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IMPACT OF RETURN AIR STRATEGY ON INDOOR AIR QUALITY AND BUILDING SECURITY

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by

Dylan Montgomery McWhirter

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The thesis of Dylan Montgomery McWhirter was reviewed and approved* by the following:

William P. Bahnfleth
Professor of Architectural Engineering
Thesis Advisor

Stanley A. Mumma
Professor Emeritus of Architectural Engineering

James D. Freihaut
Associate Professor of Architectural Engineering

Chimay J. Anumba
Professor of Architectural Engineering
Department Head

*Signatures are on file in the Graduate School

ABSTRACT

The impacts of ducted air distribution system design and performance on buildings, particularly residential structures in which ducts are frequently outside condition space, has received significant study. Less work relative to return systems in non-residential buildings can be found in the literature. Some previous studies have considered the pros and cons of return system alternatives based on limited field measurements and experience; extensive analytical or controlled experimental studies providing a systematic quantitative energy and IAQ impact assessments for the various return strategies are very few.

Tracer gas releases were conducted in the Iowa Energy Center to compare resistance of ducted and plenum return air systems to interzonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space. Contrary to recommendations found in much building security literature, tracer gas results indicate plenum return does not inherently pose a greater risk of exposure to building occupants. In some cases, plenum return may provide greater protection to occupants during the time immediately following a contaminant release, during which evacuation can take place by delaying the entry of contaminants into occupied spaces. Fan powered VAV boxes tend to diminish the buffering effect of the plenum because they may inject highly contaminated return air into occupied space. Results from parametric multizone model simulations seem to support the observation from laboratory experiments that the plenum functions as a buffer zone that can delay and flatten the peak concentration in occupied space following a release held true in these simulations. Exposure results indicate that plenum return systems have the potential to significantly reduce short term occupant exposure to contaminants released in occupied spaces.

To test the applicability of mutlizone model simulation for determining inter-zonal contamination vulnerability of each return air strategy, CO_2 tracer gas test results were compared to multizone model simulation results. Assumptions inherent in multizone modeling, most notably well mixed zones with uniform contaminant concentrations, restrict multizone modeling's applicability in determining inter-zonal contamination vulnerability of return air strategy. Since the model assumes a well mixed plenum, simulating the transport of contaminants from the plenum to conditioned spaces by parallel fan powered boxes was not possible. Although there were instances in which multizone modeling accurately simulated inter-zonal contaminant concentration with release zone mixing, simulations were not consistent for different release zone locations and return air strategies.

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Chapter 1

INTRODUCTION

Many buildings are conditioned and ventilated by centralized air distribution systems. In current commercial construction practices, supply air systems are almost always ducted, as seen in Figure 1-1**,** while return air systems utilize ducts or unducted ceiling plenums and architectural shafts, as seen in Figure 1-2. In a variable air volume (VAV) system design guide Hydeman et al. (2003) describe three return air configurations: (1) fully unducted, using both the ceiling cavity and architectural air shaft as return air plenums, (2) partially ducted from the fan down risers and part way to local plenum returns, and (3) fully ducted.

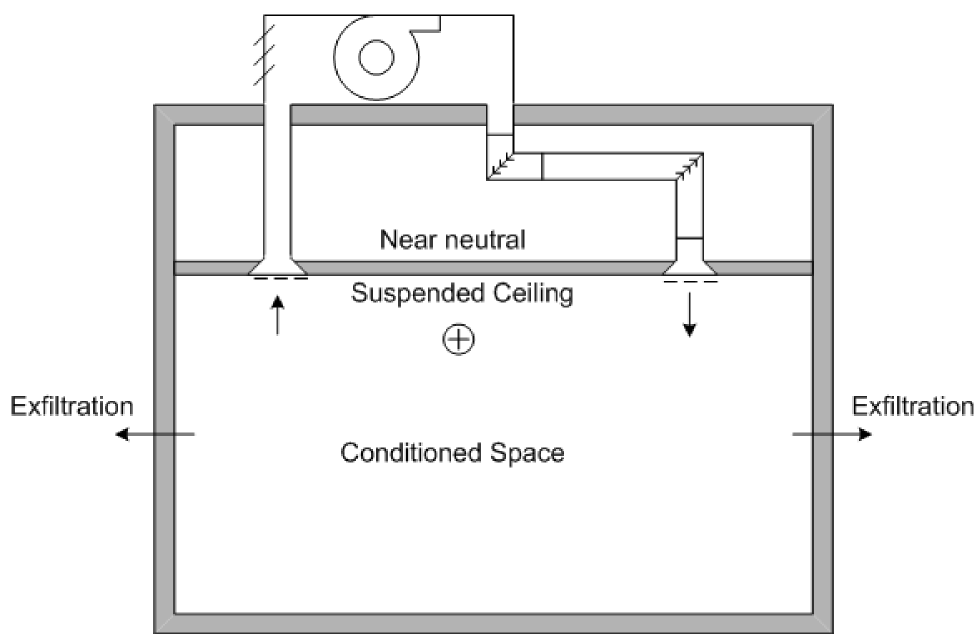


Figure 1-1: Simplified ducted return configuration

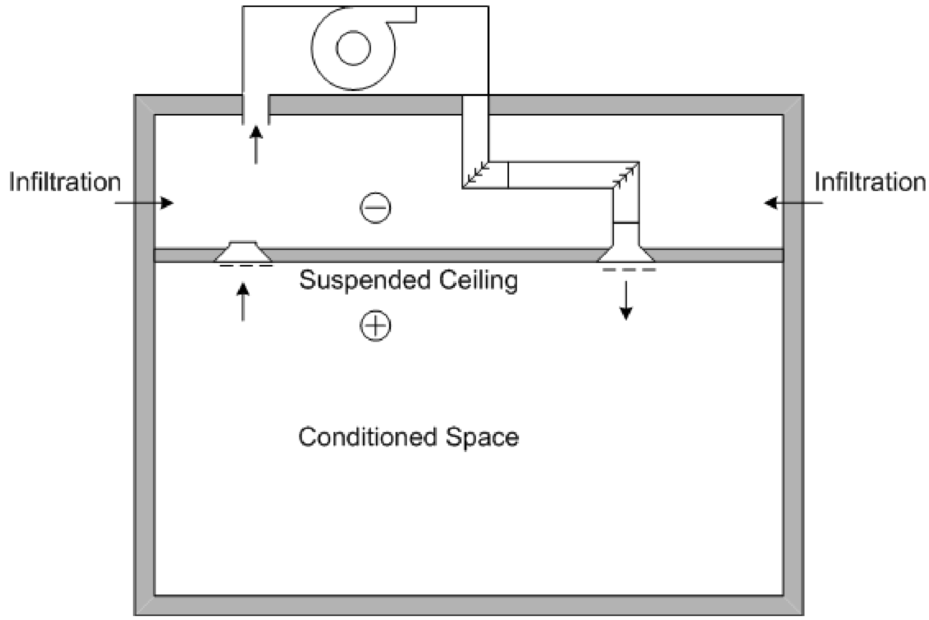


Figure 1-2: Simplified plenum return configuration

Hydeman *et al.* (2003) recommend using plenum returns whenever possible because of lower fan energy use and lower first costs compared to ducted returns. They report that typical plenum returns allow the use of relief fans with low static pressure drops of 0.25 – 0.75" w.g., while fully ducted returns require larger return air fans with static pressure drops of 1 – 2" w.g. Installed mechanical costs are less for plenum returns compared to ducted returns due to eliminated return ductwork, smaller fan motors, and less variable frequency drive horsepower. Finally, not all changes in construction cost associated with plenums are credits. Electrical costs are higher for plenum returns since wiring must be plenum rated.

However, plenum returns also have distinct disadvantages compared with ducted returns. If not designed properly, plenum returns can be depressurized below ambient pressure and outdoor air can be drawn in through the building envelope (Harriman *et al.* 2001). Infiltration of warm humid air in summer or cold air in winter can cause condensation in the plenum or envelope components that adds to system heating and cooling loads and promotes mold growth. Infiltration due to depressurization may also bring in air contaminants of outdoor origin at a higher rate. To ensure that plenum returns do not operate at negative pressures relative to outside, Hydeman *et al.* (2003) suggest pressurizing the building space (by 0.05” w.g.) to ensure that after the pressure drop from the space to the return air plenum, the plenum is still positive to outdoors.

In addition, ducted and plenum return systems offer distinct advantages and disadvantages in the area of airflow and pressurization control. With a plenum return system, return flows from different ventilation zones become mixed in the plenum space and contaminants may transfer between spaces through the plenum either by building pressurization or through the influence of fan powered VAV boxes. In large commercial buildings, separate heating, ventilation and air conditioning systems (HVAC) often supply air to different zones and draw return air from a “common plenum”, as seen in Figure 1-3, where return air from both ventilation zones mixes before being redistributed by the HVAC system. Separate HVAC systems drawing return air from a “common plenum” will spread the contaminant as if the building was one ventilation zone. ASHRAE (2003) and NIOSH (2002) suggest routing return ductwork to each air handling unit (AHU), as seen in Figure 1-4, to avoid cross contamination between ventilation zones.

Another advantage Hydeman *et al.* cite is that in VAV applications plenum returns self balance as supply air flow decreases at part load. In a typical VAV system with ducted return systems, return air quantity is balanced at full load airflow by fixed manual balancing dampers. When supply airflow varies in response to the cooling load in each zone, zonal return airflow will change proportionately according to the balanced return airflows at design, and room pressurizations will fluctuate. For certain facility types, e.g. hospitals and research laboratories, individual room pressurizations are essential and plenum returns do not allow individual room pressurizations. Therefore, hospitals and research labs require the use of ducted return systems with “one-pass” 100% outdoor air systems for occupancy safety, room pressurization. For example, if an operating room suite is designed to operate with a negative differential pressure to an anteroom, the exhaust air system will continually exhaust more air than is supplied. Therefore, the discussion of the resiliency of plenum return systems when compared with ducted return systems should be limited to low priority commercial buildings, such as office buildings.

Some previous studies have considered the pros and cons of return system alternatives based on limited field measurements and experience; extensive analytical or controlled experimental studies providing a systematic quantitative energy and indoor air quality (IAQ) impact assessments for the various return strategies are very few. This thesis investigates the impact of return air system performance IAQ and building resiliency in the CBR agent release through laboratory experiments and multizone modeling.

