistance reheat coils, seem to be manufactured only on demand. The value of these diffuser options to reduce energy loads, increase comfort and air quality, and support far more dynamic workplace designs needs to be fully studied as well as the performance concerns and barriers to their use.

4.8 Floor Diffuser Material Specifications – Strength, Fire, Tightness, Appearance, Noise

The material performance specifications for floor air diffusers could benefit from industry wide standards for strength, fire ratings, tightness, and acceptable noise levels. The manufacturers' literature does identify a number of standard practices:

For strength, floor air diffusers must have psi minimums to bear rolling loads. The size of the diffuser and its location(s) in the floor tile will impact the strength of the assembly and needs to be clearly defined for both high impact polycarbonate diffusers and for the "heavy gauge" extruded or die-cast aluminum diffusers.

For fire resistance, most diffusers have been designed to meet UL 94-5V for flammability and smoke, and/or NFPA 90A. Arguments that the polycarbonate diffusers do not meet smoke standards seem to have disappeared, possibly due to material composition changes.

For air tightness, to avoid pressure loss in the plenum and to prevent dust from entering the plenum, most manufacturers require a gasket ring to ensure compression tightness for air. There appear to be no measurable standards for the assembly.

For appearance, diffusers are often available in colors to match the carpet, and a wide flange ring is provided to cover carpet edges and to prevent the carpet from pulling away from the diffuser.

For noise, most swirl diffusers have set an NC15 – NC20 maximum, while linear diffusers seem to deliver NC20 – NC30. For fan diffusers, no NC targets appear to be set. Again, there are no standards of acceptable maximums for either pressure loss or noise.

4.9 Other Flexible and Adaptive Diffuser Locations – Desks, Partitions, Ceilings

While the majority of flexible and adaptive HVAC systems are underfloor air systems with floor air diffusers, there are three alternative diffuser locations - desks, partitions and ceilings - that will impact diffuser design specifications.

The most significant advantage of floor diffusers for flexible and adaptive systems is the ease of reconfiguration of diffuser locations and densities providing greater spatial planning flexibility (Shute 1992a). In addition, there are major cost savings along with the ease of duct/plenum maintenance to reduce dust and microbial build-up in the air stream of an underfloor system (see Figure 4.28). On the other hand, desk and partition based air supply have benefits as well.

Other advantages to the floor locations for air supply include:

- lower cooling energy consumption due to the convection cooling effectiveness of air flow at higher supply temperatures (potentially as high as 68°F);
- ease of reconfiguration of diffuser locations and densities providing greater spatial planning flexibility (Shute 1992a);
- ease of duct/plenum maintenance to improve reliability and reduce dust and microbial build-up;
- greater flexibility in ceiling design and use; and
- the ability to connect to desk-top diffusers and controllers for individual occupant control of air volume, speed and direction.

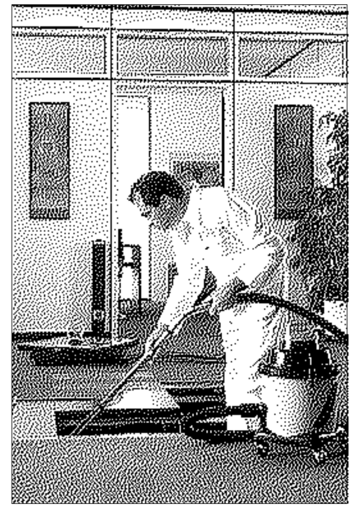


Figure 4.28- Vacuuming the plenum- Advanced Ergonomic Technologies, Flexible Space System (AET-FSS)

4.9.1 Flexible and Adaptive Desk Air Diffusers

Studies by Drake et. al. (Drake et. al. 1991) and Kroner et. al. (Kroner et. al. 1992) show that desktop delivery (Figure 4.6) and control of air are preferred by users and are rated as even more effective than floor air supply locations. A logical explanation of this advantage is shown in the Hanzawa and Nagasawa histogram (Figure 4.29) in which the neck and shoulder region is shown as the most responsive to the feeling of air movement among the various regions of the body (given appropriate temperature and turbulence control to avoid drafts). A study by the Center for the Built Environment (CBE) identified that the face dimensions of the desktop diffusers was critical to thermal comfort, however, in combination with control of air speed and direction (Bauman et. al. 1993). For desktop fan-powered diffusers, 150-180 cfm is possible, however volume, direction, and speed controls should be considered. Larger face dimensions of the desktop air diffusers increase thermal comfort (Bauman et al 1993). Sodec and Craig (Sodec and Craig 1990) state that, “In order to avoid excessive air velocities, no more than 30 cfm (14 L/s) are discharged from the desk outlet. It is only enough to cover the outside air rate. The rest of the supply air volume flow rate (1-1.4 cfm/ft2 or 5-7 L/s/m2 at the perimeter and .6-1 cfm/ft2 or 3-5 L/s/m2 in the core) and is discharged via floor outlets.”

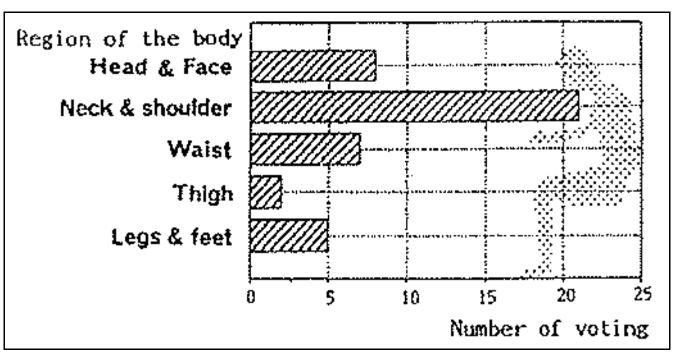


Figure 4.29: Histogram showing the feeling air movement related to region of the body (Hanzawa and Nagasawa 1990).

For desktop fan-powered diffusers, 150-180 cfm is possible, however volume, direction, and speed controls should be considered. Larger face dimensions of the desktop air diffusers increase thermal comfort (Bauman et al 1993).

Studies need to be completed that verify the need for two diffusers per workstation (one per work surface), and whether relocation is required so that desktop computers and open work areas can be reconfigured. At one point in time, the VOKO furniture company had developed desk legs that acted as duct distribution options for desk-based air. Today, most hollow legs are engineered for data and power distribution, although the option of duct and diffuser integration into desks is still a possibility.

Agreeing with the advantages of desktop delivery, David Wyon (Wyon 1991) cautions, however, that the height adjustment of desktop air supply is critical, since air flow towards the eyes may render the eye unable to cope with airborne irritants such as dust, gases, or chemical vapors. Moreover, Wyon argues that the most effective convection cooling is achieved not at the chest but at waist height, resulting in the development of the Climadesk system (Figure 4.20), as well as the Argon desk air diffusers (Figure 4.21). Both of these diffusers are created by integrating a channel under the work surface and creating a linear diffuser along the front edge of the desk. These diffusers also have volume, vertical direction (not horizontal) and speed controls for the end user.

One significant advantage of desktop air supply is the ability to "float" ambient temperatures in the office space within a broad temperature band while providing task air temperatures in the workstation to meet ASHRAE comfort standards. The split ambient and task conditions offer considerable energy savings over the conventional ceiling delivery of uniform task-ambient environments, while achieving higher comfort ratings from the user. Given large variations in percent of occupancy over the day, these split task and ambient systems offer significant savings in operating costs (see Figure 4.30).

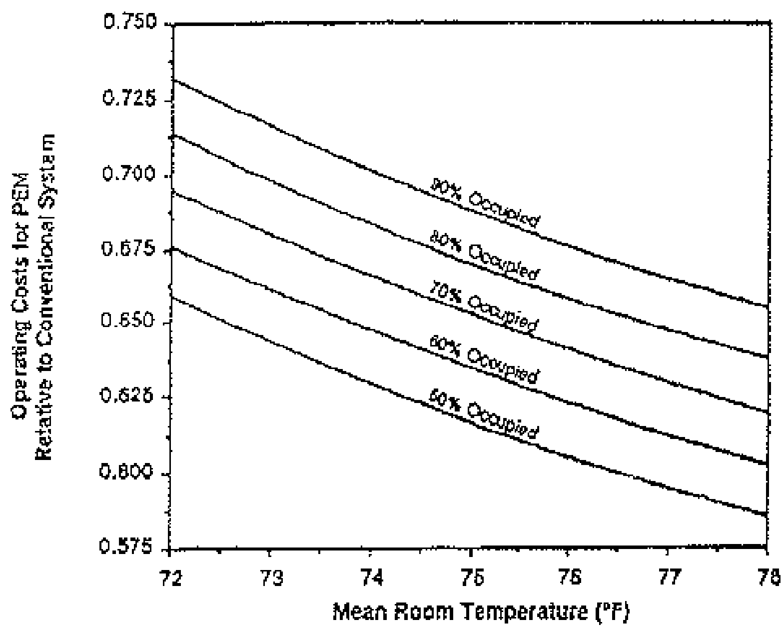


Figure 4.30: Operating costs for Personal Environmental Module (PEM) for various occupancies (Drake et. al. 1991).

Increases in occupant comfort and environmental satisfaction have also been shown to translate into productivity dollar savings, as shown in the Kroner/Westbend study, where the disassembling of the desktop task air systems (PEM^{TM} from Johnson Controls) resulted in a measurable loss of 2% productivity in an insurance company (Figure 4.31).

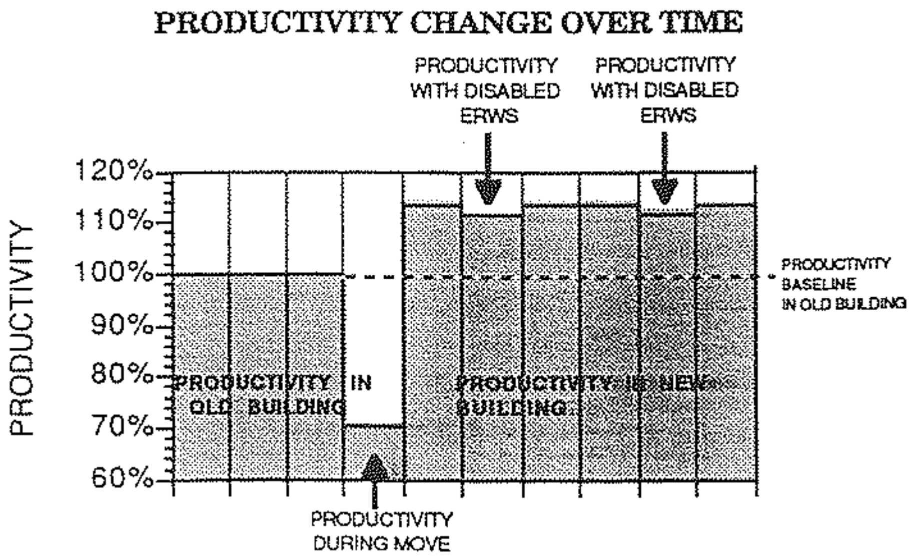


Figure 4.31- A study at the West Bend Mutual Insurance Headquarters shows that the disassembling of the desktop task air systems resulted in a measurable loss of 2% productivity (Kroner et al 1992).

A second significant advantage of desktop air supply is the ability to introduce significant mixing temperature control for the end user, as well as local filtration. With the fan units above the floor line, room air can be pulled into a mixing box and through single, double or triple filters (particle, carbon/VOC and even UV filtration). Recent developments in floor boxes may also allow for mixing room air with primary air. This allows the task air systems to improve air quality and thermal comfort, as demonstrated in the PEM^{TM} studies identified in the performance gains chapter.

4.9.2 Flexible and Adaptive Wall/Partition Air Diffusers

Several manufacturers have integrated ducts and diffusers into workstation partitions, either to bring air from a ceiling diffuser or an underfloor plenum. The Centercore Airflow 2000 system (Figure 4.22) utilizes a central duct/post to bring primary air to a mixing box for each desk with volume, fan speed, and horizontal directional controls. The most recent Inscape AirStream system utilizes a partition top duct and linear diffuser with volume controls from 0-45 cfm (22.5 L/s) for the end user – as an extension of the building's HVAC system (Figure 4.32).

The conclusions of the Hanzawa and Nagasawa study, however, state that the neck and shoulder regions are the second most critical areas affected by drafts after the head and face, even at 19.4 m/s (Hanzawa and Nagasawa 1990). It is important to have these wall/partition air diffusers studied for comparative performance, given maximum air speeds, minimum temperatures and variations in user control (volume, speed, horizontal and vertical directional control, mixing).

4.9.3 Flexible and Adaptive Ceiling Air Diffusers

While underfloor air systems will eliminate the need for drop ceilings to house HVAC infrastructures and allow for higher, more articulated ceiling forms, many building projects will have to continue to rely on ceiling based infrastructures. In addition to the use of walls or partitions to bring ceiling air down to the workstation, the ceiling HVAC system can be designed to support relocatable supply and return diffusers. Three manufacturers have pursued ceiling based air distribution systems that can support the "flexible-grid, flexible-density, and flexible closure" approaches to servicing needed for the dynamic workplace.

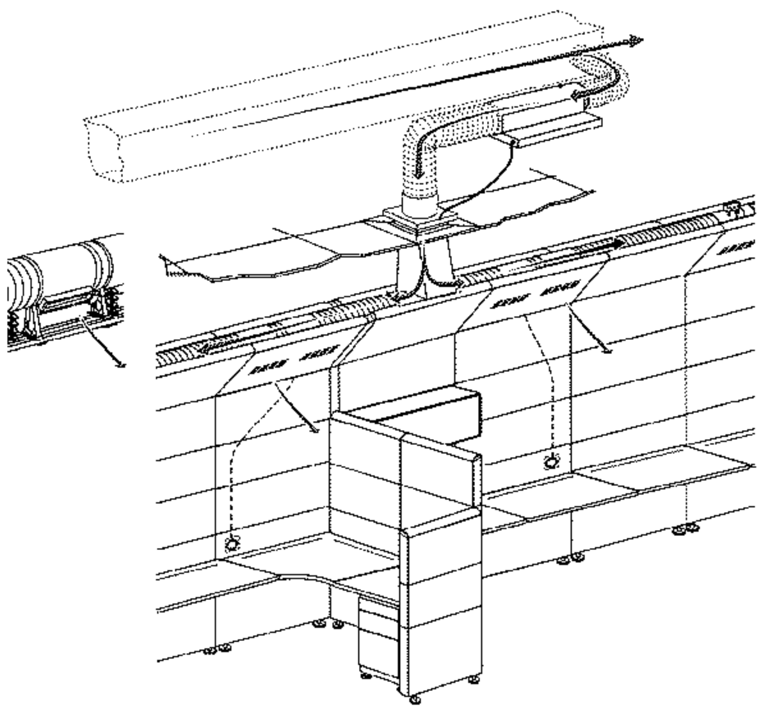


Figure 4.32- Inscape Airstream desk-based system.

In the U.S., Acutherm™ has developed a dual duct approach that brings a small 100% outside air ventilation duct and a large cooling air duct as a grid of service to each floor area, and utilizes flexi-duct connections and local mixing box diffusers to provide for both individualized ventilation and thermal conditioning needs. Both the density and the location of diffusers in the ceiling can be modified on demand, and users can change the mix of primary and return air (see Figure 4.25). In addition, Acutherm™ offers controls for automatic airflow redirection dependent on supply air temperature. The TRAV unit, still in development from The Hartman Company, utilizes a mixing box diffuser fed by a constant volume ventilation duct and room air drawn from the ceiling. Infrared controllers allow the end user to vary the mix of primary and room air, as well as vary the direction of the airflow. Directional control is possible because there are minimum fresh air settings, and the provision of at least one diffuser per workstation, such that maintaining workplace airflow distribution patterns are not critical to effective coverage.

In France, Carrier has joined forces with SARI Engineering to develop an individually controllable and relocatable ceiling based air distribution system. By providing a fan-coil unit per person in distributed mechanical rooms, the end user can select the percent of primary air fed to each mechanical room, and the mix of room air, to lower or raise air temperature, or purge the facility. The flexi-ducted diffusers can be relocated as needed to match furniture/wall layouts, and the airflow direction from each diffuser can be modified to maintain effective air distribution during summer and winter seasons without drafts. The Carrier/SARI team continues the development of these fan-coil and flexible diffuser systems to include underfloor options as well as advanced individual filtration capabilities including UV (see Figure 4.33).

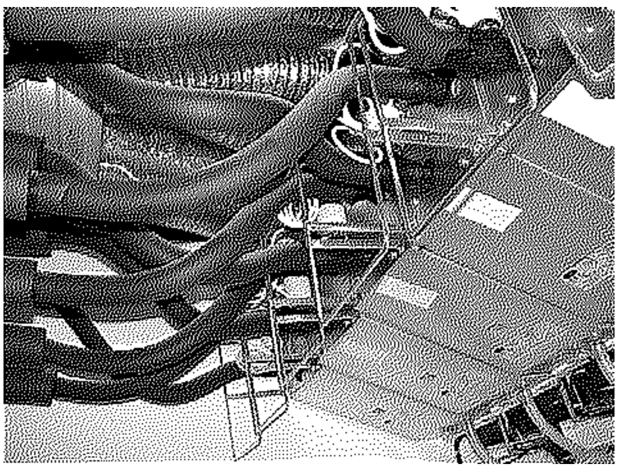


Figure 4.33: Fan coil units used at IBM Paris by the Carrier/SARI team.

The introduction of these diffuser capabilities in ceiling based conditioning constitutes a major opportunity for flexible and adaptive HVAC systems:

1) relocatable diffusers and changeable diffuser densities to match loads and furniture layouts through a duct grid (sized to maximum loads) and “plug and play” nodes/diffusers.
2) Directional control of air flow through operable vanes in overhead diffusers (without shut down).
3) Separate thermal and ventilation ducting with user-based mixing potential for temperature control as well a potential purge cycles.
4) Local filtration – particulate, carbon/VOC, UV with user and central maintenance options.

Ceiling based flexible and adaptive HVAC systems are significantly less developed or tested than UFA systems, and merit further study. The manufacturers of these systems should also be tapped to develop underfloor components for thermal conditioning and ventilation improvements – to enrich the choices and performance of flexible and adaptive HVAC components.

4.10 Return Air Diffusers

There is remarkably little discussion of the importance of the design specifications of the return air system. Int-Hout (Int-Hout 2000) argues that, “The return air grilles should be uniformly spaced across the ceiling, as asymmetrical spacing can result in instability of plumes.”

Faulkner et. al. (Faulkner et. al. 1993) argue for return air diffuser densities of no less than one per 300 square feet. Indeed, the density of return air diffusers in the traditional mechanical system configuration for offices, has been even sparser than the density of supply air diffusers. Sweeping recirculating airflows through occupied spaces can result in mixing with locally generated heat and pollution that diminishes ventilation efficiency from the supply air diffusers. Murakami (Murakami 1990) states that a contaminant discharged from a supply air diffuser “would not diffuse widely within the room if the air exhaust (return) opening is installed at the same flow area and air exhaust rate".

Experiments by Murakami et. al. (Murakami et. al. 1992) demonstrate that when supply and exhaust airflow rates are locally balanced, local heat is exhausted before it diffuses into the space. “With return registers located immediately above occupants and equipment, with an increased exhaust air-flow rate, the waste heat and local pollution will be 98% exhausted, with only 2% convected and transported… If exhaust rate is 45% less than supply, room temperature is raised 1-2^{o}C; if exhaust is 25% more, then it is even better if all exhausts are balanced.”

Although these central system modifications may not seem to be user control strategies, the matching of supply and return diffuser densities to occupant and equipment densities is a critical step towards improving environmental quality at the individual workplace, and towards initiating the possibility of individual or local environmental control. Most of the UFA projects identified have return air in the ceiling to maximize the vertical airflow patterns for pollution removal and stratification benefits. Shute suggests that a nominal 12-inch ceiling plenum (300mm) can also provide an effective return air path, conceal sprinkler piping, and provide acoustic control (Shute 1992a). As another variation on return air strategies, the Intelligent Workplace at Carnegie Mellon University introduces an underfloor return air duct with flexi- connections to relocatable return air towers. This system supports laboratory studies of the performance of a completely floor based HVAC system to free the ceiling for light, acoustics and spatial interest (see Figure 4.34). Again, the sizing, density and location of return air diffusers and the duct/plenums they feed should be the subject of field, laboratory and simulation study to identify the importance of these specifications to the performance of flexible and adaptive systems.

Figure 4.34: The density of return air diffusers and their location directly overhead is key to indoor environmental quality and energy efficiency. In the Intelligent Workplace, return air columns allow the floor to be the sole HVAC distribution layer.

5.1 Level of Control in Flexible and Adaptive Systems

In the past, ambient and task provisions for thermal comfort and air quality have typically been combined in all-air systems. The assurance of appropriate zone controls for both thermal comfort and air quality have relied on a finalized floor plan indicating occupant densities and closed space allocations to ensure that variations in thermal and ventilation loads would be met. Ducting layouts and diffuser densities and locations are typically fixed, with the assignment of thermal zone sensors and controllers preset in relation to layout. In open office spaces, a fixed grid of diffusers, evenly distributed across the ceiling in a fixed density, attempts to service the dynamic configurations of occupants and equipment. However, the significant level of dissatisfaction with high or low temperature conditions, air freshness, air movement, and drafts in both open office workstations and shared closed spaces such as conference rooms (IFMA 1991, Loftness et. al. 1995), must be attributed to a number of factors:

1) Over time, a significant mismatch occurs between the original fixed-grid fixed-density supply air configuration and the changing (typically increasing) occupancy and equipment density in the space.

2) Ventilation effectiveness and thermal comfort is further aggravated by the increase in office partitioning for acoustic and visual privacy and fixed locations for work surfaces. In most buildings, the fixed-grid, fixed-density diffuser layout was designed for both much lower occupant densities and a more fully open plan, unencumbered by higher partitions and storage units.

3) Seppänen (Seppänen et. al. 1989) further points out that design rates for the outside air contribution to this supply air are based on flow per floor area, not on the projected density of occupants and equipment. Chiller capacity, duct sizing and diffuser densities for air conditioning are also often designed on a fixed density floor area basis with inadequate capacity and reconfigurability for today's office densities.

Despite these growing concerns about thermal comfort and indoor air quality, the requirements for flexible zoning of commercial buildings have not been increased. Moreover, as building floor plate sizes grow, the number of people housed in a thermal (and thus air quality) zone is growing as well. While advanced office buildings move towards micro-zoning, with an optimum of one zone per workstation, the standard commercial building is moving towards macro-zones with as many as a hundred workstations in a single thermal zone (Figure 5.1).

Underfloor air (UFA) buildings offer the opportunity to provide some level of individual control of thermal and air quality conditions through six strategies (listed from most prevalent to least prevalent at this time: 1) Location and density of diffuser, 2) Volume of airflow, 3) Direction of airflow, 4) Speed of airflow, 5)

Temperature control, and 6) Air Filtration, outside air content & natural conditioning options.

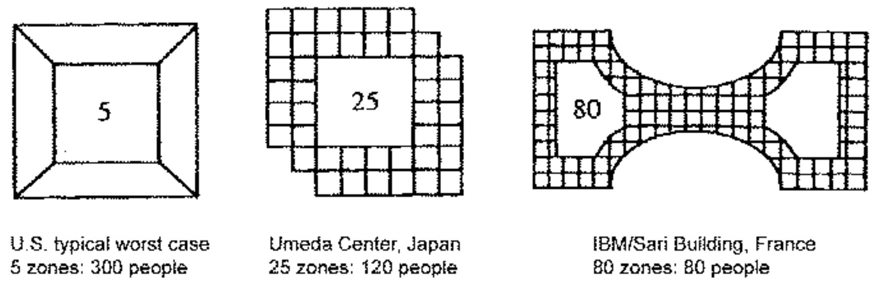


Figure 5.1: Comparison of average HVAC zone sizes per floor.

5.2 Levels of Control in Flexible & Adaptive HVAC

These controls rely on replacing the method of distributing ventilation air through predicted "throw" patterns in a pressurized building by either the separation of a constant volume ventilation system from the thermal conditioning system, or the introduction of relocatable diffusers in each individual workstation. In his chapter on Sustainable Design, David Lehrer (Lehrer 2000) argues that these provisions for "downstream control" will offer improvements in temperature and air quality because, "upstream methods do not easily lend themselves to the addition of new zones, which is likely to be disruptive as well as expensive."

Given the ten or more types of underfloor air terminal units on the market (Figures 4.1– 4.24), the first three levels of control – diffuser location/density, air direction, and air volume – are significantly more prevalent than the next three levels of control – air speed, temperature and outside air control. However, before both first cost and market readiness decide the future of user controls in underfloor air, each of six user control alternatives should be studied in both laboratory and field research as to their cost-benefits for improved human comfort and health, reduced energy and churn/asset costs, as well as in relation to individual and organizational productivity over time.

5.3 User Control of Diffuser Location and Density

Changing the density and location of diffusers is the central strategy of underfloor air (UFA) systems to effectively deliver breathing air and cooling to the range of functions and layouts that occur in the dynamic workplace environment. The ability to relocate diffusers can compensate for the frequent mismatch between diffuser and furniture layouts, and for the comfort differences between cold air and warm air distribution patterns from the same diffuser. The ability to add or subtract diffusers can compensate for the changing loads that occur when more heat-generating equipment is added, when layouts become more dense, or when new teaming spaces are introduced. Moreover, the ability to relocate diffusers is critical to churn cost savings, and all systems should be coordinated to make this possible (carpet, diffusers, tethers, power).

Changing the density and location of diffusers is the central strategy of underfloor air (UFA) systems to effectively deliver breathing air and cooling to the range of functions and layouts that occur in the dynamic workplace environment.

Every UFA installation identified has been designed to fully support continuous changes in the density and location of air diffusers, to match the changing needs of workstation layouts and occupant and equipment densities. Referring to the categories in Chapter 2, in 1) the pressurized, unducted and 2) partially ducted underfloor air systems, the modification of diffuser locations and densities is as simple as relocating the tile in which the diffuser is located. In 3) fully ducted and 6) fan fed partially ducted underfloor air systems, the flexible ducts must have snap connections and multiple tap locations at the underfloor source to allow for changing locations and densities of diffusers. In 4) and 5) unpressurized, suction fan diffusers in the floor or in the desk, the modification of diffuser locations does require local power outlets (underfloor or underdesk) along with the simple relocation of the tile.

Carpet tile selection is also critical to user control of density and location of air diffusers. In all six of these underfloor configurations, the specification of the floor tile and the carpet tile for ease of relocation is critical. Few of the UFA projects match the module of the carpet tile to the access floor tile, either directly set with the floor tile, or 50% offset so that no carpet must be wasted when a diffuser is relocated. Ideally, the weave should be rotatable (parquet pattern) to allow for more fine-tuned choices for relocating the air diffuser (possibly even quadrant options) that is becoming more important as workplaces become smaller and furniture/wall conflicts become more frequent. Finally, the carpet tile's method of adhesion must support ease of reconfigurability, as well as ensure low/no outgassing and ease of maintenance without toxins or waste.

The ability to relocate diffusers is critical to churn cost savings, and all systems should be coordinated to make this possible (carpet, diffusers, tethers, power).

5.4 User Control of Supply Air Volume

Most of the underfloor air diffusers that are manufactured offer manual or automatic volume controls. In passive diffusers, the volume control is usually accomplished by rotating the face of the diffuser which in turn rotates an inside basket in relation to an outside basket increasing or decreasing the volume that is admitted through a series of slots.

A number of the early basket designs had no minimum aperture, so facility managers often removed the inner basket to ensure the delivery of breathing air and avoid excessive shut-down of local air diffusers that might compromise ambient comfort. In these installations, the only control left to the end-user would be diffuser location and density, yet most occupants do not have the tools (tile lifters) or knowledge of the ability to do so.

User controls improve user satisfaction with thermal comfort despite the finding that "a majority of the volume controls of floor air diffusers seem to be set once and left, possibly because of lack of discomfort or lack of awareness (Hedge et. al. 1993).

More recent basket designs do have a minimum open position to ensure ventilation air delivery, but still often have unreadable cues as to whether a diffuser is in a full open or partially closed position. As a consequence, simple aperture readouts and occupant training is critical to the use of volume controls, unless cold draft conditions make occupants desperate enough to learn on their own. At the moment, user controls improve user satisfaction with thermal comfort despite the finding that "a majority of the volume controls of floor air diffusers seem to be set once and left, possibly because of lack of discomfort or lack of awareness (Hedge et. al. 1993)."

However, the authors would argue that this is true for ergonomic chairs as well. Nonetheless, the customization of service to the needs at move in and tenant rollover, and the addition of volume controllers at every diffuser, is a significant improvement over present air distribution options.

Digital volume controls with local thermostats could be a benefit if they do not eliminate individual user control or limit the relocatability of the diffusers.

A few market available diffusers have DDC volume controllers on every diffuser. These diffusers will respond to distributed temperature sensors to open and close dampers, varying the volume of cool air delivered. The strengths of these automated volume control units will be dependent on the density and quality of sensors and the up-to-date management of the building automation software in relation to space use – the same conditions that must be met by ceiling based central VAV systems. The advantage of having volume control on every diffuser is a gain in thermal comfort, but should be offered without compromising the ability of the diffuser to be relocated or manually controlled for individual comfort. Indeed, digital volume controls with local thermostats could be a benefit if they do not eliminate individual user control or limit the relocatability of the diffusers.

