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FINAL REPORT

NATIONAL CENTER FOR ENERGY MANAGEMENT AND BUILDING TECHNOLOGIES TASK 2: UNDER FLOOR AIR DISTRIBUTION (UFAD) – RESULTS OF SEMINARS

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NOTICE

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1. EXECUTIVE SUMMARY

Introduced in the 1990s as a novel alternative to conventional air distribution (CAD) for commercially occupied spaces in the US, underfloor air distribution (UFAD) has evolved as a significant design concept since the US Green Building Council began allocating specific points for UFAD in the LEED™ rating system in 2000 (USGBC 2000). The benefits claimed for UFAD systems have focused on flexibility and adaptability in response to rapidly changing requirements in office spaces due to "churn" and to information technology (IT) changes. Additional claims have also included improved thermal and air quality, reduced energy requirements, and improved cost effectiveness. However, as discovered in a literature search conducted by Building Diagnostics Research Institute (BDRI) for National Energy Management Institute (NEMI) (Woods 2002) and summarized in a technical article (Woods 2004) these claims were primarily based on anecdotal and marketing information that had not been validated with scientifically or technically derived data obtained in actual facilities. Moreover, there is a dearth of design guidance that is based on established engineering principles of load analysis, psychrometrics, and air distribution.

To provide technical guidance to the design community, NEMI commissioned BDRI in 2003 to develop a two-day training course and a seminar series on *"UFAD: Design Issues, Principles and Practices.*" The training course was piloted in September 2003 to twenty invited design engineers from the US. Feedback from this pilot training course was then used to develop the professional seminar series. The seminars were delivered four times to architects and engineers throughout the US: 30 October 2003 in St. Louis, Missouri, 19 January 2004 in Des Moines, Iowa; 18 February 2004 in Phoenix, Arizona, and 27 May 2004 in New York, New York.[1] The objective of these seminars was to explore design issues in various geographical locations across the US and to address applications for various building types and in various climatic zones. Each seminar was intended to build on information obtained from the previous ones. Feedback from each of these seminars has been reported elsewhere (NCEMBT 2004a, b). The objective of this report is to summarize the technical findings from the seminars.

The fundamental premise learned from this series of seminars is that neither a generic UFAD system nor a generic CAD system exists. Corollaries to this premise are:

1. *There is "no silver-bullet" -- UFAD is another "tool" that can be used to provide heating, ventilating, and air-conditioning (HVAC) for specific applications;*
2. *Successful UFAD systems must be designed through an integrative design process; and*
3. *Each facility requires a unique design analysis in order to objectively select the appropriate site-specific HVAC system that meets the owner's requirements and customer satisfaction.*

The foundation for this premise and its corollaries is derived from a set of issues that were explored throughout the seminar series. These issues, which can be nested in four categories, are the subjects of this report. A summary of these categories and issues is shown in Table 1.

[1] The set of Power Point slides for the New York Seminar, which is the latest version, is attached as Appendix A.

Table 1. Issues pertaining to the acceptable performance of UFAD systems

Category	Issue	Examples	References
Evaluation criteria	Health and comfort	Acceptable parameters and values for thermal, indoor air quality, acoustics and vibration, lighting exposures in occupied spaces	ASHRAE Stds 55, 62, ASHRAE Handbook Chapters, GSA/PBS P-100-2003, LEED™ Version 2.1
	Safety and security	Fire and smoke requirements, isolation and containment, preparedness and protection, evacuation pathways	CDC and ASHRAE Guidance, GSA/PBS P-100-2003, NFPA, FEMA Guidance
	System performance	System capacity to load ratios, controllability, access and maintainability, flexibility, functionality, reliability, durability	Architectural Program, ASHRAE Std 90.1, GSA/PBS P-100-2003
	Energy and economic performance	Energy budget, first-costs, life-cycle costs, benefit/cost ratio, productivity	ASHRAE Std. 90.1, GSA/PBS P-100-2003 LEED™ Version 2.1
Load analyses	Space loads, block loads, plant loads	Thermal and mass balances, psychrometrics, energy and force balances (including acoustic, vibration and seismic, and structural loads)	Architectural Program, Tenant leases and agreements, ASHRAE Std 90.1, GSA/PBS P-100-2003 ASHRAE algorithms, ELITE® and Trane TRACE® computer programs
System selection	Architectural, structural and system integration	Deck-to-deck heights and façade requirements, raised floor requirements, seismic protection, vibration and acoustics control, equipment size and location	Architectural Program, Tenant leases and agreements, GSA/PBS P-100-2003 ASTM Standards LEED™ Version 2.1
	Safety and security	Fire and smoke management in supply and return plenums, isolation and containment of contaminants (CBR issue), emergency egress and personnel access, system preparedness	NFPA Codes and Standards, ASTM Standards FEMA, CDC and ASHRAE Guidance, GSA/PBS P-100-2003
	HVAC control	Sensible and latent heat transfer, air distribution within occupied spaces, supply and return air distribution, air cleaning and pressurization control, reliable and responsive control systems	Site-specific load analyses, ASHRAE Handbook Chapters, SMACNA Standards ASHRAE Guidelines on TAB and Commissioning GSA PBS P 100-2003
	Operations and Maintenance	Equipment room accessibility, safe and easy access to components in equipment rooms and plenums, durable and reliable equipment and components	NFPA and FEMA Guidance OSHA Regulations BOMA Guidance ASHRAE Handbook Chapters GSA PBS P-100-2003
Energy and economic analyses	Energy efficiency	Energy requirements to sustain functional performance throughout facility, system energy efficiency, energy	ASHRAE 90.1, GSA/PBS P-100-2003 LEED™ Version 2.1
	Cost effectiveness	First costs, life-cycle costs, productivity	ASHRAE 90.1, GSA/PBS P-100-2003 LEED™ Version 2.1 GSA and EPA methods for calculating productivity

2. LESSON CATEGORY 1: EVALUATION CRITERIA

Posited in the training course and evolved through the four seminars, the first lesson learned is:

During the conceptual design process, a common set of site-specific evaluation criteria must be defined in order to objectively diagnose and compare the predictive performance of UFAD and CAD systems.

These criteria are defined in terms of performance or prescriptive parameters and values that are controllable. As validated in this seminar series, a critical first step in conceptual design is to define an integrated set of parameters and values in terms that are common to the various systems being considered. Until this set of criteria has been defined and accepted for concurrent compliance, the structural and seismic, thermal and air quality, acoustic and vibration loads cannot be accurately calculated; systems cannot be objectively specified; and energy use and cost effectiveness cannot be reliably estimated.

2.1 HEALTH AND COMFORT

Based on the two fundamental principles shown in Figure 1 (Maslow 1968), a set of relational criteria has been identified that addresses the four issues shown in Table 1. The first issue is how to define, in controllable terms (i.e., parameters and values), the primary environmental stressors that are sensed by the occupants' physiological receptors and influence occupant health and comfort.

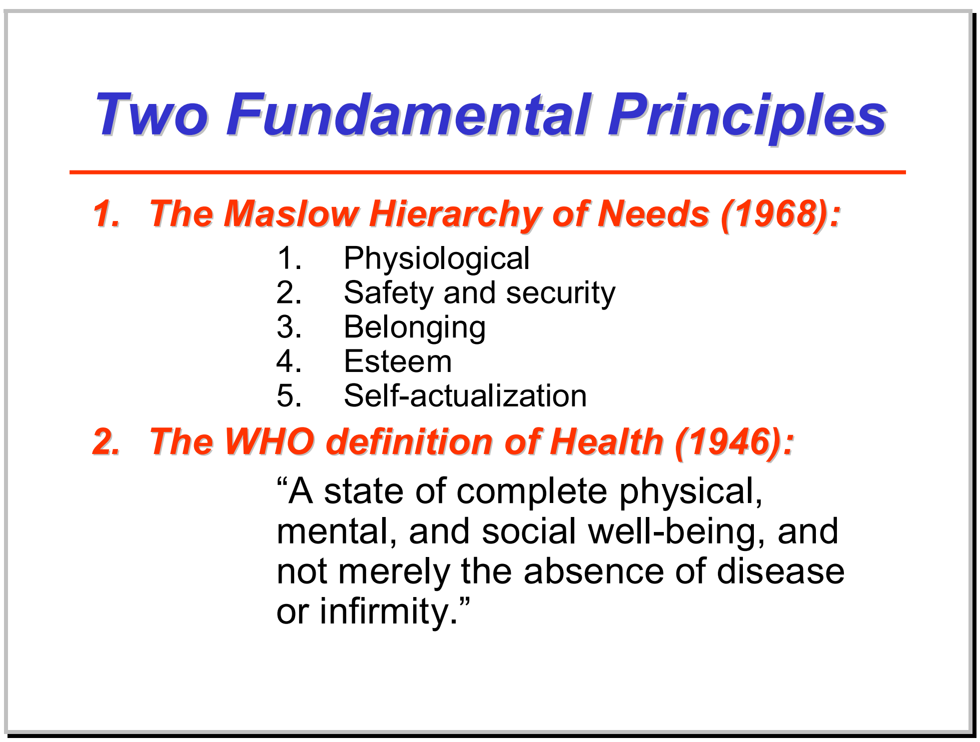

Figure 1. Fundamental Principles Addressing Building Occupant Health

As verified in this seminar series, these parameters and values are defined in terms of thermal, acoustic, visual, and chemical exposures.[2] Also verified in this seminar series, system selection can result in variations in occupant responses to the set of exposure criteria, therefore, care is required in defining the exposure parameters and values that are to be used for: 1) comparisons between predicted system performance during design; and 2) evaluation of actual system performance during operations. Examples of these parameters and values are given in Slides 83 – 86 in Appendix A and in Woods (2004). The parameters and compliance values for air quality, acoustic and vibration exposures should not be different for CAD and UFAD systems, however, the parameters and compliance values for thermal performance are likely to be different.

Note that the temperature range in the occupied space is expressed as Operative Temperature (e.g., 74 ± 2°F), which is the average of dry-bulb and mean-radiant temperatures. This is the parameter that is cited in ASHRAE Standard 55-2004, and represents the compensation for the physiological sensation of solar and other radiant loads within perimeter and interior zones. In UFAD systems, the floor surface temperatures are expected to be lower than in CAD systems and, thus, to cause increased radiant exchange with the occupants. Also note that the acceptable air speed in the occupied space is defined as ≤ 50 feet per minute (fpm) in accordance with ASHRAE Standard 55-2004, and the acceptable relative humidity range is defined as 30 - 60%, in accordance with ASHRAE Standard 62-2001. As verified in the seminar series, these values are more difficult to achieve in all occupied areas with UFAD systems than in comparable areas with CAD systems, primarily due to the need to limit the supply air temperature to not less than 63 – 65°F dry bulb temperature and the discharge the air velocities to > 50 fpm through the floor diffusers in order to create the turbulent mixing needed in UFAD. Field data on the combined effects of increased radiant exchange and "draft" in UFAD systems are not well documented, but design guidance from a thermophysiological response perspective is readily available in the ASHRAE Handbook of Fundamentals, and elsewhere.

As UFAD systems may have three vertical zones above the floor (i.e., turbulent mixing zone, uniformed mixed zone, and stagnant zone[3]), it became evident during this seminar series that compliance with the exposure criteria is expected to be more difficult to measure during occupancy. Therefore, a lesson learned is that additional care is needed in UFAD design to assure that the specified exposure values can be achieved during occupancy (i.e., effects of occupant disturbance of airflow patterns).

2.2 Safety and Security

The second issue that must be resolved is how to define, in terms of controllable parameters and values, the factors that affect occupant safety and security, and property assets, due to extraordinary conditions such as natural disasters (e.g., seismic, flood, wind incidents); accidents (e.g., fire and smoke, chemical spills, internal floods); and intentional incidents (e.g., arson, employee disruption, releases of chemical or biological agents). Criteria for protection (e.g., wind and seismic forces, flood and rain rates, flame and smoke rates) and emergency response (e.g., egress time, and duration and conditions for emergency shelter) are usually specified by codes, with which both UFAD and CAD systems must comply. Although protection and response criteria for intentional incidents have not yet been codified, guidance documents are available. UFAD and CAD systems should also comply with these criteria.

Even though protection and response criteria are available for some extraordinary incidents, the characteristics of raised flooring and underfloor plenums present special issues that must be addressed. As verified in this seminar series, internal floods in raised floor systems, with or without UFAD, can result in additional structural loads; local seismic conditions or live (e.g., rolling) loads may require heavy duty pedestals, stringers and cross-bracing; and special transitions at the interfaces with non-raised

[2] For purposes of this seminar series and this report, "exposure" is defined as the product of the concentration and the duration of the environmental stressor that the physiological receptors sense. "Total exposure" is defined as the sum of the individual exposures. These terms are based on principles of neurophysiology.