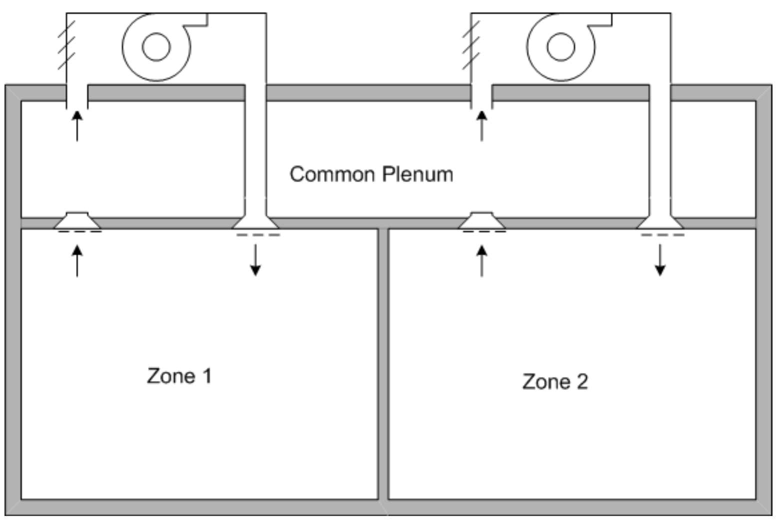


Figure 1-3: Simplified multizone building with a common plenum return

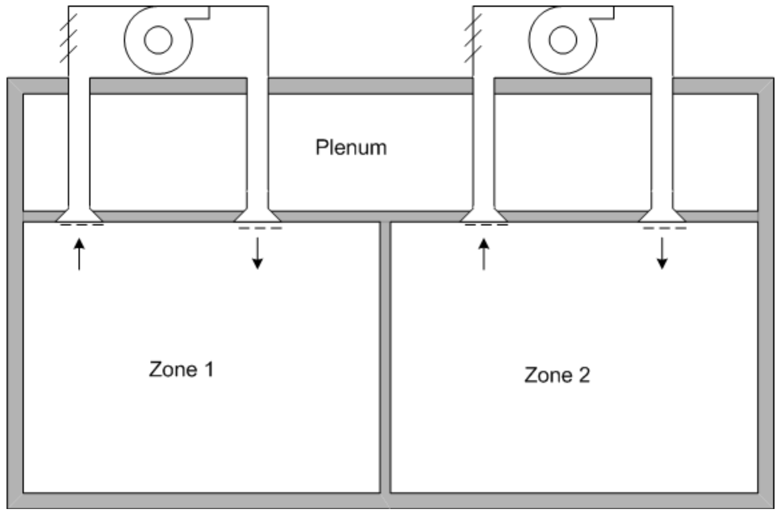


Figure 1-4: Simplified multizone building with ducted return

Laboratory Experiments

The literature lacks experimental data quantifying the impact of return air system performance on building energy consumption and lacks studies comparing return air system resistance to an accidental spill or intentional CBR attack. Laboratory experiments were conducted to investigate the impact of different air return methods on IAQ and CBR agent dispersion resistance under controlled conditions in a well instrumented test facility. Return air strategies in the scope of work include overhead ducted and plenum return air systems and plenum return system with parallel fan powered VAV boxes.

The Iowa Energy Center Energy Resource Station (Lee *et al.* 1998, Price and Smith 2000) was used to conduct experiments comparing ducted and plenum return air systems. Since the Energy Resource Station (ERS) test room facilities allow simultaneous testing of two full scale building systems with identical thermal loads, side-by-side controlled experiments were conducted comparing the impact of return air system performance on AHU air flows and building pressurization.

Multizone Modeling Simulations

In multizone modeling, a building is represented by well-mixed zones connected by airflow paths were the airflow between each zone is calculated by conservation of mass and airflow-pressure relationships. Since zones are assumed to have uniform pressure and contaminant concentrations, multizone modeling is best suited for macro building simulations.

To compare resistance of ducted and plenum return air systems to inter-zonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space, CO_2 tracer gas tests in the Iowa Energy Center were conducted. The applicability of multizone model simulation for determining inter-zonal contamination vulnerability of each return air strategy was determined by comparing Iowa Energy Center CO_2 tracer gas results to simulation results.

A parametric multizone modeling plan was created with three goals in mind: (1) to assess the inter-zonal contamination resistance of different return air systems on a whole building level and (2) to investigate the impact of building and site parameters, such as climate, envelope air tightness and return air system type, and HVAC parameters, such as HVAC system type, zoning, and duct leakage on contaminant dispersal and moisture intrusion for each return air system type.

Chapter 2

LITERATURE REVIEW

The impacts of ducted air distribution system design and performance on buildings, particularly residential structures in which ducts are frequently outside conditioned space, has received significant study. Duct leakage in unconditioned spaces wastes substantial energy and may entrain contaminants into a building. Less work relative to return systems in non-residential buildings can be found in the literature. It is at least plausible that different return system types will have a significant effect on infiltration rates and internal air flow patterns in a building, thereby affecting energy consumption, air quality, and security. The following literature summarizes the state of knowledge regarding the impact of return air strategy on building energy consumption, indoor air quality, and building resiliency in the event of a CBR release. As noted in the review, many areas of the literature are quite sparse. In order to supplement published literature, a number of designers, owner/operators, and contractors were contacted with questions regarding design and installation practices and operating experience.

Leakage Metrics, Measurement Methods and Data

Ducts leak under both positive and negative pressure, resulting in energy losses and air quality impacts. In order to characterize the relative performance of ducted and plenum return systems, it is necessary to describe and bound the range of duct leakage. Duct leakage can be expressed as a leakage area, a leakage flow rate, or a leakage flow fraction. Since static pressures vary along duct length and distribution of leakage along a duct segment is unknown, it is effectively impossible to estimate the leakage of individual holes. To estimate leakage and compare leakage between buildings, all leaks in a duct segment are subjected to the same static pressure (Wray et *al*. 2005). This section reviews common measures of leakage found in the literature.

Leakage Metrics

The following leakage metrics found in the literature range from empirical metrics to measured leakage flow fractions.

Effective Leakage Area

Effective leakage area (ELA) is the area of a single orifice that would produce the same flow as the all leaks in an isolated duct section at a reference pressure difference, typically 25 Pa. The ELA of a duct can be calculated from a standard fan pressurization test (ASTM 2003a). Delp *et al.* (1998b) describe the test method in detail. All registers are sealed except one return. A calibrated fan is installed in this return register. Air is injected into the duct system and the airflow rate required to maintain a pressure difference is recorded. The ELA and pressure exponent, n, are found by fitting Equation 2-1 to multiple airflow rates/pressure difference pairs.

$$ELA = Q\sqrt{\frac{\rho}{2}}\left[\frac{\Delta P_{ref}^{\;n-0.5}}{\Delta P^{n}}\right]$$

Equation 2-1

where:

Q = duct leakage rate
ρ = air density
ΔP_{ref} = reference pressure, typically 25 Pa
ΔP = pressure, Pa
n= empirical flow exponent

Leakage Rate

Leakage measured by a pressurization test is frequently represented in the form of a power law equation (SMACNA 1985; Swim and Griggs 1995; ASHRAE 2007) as shown in Equation 2-2. Equation 2-2 implies that all leaks are subjected to the same pressure difference.

$$Q = C\Delta P^{n}$$

Equation 2-2

where:

Q = duct leakage rate, (L/s per m^2)
C = leakage rate coefficient reflecting the leakage path area
ΔP = static pressure differential across duct, interior to exterior, (Pa)
n = empirical flow exponent

Swim and Griggs (1995) measured duct leakage from rectangular and round sheet metal ducts with different types of transverse joints and longitudinal seams. Five pairs of duct sections with one joint were tested to produce multiple data points. After the pairs of duct sections were tested, the pairs of duct sections were tested as units with multiple joints. Leakage rates were determined by measuring the makeup air required to maintain a specified internal pressure across the duct, over a range of 250 Pa to 750 Pa, for both positive and negative pressures. The measurements followed a power law model of essentially the same form as Equation 2-3.

$$Q = C\left(\frac{\Delta P}{\Delta P_{ref}}\right)^{n}$$

Equation 2-3

where:

Q = duct leakage rate (L/s)
C = leakage rate coefficient reflecting the leakage path area (L/s)
ΔP = static pressure difference across the duct, interior to exterior (Pa)
ΔP_{ref} = reference static pressure difference across the duct (250 Pa)
n = empirical flow exponent

The authors tabulated average values of *C* and n for two duct sections and one joint, for joint-only leakage, and seam-only leakage. Values of C_D, the recommended design value of C for repetitive duct elements (one duct section and one joint), ranged from 0.005 L/s to 8.7 L/s; however, most test sections had values of C_D between 3 and 4 L/s . Values of n for one duct section and one joint ranged from 0.52 to 0.64, with most values lying near 0.58. Joints were the major source of leakage, accounting for 62% to 90% of the total leakage. Leakage rate constants were lower for round ducts compared to rectangular ducts. The authors also present a design methodology to predict the leakage of a duct system with different sizes of ducts and different types of joints and seams prior to construction.

SMACNA Leakage Class

The Sheet Metal and Air Conditioning Contractors National Association (SMACNA) introduced the concept of defining duct leakage as a function of pressure in the duct and surface area of the duct since specifying leakage as a percentage of fan air flow rate does not take into account the size of the duct system and the pressure in the ducts (SMACNA 1985). The leakage class, C_L, calculated from Equation 2-4, is defined as is the air leakage rate per 9.29 m^2 (100 ft^2) of duct surface area with a 250 Pa pressure difference across the leaks, expressed in cfm.

$$C_L = 710F / \Delta P^{0.65}$$

Equation 2-4

where:

F = leakage flow rate (L/s per m^2 duct surface area)
ΔP = static pressure in duct (250 Pa)

ASHRAE (2007) lists leakage classes of 3 to 12 "for quality duct construction and sealing practices" and 30 to 48 for unsealed ducts. ASHRAE's estimates of attainable leakage classes do not consider leakage at grilles, diffusers or duct mounted equipment, such as VAV boxes.

Leakage Flow Fraction

Duct leakage can also be quantified by the leakage flow fraction, the leakage flow divided by a reference airflow. However, leakage flow fractions cannot be compared between buildings because the system size and duct differential pressure are not considered.

Measurement Methods

The duct leakage metrics described in the preceding section generally depend upon field or laboratory measurements. This section describes techniques commonly used to determine duct leakage experimentally.