5.5 User Control of Supply Air Direction

Many of the floor and all of the desktop air supply systems offer directional control for the user. These controls can be multi-directional in the floor and both horizontal and vertical at the desktop, depending on the manufacturer. In all cases, the directional control is manual, capable of being oriented directly at the occupant for convective cooling, or away from the body for space cooling without drafts. A number of engineers interviewed argued that directional control is a benefit for higher velocity and non-swirl diffusers where supply air streams at 65°F (18.3°C) could be uncomfortable on the lower body. As was stated in Section 4.2, most of the engineers who consistently design underfloor air systems argued strongly for turbulent mixed flow or "swirl" diffusers for floor based systems, which generally do not have directional control, to ensure thermal comfort and air quality.

Directional control is a benefit for higher velocity and non-swirl diffusers where supply air streams at 65°F (18.3°C) could be uncomfortable on the lower body.

Control over the direction of the air supply could provide a less costly alternative to control over air speed/volume as a thermal comfort strategy. Control over airflow direction not only allows for user access to convective cooling (a strategy used in cars), but also allows users to compensate for the comfort differences between summer colder-air and winter warmer-air distribution patterns from the same diffuser. Two concerns emerged in relation to directional controls. First, if air diffuser densities are sparse, the guaranteed delivery of ventilation air could be compromised because of adjustments for thermal comfort. Second, for desktop diffusers, the ability to direct air flow to the face could result in drier eyes. Studies have revealed that air flow around the waist might be the most effective for convective cooling without negative ramifications.

5.6 User Control of Supply Air Speed

By the 1970's, the National Bureau of Standards, Comfort Labs at Kansas State University, the JB Pierce Foundation, and the Danish Comfort Research Institute in Denmark, had already redefined the parameters of thermal comfort to relate effective air temperatures to air speed (Fanger 1973). Unlike ceiling distribution systems, some of the floor and all of the furniture-based air supply systems do provide user control of air speed. The Advanced Ergonomic Technologies Flexible Space System (AET-FSS™) Floor Terminal Units (FTU's) provide speed control. The Tate distributed fan air terminals (TAM™) provides both speed and directional control (without temperature control). The Climadesk™ desktop diffusers also offer speed and directional control, as well as the Johnson Controls PEM™ that provides air speed, multi-directional control, as well as local filtration and temperature control which will be discussed later.

Given that fan speed control will clearly impact volume of air and cooling capacity, user control of air speed can only be offered if the central system has variable speed fans to support changes in pressurization as more users increase or decrease air speed/ quantity. These distributed fans must be carefully selected for quietness as well as ease of relocatability through 'plug-and-play' power connections. Some engineers voice concerns about the maintenance of having a fan at every workstation, but the authors argue that there is already a computer processor fan at every desk with little user or management concern.

5.7 User Control of Supply Air Temperature and Radiant Temperature

Scandinavian studies demonstrate that workers who were able to adjust the temperature in their workplace reported less sick-leave than those who were not (Preller et. al. 1990). Research findings continue to reveal that individual control of temperature by occupants will increase satisfaction and decrease sick building symptoms (Jaakkola et. al. 1989). Even in the comparatively non-demanding Japanese workforce, more than 50% of the occupants desire control over temperature conditions, in addition to air movement and air freshness (ABSIC 1988).

There are at least three strategies for temperature control in underfloor air (UFA) systems: 1) separate thermal conditioning systems from ventilation air, 2) mixing control of cool supply air with warmer room air, and 3) additional water or air-based heating or cooling components.

There are at least three strategies for temperature control in underfloor air (UFA) systems: 1) separate thermal conditioning systems from ventilation air, 2) mixing control of cool supply air with warmer room air, and 3) additional water or air-based heating or cooling components.

The most prevalent example of individual control over supply air temperature is found in separating ventilation air requirements from thermal conditioning. These strategies are widespread in Europe where underfloor displacement ventilation (or ceiling constant volume ventilation) is combined with perimeter thermal conditioning systems such as fan-coil units, heat pumps and induction units. The AET-FSS™ underfloor HVAC system relies on changing numbers and locations of fan-coil units set out on the floor or in closets as needed to support changes in thermal conditioning control zones with re-partitionable underfloor air “zones.” More recently, there are a growing number of radiant ceiling and “cool beam” components that are being combined with underfloor ventilation (and partial cooling) systems - carefully controlled for humidity. In each of these systems, the user can locally set supply air or radiant temperature, either through water flow control or air mixing control.

The mixing of primary ventilation air at cooler temperatures with room air can be accomplished in both floor and desk based systems. Some floor diffusers allow for adjustments in the induction rate for mixed air distribution, which will allow occupants to modify temperature. The Johnson Controls desktop PEM™ unit provides temperature control by enabling individuals to proportionally mix cooled, filtered ventilation air with warmer room air by introducing a mixing box at every desk. In the West Bend Mutual headquarters, the facility manager found that the introduction of these temperature control alternatives, with a maximum band of +/- 2°C has minimized calls to facilities management about overheating and drafts (Kroner et al 1992). Whenever large numbers of individuals are calling for maximum heating or cooling, the central system can respond with modified supply air temperatures. The combination of these workstation thermal conditioning systems (driven by occupancy presence and comfort settings) with ambient thermal systems set to much broader standards of comfort, can yield maximum energy savings to accompany the gains in individual comfort.

A third strategy for delivering individual temperature control is through additional water or air-based thermal conditioning components, beyond the ambient conditioning systems. Many of the underfloor air engineers will introduce local water-based or electric cooling equipment in spaces where additional cooling is required, such as conference rooms and equipment rooms. L.D. Astorino’s PNC Firstside Bank building in Pittsburgh, PA is one of the first UFA projects that combined a ceiling based VAV cooling system with an underfloor air ventilation system. Classified as the 8th approach to underfloor flexible and adaptive HVAC (see Chapter 2), the engineers estimate that 60% of the cooling load and all of the breathing load will be met by the underfloor air system, which offers only diffuser location and density control, while the remaining 40% of cooling loads can be fully modulated for comfort and energy savings in relation to dynamic climate and space-use conditions without compromising ventilation (Wong 2001). It is possible that a range of closet and desk-based heating and cooling devices will be available as add-on conditioning systems for continuously improving thermal comfort.

5.8 User Control of Air Filtration, Outside Air Content, and Natural Conditioning Strategies

There has been a major effort in the U.S. to improve filtration at the central system, with tighter standards and better quality “air cleansing” products on the market. However, the success of this filtration will depend on the reliability of facilities management, and on their ability to access the air handlers, humidifiers and ducts that supply and carry the air to the workstation. Numerous surveys have found these reliabilities to be inadequate (EPA BASE study – Shankavaram, 1999), suggesting that a second layer of filtration control should be introduced at the end unit of the HVAC system.

One of the most affordable first-cost approaches is to "scrub" task-ambient air supplies at the individual workstation. Several of the mixing floor diffusers available have a screen inset capable of collecting lint and large particulates. Inscape and CenterCore are desktop air manufacturers that offer local filtration.

Ole Fanger from the Danish Comfort Research Institute identifies local filtration as a recommended approach with three pre-conditions (Fanger 1988). First, reduce the unnecessary pollution sources in building materials, furniture, finishes and ventilation systems. Second, exchange and clean the local filters often, using only filters that meet standards for composition, performance, and maintainability (since filters may absorb pollutants from the ventilation air and release them again). Third, ensure that the filtration of recirculating air is considered only a supplement to the supply of sufficient quantities of filtered outdoor air.

Going beyond user-based filtration, however, one of the most difficult controls to offer individuals or workgroups is control over the percent of outside air to be supplied in the workstation. Present buildings with their "sealed box" approach and high percentage recirculation systems frequently depreciate the quality of air inside the building to unacceptable limits. Scandinavian HVAC standards resolve this predictable need by mandating operable windows in all workplaces. Alternatively, user control of outside air quantities through the HVAC system can be considered.

Johnson Controls' Personal Environmental Module (PEM™) provides individual control of air temperature by putting a mixing box at every desk. This module allows conditioned outdoor air to be delivered directly to the desk without an energy penalty, with the end-user deciding the quantity of filtered room air that will be mixed in for thermal control. By lowering the temperature set point, the individual receives a blast of outside air for rejuvenation mid-morning, after lunch, and late afternoon- options that are consistently used by a high number of employees in the Johnson Controls alpha test site (Drake et. al. 1991). In addition, the individual can personally check the condition of two staged filters in the under-desk mixing box unit if they are highly sensitive to particulates and VOC's. Given the desktop location of the diffusers and horizontal and vertical directional control, the age of air is also significantly younger than ceiling and also floor-based systems (Mahdavi et al 2000).

In the IBM buildings in La Defense, Paris by SARI Engineering, the facility manager can independently set the outside air content for each workstation through the decoupled ventilation and thermal conditioning system that is merged in mechanical rooms on each floor. With a fan-coil unit for every occupant, the facility manager can respond to high pollutant loads, high occupancies, smokers, and individual user demands independently, without in any way hurting the effectiveness of the overall system. In addition, the system has allowed SARI Engineering to install a 5-minute "purge" button for each workstation, so that individuals can call for 100% outside air for a five minute period to clear the air as needed after intense working (or cleaning) sessions. A flexible and adaptive ceiling based HVAC system developed by Carrier France, the SARI strategy, is now being further developed for an underfloor installation, including individual ultraviolet (UV) air cleaning strategies.

Fanger and Clausen (Fanger and Clausen 1992) demonstrate that with user control over the percent of outside air (in liters per second), occupant satisfaction goes to almost 100% at much lower overall ventilation rates. They further argue that, "ventilation systems should be designed so that recirculation of return air is not a prerequisite. If recirculation is used, proper maintenance and cleaning of the ventilation system is mandatory."

***Replacing pressurized buildings with the natural stratification distribution of conditioned air, (rising from an under floor air system to a ceiling return) allows for local opening of windows without compromising ventilation effectiveness*.**

Finally, underfloor air (UFA) systems offer the opportunity for natural ventilation of buildings by ensuring adequate delivery of breathing air to every occupant without sealing the building for pressurization. Replacing pressurized buildings with the natural stratification distribution of conditioned air, (rising from an under floor air system to a ceiling return) allows for local opening of windows without compromising ventilation effectiveness. With the appropriate design of the building for natural ventilation, through "finger plan" or courtyard designs, the HVAC conditioning system can be shut off for long periods of time until thermal conditioning is required. In the northeast and northwest U.S., in Canada, as well as in large areas of Europe, the ability to balance internal loads through natural ventilation without auxiliary heating or cooling for long periods of time offers major energy savings and benefits in user satisfaction, health and possibly even productivity (see Chapter 9).

5.9 Control Challenges for Underfloor Air Systems: User Interfaces

A number of engineers have found that the flexibility of relocating and adding UFA diffusers in flexible and adaptive HVAC systems, even without any additional controls, provides a level of thermal comfort and ventilation effectiveness equal to ceiling-based VAV systems, especially in cool climates (McCarry 2001, McGregor 2001, Lehr 2001). They do agree, however, that controls are good for user sense of well being, at the very least, although the frequency of adjustment of controls will depend on user training and on discomfort.

There is a significant need for further development of both manual and digital controls that are easily understandable by the occupant.

Studies indicate that the level of satisfaction and well-being in an open plan office is related to the amount of perceived control that an individual has over his or her local or task environment (McCarrey et. al. 1974). Through extensive occupancy questionnaires, Drake (Drake et. al. 1991) removes the "perceived" status concluding that, "It is not enough to provide controls. User controls must be effective at increasing ventilation and thermal variations within the individual workstations, and the response time must be relatively short."

To this end, there is a significant need for further development of both manual and digital controls that are easily understandable by the occupant. This includes easy recognition of the percent of aperture that is open in volume control, and the direction of airflow, fan-speed, and real temperature indications for warmer and cooler settings. This may also include filtration management. Chapter 9 identifies some of the performance gains that greater levels of control can offer.

5.10 Control Challenges for Underfloor Air Systems: Perimeters and Teaming Spaces

A reliance on diffuser density and even DDC volume controls will not typically be adequate for meeting the thermal loads of building perimeters in cold or hot climates, or for meeting the thermal loads of conference rooms and other teaming spaces. In most case study buildings, the thermal loads of the perimeter have been dealt with by a separately ducted and zoned system. A number of engineers have created site-built underfloor partitions to separate the perimeter air stream from the core, while others have introduced water based cooling and heating at the perimeter, borrowing ventilation air from the plenum. Here, it is important to control for the dewpoint temperatures and provide condensate pans for the water based cooling systems. In Lloyds of London and in the GEW building in Cologne, Germany, the underfloor air systems have been combined with double enclosure systems that return air through the curtain wall to "neutralize" the facade. In these projects, the building facade is acting as a natural dissipater of internal gains, much like our circulatory system and skin dissipates internal loads to keep us thermally neutral. In an effort to potentially eliminate the need for perimeter heating and cooling, a number of underfloor air engineers are actively involved in the design of the building enclosures – towards regionally neutral facades through balanced conservation and natural conditioning.

There is a significant need for further development of modular, plug-and-play local air conditioning units that are quiet, energy efficient and easily controllable to address the rapidly changing space layouts and densities in modern office buildings.

The high cooling requirements of meeting spaces, however, cannot always be met by increasing natural ventilation, especially in warmer climates and given the increasing number of internalized rooms. In most of the UFA projects, a greater density of diffusers, typically fan-powered, are installed in conference rooms to ensure temperature control. In some projects, dedicated VAV duct runs and underfloor partitioning isolate these rooms from adjacent spaces. In other projects, additional cooling units (air or water based) are installed either in closets or under the floor. In all of these installations, local controls are provided for the room, sometimes with occupancy sensors or timers. Most of the engineers interviewed felt that there is a significant need for further development of modular, plug-and-play local air conditioning units that are quiet, energy efficient and easily controllable to address the rapidly changing space layouts and densities in modern office buildings.

5.11 Control Challenges for Underfloor Air Systems: Relative Humidity

Finally, all of the engineers interviewed identified relative humidity (RH) control as a major design challenge, especially as underfloor air systems become more prevalent in climates other than northern ones. Although supply air temperatures are often not below 60^{o}F (15.5^{o}C), the exposed concrete mass in the air plenum, and the use of night-time "flushing" to use the building mass as a flywheel, raises the concern that condensation might occur in the air supply plenum. Although none of the engineers interviewed had experienced condensation in their own buildings, they took a number of steps to prevent the possibility:

1) Outside air is cooled below dew point, dehumidified, and mixed (in most cases) with return air to provide the 63-68^{o}F (17-20^{o}C) supply air temperature.
2) Wherever night-time flushing is designed, such as in Lloyds of London, thermal sensors on the slab ensure that the slab temperature is not allowed to get within 2^{o}C (3.6^{o}F) of dewpoint.

Future research should address the necessity for ducted underfloor air systems in humid climates, forgoing any opportunity for flywheel cooling.

Once again, before both first cost and market readiness decide the future of user controls in underfloor air, each of six user control alternatives should be studied in both laboratory and field research as to their cost-benefits for improved human comfort and health, reduced energy and churn/asset costs, as well as in relation to individual and organizational productivity over time.

CENTRAL SYSTEM ISSUES Chapter 6

The necessity for rethinking central systems in response to flexible and adaptive HVAC distribution has not been fully debated or researched. A number of engineers interviewed and sources referenced argued that the central cooling/heating source and air handlers would not be substantially altered, and that the need for perimeter and conference room auxiliary conditioning is a traditional engineering challenge. However, there are at least seven decisions that should be made in regard to central system engineering at the outset of the design of a flexible and adaptive HVAC distribution system.

6.1 Separating Thermal Conditioning and Ventilation Systems

Repace (Repace 1988) states that "the delivery of thermal conditioning should be divorced from the delivery of breathing air."

There are many reasons to support this argument. First of all, the widespread use of variable air volume (VAV) systems, in which the supply of any air (recirculated or outdoor air) is dependent on thermal demand has led to complaints in swing seasons and inadequacies in multiple spaces that are tied to a single sensor/controller. Although minimum air settings on VAV are of some benefit, a 20% minimum setting of the 20% outside air content promises only 4% "fresh air," with even less delivered to the nose due to the mixing patterns with existing air in the space. In addition, the ventilation effectiveness of the entire duct distribution system is the subject of numerous studies, with a 20% minimum setting at the air handler not correlating to a 20% outside air contribution at the diffuser. Moreover, the combining of thermal and ventilation systems leads to pressurized buildings to ensure the guaranteed distribution of breathing air, a solution which eliminates the opportunity for operable windows, not just in high rises, but in low-rise offices, schools, community centers and more.

As a result, the design team must decide at the outset whether the provision of breathing air or ventilation will be independent of the delivery of cooling and heating. The commitment to separating these systems will result in different specifications for the underfloor air system as well as the early decision about the thermal conditioning strategy and the potential for individual controls.

Designing a separate thermal conditioning strategy is a necessity for displacement systems in most climates, because displacement ventilation rates cannot meet higher cooling requirements. Int-Hout (Int-Hout 2000) states, "European research and experience dictates that displacement ventilation, when used alone for comfort cooling applications, is suitable for loads in the order of 40-50W/m^2 (4-5W/ft^2). This may be adequate for the internal zones in modern office buildings but needs to be supplemented, typically with chilled ceilings or separate cooling means, for internal or perimeter zones where the cooling loads are higher due to occupant density or solar gain and thermal conduction through the facade."

Underfloor air systems can handle up to 300 W/m^2 while displacement ventilation can handle 40 W/m^2 - 120 W/m^2.

In general, underfloor air systems can handle up to 300 W/m^2 while displacement ventilation can handle 40 W/m^2 - 120 W/m^2. As a result, it is important to clearly differentiate the air handling requirements for the low-velocity air distribution strategy in displacement ventilation, which can only handle low cooling loads, and the higher air velocities of underfloor air systems. Both Int-Hout (Int-Hout 2000) and Yuan et. al. (Yuan et. al. 1999c) argue that the displacement ventilation air is unsuitable for space heating and is best dealt with by a separate system. According to Yuan et. al. 1999c, it should not be used for heating because the buoyancy and low air supply velocity will drive the hot supply air to the ceiling level. A separate system, used for thermal conditioning, can be either water based (such as heat pumps or fan coil units) or air based (such as the ceiling-based VAV systems demonstrated in PNC Bank Firstside in Pittsburgh, PA).

6.2 Separating Ambient and Task Systems, Micro-zoning and Flexible Zone Systems

Typically, flexible and adaptive HVAC distribution systems support dynamic changes in location and density of diffusers as well as individual control of supply air volume. While this individualization of thermal conditions (beyond minimum ventilation requirements) is a major gain for the individual worker, the ambient thermal conditions still need to be maintained – albeit to a broader band of comfort. As a result, the HVAC system must be sized and controlled to two conditioning standards – ambient environments and task environments. While ASHRAE standards set limits on the maximum delta in temperatures allowed from head to toe, new standards may be required to reflect the energy and thermal comfort issues in an HVAC system where ambient environmental conditions are controlled on a different standard than individual task environments.

At least three different strategies have been deployed for supporting individual control of task environmental conditions – split thermal and ventilation systems, microzoning, and continuously flexible zones. The Dutch Embassy in Washington D.C. demonstrates a split thermal and ventilation system with individual heat pumps and a separate ceiling-based ventilation system with some additional conditioning potential. The heat pumps, under each window throughout the facility, are designed with quick-connects for ease of maintenance. The constant volume ventilation system allows windows to be opened by the occupants, and allows for individual temperature control without compromising ventilation.

The IBM leased headquarters building in Paris (La Defense) demonstrates microzoning with a fan-coil for every occupant in the building, numbering over 1,800 fan-coils in a modern high rise. These micro HVAC systems are located in several mechanical rooms on each floor with short flexi-duct runs to adjustable ceiling air diffusers (see Figure 6.1). Not only can the occupants set personal temperature conditions within a +/- 2°C (3.6°F) band, but they can call for a five minute 100% outside air (OA) purge cycle to eliminate local pollutants. The maintenance of this newly engineered Carrier system is almost trivial, with plug-in electronic diagnostic equipment used on a twice a year cycle. Whenever a fan-coil unit is not performing acceptably, it is pulled from its quick-connect mount and replaced by one of several spares. This allows the facility manager to ship malfunctioning equipment to the factory for repair rather than attempt on-site maintenance. This also allows the key HVAC equipment to be replaced on an appropriate cycle (less than 50 years), similar to replacing components of a car. While the IBM fan-coil HVAC system merges ventilation air before ceiling-based delivery of conditioned air to the workspace, the Dutch Embassy heat pump system keeps air and thermal conditioning separate. Both maintain the constant delivery of air from dedicated outside air ducts, which may be key to the long-term promise of indoor air quality (IAQ).

Figure 6.1: In the SARI/Carrier building in Paris, outside air is merged with thermal conditioning at each fan coil in distributed mechanical rooms.

A major innovation to improve the IAQ, thermal and energy performance of buildings may be the further development of smaller, packaged HVAC systems that can be added as needed, or components with plug-and-play characteristics to continuously maintain or improve performance delivery. While packaged heat pump, fan-coil and window air conditioning units have received very poor scores from facilities managers due to maintenance problems, noise, and inefficiency, the next generation of expandable, ‘plug-and-play’ technologies may be the key to continuously flexible zoning of ventilation and thermal conditioning, for significantly improving indoor environmental quality in dynamic buildings.

6.3 Central System Sizing & Configuration

There is considerable debate as to whether the size of the air handler or the heating and cooling source is affected by the use of flexible and adaptive HVAC systems. A number of references (Akimoto et. al. 1999, Spoormaker 1990, Webster et. al. 2000, Int-Hout 2000) state that the central system – fans, cooling coils, chiller can be downsized because loads are 20-25% less then those used in the sizing calculations of a conventional system (for details refer to the Performance Gains Chapter 9). Some references (Int-Hout 2000, Houghton

1995a, Loudermilk 1999) argue that chiller capacity can also be reduced in underfloor air systems because of higher supply temperatures, and the chiller operates at a slightly higher efficiency. Cooling coil sizing can be 80% of coil sizes for conventional ceiling VAV, because of the benefits of stratification that eliminate some of the impact of equipment loads. However, Shute (Shute 1992b) and several engineers interviewed (Wong 2001, Yates 2000) argued that system sizes would not be measurably reduced.

The arguments for downsizing air handlers are based on lower levels of pressurization based on natural buoyancy and stratification for distribution. Arguments for downsizing cooling coils and chillers are based on higher supply air temperatures, typically 65^{o}-68^{o}F, and a greater use of economizer cycles.

Int-Hout (Int-Hout 2000) enumerates four ways the downsizing of the central system can be achieved:

Chiller capacity can also be reduced in underfloor air systems because of higher supply temperatures, and chiller operation at a slightly higher efficiency. Cooling coil sizing can be 80% of coil sizes for conventional ceiling VAV, because of the benefits of stratification that eliminate some of the impact of equipment loads.

- "It is possible to consider the floor area as being made up of occupied and unoccupied equipment zones. This allows some reduction in total supply air volume as higher levels of stratification are permitted in the equipment zones. Furthermore, roof loads and convection loads from lighting can be ignored in space loads used for calculating supply air quantities although they will be reflected in total air conditioning load" (if a return ceiling plenum is used).
- Due to the movement of conditioned air from the floor to return air in the ceiling, Int-Hout further argues that the effective sensible heat gain in the space is only 64% of a ceiling based system, allowing for 20% reductions in airflow requirements.
- "Due to elimination of ductwork downstream of the zone terminal boxes, requirements for fan static pressure are lowered."
- "The reduced airflow and higher return air temperatures inherent to underfloor systems often lead to lower required refrigeration equipment capacities as well."

At the same time, there is considerable debate as to whether the configuration of the central HVAC system is affected by the use of flexible and adaptive HVAC systems. Int-Hout (Int-Hout 2000) states that DX chillers may no longer be viable, because the supply to room temperature differential cannot be greater than 4-5^{o}C (8-10^{o}F). The configuration of air handling units (AHU's) may also be affected. While a number of engineers interviewed argued that the number and location of AHU's would not vary (Wong 2001), several references argued for a shift to smaller, distributed air handlers for system flexibility. Int-Hout (Int-Hout 2000) states, "a typical building would have a separate supply for each underfloor plenum."

Nakamura (Nakamura 1996) recommends one AHU per 10,000 square feet, and Bauman and Arens (Bauman and Arens 1996) mention using one medium or small sized AHU per floor to minimize or eliminate duct work and to improve zone control. What is clear is that the design of the air handling system will be affected by the type of flexible and adaptive HVAC system selected – from pressurized plenum; neutral plenum with distributed fans; displacement ventilation with separate thermal conditioning; to ceiling-based systems - as identified in Chapter 2.

6.4 Perimeter System Alternatives

While many of the engineers interviewed and sources referenced argued that the need for perimeter and conference room auxiliary conditioning is a traditional engineering challenge, flexible and adaptive HVAC distribution systems have introduced changes in engineering practice with regards to perimeter systems and supplemental cooling. Mass (Mass 1998) states that, "underfloor air systems almost always require tailor-made solutions at building perimeters (especially glazed exterior walls) and demand that building cores be designed in ways that can vary from traditional approaches."

As Shute (Shute 1992b) mentions, the advantage of a separate perimeter system is that "the perimeter system neutralizes ambient load influences, leaving all internal loads to be assigned to plenum air delivered through the air terminals. This simplifies the concepts for space conditioning, eliminating the design differences between perimeter and interior zones. The designer has one set of rules for all future design, leaving the perimeter units as a permanent building facility."

Three strategies have emerged for perimeter conditioning in flexible and adaptive HVAC systems: sub-divided air only systems; split air and water systems; and high performance enclosures where the load has been eliminated or neutralized.

Such a perimeter system can be either an active system (sized to neutralize the building envelope heat gains and losses) or it can be a passive system (high performance glazing, high quality envelope) or a combination. Based on climate, perimeter conditioning will be separate, unless the enclosure is very well designed. Three strategies have emerged for perimeter conditioning in flexible and adaptive HVAC systems: sub-divided air only systems; split air and water systems; and high performance enclosures where the load has been eliminated or neutralized (for example air flow windows).

6.4.1 Sub-divided Air Systems

One approach to perimeter conditioning is the separation of the underfloor air plenum into two zones with plenum dividers. The perimeter zone would be configured as a higher speed duct or provided with distributed fans to increase airflows at the window wall. The supply air at the perimeter might be conditioned at lower or higher temperatures than the underfloor air serving the center of the building, either centrally or through local reheat/recool coils. Strategies to support rapid temperature modifications would be required to deal with variations in load by orientation or in response to seasonal swings. Sodec and Craig (Sodec and Craig 1990) argue that, "floor outlets are not adequate to eliminate down drafts from windows in winter. Forced ventilation would be required, or auxiliary perimeter radiant or convective heating, or air flow windows (upflow preferably), or high performance (triple) glazing to minimize cold mean radiant temperature and downdrafts."

The underfloor air system at Owens Corning in Toledo, OH by Cosentini Associates Engineers, deploys a perimeter duct floor-mounted below the window to meet perimeter loads. Other underfloor air projects have fan-powered terminal (VAV) boxes with reheat (electric or hot water) in the underfloor plenum.

6.4.2 Split Air and Water Systems

The literature shows that there are numerous types of water-based terminal units that can be used for perimeter conditioning - fan coils, heat pumps, radiation or convector units located under window sills, ceiling mounted radiant heaters or chilled ceilings/beams, as well as water mullions that neutralize the facade (Nakamura 1996, Nall 1998, Int-Hout 2000, Bauman and Arens 1996, York 1994, Shute 1992a, Milam 1992).

Some authors make a distinction between the perimeter heating and perimeter cooling needs. According to Milam (Milam 1992), “while exterior zone cooling requires more supply air, a combination of Kranz KB-200 diffusers and linear floor grilles adequately handles this cooling demand. However, exterior heating zones present a challenge to every HVAC designer.”

Dan Nall (Nall 2001) of Flack and Kurtz Engineers raises a concern in relation to water based perimeter conditioning within the raised floor plenum, “There is no mention of the significant problem associated with supplying supplemental cooling, both perimeter (high glass load situations) and interior (conference rooms), when using 65°F underfloor supply air systems. These are significant, as the solution often drives the selection of the entire system! The main problem is the location of the condensate pans with supplemental cooling coils when located below the floor. I suspect that the reason we haven't seen anything in the literature is because most of the documented installed systems have been in the Northern US and Canada (California, Vancouver), and Europe; all relatively dry when compared to the major opportunity in the US (the south and Gulf Coast) where most new construction is slated!”

Int-Hout (Int-Hout 2000) agrees with this design directive for water-based perimeter conditioning, “When using underfloor fan coils to condition the perimeter in cooling mode, the unit will have the condensate pan at the lowest point on the slab, and will probably require condensate pumps. These need to be very reliable to prevent condensation below the floor, where it may not be noted until serious bio-contamination has resulted.”

6.4.3 Passive/ Neutral Enclosures

Many of the engineers involved in the design of underfloor air systems are aggressively pursuing architectural innovations for passive conditioning. A number of references introduce unique approaches such as airflow windows (Nakamura 1996) and double envelope facades (Faulkner et. al. 1993). Interviews further emphasized the value in improving the building enclosure design to dramatically reduce or eliminate perimeter loads. These high performance facades demonstrate very high thermal resistance, benign mean radiant conditions and no thermal bridging as well as passive and active solar heating for winter, and high thermal resistance and solar load minimization for summer, as well as supporting daylight and natural conditioning. In the U.K., the engineering profession is actively designing building enclosures and HVAC systems as “mixed-mode” conditioning systems, with natural ventilation and passive conditioning taking over for more than 50% of the conditioning requirements (McCarry 2001). The effective design of building enclosures in some climates can eliminate the need for perimeter HVAC systems, or reduce them to a level that new, highly responsive low-cost technologies can be developed. Moreover, the design of neutral or mixed-mode building enclosures enables mechanical systems to be shut down seasonally for significant energy savings and a more sustainable work environment.