[3] These zones and their characteristics will be discussed later in this paper.

flooring and other surfaces are required to minimize accidents, flame spread, and air leakage. For UFAD systems, criteria for isolation and containment of chemical or biological releases, and fire and smoke control must be defined, especially for pressurized plenums that maximize exposures to seated occupants. For example, the PBS-P-100-2003 (GSA 2003) permits a maximum UFAD plenum zone of 5,000 ft^2 for fire-safety control. When water from floods or leaks accumulates in the supply plenum, the risk of electrical fires increases because the power wiring is typically not waterproofed. As verified in this seminar series, "Emergency Power Off" (EPO) switches are now being specified for each fire zone in UFAD systems to disengage all power in "wet plenums."

2.3 System Performance

The third issue is how to define the objective system performance criteria (i.e., parameters and values) with which to identify, compare, and design the appropriate system, or combination of systems, for the site-specific applications during normal and extraordinary conditions. As verified in this seminar series, these criteria must specify system performance not only in terms of complying with the first two sets of issues (i.e., health and comfort, and safety and security), but also in terms of functionality, maintainability, flexibility, reliability, and durability. This series also verified that that solutions to most architectural programs require the use of various types of HVAC systems, as some parts of the facility are not amenable to UFAD (e.g., mailrooms, unsecured lobbies, kitchens, other areas where spillage is likely). Thus, system performance criteria must be defined by functional category of the facility.

Also verified during this series of seminars is that assurance of system performance leads to evaluations at three scales: within the occupied spaces (space loads), within areas served by the same HVAC system (block loads), and for the entire facility (plant loads). An example of such system performance criteria is shown in Fig. 2 (Slide 87 in Appendix A) for achievement of the health and comfort, and safety and security criteria. Moreover, these system performance criteria are intended to be achieved at all three scales, in conjunction with the defined criteria for functionality, maintainability, flexibility, reliability, and durability.

Fig. 2. Examples of System Performance Criteria

Evaluation Criteria	Comments
System Capacities: *Capacity/Load Ratio = 1 $\pm$ 0.10 for design thermal and contaminant loads*	*Zone and system capacities should be selected for "design" or peak thermal and contaminant loads, including pressurization requirements.* *Floor and ceiling plenum compartment sizes for fire-smoke, and CBR control should be defined.*
System Controllability: *Capacity/Load Ratio = 1 $\pm$ 0.10 for all thermal part loads*	*Zone and system control strategies should be designed to maintain the differential pressures, temperatures, and airflow rates in response to changes in loads within perimeter and interior zones, during normal and extraordinary conditions.*

Figure 2. Examples of System Performance Criteria

2.4 ENERGY AND ECONOMIC PERFORMANCE

The fourth issue to be resolved during conceptual design is how to define objective and measurable energy, cost, and economic performance criteria with which to identify, compare, and design the appropriate system (i.e., CAD, UFAD, or combination) for the site-specific application during normal conditions, including preparedness for extraordinary conditions. As verified in this seminar series, these site-specific parameters and values must be defined during conceptual design to establish the energy and cost budgets that assure compliance with the system performance, health and comfort, and safety and security criteria. These criteria should also be used for compliance analysis during design development, value engineering, construction, and operations. An example of such energy and economic criteria is shown in Figure 3 (Slide 88 in Appendix A). This seminar series also verified that these criteria should be based on historical data and information, when available, but that actual energy and cost data for UFAD systems are difficult to find.

Fig. 3. Examples of Energy and Economic Criteria

Evaluation Criteria	Comments
Energy: Energy Consumption = 55 ± 10 KBtu/ft^{2}yr Annual Building Energy Efficiency ≥ 70%	The Energy Requirement to achieve exposure control throughout the year, and the parasitic losses should be estimated through psychrometrics and energy and mass balances over the period being analyzed (annual?) for the CAD and UFAD systems
Economics: Annual cost of housekeeping ≤ \$3/ft^{2}yr Annual cost of maintenance ≤ \$2/ft^{2}yr Annual cost of "churn" services ≤ \$1/ft^{2}yr	Estimates of these costs for UFAD and CAD systems should be based on procedures that are currently used by the owner.

Figure 3. Examples of Energy and Economic Criteria

3. LESSON CATEGORY 2: LOAD ANALYSES

The second major lesson learned during the seminar series is:

Methods of load analyses for UFAD systems differ from those typically used for CAD systems, resulting in the need for close integration with architectural and structural design.

As verified in the seminar series, the commitment to use UFAD systems can require significant changes in architectural, structural, mechanical, and electrical loads and designs. For example, the height of the supply air plenum and choice of using return air plenums can affect the size and locations of windows, the seismic load imposed on the floor, and the external and internal thermal loads to be dissipated by the HVAC system. However, the exposure criteria to be maintained in the occupied spaces should not be different for UFAD than for CAD systems.

Methods of structural, seismic, and acoustic and vibration loads analyses are common to both CAD and UFAD systems, and are beyond the scope of this white paper. However, during the development of this seminar series, much discussion focused on methods of determining thermal loads in UFAD systems. Therefore, in this lesson category, the technical issues regarding thermal load analysis of UFAD systems are highlighted.

The principles for heating and cooling load calculations have been established for many years, and are available in the ASHRAE Handbook, manuals, and other related publications. As verified in this seminar series, the primary purpose for the load calculations is to determine the capacities of the HVAC systems and the appropriate control strategies, and the secondary purpose is to use the results to estimate the energy usage for the facility. A schematic of a UFAD system is shown in Figure 4 (Slide 67 in Appendix A), together with the psychrometric profile for this system.

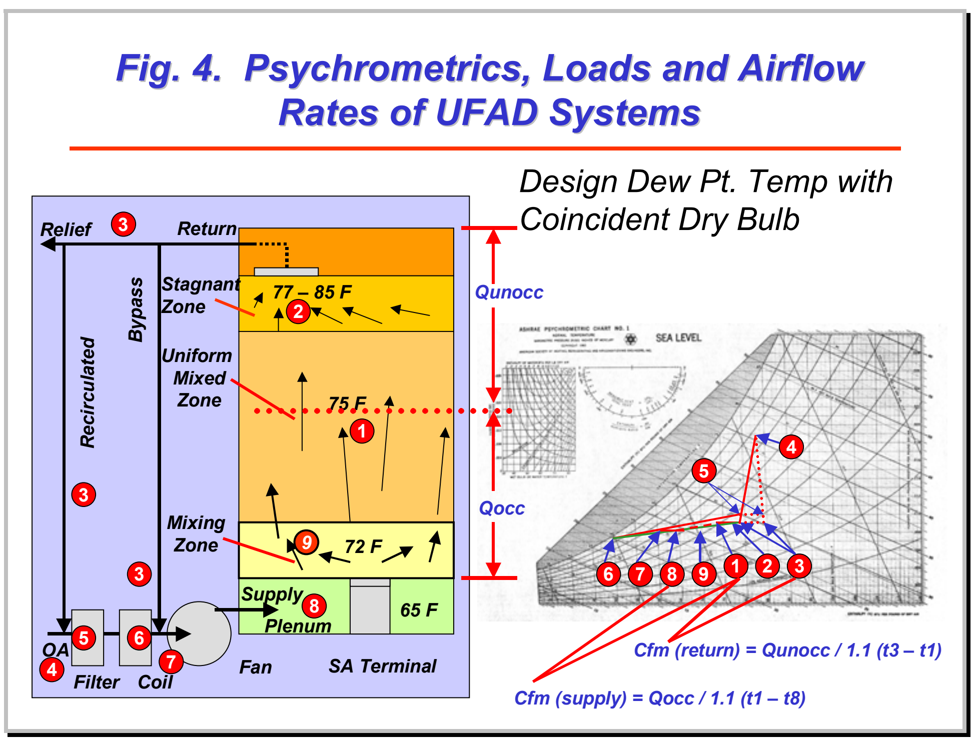

Figure 4. Psychrometrics, Loads and Airflow Rates of UFAD Systems

Fundamentally, the sensible cooling load for a particular zone is calculated as the sum of the sensible heat exchanges across the building envelope in that zone, Q_e, the internal loads, Q_i, and occupancy loads, Q_o:

$$Q_s = Q_e + Q_i + Q_o \quad [1]$$

Then, for the "uniformly mixed zone" in a CAD system, the steady-state volumetric airflow rate required to meet the sensible cooling load is calculated as:

$$v = Q_s / (1.1(t_r - t_s)) \quad [2]$$

or

$$v = Qs / (1.1(t_3 - t_6)) \text{ in Fig. 4} \quad [2a]$$

Where:

v is the volumetric airflow rate through the CAD zone (cfm)

Q_s is the sensible cooling load (BTU/hr)

t_r (t_3) is the dry bulb temperature in the return air (°F) (assumed to be the same as the temperature in the uniformly mixed zone); and

t_s (t_6) is the supply air temperature (°F).

A very important lesson learned in during this seminar series is that the total load across the cooling coil (i.e., $v(1.1(t_3 - t_6))$) is the same for CAD and for UFAD systems, however, the means of dissipating the loads within the occupied spaces of UFAD (i.e., "displacement") systems differ from those in CAD (i.e., "uniformly mixed") systems.

Although the principles for calculating heating and cooling loads for UFAD systems are the same as for CAD systems, several different methods have been proposed in the literature. The rationale for these different methods is that the multi-compartment vertical zones and the unidirectional airflow in UFAD systems are not adequately modeled by Equation [2 or 2a]. Not all of the loads may be attributed to the "uniformly mixed (i.e., occupied) zone," and the supply air temperature must be increased from approximately 55°F for CAD systems to approximately 63 – 65°F for UFAD systems to prevent cold discomfort (i.e., see process 3-6-7-8 in Figure 4). As a result, some researchers (Bauman 2003) are now recommending that the supply and return airflows (v_s and v_r) be calculated in series, as follows:

$$v_s = Q_{s,m} / (1.1(t_{os} - t_s)) \quad [3a]$$

and

$$v_r = Q_{s,s} / (1.1(t_r - t_{os})) \quad [3b]$$

Where:

v_s = volumetric supply airflow rate from the plenum to the uniformly mixed (occupied) zone, cfm

v_r = volumetric supply airflow rate from the uniformly mixed zone to the return air (i.e., through the stagnant zone), cfm

$Q_{s,m}$ = sensible cooling load in the uniformly mixed zone and the floor mixing zone, BTU/hr

$Q_{s,s}$ = sensible cooling load in the stagnant zone, BTU/hr

t_{os} = (i.e., t_1 in Fig. 4) dry bulb temperature in the uniformly mixed zone, °F

t_s = (i.e., t_8 in Fig. 4) supply air temperature in the floor plenum, °F

t_r = (i.e., t_3 in Fig. 4) dry bulb temperature in the return air, °F

Theoretically, Equations [3a] and [3b] will provide reasonable estimates of volumetric airflow rates for supply and return in turbulent mixing UFAD systems. However, as learned in the seminar series, they do not provide reasonable estimates of airflow rates for heating in hybrid systems, or for heating or cooling airflow rates for membrane systems.[4] Moreover, feedback from seminar participants and our own observations revealed that significant errors in coil selections and control strategies have resulted from the use of Equations [3a] and [3b]. Several practical reasons for these errors have become apparent:

- The methodology for separating $Q_{s,m}$ from $Q_{s,s}$ is not well established. Some researchers and designers have recommended splitting these terms evenly, some have suggested 1/3 – 2/3 splits, some have suggested considering all of the load as being in the occupied space, and some have proposed weighting factors for various loads (Addison 2001).
- Some researchers and designers have suggested that halving the Δt from supply to "uniformly mixed zone" and allowing the airflow rate to stay constant can be compensated by letting the return air temperature rise so the total Δt from supply to return remains the same as for a CAD system. This suggestion results in an assumed stagnant air (return air) temperature approaching 85°F. Moreover, the total load must still be transferred to the HVAC cooling coil. Feedback from the seminars and our observations indicates that the 85°F temperature is seldom realized, with the implication that the airflow pathways are different than assumed.
- If the stagnant air temperature is allowed to increase, additional heat transfer will occur, thus increasing the supply air temperatures in floor plenums for multi-story installations.
- The supply air temperature in the floor plenum is assumed to remain constant. As verified in the seminar series, this assumption is not valid: temperture variations of as much as 10°F in the supply plenum have been observed. It is noted that this deviation can affect load dissipation by as much as 100% in the "occupied zone."
- If the stagnant air temperature is assumed not to increase, an imbalance results between the supply and return airflow rates.
- The assumption of splitting the loads and halving the Δts is inappropriate for heating load calculations for hybrid systems, and for heating or cooling load calculations for membrane systems.
- The psychrometrics of controlling for ventilation, as well and sensible and latent cooling during peak and part load conditions have not been fully developed for UFAD systems.

These findings and lessons learned clearly indicate that significant additional research is needed in developing and validating methods for accurately determining cooling, ventilating and cooling loads in the occupied spaces of UFAD systems.

[4] These variations in UFAD systems are further discussed later in this paper.

4. LESSON CATEGORY 3: SYSTEM SELECTION

The third major lesson learned during the seminar series is:

Once the commitment is made to use raised access flooring with UFAD, a lifetime of servicing this system is required.

As verified in the seminar series, the commitment to use UFAD systems requires close design coordination in the selection of the lighting, structural, acoustic and thermal support systems. Moreover, additional provisions are needed for safety and security control, and maintenance and operations during the lifetime of the facility.