Qualitative Tools

Davis and Roberson (1993) used the "pressure pan" test to find duct leaks in residences. The test does not measure duct leakage but can be used to localize areas of leakage. The building is depressurized to -50 Pa by a blower door, the air handling unit is turned off, and all supply and return registers are fully opened. A cake pan with a pressure tap and gasket material around the lip is held below each diffuser or register. High "pressure pan" readings indicate ducts connected to the attic. For a relatively tight duct section, the pressure pan will read -49 Pa with respect to the outside or -1 Pa with respect to the building space. Pressure pan readings greater than -1 Pa with respect to the building space indicate moderate to large duct leaks near those grilles or registers. If the duct pressure is different than the room pressure, a duct leak exists near that register. The pressure pan test assumes that ducts are located in zones vented to the outside, so when the occupied space is depressurized, the duct zone is near neutral with respect to outside, as is often the case in residential attics. In commercial buildings, pressure pan tests are not as reliable in locating duct leaks because ducts are often located inside the primary air barrier. With the blower door operating, the pressure in the duct zone may be closer to the inside pressure and the pressure pan readings may not be reliable indicators of significant duct leakage (Cummings *et al.* 1996).

Another diagnostic tool available used to find the location of duct leaks is a smoke stick (or other source of chemical smoke) test. Air leaking from ducts can be visualized by using a smoke stick with the air handler on. The smoke stick is placed near the duct; if the smoke moves away from a supply duct or towards a return duct, a leak exists. However, access to ducts concealed in attics or plenums is often required. Another smoke stick test can be performed by pressurizing the building with a blower door, turning the air handler off, and placing the smoke stick near registers. If the smoke does not enter a register, then duct leakage does not exist near that register. If the smoke enters the register slowly, then small duct leaks exist, and, if the smoke enters the register rapidly, significant duct leaks exist near that register (Cummings 1989).

Duct Pressurization

A fan pressurization test (ASTM 2003b) can be used to directly measure total duct leakage, and duct leakage to outdoors. All registers except one supply and one return are sealed and calibrated fans are attached to the registers. Air is injected into the system at multiple pressures (measured near the air handler and referenced to the duct zone), and the airflows required to maintain the duct pressure are recorded. The airflows from the supply and return sides are added to obtain total duct leakage. The test can be modified to obtain duct leakage to and from the outside. Duct leakage to and from outside or unconditioned spaces impact energy use and indoor comfort, so duct leakage to outside gives a better indication on the energy penalties of duct leakage. The portion of the duct leakage to outside is measured by repeating the air tightness test above while pressurizing the building to the same pressure as the duct system.

Duct Leakage Estimated From ELA and Differential Pressure

Duct leakage can be estimated from the measured ELA, measured pressure exponent, and average static pressure in the duct system during HVAC operation using Equation 2-5. This method of measuring duct leakage only gives an estimate of the actual leakage, because static pressure varies significantly along the duct and the location of leaks is not known.

$$Q = \frac{ELA}{10{,}000} \times \sqrt{\frac{2\Delta P_{ref}}{\rho}} \left(\frac{\Delta P}{\Delta P_{ref}} \right)^{n}$$

Equation 2-5

where:

Q = leakage flow rate (L/s)
ELA = measured effective leakage area (cm^2)
ρ = air density (kg/m^3)
ΔP_{ref} = reference pressure, typically 25 Pa
ΔP = average static pressure across duct, Pa
n = empirical flow exponent

Tracer Gas

A tracer gas test can be used to determine the air change rate of a zone. To prepare for a tracer gas decay test (ASTM 2000), all the supplies and registers are opened, all windows are closed, and interior doors are opened. Tracer gas is injected into the return of the air handling unit, with the fan running until the concentration in the space is uniform. Measurements of tracer gas concentration should be taken at the return grille, in a supply duct, and the expected location of leakage. Five to ten samples should be taken in a 30 to 60 minute test. A tracer gas test can estimate the amount of duct leakage in two ways Cummings (1989).

First, the infiltration rate can be measured with the air handler off and with the air handler on. If the infiltration rate with the air handler on is higher than the infiltration rate with the air handler off, the difference can be used to estimate the amount of duct leakage. The infiltration rate can be calculated by Equation 2-6.

$$ACH = \frac{60}{N}\ln\left(\frac{C_i}{C_f}\right)$$

Equation 2-6

where:

ACH = air change rate (h^{-1})
C_i = initial room concentration (ppm)
C_f = final room concentration (ppm)
N = duration of test (minutes)

Second, the concentrations of tracer gas in the room near the return grille (A), the supply duct register (B), and the buffer zone or location of return leak (C), can be used to estimate the return leak fraction determined from a mass balance analysis, shown in Equation 2-7. Air from the room (A) mixes with air from the buffer zone (C) to form a supply air stream (B). The fraction of air from the buffer zone (C) is the RLF, and the fraction of air from the room (A) is 1-RLF. Finally, the RLF can be calculated using Equation 2-8.

$$(RLF) \cdot C + (1 - RLF) \cdot A = B$$

Equation 2-7

$$RLF = \left(\frac{A - B}{A - C} \right)$$

Equation 2-8

where:

RLF = return leakage fraction
A = tracer gas concentration in the room at the return grille (ppm)
B = tracer gas concentration at the supply duct (ppm)
C = tracer gas concentration at the buffer zone (ppm)

Leakage Data

Measurements of duct leakage in residences have been a focus of researchers for the past decade. Numerous studies (Cummings et al. 1990; Jump et al. 1996; Proctor 1997; Siegel and Walker 2003) have shown that leakage fractions in residential forced-air distribution systems are consistently between 5 to 20% of air handler flow on both the supply and return side. Since residential thermal distribution systems are often located in unconditioned crawl spaces, attics or basements, leaks can have a catastrophic impact on energy use.

- Cummings et al. used tracer gas dilution to measure the return leak fraction (RLF), the portion of the air returning to the air handling unit (AHU) from outside the conditioned space. In 91 Florida homes tested, the average RLF was 10% of air handler flow and 30% of the homes had a RLF greater than 10%.

- Jump et al. tested 24 houses in Sacramento before and after duct retrofits to estimate the magnitude of duct leakage and conduction and their impact on

HVAC energy consumption. Prior to sealing the ducts, the average supply leakage fraction was 18% and the average return leakage fraction was 17% of air-handler flow. However, leakage fractions varied significantly between residences: measured supply leakage fractions ranged from 2% to 38% and measured return leakage fractions ranged from 0% to 35%.

- Proctor measured duct leakage in new Arizona residences using a blower door and fan pressurization. The average supply leakage to unconditioned spaces was 9% of air-handler flow and the average return leakage from unconditioned spaces was 5% of air-handler flow.

- Siegel and Walker measured leakage fractions in 9 houses in California and Nevada using fan pressurization. The average total leakage fractions were 10% on the supply side and 6% on the return side. The average leakage fractions to outside were 6% on the supply side and 4% on the return side.

Until recently there has been little motivation for designers to consider duct leakage in commercial design because in commercial buildings the distribution system is assumed to be located inside the building. However, Cummings *et al.* (1996) illustrate that distribution systems are often located outside the primary air and thermal barriers.

Delp *et al.* (1998b) describe in detail the method of measuring ELA's of supply and return sides of an air distribution system. Delp *et al.* (1998a) measured duct leakage in 15 packaged roof-top HVAC systems in 8 light commercial buildings in Northern California, and compared the duct leakage to values measured by Cummings *et al.* (1996) and residential duct leakage data reported by Jump *et al.* (1996). The average normalized ELA_{25} in 25 packaged rooftop HVAC systems measured by Delp *et al*. (1998a) was 3.7 cm^2/m^2 floor area, nearly 3 times greater than the residential data, and the average normalized ELA_{25} measured by Cummings *et al*. (1996) was 2.7 cm^2/m^2 floor area, 2 times greater than the residential data.

Table 2-1 summarizes commercial duct leakage data measured by Cummings *et al.* (1996), Xu *et al.* (1999), Fisk *et al.* (2000), Carrie *et al.* (2002), and Modera *et al.* (2002). Figure 2-1 shows duct leakage measurements in the form of duct ELA normalized by floor area from 71 duct sections in the references summarized in Table 2-1. The average normalized ELA_{25} for the 71 duct sections was 2.4 cm^2/m^2 floor area. Figure 2-2 shows duct ELA_{25} measurements normalized by duct surface area from 25 duct sections tested by Xu *et al.* (1999), Fisk *et al.* (2000), Carrie *et al.* (2002), and Modera *et al.* (2002). Duct surface area was not measured by Cummings *et al.* (1996). The average normalized ELA_{25} of the 25 sections was 5.2 cm^2/m^2 duct area. The leakage measurements normalized by duct area have a larger spread in values than the leakage measurements normalized by floor area; however, the sample size was smaller for leakage measurements normalized by duct area.

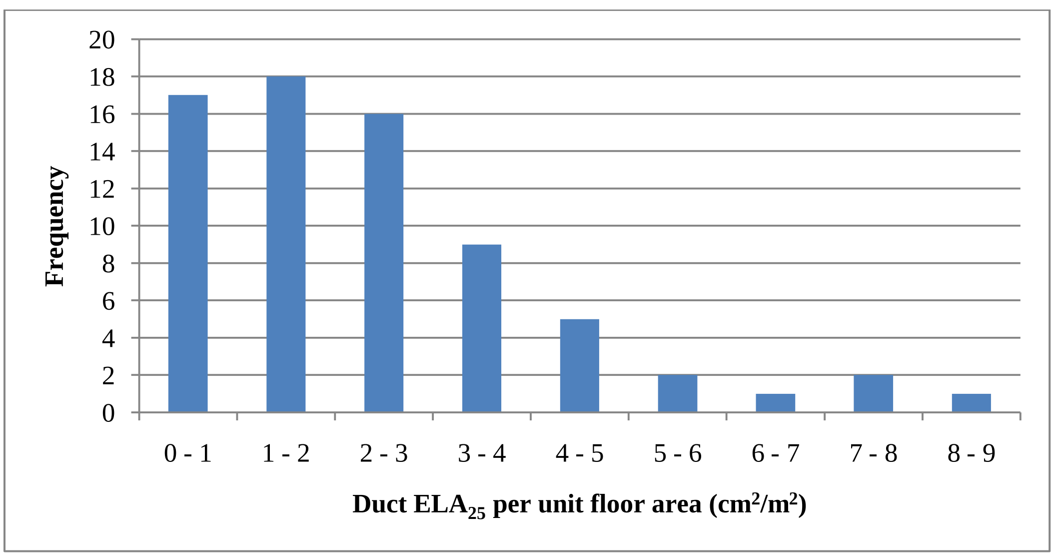


Figure 2-1: Duct ELA_{25} per unit floor area for 71 commercial duct sections (Cumming et al. 1993, Xu et al. 1999, Fisk et al. 2000, Carrie et al. 2002, Modera et al. 2002)