6.5 Supplemental Cooling

In addition to separate systems for perimeter conditioning, many office buildings will require supplemental cooling in conference rooms and internal areas with high equipment and occupant density (with higher supply air temperatures a given for underfloor air). Some engineers are convinced that the addition of more air diffusers or fan-air diffusers can meet the needs of these higher internal loads. Field studies should reveal, however, that local solutions are being identified for increasing the cooling delivery to conference rooms in both conventional and flexible HVAC commercial buildings.

Most of the supplemental cooling systems that are being introduced to meet these loads in underfloor air buildings are either local DX units (which raise moisture concerns), or surprisingly rigid (not flexible and adaptive) separate water or air based cooling systems. There are a few solutions, however, that have been introduced with continuous flexibility in mind. AET-FSS™ has introduced a series of relocatable floor-standing fan-coil units that support local cooling demands wherever a chilled water source has been established as a grid - in distributed vertical risers or chilled water or even sprinkler piping in the plenums for example. Milam (Milam 1992) describes two other flexible approaches for conditioning of conference rooms:

1. Below-floor variable air volume damper – This approach incorporates a variable air volume damper below the raised floor installed in the plenum divider of a conference room. This variable volume damper is thermostatically controlled to allow more air to enter the conference room raised floor plenum as the space temperature increases. During periods of low cooling load demand, the thermostat causes the damper to close to a minimum airflow position.
2. Fan Assisted Supply - Incorporates a low profile fan installed below the raised floor, ducted to a dedicated plenum for the conference room. Air is delivered through Kranz floor outlets in this approach. Another variation of this approach uses Donn Fan Control Units with an integral grille built in to the access floor panel. These Fan Control Units can be used alone or in combination with the Kranz floor diffusers.

Both of these air-only solutions rely on dedicated zones being introduced into the plenum. This has central system ramifications and demands flexible solutions to plenum sub-division on demand. Indeed, developments in both air-based and water-based ‘plug-and-play’ solutions to supplemental cooling are critically needed to maintain the flexibility and adaptability of the HVAC system.

6.6 Dehumidification

As previously identified by Dan Nall (Nall 2001), relative humidity control is critical, especially in humid climates. Either hyper-cooling the outside air and mixing this with return air, or additional desiccant cooling is typically necessary.

Int-Hout mentions (Int-Hout 2000) "Controlling space humidity to the ASHRAE 62 (and upcoming 55) standards of a 60% RH at 73^{o}F (23^{o}C) with discharge temperatures as high as 65^{o}F (18^{o}C) will require non-standard dehumidification designs employing heat wheels, outside air dehumidification coils, face and bypass, or other strategies."

Relative humidity control is critical, especially in humid climates. Either hyper-cooling the outside air and mixing this with return air, or additional desiccant cooling is typically necessary.

There is very little material clearly outlining the necessary steps in central system engineering in relation to underfloor air to ensure drier supply air in humid climates or in buildings where water-based cooling is proposed. Int-Hout (Int-Hout 2000) states the engineering requirement in relation to chilled ceilings employed with displacement systems as, "very careful attention must be given to the control of the panel temperatures in relation to the space humidity to avoid condensation on the panels, and the attendant water damage and bio-contamination."

Field studies will help to inform viable solutions to the dehumidification challenge. The Intelligent Workplace in Pittsburgh, PA, the Adaptable Workplace Laboratory in Washington D.C., and the Soffer office buildings in Pittsburgh, PA, rely on a desiccant system for dehumidification. PNC Firstside Bank in Pittsburgh, PA relies on the more traditional cooling coil and reheat combination in the central air handler for dehumidification. Test results and system innovations are both greatly needed.

6.7 Central System Control Responses

Chapter 5 fully explores the end-user control options in flexible and adaptive HVAC distribution systems, including:

1. Location and density of diffuser
2. Direction of airflow
3. Volume of airflow
4. Speed of airflow
5. Temperature control
6. Air Filtration, outside air content & natural conditioning options

However, these distributed controls also have significant impact on the central system, in relation to pressure controls, variable speeds fan controls, temperature controls, and outside air controls.

The continuous change in density of diffusers will affect the pressure in the plenum, which in turn will affect the volume of airflow through these diffusers. If many diffusers are located close to the vertical riser, it might be difficult to obtain air from the diffusers, which are away from the riser (Wong 2001). An increase or decrease in density of the diffusers will also affect the pressurization and airflow volume at the diffuser. As a result, the central system fans (or distributed AHU's) must have the capacity to measure and respond to changes in pressure caused by variations in density or location of diffuser by increasing or decreasing the volume of the airflow. Some engineers interviewed argued that pressure gauges may be less reliable than monitoring temperature or the supply and exhaust airflow rate, although no data could be found in the literature.

Giving end users fan speed control will clearly impact the quantity of air and cooling requirements that the central system must deliver. Again, variable speed fans to support changes in pressurization and quick response cooling/heating units may be required.

If occupants have task temperature control through local coils or mixing boxes, the central system should be able to respond by modifying ambient conditioning temperatures. In addition, if a majority of occupants are calling for lower temperatures (by using more primary air fed to the Johnson Controls PEM™'s for example), the central system should respond by lowering the overall temperature of the supply air to meet the rising loads.

Finally, central systems in flexible and adaptive HVAC distribution will need to have new approaches to outside air utilization. There is evidence that underfloor air systems can use significantly higher percentages of outside air for cooling due to the higher supply temperatures, especially in mild or cool climates. The central system controls should maximize the use of outside air using temperature, pressure and CO_2 sensors to ramp down the recirculated air. The central system controls should also be designed to support the extensive use of operable windows in mild or cool climates, with shut-down capability connected to distributed controls or communication systems to ensure that windows are closed when conditions are inappropriate for natural ventilation. Finally, underfloor air systems have the potential to introduce flywheel cooling, using 100% outside air on cool nights to reduce the daytime cooling loads (Int-Hout 2000). Not only should the central system carefully track outside temperature and humidity levels, but it should also track slab temperatures to avoid dewpoint while maximizing the flywheel cooling system.

7.1 "The Plenum Real Estate Challenge"

As described in the plenum infrastructure design chapter, one of the worst examples of non-collaborative design/engineering may be in ceiling plenums. From three to five feet (1 to 1.5 meters) of plenum space is dedicated to linear, non-integrated decision-making, resulting in poor access, poor flexibility, and in most cases, poor performance. Systems are idiosyncratic, tangled, and designed to serve a specific floor plan at a specific point in time - quickly obsolete. The density of service nodes (air diffusers, controllers, outlet boxes, lights) is inadequate for the occupant and equipment densities common in today's workplace. The Center for Building Performance and Diagnostics argues that a critical step should be introduced early in the design process – "the plenum real estate challenge". This one-day design "charrette" would require the presence of all seven disciplines who have components they intend to introduce into the plenum and its surface interfaces:

- HVAC supply and return ducts, zone boxes, diffusers, sensor/controllers
- HVAC piping, terminal units; separation of ventilation and thermal conditioning
- Lighting - power conduit, fixtures, controllers
- Connectivity - data, power, voice, environment, security – conduit, trays/baskets, poles/partitions, and terminal boxes
- Fire piping, pressure valves, sprinklers, sensors/ controllers, smoke separations
- Structural components, columns, beams, trusses, openings
- Flooring components.
- Ceiling components and acoustic materials (ceiling 'plenum' responsibilities).

The challenge is for each of these disciplinary experts to bring the physical components that they intend to introduce – 3-dimensional elements and specifications, not symbols and line drawings – to ensure full debate about the cross-sectional integration and the surface integration of all building systems. The maximum performance of each system should be sought in relation to first cost, constructability, as well as life cycle maintenance and reconfigurability - the added value of the systems integration effort.

7.2 Emerging Industrial Partnerships

Today, a number of industry partnerships have formed to offer collaborative solutions to flexible infrastructures - floors, data/voice, power, thermal conditioning and ventilation. Moreover, with these modular, floor-based services, the ceiling can become more playful and elegant - as a light and acoustic diffuser - defining working groups, neighborhoods, and landmarks. This collaboration is not only critical to keeping down plenum heights and system costs, but critical for maintaining the maximum choice in locating diffusers and outlet boxes (flexible 'nodes of service') without the interference of underfloor distribution systems - to the benefit of overall performance. Specifically, drawings should be to scale in plan and section, not diagrammatic. The exact dimensions and location of the ducts, underfloor piping, and underfloor cabling must be shown on the drawings with enough plenum height to support diffusers and outlet boxes above, or a recognition that the duct/pipe/tray areas are "black-out" locations for terminal units.

A range of industry players today are leading the underfloor air market; from raised floor manufacturers, to HVAC companies, to furniture companies, to developers. Ira Krepchin, in a 2001 E-Source publication, identified that, "more players are entering the underfloor air market, and engineers used to working with HVAC manufacturers will probably feel more comfortable knowing they are behind it" (Krepchin 2001).

While raised floor manufacturers Tate and then InterfaceAR led the North American introduction of underfloor air, HVAC companies York, Titus and now Carrier as well as Honeywell have joined into partnerships. Most recently, Steelcase has forged an alliance with real estate developers Gale and Wentworth and Morgan Stanley Real Estate Funds to form Workstage™ (a prefabricated building system). Hines Development has also forged alliances with Rocky Mountain Institute, Flack and Kurtz and Gensler Architects to "design a modern building prototype that features underfloor air as a key element." Parallel trends can be seen in Europe, with raised floor manufacturers such as Mahle leading the underfloor air movement, joined by HVAC industries LTG, Kranz, Trox and Schmidt-Reuter. Three European manufacturer-based developers, AET-FSS, SARI/ Carrier France and Nixdorf have over 15 years of fully integrated building solutions based on flexible and adaptive infrastructures. What is clear is that at least 4 of the 7 partners in the "plenum real estate challenge" need to be in the partnership – the raised floor manufacturer, the HVAC integrator, the connectivity integrator, and the floor covering manufacturer.

7.2.1 Messages to Partnering Industries in Underfloor Infrastructures

Key system detail issues were introduced in numerous references and by the professionals interviewed as to what partnering industries should more fully address:

- Raised floor manufacturers need to actively market underfloor air (HVAC) as part of their package.
- Coordinating strategies for the horizontal distribution and relocatable nodes for the under floor HVAC and power/data/voice and controls wiring should be prototyped, tested for performance, priced and installed with performance guarantees.
- Diffuser alternatives need to be tested with human subjects to the same level as European manufacturers' testing.
- There is a need for underfloor partitioning system in the raised floor kit of parts. Dimpled floor tiles are difficult to seal to a duct board or sheet metal partition on the site.
- Raised floor manufacturers should develop "framing" tile modules to deal with column grids and building edge conditions in order to support

the consistent location of raised floor modules instead of idiosyncratic cutting on site.
- There is a need for reliable drop-in fan coil units or in-room cooling units for conference rooms and other density driven cooling loads. These fan-coils should be quiet, modular and prepackaged with piping and control, for performance and affordability.
- Ceiling manufacturers need to explore the opportunities of non-flat, non-continuous forms to take advantage of UFA work environments, while resolving acoustics, up-lighting and possibly return air and sprinkler system integrations.

7.3 The Integration of the HVAC Package in Flexible and Adaptive HVAC systems (from B to C – Business to Consumer)

Today, an on-site-integrated HVAC system is responsible for the effective delivery of ventilation and thermal conditioning. However, the system is typically an untested assembly of a series of somewhat specified components from different manufacturers, with on-site substitution allowable, and commissioning not a requirement. The level of fragmentation of the process is a serious issue for building owners and occupants:

Fragmented HVAC delivery-

- Components independently manufactured, never tested as an assembly:
  chilled water and hot water generators
  air handlers
  piping and valves
  ducting and dampers
  diffusers
  fan-coil or heat pump units
  mixing boxes
  sensors
  controllers
  building automation systems
- 2-D Engineering design with broad performance specifications (not tested assemblies)
- Value engineering of performance specifications and on-site substitution allowed
- Testing & balancing, but no-mandatory commissioning
- No mandatory training of facilities management (FM) or users
- Fighting control hardware and software, no single point of responsibility

Inadequate thermal comfort, air quality, and energy costs often result, with the growing demands of flexibility impossible to address. Given the dynamics of building use today, it is critical for a new generation of integrated HVAC systems to be developed and delivered with performance contracts directly from business to customer. In underfloor flexible and adaptive HVAC systems, the manufacturer AET-FSS continues to refine a kit-of-parts for the delivery of thermal conditioning in dynamic workplaces, with independent design of central systems.

It is past time for the major players in the HVAC manufacturing community – central system manufacturers or control companies – to develop regional solutions to flexible and adaptive but fully integrated HVAC systems – to be delivered as performance contracts directly from business to customer.

In a ceiling-based flexible and adaptive HVAC system, Carrier France with SARI Engineering have developed a fully integrated and tested ***entire*** HVAC system for the flexible delivery of thermal conditioning and air quality. The assembly of chillers and air handlers, riser ducts and pipes, individual fan-coils with quick connects, flexible ducting and air diffusers is a fully integrated system that has delivered the highest FM and user satisfaction of any IBM building in France, as well as long term energy efficiency. The system is similar to developments in the automobile climate, with further improvements in user control, acoustics and UV filtration. Most critically, the Carrier France and SARI joint venture takes full responsibility for the delivery of performance – from Business to Consumer – in contrast to the 'finger-pointing' that is so common between the fragmented responsibilities of the generation, distribution and controls manufacturers as well as the engineering, installation and management personnel. The performance of installed HVAC systems is continuously compromised by the fragmented delivery of hot and cold water generators, air handlers, piping and valves, ducting and dampers, mixing boxes and fan coils, diffusers, sensors and controllers and building automation system. It is past time for the major players in the HVAC manufacturing community – central system manufacturers or control companies – to develop regional solutions to flexible and adaptive but fully integrated HVAC systems – to be delivered as performance contracts directly from business to customer.

7.4 The Integration of Enclosure in Flexible and Adaptive HVAC Systems

To ensure sustainable buildings as well as to improve indoor environmental quality, the design of the building enclosure must be seen as part of the HVAC system design, regardless of whether HVAC is to be flexible and adaptive. The growing developments in "mixed-mode" conditioning – combining natural conditioning strategies with efficient mechanical systems – have demonstrated that the building enclosure can be a major source of heating, cooling and ventilation.

An extremely well designed building enclosure can support the elimination of a separate perimeter thermal conditioning system, with the significant cost savings available for improving the facade.

Moreover, an extremely well designed building enclosure can support the elimination of a separate perimeter thermal conditioning system, with these significant cost savings available for improving the facade. Numerous underfloor HVAC designers have taken on the challenge of improving the building's facade – through the use of high performance glazing, air flow windows, water flow mullions – to maximize the use of natural energies and waste energies instead of central systems for perimeter conditioning (see Figure 7.1). All of the engineers interviewed argued that it is imperative for the mechanical engineer to be actively involved in the design of the building enclosure towards the optimization of the HVAC system – on a region-by-region basis.

This regionalism would require a shift away from the pervasive sameness of building enclosures, favoring neither the international styles with unshaded glass and un-thermally-broken concrete, steel and aluminum nor the post-modernism of today. "Architecture Unplugged" would require enclosures that demonstrate serious attention to the management of solar gain, heat transfer, moisture migration, and day-night load balancing. These mass, color, venting, and thermal insulation characteristics are key to energy conservation in buildings, requiring entirely regional solutions. Heavy capacitance masonry facades will be seen in desert climates with large diurnal swings; heavily shaded and highly operable facades will be seen in warm, humid climates; and solar exposed yet well insulated facades will be seen in cold climates. In each climate, the massing, orientation, and selection of facade materials should be regional in character, providing the maximum natural comfort before mechanical systems need to be introduced.

Figure 7.1: The Intelligent Workplace façade integrates water flow mullions for perimeter conditioning.

At the same time, the HVAC system must be re-designed to support the use of natural energies, and "waste" or "reject" energy, with modifications required within the areas of generation, distribution, terminal units and controls. Given that commercial buildings have continually increasing internal loads, there is a real justification for increasing the periphery of buildings with the facade designed as an integral part of the mechanical system.

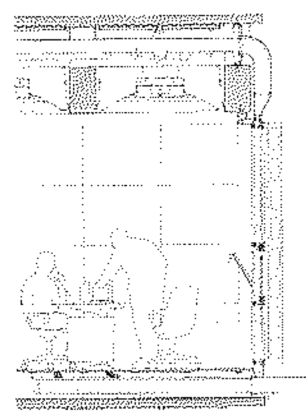


Figure 7.2- Lloyd's of London demonstrates the use of a triple-glazed enclosure as a return air duct.

Both air flow windows and water flow mullion systems enable excess heat from the core – heat from occupancy, lights and equipment - to be effectively dissipated through the facade. By taking return air through the "glass duct" of a triple glazed airflow window, core cooling loads are dramatically reduced and perimeter heating is almost eliminated (as seen in the Comstock building in Pittsburgh, PA, GEW in Cologne, Germany, and Lloyd's of London in England - Figure 7.2). Indeed, the perimeter heat pumps installed at Lloyds have never been used because return air through the facade effectively eliminated the perimeter loads and ensured thermal comfort.

Water-flow mullions (thermally broken from the outdoors) can also use "waste" heat from the core to minimize loads. In this system, waste heat from building cooling or even power generating systems can eliminate perimeter heating requirements and radiant imbalance, while allowing an increase in building periphery for views and light at every workstation. Indeed, the building facade could be seen as the natural dissipater of energy, a "circulatory system" resembling that of a healthy human - with appropriate surface to volume ratios.

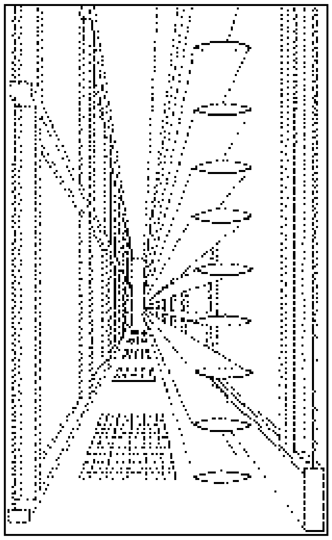


Figure 7.3- The Occidental Building double façade.

One other facade mechanical system of note is the use of double envelopes to provide north-south, east-west load balancing in climates where solar loads are significant and beneficial. The Occidental building in Niagara Falls is one of the earliest examples of a double envelope construction (Figure 7.3). When solar energy is received on the east, a natural convective loop of solar heated air wraps the entire building (Rush 1986). This continues throughout the day to eliminate simultaneous heating and cooling, to maximize passive solar contributions to the heating load, and to ensure excellent mean radiant conditions. In summer, the double envelope is vented to the outside, and precautions are taken for fire protection. The Occidental building uses less than 30% of the heating and cooling energy of a conventional office building in upstate New York (Bazjanac 1980).

In North America, a majority of the population works in climates where a large percentage of the thermal and ventilation demands in their buildings could be met by natural energies or waste energies through the building facade, requiring that HVAC engineers play an active role in enclosure design and a responsive role in the design of their conditioning systems.

7.5 The Integration of Massing, Structure & Vertical Cores

Flexible and adaptive HVAC systems impact a number of decisions about building massing, structural grids and the introduction of vertical cores.

Floor to floor height is not necessarily increased in underfloor projects, and can in fact be decreased due to systems integration efficiencies within the plenum.

The most common debate about underfloor air is whether it increases floor to floor height, and thus building cost. Several studies (Tu 1997, Chiu 1991) illustrate that floor to floor height is not necessarily increased in underfloor air projects, and can in fact be decreased due to systems integration efficiencies within the plenum (Figure 7.4). Moreover, the effective integration of HVAC and networking/power systems underfloor can eliminate the need for deep ceiling plenums, allowing the ceiling to undulate with the structural elements for increased ceiling heights and articulated ceilings in offices.

While raised floor systems must be carefully designed in seismic zones, the elimination of the traditional penetrations in the structural floor slab for networking and power improves the structural integrity of buildings. Indeed, the building can be designed with thinner slabs, reducing floor to floor heights or increasing ceiling heights.

Well before construction, the raised floor pedestal configuration must be resolved in dimensioned drawings in relation to columns, exterior walls and all underfloor infrastructures.

At the same time, vertical cores and structural bay sizes must be carefully designed to support the flexible and adaptive “nodes” of service, and to meet the needs of dynamic interior space planning. As previously described, the lowest-cost plenum air supply systems work most effectively if maximum distance from the point of feed is no more than 40-70 feet. This suggests vertical risers for each 5,000 to 10,000 square feet. The structural grid and core to window wall dimensions must also be designed in relation to the raised floor grid. Well before construction, the raised floor pedestal configuration must be resolved in dimensioned drawings in relation to columns, exterior walls and all underfloor infrastructures. Indeed, the raised floor manufacturers should develop "framing" tile modules in relation to column grids and building edge conditions that can support the consistent location of raised floor modules (instead of idiosyncratic cutting on site) for maximizing the flexible and adaptive nodes for HVAC and networking of the dynamic workplace.

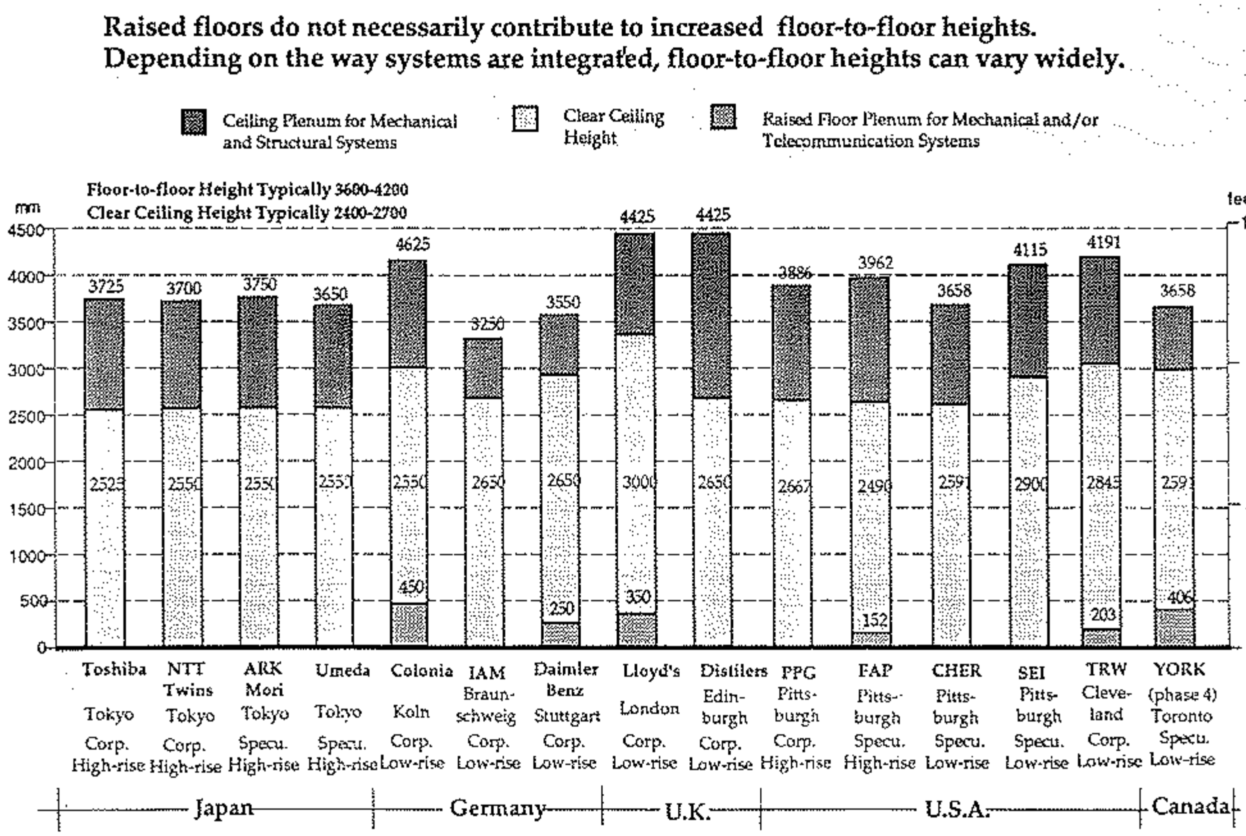


Figure 7.4: Floor-to-floor heights in advanced buildings worldwide (CBPD 1991).

Finally, a critical early design decision for indoor environmental quality and energy loads relates to building massing - the height, depth and orientation of buildings. Neither the tallest building in the world nor the largest building under one roof offer sustainable work environments in the event of a power failure. Indeed, these buildings guarantee significantly higher energy loads in almost every climate because they eliminate any use of daylight, natural ventilation or natural dissipation of internal heat gains (Mahdavi et al. 1996). They guarantee that the building must be abandoned in the event of a power outage. If air quality, comfort and energy are a driver for building form, then the next generation of buildings will strive towards controlling building depth, height and orientation to achieve environmental comfort for a maximum percentage of the year – as if "unplugged."

7.6 The Integration of Fire & Security in Flexible and Adaptive HVAC Systems

In some locations, sprinklers are required if a plenum is over 16", and in other locations, wiring must be in conduit or plenum rated cables. Some codes may require that diffusers are of fire resistant material, though others contest the necessity of this.

In general, fire issues in underfloor air plenums are not fundamentally different than in ceiling plenums. Fire issues vary by location. In some locations, sprinklers are required if a plenum is over 16", and in other locations, wiring must be in conduit or plenum rated cables. Some codes may require that diffusers are of fire resistant material, though others contest the necessity of this. Large unducted plenums must have plenum dividers for smoke and fire control. The first UF air project in a region seems to establish the code/standard rules for future projects. Again, the engineers often argued that the emerging partnerships should not only provide alternatives in their "kit-of-parts" to address variations in local code requirements, but should take a lead role in ensuring that the introduction of underfloor air systems are not undermined by local misunderstandings about the innovative systems.

Security issues are just emerging in the use of underfloor air systems because of the potential openness of the plenum, and access to locations throughout the building. None of the references addressed these concerns, or how they differ from ceiling plenums, and no solutions have been proposed. However, it is clear that the accessibility and maintainability of underfloor air systems ensure that supervision is constant – possibly reducing rather than increasing security risks.

7.7 The Integration of the Connectivity in Flexible and Adaptive HVAC Systems (from B to C)

In the modern office, the development of underfloor air systems is predominantly considered to accommodate dynamic data, power, voice, video, and controls cabling. Indeed, once a raised floor has been cost-justified for connectivity, the introduction of underfloor air should be cost neutral or a cost savings. The continued refinement of data, power, voice, and controls distribution underfloor, however, mandates further integration of connectivity services in the horizontal plenum area. Just as the HVAC system needs to be fully integrated by the industry with performance delivery to the customer, the "connectivity" system needs to be fully integrated by the industry with performance delivery to the customer. This "B to C connectivity" initiative requires the integration of data, power, voice, video, security and control services from a reconfigurable grid to reconfigurable 'nodes of service' as described below.

7.7.1 Upgradable Wiring Harnesses to Provide a 'Grid of Service'

Upgradability, expandability and reconfigurability are key to successful connectivity. In addition to distributed vertical risers and open horizontal plenum distribution spaces, the selection of the wiring harness and its flexibility is very important. Ideally, connectivity services are "home-run" from the individual workstation to the satellite closet, through data and power distribution modules as needed in larger floor plates (see Figures 7.5 to 7.8). For data, environmental control, security and voice, the cable type should provide the maximum speed and reliability available (Category 5+ or higher) with the flexibility to be used interchangeably for data, voice or video demands with simple modifications in the satellite closet. For power, no less than six outlets per employee should be supported, using a power distribution module to maintain "home-run" configurations for all workstation, while shortening the length of the tether for relocating the outlet boxes.

Figure 7.5: Power, voice, and data floor box

The connectivity infrastructures must be developed collaboratively by the data, voice, power, environmental control, security and fire professionals. The team must select the wiring and cabling type, design "harnesses" that can be prefabricated for roll-out installation, establish the 'grid of service' required for move-in densities and the mode of expanding, replacing and relocating service to accommodate workplace dynamics. Almost all desktop technology today requires access to both power and data/voice connections, as well as individual controls, with continuously changing demands as to location, density and capacity of service.

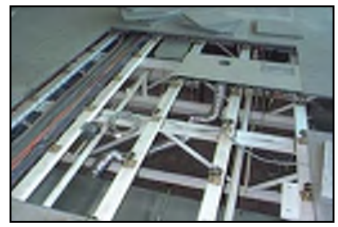


Figure 7.6: 'Grid of service'

7.7.2 Reconfigurable Nodes for Data, Power, Voice, Environmental Connectivity – Modular Outlet Boxes, Home-run to Distributed Satellite Network Centers

Each individual requires multiple data, voice, and power outlets, with significant variations in density and functionality to fully support today's constant layout activity and technology changes. As a result, modular floor or desktop outlet boxes are needed, with interchangeable outlet densities for data, phone, power, video, security and environmental controls - to provide reconfigurable infrastructures without waste (see Figures 7.5 to 7.8). Data, voice and power wiring should no longer be independent activities performed by independent unions. Outlet boxes should no longer be in fixed locations with fixed numbers of power or data or voice ports. The boxes should harness all connectivity services, be relocatable by the end-user, and support modifications in density and type of outlets over time. Relocatable "connectivity" boxes, or nodes, that can plug into the 'grid of service' managers to purchase fewer outlet boxes of higher quality (greater modifiability), and move them around for maximum utilization, only purchasing additional 'nodes of service' when the existing infrastructure is fully loaded – just-in-time.