4.1 Architectural, Structural and System Integration

The height of the raised access flooring and the deck-to-deck height of the stories are fundamental issues that must be resolved during conceptual design. As verified in the seminar series, deck-to-deck heights may range from 12 feet to more than 20 feet for certain types of public facilities (e.g., courtrooms, theaters). Moreover, the use of suspended ceilings has typically not been alleviated due to the selection of UFAD. Rather, most UFAD facilities now have two plenums, the ceiling plenum that contains, plumbing, sprinkler systems, lighting, power wiring and return and exhaust air ductwork; and the raised floor plenum that contains, some power wiring, some hydronics, IT cabling, and supply air. As a result, raised floor heights are typically 12 – 18 inches. The height of the occupied zone therefore varies considerably in these systems, and the methods of maintaining stratification must be adapted, accordingly.

Other issues that must be resolved include accessibility to equipment in the raised floor, seismic protection and size of pedestals, stringers, and cross-bracing; and their effects on ductwork in the supply plenums; vibration (i.e., deflection and frequency) and acoustic control; and air-handling units' sizes and locations.

4.2 Safety and Security

When the decision to use UFAD is made, additional issues regarding safety and security must be resolved, in accordance with the pre-determined criteria. As verified in the seminar series, means and methods of fire and smoke management in the supply plenums must be specified, installed and verified; air cleanliness and contaminant control must be assured; zone isolation and containment must be assured, and emergency egress and access on the raised flooring must be assured.

4.3 HVAC Control

Based on the analyses of thermal, contaminant, and pressurization loads, the pathways of room air distribution and system air distribution must be determined, the equipment sized and located, and the control strategies must be selected.

During the evolution of the seminar series, four basic types of UFAD systems were identified, characterized, and discussed:

- Two basic configurations were discussed in the Washington and St. Louis seminars: Vertical Displacement (VD), and Turbulent Mixing (TM). Both of these systems introduce supply air from the floor plenum and return it through the ceiling or an upper zone.
- A third configuration was observed, introduced, and discussed at the Des Moines seminar: "hybrid (York MIT) systems" that returns air either high for cooling, or low into ducts in the floor plenum for heating.

- And a fourth configuration was introduced at the Phoenix seminar, after discussions at the ASHRAE Seminar in Anaheim in January 2004: the "membrane (Liebert - Hiross) system" that returns air to a divided floor plenum for heating and cooling.

Each of these UFAD systems differs in principle from conventional air distribution (CAD) systems, which are considered to have two vertical zones: 1) an *induction zone* where primary (i.e., supply) air is mixed with room air before delivery at or below a "terminal velocity" (e.g., $\leq$ 50 fpm) into the *occupied zone*; and 2) the occupied zone where the air is uniformly mixed and exposed to the occupants to provide ventilation and thermal exchange for occupant acceptability. For CAD systems, a metric, defined as the Air Diffusion Performance Index (ADPI) (see ASHRAE Handbook), can be used to select and locate supply air devices (i.e., diffusers, grilles, or registers in ceilings, high or low sidewalls, sills or perimeter floor grilles) to achieve "acceptable" thermal responses (see ASHRAE Standards 55, 70 and 113). In principle, the ADPI is a function of the room size and its sensible thermal load, the isothermal throw characteristic of the supply air device, and a room "characteristic length":

$$\mathbf{ADPI = f(Q_s, T_{50}/L, \Delta t, V)} \qquad \textbf{[4]}$$

Where:

ADPI	=	percentage of points in occupied zone that comply with thermally acceptable conditions
Q_s	=	room sensible thermal load, BTU/hr
T_{50}/L	=	ratio of the distance of the isothermal throw of the supply air device to the room characteristic length
Δt	=	difference between the local temperature at the point being measured and the reference temperature of the occupied zone (e.g., thermostatic set point), °F
V	=	local air velocity at the point being measured, cfm

These functional relationships for various types of supply air devices have been determined through research and published in the ASHRAE Handbook and other literature, including manufacturers' literature. It is therefore practical to use ADPI for selection and placement of supply air devices in CAD systems based on the measured or calculated thermal loads, the room characteristics, and the characteristics of the selected supply air devices. Placement of return air devices in CAD systems is typically not considered as a critical issue for thermal control (as the space is assumed to be uniformly mixed), although placement too close to the supply air devices has been shown to cause bypass losses, reduced ventilation efficiency, and reduced energy efficiency.

Each of the UFAD systems discussed in this seminar has a different method of providing ventilation air and thermal exchange within the occupied zones. Therefore each must be considered separately when calculating the load, and selecting and placing the supply and return air devices:

- The "VD system" theoretically has three zones: a lower "mixing zone," which functions as an inverted induction zone (as in the CAD system) and extends 1 – 2 feet upward from the floor; a "gradient (i.e., occupied) zone," which may have up to 5°F vertical temperature gradient, and an upper "stagnant zone" from where the air is returned or exhausted. This system is primarily used for ventilation only, as its airflow rate and temperature gradient are insufficient to dissipate significant room sensible or latent loads. With this system, other means of dissipating thermal loads must also be used such as radiant systems, fan coils, or other conventional systems. The return or exhaust air devices are typically placed above the "occupied zone."
- The "TM system," which can dissipate thermal loads and provide ventilation air, theoretically also has three zones: a lower "mixing zone," which functions as an inverted induction zone

(as in the CAD system) and extends 2 – 4 feet upward from the floor; a "uniform mixed zone," which functions similarly to the "occupied zone" of a CAD system, but is limited in height from 2-4 feet above the floor to approximately 6 feet above the floor; and a "stagnant zone," above the "uniform mixed zone," from where air is returned or exhausted. When heating is required, fan-powered boxes, or reheat coils can be incorporated into the system. Uniform placement of the return air devices in the "stagnant zone" is recommended to minimize instability of the plume, but guidelines or standards for determining this placement have not yet been developed.

- The "hybrid system" functions as a TM system when cooling is required throughout the area being served (i.e., supply air temperatures are below those in the occupied zone). However, when heating, or heating and cooling, is required, dampers are engaged to change the direction of airflow in some of the floor air devices (i.e., they become return air devices); this air is then heated and ducted to other supply air devices. In the heating mode, the "hybrid" system does not have unidirectional airflow to the return air devices, as the lower "mixing zone" converges to the "uniform mixed zone" temperature, and not all of the supply air is returned through the "stagnant zone." Thus, in the cooling mode, the "hybrid system" functions with the same three vertical zones as the "TM system." *In the heating mode, however, the "hybrid system" functions with three vertical zones in the part of the room where cooling is provided but with only two vertical zones where the return air causes the "mixing zone" and "uniformly mixed zone" to converge (i.e., the temperature of the return air is the same as the in the "uniformly mixed zone").* The complexity of this arrangement affects objective design for comfort and significantly affects heating load calculations (see below).
- The "membrane system" divides the underfloor plenum by a membrane into a supply air compartment and a return air compartment. Theoretically, this system does not have a "stagnant zone," as the air introduced into the room from the supply compartment is returned to the HVAC system through floor grilles. Thus, the supply compartment has two vertical zones: "the mixing zone" and the "uniformly mixed zone" as with the TM system, but the return compartment has only one zone: "the uniformly mixed zone."

The ADPI principles have not yet been extended to UFAD systems, and rational equivalent methods of selection and placement of supply air devices have not been developed. Rather, an anecdotal concept called the "Clear Zone Radius" has been proposed by some researchers and manufacturers (Bauman 2003, York 1999). This concept is based on two principles: 1) a vertically upward throw of the device is necessary to dissipate the thermal loads; and 2) a "Clear Zone Radius" is needed within which to induce turbulent mixing with room air to prevent discomfort complaints from high velocities and cold temperatures of the supply air. The literature recommends vertical throws of ≤ 2 feet for VD systems, and ≤ 6 feet for TM systems; recommendations for vertical throw have not been found in the literature or from the seminar feedback for heating applications with "hybrid systems," or for heating or cooling with "membrane systems." The literature also recommends Clear Zone Radii of 1 – 2 feet for VD systems, and 2 – 4 feet for TM systems, dependent on thermal loads. The percent of room volume represented by these recommended "cylinders" ranges from 1 – 3% for VD systems and 9 – 37% for TM, hybrid, and membrane systems. Our literature review and seminar feedback reveal that these recommendations are primarily based on anecdotal information, and that little theoretical or applied research has been conducted to extend or to provide an equivalent method to the ADPI. It is anticipated that research could be developed that will improve methods for sizing and locating the diffusers for load dissipation and thermal comfort.

As shown in Figure. 4, psychrometric control of UFAD systems is more complicated than CAD systems. This lesson learned from the seminar series refutes some that claim UFAD control is simple. Zone and pressurization control that involves not only a supply air plenum, but often a return air plenum, becomes more difficult when precise control of contamination is required in addition to thermal control. An important lesson from this seminar series is that psychrometric analysis is critically important to designing and controlling a successful UFAD system.

4.4 Operations and Maintenance

As verified in the seminar series, equipment room accessibility, and safe and easy access to the components, have been often compromised in UFAD design. One of the claims about these systems is that they are not as complicated and do not need the same care as CAD systems. Many of the systems being installed are in large federal buildings that have 100-year life expectancies, which demand long and reliable service of the systems. A lesson learned from the seminar series is that operations and maintenance provisions for UFAD systems are at least as important as in CAD systems.

5. LESSON CATEGORY 4: ENERGY AND ECONOMIC ANALYSIS

The fourth major lesson learned during the seminar series is:

Energy and economic analyses must accurately reflect the predicted performance of the system

As verified in the seminar series, the commitment to use UFAD systems as often been based on unsubstantiated claims of superior energy performance, lower first and life-cycle costs, and improved occupant performance and productivity than CAD systems. As verified in this seminar series, when detailed analysis are performed and validated, finding are often the reverse: when all of the criteria have been determined to be in compliance, energy and economic values for UFAD systems have been found to be similar to CAD systems.

The lesson learned from the seminar series is that modeling techniques for UFAD systems have not been as well developed as they are for CAD systems, and the energy and economic predictions are highly dependent on "input assumptions" being made by the modelers. When objective models are used for comparison with similar CAD systems that achieve the same criteria compliance, more reliable results are expected.

6. CONCLUSION

This series of seminars resulted in a reality check with engineers and architects who have had *some* experience with UFAD system design and/or operations. The feedback from them was invaluable. Based on these lessons learned, it is anticipated that more objective decision-making will result in improved system performance of both CAD and UFAD systems.

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APPENDIX A – JAMES E. WOODS PRESENTATION

Slide 1

Underfloor Air Distribution (UFAD) Systems:

Design Issues, Principles and Practices

Sponsored by
Testing Adjusting and Balancing Bureau
with
SMACNA of New York City, Inc. and
SMACNA, Long Island Chapter

Presented By
James E. Woods, Ph.D., P.E
27 May 2004

The Building Diagnostics Research Institute, Inc.

Slide 2

Purpose

The purpose of this seminar is to explore the expected performance of underfloor air distribution (UFAD) systems as alternatives to conventional air distribution (CAD) systems during design.

Slide 3

Objectives

- Highlight issues revealed in literature searches of occupied UFAD systems,
- Compare psychrometric and air flow characteristics of UFAD and CAD systems,
- Suggest protocol and criteria for site-specific evaluation during design, commission, operation.

Slide 4

Educational Outcomes

- Increased understanding of advantages and disadvantages of UFAD systems.
- Increased ability to predict, through diagnostic procedures, the performance of UFAD systems for site-specific applications.