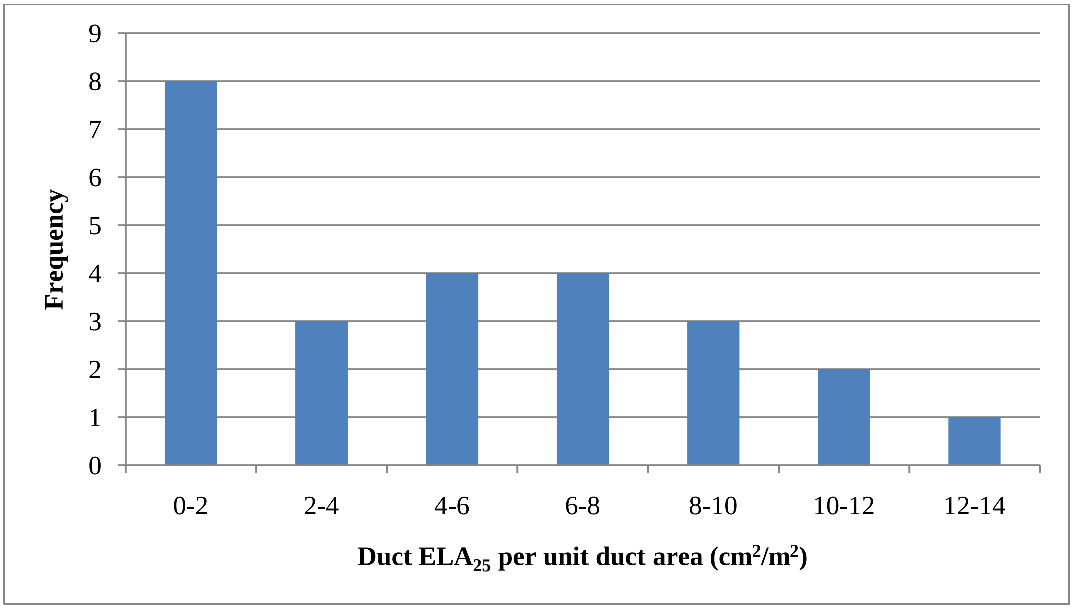


Figure 2-2: Duct ELA_{25} per unit duct area for 25 commercial duct sections (Xu et al. 1999, Fisk et al. 2000, Carrie et al. 2002, Modera et al. 2002)

ASHRAE (2007) states that leakage classes of 3-12 are attainable for "commonly used duct construction and sealing practices," and that leakage classes of 30-48 are attainable for unsealed ducts. Connections to diffusers and grilles are not included in these estimates. Numerous investigations of duct systems indicate that ducts are leakier than ASHRAE's estimates. Figure 2-3 shows leakage class measurements of 25 commercial duct sections taken by Xu *et al.* (1999), Fisk *et al.* (2000), Carrie *et al.* (2002), and Modera *et al.* (2002). Duct surface area was not measured by Cummings *et al.* (1996). The average leakage class of the 25 commercial duct sections was 261, roughly 95% leakier than ASHRAE's estimate for leakage classes attainable for sealed duct sections.

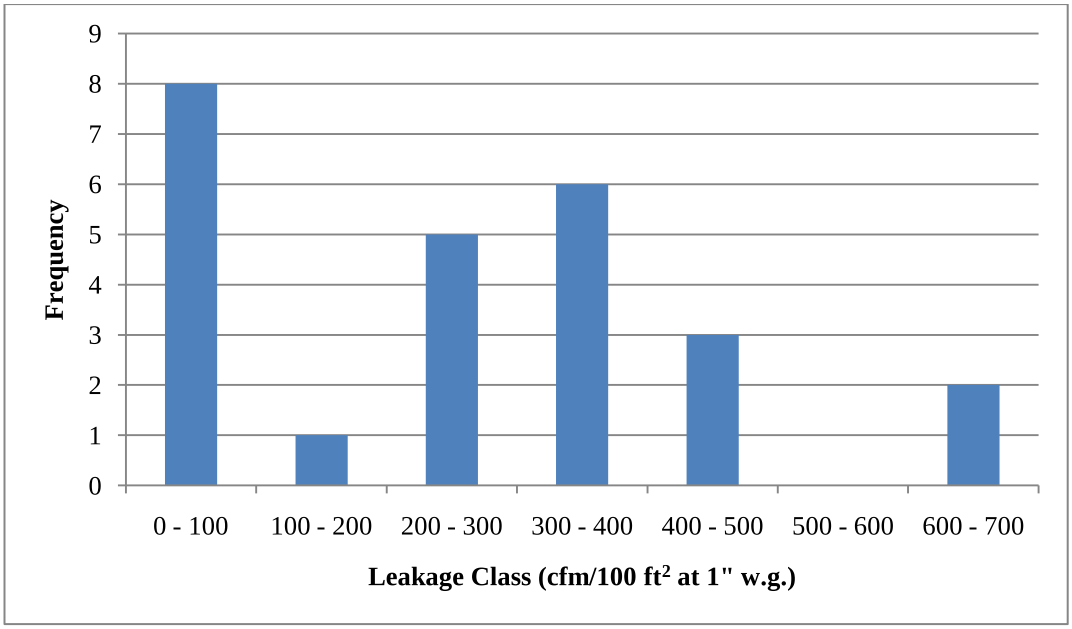


Figure 2-3: Leakage Class of 25 commercial duct sections (Xu et al. 1999, Fisk et al. 2000, Carrie et al. 2002, Modera et al. 2002)

Table 2-1: Summary of commercial duct leakage data

Source	Bldg	Age	Location	Measured pressure exponent	ELA_{25} per unit duct area (cm^2/m^2)	Leakage Class	ELA_{25} per unit floor area (cm^2/m^2)
Fisk *et al.* 2000	L6	35	CA	0.58	1.05	60	0.4
	L5a	41	CA	0.62	4.1	230	1.5
	L5b	41	CA	0.58	4.8	270	1.9
	L5c	41	CA	0.58	4.6	260	2.0
Carrie *et al.* 2002	L5	9	CA	0.65	11.57	657	3.9
	L2	20	CA	0.65	0.96	40	0.1
Modera *et al.* 2002	LS1	39	CA	-	4	230	1.5
	LS2	N/A	CA	-	1.06	60	0.4
Xu et al. 1999	L1 supply	3	CA	0.59	2.5	121	0.3
	L1 return	3	CA	0.52	8.8	370	0.3
	L2 overall	20	CA	0.59	1.9	96	0.3
	L2 supply	20	CA	0.6	0.7	36	0.1
	L3 main	20	CA	0.61	0.7	34	0.1
	L3 branch	20	CA	0.7	5.4	341	0.7
	L4 branch	17	CA	0.69	0.9	58	0.3
	L4 branch	17	CA	0.63	1.3	70	0.3
	L5a	9	CA	0.55	9.9	441	5.1
	L5b	9	CA	0.57	12.9	606	2.0
	L5c	9	CA	0.6	11.5	394	7.7
	L5d	9	CA	0.6	9.7	490	5.0
	S1	11	CA	0.69	3.7	232	0.8
	S2	11	CA	0.71	6.4	414	1.7
	S3	3	CA	0.61	6.2	319	5.3
	S4	3	CA	0.57	6.8	320	1.8
	S5	3	CA	0.6	7.5	380	3.4
Cummings *et al.* 1996	Dentist 1	4	FL	0.59	-	-	2.4
	Church	26	FL	0.58	-	-	3.3
	Church Hall	37	FL	0.62	-	-	3.8
	Engr. Office	15	FL	0.59	-	-	1.6
	Dentist 2	37	FL	0.34	-	-	2.1
	HVAC Supply	36	FL	0.65	-	-	1.9
	Day Care	26	FL	0.7	-	-	1.2
	Manuf Class	6	FL	0.6	-	-	3.6
	Manuf Office 1	8	FL	0.52	-	-	3.0
	Health Clinic 1	10	FL	0.49	-	-	3.7

Table 2-1: Summary of commercial duct leakage data (continued)

Source	Bldg	Age	Location	Measured pressure exponent	ELA_{25} per unit duct area (cm^2/m^2)	Leakage Class	ELA_{25} per unit floor area (cm^2/m^2)
Cummings *et al*. 1996	School	21	FL	0.67	-	-	3.9
	Pizza Restaurant	21	FL	0.54	-	-	0.5
	City Hall	27	FL	0.59	-	-	4.4
	Health Clinic 2	9	FL	0.65	-	-	7.9
	Sports Complex	9	FL	0.68	-	-	2.3
	Realty 1	2	FL	0.59	-	-	1.1
	Food Office	2	FL	0.6	-	-	1.2
	Manuf Office 2	13	FL	0.74	-	-	2.2
	Sail Manuf	55	FL	0.48	-	-	0.8
	Bar and Grill	10	FL	0.6	-	-	2.1
	Golf Club House	2	FL	0.56	-	-	1.9
	Chicken Rest 1	2	FL	0.58	-	-	3.2
	HVAC contractor	65	FL	0.58	-	-	2.9
	Realty 2	24	FL	0.6	-	-	2.4
	Realty 3	50	FL	0.68	-	-	4.7
	Safety Class	30	FL	0.55	-	-	4.1
	Pet Grooming	30	FL	0.62	-	-	2.4
	Gov Office	30	FL	0.82	-	-	8.7
	Bar	30	FL	0.62	-	-	0.7
	Saftey Office	30	FL	0.7	-	-	2.1
	School Supply	30	FL	0.66	-	-	1.3
	Court Office	30	FL	0.98	-	-	1.7
	Martial Arts	30	FL	0.82	-	-	2.5
	Office Supply	30	FL	-	-	-	2.3
	Retail Vacant	30	FL	0.57	-	-	1.9
	Retail Vacant	30	FL	0.58	-	-	1.5
	Gas Company	45	FL	0.62	-	-	6.6
	Tax Service	32	FL	0.62	-	-	2.1
	Metal Bldg Co	10	FL	0.66	-	-	3.0
	Realty 4	20	FL	0.76	-	-	2.6
	Amusement Park	14	FL	0.48	-	-	1.4
	Hardware Store	2	FL	0.62	-	-	0.7
	Carpet Store	23	FL	0.73	-	-	0.8
	Manuf Office 3	11	FL	0.61	-	-	2.4
	Manuf Office 4	13	FL	0.59	-	-	4.7
	Conv. Store 1	7	FL	0.62	-	-	2.5

Aerosol-Based Duct Sealant Technology

An aerosol-based duct sealant technology developed and patented by researchers at Lawrence Berkeley National Laboratory (LBNL) simultaneously seals duct leaks and measures effective leakage areas (Carrie et al. 2002, Modera et al. 2002). Aerosolized sealant particles (2μm -20μm) are injected into a pressurized duct section, so aerosol particles seek to escape the leaks from the inside. Studies investigating the cost of conventional sealing practices have shown that labor costs dominate material costs (Jump et al. 1996). Labor costs include running diagnostic tests to find duct leaks and include time spent reaching ducts in inaccessible spaces like attics, crawl spaces, and ceiling plenums. Sealing ducts remotely by aerosol injection has the potential of reducing labor costs.