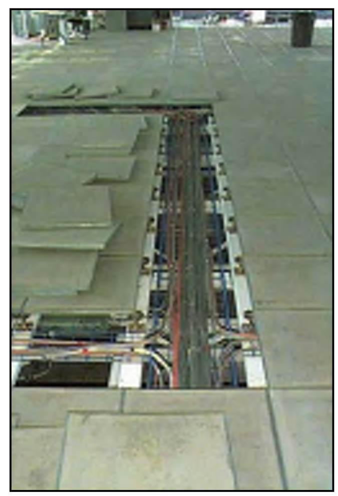


Figure 7.8: Underfloor cable-tray

Wireless capabilities are improving so rapidly that many argue that wiring in buildings will be unnecessary in the future. However, capacity and speed still remain one generation behind wired connectivity, and power continues to rely on wired infrastructures. Moreover, wireless infrastructures typically require as much hardware and design responses as wired infrastructures. "Smart buildings" must support both wired and wireless infrastructures fully. Wireless antennas will rely on the same satellite closets that serve 35-50 people, and investments will have to be made in receivers for each desktop technology. The continued improvements in power batteries for laptops and phones may lead to greater utilization of the wireless infrastructure for communication than the wired infrastructure. However, both will be continue to be central to the flexible and adaptive workplace. The raised floor, that also supports a flexible and adaptive HVAC system, will continue to provide ease of access, service expansion and reconfiguration of the connectivity system.

Figure 7.7: Satellite closets

7.8 The Integration of Raised Floor, Carpet, Outlet and Diffuser Package (from B to C):

Grids and Nodes for "Just-In-Time" Space Layout and "Just-In-Time" Product Purchasing

While industrial partnerships are attempting to address each of these systems integration challenges – the integrated HVAC package and the integrated connectivity package – there is still significant fragmentation in the systems' delivery. For example, the ultimate flexibility of both the connectivity and HVAC system in the face of space dynamics will be determined by the effective integration of the raised floor module, the carpet module, and the outlet and diffuser package.

In the face of rapidly changing desk layouts and densities, it is critical for the outlet boxes and air diffusers of the flexible and adaptive systems to be easily relocatable and able to be increased or decreased in number. For this reason, diffuser and outlet cutouts should be in locations that allow the easy reconfiguration of systems without carpet waste. Indeed, carpet tiles should be identical in size to access floor tiles, so that cutouts are continuously re-usable, although they can be offset 50% to reduce leakage from the plenum. Carpets should be selected for benign and recycled materials with benign adhesives (low VOC emitting) that support relocations, and should not "pill" or release carpet fragments into the diffuser baskets. Air permeable tiles should be further explored.

Diffuser and outlet cutouts should be in locations that allow the easy reconfiguration of systems without carpet waste. Indeed, carpet tiles should be identical in size to access floor tiles, so that cutouts are continuously re-usable, although they can be offset 50% to reduce leakage from the plenum.

One trade-off of major importance in the effective integration of access floor, carpet, outlets and diffusers is the choice between desk and floor locations for the HVAC and connectivity 'nodes of service' (see Figure 7.9). On one hand, keeping both power/data/voice outlets and air diffusers in the floor will support rapid space reconfiguration without having to "un-tether" furniture components.
On the other hand, putting both outlets and diffusers at the desktop maximizes user satisfaction. The former CEO of ALCOA argued strongly for desk-based outlets in their headquarters so that the employees could quickly connect their laptops on arrival. Numerous research findings (see Chapter 9) argue strongly for desk-based air delivery to ensure maximum air quality and thermal comfort and control.

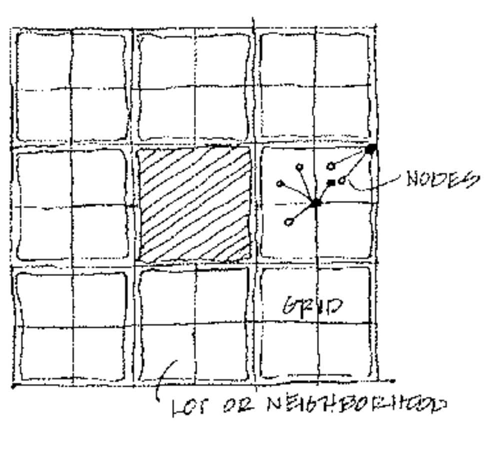


Figure 7.9: Concept of 'grid and nodes'

Underfloor air projects around the world demonstrate the full set of four alternatives in locating the nodes of service for air and connectivity. In relation to outlet boxes for power, data, and voice connectivity, several recommendations have emerged:

- Cutouts in the raised floor for outlet boxes or cabling should be coordinated with cutouts for the air diffusers. If outlet boxes will be in partitions or desks instead of in the floor, cutouts for diffusers and cabling could be the same dimension for maximum flexibility.
- Floor outlets for data, voice, power, video, and environmental controls need further development for: ease of relocation with quick-connect/ tethers as well as the ability to reconfigure the number and types of outlets.
- Desktop outlets need further development for: ease of relocation (clip-on to desk, easy-connect underfloor), reconfigurable numbers and types of outlets (data, voice, power, video, environmental controls), and for general elegance or fun as a desktop object.

In order to evaluate the relative benefits of floor and desktop diffuser locations and diffuser specifications, there is a need for both laboratory and field studies to assess the thermal and air quality performance of a range of products in diverse climates and building use patterns.

7.9 The Integration of Interiors – Furniture, Walls, Ceilings, Lighting

The ultimate success of flexible and adaptive HVAC systems is the ability to design interior strategies at the outset, at the last minute, and continuously as the organization evolves – with confidence that the delivery of thermal comfort and indoor air quality can be ensured. There are a few interfaces that will be critical to flexibility, however – ensuring the maximum possible locations for diffusers and outlets in the floor, the use of furniture and walls to bring services to the desktop, and new design standards for ceilings and lighting.

To begin with, coordinating the design of systems that require underfloor 'real estate' is critical to ensure adequate opportunities for adding or relocating air diffusers and outlet boxes for the dynamic workplace. The architects and interior designers must be given a set of drawings highlighting the maximum number of possible location of air terminal units and outlet boxes, given possible underfloor obstructions (Shute 1992a). If multiple carpet tiles must be moved to relocate a diffuser or outlet, methods of quickly lifting partitions/furniture off of those tiles must be developed. Easy connections for relocating both diffusers and data/power/voice boxes must be installed, so non-union facilities personnel can reconfigure infrastructures to match changing space uses.

The architects and interior designers must be given a set of drawings highlighting the maximum possible location of air terminal units and outlet boxes, given possible underfloor obstructions (Shute 1992a).

If furniture legs, partitions, or relocatable wall components are used to bring HVAC and/or connectivity services from the floor or ceiling to the desktop, these components must also be designed to allow non-union facilities personnel to reconfigure infrastructures as space uses change. The vertical chases must not only be easy to access, but adequately sized to handle the ever growing demand

for "nodes of service" by the end users. Moreover, each individual should be given the ability to relocate the outlets and air diffusers at their workstation to match their particular work patterns and equipment layout.
Finally, the use of underfloor air systems enables the architect or interior designer to eliminate the conventional hung ceiling (that must be positioned below the lowest beam and duct combination) and to increase ceiling height in the occupied space. The elimination of a hung ceiling that must be positioned below the lowest beam and duct combination can increase ceiling height in the occupied space. However, acoustics must be resolved through floating acoustic ceilings and improved wall and floor absorption. In addition, the design of lighting, sprinklers, and return air need to be resolved in new ways. However, several of the traditional performance requirements of the ceiling plane must be resolved: acoustics must be addressed through acoustic ceiling elements and improved wall and floor absorption; sprinklers and return air need to be resolved in relation to the structural grid, with the assumption that the "nodes" – sprinkler heads and return air diffusers - will also need to be flexible to match interior space planning changes. As discussed in Chapter 4, dedicated return air diffusers evenly spaced along a return air duct help to ensure that stratified heat and the heat of lights is carried away before it becomes a cooling load for the space.

7.9 Other Innovations Needed in the Building Delivery Process

In addition to seeking the appropriate industrial partnerships dedicated to performance delivery rather than marketing a series of products (Performance 'Service' directly from Business to Customer), there are a number of innovations or changes needed in the building delivery process – from assembling the team to commissioning and training.

There are far more engineers who have never completed an underfloor air project than there are 'veteran' UFA engineers. While veteran underfloor air designers have built up an understanding of the sensitivity of performance to design decisions (such as diffuser type and density), there are no industry standards as of yet. Moreover, there are a significant number of engineers who are convinced that underfloor air is risky, and who have a long list of concerns as identified by Bauman and Arens (Bauman and Arens 1996); "New and unfamiliar technology, perceived higher costs, limited applicability to retrofit, lack of information and design guidelines, problems with applicable standards and codes (ASHRAE 55 was a problem but that has been fixed, and ASHRAE 113 is a problem because it only deals with a conventional overhead distribution), limited availability of task conditioning products, cold feet and draft problems with cold floors if underfloor distribution is used, problems with dirt and spillage entering underfloor distribution channels, condensation problems and humidity limits with underfloor systems."

To counter these arguments, it is becoming increasingly clear that, 1) underfloor air systems perform as well if not better than ceiling-based systems; 2) support a greater level of spatial change; 3) after the first experience most engineers are proponents; and that 4) underfloor air has taken over as much as 10% of the market, including many of the newest headquarters and "green" building landmarks.

Following a careful review of over 140 references and interviewing a dozen engineers, the research team recommends working with an engineer with experience designing an underfloor air system, and avoiding those who are not fully supportive of the concept. The entire design team should also be dedicated to the flexibility of a raised floor infrastructure, and be comfortable with the use of a "plenum design charrette" to assemble all the disciplines designing or utilizing the flexible infrastructures.

Although the use of three-dimensional CAD and physical mock-ups of the integrated infrastructures would be invaluable with any type of HVAC system, these steps are especially critical for flexible and adaptive systems. 3-Dimensional conflicts must be resolved before construction, and the flexibility of the system to allow constant relocation of diffusers and outlet boxes, zone controllers and fire separation, requires that all of the "kit of parts" – raised floor, carpet, HVAC distribution, nodes and controls, data/ power/ voice/ environment and security distribution, nodes, and controls, as well as earthquake, fire and security details - must be fully resolved. The use of line drawings with symbols and broad specifications, which can result in dramatically different products and product assemblies, must be replaced by 3-D models and physical mock-ups of competitive products to ensure on-site flexibility and adaptability.

Flexible and adaptive infrastructures are typically a series of prefabricated components that have been designed for 'plug and play' on-site assembly. Indeed, the 'plug-and-play' components can be assembled without unions, offering major speed and cost savings during construction, but raising serious concerns about job loss. For those industry partnerships where trained construction teams arrive with the product, construction sequencing and system interfaces, this is not a concern. If conventional construction crews for mechanical, electrical, data, and interior systems are to be coordinated, either on-line training or physical mock-up training will be required to ensure that the infrastructures are efficiently installed and maintain the flexibility required. Two examples of sequencing errors include: one installation where partial ducting was laid down too early, making the distribution of other components in wheeled carts unnecessarily difficult, and a second installation where the raised floor was installed prior to the data/power and voice cabling, requiring innumerable floor tiles to be opened and cabling to be threaded unnecessarily (see AWL time-lapse – Figure 7.10). A simple construction sequencing video on-line or hands-on training of the construction crew can ensure the construction time and cost savings possible with underfloor infrastructures (see cost savings in Chapter 9).

A simple construction sequencing video on-line or hands-on training of the construction crew can ensure the construction time and cost savings possible with underfloor infrastructures.

Finally, the importance of commissioning and training cannot be over-emphasized. While the integrated, 'plug-and-play' technologies of flexible and adaptive HVAC systems should be effective immediately "out-of-the-box", the general lack of familiarity with underfloor air systems would suggest the active involvement of a commissioning agent from the outset of design. Just as with engineer selection, the commissioning agent should have experience with underfloor air. The commissioning agent should take on responsibility for all of the flexible and adaptive infrastructures, including 1) drawing and specifications review, 2) site acceptance for the client, and 3) field commissioning and training of the facilities personnel and occupants. Alternatively, performance contracts could be written with the "flexible infrastructure" partner for the delivery of thermal, air quality, and connectivity service – with assurance that each of the three "commissioning" tasks will be fully completed.

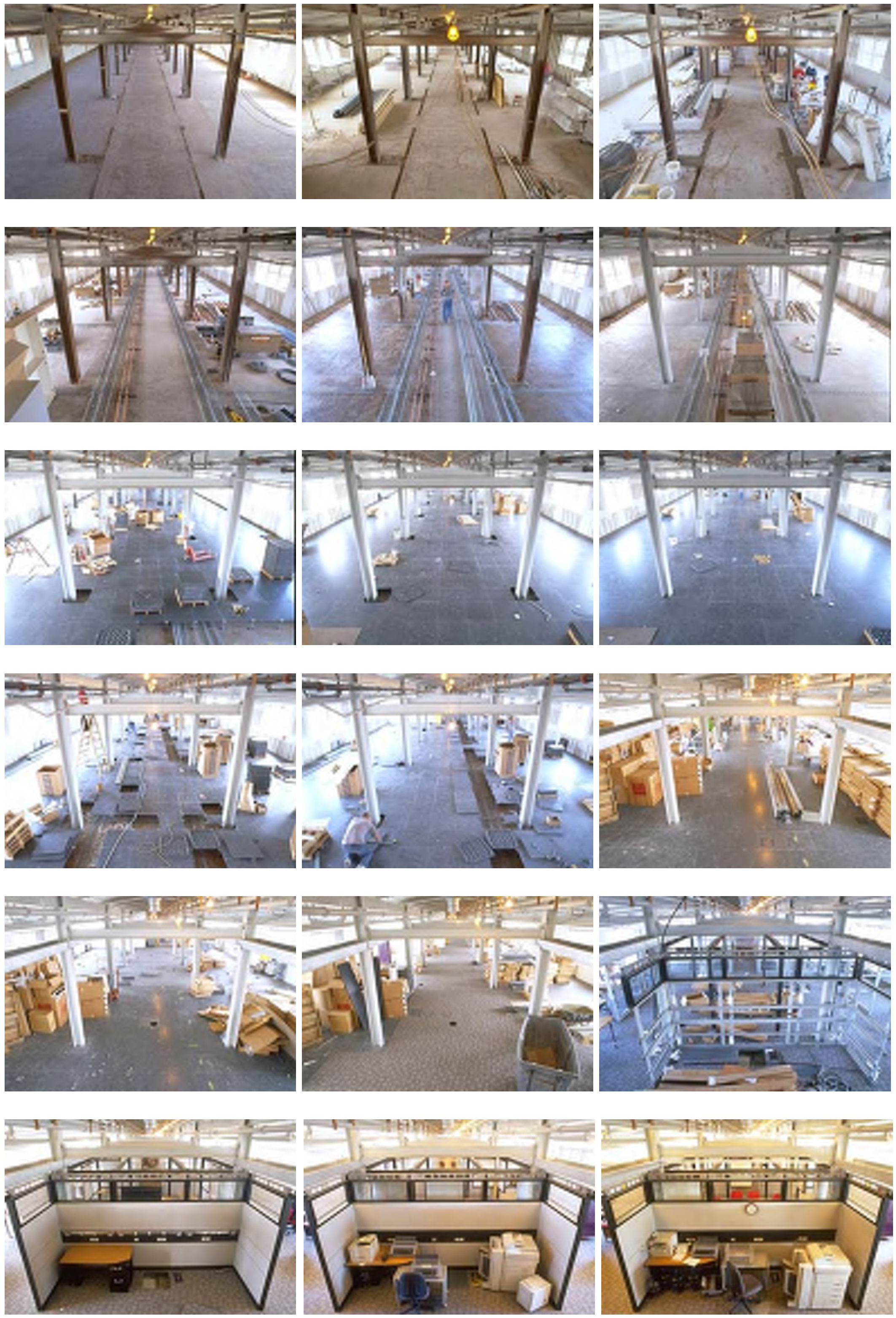


Figure 7.10: Adaptable Workplace Laboratory construction time-lapse sequence.

There are at least four areas where the performance of underfloor flexible and adaptive HVAC systems has led to concerns in comparison to more traditional ceiling-based VAV systems:

8.1 First Cost Concerns

Although past underfloor air (UFA) systems have resulted in first cost increases of up to 10%, the most recent new construction projects demonstrate first costs that are equal to or lower than ceiling systems (see Figure 8.1). These savings are due to downsizing of equipment, reduced ducting and zone boxes, as well as construction cost savings (time and materials). Increases in first costs are almost completely attributable to the cost of the raised floor that is often charged to the underfloor air system despite the fact that the plenum also serves networking installation and modification cost-savings.

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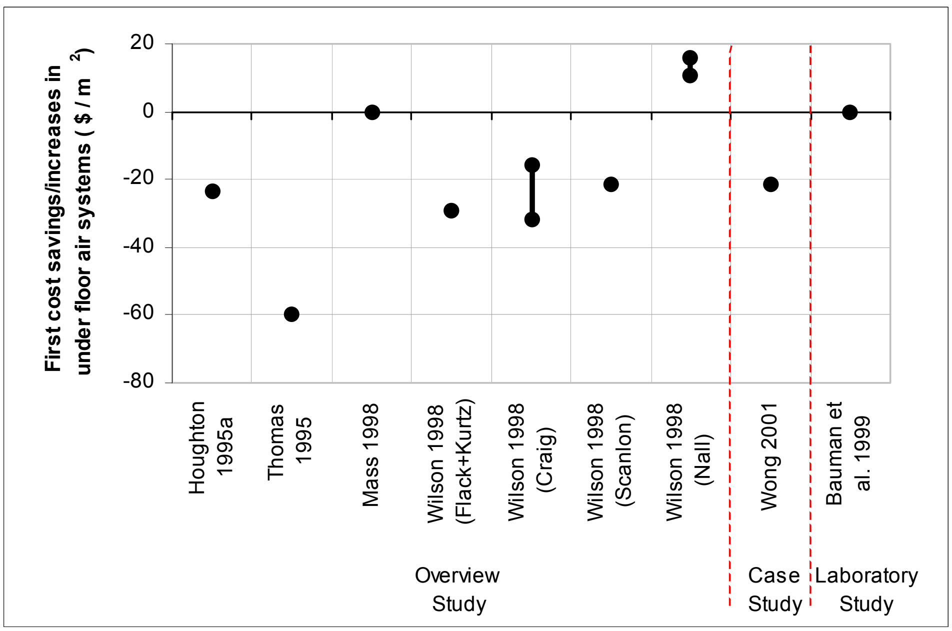

Figure 8.1: First cost savings/increases in underfloor air systems, collected from various references (Center for Building Performance and Diagnostics, 2002).

In relation to displacement ventilation (DV) systems, Sodec and Craig (Sodec and Craig 1990) state that, “In Europe, the total costs of displacement ventilation systems are at most 10% below the costs of conventional air-conditioning systems, not including the cost of the access floor.”

In buildings with significant cooling requirements, the more moderate supply air temperatures and lower capacity of underfloor air systems may require additional cooling infrastructure. Seppänen identified that while displacement ventilation results in lower energy costs, the first cost will be increased whenever additional cooling capacity requirements exceeds 13 Btuh/ft^2 (40 W/m^2). He estimates the first cost increases range from \$2-5/ft^2 (\$20-50/m^2) (Seppänen et. al. 1989).

L.D. Astorino in the PNC Firstside Bank check-processing center in Pittsburgh, PA installed underfloor air for ventilation and a percent of cooling, as well as a ceiling-based VAV system for the additional cooling requirements of the high-density office. This combination system still resulted in around a 12% lower first-cost than a conventional HVAC system.

In retrofit projects, the 5-20% increase in first costs for underfloor air systems are typically due to modifications required to ramp or rebuild elevator cores, fire stairs and bathrooms to the raised floor height.

In retrofit projects, the 5-20% increase in first costs for underfloor air systems are typically due to modifications required to ramp or rebuild elevator cores, fire stairs and bathrooms to the raised floor height. However, many existing buildings have core services that no longer meet the American Disabilities Act (ADA) standards and are due for renovation. Then, raised floor dimensions of UFA systems can be reduced to one or two fire stair riser dimensions to facilitate these integrations.

In addition, Val Lehr (Lehr 2001) states, "In retrofit projects, between 10-20% increased first costs are possible due to 'contractor fear.'

Whenever networking installation and churn are included in the cost equation, however, the costs of underfloor air (UFA) systems are typically competitive with ceiling systems. Value must also be placed on the ability to redesign for tenant requirements almost until move-in and to pursue "just-in-time" purchasing of terminal devices. Even in 1992, when underfloor air systems were not common in North America, Shute (Shute 1992a) of The Mitchell Partnership identified, "In the Toronto area, with the access floor excluded from the cost equation, the typical system has about a 10% cost premium compared to conventional VAV equivalent systems. …. The air terminal units, primary duct distribution, access floor and power distribution can be held back until just before turning the space over to the tenant, an interim financing savings nearly equates to the premium cost."

8.2 Thermal Comfort Concerns

8.2.1 Maximum Cooling Capacity and Thermal Decay in the Air Stream

Seppänen (Seppänen et al. 1989) reported that the maximum cooling capacity of displacement ventilation may be limited to 13Btuh/ft^2 (40W/m^2). While reductions in both first cost and energy cost have been reported with displacement systems, applications with a high cooling load may require supplementary cooling with higher first cost (Seppänen et al. 1989). Data demonstrating the effectiveness of underfloor air systems in delivering indoor air quality and thermal comfort without supplementary cooling - throughout most of northern Europe and North America– continues to accrue and needs to be captured for the engineering community.

While the use of thermal mass in the plenum for flywheel cooling may offer energy savings, there are recorded examples of thermal decay in the supply air temperatures from the vertical riser to the furthest air diffuser. In a long-term study of the York Mills project in Toronto, Canada, Shute (Shute 1995) of The Mitchell Partnership identified 3^{o}F (2^{o}C) of decay when distances from the point of source (riser) exceeded 30 feet. In a 1992 ASHRAE paper, Shute (Shute 1992) mentions, “Primary supply air ductwork should be induced down column furring spaces or in distributed cores nominally at centers not greater than 30 ft (9m). The access floor plenum area must be subcooled before each day’s operation to allow cool air to migrate without significant changes in air temperature (typically a 4 am startup).”

8.2.2 Stratification Concerns

Underfloor air systems rely on stratification for their energy savings and delivery of comfort and indoor air quality. Bauman (Bauman et al. 1995) identifies that an effective underfloor air system creates 2 zones in the occupied space; the lower zone is the cooler, fresher air supply that moves upward, and the upper zone is mixed air that is warmer and has more contaminants. The zones are separated by a horizontal plane; with the height of the plane determined by the strength of the internal heat sources vs. amount of supply air at the floor level. Ideally, the plane is above the occupant breathing level but well below the ceiling – with 6 ft (2 m) as a potential target.

However, ASHRAE standards call for no more than 5^{o}F (3^{o}C) of temperature stratification in the occupied zone, which may not be an appropriate standard for underfloor air systems (Heinemeier et al 1990).

“Only the cases of a large supply air volume (471 cfm [800 m^3/h]) and a small heat load (8 Btu/h.ft^2 [25 W/m^2]) met with displacement ventilation could meet the ASHRAE standard for thermal comfort in terms of vertical temperature difference” (Akimoto et al. 1999).

Webster et. al. 2000 mentions, “Stratification in the room is strongly dependent on the supply air volume and location, and heat load density.”

Especially with fan floor boxes (e.g. Tate’s TAM™), temperature stratification may exceed the comfort limits for vertical temperature difference of 3^{o}C between the 0.1m and 1.7m levels. In fact, due to the angle of the supply jet, a larger temperature difference exists between the 0.6 m and 1.7 m levels (Arens et. al.1991). “Under similar conditions, the smaller workstation is always cooler than the larger. This suggests that floor supply modules should not be located in small workstations where the supply jet enters directly into a regularly occupied workspace. The larger workstation allows the module to be positioned further away at a location that is only occasionally occupied” (Arens et. al.1991).

To reduce stratification concerns, underfloor air systems should be designed with larger diffuser sizes, greater diffuser densities, and lower air speeds. Low ceiling heights and inappropriate thermostat locations also play a role in reducing stratification concerns. Lower ceilings will lower the “horizontal plane” of stratified air and make thermal comfort conditions unacceptable. Sodec and Craig (Sodec and Craig 1990) and Adam (Adam 1986) identify a thermally comfortable 5^{o}C stratification between the occupied zone and a 3 meter high (9 ft) ceiling, but an inappropriate stratification in the occupied zone with a 2.5 meter (8 ft) ceiling. Thermostat location is also important, with Houghton (Houghton et. al. 1995a) arguing for thermostats that are not too close to diffusers or too high.

Finally, a number of engineers interviewed argued that induction swirl diffusers more effectively address stratification concerns by establishing the appropriate "horizontal plane" for stratified air with effective thermal mixing in the occupied zone, and more effectively addressing concerns of drafts.

8.2.3 Drafts

Many ceiling based VAV systems have resulted in occupant complaints about drafts, especially if diffuser densities are sparse and air velocities have been increased or temperatures lowered to meet rising cooling loads. Because of the ability to relocate and add diffusers in underfloor air systems, to meet changing cooling load conditions, UFA systems should have fewer complaints about drafts.

However, Melikov and Nielsen (Melikov and Nielsen 1989) evaluated the thermal comfort condition in 18 displacement ventilation (DV) spaces. Within the occupied zone, they found that 33% of measured locations had higher than 15% dissatisfied people due to draft conditions. These concerns have led to a consistent recommendation for relocatable, swirl diffusers. They also found that 40% of the occupied locations had a temperature difference between the head and feet larger than 5F (3K), the limit defined by ANSI/ASHRAE Standard 55-1992 on thermal conditions for human occupancy. Thermal Environmental Conditions for Human Occupancy. Akimoto (Akimoto et al. 1999) also identified the risk of drafts from a displacement air system, "The floor-supply displacement produced a uniformly low air velocity at each measurement height. A considerably higher air velocity near the floor, which may cause draft discomfort, was observed for the displacement ventilation system with a side wall mounted diffuser".

One research team, Melidov and Nielsen, found that 33% of measured locations had higher than 15% dissatisfied people due to draft conditions. These concerns have led to a consistent recommendation for relocatable, swirl diffusers.

The critical design decisions for reducing complaints of drafts will be air speed, face dimensions and user control. The Center for the Built Environment (Arens et. al. 1991) identified that, "The jet flow characteristics of both PEM^{TM} and TAM^{TM} systems produced high velocity in their immediate vicinity, increasing the risk of draft discomfort in these regions" and recommends that lower velocity from desktop nozzles may be desirable as well as larger face dimensions.

Bauman (Bauman et al. 1995) argues for a greater level of user control to limit complaints about drafts. ASHRAE limits air velocity to 0.15 m/s (30 fpm) maximum in winter and 0.8 m/s (160 fpm) summer because neither the velocity nor direction is controllable by occupants and the flow will be perceived as a draft. Therefore, Bauman (Bauman et al. 1995) recommends task air systems with higher air supply volumes but lower velocity where the local air supply can be controlled by the occupants to effectively provide for thermal conditioning without drafts (although it may create a non-uniform thermal environment).

Heinemeier (Heinemeier et. al. 1990) adds that further study is needed to quantify the comfort and energy benefits if air velocity or direction can be controlled by the occupants. While diffuser location and density is almost a given in underfloor air systems, the awareness of the occupants that they can individually modify even these conditions is rare. Chapter 5 identified five other control opportunities – direction of airflow, volume of airflow, fan speed, task temperature, and outside air content – that exist in the flexible and adaptive HVAC systems. The level of occupant training and use, and the impact this training has on individual comfort has not been fully studied.

8.3 Relative Humidity, Condensation and IAQ

Three indoor air quality concerns have been raised in the literature or by practicing engineers in relation to plenum underfloor air HVAC systems: 1) the inability to fully dehumidify and control relative humidity given higher supply air temperatures; 2) potential condensation in the plenum; and 3) dust and debris accumulation in the plenum. At the same time, some manufacturers argue that the plenum "duct" can be most effectively monitored and vacuumed for the highest IAQ.

8.3.1 Inability to Dehumidify Supply Air

Houghton (Houghton 1995a) identifies that the "warmer chilled water reduces the cooling coil's capacity to dehumidify." This is echoed by Bauman and Arens (Bauman and Arens 1996), "If a higher cooling coil temperature is used (allowing an increased chiller efficiency) to produce the warmer supply air temperatures needed in task air systems, the cooling coil's capacity to dehumidify will be reduced."

Both of these authors argue that a separate system will be required to dry outside air. According to engineers Earl Wong (Wong 2001) and Rick Yates (Yates 2000), humidity control can also be obtained by maintaining the conventional cooling coil temperature to dry out the incoming outside air, and then using the warmer return air (or outside air) to reheat the supply air, thus producing the desired 65-68 ^{o}F supply air temperature.

8.3.2 Condensation in the Plenum

Whenever unducted or partially ducted plenum air supply is introduced, there is a potential for condensation in the plenum if supply air wet bulb temperature approaches slab temperature. As previously described, Ove Arup in Lloyds of London used distributed thermo-sensors on the slab to ensure that slab temperatures would always be kept 2^{o}C (3.6^{o}F) above dewpoint. Shute (Shute 1992a) of The Mitchell Partnership argues, "In most environments, the floor plenum must maintain a mixed air temperature above 63^{o}F (17^{o}C) to prevent condensation on the structure."

Condensation concerns may limit the use of open plenum air supply in very humid climates, unless separate dehumidification systems are introduced.
A second source of potential condensation in underfloor air systems is the utilization of fan-coils and radiant cooling panels for additional cooling capacity. These thermal conditioning systems must be carefully designed to avoid dewpoint conditions and to ensure condensate management.