Slide 5

Seminar Content

Session 1: **Introduction and Overview:** Review of design issues and available literature/information (1 hour)
(8:30 – 9:45 AM)

Session 2: **Principles and Procedures:** Psychrometrics, Air Distribution, and Energy and Mass Balances, Diagnostics and Commissioning (1 ½ hours)
(10:00 AM – Noon)

Slide 6

Session 1:

Introduction and Overview:

Review of design issues and available literature/information (1 hour)

Slide 7

Current Drivers and Balances

Environment

- Green Buildings
- Sustainability
- Global warming
- Moisture and Mold
- Weather and Seismic Protection
- Fire and Life Safety
- Environmental Security

Energy

- Reduced loads and capacities
- Advanced control strategies
- Changes in O&M procedures
- "Zero Energy" Buildings

Productivity

- Health and Comfort
- Occupant performance
- Health care costs
- Employee absences
- First and O & M costs
- Value Engineering
- Fear of terrorism

Slide 8

Brief History of UFAD Systems

- **Prior to 1900s**
  - *Heating and ventilation (Monticello, Houses of Parliament, Chicago Auditorium, Metropolitan Opera House)*
- **Cleanrooms and Computer Spaces (1960s - current)**
  - *Cooling of sensible loads (floor return for contamination control, floor supply for thermal control)*
- **Flexible Workspaces (1990s - current)**
  - *Heating, cooling, and ventilation of interior and perimeter zones*

Slide 9

Summary of Literature Review

- Background and Issues of Concern
- Procedures
  - ✓ Preliminary Literature Search
  - ✓ Evaluation and Classification Criteria
  - ✓ Subsequent Literature Search
- Findings
- Discussion and Interpretation
- Conclusions and Recommendations

Slide 10

UFAD Background and Issues

- UFAD systems are not new
- Demands for flexible work environments have increased interest
- Millions of sq ft of office space with UFAD are being designed
- Concerns include:
  - ✓ Latent cooling capacities
  - ✓ Accumulation of particulate matter and moisture
  - ✓ Pressurized floor plenums
  - ✓ TAB difficulties
  - ✓ Compartmentalization and Isolation during incidents

Slide 11

Procedures

- Preliminary Literature Search
  - ✓ 13 occupied facilities with UFAD
  - ✓ Initial functional characteristics identified
  - ✓ Systems installed within the last 15 years
  - ✓ Characteristics used as basis to modify the BDRI Evaluation Criteria for comparison of UFAD and CAD systems Characteristics used to define keywords for subsequent literature search

Slide 12

Procedures

- **Subsequent Literature Search**
  - ✓ Search engine found 2990 citations
  - ✓ Analysis of 500 of these yielded 9 general review articles
  - ✓ Four additional articles were added from our library

Slide 13

Findings

- **Preliminary Literature Search (Fall 2002)**
  - ✓ Size from 20K to 290K sq ft, but % UFAD generally less than total floor area
  - ✓ Climatic conditions did not represent high dew point or latent load conditions
  - ✓ None reported to have ducted supply air to floor or desk outlets
  - ✓ Plenum supply air temp ranged from 55 – 70 F
  - ✓ Period of occupancy ranged from 1 – 5 years
  - ✓ More than half had thermal and draft complaints
  - ✓ Other complaints included noise, dirt in diffusers, and air distribution and TAB problems
  - ✓ Energy savings were claimed but not validated
  - ✓ In several cases, hard or flex conduit was required for wiring and cabling in plenums

Slide 14

Findings

- **Subsequent Literature Search (Fall 2002)**
  - ✓ 65 buildings identified with UFAD systems
    - 33% in western/northwestern US (e.g., light latent loads)
    - 47% in midwestern/eastern US (e.g., large heat losses and large sensible heat loads in summer)
    - 18% in southern US (e.g., light sensible heat losses and large sensible and latent heat loads in summer)
  - ✓ Size from 2K to 3M sq ft, but % UFAD generally less than total floor area
  - ✓ 30% were installed as part of new construction
  - ✓ No illnesses or symptoms reported but the author has investigated such complaints
  - ✓ Occupant discomfort reported for thermal, lack of air movement/drafts, noise, dust and dirt
  - ✓ Non-compliance with relative humidity and air movement criteria reported, while gas and particulate concentrations were more frequently in compliance
  - ✓ System problems included insufficient latent heat capacity, lack of controllability of temperature, pressurization, and compartmentalization
  - ✓ Energy and first cost justifications were not validated

Slide 15

Discussion and Interpretation

- UFADs are attractive alternatives to CADs, but more limited than marketing suggests
- Many variations of UFADs preclude simple characterization of their advantages and disadvantages
- General Claims of superior performance of UFADs over CADs are probably meaningless
- Frequency of non-compliance with evaluation criteria expected to be similar for UFADs and CADs
- More specific design guidance being provided regarding the use of UFADs (e.g., LEED 2.1 and GSA PBS-P100-2003)

Slide 16

Conclusions and Recommendations

- Each of the initial "issues of concern" has been validated in the literature search
- Both UFAD and CAD systems will require more care in design, installation and operation as consequences of system performance become more apparent
- TAB, commissioning, and building diagnostic techniques continue to improve and provide greater assurance of system performance
- Continue to develop and validate methods and procedures to assure system performance

Slide 17

Types and Variations of Current UFAD Systems

Supply Air

Positive Pressure Plenum
- Unducted, "Push" Type
  - ✓ Diffusers & Grilles
  - ✓ VAV Units

"Neutral" Pressure Plenum
- Ducted to VAV or FC Units
- Unducted, "Pull" Type
  - ✓ Fan-powered VAVs
  - ✓ Fan Coil Units
  - ✓ Fan-powered diffusers & Grilles

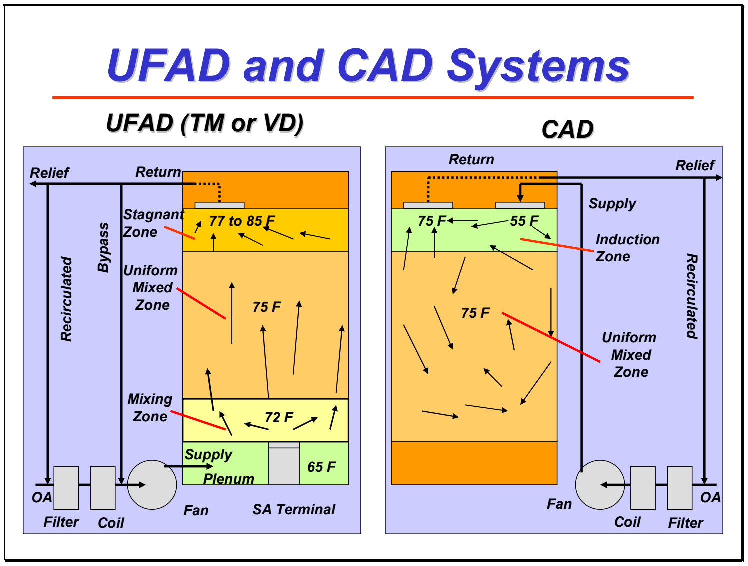
Return Air

Ceiling Plenum
- Ducted
- Partially Ducted
- Unducted

High Sidewall Grilles
- Ducted or unducted to Ceiling
- Ducted to VAV or FCU in Floor

Floor Plenum
- Ducted from Kiosk to VAV or FCU
- Ducted from Grille to VAV or FCU
- Membrane to separate floor plenum for supply and return

Slide 18



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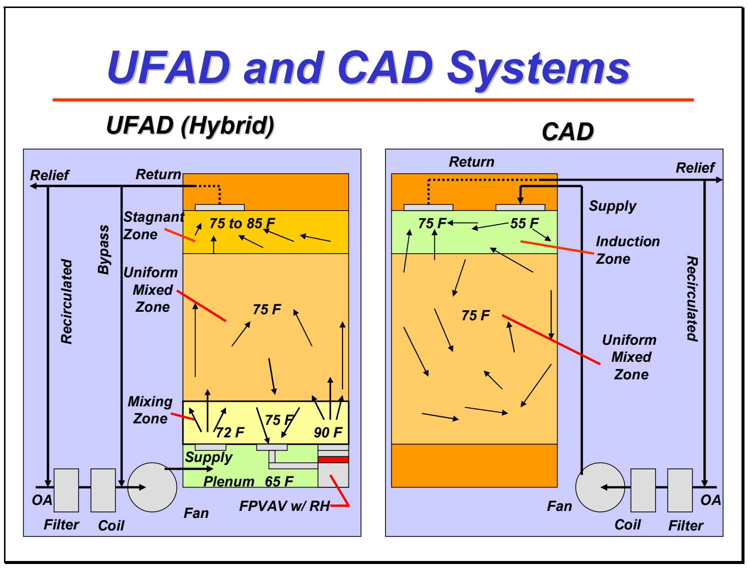

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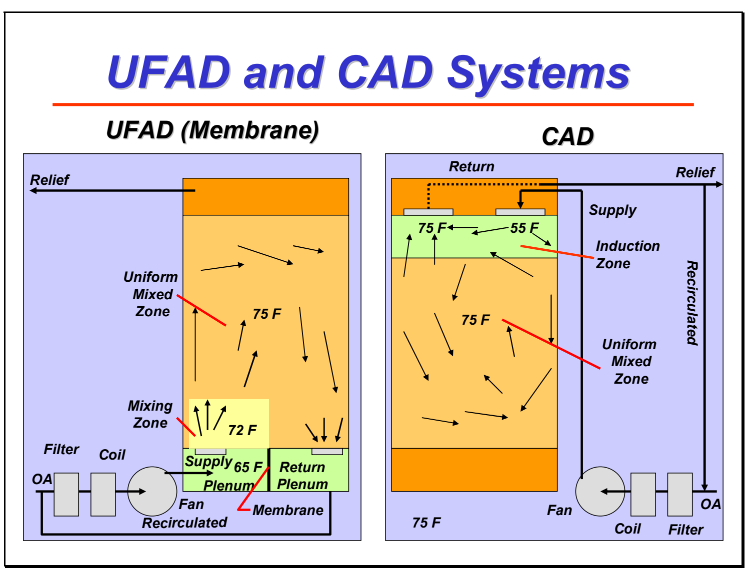

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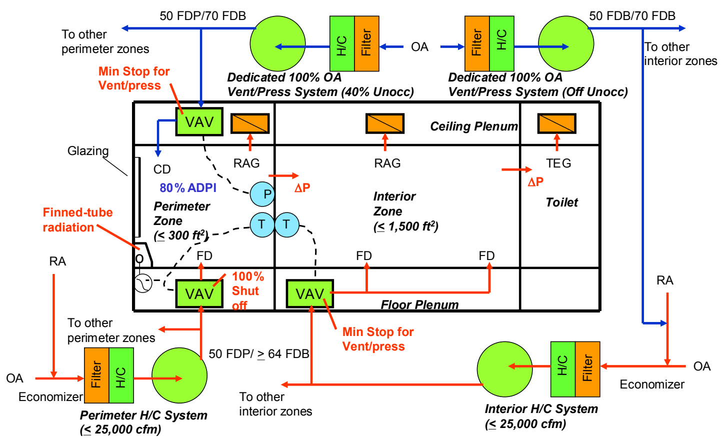
Example Schematic of UFAD Systems Specified by GSA: Thermal, Ventilation, Pressurization Zones



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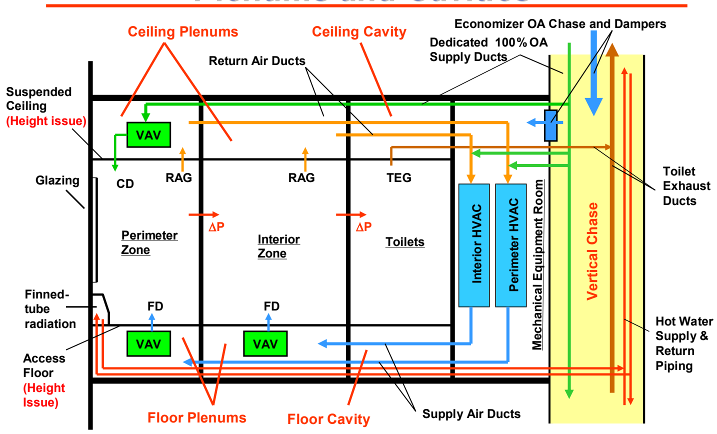
Plenums and Cavities



Slide 23

Interfacing Functions

The heights and configurations of plenums and cavities must accommodate:

- *Required vertical and lateral (stringer) structural support for:*
  - ✓ *Seismic and live loads*
  - ✓ *Vibration control*
- *Barriers and sound traps for acoustics control*
- *Fire retardants, fire stopping, fire protection accessories (e.g., fire dampers, fire and/or smoke detectors)*
- *Barriers and retardants for moisture and contaminant control*

While providing access to:

- *Piping for hydronics, plumbing, and fire protection*
- *Electrical power wiring and lighting fixtures*
- *IT wiring and cabling*
- *Supply and return air ductwork and terminal devices*

Slide 24

Plenum Losses

- Pressurized plenums are likely to have significant air leakage (e.g., 20-30% @ 0.1 inch wc) and supply air temperature rise (e.g., 3 to 10 F)
- Air leakage pathways not obvious:
  - ✓ Into occupied zones – air mixing, thermal and pressurization control countermanded
  - ✓ Into other areas (wall cavities) – unintended consequences (moisture, mold, energy waste)
  - ✓ Pathways must be carefully sealed.
- Diffusers and grilles must be sized for ΔP (e.g., 0.1 in. wc), vertical throw (e.g., 6 ft), clear zone radius (e.g., 2 ft), and noise criteria (e.g., 45 RC).
- Vertically downward fan discharges into supply plenums are likely to add 0.5 inch wc to system ESP.

Slide 25

Influence of Ducted Supply and Return

- Ducted supply air to terminal units reduce need for plenum pressure
  - ✓ Reduce air leakage
  - ✓ May be more energy efficient
- Whole system must be balanced, not just supply air
- When pressurization between zones is needed, ducted return air may be required

Slide 26

Session 2:

Principles and Procedures:

Psychrometrics, Air Distribution, and Energy and Mass Balances, Diagnostics and Commissioning (2 hours)

Slide 27

Fundamental Objectives of Environmental Control

- Prevent adverse health and safety effects
- Provide for desired conditions:
  - Human Response
  - Occupant Performance
  - Productivity
- Achieve by simultaneous control of exposure parameters:
  - Thermal
  - IAQ
  - Lighting
  - Acoustics

Slide 28

Two Fundamental Principles

1. The Maslow Hierarchy of Needs (1968):
   1. Physiological
   2. Safety and security
   3. Belonging
   4. Esteem
   5. Self-actualization
2. The WHO definition of Health (1946):
   "A state of complete physical, mental, and social well-being, and not merely the absence of disease or infirmity."