Tests by Modera *et al.* (1996) on 47 residences in Florida indicate that after sealing catastrophic leaks, such as connections to diffusers and leaks at air handlers, roughly 80% of leaks encountered were sealed by the aerosol-based sealant technology. For 36 homes, ELA was tracked throughout the sealing process and was reduced by 78% from an average pre-retrofit ELA of 0.42 cm^2/m^2 floor area.

The sealing time required by the aerosol-based sealant process was compared to sealing times for conventional duct sealing practices estimated by Florida Power and Light's (FPL) standard audit. The time required for sealing the first half of the houses using the aerosol-based sealing process was 6.1 labor-hours compared to 9.5 labor-hours for the conventional sealing process, a 35% reduction in labor. For the second half of the houses sealed, the aerosol-based sealing process required 4.4 labor-hours compared to 11.5 labor-hours for the conventional sealing process, resulting in a 60% reduction in labor. The improvement in labor times between the first and second samples indicate that labor times for the aerosol-based sealing process can be reduced through experience and training.

Carrie *et al.* (2002) and Modera *et al.* (2002) performed laboratory experiments and field tests to evaluate the feasibility of applying aerosol duct sealing in commercial buildings. Although the process has been commercialized for residential applications, the size of commercial buildings and the complexity of their air distribution systems pose challenges for commercial applications. Challenges include a requiring a higher aerosol production rate, reduced sealing efficiency due to aerosol deposition in long ducts, higher operating static duct pressures, and sensitive sensors and controls in mixing boxes.

In residential applications, only one aerosol injector is used. To increase the aerosol production rate, duct sections were isolated and multiple injectors were operated simultaneously. To seal main trunks, multiple injectors are operated simultaneously and to seal branch ducts, injectors are operated downstream of VAV boxes. In laboratory testing, bursting pressures of properly sealed slot leaks exceeded 5,000 Pa, far beyond normal operating pressures in large commercial buildings (Carrie *et al.* 2002). Although sensitive equipment like filters, coils, and mixing boxes can be isolated, labor would be reduced if the aerosol could be injected through duct sections without impacting the performance of VAV terminal units. Modera *et al.* (2002) injected aerosol through three VAV boxes in building LS2 and tested the flow calibration of one box by simultaneously measuring velocity with a hot-wire anemometer in the duct downstream of the VAV box while measuring the pressure signal from the VAV flow sensor. Calibrations did not change before and after the particles were injected and damper operation remained normal, however Modera et al. did not discuss the impact of the aerosol on reheat coils

Figure 2-4 shows data from duct sealing tests by Modera *et al.* (1996), Carrie *et al.* (2002), and Modera *et al.* (2002) and average leakage values from Table 2-2. Duct leakage was reduced significantly in four duct sections sealed. ELA_{25} per unit floor area from 36 houses sealed by Modera *et al.* (1996) was reduced by an average of 78%. Duct leakage in two sections sealed by Carrie *et al.* (2002) was reduced by 83% and 92%, and duct leakage in two sections sealed by Modera *et al.* (2002) was reduced by 66% and 86%. However, the sealing process was not completed in building LS1 sealed by Modera *et al.* (2002). Clear tape used to seal diffusers failed due to elevated temperatures associated with the aerosol generator. The researchers modified their sealing process and the sealing process was completed in building LS2. With the modified sealing process, the authors contend that duct leakage in building LS1 would be reduced by over 80%.

Table 2-2: Results from Aerosol Based Duct Sealant Technology

		ELA25 per unit floor area (cm^2/m^2)		ELA25 per unit duct area (cm^2/m^2)		Leakage Class		% reduction
Source	Bldg	Pre-seal	Post-seal	Pre-seal	Post-seal	Pre-seal	Post-seal	
Carrie *et al.* 2002	L5	3.9	0.68	11.57	2.02	657	103	83
	L2	0.11	0.01	0.96	0.09	40	3	92
Modera *et al.* 2002	LS1	1.5	0.5	4	1.38	230	80	66
	LS2	0.4	0.05	1.06	0.13	60	8	86
Modera *et al.* 1996	36 homes	0.42	0.09	-	-	-	-	78
Commercial Data from Table 2-1	Avg. (n=71)	2.4	-	-	-	-	-	-
Commercial Data from Table 2-1	Avg. (n=25)	-	-	5.2	-	261	-	-

Figure 2-4 shows leakage measurements of 36 residential duct sections sealed by Modera *et al.* (1996), and four commercial duct sections sealed by Carrie *et al.* (2002) and Modera *et al.* (2002). The average pre-seal ELA_{25} per unit floor area in the 71 commercial duct sections tested (Cummings *et al.* 1996; Xu *et al.* 1999; Fisk *et al.* 2000; Carrie *et al.* 2002; Modera *et al.* 2002) was 2.4 cm^2/m^2, while the average pre-seal ELA_{25} per unit floor area in the 36 residences tested (Modera et al. 1996) was 0.42 cm^2/m^2. Although the commercial duct sections are generally leakier than the residential duct sections, the pre-seal ELA_{25} in buildings LS2 tested in Modera *et* *al.* (2002) and L2 tested in Carrie *et al.* (2002) were less than the average pre-seal ELA in the 36 homes tested by Modera *et al.* (1996). Figure 2-5 and Figure 2-6 show leakage measurements of four commercial duct sections sealed by Carrie *et al.* (2002) and Modera *et al.* (2002).