8.3.3 Dust and Debris

In unducted or partially ducted underfloor air systems, a number of references express concern about the potential of dust or debris to compromise the air quality of the plenum. The first concern is with the construction materials and construction debris itself, and the second with the introduction of dirt and pollutants from the occupied space. The air velocities in supply air plenums are low enough that measurable dirt and debris should not be entrained in the air supply; however, VOC's and molds can pose a risk, as well as pollutants migrating from other parts of the building through vertical shaft leaks.

To avoid a number of these concerns, Int-Hout (Int-Hout 2000) concludes that, "the concrete slab in an access floor air distribution system should be sealed properly to decrease the amount of dust produced by the concrete. If dirt falls into the underfloor plenum it would not be entrained into the supply air because the velocities in the underfloor plenum are low. It is recommended that access floor diffusers be avoided in locations where there will be a high possibility of liquid contamination, such as laboratories, cooking areas, or other sensitive areas."

Moreover, he states, "The use of in-floor supply air diffusers offers a potential for contamination from the occupied zone. The access floor diffuser should employ a catch basin as part of the volume regulation system. A typical basin will hold approximately 5.5 fl oz of liquid and should be cleaned as part of the regular maintenance system."

While Houghton (Houghton 1995) cautions that spillage into the plenum space can cause IAQ concerns, the ability to access and monitor potential pollutant sources in the easily accessible plenum can help to ensure that IAQ hazards in underfloor air systems are less than or no greater than build-up in conventional ceiling-based air delivery systems, including ductwork that is seldom cleaned.

8.3.4 Indoor Air Quality with Controls – the Need for Separating Task and Ambient

One additional IAQ concern that has been raised in relation to UF air system is the possibility that an excessive number of air diffusers would be dampered closed by the occupants, compromising the delivery of ventilation air. Early air diffusers were introduced without minimum air settings, and early diffuser densities were set without separating task and ambient conditioning solutions.

One additional IAQ concern that has been raised in relation to UF air system is the possibility that an excessive number of air diffusers would be dampered closed by the occupants, compromising the delivery of ventilation air.

Shute (Shute 1992a) argues, "Occupants should be encouraged to adjust diffuser location and volume but not to shut off the units entirely (to ensure ventilation requirements are met and for ambient cooling when they are away from their workstations). Manually controlled air terminals should have a minimum position between 30-50% of full flow to ensure ventilation."

Today, it seems that most dampered diffusers have minimum settings, and that many engineers are establishing a percentage of diffusers for the shared areas of the building. With these conditions, task air diffusers can be designed to allow each occupant to fine tune task thermal conditions within the broader-band ambient conditions.

8.4 Noise, Security and Fire Concerns

Given the availability of an open plenum that can extend from one end of a building to another, floor plenums raise the same concerns as ceiling plenums in relation to sound transmission, security, and smoke and fire migration. Consequently, the development of plenum dividers by manufacturers of raised floor is critical to the effective compartmentalization of these plenums.

While sound transmission may be an issue in underfloor air plenums for extreme privacy requirements, Sodec and Craig (Sodec and Craig 1990) identified that, "The total attenuation between two floor outlets in adjacent rooms depends on the distance between the air outlets. However, it is at least 29 decibels (dB) which corresponds roughly to an NC value of 10. Such a low sound pressure level can no longer be heard, so conversation transmission through floor outlets is negligible."

At the other end of the acoustic discussion, underfloor air systems have been challenged as being too quiet, eliminating the persistent mechanical system fan noise that is often relied on for partial sound masking. The frequency distribution of mechanical noise, however, and its' cycling, is inappropriate as a sound masking system for open office environments. Professionally installed sound masking systems carefully "sculpted" to mask speech cannot be replaced by 'noisy' HVAC systems.

Smoke and fire migration in the underfloor plenum is an issue to be resolved. Plenum dividers need to be further developed to ensure that HVAC modifications can be made with spatial change while still providing both security and smoke separation in the plenum for various tenants. The requirements for sprinklers or plenum rated cabling should be resolved on a national scale so that professionals do not have to negotiate each project. Given the low level of combustibles under the floor, most UFA installations under 18 inches deep have not been required to have sprinklers. Indeed, with only cabling as a potential source of fire, water would not be the best response for occupant safety. Smoke migration, on the other hand from fires either in the plenum or migrating from occupied spaces into the plenum could be addressed by some level of plenum subdivision (as in ceiling plenums) as well as with fire and smoke detectors. Since the most serious concerns related to fire and smoke migration occur at the ceiling level, design modification in the underfloor air plenum are secondary to the ceiling plenum. If sprinklers are mandated by the local codes, the opportunity to use the sprinkler piping for auxiliary cooling with fan-coils or heat pumps could be considered,

Plenum dividers need to be further developed to ensure that HVAC modifications can be made with spatial change while still providing both security and smoke separation in the plenum for various tenants.

but must be approved by local officials or pursued as an alternative for commercial buildings with NFPA (National Fire Protection Association).

There are at least seven areas where the performance of underfloor flexible and adaptive HVAC systems is compared to the performance of conventional ceiling-based VAV systems:

- *First Cost Gains*
- *Churn Cost Benefits – Organizational Effectiveness*
- *Individual Productivity Gains*
- *Thermal Comfort Gains*
- *Indoor Air Quality (IAQ) Gains*
- *Energy Savings*
- *Facilities Management (FM) Cost Benefits*
- *Marketing and Aesthetics*
- *"Just-in-Time" Purchasing of Infrastructure*

The gains identified in simulation and field case studies are summarized in this paragraph, with further detail in the following sections. Underfloor air, more and more frequently, has first cost parity with conventional ceiling systems, and measurable churn cost savings ranging from $1 - $5 per square foot per move – a substantial financial gain. In addition, these 'task-air' approaches have demonstrated measurable improvements in thermal comfort and indoor air quality, and in user satisfaction studies (Int-Hout 2000, Sodec and Craig 1990, Milam 1992, Faulkner et. al. 1991, Akimoto et. al. 1999, Houghton 1995a, Bauman and Arens 1996). They reduce age of air, support changing space layouts with continued levels of HVAC delivery, and provide an unprecedented level of user control - albeit still far short of the level of control we expect in our cars. By combining individual or workstation-based thermal conditioning systems (driven by occupancy presence), with ambient thermal conditioning (to much broader standards of comfort), 20-35% of energy savings can accompany the gains in individual comfort. Finally, facility management costs are often reduced, with more preventative maintenance of systems is possible. To quantitatively confirm these simulation and case study findings, however, a coordinated field research effort is critical.

9.1 First Cost Gains

While the professionals are divided on whether first costs for underfloor air (UFA) systems are slightly lower (Int-Hout 2000, Milam 1992, Hu et al. 1999, Thomas 1995), slightly higher (Loudermilk 1999, Bauman et al. 1999, Ellison and Ramsey 1989, Mass 1998) or neutral (York 1994), the increasing number of underfloor air projects and the growing experience of the industry are definitely reducing the costs of these flexible HVAC systems. In general, the literature concludes:

- In new construction, first costs of underfloor air systems are equal or lower than ceiling HVAC systems. Once a raised floor has been cost-justified for connectivity, the introduction of UFA should be cost neutral or a cost savings.

- In retrofit projects, the 5 - 20 percent increase in first costs that have been identified for UFA are possible, due to “contractor inexperience” and due to difficulties in integrating raised floors with existing building systems.

***In new construction, first costs of underfloor air systems are equal or lower than ceiling HVAC systems. Once a raised floor has been cost-justified for connectivity, the introduction of UFA should be cost neutral or a cost savings*.**

The full list of variables that have resulted in lower first costs for numerous under floor air systems include:

- Reduction in HVAC construction sequencing and installation costs
- Reduction in power, data/voice networking installation costs
- Reduced ductwork, lighter duct materials
- Reduction in HVAC controls
- Lower horsepower fans
- Smaller chillers
- Building height reduction
- Construction time and materials cost savings

The most detailed article on the first cost savings of underfloor air systems is Milam (Milam 1992), with the following summaries:

“Most HVAC equipment installation occurs below the raised floor, therefore laborers perform little work on ladders, platforms, or hoists. Most work can be conducted at floor level or on your knees. This allows substantial increases in laborer productivity that corresponds to savings in labor costs.”

“Since less cooling capacity is required at each air handling unit, smaller piping, insulation, pumps and refrigeration equipment are installed. Since smaller equipment can be installed easier and faster, additional labor savings are obtained.”

In retrofit projects, the 5 - 20 percent increase in first costs that have been identified for UFA, are possible due to “contractor inexperience” and due to difficulties in integrating raised floors with existing building systems.

“The majority of ductwork is eliminated from overhead distribution systems. While the return air systems are practically identical … the majority of ductwork is eliminated for the underfloor air system. This saves thousands of dollars per floor in both material and labor costs.”

“The underfloor air distribution system operates at a much lower static pressure than the conventional overhead system. This provides first cost savings in two areas:

- All ductwork can be constructed at low velocity and pressure classifications … A significant cost savings is accomplished by using lighter gauge metal in the limited amount of ductwork required in the system.

- The air-handling unit does not have to produce as much static pressure for the underfloor air distribution system. Typical VAV air-handling units operate at a total static pressure of 3.0-4.0 inWG. An UFA distribution system only needs to operate at a total static pressure of 1.0 to 1.25 inWG to maintain the 0.10 inWG static pressure in the supply plenum.” (It is important to note here that in their report, Webster et. al. [Webster et. al. 2000] mention that the total static pressure of a UFA system is approximately 25% less than a conventional system).

In one building project, “the lower pressure requirement allows a fifteen horsepower fan motor to be used for the underfloor system instead of the twenty-five horsepower fan motor required for the overhead system. This reduction in motor capacity translates into a first cost savings of $1000 to $2000 per floor. The smaller fan motor also represents an operating cost savings of $1500 to $3000 per year per floor" (Milam 1992). In relation to the use of underfloor displacement ventilation systems in the European market, Sodec and Craig (Sodec and Craig 1990) state, "In Europe, the total costs of displacement ventilation systems are at most 10% below the costs of conventional air-conditioning systems, not including the cost of the access floor." Thomas (Thomas 1995) identified considerable cost saving implications in construction, "A major pension fund has found savings in the construction costs in the order of £100/m^2; new property can benefit from a significant height reduction or additional floors." For new construction in the US market, Flack and Kurtz identified $2.70/ft^2 of construction cost savings (Wilson 1998, Figure 9.1). York (York 1994) concludes, "The cost of an intelligent building with a good quality access floor, a modular electrical distribution system and under-floor air is very close to the cost of a traditional poke-through building (less than 1 % greater)."

First Cost Savings with Access Floors

Description	Standard HVAC (overhead mixing)	Access Floor (underfl. air dist.)
BUILDING SHELL & CORE SYSTEMS		
Steel beam duct penetrations	$8,000	$0
Floor stop at core/ tenant space transition	$0	$4,200
TENANT FIT-OUT		
Drywall partitions allowance (to struct. floor)	$75,000	$82,000
Drywall furring of cols./ext. wall to 10 ft.	$38,620	$42,372
Raised flooring (incl. floor-mounted diffusers)	$0	$400,000
Acoustical and/ or drywall ceilings	$150,000	$150,000
Carpeting (rolled goods vs. tile)*	$111,128	$12,600
Fire sprinklers	$12.500	$12,500
HVAC		
Main duct**	$115,500	$0
Branch ducts to VAV terminals	$31,500	$16,000
Branch ducts to diffusers	$66,000	$0
Diffusers**	$46,876	$0
Ceiling registers	$31,260	$1,000
Duct insulation	$30,000	$0
Hot water reheat piping	$45,000	$45,000
VAV boxes	$76,600	$75,000
ELECTRICAL		
Power distribution	$100,000	$75,000
Receptacles	$34,725	$11,250
Data/ communication devices	$16,650	$0
Data/ communications cabling allowance	$200,000	$150,000
Cable tray vs. hard floor "routing"	$26,000	$3,000
Light fixtures	$156,500	$156,500
Low-voltage systems/ security/ video allow.	$100,000	$100,000
TOTAL	$1,471,859	$1,336,422
Cost per square foot	$29	$26
Cost per square meter	$316	$287

Data from 50,000 sq. ft. (4,650 sq. m) office building in California.
** Access flooring system included finished surface*
*** Main duct and diffusers included in cost of access floor*
Source Data provided by Flack & Kurtz Consulting Engineers and E Source Inc.; adapted by EBN to reflect more common practice.

Figure 9.1 – An example of first cost savings with access floors (Wilson, 1998).

9.2 Churn Cost Benefits – Supporting Organizational Effectiveness

The major cost of the underfloor air system is the raised floor itself – from $3-10 per square foot depending on manufacturer, quality and integrated components. However, the ability of the 'nodes of service' – diffusers and outlet boxes – to be relocated and increased in density ensures major churn cost benefits. Churn can be defined as the number of times per year that furniture, technology and environmental infrastructures are modified or relocated to meet the changing needs of the occupants. These changes can range from simple "box moves" of occupants' files and belongings, to furniture reconfiguration, to partition wall relocation or densification, to completely modified layouts for organizational reengineering, to "gut rehab." Given a mix of these types of moves and changes, "IFMA estimates the average annual churn rate in office buildings is 41% or more" (InterfaceAR 2001), with high tech companies often supporting 100-150% churn. This amounts to every individual in the organization moving at least once a year.

The cost of churn, for relocating furniture, walls, technology and people can be from $100 to $1,000 per person moved. This range of costs relates to the number of building components moved and the difficulty in moving them. Outlet boxes for power, data and voice are the most expensive components to move in many buildings as well as ducts, zone boxes, diffusers and controller assemblies. Flexible and adaptive HVAC systems such as underfloor air are specifically designed to make these moves and changes inexpensive in labor, materials and lost professional work time.

Every organization that has tracked the cost of churn is finding significant cost savings with raised floor systems that include HVAC and networking components designed for modification.

Every organization that has tracked the cost of churn is finding significant cost savings with raised floor systems that include HVAC and networking components designed for modification. Churn cost savings - for relocating a mix of furniture, walls and people - can be from $100 to $500 per person moved. Owens Corning has identified reductions from $450 per person to $140 per person moved as a result of their flexible infrastructures in the new headquarters building (Wilson 1998). Ray Engineering in Pittsburgh, PA identified $4.66 per square foot savings with each churn due to labor and material savings (Figure 9.2). Int-Hout (Int-Hout 2000) also identifies gains in employee work time, in addition to facility management labor and materials, "The access floor system, which utilizes access floor diffusers, allows modifications to the layout of the office space to be completed with little or no lost work time."

Ellison and Ramsey (Ellison and Ramsey 1989) identify, "When staff mobility rates are between 40 and 70% with a computer usage rate of 50%, paybacks of four to six years are not uncommon."

The HVAC savings in supporting spatial changes are related to the simple relocation or addition of floor outlets, without additional materials or external contractors. In several buildings, Shute (Shute 1992a) identified, "Local workstation air conditioning control devices can be relocated in less than five minutes with a screwdriver being the only tool required. Since the plenum is a common cool air reservoir, capacity to any zone may be adjusted by the addition or removal of an air terminal. No ductwork revision is required to alter control zones or capacities."

Square Foot Costs of Conventional Mechanical and Electrical Systems vs. Raised Floor Systems

	Tenant Fitout			Estimated First Churn Costs		
	Conventional Systems	*Raised Floor Systems*	*Savings*	*Overhead Systems*	*Raised Floor Systems*	*Savings*
Electrical Power						
Labor	0.98	0.28	0.70	0.98	0.28	0.70
Material	1.67	1.26	0.41	0.85	0.00	0.85
Subtotal	2.65	1.54	1.11	1.83	0.28	1.55
Telephone/Data						
Labor	0.56	0.32	0.24	0.56	0.32	0.24
Material	0.94	0.55	0.39	0.53	0.00	0.51
Subtotal	1.50	0.87	0.63	1.07	0.32	0.75
Mechanical HVAC						
Labor	1.15	0.10	1.05	1.15	0.09	1.06
Material	2.69	0.72	1.97	1.30	0.00	1.30
Subtotal	3.84	0.82	3.02	2.45	0.09	2.36
TOTAL	7.99	3.23	**$4.76**	5.35	0.69	**$4.66**

Figure 9.2: Pittsburgh developer Soffer identified a slight increase in first cost, but a $4.66/sf savings for each 100% churn (Loftness et. al. 1999).

The ease of relocating and adding diffusers and power/data/voice outlets also enables end-users to customize environmental and technical conditions when new space arrangements are created. This is a major gain in service over present churn which often occurs without modifying servicing systems, since the cost and difficulty of modifying traditional HVAC and power/data/voice systems is often prohibitive. The greatest cost savings undoubtedly occur at tenant rollover, where all individual workstations and shared spaces are reconfigured.

9.3 Individual Productivity Gains

The importance of thermal comfort and user control of thermal conditions on individual productivity has been the focus of a number of research efforts (Wyon 2001). At least two field studies have drawn correlations between underfloor air systems utilizing Johnson Controls PEM's™ and increases in worker productivity. An RPI study of the West Bend Mutual Insurance Headquarters identified a 2.8% benefit in individual productivity for those workers with operational task air systems (compared to 'dummy' systems) over a six-month period (Kroner et. al. 1992).

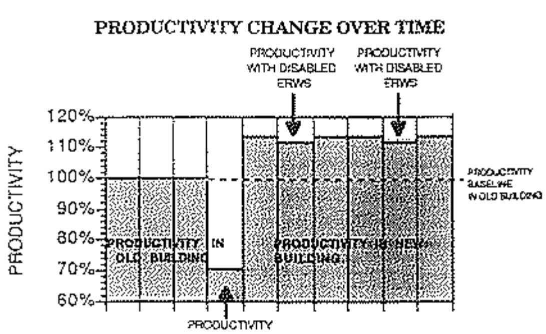

Figure 9.3: Productivity change at the West Bend Mutual Headquarters (Kroner et. al. 1992).

An RPI study of the West Bend Mutual Insurance Headquarters identified a 2.8% benefit in individual productivity for those workers with operational task air systems (compared to 'dummy' systems) over a six-month period (Kroner et. al. 1992).

This 2.8% is specifically related to the HVAC system, with overall productivity increases in the new building at 16%, given the multi-variant index that West Bend had been using for many years to measure individual productivity. Since productivity and health are two critical agendas for US employers, there is a need to complete a significant number of field studies on the productivity and health benefits of flexible and adaptable HVAC systems in relation to more traditional VAV systems.

9.4 Thermal Comfort Gains

According to the 1992 Corporate Facilities Monitor, conducted by the International Facility Management Association (IFMA), "the greatest complaint from employees working in a multitude of environments is unsatisfactory temperature comfort."

A majority of references stated that thermal comfort improves with underfloor air systems, although there can be significant variations in success given the type and location of diffuser and the level of individual control provided (see Thermal Concerns in Section 8.2). Bauman and Arens (Bauman and Arens 1996) state, "task/ambient conditioning systems have the potential to satisfy all occupants… as compared to the 80% satisfaction quota."

Measured studies show that thermal comfort is greater in underfloor air systems if air velocities are low and diffusers are designed for effective mixing without drafts, given measurements of predicted mean vote and percentage people dissatisfied.

Measured studies show that thermal comfort is greater in underfloor air systems if air velocities are low and diffusers are designed for effective mixing without drafts, given measurements of predicted mean vote and percentage people dissatisfied. Reductions in facility complaints have also been recorded, down to less than 10 calls per 1000 employees per year (1%). The very low velocities in displacement ventilation (DV) systems specifically have yielded measurable thermal comfort gains. Yuan (Yuan et al. 1999b) measured a Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) of less than 15% in the occupied zone with displacement ventilation if design guidelines are followed. "With proper design, displacement ventilation can maintain a thermally comfortable environment that has a low air velocity, a small temperature difference between the head and foot level, and a low percentage of dissatisfied people. …To maintain comfort levels, the temperature difference between the head and foot level of a sedentary occupant should be less than 3.5^{o}F" (Yuan et al. 1999b).

Seppänen et al. (Seppänen et al. 1989) also identified that displacement ventilation results in less than 4% predicted percentage of occupants who are thermally dissatisfied, as compared to over 15% in southern zones of buildings with VAV systems, in four climates.

The success of displacement air systems is the introduction of supply air at higher temperatures than ceiling HVAC systems, and at lower air velocities. For example, Yuan (Yuan et al. 1999b) states, "The air velocity in the room with displacement ventilation is generally small – less then 40 fpm – except in the thermal plumes and the flow near the floor and walls." He further states, (Yuan et. al. 1999c) "The temperature is nearly uniform in the horizontal direction except in the region close to an occupant (71.6 – 73.4^{o}F)."

In addition to more uniform temperatures, Burnley (Burnley 1993) identifies the comfort benefit of eliminating drafts, "At 1800 cfm, the velocity through the floor was approximately 10 fpm. Pressure drop across the carpet was measured at 0.025 in. H_2O (6.2 Pa). Point to point velocities across the entire floor were very uniform (within 10%). At this low velocity, there is no draft on feet or ankles."

In addition to careful design of supply air temperatures and speed, as well as room air mixing through diffuser type, the provision of individual control of diffuser location, volume and even direction is very important to user comfort. Ole Fanger clearly demonstrates that user control over temperature variables (air volume, speed, direction, or temperature) is critical to achieving 100% satisfaction, as well as supporting the changing comfort requirements of individuals and organizations facing increasingly more rapid changes in occupancy conditions.

9.5 Indoor Air Quality (IAQ) Gains

Three variables are often cited to quantify how underfloor air systems ensure greater indoor air quality – improved ventilation effectiveness/ age of air, the upward removal of pollutants out of the breathing zone, and the ability to effectively maintain the "ducts" in the form of open plenums.

A number of studies reveal a ventilation effectiveness of 1.0-2.0 as compared to typical field studies of overhead systems with a ventilation effectiveness of 0.5-1.0 (Milam 1992, Loudermilk 1999, Yuan et al. 1999a, Figure 9.4). These indoor air quality improvements are due to:

A number of studies reveal a ventilation effectiveness of 1.0-2.0 as compared to typical field studies of overhead systems with a ventilation effectiveness of 0.5-1.0.

1) the ability to relocate and add diffusers to match use patterns and to eliminate stagnant air regardless of the height of partitions and the degree of workspace enclosure (Hedge et al. 1990);
2) the proximity of the diffusers to the individual's breathing zone; and
3) the elimination of ceiling diffuser air distribution patterns that force lateral mixing and dispersion of the more polluted air at the ceiling level into the occupied zone (Int-Hout 2000).

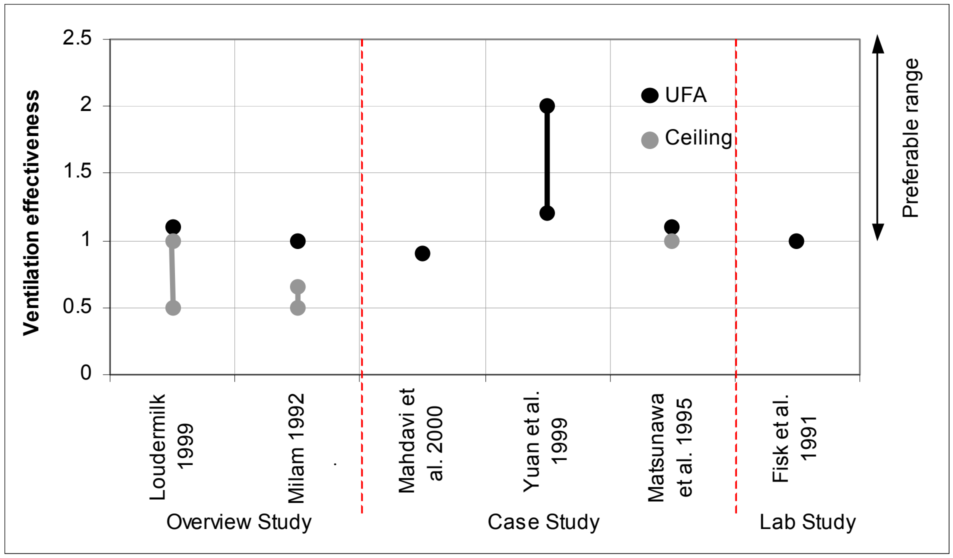

Figure 9.4: Range of ventilation effectiveness values reported in the literature (Center for Building Performance and Diagnostics, 2002).

Yuan et. al (Yuan et al. 1999c) also found that floor-based supply air typically yielded an age of air at the occupant's breathing level that was around 35% younger than the age at breathing-level locations with ceiling air diffusers. A measurement study by Mahdavi et. al. (Mahdavi et. al. 2000) has shown that desk-based air diffusers provide the best ventilation, with the mean age of air 4-6 minutes younger than air from ceiling based air diffusers.

Secondly, the upward delivery of ventilation air with ceiling based returns improves the immediate removal of local pollutants from occupants and equipment that typically is dispersed and pushed back to the occupants by ceiling based supply. Burnley (Burnley 1993) states that underfloor air delivery improves IAQ by, “sweeping airborne substances up and away from the breathing zone of the rooms’ occupants, and reducing cross-contamination from other parts of the room.”

Several studies (Sodec and Craig 1990, Kim and Homma 1992) identified that contaminant levels and CO_2 levels are lower with underfloor air systems (Figure 9.5).

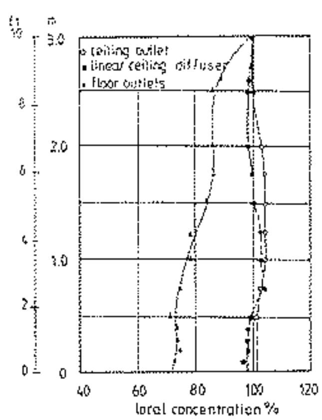

Figure 9.5: Concentration levels for different diffuser locations and types (Kim and Homma 1992).

While the IAQ issues of cumulative dust and pollutant sources in the UFA plenum (including cabling materials) must be further studied, especially in unducted systems, most manufacturers argue that the plenum "duct" can be more effectively monitored and vacuumed for the highest IAQ of any HVAC distribution system. A number of underfloor air manufacturers have diffuser baskets designed to catch falling dust and debris, as well as procedures for effective maintenance and cleaning of the underfloor air plenum.

In relation to IAQ gains, is important to discuss displacement ventilation (DV) and other underfloor air systems that separate ventilation and thermal conditioning, from the other flexible and adaptive systems. Underfloor air systems that have the potential to vary the quantity of outside air delivered to each occupant, will have the greatest potential to deliver outstanding indoor air quality.

A research study by Burnley (Burnley 1993) identified a 50% improvement in ventilation effectiveness in public building smoking rooms with displacement ventilation, "The ventilation rate procedure of ASHRAE (ASHRAE 1989) would require 1,800 cfm (850 L/s) of outside air to ventilate the room. Measurements of particulate, nicotine, and ammonia were used as tracers so that the effectiveness of displacement ventilation in a high-density smoking environment could be evaluated. Based on these results, it was found that 900 cfm of outside air mixed with 900 cfm of treated recycled air, produced acceptable air quality with upward displacement ventilation system."

Seppänen (Seppänen et al. 1989) and Yuan (Yuan et al. 1999b) also argue that displacement ventilation can ensure better average air quality in the occupied zone than traditional mixing VAV systems with recirculation - with little or no energy penalty. In studies using CO_2 as an indicator of contaminants, Yuan (Yuan et al. 1999b) cautions that, "With displacement ventilation, the CO_2 concentration is indeed lower in the lower zone (~550) than in the upper zone (~700). However, displacement ventilation may not provide better indoor air quality than mixing ventilation if the contaminant sources are not associated with heat sources, such as volatile organic compounds from building materials."

The separation of ventilation from thermal conditioning (possible in a number of flexible and adaptive HVAC system approaches) can dramatically reduce the quantity of air ducted through buildings (to as low as 10%), with greater control of the quality of that air, and the effective delivery of the air to the individual occupant.

Nonetheless, separate ventilation and thermal conditioning systems typically deliver 100% outdoor air without recirculation, and generally yield superior air quality and thermal comfort (Heinemeier et al. 1990, Seppänen et al. 1989, Yuan et al. 1999b). These systems also reduce the volume of air ducted through buildings, with a far greater potential to monitor and maintain IAQ. The separation of ventilation from thermal conditioning (possible in a number of flexible and adaptive HVAC system approaches) can dramatically reduce the quantity of air ducted through buildings (to as low as 10%), with greater control of the quality of that air, and the effective delivery of the air to the individual occupant.

9.6 Energy Savings

Numerous studies have identified that energy savings of underfloor air systems are between 20-35% due to improved ventilation effectiveness, stratification savings on fan power, higher supply temperatures (and the impact on central systems), and increased use of outside air (extended economizer). Int-Hout (Int-Hout 2000) summarizes a UFA system's contribution to energy savings: higher HVAC equipment efficiencies due to warmer air supplies (more "free cooling" at 60-65°F rather than 55°F), lower horsepower fans due to larger volume and lower pressure drops (at 0.1 inWG), better heat removal in an upflow to ceiling returns, storage effect of the slab that reduces load fluctuation, and higher air temperatures that allow chiller selection with higher operational efficiencies (higher evaporator temperatures).

Energy savings of underfloor air systems are between 20-35% due to improved ventilation effectiveness, stratification savings on fan power, higher supply temperatures (and the impact on central systems), and increased use of outside air (extended economizer).