Slide 29

Four Principles for Design of Healthy Buildings

1. Design to provide for Wellness rather than to prevent Illness
2. Design to achieve Functional Requirements rather than just to meet codes and standards
3. Design for the Last Day of Occupancy rather than for Initial Occupancy
4. Verify with Building Diagnostic Methods for virtual and actual buildings

Slide 30

Methods of Evaluation

Psychrometrics

Psychrometrics deals with determining thermodynamic properties of moist air, and using these properties to analyze conditions and processes involving moist air (ASHRAE HOF)

Building Diagnostics

A process in which a skilled expert draws on available knowledge, techniques, and instrumentation in order to predict a building's likely performance over time (BRB 1985)

Slide 31

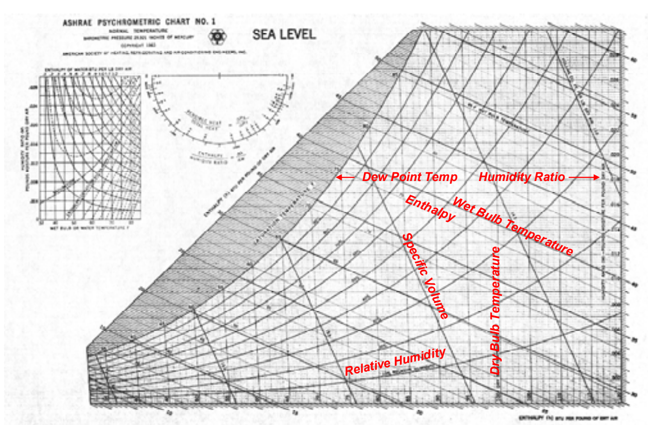
Air Conditioning

"Air Conditioning is the control of the humidity of air by either increasing or decreasing its moisture content. Added to the control of the humidity is the control of temperature by either heating or cooling the air, the purification of the air by washing or filtering the air and the control of the air motion and ventilation."

- Willis H. Carrier

Slide 32

ASHRAE Psychrometric Chart



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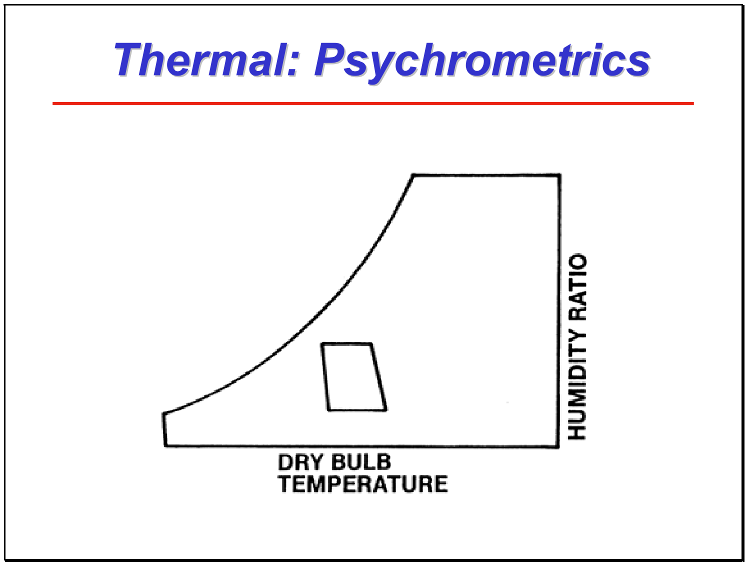

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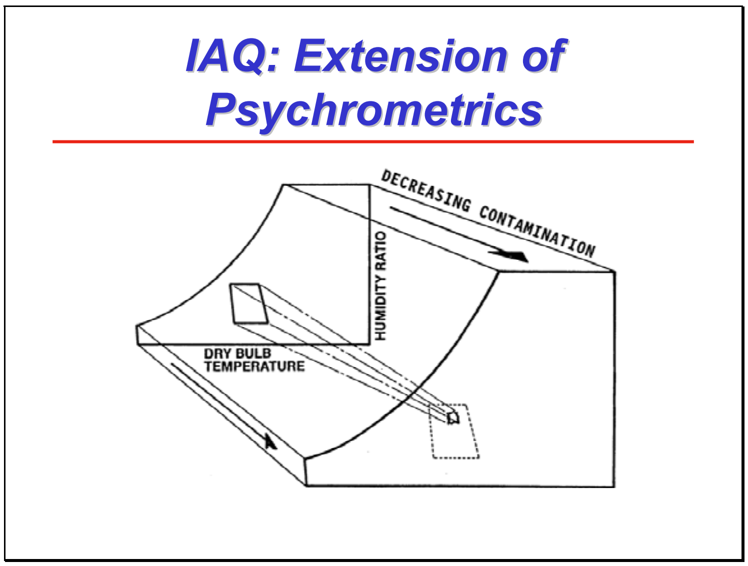

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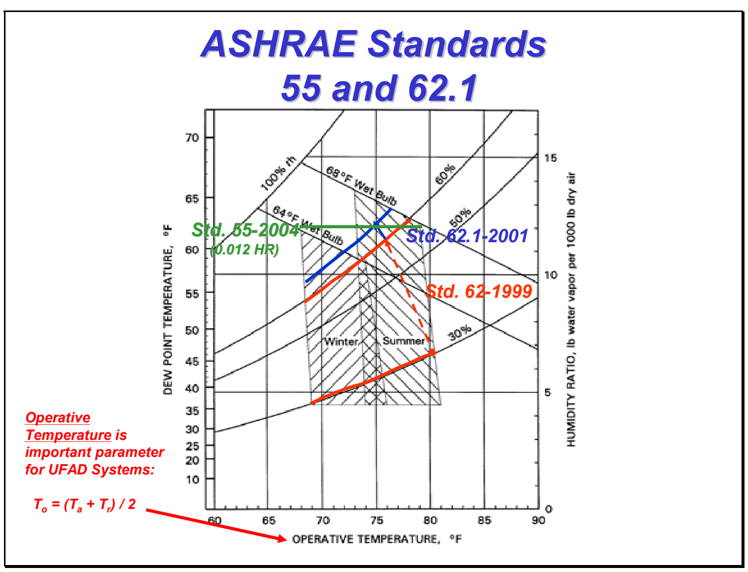

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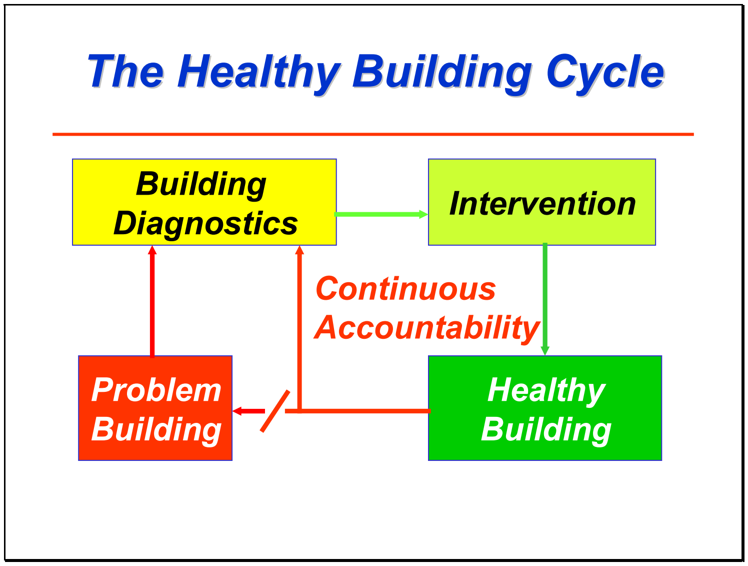


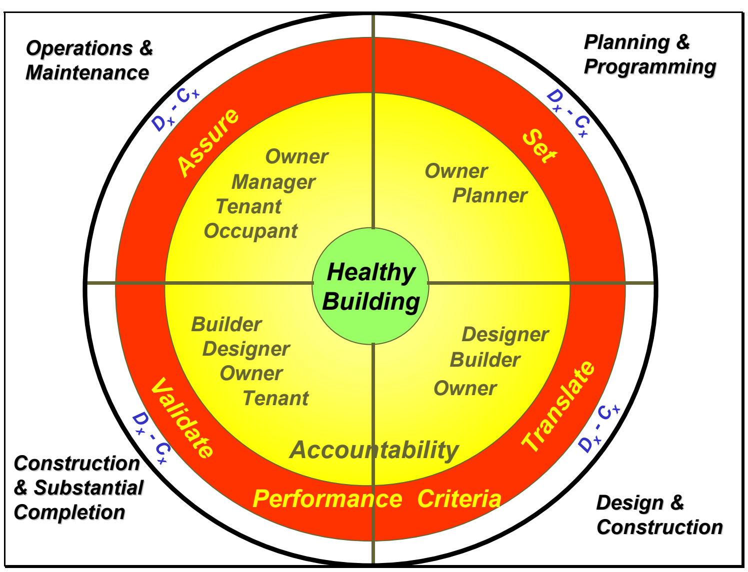
Slide 37

Commitments needed for Continuous Accountability

***Accountable person* must be:**

- ***Explicitly identified* for each phase in building's life**
- ***Empowered* with authority to assure building performance**
- ***Educated and trained* to assure adequate building performance and occupant protection**

Slide 38



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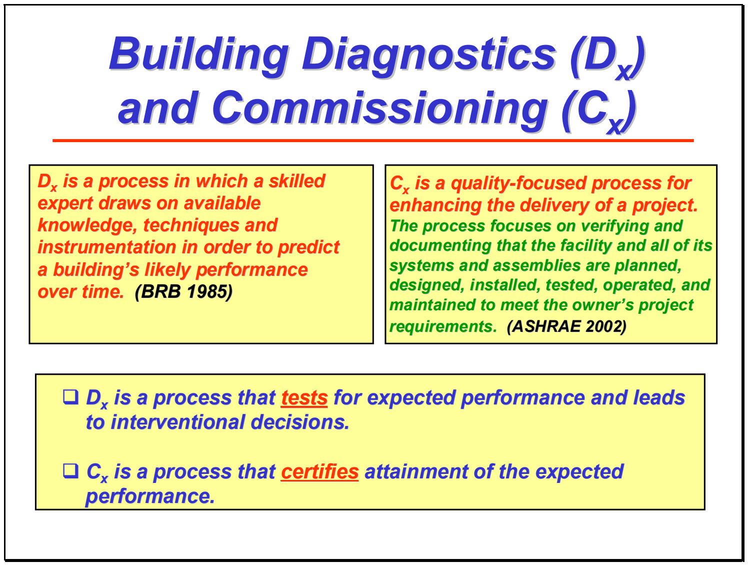

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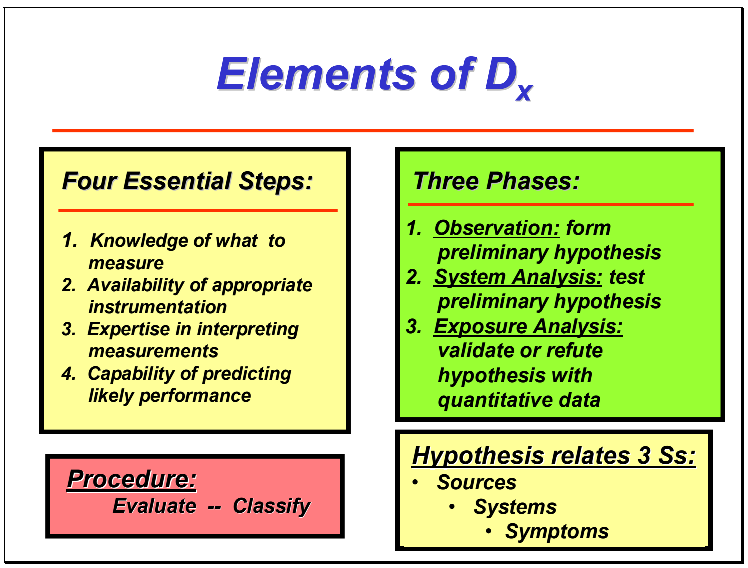

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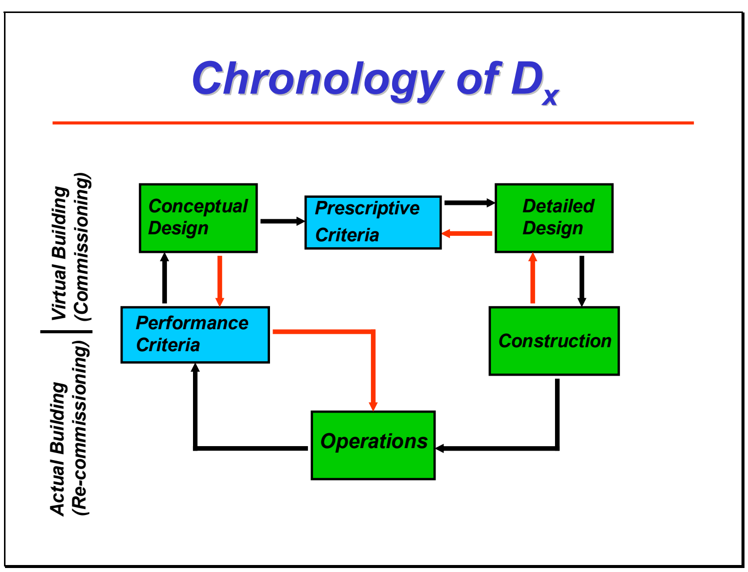