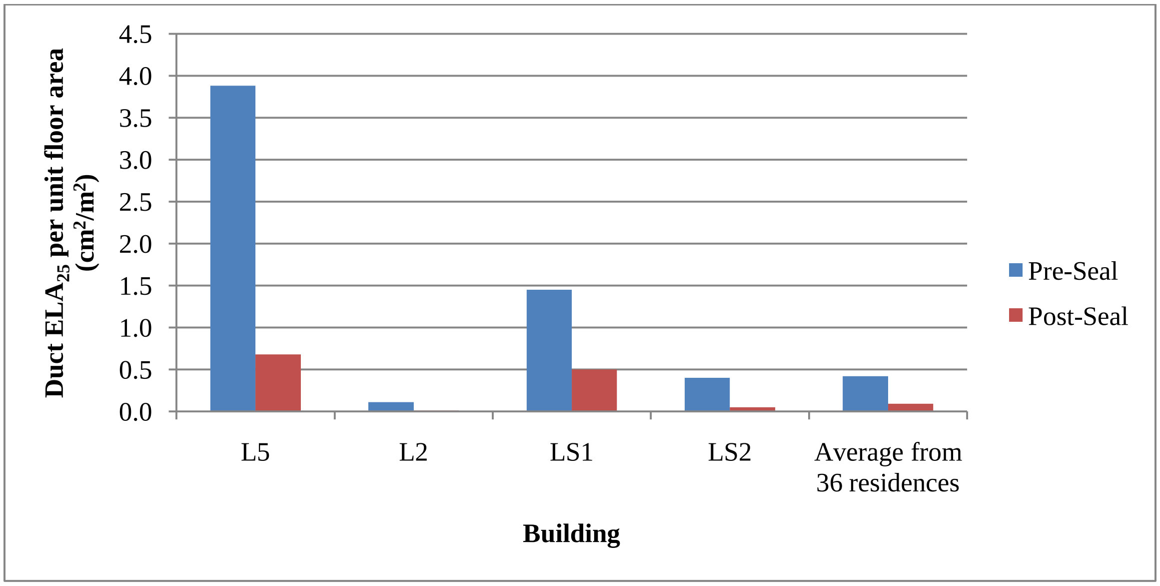


Figure 2-4: Aerosol Duct Sealant Technology – Duct ELA per unit floor area

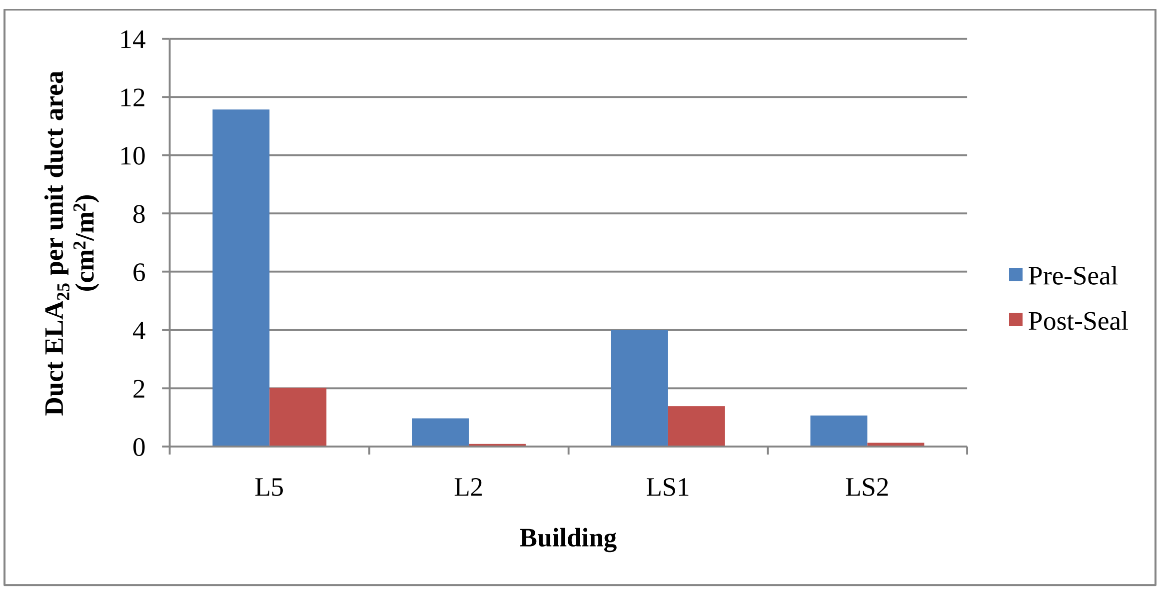


Figure 2-5: Aerosol Based Duct Sealant Technology – Duct ELA per unit duct area

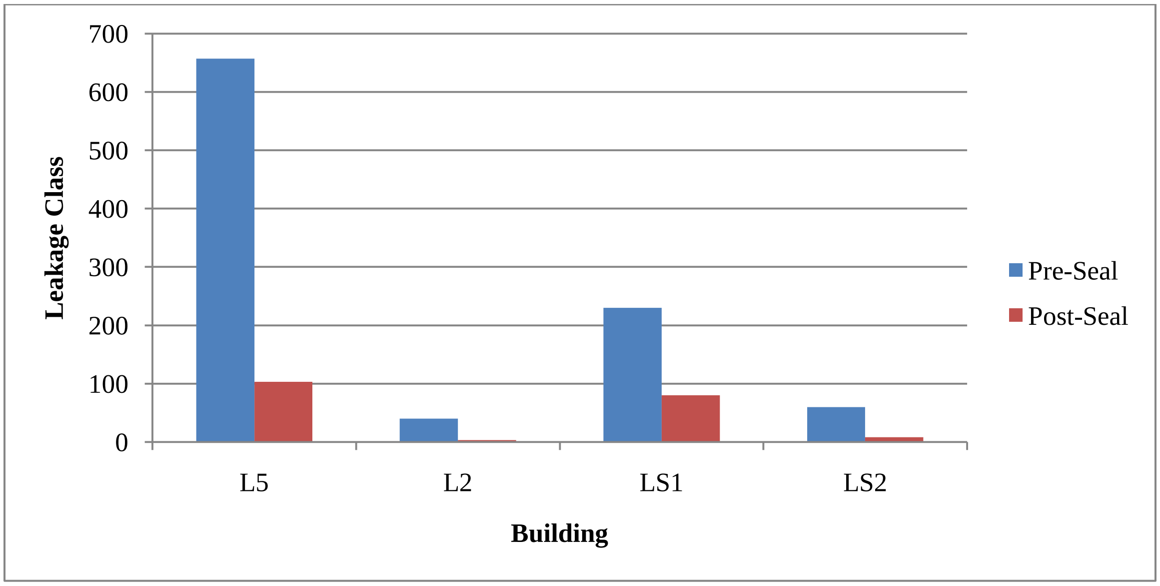


Figure 2-6: Aerosol Based Duct Sealant Technology – Leakage Class

Field measurements from commercial buildings indicate that both relatively leaky and relatively tight duct sections can benefit from aerosol-based duct sealing. For example, as seen in Table 2-2, building L5 (Carrie *et al.* 2002) was leaky compared to the average building in the commercial data; however, duct leakage was reduced by 83% from aerosol-based duct sealing. In contrast, building L2 (Carrie *et al.* 2002) was relatively tight compared to the commercial data. Duct leakage in building L2 was reduced by 92% from aerosol-based duct sealing. The results also indicate that duct leakage can be reduced to values consistent with ASHRAE's estimate of leakage classes of 3 to 12 attainable for "commonly used duct construction and sealing practices." The leakage class was reduced from 40 to 3 in building L2 (Carrie *et al.* 2002) and from 60 to 8 in building LS2 (Modera *et al.* 2002).

Design, Installation and Operation Practices

To minimize energy consumption and achieve acceptable IAQ within a building, architects, engineers, contractors, and owners must consider the interaction of the HVAC system and the building structure and envelope. HVAC system designers should interact with architects, the party most often responsible for building envelope design, to insure that the HVAC system will operate as planned. Architects should interact with HVAC system designers to understand how their placement of thermal and air barriers will impact the performance of HVAC systems. However, in the traditional design-bid-build construction process, design teams are not necessarily interactive. Spengler and Chen (2000) cite the traditional design-bid-build process as a likely source of IAQ problems, because parties have distinct responsibilities, do not participate throughout the project, and have different financial incentives. Misunderstanding or ignoring the interaction of the HVAC system and the building structure and envelope can cause unplanned airflows through buildings and moisture problems within building assemblies. Even if building envelopes and HVAC systems are designed correctly, they may not operate as planned because of poor construction. The literature contains very little information on criteria and practices for return system design, so this summary is based almost entirely on the practices of several professionals as reported in response to questions from the research team.

Design

When asked to discuss the factors involved in choosing between using a ducted return or plenum return, designers provided four common responses: type of facility and occupancy, sensitivity to pressurization gradients, budget, and available ceiling space. Informal information from 14 mechanical designers can be found in Appendix A.

Return Air System Type

All designers noted that due to concerns of cross-contamination, codes require ducted returns in hospitals and single pass 100% exhausted systems in critical spaces such as research laboratories. Designer 14 cited a clause from the Washington Administrative Code, WAC-246-320-525, which states, “Hospitals will provide heating, ventilation, and cooling including…use of space above ceilings for return plenums only in non-sensitive areas…” In large commercial buildings, separate HVAC systems often supply air to different zones and draw return air from a “common plenum” which mixes air from each zone before being redistributed by the HVAC system. Air movement between zones is also an issue in critical areas. With plenum returns, constant room pressurization relationships cannot be achieved.

However, designers stated that budget limitations and available above-ceiling space also contributed to the choice of a return air strategy. Since budgets for HVAC systems may be quite constrained, mechanical designers often must look for ways to reduce system cost. Many designers stated that plenum returns are appealing because they result in lower bid prices. Compared to a ducted return, a plenum return will have a lower first cost due to less sheet metal and less labor. Table 2-3 shows designer’s estimates of the difference in mechanical cost of ducted and unducted return systems. Ducted returns also require greater ceiling heights for supply and return ducts, which would increase architectural, structural, and envelope costs. With typical supply air quantities for all-air systems being on the order of 1 CFM/ft^2, this is a significant impact not only on the mechanical bid cost, but also on total building cost. Although architectural, structural, envelope, material, and labor costs will decrease for a plenum return compared to a ducted return, electrical and plumbing costs will increase. In plenum returns electrical wires must be plenum rated and PVC pipes must be insulated or cast iron must be used. Designers also stated that sometimes the architectural design precludes the use of ducted returns.

When HVAC designers are not involved in the preliminary design of the building, the available ceiling depth is often specified by the architect. HVAC designers in full-service firms are involved early in the project and have more input in the ceiling heights.

Table 2-3: Estimate of decrease in construction cost by implementing plenum return system instead of ducted return

Designer	**\$/cfm**	**\$/ft^2 floor area**
Designer 4	5	-
Designer 11	-	3-10
Designer 14	7.50-15	-

Return Grille Sizing and Placement

Several designers indicated that air circulation, pressurization issues, noise criteria, and aesthetics were the most influential factors in determining the number, location, and size of return air grilles. One designer locates supply diffusers near the exterior of the zone and places return grilles in the middle of the zone to get good air circulation. Another designer stated that return grille layout depends on the location of the zone. In exterior zones the designer places return grilles near exterior walls to draw conditioned air past the building envelope and in interior zones the designer would places return grilles near the thermostat. (Note: this concern with return grille layout is somewhat misplaced, as it is well known that the placement and characteristics of inlet jets have a much stronger impact on air flow. However, there are exceptions to this blanket statement. For example, returns placed too close to supply diffusers may promote short-circuit air flow paths.)

Most designers questioned size return air grilles using the minimum amount of returns to keep the noise criteria (NC) level below 30 at maximum air flow. Designer 5 selects returns based a maximum velocity of 500 fpm and a maximum static pressure drop of 0.1" w.g. through each grille. If the velocity or static pressure drop exceeds the limits, return air grilles are added as necessary. Typical maximum air flows through return air grilles were cited to be1200 CFM by Designer 3 and 1400 CFM by Designer 4. To avoid excessive pressurization or depressurization, designers placed at least one return air grille in a room containing supply air diffusers.

Thermal and Air Barriers

Responses on insulation practice for roofs and plenums varied widely. A majority of designers stated that the insulation should be placed at the roof deck, so sprinklers would not be subjected to freezing conditions and ducts would be in a conditioned space. However, some designers stated that plenums typically are not insulated. Designer 4 stated that the placement of insulation depended on whether ducted returns or plenum returns were used. For both ducted and plenum returns in the lower stories of a building, the suspended ceiling tiles and floor above provide adequate insulation. However, a plenum return below a roof deck requires additional roof insulation. Designer 10 indicated that the plenum design is specified by the architect to meet minimum energy standards, specifically the International Energy Conservation code. Section 503.2.7, "Duct and plenum insulation and sealing," states that "All supply and return air ducts and plenums shall be insulated with a minimum of R-5 insulation when located in unconditioned spaces and with a minimum of R-8 insulation when located outside the building. When located within a building envelope assembly, the duct or plenum shall be separated from the building exterior or unconditioned or exempt spaces by a minimum of R-8 insulation."

Airflow Control

Building pressurization is handled in a variety of ways. Designer 3 begins with equal supply and return air quantities, and then reduces the return air flow. For example, initial flows might be 1200 CFM with the return then reduced to 1000 CFM to provide pressurization. Designer 9 uses a specified CFM offset, providing more outdoor air than exhaust air, to positively pressurize the building and return 500-1000 CFM less per floor.

When asked whether they considered supply and return duct leakage in their designs, designers gave responses that varied based on the size and importance of the system. In general, careful estimates of expected leakage rates or their consequences are not part of the design process. To compensate for leakage, Designer 5 anticipates 10% duct leakage and allows "growing room " by oversizing main duct risers and trunks and often adds extra capacity in air handling equipment. Supply air quantity is typically increased in the testing and balancing stage to compensate for duct leakage. However, Designer 8 specifies allowed leakage levels to be 1% to 3 % of total air flow and requires SMACNA leakage testing. Most designers specified duct leakage testing and sealing using the SMACNA HVAC Air Duct Leakage Testing Manual (SMACNA 1985) by specifying a minimum pressure class and seal class. For example, Designer 9 specifies Leakage Class 12 for static pressures below 2" w.g. and Leakage Class 6 for static pressures between 3 and 6" w.g. With the exception of Designer 8, designers acknowledged that plenum returns may be depressurized with respect to the outside and acknowledged that leakage from plenums was not considered to be an issue because plenum returns are believed to operate at near neutral pressure differences, typically at hundredths of an inch water gauge. Designer 8 stated that since plenums leak, the architect should design the plenum boundaries to be air tight.