The calculation of energy savings involves careful identification of at least five variables:

- Reduced fan power
- Reduced chiller capacitance and higher chiller efficiencies
- Extended economizer
- Shut-down of task systems – zoning and flex-time savings
- Flywheel cooling

9.6.1 Reduced Fan Power

While meeting ASHRAE maximum acceptable standards for stratification of 3.5-5°F (from foot to head), the ability of UFA to condition only the first six feet of air volume to comfort standards, employing the natural buoyancy of thermal plumes, offers a significant benefit in fan power energy savings. The fan power energy savings has been estimated at 5-30% (Figure 9.6) and attributed to reduced volume requirements for conditioned air resulting from the stratification benefits, and to better ventilation effectiveness for heat and pollutant removal (Sodec and Craig 1990, Hu et al. 1999, Loudermilk 1999, Bauman et al. 1999, Mass 1998).

The fan power energy savings has been estimated at 5-30% and attributed to reduced volume requirements for conditioned air resulting from the stratification benefits and to better ventilation effectiveness for heat and pollutant removal.

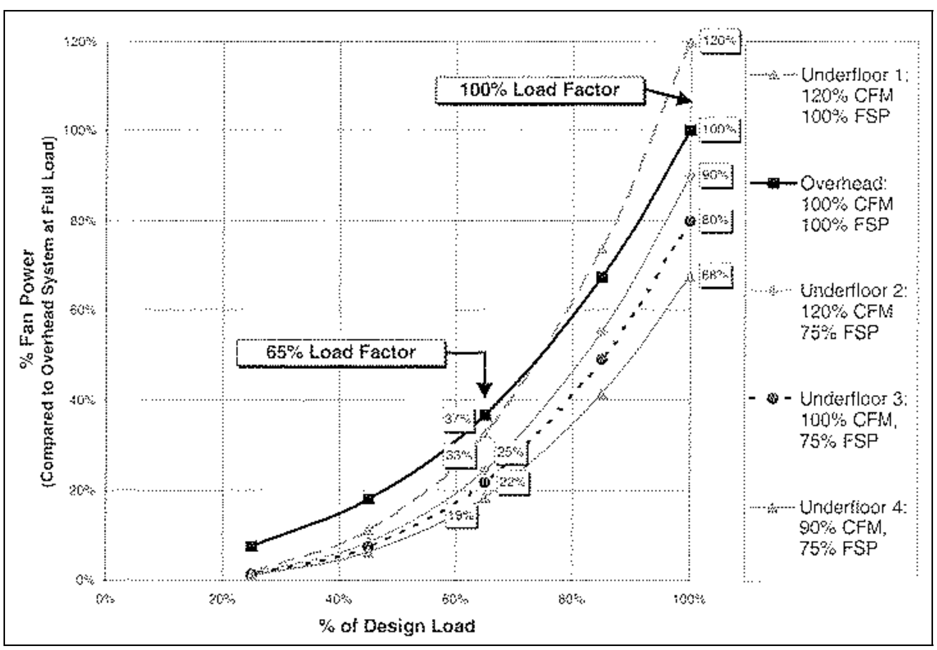

Figure 9.6: Fan power consumption in overhead versus underfloor systems (Webster et al 2000).

Loudermilk (Loudermilk 1999) states that the lower air flow requirements given the reduced volume to be conditioned, and the lower pressure requirements given naturally rising thermal air flow patterns, results in lower fan horsepower requirements with reduced mechanical ventilation costs. Bauman (Bauman 1999) breaks down the fan energy savings of 20-30% into: 20% reduction in supply volume due to stratification, 40% increase in supply volume due to higher supply temp, 40% decrease in system static pressure.

Kim and Homma (Kim and Homma 1992) argue that more effective pollutant removal in underfloor air systems reduce ventilation requirements, "With upward ventilation, the ventilation requirement per person, if the only contaminant source is the occupant, could be lessened to about 11.8 cfm (5.6 L/s) without exceeding a CO_2 concentration of 1000 ppm in the breathing zone."

In relation to displacement ventilation systems (DV), Hu et. al. (Hu et. al. 1999) also identifies ventilation effectiveness as assurance of fan energy savings, "Because of higher ventilation effectiveness, the displacement ventilation system can use less outdoor air than the mixing ventilation system to achieve the same indoor air quality. This investigation uses 7.7 L/s per person as minimum outdoor air for displacement ventilation and 10L/s for mixed ventilation."

While Milam (Milam 1992) identified the reduced static pressure in plenum distribution as contributing to reduced energy use, Houghton (Houghton 1995) argues that, "systems with an underfloor duct network (instead of an underfloor supply plenum) require at least as much fan power as ceiling-based duct systems."

There is some debate as to whether plenums with fan distribution boxes "pull UFA systems" – either in the floor or desk – will reduce or increase fan energy costs. While the central system's fan requirements can be reduced, the energy costs of distributed fans with local volume, air speed, and shut down controls has not been thoroughly studied. In an early study, Arens et. al. (Arens et. al. 1991) identified the potential of annual energy savings from 4% (hot climate) to 21% (mild climate) for floor based fans (Tate's TAM™), and 9% (hot climate) to 27% (mild climate) for desk-based fan mixing boxes (Johnson Controls PEM™). Moreover, the floor based TAM™'s demonstrated peak energy savings of 6%, while the desk based PEM™'s had increased peak energy costs. They conclude, however, with a design mandate, "In terms of energy, fan diffusers are useful only with occupancy sensors."

9.6.2 Reduced Chiller Capacity and Higher Chiller Efficiencies

The paired benefits of higher supply air temperatures possible in underfloor air delivery (60-68°F) (see Figure 9.7) and reduced conditioned volume through stratification, allows a warmer cooling coil and warmer evaporator temperatures, resulting in reduced chiller capacitance (0.60 kW/ton to 0.37 kW/ton according to E-Source in Houghton 1995a) and 3-15% higher chiller efficiencies (Int-Hout 2000, Houghton 1995a, Loudermilk 1999). Heinemeier (Heinemeier et al. 1990) argues that cooling supply air temperatures can be higher since they are delivered directly to the occupant, with each 1°C rise in the evaporator temperature yielding 3.1% increased Coefficient of Performance (COP) (1.7% for 1^{o}F). "For example, if the supply temperature can be raised from 13^{o}C to 18^{o}C (with a corresponding increase in the evaporator temperature), the COP can be increased by about 17%" (Sodec and Craig 1990).

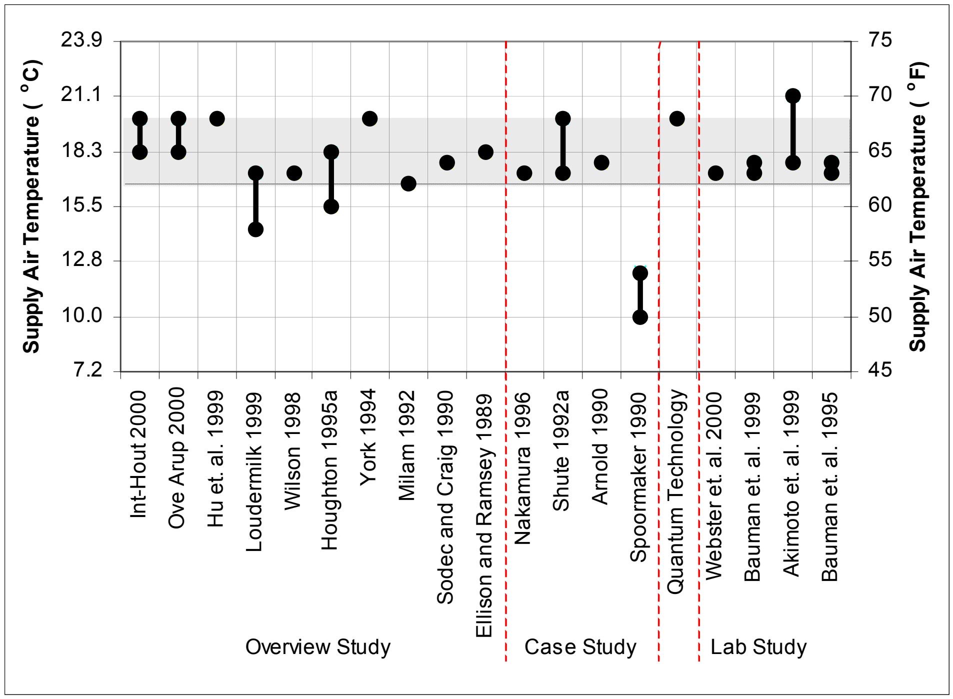

Figure 9.7: Range of supply air temperatures for underfloor air, typical range: 62-68^{o}F (Center for Building Performance and Diagnostics, 2002).

The upflow air pattern builds on the natural thermal buoyancy of heat loads, returning some heat gain unneutralized to the return air stream, reducing the cooling capacity requirements by as much as 15% (Heinemeier et al. 1990, Sodec and Craig 1990). Heat from ceiling-mounted lights is also more effectively removed before it enters the occupied zone with ceiling located return air (Int-Hout 2000). Moreover, the higher supply air temperatures with chilled water temperatures of 10-12^{o}C (vs. 5-6^{o}C) allow alternative cooling sources to be competitive, including aquifer and ground sources.

In relation to displacement ventilation (DV), Hu (Hu et. al. 1999) cites that the, "Higher supply air temperature means that the cold-water temperature can also be higher than that for mixing ventilation. Therefore, the chiller in displacement ventilation can have better performance. In this paper, the authors have used a slightly higher COP for displacement ventilation chiller (3.0) than for mixing system (2.9)."

Akimoto (Akimoto et al. 1999) cites for all underfloor air systems that the, "Efficiency of the refrigerating machine can be improved with a higher set point of supply chilled water temperature. This effect depends on the type of refrigerating equipment – For example, a double-effect absorption refrigerating machine can achieve almost 5% energy reduction when applying 45^{o}F for the supply chilled water temperature in comparison to applying the normal 41^{o}F. "If the temperature difference between supply and return chilled water is 13°F instead of the normal 9°F, 29% energy conservation can be expected."

In a case building, E-Source presents the benefits of underfloor air on reduced chilled water temperature in terms of increased chiller efficiency from 0.60 kW/ton to 0.37 kW/ton (Houghton 1995a).

9.6.3 Extended Economizer - Free Cooling

A number of the engineers interviewed identified the significant energy benefits of higher cooling air temperatures in underfloor air systems to extend the economizer or free-cooling capabilities of HVAC systems (Heinemeier et al. 1990, Int-Hout 2000). These savings are most significant in mild climates and, "when both supply and return temperatures are increased" (Arens et. al. 1991).

McGregor of Ove Arup (McGregor 2001), McCarry of Keen Engineering (McCarry 2001), and Wilson (Wilson 1998) further argue that appropriately designed underfloor air buildings could allow mechanical systems to be shut off altogether to take advantage of natural ventilation as the primary ventilation source during mild and cool months.

9.6.4 Shut-Down of Task Systems – Zoning and Flex-Time Savings

With the introduction of one or more diffusers in each workstation, and the willingness to separate task conditions from ambient conditions, underfloor air systems offer far greater capability to yield operational energy savings through partial conditioning based on zone and flex-time requirements (Heinemeier et al 1990, Sodec and Craig 1990, Bauman et al. 1997).

With the introduction of one or more diffusers in each workstation, and the willingness to separate task conditions from ambient conditions, underfloor air systems offer far greater capability to yield operational energy savings through partial conditioning based on zone and flex-time requirements.

Arens et. al. (Arens et. al. 1991) state, "Localized thermal distribution (LTD) systems have the potential to improve the energy efficiency of the building's air distribution system by enabling only the local workstation environments to be tightly controlled while relaxing the energy and comfort requirements in less critical areas."

Given the volume/speed and shut-down capabilities of task air "pull" systems, the distributed fan energy use can vary from 0 to 80 watts, with significant reductions in the central system fan. Arens et. al. (Arens et. al. 1991) calculate the fan wattages at:

TAM™ – rated for 47W for 175 cfm, 20W for 92 cfm
PEM™ - 82W for fully on, 50W for the middle position, 15W at the lowest position

"The savings are because of the flexibility in operation and the resulting reduction in the central system fan. If these are not considered, there will be penalty" (Arens et. al. 1991).

Given the use of occupancy sensors to limit excessive energy use, a building energy simulation using DOE2 done by Bauman et. al, 1997, compared three different task/ambient conditioning system configurations versus a base case building consisting of a reasonably efficient standard overhead system with economizer. The results showed that the PEM™ desk-based task air system in a

San Jose, CA office building could save annually as much as 18% of the cooling energy, 18% of the fan/pump energy, and 10% of the total electricity.

9.6.5 Flywheel Cooling through Night Air or Off-peak Energy Use

In unducted or partially ducted underfloor air systems, there is a potential to use the mass of the floor slab and the raised floor tiles as thermal capacitance to store night-time "coolth" and forestall daytime overheating (Int-Hout 2000). The effectiveness of underfloor air systems to deliver this 'flywheel' cooling, through night-time flushing of the exposed concrete surfaces in an underfloor air plenum, has not been fully quantified. Although Lloyds of London facility managers report significant comfort benefits of night 'flushing' to cope with the morning influx of 6000 insurance traders, the cost-benefits of using off-peak electricity to mechanically cool the plenum are just beginning to be explored.

9.6.6 How Much Total and Peak Energy Savings?

Figure 9.8 begins to log the range of energy savings that have been found through field studies, simulations, and laboratory studies of underfloor air systems. Although not differentiated by system or climate type, the figures identify between 5-40% savings. A comparative engineering study for the NEC headquarters building in Japan identified 30-50% reduced energy consumption for the underfloor air system compared to conventional systems (Murakami et al. 1992).

In initial cost savings of the mechanical system, with proportional benefits in peak power savings and annual energy savings, both the air handler and the chiller can be downsized. A major manufacturer of air diffusers for underfloor air systems, Kranz, suggests that with a 15,000 ft^2 (1500 m^2) floor plate, the air handler can be downsized from 25 to 10 horsepower (19,000-7,500 watts) with underfloor air distribution. Milam (Milam 1992) states that both cooling and heating system capacities can be reduced in underfloor air systems, cooling by 13-14%, and heating by 35%. However, chiller sizing must also be studied in relation to latent load requirements, and it is not clear from the literature if chillers can be downsized – especially in climates where humidity control and latent loads may dictate chiller size.

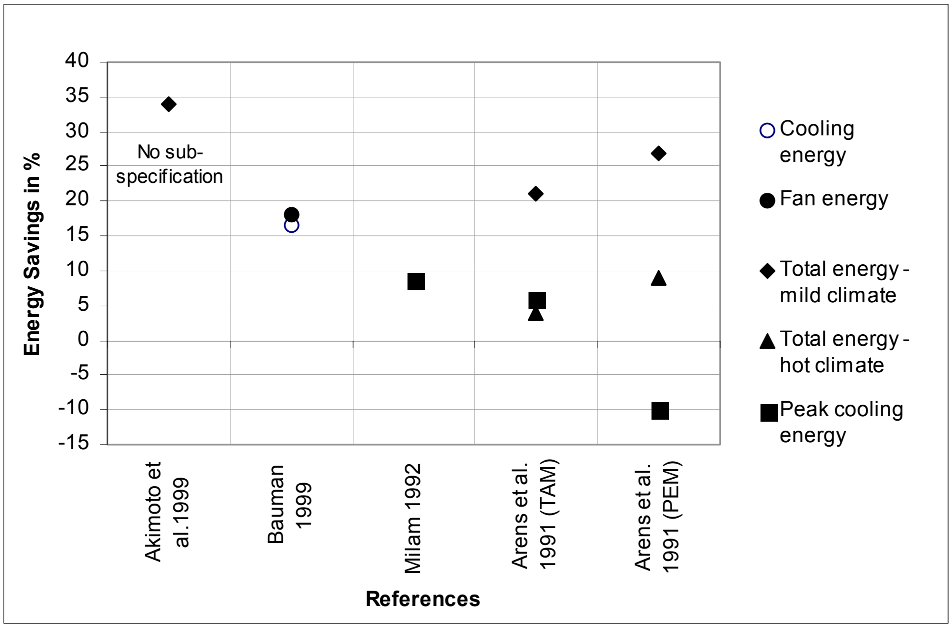

Figure 9.8: Five researchers show annual energy savings from 5-35% with underfloor air systems (Center for Building Performance and Diagnostics, 2002).

9.7 Facilities Management (FM) Cost Benefits

The facility management benefits of underfloor air have not been fully quantified. However, examples of reduced commissioning requirements, reduced complaints and subsequent time and labor, lower maintenance and churn costs, and greater equipment durability have been cited.

Reduced commissioning requirements are provided by the ease of access and reconfigurability to meet last minute occupancy conditions. Thomas (Thomas 1995) identified at 4 Millbank in Westminster “savings of £103/m^2 and £170/m^2 respectively had been achieved in fitting out and refitting this business center which incorporates underfloor air-conditioning throughout.”

Houghton (Houghton 1995) stated commissioning gains from the self-balancing configuration of an underfloor air system because, "all diffusers operate at nearly the same pressure conditions."

While complaint records are kept by most organizations, the cost of response is not well documented. Nonetheless, a number of facility managers in underfloor air buildings have identified significant reductions in occupant complaints (Hedge et al. 1990). Numerous survey studies in underfloor air buildings have indicated significant gains in user satisfaction with thermal and air quality conditions (Hedge et. al. 1993, Bauman et. al. 1997). The benefits of fewer complaints, aside from the obvious improvement in user satisfaction (one primary goal of ASHRAE standards), is the ability of the FM team to address preventative maintenance. The facility manager of the West Bend Mutual Insurance headquarters, with a UFA plenum and desktop air PEM™ installation, identified a reduction in staff requirements per square foot or occupant, as well as the first-time-in-his-career opportunity to complete preventive maintenance tasks.

In passive diffuser plenum supply systems, Mass (Mass 1998) argues that maintenance costs are sure to plummet since there are no variable air volume (VAV) boxes - and therefore fewer devices that need inspection, repair, and replacement. Milam (Milam 1992) identified that renovation requires only the relocation or addition of floor outlets and the relocation or addition of plenum dividers (as needed) to meet the changing zone demands. “This process is cheap and can be completed much quicker than relocating ductwork and Powered Induction Units or VAV units” (Milam 1992).

Despite concerns about the maintenance of distributed fans in “pull” underfloor air systems, some facility managers have identified reduced overall maintenance costs and reduced churn costs, in addition to higher user satisfaction.

Finally, there is anecdotal evidence that equipment durability is improved because of the ease of access for maintenance and the reduced necessity to meet all load variations through continuous adjustments of the central system.

9.8 Marketing and Aesthetics

A number of U.S. markets have recorded an increase in the ability to attract tenants in underfloor air buildings, especially if there are no increases in rent costs, due to perceived and real gains in thermal comfort, spatial flexibility, and aesthetics.

Numerous IFMA and BOMA studies found that the tenants’ ability to control temperature in their space was on the list of most important features for 96% of respondents, and also showed up on the list of capabilities with which tenants were least satisfied (65% 1999 BOMA / ULI survey). Underfloor air systems are earning a reputation for providing higher user satisfaction with thermal conditions.

Developers are also receptive to the idea that the flexibility of UFA systems can reduce move-in time and allow for office space customization for a wide range of potential tenants. The ease of churn as well as the cost savings in churn can enable developers to propose higher rental rates or to accrue greater savings in meeting the spatial, technical and environmental changes of their tenants. Ellison and Ramsey (Ellison and Ramsey 1989) added that in the residential Alameda Towers in Kansas City, MO, “The raised floor eliminates the need to break through another unit’s ceiling for a service connection,” which ensures that tenants will not have to anticipate disruption time and costs.

The reduced demand for servicing from the ceiling can also allow for decreased floor to floor requirements or provide new tenant amenities, such as higher articulated ceilings. Wilson (Wilson 1998) concludes that, “access floor plenums are usually significantly shallower than ceiling plenums”- offering to increase ceiling height or reduce slab-to-slab distance”.

Finally, there is the up-to-date image offered by 'plug-and-play' underfloor air systems that appeals to today's dynamic knowledge worker. Many underfloor air buildings take advantage of the elimination of ceiling based distribution of HVAC, lighting and networking to create playful acoustic ceiling elements, exposed structural trusswork and combined indirect and direct lighting approaches – capturing the loft aesthetics of the next generation.

Sodec and Craig (Sodec and Craig 1990) identified an entire string of potential benefits of underfloor air in their report – which translates into a powerful marketing strategy: improved occupant thermal comfort, improved ventilation and air quality, improved ability to handle local load variations, reduced building energy use, lower life-cycle building costs, improved flexibility in providing and maintaining building services, improved occupant satisfaction and increased worker productivity.

9.9 "Just in Time" Purchasing of Infrastructure

A major advantage of flexible and adaptive HVAC systems is the ability to increase or decrease the 'nodes of service' – diffusers, outlet boxes, even local fan-coils – as needed. This allows the building owner or tenant to purchase a percentage of the infrastructure as needed over time, removing the expenditures from the first cost package.

For the developer, these 'nodes of service' can be shifted into the tenant fit-out budget, and again purchased as needed rather than redundant purchasing for maximum future requirements. Shute recommended in 1992 (Shute 1992a), that while the typical system had about a 10% cost premium compared to conventional VAV equivalent systems in the Toronto area, the air terminal units, the primary duct distribution, access floor and power distribution could be held back until just before turning the space over to the tenant, an interim financing savings that nearly equates to the premium cost. Moreover, the 'plug-and-play' nature of underfloor air systems allows the first round purchases of nodes – diffusers, outlet boxes, local fan-coils – to be redeployed from one area in the building to another for maximum utilization before additional nodes need be purchased. The slow addition of terminal units as needed will 'enrich' the building for future occupants, or enable tenants to pack up their high performance 'plug-and-play' infrastructures with the desktop computers and furniture.

This study identifies the state-of-the-art in flexible and adaptive HVAC distribution systems for office buildings, as well as known performance concerns and performance benefits. These innovative systems have demonstrated measurable gains for energy conservation, thermal comfort and for organizational change cost-savings, benefits which should be quantitatively verified in field studies. At the same time, there is significant need for further system and component innovation to address first costs, individual control, and moisture/IAQ issues - innovations that should be substantially developed in laboratory studies. As a result, it is proposed that ARTI should pursue two additional phases of research:

Phase 2: **Field Case Studies** of Flexible and Adaptive HVAC Distribution Systems
Phase 3: **Laboratory Studies** of Flexible and Adaptive HVAC Distribution Systems

10.1 Field Case Studies

The list of buildings with flexible and adaptable HVAC distributions system, and the engineering and architectural firms involved in their design, is attached as Appendix A2. Well over 200 recently completed buildings demonstrate flexible and adaptive HVAC Distribution Systems, designed to support the 'dynamic workplace' by delivering networking, ventilation and thermal conditioning to each workstation, either at floor level or at desktop, with greater ease of reconfiguration. The research team anticipates that a second phase of this ARTI research effort will fully utilize field studies of selected building examples to further explore the design choices and performance differences of different flexible and adaptive HVAC systems. The apparent success of these existing projects is driving a number of industry collaborations to offer "packaged" solutions to flexible infrastructures – a packaging of raised floors, data/voice/power networking and outlets, thermal conditioning and ventilation ducting, piping and terminal units. While this study has attempted to group the flexible HVAC approaches into four broad system types, there are a significant number of subsystem variations within these groupings:

- Pressurized or 'Push' Underfloor Air Systems for Ventilation and Thermal Conditioning
- Distributed Fans or 'Pull' Underfloor Air Systems for Ventilation & Thermal Conditioning
- Underfloor Ventilation with Separate Thermal Conditioning
- Ceiling-based Flexible and Adaptive Systems

The Field Study phase of flexible and adaptive HVAC distribution systems should update the salient and comparative features of the range of facilities, which could be grouped based on a different structure, with facilities preidentified and approached for in-depth field study. The performance of flexible and adaptive HVAC, including operational and waste cost-savings, should be studied relative to more conventional infrastructures (control buildings), working with owners who maintain historical records.

The development of a uniform field data collection, recording and analysis method will be required for ensuring statistically significant results from the field study effort. Field data collection and analysis should combine portable instrumentation with questionnaires and interviews to establish a number of the following factors:

- System availability, level of industrial prototype testing, robustness in practice given various functions and climates.
- First costs of components and entire systems – materials, labor, engineering
- Energy costs – peak and annual operational costs/cost savings
- Thermal Comfort – instrumentation and user questionnaires in various space types, various occupant and equipment densities
- Air Quality – instrumentation and user questionnaires in various space types, various occupant and equipment densities
- Acoustic Quality – instrumentation and user questionnaires in various space types, various occupant and equipment densities
- Facility management cost/benefits – staffing numbers, complaint numbers, cost of response
- Organizational Churn cost/benefits – spatial reconfigurations and technology changes
- Individual and Organizational Productivity cost/benefits – multi-year comparative data on individual productivity, customer satisfaction, health and absenteeism, attraction/retention, or other indices of employee cost/benefits.

The in-depth field studies should also address the barriers and opportunities for both industry and professional practice in the implementation of high performance innovative, flexible and adaptive HVAC distribution systems.

These field studies would result in a series of reports with uniform field data collection and analysis to ensure comparative conclusions and a white paper on the barriers and opportunities for the widespread implementation of energy efficient flexible and adaptive HVAC distribution systems.

10.2 Laboratory Research Effort

While “consumer” and industrial assemblies in almost every market sector are iteratively and collaboratively engineered, prototyped, and tested, the building sector continues to assemble building systems idiosyncratically, in a non-repetitive, non-robust fashion. The importance of HVAC distribution and control strategies to indoor air quality and thermal comfort, as well as substantial proportions of the building’s first and life cycle costs, make collaborative design, prototyping and testing imperative. This final phase of the effort to evaluate innovative, flexible and adaptive HVAC distribution strategies would require working directly with the range of U.S. industries involved in manufacturing generation, distribution and terminal units to establish comparative configuration "packages" for laboratory testing. This phase would require the identification of an appropriate testing facility or the construction of a new facility for iterative testing. The results of this research would significantly contribute toward improvement of the affordability, performance, reliability and professional commitment to flexible and adaptive distribution systems.

Beginning with the most common 'integrated' approaches to flexible and adaptive HVAC seen in the field, these laboratory studies would be responsible for comparatively quantifying the full list of performance concerns and benefits, as well as issues of constructability and modification. By working with several multi-disciplinary design and manufacturing teams, this laboratory study effort should also explore the potential of system refinement and of new "plug and play" technologies - an approach well developed in other market sectors to support distributed capability, user customization, and the ability for end users to help themselves if systems are not meeting requirements. By bringing together multi-disciplinary design teams with manufacturers, the development of innovative assemblies for laboratory testing could shift the industry from independent manufacturing and delivery of generator/ distribution/ terminal units to compatible assemblies and integrated systems. Opportunities for prototyped and tested modular HVAC systems - thermal and air supply - with pre-engineered distribution and terminal units are a major market opportunity with significant performance gains - bringing 'car-like' functionality and cost effectiveness into the commercial building sector.

10.3 Additional Questions for Field Study and/or Laboratory Research Phases (by Chapter)

This ARTI phase 1 study describes the range of flexible HVAC distribution approaches documented in available literature, the frequency of their occurrence, and the range of their recorded performance. The document includes figures and tables of the quantitative and qualitative performance indices available, as well as illustration of products and integrated systems. Key design or performance conclusions have been highlighted throughout the report. The next two phases of study – field case studies and laboratory studies – should further address the performance concerns and benefits of innovative HVAC distribution approaches, addressing a host of questions raised in the nine preceding chapters of this report, recaptured below. While the research team is reasonably confident that they have a comprehensive overview in relation to North American references, international practices need further study to identify European, Australian, South-African and Asian approaches to flexible and adaptive HVAC distribution systems.

Chapter 2: Defining Flexible and Adaptive HVAC System Types

The four significantly different system configurations outlined and the 15 variations that have been identified from over 300 buildings worldwide, have all yielded measurable performance gains for the owners and end-users. The need remains, however, to fully study the cost/benefits of these system types, by region and building function, to improve the next generation of flexible and adaptive HVAC systems.

The advantages of a “pull” underfloor air system with neutral or zero pressure plenums as compared to the “push” underfloor air has not been adequately studied – neither for thermal, ventilation, maintenance, user satisfaction or air quality. The additional cost of fan air diffusers over passive diffusers and the perception of maintenance and noise issues may have prematurely led most manufacturers and engineers away from the potential advantages of fan air diffusers.

A number of projects combine central fans for pressurized plenums (push) with distributed floor fans for increasing local delivery of conditioned air, especially in conference rooms (pull). It is unclear to what extent this will cause short-circuiting as the fan diffusers pull air down into the plenum through the passive diffusers. The importance of clearly designing either a pressurized plenum or a neutral plenum with distributed fans must be carefully studied.

Two concerns have been raised that should be further studied for pressurized plenum systems (both separate and combined thermal/ ventilation systems). First, the air velocity is so low that users often cannot tell if the system is on, with no convective airflow felt at the diffuser. Despite effective ventilation at every workstation, the system does not give the occupant the ‘feel’ of air movement, which is often used as a cue that the system is working. Second, the possibility that an open plenum might be a source of migrating pollutants - from unsealed risers or of local air quality concerns such as dust and water accumulation - should be studied.

The fully ducted underfloor system often preferred in Europe due to air quality concerns, can be designed to combine highly pressurized ducts with passive diffusers (ducted, push UFA) or low pressure ducts with distributed floor or desk fans (ducted, pull UFA). There is a need for comparative study of the performance of these two fully ducted variations, and their cost-benefit.

Flexible and adaptive ceiling based HVAC distribution systems have not been well documented, either for their flexibility to support organizational change or for their performance in the field.