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Evaluation Criteria

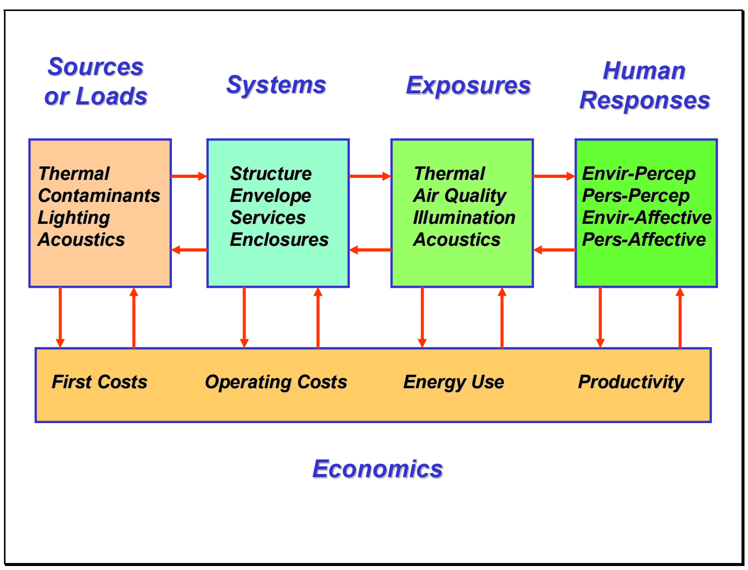
- Set of measurable and controllable parameters and corresponding values
- Mandatory Criteria:
  - ✓ Directly affect occupants
  - ✓ (Exposure & Human Response criteria)
  - ✓ Non-compliance = failure
- Flexible Criteria:
  - ✓ Indirectly affect occupants
  - ✓ (System and Economic Performance criteria)
  - ✓ Non-compliance = fault

Slide 43

Seven Steps for Design of Healthy Buildings

1. Establish design requirements and criteria
2. Determine the design loads
3. Determine the system capacities
4. Design control system for partial loads
5. Assemble the design documentation
6. Commission the system or building
7. Periodically re-evaluate system performance

Slide 44



Slide 45

Four Domains of Human Response

Object of Response	Aspects of Response	
	Perceptual	Affective
Environmental	•External Sensory Responses	•Acceptability •Preference
Personal State	•Internal Sensory Responses	•Comfort •Well being

Slide 46

Exposure Criteria

Human Response Criteria: Percent Acceptability	Continuous Exposure Parameters			
	Thermal Std 55	IAQ Std 62	Lighting Std 90	Acoustics Ch 46 App
Feasible Max	95%	95%	95%	95%
Selected Percentage	?	?	?	?
Predetermined Min	80%	80%	80%	80%

Slide 47

System Performance Criteria

Based on exposure criteria and loads

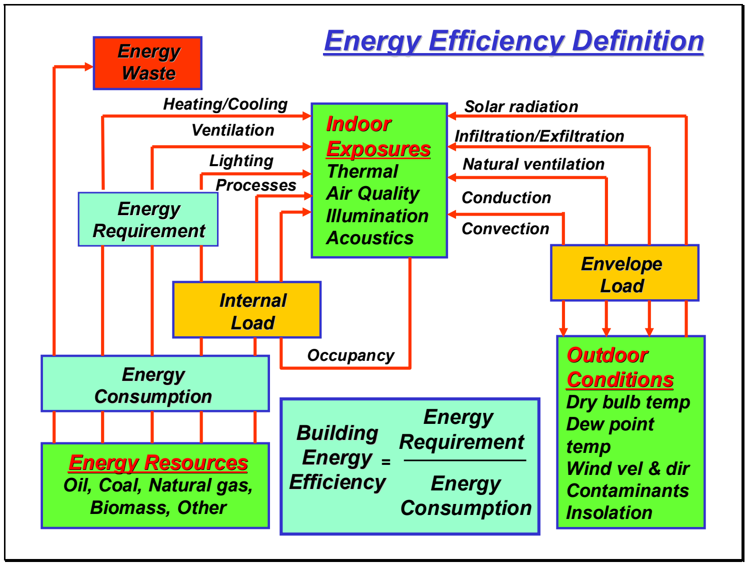
At design loads, system capacity should:

- maintain the exposure values within the specified limits

At part loads, the system controls should:

- maintain the exposure values within the same limits as at design loads

Slide 48



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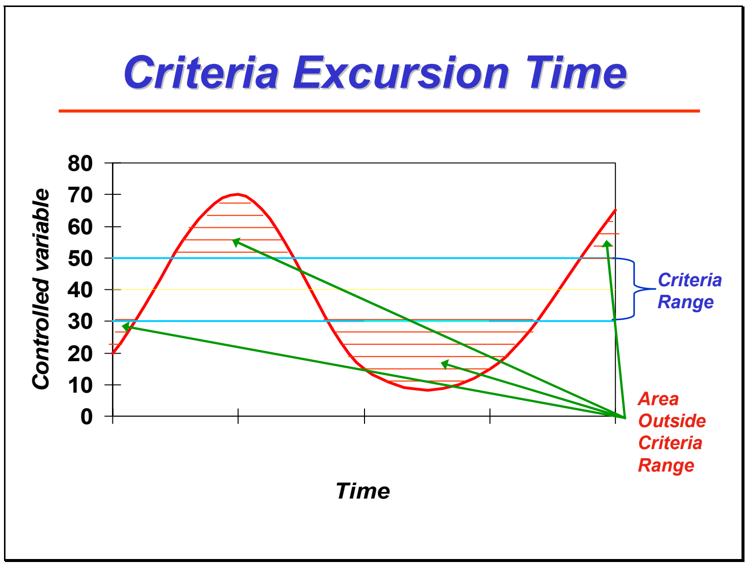
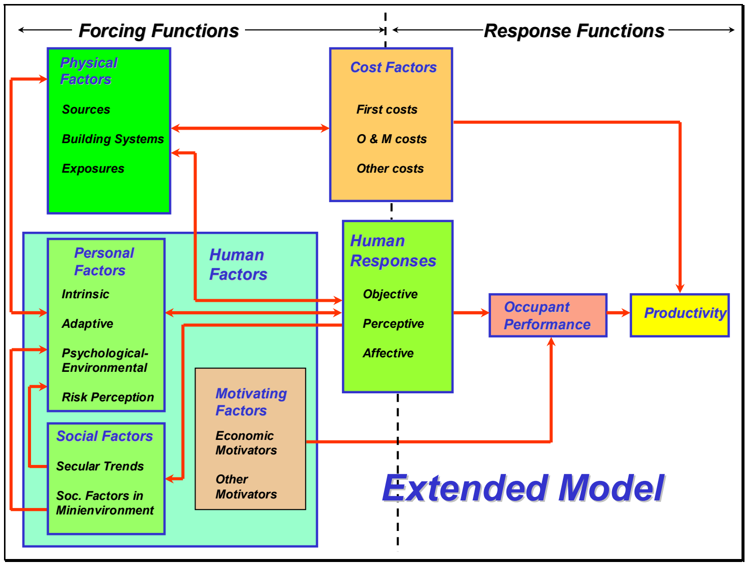


Slide 50

Energy and Economic Performance Criteria

- System energy efficiency of at least 70% should be achieved
- Selected system should incur minimum life-cycle cost, wherein comparison of alternatives includes weighting for productivity and preparedness improvements in the environment

Slide 51



Slide 52

Measures of Occupant Performance (Ex: Schools)

	Exposed Occupants	
	Long-term	**Short-term**
Occupancy	•Teachers •Librarians •Faculty •Students •Staff	•Students •Parents and visitors •Faculty •Inspectors •Accreditors
Figures of Merit	•% lost concentration •# medical visits/yr •% hampered performance	•% lost concentration •% achievement •% absentees •# medical visits/yr

Slide 53

Measures of Productivity

- Cost of salaries and wages for substitute workers due to sick leave
- Lost revenue due to absence of workers
- Direct and indirect health-care costs due to worker illnesses
- "Productivity Impact Factors":
  - ✓ Ratio of cost savings from intervention to costs at risk (I.e, salaries, health -care costs, etc.)

Slide 54

Measures of Preparedness

- Time to isolate impacted zone from other zones
- Time to compartmentalize and pressurize or de-pressurize zones
- Time of egress from impacted zone
- Effectiveness of removal control strategies (e.g., contaminant removal rate)

Slide 55

Diagnostic Objectives: Contingency Matrix

Problem Buildings:
- Maximize True Positive
- Minimize False Negative

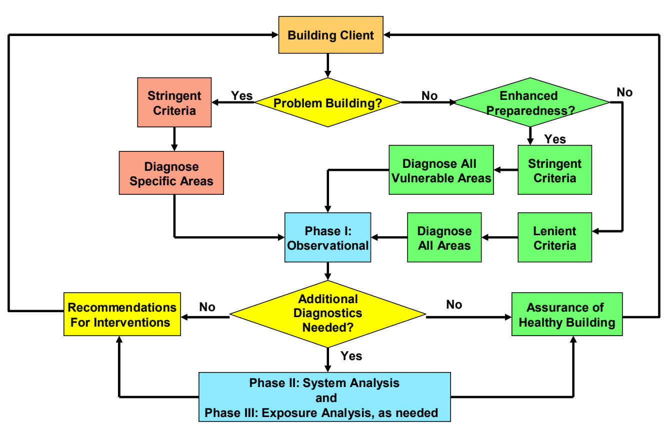
Healthy Buildings:
- Maximize True Negative
- Minimize False Positive or False Negative, depending on consequences

Enhanced Preparedness:
- Maximize True Negative
- Minimize False Negative

Measurement	Event Occurrence: Yes	Event Occurrence: No
Yes	True Positive	False Positive
No	False Negative	True Negative

Slide 56

Three Phases of D_x



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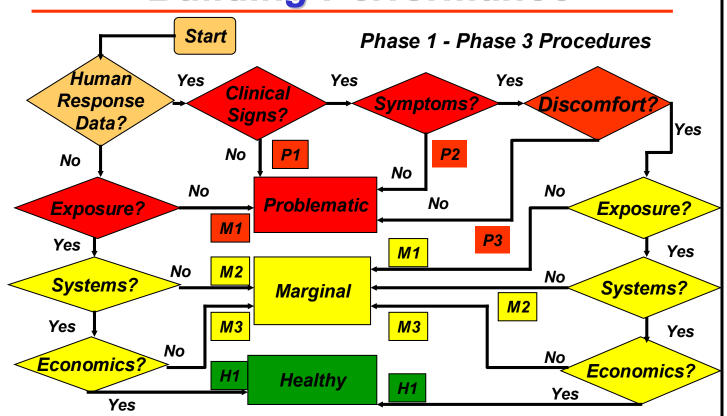
Classification Criteria

- **Healthy Category**
  - H2: Compliance with all Evaluation Criteria (Enhanced Performance)
  - H1: Compliance with all Evaluation Criteria (Transparent Performance)
- **Marginal Category**
  - M3: Non-compliance with Economic Criteria
  - M2: Non-compliance with System Performance Criteria
  - M1: Non-compliance with Exposure Criteria
- **Problematic Category**
  - P3: Non-compliance with Discomfort Criteria
  - P2: Non-compliance with Symptom Criteria
  - P1: Non-compliance with Illness Criteria

Slide 58

Flowchart for Classifying Building Performance



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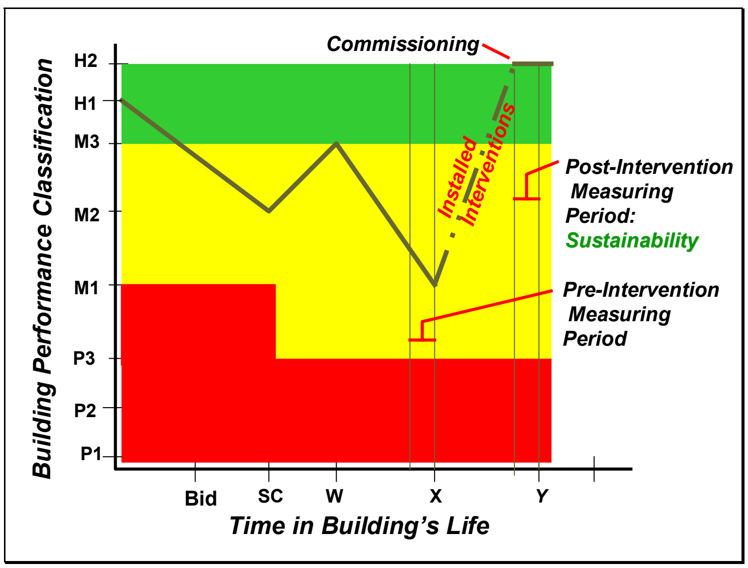