Energy Consumption, Indoor Air Quality and Security

Although designers did not want to speak in generalities and could not provide specific design calculations, all but two of the designers questioned stated that a system with ducted returns will consume slightly more fan energy than plenum returns due to higher friction losses of return ductwork. Designer 5 stated that the relative energy use of the two system types depends on the construction quality and workmanship of specific installations. For example, a crowded plenum may have obstructions blocking airflow and a ducted return may be constructed with square elbows that have no turning vanes. Designer 3 believed that plenum returns would consume more fan energy than ducted returns because plenum returns are not in balance, which conflicts with the claims by Hydeman et al. (2003) that plenum return air systems are inherently self-balancing. Rooms with unplanned pressurizations or depressurizations would put stress on air handling equipment. Although a plenum return may have a higher heat gain from the ceiling space due to roof heat load and lighting heat gain, designers stated that higher fan energy from ducted returns to have more of an impact.

Designers responded that differences in fan power would be job specific and were hesitant in talking about rule-of-thumb estimates and generalizations. Designer 11 replied that differences in fan power would depend on the system size. “For example it is easy to visualize a large central AHU for say a 500,000 sq ft, single story, building with a fully ducted return with as much ductwork on the return as on the supply. Compare that to the space above the ceiling being one large open plenum with only a short piece of duct from the AHU to the plenum. In this case you are comparing hundreds of feet of ductwork and air devices with friction loss to a large open plenum with only friction loss at the air devices and minimal entry losses at the return duct at the AHU. Here the additional static pressure is appreciable resulting in additional HP. Now compare this to a 10,000 sq ft building. The amount of ductwork is less as is the total friction loss and therefore the disparity between ducted and plenum will not be as large as the 500,000 sq ft bldg."

When asked whether they expected differences in IAQ between ducted returns and plenum returns, designers stated that as long as cooling coils were sized properly, building envelopes were designed properly by architects, and the correct amount of ventilation air was supplied, the two systems would not perform differently. IAQ was perceived to be a function of the percentage of outdoor air in the supply air and the air change rate.

Designers stressed that for critical spaces, the HVAC system should be a dedicated or single pass unit with 100% exhausted ductwork. For spaces where room pressurization is controlled, return ductwork must be used. For example, in restaurants moisture and contaminants must be exhausted. According to Designer 3, with a ducted return, a return grille can easily be balanced to a certain CFM so as not to interfere with an exhaust fan or kitchen hood. However, with a plenum return moisture and kitchen contaminants will spread more easily.

Installation

To minimize duct leakage designers typically specified that contractors and installers seal ductwork using a minimum pressure class and corresponding seal class from the SMACNA HVAC Air Duct Leakage Testing Manual (SMACNA 1985). For example, Designer 5 specifies a 2" w.g. pressure class and Class C seal for low velocity applications. For higher velocity applications, such as hospitals, Designer 5 specifies a 2" w.g. pressure class and a Class C seal for ducts downstream of terminal units, and a 3-4" w.g. pressure class and a Class B seal for ducts upstream of terminal units. A Class C seal calls for sealing transverse joints and a Class B seal calls for sealing transverse joints and longitudinal seals. Designer 10 requires SMACNA leakage testing depending on the pressure classification specified in the construction documents. For ductwork of 2” w.g. or less, visible and audible leaks perceptible to the owner’s representative must be sealed. For ductwork exceeding 2” w.g., leakage testing as indicated in the SMACNA Air Duct Leakage Testing Manual is required. A testing pressure, duct construction pressure class, and a leakage class are specified in the master specification, with instructions for completing a test report and test agenda.

Operation and Maintenance

Two operators responded that ducted returns were preferred, while two operators stated that they had no preference, and that the decision was left up to the designer. Operator 4 responded that ducted returns were preferred because quality assurance was more difficult in plenum returns, since one contractor constructs the ducts, while another contractor constructs the plenum. However, from design experience Operator 4 expected that given the choice, designers would choose plenum returns over ducted returns. Designing plenum returns takes less time and yields more profits from a fee standpoint due to fewer duct design calculations to perform, reduced need for coordination, and easier cost estimation. All four operators responded that specific maintenance problems were not associated with one return air strategy compared to another, and that IAQ problems, when they occurred were due to other reasons, not the return air strategy. According to Operator 3, return air design will not affect the spread of contaminants, unless a purge cycle is initiated. Generally recirculation will spread contaminants throughout a ventilation zone regardless of return air design.

Impact of Return Air System on Building Energy Consumption

In residential buildings, ductwork is often located in attic spaces or crawl spaces. Leaks in such unconditioned space result in losses of conditioned air when the relative duct pressurization is positive and take in unconditioned air when the relative pressurization is negative. In either case, the impact on energy use is adverse. Simulation and experiments indicate that duct heat transfer and duct leakage increase residential heating and cooling energy use dramatically. Parker *et al.* (1993) simulated the impact of duct heat transfer and leakage on a residential air-conditioner in Florida, and found that with no duct leakage or conduction losses, the air-conditioning energy consumption was lower by 24% and peak cooling electrical demand was lower by 30% than in a building with typical duct leakage and thermal losses. O'Neal *et al.* (1992) used a psychrometric test room to investigate the impact of duct leakage from a hot, humid residential attic on the performance of a residential air conditioner. With 10% leakage, an air-conditioner's capacity to cool the conditioned space was reduced by as much as 40%. In other words, 40% of the capacity produced by the unit was lost to leakage or duct heat gain. In application, if an air-conditioner so drastically derated could meet the space cooling load, it would do so at only a fraction of its nominal efficiency.

Measurements

Typical duct repairs consist of applying mastic and fiberglass tape to duct leaks. As mentioned in Section 3.2, leaks are often detected by visual aids, such as a smoke sticks, or with a pressure pan. A series of studies (Cummings *et al.* 1990; Davis and Roberson 1993; Parker *et al.* 1993; Jump *et al.* 1996) confirm that performing duct retrofits in homes using forced air distribution is a cost effective method of reducing cooling and heating energy consumption and peak power demand:

- Cummings *et al.* used tracer gas dilution to measure the return leak fraction (RLF), the portion of the air returning to the air handling unit (AHU) from outside the conditioned space. In 91 Florida homes tested, the average RLF was 10% of air handler flow and 30% of the homes had a RLF greater than 10%.

- Davis and Roberson quantified duct leakage in 17 Arkansas homes and measured pre and post retrofit heating energy consumption. Duct retrofits reduced average energy consumption by 31.3% for houses with heat pumps and by 19.7% for houses with gas furnaces. With an average cost of $500 for duct repair and modest cooling energy savings, duct retrofits would result in simple payback periods of 3.9 years for homes with gas furnaces and 3.2 years for homes with electric heat pumps.

- Parker *et al.* repaired ducts in a typical Florida home and found that air conditioning energy consumption was reduced by 19% for a group of days with similar interior to exterior temperature differences. The cooling energy use was measured before and after retrofit for the two hottest days in the analysis period. Average daily consumption was reduced by 41%, from 58.4 kWh to 34.2 kWh. The peak electrical demand was reduced by nearly 2.2 kW.

- Duct retrofits performed by Jump *et al.* on 24 California homes containing air conditioners, gas and electric furnaces, and electric heat pumps reduced average HVAC energy consumption by 18%. Reductions of normalized power consumption ranged from 5% to 57%. Based on these results, the authors recommend that diagnostic tests should be developed to indicate which homes will benefit from repairs.

Studies characterizing the impact of duct retrofits on energy use in commercial buildings are rarer. Researchers from the Florida Solar Energy Center (FSEC) investigated 70 light commercial buildings and repaired sources of uncontrolled airflows (Cummings *et al.* 1996; Withers *et al.* 1996; Cummings and Withers 1998). In 20 of the buildings, repairs were made and energy use and peak electrical demand savings were calculated by plotting cooling energy consumption against the outdoor to indoor temperature difference. Repairs mainly consisted of sealing duct leakage, but also included turning off attic fans, envelope air tightness improvements, and reducing oversized outdoor air intakes. Average cooling energy use was reduced from 87.4 kWh/day to 75.1 kWh/day, a reduction of 14.7%. In one building, energy use increased as a result of the repairs. The building had the leakiest envelope out of the 70 buildings tested, and Withers *et al.* theorize that because of the leaky ceiling and vented roof deck, air exchange from wind is more significant than the reductions of infiltration resulting from duct sealing. In the 18 buildings that showed energy savings, reductions varied from 4.3% to 36%. Average peak electrical demand was reduced from 7.61 kW to 6.90 kW, a reduction of 9.4%. In four buildings peak electrical demand increased. In one building, return leaks were sealed but an exhaust system drawing attic air into the building space was found after the repairs. Operation of the exhaust system negated the improvements from sealing return duct leaks. In the other buildings that saw increases in peak power demand, an insulation deficit at the roof deck caused cooling loads from solar radiation to peak during the middle of the day. Withers *et al.* (1996) speculate that increasing insulation levels would reduce energy use and peak demand. In the buildings that showed a reduction in peak electrical demand, reductions varied from 1.4% to 28%.

The impact of duct leakage on energy use depends on the pressure difference across the leak and the condition of the air entering the leak. Cummings *et al.* (1996) identified 7 typical ceiling configurations used in Florida commercial buildings based on the location of the primary thermal and air barriers and whether or not the attic space was intentionally vented to the outside. The primary thermal barrier was defined as, "the portion of the building envelope which provides the greatest resistance to heat flow," and the primary air barrier was defined as, "the portion of the building envelope which provides the greatest resistance to air flow and the greatest pressure drop when the building is exposed to a significant pressure differential compared to the outdoors." The authors found that in a majority of the buildings they investigated, the primary thermal and air barriers were separated, and that attics were intentionally ventilated to outdoors, often leading to an unconditioned ceiling space. Supply leakage to or return leakage from inside conditioned space generally has a minimal impact on energy use, while leakage to or from a ventilated attic space or from an unconditioned space will have a significant impact on energy use. Consequently the authors suggest placing the both the primary air and thermal barriers at the roof deck (Cummings *et al.* 1996).

Conat *et al.* (2004) demonstrated that repairing return duct leakage using aerosol-sealant technology can save energy. Return ducts in three light commercial buildings were located in unconditioned space, with insulation placed above suspended tile ceilings. After sealing return ductwork, return duct heat gain was reduced average of 12.4% of the system's sensible capacity at a 30 °F outside-inside ΔT. Return duct heat gain was defined as the temperature increase between the return grille and return plenum as a function of outside to inside temperature difference. After correcting refrigerant charge and sealing return duct leaks, the sensible steady state EER was improved by an average of 18% at a 30 °F outside-inside ΔT. Sensible steady state EER was based on the temperature difference between the return air grille and the supply plenum temperature and was defined as the amount of sensible cooling (Btu/h) per watt at steady state.