Chapter 3: Plenum Design Alternatives

While laboratory studies have been completed on the impact of plenum height on pressure drops and thermal decay, there is a need for field studies to establish the importance of:

- Distance from vertical riser
- Pressurization and tightness
- Plenum materials and thermal storage
- Module and carpet tiles

Several raised floor systems make underfloor partitioning difficult by eliminating the flat face on the underside of the floor for structural or material reasons, or introducing unwieldy pedestals, making simple partition shapes unusable. The lack of prefabricated plenum dividers that can be reconfigured as occupant layouts change is a serious annoyance to professionals and should be developed as part of the raised floor package. Laboratory studies could more clearly establish the potential performance of all integrated systems in the “plenum real estate challenge” including the raised floor, networking, fire and HVAC components.

The value of ‘flywheel’ cooling in climates with significant diurnal swing and manageable humidity conditions should be fully studied in the field and laboratory.

Chapter 4: Diffuser Design Alternatives

There is very little discussion in the literature of diffuser size or total percent of aperture and its impact on cooling, ventilation and user satisfaction. Most manufacturers offer 5 – 6 inch floor air diffusers. Several manufacturers offer 8 and 10 in diffusers, and several manufacturers bundle two to four in diffusers into one floor tile. Clearly, the cooling and ventilation capacitance will vary based on diffuser size, as will thermal comfort. Further study of the relationship of diffuser type (swirl, jet), diffuser size, and aperture area is needed in relation to the velocity and temperature of air for effective thermal comfort and air quality. Correspondingly, there appears to be little comparative study of the impact of diffuser densities on thermal comfort and air quality and there are no published standards available.

Most of the manufacturers of floor air diffusers incorporate two details to ensure that plenum air quality is not compromised. Diffuser slots are kept to a minimum (7 mm or less) to avoid objects falling or being caught in the slots. And a dirt/dust receptacle to collect carpet fibers and dust is included in each floor air diffuser, easily removable for cleaning. Again, the performance of these details, and any requirements for additional details to ensure air quality, should be the subject of study.

While design guidelines are emerging for floor diffusers, diffuser design for desk, partition and ceiling-based flexible and adaptive systems need to be fully evaluated. Studies need to be completed that verify the size, height and number of diffusers needed per workstation for air quality and thermal comfort and to what extent relocation is required so that desktop computers and open work areas can be reconfigured. It is important to have these wall/partition air diffusers studied for comparative performance, given maximum air speeds, minimum temperatures and variations in user control (volume, speed, horizontal and vertical directional control, mixing).

Ceiling based flexible and adaptive HVAC systems are significantly less developed or tested than UFA systems, and merit further study. The manufacturers of these systems should also be tapped to develop underfloor components for thermal conditioning and ventilation improvements – to enrich the choices and performance of flexible and adaptive HVAC components.

Chapter 5: Individual Control Alternatives

The most common user control for floor air diffusers is volume control, either passive control by manually closing inlets (through an optional basket in the basket) or active control with VAV dampers connected to local thermostats. The importance of this control to thermal comfort must be studied, as well as the impact of volume adjustments on overall system effectiveness.

Almost all of the manufacturers have added a minimum setting for volume control to ensure that ventilation air is delivered regardless of thermal demands, or have recommended a percentage of “ambient” diffusers. The importance of minimum air delivery in unoccupied or “too cold” shutdown conditions should be fully tested in the field or laboratory.

Before both first cost and market readiness decide the future of user controls in underfloor air (volume only), each of six user control alternatives should be studied in both laboratory and field research as to their cost-benefits for improved human comfort and health, reduced energy and churn/asset costs, as well as in relation to individual and organizational productivity over time. The comparative value of air speed control, air direction control, air temperature/mixing control, and local filtration control needs to be studied in relation to thermal comfort, air quality and energy effectiveness. In all cases, the intuitive nature of the user interfaces for controls will need further development for their effective use.

Floor diffusers that interface with or incorporate coils for thermal conditioning – cooling or heating - seem to be manufactured only on demand. The value of these diffuser options to reduce energy loads, increase comfort and air quality, and support far more dynamic workplace densities needs to be fully studied, as well as the performance concerns and barriers to their use.

Chapter 6: Central System Issues

The necessity for rethinking central systems sizing and configuration in response to flexible and adaptive HVAC distribution has not been fully debated or researched. Effective modifications to central cooling/ heating sources and to central or distributed air handlers should be engineered and studied, in addition to further development of conditioning solutions for perimeter zones.

In addition to separate ‘systems’ for perimeter conditioning (possibly high performance enclosures), many office buildings will require supplemental cooling in conference rooms and internal areas with high equipment or occupant density. Some engineers are convinced that the addition of more air diffusers or fan-air diffusers can meet the needs of these higher internal loads. Field studies should reveal diverse solutions for increasing the cooling delivered to conference rooms in both conventional and flexible HVAC commercial buildings.

Central systems fans (or distributed AHUs) must have the capacity to measure and respond to changes in pressure, caused by variations in density or location of diffusers, by increasing or decreasing the volume of the airflow. Some engineers interviewed argued that pressure gauges may be less reliable than monitoring temperature or the supply and exhaust airflow rate, although no data could be found in the literature.

There is very little material clearly outlining the necessary steps in central system engineering in relation to underfloor air to ensure drier supply air in humid climates or in buildings where water-based cooling is proposed.

Finally, both field and laboratory studies are needed to evaluate the performance of separating ambient and task conditioning and the performance of separating thermal conditioning from ventilation on indoor air quality, thermal comfort and energy effectiveness. If ventilation is a separate, more constant volume system, the relative performance of ceiling and floor based delivery as well as displacement ventilation should be explored, again in relation to indoor air quality, thermal comfort and energy effectiveness.

Chapter 7: Systems Integration and Delivery Process Issues

Field studies should clearly reveal the extent with which flexible and adaptive HVAC systems rely on collaborative design/ engineering and integrated solutions. The field study research team should also build up-to-date descriptions on emerging industrial and design partnerships and their range of approaches to:

Systems Integration Issues for Flexible and Adaptive HVAC

- Managing the Plenum Real Estate Challenge
- The Integration of the HVAC package (from B to C)
- The Integration of Enclosure
- The Integration of Massing, Structure & Vertical Cores
- The Integration of Fire & Security
- The Integration of Connectivity package (from B to C)
- The Integration of raised floor, carpet and diffuser package (from B to C)
- The Integration of Interior Systems
- Innovations needed in the Building Delivery Process:

These integrated system strategies then need to be compared to the full range of performance concerns and benefits to enable practitioners and clients to select the highest performance approaches and to pressure the building industry to further prototype and refine integrated solutions. Based on field studies, a discrete set of integrated flexible and adaptive infrastructure systems should be identified for laboratory study. At the same time, several multi-disciplinary teams should be assembled with the primary manufacturers of flexible infrastructures to develop further innovations and refinements for side-by-side laboratory evaluation.

The need for new industrial/ manufacturing partnerships dedicated to performance delivery rather than product delivery is more fully discussed in Chapter 7, with a list of challenges to the HVAC, networking, raised floor, carpet, fire safety, and ceiling industries. Innovations will also be needed in the building delivery process to ensure that design professionals, industry and labor work in a iterative, trans-disciplinary manner.

Chapters 8 & 9: Performance Concerns and Gains

The phase 1 research effort identified a significant greater number of performance gains than concerns for flexible and adaptive HVAC systems including: first cost savings, organizational and technological ‘churn’ cost savings, thermal comfort gains, indoor air quality gains, energy cost savings, and individual productivity gains. Both phase 2: Field Studies and phase 3: Laboratory Studies must quantitatively confirm these simulation and case study findings, substantiating the gains and find solutions to the concerns:

Performance Concerns
First Cost Concerns
Thermal Comfort Concerns
Relative Humidity, Condensation and IAQ concerns
Noise, Security & Fire Concerns

Performance Gains
First Cost Gains
Churn Cost Savings – Organizational Effectiveness
Individual Productivity Gains
Thermal Comfort Gains
Indoor Air Quality (IAQ) Gains
Energy Cost Savings
Facilities Management (FM) Cost Savings
Marketing & Aesthetics
Just-in-Time (JIT) Cost Savings

Since productivity and health are two critical agendas for US employers, there is also a need for substantial research funding to support multi-site, multi-year studies on the productivity and health benefits of flexible and adaptable HVAC systems in relation to more traditional VAV systems.

10.3 Conclusion

It is becoming increasingly clear that flexible and adaptive HVAC systems, such as underfloor air: perform as well if not better than ceiling-based systems most notably because they support a greater level of spatial change. Leading engineers are active proponents of underfloor air after their first experience, and these flexible and adaptive systems are now more than 10% of the market, including many of the newest headquarters and “green” building landmarks.

The performance concerns of flexible and adaptive HVAC systems should be fully addressed by the manufacturing industry to resolve: potential higher first costs especially in existing buildings; component and integrated system availability and robustness; thermal comfort control in relation to widely varying interior functions; maintaining humidity control and the air quality of the underfloor air; and fire and security protection in the plenum. Working collaboratively with research laboratories in different climates, system innovations should be explored towards the widespread introduction of energy efficient, flexible, user based HVAC for commercial buildings.

The significant number of performance gains of flexible and adaptive HVAC systems should be fully documented in detailed field studies, to irrefutably confirm the: first cost savings, organizational and technological 'churn' cost savings, thermal comfort gains, indoor air quality gains, energy cost savings, and individual productivity gains.

Given the increasing level of spatial and functional change in commercial buildings today, the importance of equally flexible and adaptive HVAC infrastructures has never been more important. The major types of flexible and adaptive HVAC systems identified in this Air-Conditioning and Refrigeration Technology Institute (ARTI) report offer significant opportunities to cost-effectively improve the quality of indoor environments for all building occupants, and sustain that improvement over time.

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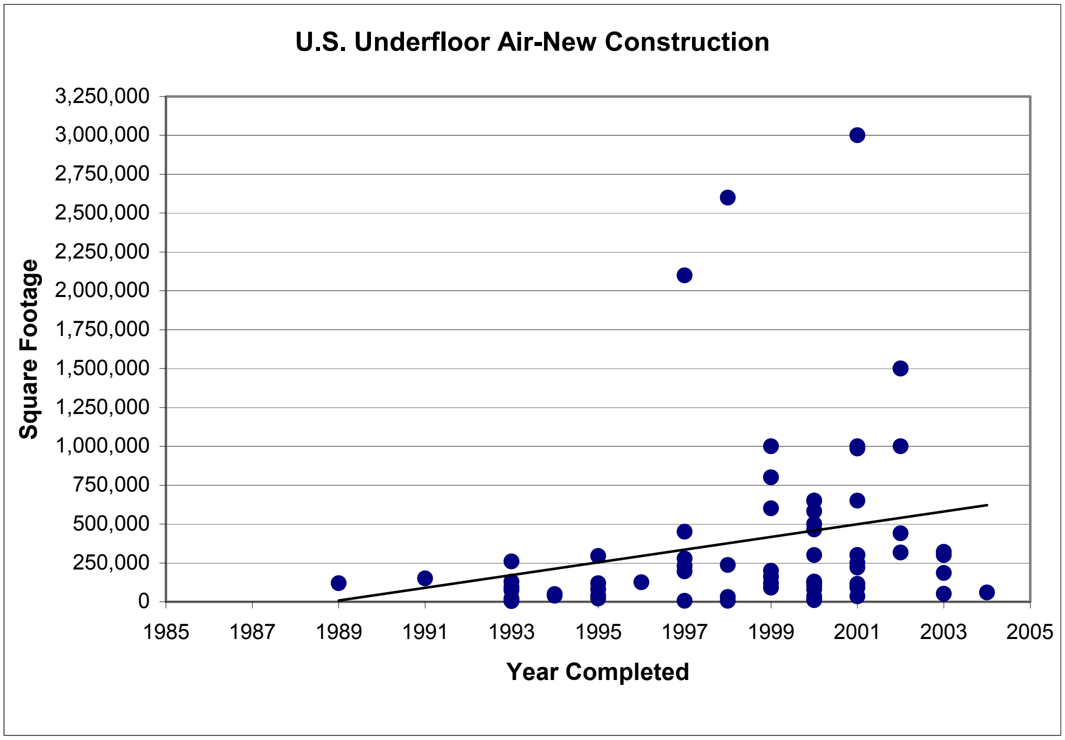
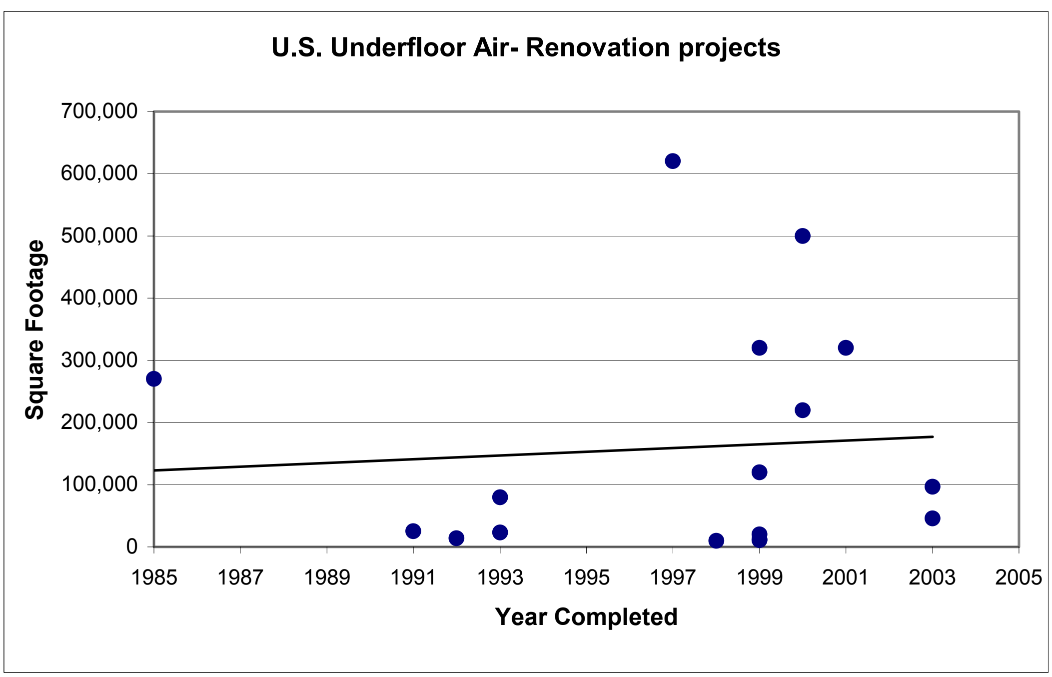

U.S. Underfloor Air-New Construction
Square Footage
Year Completed
3,250,000
3,000,000
2,750,000
2,500,000
2,250,000
2,000,000
1,750,000
1,500,000
1,250,000
1,000,000
750,000
500,000
250,000
0
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005


U.S. Underfloor Air- Renovation projects
Square Footage
Year Completed
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
North America								
1010 Building	Minneapolis, MN	USA	Emert Design		10,000 sf		May-88	Tate Task Air
117 Water Street	Baltimore, MD	USA	Dalsemer Catzen	Frosty Refrigeration	50,000 sf		1984	Tate Task Air
50 West Jackson Office Tower	Chicago, IL	USA	Anthony Belluschi Architects	Cosentini Associates	985,000 sf	new construction	2001	
909 Building Dept. of Environmental Protection Agency	Susquehanna, PA	USA	Kulp Boecker Assoc.- John Boecker	G.R. Sponaugle (Design Build Contractor)	73,000 sf		Jan-98	
911 Communications Center	Rochester, NY	USA			9,000 sf		1993	Tate Floors
AAA	Detroit, MI	USA		Giffels Assoc.- Al Woody	620,000 sf	renovation	1997	
AAA	Livermore, CA	USA						
AAA Phase II	Detroit, MI	USA	Giffels Associates	Giffels Associates	170,000 sf			
Abovenet	Seattle, WA	USA			82,000 sf			Maxcess Technologies
Abovenet	Los Angeles, CA	USA			88,000 sf			Maxcess Technologies
Adtech Office Building (CNF Headquarters)	Portland, OR	USA		Glumac International	250,000 sf	new construction	2001	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
AFLAC Phase II	Columbus, GA	USA	Hecht, Burdeshaw & Johnson- Phil Johnson	Andrews, Hammock & Powel Assoc	126,500 sf	new construction	Fall 96	
Alameda Towers Condominiums	Kansas City, MO	USA	Howard Needles Tammen & Bergendoff	Howard Needles Tammen & Bergendoff	20 stories	new construction		
ALCOA World Headquarters	Pittsburgh, PA	USA	The Design Alliance- Lisa Davinett	Dodson Engineering- Greg Calabria	236,200 sf	new construction	1998	Tate
Allegan High School Performing Arts Center	MI	USA		Peter Basso Assoc.				
America On-Line Headquarters	Washington, DC	USA	APM Engineering	APM Engineering- Teresa Rainey	300,000 sf		Fall 98	
American Bank Stationary	White Marsh, MD	USA	Nichols & Associates	PCI	45,000 sf		May-88	Tate Task Air
American Family Life Assurance	Columbus, GA	USA	Hecht, Burdeshaw & Johnson- Phil Johnson	Andrews, Hammock, Powel Assoc.- Chuck Hammock	23,000 sf	renovation	Sep-93	
American Family Life Insurance	Macon, GA	USA		Andrews, Hammock & Powell	23,000 sf			Tate Floors
AMP Headquarters Building	Harrisburg, PA	USA		JDB Engineers- Jeff Pauley	120,000 sf	new construction	Winter 95	
Apple Computer Retail Store	San Francisco, CA	USA		Flack+Kurtz San Francisco- Jeff Blaevoet	4,000 sf		Sep-93	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Baltimore Gas & Electric		USA		Whitman-Requart- Gary Kohnson	4,000 sf			
Bank of America Gateway Village	Charlotte, NC	USA			650,000 sf	new construction	2001	Maxcess Technologies
BANKONE	Columbus, OH	USA	H. A. Williams		20,000 sf			
BC Hydro Edmonds Centre	Burnaby, BC	Canada		Keen Engineering	600,000 sf	new construction	1998	
BC Hydro Headquarters	Vancouver, BC	Canada	Atkins-Wregelsworth-Randy Fasan	Keen Engineering-Wilson Cheng	554,000 sf	new construction	May-92	Tate Floors
Belfry Point Building	Grand Rapids, MI	USA	Concept Design Group	Van Dyken Mechanical, Inc.	160,000 sf	new construction	1999	
Bellagio Show Palace (Bellagio Casino)	Las Vegas, NV	USA	Marnell Corraro Assoc.- Mitch Trageton	Dupras Assoc.- Andre Dupras	2,600,000 sf	new construction	Oct-98	
Bick Corporation	St. Louis, MO	USA	in-house	in-house	10,000 sf		Feb-89	Tate Floors
Bond Street Wharf Project	Baltimore, MD	USA	Einhorne, Yaffe & Prescott	Einhorne, Yaffe & Prescott	220,000 sf	new construction	Feb-01	
Burnaby Fraser Tax Services	Vancouver, BC	Canada			105,000 sf	new construction	1999	Camino
C&S Nations Bank	Atlanta, GA	USA		Brady & Anglin	14,000 sf		Feb-92	Tate Floors
Caisse Depot	Montreal	Canada	GDL, SAEG, Lemay Assoc. Consortium	Dupras Assoc- Andre Dupras & Luc Fortin	600,000 sf			

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
California Dept. of Transportation District 7 HQ	Los Angeles, CA	USA	AC Martin & Partners	IBE Consulting Engineers, CTG Energetics	60,000 sf	new construction	2004	
California State Automobile Assoc.	Sacramento, CA	USA	Cynthia Easton	Flack+Kurtz San Francisco- Jeff Blaevoet	40,000 sf	new construction	Jun-94	
California State Automobile Assoc.	Stockton, CA	USA		Flack+Kurtz San Francisco- Jeff Blaevoet	50,000 sf	new construction	Sep-94	
California State Automobile Assoc.	Livermore, CA	USA	Gensler Associates San Francisco	ACCO Design Build Contractor- Mike Savage	8,000 sf		Spring 97	
Calpro Office Complex	Sacramento, CA	USA	Paddon & Williams	AIRCO Mechanical Contractor	110,000 sf			
Candlestick Office Building #1	San Francisco, CA	USA	Fiola & Archuletta- Andy Fiola		600,000 sf			
Candlestick Office Building #2	San Francisco, CA	USA	F+A Architects, Glendale	Hellman/ Lober- Steve Hellman	400,000 sf			
Capitol Area East End Complex Block 225	Sacramento, CA	USA		Critchfield Mechanical (Design Build Contractor)	330,000 sf			
Carson Business Interiors	Detroit, MI	USA	Luckenbach/ Ziegelman	Superior Heating & Air Conditioning	20,000 sf		Mar-88	Tate Task Air
CCI Center	Pittsburgh, PA	USA	Tai+Lee Architects, Bob Kobet	Bert Davis	10,000 sf	renovation	Apr-98	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Central Trust Bank Corporate Office	MO	USA	Skidmore, Owings & Merrill	Skidmore, Owings & Merrill- Luke Leung	300,000 sf	new construction	2003	
CFC Leithrum (Canadian Royal Air Force)	Ottawa	Canada			15,000 sf			
Channing Bete	Springfield, MA	USA	Bednarski/ Stein	Lindgren Associates	16,000 sf		May-88	Tate Task Air
Children's Museum	Rancho Mirage, CA	USA	MGA- Larry McEwen	Ove Arup+Partners, Los Angeles	20,000 sf	new construction	1995	
Cincinnati International Airport Control Tower	Cincinnati, OH	USA		Newcomb & Boyd- Steve Hayne	5,000 sf	new addition	Sep-93	
Citicorp Campus	Tampa, FL	USA	HKS Architects, Dallas		500,000 sf	new construction	2000	Maxcess Technologies
Colonial Williamsburg Admin. Building	Williamsburg, VA	USA			80,000 sf			Tate Floors
Columbus State University Tech/ Commerce Center	Columbus, GA	USA	Farrington Group		90,000 sf	new construction	2001	
Complex Cenematographique et Multimedia	Montreal	Canada		Dupras Ledoux Assoc.- Andre Dupras				
Compuware Headquarters Building	Detroit, MI	USA		Peter Basso Assoc.	1,000,000 sf			

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Contract Freighters, Inc.	Joplin, MO	USA	Interior Planning Consultants- Vincent Brannon	Malone Kinkle & Assoc.- Mark Malone	10,000 sf		Jun-93	Tate Floors
Daimler-Chrysler Building	Auburn Hills, MI	USA		Harley Ellis- Don Rudko	400,000 sf	new construction		
Dearborn Center	Chicago, IL	USA	DeStefano Partners and Ricardo Bofill	ESD Chicago	1,500,000 sf	new construction	2002	Interface AR
Dell Computer Building	Dallas, TX	USA	Gensler Associates Los Angeles		800,000 sf	new addition		
Dell Computer Company	Nashville, TN	USA		Smith, Seckman & Reed	500,000 sf ?			Maxcess Technologies
Dept. of Transportation for Commonwealth of Kentucky	Lexington, KY	USA		Stags & Fisher	700,000 sf			
Designtex, Inc. Showroom	Manhattan, NY	USA	Lee Stout, Inc.	Pavane & Kwalburn- David Kwalburn	20,000 sf	renovation	1999	
Dr. G.W. Williams Secondary School	Toronto	Canada		Keen Engineering, Toronto	10,000 sf		Dec-97	
Drug Enforcement Agency (DEA)	Johnstown, PA	USA			10,000 sf			Tate Floors
Eastern Utilities	West Bridgewater, MA	USA	Ganteaume & McMullen Inc.	Ganteaume & McMullen Inc.	80,000 sf		Nov-87	Tate Task Air

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Eastern Utilities/ Systems Operations Center	Lincoln, RI	USA	Keyes Associates	Keyes Associates	5,000 sf		Aug-92	Tate Task Air
Electronic Arts	Vancouver, BC	Canada		Keen Engineering, N Vancouver	300,000 sf			
Electronic Arts-Phase II	Redwood City, CA	USA	Skidmore, Owings & Merrill/ Gensler	Taylor Engineering	316,000 sf	new construction	Mar-02	
Electronics Arts Headquarters	Burnaby, BC	Canada		Keen Engineering	200,000 sf	new construction		
Employment Security Office Building	Reno, NV	USA		Dinter Engineering	80,000 sf		1993	Tate Floors
Epson America, Inc. Headquarters	Torrence, CA	USA	Gensler Assoc. San Francisco	Syska & Hennessy	200,000 sf		Fall 1989	Tate Task Air
FCCI	Sarasota, FL	USA			160,000 sf			Maxcess Technologies
Federal Express World Headquarters	Memphis, TN	USA		Cosentini Associates	1,000,000 sf	new construction	2002	
First Bank of Golden	Lakewood, CO	USA	Andy Barnard	Gordon, Gumeson Assoc.- Juan Zembrano	80,000 sf	new construction	Fall 95	
First Bank of Golden Colorado Branch		USA			5,000 sf			
First Boston Bank	Manhattan, NY	USA		Syska & Hennessy	25,000 sf	renovation	Oct-91	Tate Floors