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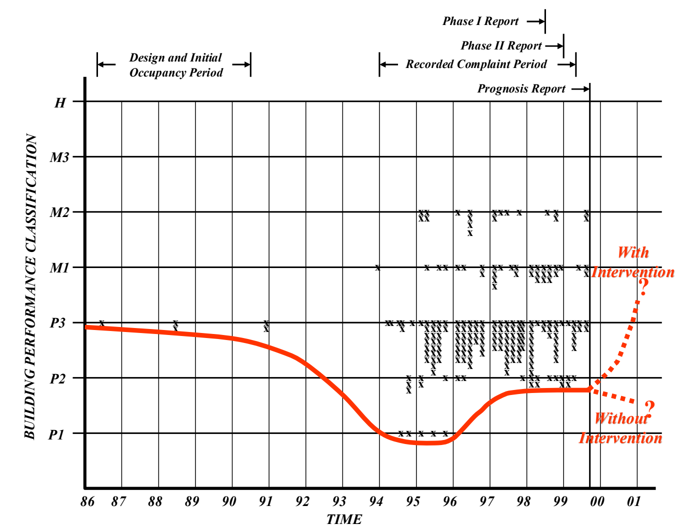

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Psychrometrics for Thermal and Contaminant Control

- One-compartment Model
- Air Quality Control
  - Thermal
  - Chemical
  - Particulate
- Two-compartment Model
  - Non-dimensional Parameters
  - Energy, Air, and Contaminant Balances

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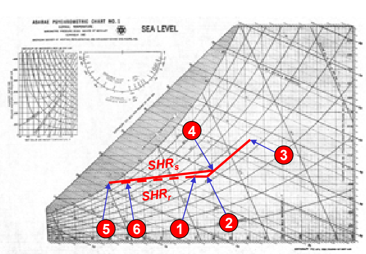
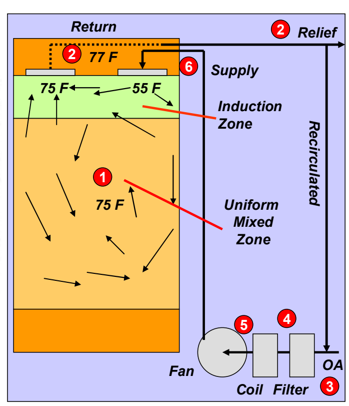
Psychrometrics of CAD System

Design Dry Bulb Temp with Coincident Wet Bulb Temp





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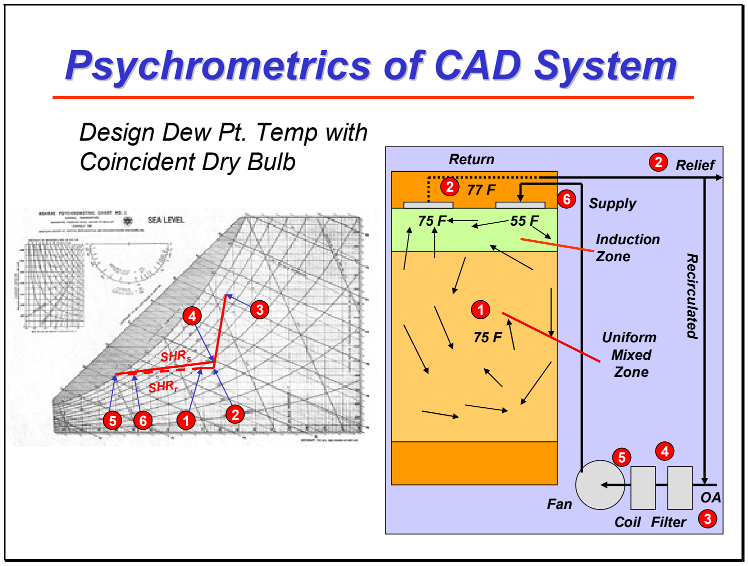

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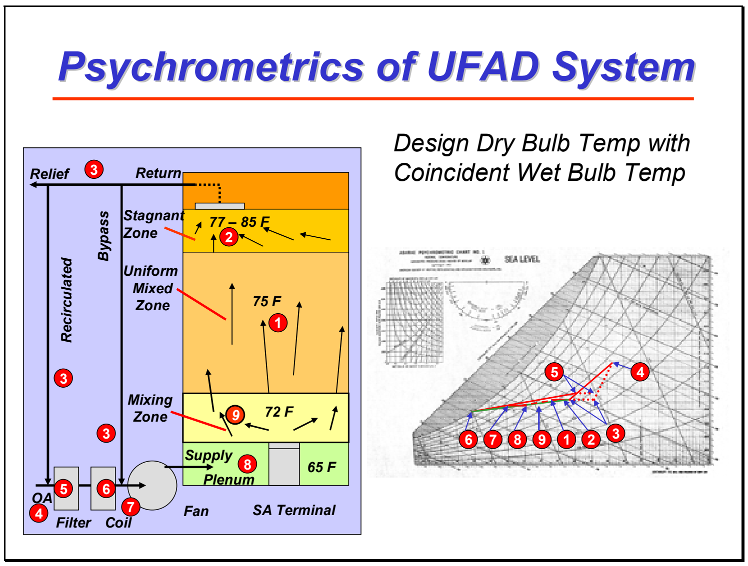

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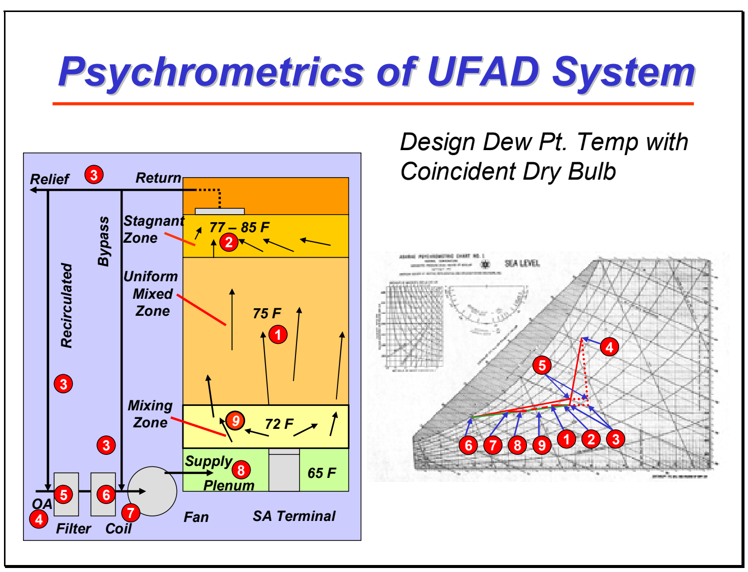

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Thermal Loads

The load calculations for UFAD systems must be carefully considered. Some researchers (Addison and Nall) recommend splitting the load for the occupied space as 1/3 in the mixed zone and 2/3 in the stagnant zone; others are splitting ½ and ½; 2/3 in the mixed zone and 1/3 in the stagnant zone; yet others are assuming the whole load in the occupied space. One researcher (Loudermilk) has developed a table of values: the "Equivalent Sensible Heat Gain (ESHG) Factors.

Bauman (ASHRAE) recommend that the flow rates be calculated as:

cfm (supply air) = Qocc / 1.1 (t1 – t8), and

cfm (return air) = Qunocc / 1.1 (t3 – t1)

However, they did not recommend how to split the sensible loads or how to select cfm for latent loads.

The consequences of these assumptions affect the supply plenum temperature and stagnant zone dry-bulb and dew-point temperatures, and may cause significant undersizing of the AHU air flow and heat transfer capacities.

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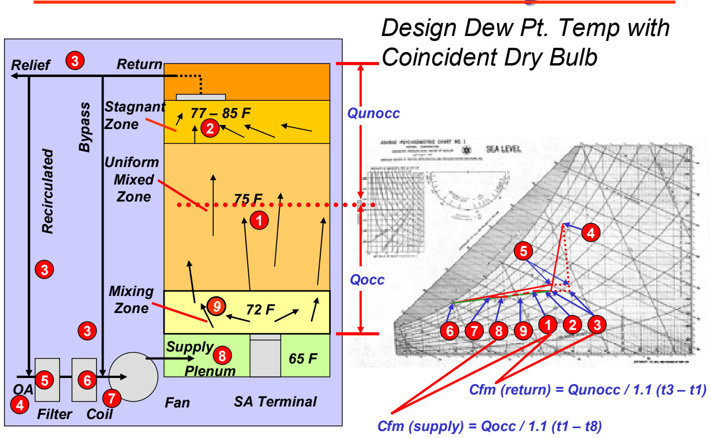
Psychrometrics, Loads and Airflow Rates of UFAD Systems



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Air Distribution for Occupied Spaces

- **Zonal Air Distribution**
  - **Physical Boundaries**
  - **Functional Zones or Boundaries**
  - **Thermostatic Zones**
  - **Moisture, Contaminant and Pressurization Zones (Health, Fire-Safety, Environmental Security)**
  - **Supply, Return, and Exhaust Airflow Rates**
- **Air Distribution in Occupied Spaces**
  - **CAD Systems (Supply [ADPI], Return [Ventilation Efficiency])**
  - **UFAD Systems (Supply [ΔT vs V/A], Return [?])**

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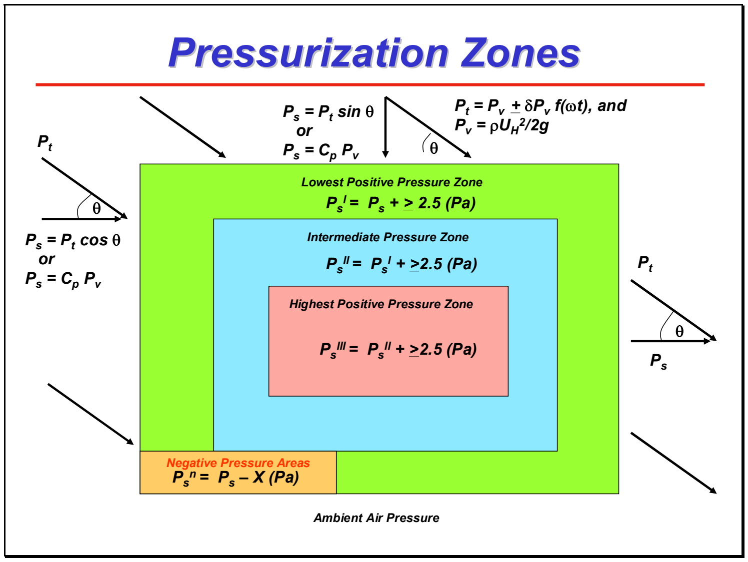

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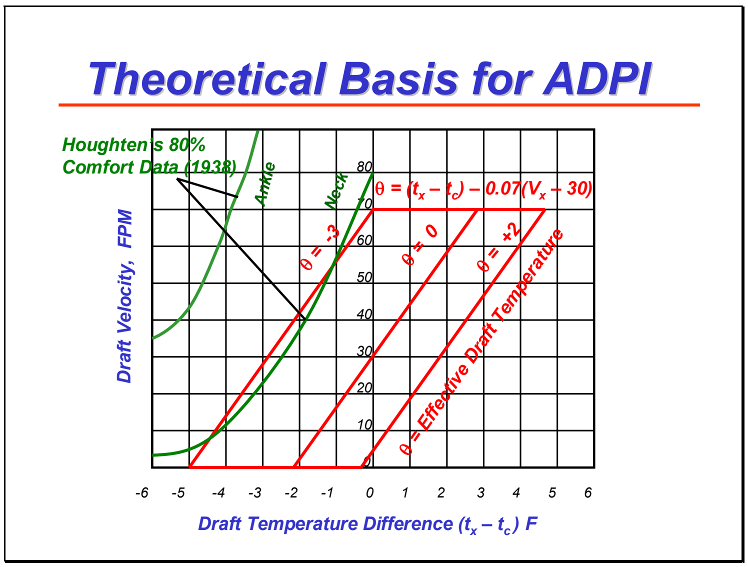

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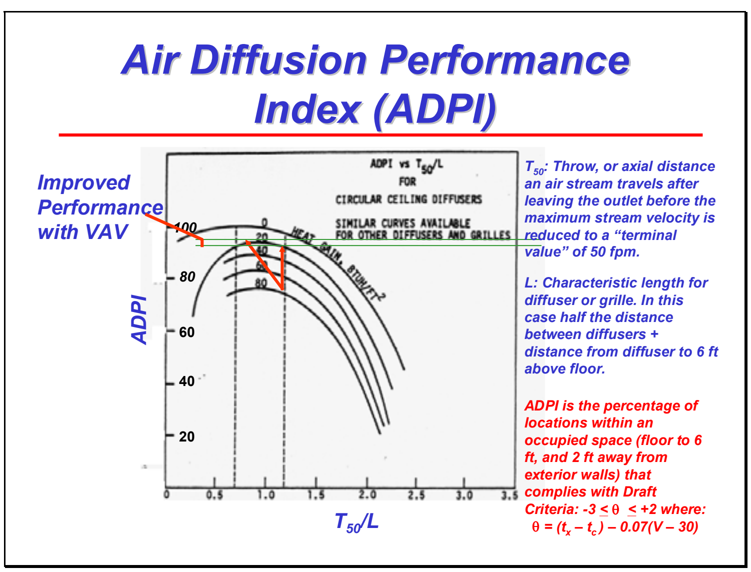

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Characteristics of CAD and UFAD Diffusers

Characteristic	CAD	UFAD	
		Turbulent Mixing	Displacement
Heat Gains	All space loads	Most space loads	Max loads of 4 – 5 W/ft²
Room Temp	Uniform in Occ. Space	Uniform from 4 ft above floor	Max gradient < 6 F
Air Velocity	≤ 50 fpm in Occ. Space	≤ 50 fpm in Occ. Space	30 - 40 fpm in Occ. Space
ADPI	≥ 80% for all space loads	NA	NA
Throw	From ADPI	< 6 ft vertical	Minimum (< 2 ft vertical)
Clear Zone	No minimum	2 – 4 ft radius	1 – 2 radius
Supply Air Temp.	55 – 62 F	62 – 67 F	68 – 70 F
Occ.Sp. – SAT	12 – 20 F	8 – 13 F	2 – 6 F
Ventilation Effectiveness	1.0 at 80% ADPI and Min. bypass to RAG	1.0 – 1.2 estimated	1.0 – 1.2 estimated

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Characteristics of Return Air CAD and UFAD Grilles

Characteristic	CAD	UFAD	
		Turbulent Mixing	Displacement
Location	Ceiling, High Sidewall, Low Sidewall, Floor	Ceiling, High Sidewall, High Kiosk	Ceiling, High Sidewall
Spacing	Minimize Bypass Losses	Uniform spacing to minimize plume instability	Spacing less critical for high bay areas
Inlet Velocity	≤ 750 fpm or as limited by noise criteria	Limited to minimize plume instability	Limited by noise criteria

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Focus of Session 5: Practice

- Discuss "Problem Statement"
- Select a set of Evaluation Criteria
- Conduct a Phase 1 D_x
- Form Preliminary Hypotheses and Recommendations for Discussion
- If needed, Conduct a Phase 2 D_x
- Validate, Refute or Revise Preliminary Hypotheses
- Revise Recommendations for Discussion

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Example Problem: Project

A general office area for a mid-level floor of a new speculative building in Washington, DC

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Example Problem: Program Objectives

Provide an office environment that is:

- *Conducive to high expectations of human response and occupant performance*
- *Protective of exposures from contaminants that are naturally occurring (e.g., mold), accidental (e.g., spills, fire and smoke), and intentional (e.g., chemical, biological, radiological)*
- *Energy Efficient and Cost Effective*

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Example Problem: Problem Statement

Determine if CAD, UFAD, or a combination of systems is appropriate to meet the "Program Objectives"

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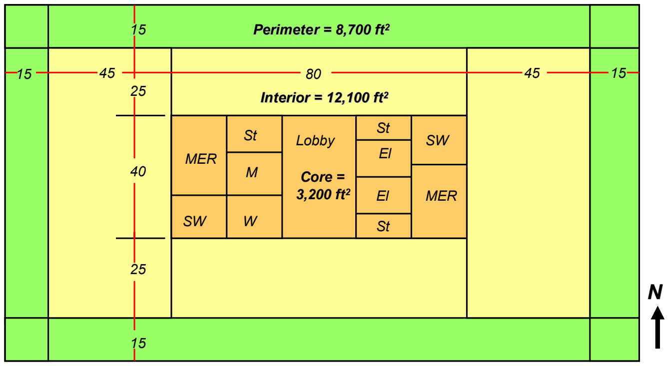
Example Problem: Sketch of Floor Plan



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Example Problem: General Floor Characteristics

Characteristic	Interior Space	Perimeter Space
Floor area	12,100 ft^2	8,700 ft^2
Deck-deck height	12 ft	12 ft
Clear ceiling height	9 ft	9 ft
Glazing/wall percentage	NA	50%
T'stat zone limits	≤ 2,000 ft^2, or ≤ 3 enclosed offices	≤ 300 ft^2, and ≤ 15 ft from outside wall
Pressurization	+ wrt core and perimeter	+ wrt outside (wind dependent)
Occupant density	75 ft^2/person	100 ft^2/person
Lighting load	2.5 W/ft^2	2.5 W/ft^2
Plug load	3 W/ft^2	3W/ft^2

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Example Problem: General System Characteristics

Characteristic	Supply Air Flow Rate Capacities (cfm)	Exhaust Air Flow Rate Capacities (cfm)
Floor AHU (VFD)	2 @ 12,000 ea	
Outdoor Air	4,800 (20%)	
Interior Floor Diffusers (not in contract)	120 @ 100 cfm = 12,000	
FB VAV for perimeter	TBD	
Toilets	2 @ 150 cfm = 300 cfm	6 @ 175 cfm = 1,050
Kitchen Exhaust		
Eq. Rm Exhaust		
Elevator Lobby		
Infiltration		

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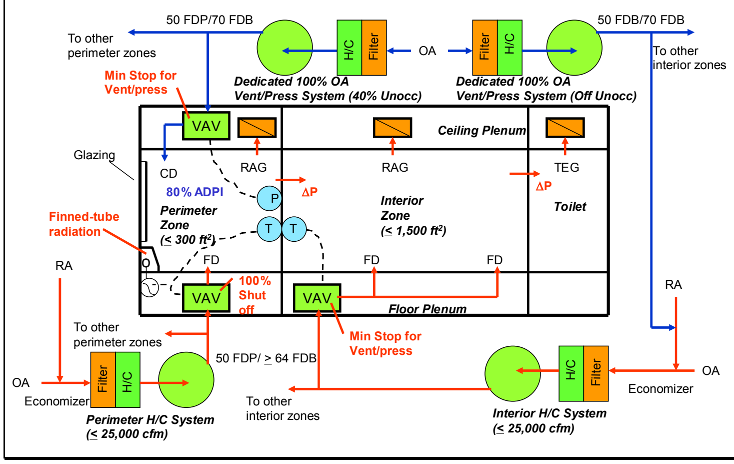
Example Schematic of UFAD Systems Specified by GSA: Thermal, Ventilation, Pressurization Zones



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Example Problem:

Evaluate the UFAD Problem to determine if it is:

- In compliance with Evaluation Criteria
- Conducive to high expectations of human response and occupant performance
- Protective of exposures from contaminants that are naturally occurring (e.g., mold), accidental (e.g., spills, fire and smoke), and intentional (e.g., chemical, biological, radiological)
- Energy Efficient and Cost Effective
- Conducive to objective and credible TAB (i.e., how would you balance this floor?)

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Example Set of Evaluation Criteria

- Human Response
- Exposures
- System Performance
- Energy and Economic Performance
- Healthy Building Performance

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Examples of Human Response Criteria

Category	Classification	Evaluation Criteria
Problematic: A facility or area within it is considered to have problematic performance if non-compliance with human response criteria is detected.	***P3: Compliance with Personal-objective and Personal-perceptual Criteria, but non-compliance with Environmental-affective Criteria.***	**At least 80% of both short term and long term occupants (i.e., assigned occupants and visitors) in the area being evaluated shall consider the overall environment in the space as "acceptable."**
	P2: Compliance with Personal-objective Criteria, but non-compliance with Personal-perceptual Criteria.	Not more than 20% of the occupants being evaluated shall report more than two symptoms characteristic of SBS that are alleviated upon leaving the area being evaluated, that recur upon re-entry, and that persist for more than two weeks.
	P1: Non-compliance with Personal-objective Criteria.	Not more than one occupant in the area being evaluated shall be documented to have building related disease or illness.

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M1: Examples of Thermal Exposure Criteria

Evaluation Criteria	Comments
Operative Temperature = 74 $\pm$ 2 F at thermostat location	*Careful placement of DDC sensor can accommodate this criterion for UFAD and CAD systems*
Thermal gradient $\leq$ 5 F, and *Air speed < 50 fpm in occupied space from floor to 6 ft above floor*	*Compliance is expected when:* • *An ADPI > 80% is obtained for CAD at SAT $\geq$ 55 F* • *Clear Radius Zones $\leq$ 2 ft and vertical throws $\leq$ 6 ft are obtained for UFAD at SAT $\geq$ 65 F*
Relative Humidity $\geq$ 30% and $\leq$ 60% throughout occupied space, during occupied and unoccupied conditions	*If RH is not maintained in this range at all times, the likelihood of mold growth increases. Also, control of RH in UFAD floor plenums is needed to prevent condensation on surfaces*

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M1: Examples of Contaminant Exposure Criteria

Evaluation Criteria	Comments
CO_2 $\leq$ 800 ppm throughout occupied space, during occupied and unoccupied conditions	*This is more stringent than differential of 700 ppm (indoor-outdoor) in ASHRAE 62.1-2001, as M1 compliance is for Overall Human Response criteria, not just the disaggregate CO_2 response*
PM10 $\leq$ 50 $\mu g/m^3$, and *Bioaerosol Indoor/Outdoor Ratio $\leq$ 0.5 throughout the occupied space, during occupied and unoccupied conditions*	*These values are expected to be achieved with particulate filtration now recommended in 62.1 (i.e., MERV > 6)* *For "Preparedness" to respond to accidental or intentional releases, ASHRAE recommends MERV 16 – 20* *Filtration in UFAD plenums needs special consideration*
TVOC $\leq$ 500 $\mu g/m^3$ (reported as equivalent toluene)	*This value can is expected to be achieved with ventilation rates recommended in ASHRAE 62.1-2001* *For "Preparedness to accidental or intentional releases, additional gaseous removal devices should be considered per ASHRAE Report* *Protection against these releases in UFAD floor plenums needs special consideration*

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M1: Examples of Lighting and Noise Exposure Criteria

Evaluation Criteria	Comments
Lighting: 500 $\pm$ 100 Lux and Contrast Ratio = 0.8 $\pm$ 01 See Section 6.15 and Tables 6-3 and 6-4, PBS-P100.	Illumination levels and lighting efficacy affect thermal loads Some designers recommend that the lighting load not be considered as space load in UFAD systems. However, the radiant component remains a space load, and the total lighting load must still be removed by the system
Noise: 40 max dB Noise Criteria Curve for open plan offices, lunch rooms, lobbies; 30 max dB Noise Criteria Curve for private offices; and 25 max dB Noise Criteria Curve for meeting rooms (See Section 3.3 and Table 3-4, PBS-P100)	Supply air diffusers and return air grilles for CAD and UFAD systems should be selected to comply with these noise criteria Noise transmission from floor and ceiling plenums must also be considered

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M2: Examples of System Performance Criteria

Evaluation Criteria	Comments
System Capacities: Capacity/Load Ratio = 1 $\pm$ 0.10 for design thermal and contaminant loads	Zone and system capacities should be selected for "design" or peak thermal and contaminant loads, including pressurization requirements. Floor and ceiling plenum compartment sizes for fire-smoke, and CBR control should be defined.
System Controllability: Capacity/Load Ratio = 1 $\pm$ 0.10 for all thermal part loads	Zone and system control strategies should be designed to maintain the differential pressures, temperatures, and airflow rates in response to changes in loads within perimeter and interior zones, during normal and extraordinary conditions.

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M3: Examples of Energy and Economic Criteria

Evaluation Criteria	Comments
Energy: Energy Consumption = 55 $\pm$ 10 KBtu/ft^2yr Annual Building Energy Efficiency $\geq$ 70%	The Energy Requirement to achieve exposure control throughout the year, and the parasitic losses should be estimated through psychrometrics and energy and mass balances over the period being analyzed (annual?) for the CAD and UFAD systems
Economics: Annual cost of housekeeping $\leq$ \$3/ft^2yr Annual cost of maintenance $\leq$ \$2/ft^2yr Annual cost of "churn" services $\leq$ \$1/ft^2yr	Estimates of these costs for UFAD and CAD systems should be based on procedures that are currently used by the owner.

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H1 and H2: Examples of Healthy Building Criteria

Evaluation Criteria	Comments
H1: Transparent Performance: Compliance with all Evaluation Criteria, including M3.	Continued performance at H1 (i.e., sustainability) is achievable for CAD and UFAD systems. However, the data regarding long-term performance of UFAD systems is limited, especially with regard to contaminant exposures, and energy and economic performance.
H2: Enhanced Performance: The values of incremental occupant performance and/or preparedness achieved from interventions (e.g., value engineering) are greater than their costs: The benefit/cost ratio > 1	If the impacts of UFAD and/or CAD systems are to be analyzed, procedures agreed upon with the owner should be utilized.

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H1 and H2 Classification

Compliance with H1 or H2:

- Does not necessarily assure compliance with LEED 2.1 or similar design guidelines, but
- Should assure that the project has been designed and does perform in accordance with PBS-P100-2003.

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Discussion

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