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
First & Howard	San Francisco, CA	USA		Flack+Kurtz	440,000 sf	new construction	2002	
First National Bank of Maryland	Baltimore, MD	USA			270,000 sf	renovation	1985	
First National Bank of Omaha (FNBO)	Omaha, NE	USA						
First Union Bank Office	Charlotte, NC	USA	Little Associates	Little Associates-Greg Perry	67,000 sf		Jan-96	
First Union Bank Phase II	Charlotte, NC	USA	Little Associates	Little Associates-Greg Perry	60,000 sf			
Ford's Premier Automotive Group North American HQ	Irvine, CA	USA	LPA, Inc.	Tsuchiyama & Kaino, CTG Energetics	300,000 sf	new construction	2001	
Fox Theater	San Jose, CA	USA		Guttmann & Blaevoet	51,000 sf/ 46,000 sf	new construction/ renovation	2003	
Franklin & Marshall College, Henfel Hall Auditorium	Lancaster, PA	USA	N. Beha Assoc., Boston	Altieri, Seibor & Weibor Assoc.	500 seats	renovation	Mar-00	
Fresno Federal Courthouse	Fresno, CA	USA		Tsuchiyama , Kaino & Gibson	250,000 sf			
Gap Inc. - 250 Embarcadero	San Francisco, CA	USA	Johnson Fain Partners	Taylor Engineering	583,000 sf	new construction	Dec-00	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Gap Inc. - 901 Cherry, Phase I	San Bruno, CA	USA	William McDonough / Gensler Associates	Ove Arup San Francisco-Alisdair McGregor	195,000 sf	new construction	1997	
Gap Inc. - 901 Cherry, Phase II	San Bruno, CA	USA	William McDonough + Partners/ Gensler	Ove Arup	171,000 sf	new construction	design development	
Gap Inc. Headquarters Phase II	San Francisco, CA	USA			600,000 sf	new construction	1999	
Gap Inc. Old San Francisco Post Office	San Francisco, CA	USA	Gensler Associates San Francisco	Charles & Braun	200,000 sf			
Gemological Institute of America	Carlsbad, CA	USA	LPA, Inc.	Tushiyama, Kaino & Gibson	230,000 sf	new construction	1997	Tate - 18" pressurized
GM VEC Complex	Warren, MI	USA	Gensler Associates	Ove Arup & Partners San Francisco	1,000,000 sf	new construction	1999	
Griffin, Kubick, Stephens & Thompson	Chicago, IL	USA	Tilton & Lewis-Michael Kelly	ESD, Inc.-Michael Cole	5,000 sf		Sep-93	Tate Floors
GSA Adaptable Workplace Laboratory	Washington, DC	USA	Oudens & Knoop Architects	Grotheer & Company	11,000 sf	renovation	Fall 1999	10" pressurized plenum
GSA Office Building No. 6	Kansas City, MO	USA		Larson & Binkley-Chris Larson	20,000 sf		Oct-92	Tate Floors
Ha-Lo Building	Niles, IL	USA	Murphy/ Jahn	Cosentini Associates	465,000 sf	new construction	Fall 2000	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Hamilton Landing	San Rafael, CA	USA			500,000 sf	renovation	2000	
Harvard Business School	Cambridge, MA	USA	RTKL Baltimore	RTKL Baltimore	200,000 sf			
Herman Miller SQA Factory and Offices	Holland, MI	USA	William McDonough+Pa rtners		295,000 sf	new construction	1995	
Hines Woodfield Building	Woodfield, IL	USA	Wright Architects	Cosentini Associates	300,000 sf/ 320,000 sf	new construction/ renovation	2001	
Houston Power & Light Company	Houston, TX	USA		Robert Young & Assoc.- Robert Young	12,000 sf		Dec-94	
Hydra-Matic, Division of General Motors Corp.	Ypsilanti, MI	USA			3,736 sf		Aug-92	Tate Task Air
Infonet	Los Angeles, CA	USA	Gensler Associates San Francisco	Flack+Kurtz San Francisco	200,000 sf	new construction	1999	
Intel CS/ NADC	Chandler, AZ	USA	Com 3 Architects Ltd.	Fluor Daniel	6,100 sf		Jun-92	Tate Task Air
Internal Revenue Service	Ogden, UT	USA	RMA (Design Build Contractor)		110,000 sf			
IRS Customer Service Center	Atlanta, GA	USA			330,000 sf			Maxcess Technologies
Jay Doblin & Associates	Chicago, IL	USA				renovation	Oct-90	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Johnson Controls, Inc. Brengel Technology Center	Milwaukee, WI	USA	Zimmerman Design Group		130,000 sf	new construction	2000	
Kansas City 911 Center	Kansas City, MO	USA	Bell Knott & Assoc.	Clark Richardson & Biskup	74,000 sf	new construction	Sep-93	
Kansas City Southern Railroad	Kansas City, MO	USA			10,000 sf		Jun-91	Tate Floors
Keen Engineering Headquarters	N Vancouver, BC	Canada		Keen Engineering- Brian Johnson	25,000 sf	new construction	Mar-92	Tate Floors
Keystone Building	Harrisburg, PA	USA	Bohlin, Cywinski, Jackson- Philadelphia	Brinjac, Kambic & Assoc.	800,000 sf	new construction	Fall 99	
KSBA Architects Office	Pittsburgh, PA	USA	KSBA Architects			renovation	1998	
Lake Superior State University Fine Arts Theater	MI	USA		Peter Basso Assoc.				
Libertyville Business Park	Libertyville, IL	USA	Epstein & Sons International	ESD Chicago	95,000 sf	new construction	1993	
Long Performing Arts Center	Austin, TX	USA	Skidmore, Owings & Merrill	Skidmore, Owings & Merrill- Luke Leung	2400 seats	new construction	2002	
Metro News	Nashville, TN	USA	Jim Reed & Associates	Anderson- Smith & Assoc.	2,000 sf		Mar-92	Tate Task Air
MIT Auditorium	Cambridge, MA	USA	J. Steven Holl	Ove Arup New England- Lui King	275 seats			
Montreal Police Academy Communications 911 Center	Montreal	Canada		Dupras Assoc.- Claude Dupras	10,000 sf		Jun-88	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Motorola, ATC/ BP VI	Chandler, AZ	USA	Lendrum Associates	Sterns Rogers	23,968 sf		Mar-91	Tate Task Air
Motorola Building 99	Tempe, AZ	USA	CRSS	Energy System Designs	66,000 sf		1995	Tate Task Air
Motorola, Diablo Way	Tempe, AZ	USA		Peterson & Associates	82,000 sf		Aug-89	Tate Task Air
Motorola Semi-Conductor Product Sector	Chandler, AZ	USA	DMJM/ GSAS	Baltes/ Valentino Assoc.	32,000 sf		May-88	Tate Task Air
National Museum of American Indians at the Smithsonian Institute	Washington, DC	USA		Cosentini Assoc. NYC- Mark Malekshahi				
Naval Construction Batallion Center, Building 850	Port Hueneme, CA	USA	Scott Ellinwood and Assoc.	Robert Bein, William Frost & Assoc. (RBF)	10,400 sf/ 6,800 sf	renovation/ new addition	1998	
New Jersey Performing Arts Center	Newark, NJ	USA		Ove Arup	2750 seats	new construction	1997	
Nike World Campus for University of Oregon	Portland, OR	USA	Allied Works	Glumac International-Steffan Brooks	1,000,000 sf	new construction	under construction	
Ninigret Office Park	Salt Lake City, UT	USA		Dave Houghten	3,000,000 sf	new addition	2001	Maxcess Technologies
Nissan Motor Company	Los Angeles, CA	USA		Syska & Hennessy- Tom Vitoo	15,000 sf		Janusry 95	
Offhutt Air Force Base	Omaha, NE	USA	US Army Corp of Engineers	US Army Corp of Engineers	10,000 sf		Jun-89	Tate Floors
Oklahoma City Federal Building	Oklahoma City, OK	USA	Ross, Barney + Jankowski	CTG Energetics	185,000 sf	new construction	2003	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Old National Bank	Evansville, IN	USA	Mills Wallace Assoc.- Don Mills	Baxter Martin Assoc.- George Baxter	80,000 sf	renovation	Jun-93	Tate Floors
One Penn Plaza	Chicago, IL	USA	OWP&P	OWP&P- Charles Eggert	400,000 sf			
Oracle Headquarters Building West	Dublin, CA	USA			833,000 sf			
Ove Arup Engineering	Los Angeles, CA	USA	Morphosis- Kim Groves	Ove Arup Partners- Alan Locke	14,000 sf	renovation	Nov-92	Tate Floors
Owens Corning World Headquarters	Toledo, OH	USA	Cesar Pelli/ Kendall Heaton	Cosentini Assoc.- Douglas Mass	450,000 sf	new construction	1997	Interface AR- 12" pressurized
P Building	Grand Rapids, MI	USA	Thomas Phifer		80,000 sf	new construction	proposed	
Pacific Telephone & Telegraph	Fairfield, CA	USA	Lionakis & Beaumont, Inc.	Flack+Kurtz San Francisco- Jeff Blaevoet	20,000 sf	new construction	Jan-93	
Palm Computing	San Jose, CA	USA	William McDonough+Partners/ HOK	Taylor Engineering- Steve Taylor	1,500,000 sf	new construction	2002	
Penn Center West, Soffer Development	Pittsburgh, PA	USA	Gardner+Pope	Ray Engineering- Rick Yates	120,000 sf	new construction	2000	
Pennsylvania DEP South Central Regional Office Building (SCROB)	Harrisburg, PA	USA	Kulp Boecker Assoc.		30,000 sf	new construction	1998	
Pennsylvania DEP Cambria Office	Ebensburg, PA	USA	Kulp Boecker Assoc.		36,000 sf	new construction	2000	
Pennsylvania Fish and Game Commission	Harrisburg, PA	USA	Maguire Group	Maguire Group	80,000 sf	new construction	2000	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Pennsylvania Turnpike Commission	Harrisburg, PA	USA			140,000 sf			
PHH Mortgage Services Building	Philadelphia, PA	USA	Interspace Consulting Architects	Bala Engineers- Gary Cohen	700,000 sf			
Phoenix Central Library	Phoenix, AZ	USA	Bruder/ DWL	Baltes-Valentino Associates	40,000 sf	new construction	1995	Tate Task Air
Pittsburgh National Bank (PNC) Firstside	Pittsburgh, PA	USA	L.D. Astorino Companies	L.D. Astorino Companies- Earl Wong	650,000 sf	new construction	Sept. 2000	Tate Floors- 18" plenum
Portland City Development Center	Portland, OR	USA		Glumac Associates	100,000 sf	new construction	2000	
Prime Group Lasalle Street Project	Chicago, IL	USA	Ricardo Bofill from Spain/ DeStefano Partners		2,100,000 sf	new construction	1997	
Prime Group Realty Trust Continental Towers	Chicago, IL	USA	Ricardo Bofill from Spain	ESD Chicago	320,000 sf	renovation	1999	
Project 2000	Victoria, BC	Canada	Hemingway Nelson- Kevin Jeffries	D.W. Thompson- Paul Marmion	300,000 sf			
Projects Three	Boston, MA	USA	The Stubbins Associates- Chris Learey		700,000 sf			
Provigo	Montreal	Canada		Dupras Assoc.- Luc Fortin				
Raymond James Financial Center Tower II	St. Petersburg, FL	USA			224,000 sf			Maxcess Technologies
Revenue Canada Office Building	Surrey	Canada		Keen Engineering	100,000 sf	new construction	1998	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Robbins International Headquarters	Cincinnati, OH	USA	Richard Ward & Associates		7,500 sf		1986	Tate Task Air
Rochester High School Auditorium Performing Arts Center	MI	USA		Peter Basso Assoc.				
Roseville Telephone Co.	Sacramento, CA	USA	Williams & Padden		130,000 sf	new construction	1993	
Sacramento Municipal Utility District (SMUD)	Sacramento, CA	USA	Williams & Paddon- Jack Paddon	Peters Engineering- Leroy Peters	260,000 sf	new construction	1993	Tate Floors- 12" pressurized
Saint Benedict's Center	Louisville, KY	USA	Gary Watrous Assoc. Architects		11,000 sf	new construction	2000	
Salt River	Phoenix, AZ	USA	SUNDT Corporation		330,000 sf		Feb-89	Tate Floors
San Jose State University Library	San Jose, CA	USA	Gensler Associates	Guttman & Blaevoet	97,000 sf	renovation	2003	
Santa Monica Public Safety Facility	Santa Monica, CA	USA	Dworsky Architects	Levine, Seegel Assoc., CTG Energetics	110,000 sf			
Santee Cooper Inc.	Santee, SC	USA	LS3P		30,000 sf		Dec-88	Tate Task Air
SC Johnson Wax Professional	Racine, WI	USA	HOK		278,000 sf	new construction	1997	Tate- 12" pressurized
Scholastic Publishers Auditorium	Manhattan, NY	USA	Gensler Assoc. NYC- Karen Andrich	Goldman-Copeland Assoc.- Bruce McKinlay	400-500 seats	new construction		
Seneca Grade School	Peru, IL	USA	Chanlin Assoc.- Greg Weisbrock	Chanlin Assoc.- Greg Weisbrock	4,000 sf		Sep-93	Tate Floors

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SGA Building	Minneapolis, MN	USA			1,000,000 sf	renovation		
Shaklee Corporate Headquarters	Pleasanton, CA	USA	Gensler Assoc.	Ove Arup	127,000 sf	new construction	2000	
Shaklee Foods	San Francisco, CA	USA	Gensler Associates San Francisco- Lou Weisbach	Ove Arup San Francisco/ Critchfield Mechanical	150,000 sf			
Sheppard Pratt Hospital	Baltimore, MD	USA	Grieves Associates	Gonnerman, Inc.	30,000 sf		Feb-90	Tate Task Air
SMUD Customer Service Center	Sacramento, CA	USA	Constructive Technologies Group	Constructive Technologies Group				
Social Security Building	Baltimore, MD	USA	Einhorn, Yaffee & Prescott	Einhorn, Yaffee & Prescott	200,000 sf			
Soft Image Computer Imaging	Montreal	Canada		Dupras Assoc.- Claude Dupras	30,000 sf		Jun-94	
Software Productivity Consortium	Herndon, VA	USA	Ward Hall & Assoc./ Arquitectonica	Silver & Associates	60,000 sf		Dec-88	Tate Task Air
South Florida Performing Arts Center	West Palm Beach, FL	USA	Spillis Candela-DMJM, Coral Gables	Spillis Candela-DMJM, Coral Gables	1000 seats			
Southern South Airbourne Building	Chicago, IL	USA	Skidmore, Owings & Merrill	Skidmore, Owings & Merrill-Ray J Clarke	1,000,000 sf	new construction		
Sprint Call Center	Charlotte, NC	USA	WGM Design		120,000 sf	new construction	1999	Maxcess Technologies
St. Catherine’s Our Lady of Angels	Los Angeles, CA	USA		Ove Arup Los Angeles- John Gautrey				

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State of Ohio Office Building	Columbus, OH	USA	State of Ohio	H. A. Williams	100,000 sf		Sep-91	Tate Floors
Steelcase Corp. Center Phase II	Grand Rapids, MI	USA	Hysen Group	Van Dyken Mechanical (Design Build Contractor)	28,000 sf			
Steelcase Corp. Development Center	Grand Rapids, MI	USA		Scott Van Dyken	10,000 sf		Aug-89	Tate Floors
Sunshine Project Office Building	Gig Harbor, WA	USA	NBBJ Seattle	Ove Arup+Partners San Francisco	35,000 sf	new construction	2001	
Suntrust Plaza	Atlanta, GA	USA	John Portman & Associates		650,000 sf	new construction	2000	Maxcess technologies
Teledesic	Seattle, WA	USA	NBBJ Seattle	Ove Arup SF	90,000 sf	new construction	1999	
Telus William Farrell Building	Vancouver, BC	Canada		Keen Engineering	127,000 sf	renovation	2001	
Texas Instruments	Dallas, TX	USA	in-house	in-house	20,000 sf		Oct-89	Tate Task Air
The Adam Joseph Lewis Center for Enviromental Studies at Oberlin College	Oberlin, OH	USA	McDonough+Partners		14,000 sf	new construction	2000	ducted
The Doblin Group Office	Chicago, IL	USA	ISI	AMS- Jack Schutte	10,000 sf		Sep-90	Tate Floors
The Ray and Maria Stata Center, MIT Computer Center	Boston, MA	USA	Frank O. Gehry	R.G. Vanderweil-Chris Schaffner	322,000 sf	new construction	2003	

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
The Robert L. Preger Intelligent Workplace	Pittsburgh, PA	USA	Bohlin, Cywinski, Jackson/ Pierre Zoelly	Ray Engineering- Rick Yates	7,000 sf	new construction	1997	ducted
Toronto Library Addition	Toronto	Canada		Keen Engineering, Toronto	5,000 sf	new construction	Apr-94	
Union Gas	Toronto	Canada			25,000 sf			
University Center, One Penn Plaza Building	Chicago, IL	USA	OWP&P	OWP&P- Charles Eggert	35,000 sf			
University of North Florida	Jacksonville, FL	USA	Rink, Reynolds, Diamond, Fisher- Chris Belyea	Reynolds, Smith & Hill- Mike Bowman/ Kirkegaard Assoc		new construction	2001	
University of Saskatchewan	Saskatoon, Saskatchewan	Canada	Wiens Architects, Ltd	Yoneda & Associates	30,000 sf		Jun-87	Tate Task Air
Vancouver Public Library	Vancouver, BC	Canada		Keen Engineering	400,000 sf	new construction	Fall 94	
Vancouver Real Estate Board	Vancouver, BC	Canada			8,000 sf		Sep-93	Tate Floors
Veterans Administration Building	Richmond, VA	USA			300,000 sf			
Veterans Administration Building	Denver, CO	USA			300,000 sf			
Washoe County Courthouse	Reno, NV	USA	ARCForm Group- Robert Hall	Dinter Engineering- Deny Newton	12,000 sf	renovation	Summer 99	
WEBCOR Building	San Mateo, CA	USA	Gensler Associates		7,000,000 sf			

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Wellpoint (Blue Cross Blue Shield)	Thousand Oaks, CA	USA	Callison Architecture, Seattle	Syska & Hennessy- Andy Watson	120,000 sf	renovation	1999	
Wells Fargo Building	Billings, MT	USA	AFT Architects	Con'eer Engineering- Jeff Gruizenga	165,000 sf			
West Angeles Cathedral	Los Angeles, CA	USA	Langdon & Wilson	Ove Arup+Partners- Jackie Perryman	116,000 sf	new construction	2001	
West Bend Mutual Corporate HQ	West Bend, WI	USA	Zimmerman Design Group		150,000 sf	new construction	1991	
Wieden & Kennedy Headquarters	Portland, OR	USA	Allied Works Architecture	Glumac Associates	220,000 sf	renovation	2000	Interface AR- pressurized plenum
Windward Technical Center	Alpharetta, GA	USA	Brady & Anglin- Harry Lockwood		120,000 sf	new construction	Aug-89	Tate Floors
Woodfield Library	Woodfield, IL	USA		B+A Engineers Ltd- Leonard A Bihler	40,000 sf			
Woodfield Preserve Office	Chicago, IL	USA			300,000 sf	new construction	2000	11" pressurized
Workmans Compensation Board	Richmond, BC	Canada	Hemingway- Nelson	Reid Crowther & Partners	120,000 sf		1993	Tate Floors
York Mills Center	Toronto	Canada	Clark, Darling & Downey Partnership	Mitchell Partnership	240,000 sf		Aug-87	Tate Task Air
Europe								
Kontrollbank Wien	Vienna	Austria						

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Kazoulis Shipping Office		Cyprus			25,000 sq meters	new construction		AET Flexible Space, plenum
110 Old Broad Street	London	England		Oscar Faber	900 sq meters			AET Flexible Space, plenum
80 Park Lane (Hong Kong & Shanghai Bank)	London	England		FHP Partnership	1,600 sq meters			AET Flexible Space, plenum
Avon House	London	England		Silcock Dawson	2,500 sq meters			AET Flexible Space, plenum
Bloomberg Phases 1-3	London	England	Powell -Tuck Associates	Rosser & Russel	6000 sq meters	renovation	98-?	AET Flexible Space, plenum
Breams Building	London	England				renovation		Protek System
British Midland Airways Reservation Centre	Castle Donnington (Nottingham)	England	Hattrell and Partners-Manchester	DSSR	2,500 sq meters	new construction	Jul-98	AET Flexible Space, plenum
British Telecom Call Centre	York	England		Troup Bywater Anders	1,600 sq meters			AET Flexible Space, plenum
Buckingham Gate, BAA Lynton	Gatwick	England		J Roger Preston	6,000 sq meters			AET Flexible Space, plenum
Civil Aviation Authority	London	England		Service Plan Ltd	600 sq meters			AET Flexible Space, plenum
Crossfield Chemicals	Warrington	England		Ernest Griffiths and Son	900 sq meters			AET Flexible Space, plenum
Customs and Excise (government)	Liverpool	England.		Climate Equipment	1,700 sq meters			AET Flexible Space, plenum
Eastern Electricity	Ipswich	England		WSP Group	1,200 sq meters			AET Flexible Space, plenum

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Endeavor House, KLM Stansted	Stansted	England		Roger Preston	6,000 sq meters			AET Flexible Space, plenum
Falcon House	Hounslow	England		Sir Frederick Snow	3,500 sq meters			AET Flexible Space, plenum
First Point Office, BAA Lynton	Gatwick	England		Buro Happold Engineering	6,000 sq meters			AET Flexible Space, plenum
GE Electronics	Acton	England		Service Plan Ltd	200 sq meters			AET Flexible Space, plenum
General Motors, 103 Wardour Street	London	England.	Modern Design Group Ltd.	Watkins Payne Partnership	1,700 sq meters	new construction	1998	AET Flexible Space, plenum
Giroflex Showroom (office furniture)	London	England				renovation		Protek System
Glaxo	Ware	England		Services Design Partnership	250 sq meters			AET Flexible Space, plenum
Hamilton Oil Company	London	England		Murray Symmonds	6,000 sq meters			AET Flexible Space, plenum
Hanover Street, BAA Lynton	London	England		Roger Preston	730 sq meters			AET Flexible Space, plenum
Helicon Building, Zurich Investments	London	England		R W Gregory	450 sq meters			AET Flexible Space, plenum
IBM Hursley Park	Winchester	England		Watman Gore	655 sq meters			AET Flexible Space, plenum
JC Decaux	West London	England	Sir Norman Foster	BDSP	1,300 sq meters	renovation		AET Flexible Space, plenum
Kingston University Library	Kingston	England.		MacDonald Design Associates	1,500 sq meters	new construction		AET Flexible Space, plenum

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Land Securities	Trafalgar Square, London	England		Haden Young	140 sq meters			AET Flexible Space, plenum
Littlewoods Corporation	Liverpool	England		Ernest Griffiths and Son	7,000 sq meters			AET Flexible Space, plenum
Lloyd's of London	London	England	Richard Rogers Partnership	Ove Arup	550,000 sf	new construction	1986	pressurized plenum
Marks & Spencer Financial Services Division	Chester	England		Building Design Partnership	200 sq meters			AET Flexible Space, plenum
News International	London	England		MacDonald Assoc.	10,000 sq meters			AET Flexible Space, plenum
No. 4 Millbank (BBC, World Bank, ITN)	London	England		MacDonald Assoc.	12,500 sq meters			AET Flexible Space, plenum
Rover Group Design Centre	Warwick	England	Weedon Partnership-John Carter	Rolton Consulting Engineers	10,000 sq meters	new construction	Oct-96	AET Flexible Space, plenum
Taisei	London	England		J Roger Preston	730 sq meters			AET Flexible Space, plenum
Time Life Building	London	England		Ove Arup	350 sq meters			AET Flexible Space, plenum
University of North London	London	England.	Rick Mather	Rockhill Assoc.	3,300 sq meters			AET Flexible Space, plenum
University of North London Technology Tower	London	England	Brady Mallalieu	John Brady Assoc.- Russel Hunter (bldg services consultants)	9 floors	new construction	Jan-00	AET Flexible Space, plenum
Williams Lea & Co	London	England		Service Plan Ltd.	300 sq meters			AET Flexible Space, plenum

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
Willis Corroon	Ipswich	England.	Sir Norman Foster	FC Forman	1,250 sq meters	renovation		AET Flexible Space, plenum
Digital	Nice	France			15,000 sq meters			AET Flexible Space, plenum
Ministry of Finance and Budget	Paris	France						
Panasonic	Paris	France			3,500 sq meters			AET Flexible Space, plenum
Bayerische Vereinsbank office	Frankfurt	Germany						
Gartner Headquarters	Gundelfingen	Germany				new construction		
Kosmos UFA-Palast cinema	Berlin	Germany						
Nixdorf Building	Koln	Germany						
Siemens AG, Transport Techn. Dept.	Berlin	Germany						
Union Zentrale Krankenversicherung	Saarbrucken	Germany						
Central European International (CEI) Bank		Hungary						AET Flexible Space, plenum
American Investment Group (AIG)	Dublin	Ireland		Winthrop Engineering		new construction		AET Flexible Space, plenum
Aster Lingotto	Turin	Italy			40,000 sq meters			AET Flexible Space, plenum

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Pallazo della Marineria	Trieste	Italy			25,000 sq meters			AET Flexible Space, plenum
Siemens office	Milan	Italy						
Gemeentelijke Electriciteit Bedrijven	Tilberg	Netherlands						
Nederlandse Spoorwegen Verkeersleiding	Amsterdam	Netherlands						
Beacon House Prudential Building	Belfast	Northern Ireland	Coogan and Company- Kevin Coogan	Philip Downie Assoc.	6,000 sq meters	new construction	April 99?	AET Flexible Space, plenum
National Provincial Building Society, St. Andrews House	Edinburgh	Scotland		K J Tait	4,500 sq meters			AET Flexible Space, plenum
Princes House, Teesland Development	Glasgow	Scotland		K J Tait	6,000 sq meters	new construction		AET Flexible Space, plenum
Quintiles	Bathgate	Scotland		RSP Edinburgh	200 sq meters			AET Flexible Space, plenum
Standard Life Insurance	Edinburgh	Scotland.		RSP	2,500 sq meters			AET Flexible Space, plenum
Alviks Strand (Ericson, Toshiba...)	Stockholm	Sweden			42,000 sq meters			AET Flexible Space, plenum
ENACAB	Gothenburg	Sweden				renovation		Protek System
FARAO	Stockholm	Sweden				new construction	2000	Protek System
Malmo Public Library	Malmo	Sweden				new construction	May-97	AET Flexible Space, plenum

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Tankebolaget	Stockholm	Sweden				renovation		Protek System
Tetra Pak		Sweden			2,500 sq meters			AET Flexible Space, plenum
Hurriyet News Papers	Istanbul	Turkey			10,000 sq meters			AET Flexible Space, plenum
Asia								
Motorola Semiconductor Building	Tel Aviv	Israel			5,000 sq meters	new construction		AET Flexible Space, plenum
News Datacom	Jerusalem	Israel			2,000 sq meters			AET Flexible Space, plenum
Chigasaki North Building of Taiyo no Sato	Kanagawa Prefecture	Japan	Takenaka Corporation		1,525 sq meters	new construction	1990	
Fujita Corporation Headquarters	Tokyo	Japan	Fujita Corporation				Dec-90	
Itoki Osaka New Office Gallery	Osaka	Japan	Nikken Sekkei				Aug-89	
Kobe Gas Building	Kobe City	Japan					May-90	
Nissan Automobile Engineering Building		Japan	Obayashi				1990	
Panasonic Information and Communications Systems Center	Tokyo	Japan	Nikken Sekkei				Jun-92	

Project Name	**Location**	**Country**	**Architect**	**Engineer**	**Project Size**	**Project Type**	**Date Occupied**	**Underfloor Air System**
Taisei Construction Company Office	Fukuoka City	Japan					1992	
Toyocho Building, Meiji Life Insurance Company	Tokyo	Japan	Takenaka Corporation		45,346 sq meters	new construction	1989	
Toyota Office Building		Japan					1990	
Umeda Center	Osaka	Japan		Takenaka Construction Company				
Yoshikawa Building, Kita-Aoyama	Tokyo	Japan	Takenaka Corporation		8,987 sq meters	new construction	1994	
ETRI (Electronic & Telecommunications Research Institute)	Seoul	Korea			30,000 sq meters	new construction		AET Flexible Space, plenum
Samsung Corp. SDS Building	Seoul	Korea						
Malaysia Telecom	Kuala Lumpar	Malaysia			60,000 sq meters		1998	AET Flexible Space, plenum
H6 (‘The Centre’) for Cheung Kong	Hong Kong	Republic of China			90,000 sq meters	new construction		AET Flexible Space, plenum
Hong Kong New Airport	Hong Kong	Republic of China			2,000 sq meters			AET Flexible Space, plenum
Taipei Smart Center	Taipei, Taiwan	Republic of China	Chen Wen, Li	Superior Heating & Air Conditioning	137,000 sf		Sep-91	Tate Task Air
Thai Airways, Lean Tower	Bangkok	Thailand	CASA Company Ltd.	W & Associates	77,000 sf		Jul-92	Tate Task Air

Project Name	Location	Country	Architect	Engineer	Project Size	Project Type	Date Occupied	Underfloor Air System
South America								
Birmann Tower #24	Santiago	Chile			200,000 sf			Maxcess Technologies
Capital Towers	Bogota	Columbia			200,000 sf			
Oceania								
CEMAC	Melborne	Australia		Rankine Hill	700 sq meters		Oct-86	Tate Task Air
Commonwealth Bank Treasury	Sidney	Australia	Smith Jesse Payne & Hunt	TWA Partnership	5,500 sq meters		Feb-90	Tate Task Air
City Council Admin. Building	Wellington	New Zealand	Stephenson & Turner	Stephenson & Turner	6,286 sq meters		Mar-91	Tate Task Air
Toyota N.Z. Head Office	Palmerston North	New Zealand	Worley Gillman Ltd.	Worley Consultants	779 sq meters		Dec-91	Tate Task Air

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- AFC Flex[4] (Access Floor Modular Wiring System)

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products:
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www.smed.ca (www.SMEDnet.com)
products:
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products:
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Walker Infloor Systems
60 Woodlawn Street
West Hartford, CT 06110
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1-800-621-0049 customer service
860-232-2062 fax

Air Distribution/ Diffusers

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Naples, FL 34108
941-597-9300 phone
941-597-9391 fax
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products:
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2400 Sterling Avenue
Elkhart, IN 46516
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870-358-2500 phone
870-358-3607 fax
www.centercore.com
products:
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1-800-972-8040
www.johnsoncontrols.com
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704-483-2050 fax
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products:
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- Rotary floor twist outlet
- Floor displacement outlet

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D70435, Stuttgart 40
Germany
0711 82 01 0 phone
0711 82 01 666 fax
www.ltg.com.sg
www.ltg-components.com
LTG Air Engineering, Inc.
101 Corporate Drive
Spartanburg, SC 29303
864-599-6340 phone
864-599-6346 fax
products:
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281-590-3086 fax
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products:
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49-28 45-2 02-0 phone
49-28 45-2 02-2 65 fax
www/trox.de
Trox USA, Inc.
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770-569-1433 phone
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products:
- Floor Diffusers, FB Series
- Displacement Flow Diffusers

Waterloo Air Management plc
Mills Road
Aylesford, Kent
England
ME20 7NB
440 1622 717 861 phone
440 1622 710 648 fax
www.waterloo.co.uk
products:
- Aircell polymer floor diffusers; WFO Series

Other Floor/ Air Products

AirFloor
- hollow concrete floor air panel system

212 S. Milwaukee Ave., Suite E
Wheeling, IL 60090
847-459-6080 phone
847-459-8350 fax

Flexible Ceiling Manufacturers

Acutherm
1766 Sabre Street
Hayward, CA 94545
510-785-0510 phone
510-785-2517 fax
www.acutherm.com
products:
- Therma-Fuser modular VAV systems

The Hartman Company
9905 39th Drive NE
Marysville, WA 98270
360-658-1168 phone
360-658-1178 fax
www.hartmanco.com
products:
- TRAV (Terminal Regulated Air Volume)

Zero Complaint Systems
Tamblyn Consulting Services
90 Sheppard Ave. E, 7th Floor
North York, Ontario
Canada M2N 6X3
416-226-6565 phone
416-226-6576 fax
Inspiraplex
3650, St.-Urbain
Montreal, Quebec
Canada H2X 2P4
514-845-8013 phone
514-845-6740 fax
products:
- Zero Complaint Air Conditioning

ENGINEERING FIRMS/EXPERTS INTERVIEWED, MOST WITH A PORTFOLIO OF UNDERFLOOR AIR PROJECTS

Appendix A4

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Int-Hout, Daniel. Carrier Corporation.

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Lehr, PE., Valentine A. Partner, Lehr Associates, Consulting Engineers, New York, NY.

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Lewis, Malcolm. President, Constructive Technologies Group Inc. (CTG), Irvine, CA.

(Luskay 2002)
Luskay, PE., Larry. Portland Energy Conservation Inc. (PECI), Portland, OR.

(Mass 2001)
Mass, PE., Douglas. Partner, Cosentini Associates LLP, Consulting Engineers, New York, NY.

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McCarry, PE., Blair. Senior Vice President, Engineering and Technology, Keen Engineering Co. Ltd., Vancouver, Canada.

(McGregor 2001)
McGregor, Alisdair. Principal, Ove Arup, San Francisco, CA.

(Nall, 2001)
Nall, Daniel, Flack & Kurtz, New York, NY.

(Roth 2001)
Roth, Dr. Ing. Hans-Werner. Development Director, LTG, Stuttgart, Germany.

(Shute 2001)
Shute, PE., Robert. President, The Mitchell Partnership Inc., Consulting Engineers, Toronto, Canada.

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Bohsali, Sam, PE, and Cindy Cogil, PE, SmithGroup, Washington, D.C.

(Wong 2001)
Wong, Jr., PE, Earl G. HVAC Department Head/ Principal, L.D. Astorino Companies, Pittsburgh, PA.

(Yates 2000)
Yates, PE., Richard. RAY Engineering, Pittsburgh, PA.