Analytical Models

The two main public domain programs available for modeling whole-building energy consumption are various versions of the U.S. Department of Energy's older DOE2 software and its successor, EnergyPlus (Crawley *et al.* 2000; Crawley *et al.* 2001, Crawley 2001). Neither of these programs is ideal for modeling the thermal impact of ducts, but both can be, and have been used for that purpose. EnergyPlus does not currently include duct leakage and surface heat transfer models, therefore researchers have on relied DOE 2, and also TRNSYS in studies published to date.

Although DOE 2 can model duct air leakage and conduction, the program has many limitations and deficiencies. Xu *et al.* (1999) and Wray (2003) discuss the modeling options available in DOE 2 and its limitations. Relative to modeling return air systems, the DOE 2.1E version of DOE2 has two main limitations: it models supply duct leakage into plenums, but does not model return duct leakage and return duct conduction, and it does not model supply/return air imbalances and the resulting unintentional air flows they produce through the building envelope and between interior zones. Simulation-based studies that consider duct leakage focus on supply duct leakage. Wray and Matson (2003) modeled the annual energy use of a low-pressure terminal-reheat variable-air-volume (VAV) HVAC system with six supply duct leakage configurations in nine office buildings representing three California climates. DOE-2.1E and custom TRNSYS component models developed by Franconi *et al.* (1998) were used to model the buildings. Franconi *et al.* (1998) simulated supply duct leakage upstream and downstream of VAV-boxes and found that with 10% upstream and 10% downstream leakage, fan energy increased by 55% compared to a duct system with no leakage. Wray and Matson (2003) modeled a typical office building in three California climates with six different supply duct leakage configurations. The fan power increased by 40-50% for a supply duct system with 19% supply leakage compared to a relatively tight duct system (5%). Annual cooling plant consumption increased by 7-10% and reheat energy reduced by 3-10%. Total HVAC site energy (supply/return fan electricity consumption, chiller/cooling tower electricity consumption, boiler electricity consumption, and boiler natural gas consumption) increased by 2-14%. Modera *et al.* (1999) modeled supply duct leakage in a prototypical office building with perimeter and core VAV-systems in Fresno and San Jose, California. Adding 30% supply duct leakage distributed uniformly along the duct to a thermally-perfect system increased perimeter fan consumption by 11%, perimeter fan peak demand by 13%, core fan consumption by 12%, and core fan peak demand by 15%.

Rock and Wolf (1997) attempted to address a gap in the literature by including the impact of floor and ceiling plenum configurations in load calculation software. The sensitivity of floor and ceiling plenum heat transfer parameters on transient energy models was determined for six different ventilation configurations, two of these being ducted supply/ducted return, and ducted supply/plenum return. Parameters investigated include plenum radiation, plenum surface emissivity, convection coefficients, floor thickness, and the number of nodes in the plenum. The energy model was not sensitive to the heat transfer parameters; however, simplifying assumptions limit the relevance of the study on existing buildings: (1) duct and plenum leakage were not modeled, (2) exfiltration/infiltration was neglected, (3) air was dry at sea level, (4) heat transfer between adjacent rooms and plenums, and heat transfer between the spaces and outside was not modeled, and (5) solar radiation was not modeled.

Guntermann (1986) simulated internal heat gains, plenum airflow rates, plenum temperatures, ceiling heat gains, total and space sensible loads, sensible heat ratios, supply air temperatures, and supply airflow rates for lighting levels of 1 to 5 W/ft^2 for ducted returns and plenum returns. With a plenum return air system, the analysis showed part of the lighting heat gain going to the return air and being conditioned by the HVAC system. With a ducted return, the lighting heat gain increased the temperature of the plenum and heat was radiated back into the conditioned space through the suspended ceiling. Since VAV-systems vary airflow rates to meet space loads, the heat load from the increased temperatures in the plenum increased airflow rates by 20 – 50%.

Impact of Return Air System Type on Indoor Air Quality

Lstiburek *et al.* (2002) list four factors necessary for indoor air quality problems to occur: (1) pollutants, (2) people (receptors), (3) pathways (connecting the pollutants to the people), and (4) pressure differences (to move the pollutants through pathways to the people). The building structure and envelope and HVAC system interact and create airflow pathways and pressure differences.

Numerous references suggest using ducted returns rather plenum returns, because fan suction causes a greater negative pressure across the drop ceiling and building envelope with a plenum return (Harriman *et al.* 2001; Brennan *et al*. 2002; Lstiburek 2002). Lstiburek (2002) counsels designers not to use plenum returns, but he provides some design rules to minimize the potential for unplanned airflows and moisture problems when use of a plenum cannot be avoided:

make sure intersecting interior walls do not contain or are not connected to leaking return ductwork/exhaust chases or ducts, and extend interior wall cladding to the underside of the roof deck. Harriman *et al.* (2001) acknowledge that although both return air strategies allow opportunities for infiltration and moisture intrusion, the pressure difference across the envelope will be greater for a plenum return.

In one case study (Lstiburek et al. 2002), poor design and construction of the foundation and interior wall systems and operation of exhaust fans and an air handler in a return plenum lead to complaints of odor, headaches, fatigue and flu-like symptoms in a single story school. The school had a crawl space foundation with vents on the perimeter walls, and interior concrete bearing walls. Exhaust fans and operation of the air handling unit in the return plenum depressurized the classrooms and the return plenum with respect to outdoors. A digital manometer showed that the classroom was operating at a negative pressure difference of 4 Pa with respect to the crawl space. As a result, warm saturated air was drawn from the crawl space to the classroom areas through joints between the interior masonry walls and foundations. Once in contact with the wall assembly, the water vapor condensed, leading to decay of the plaster and wood.

Although the return air plenum and exhaust fans were the driving forces behind the pressure difference, the source of the problem was the poor design and construction of the building structure and envelope. The primary pollutant (moisture) was controlled by installing a polyethylene ground cover in the crawl space, and the secondary pollutant (odor) was controlled by removing the decayed plaster and wood baseboard and sealing the pathway between the crawl space and the classroom areas. To alter the driving force of the pollutant transfer, the direction of airflow between the crawl space and classrooms was altered. Crawl space vents were permanently sealed and a fan was installed to continuously exhaust air from the crawl space. As a result of running the exhaust fan, the crawl space operated at a negative pressure difference of 4

Pa with respect to the classroom, and a smoke stick confirmed that air moved from the classroom areas to the crawl space.

Moisture is not the only potential source of indoor air quality problems. Spengler and Chen (2000) note that the surface area in contact with air in a ceiling plenum can be twice the floor area and that ceiling plenums contain potential sources of VOCs including unfinished wallboard, fireproofing, fiberglass, acoustical insulation, power and communication cables, and topsides of ceiling tiles. Zuraimi *et al.* (2004) used a mass-balance model to find steady state VOC emission rates from building materials, ventilation systems, and occupants and their activities. VOC emission rates from ventilation systems with ducted returns and plenum returns were compared, and generally the emission rates did not differ. However, emission rates of four compounds (dodecane, tetradecane, toluene, and styrene) were significantly higher in ventilation systems with ducted return. TVOCs were higher in buildings with plenum return. The sample size was only five buildings, so strong conclusions about the impacts of return air strategy cannot be drawn.

Impact of Return Air System Type on Building Security

Since the anthrax mail incidents that followed on the heels of the September 11, 2001 terrorist attacks, numerous reports and guidance documents have been published concerning how to protect building occupants from chemical, biological and radiological (CBR) attacks (USACE 2001; NIOSH 2002; ASHRAE 2003; FEMA 2003; Price *et al*. 2003; Persily *et al.* 2007).

Guidance and advice vary from protective action plans to mechanical and architectural design suggestions and building retrofits. A security-enhancing measure often cited in the literature is separating ventilation zones to minimize the potential of inter-zonal transfer of contaminants. Ventilation zones can be isolated by avoiding plenum returns (routing return ductwork), designing full height walls between zones and hallways, and using separate air handling units (AHUs) for each zone. However, while advice and guidance aimed at reducing a building's susceptibility to a CBR attack is plentiful; the open literature provides little data to quantify the effect return air system design on building security performance.

In large commercial buildings, separate heating, ventilation, and air conditioning (HVAC) systems often supply air to different zones and draw return air from a "common plenum" which mixes air from each zone before being redistributed by the HVAC system. With "common plenum" returns, the HVAC system will spread the contaminant as if the building was one ventilation zone. ASHRAE (2003) and NIOSH (2002) suggest routing return ductwork to each AHU to avoid cross contamination between zones. Ducted returns not only minimize inter-zonal contamination, but also offer limited access points to introduce CBR agents. CBR agents released above a suspended ceiling containing a shared plenum will most likely be redistributed by the HVAC system (NIOSH 2002; FEMA 2003). To design truly separate ventilation zones, USACE (2001) and FEMA (2003) suggest designing full height walls between zones and hallways. In buildings with common plenum returns, interior walls are extended to the suspended ceilings, leaving air pathways between zones.

Another design measure to reduce a building's susceptibility to a CBR attack is to isolate areas where intentional releases of CBR agents are more likely. ASHRAE (2003), NIOSH (2002), USACE (2001), FEMA (2003) and Price *et al.* (2003) suggest isolating high risk areas, such as mailrooms, loading docks and public lobbies, from the rest of the building. High risk areas can be isolated by providing separate HVAC systems and separate return pathways or eliminating return pathways by using dedicated outdoor-air systems.

Although building pressurization is noted in the literature to be an available protective measure from outdoor CBR releases, using ventilation as part of a protective strategy requires knowledge of the design strategy and requires that the HVAC system is operating as intended. Persily *et al.* (2007) state that buildings and zones should be continuously pressurized and that building pressurization is not intended to be a response to a contaminant release. The effectiveness of building pressurization as a protective measure hinges on over-pressurization of the interior relative to outside, while removing the agent from the outdoor intake by air cleaning or filtration. With leaky exterior envelopes, unintended airflows and infiltration could transport CBR agents through the exterior envelope bypassing air cleaners and filtration. If unducted return systems consistently induce greater pressure differentials across suspended tile ceilings and building envelopes than ducted return systems as the literature suggests (Harriman *et al.* 2001; Brennan *et al*. 2002; Lstiburek 2002), return air strategy could have a significant impact on occupant exposure and contaminant transport.

To analyze the effectiveness of retrofit options, Persily *et al.* (2007) simulated airflow, contaminant releases, and occupant exposure in three buildings using the multizone modeling software CONTAM (Walton and Dols 2005). Retrofits considered included specific technologies, such as filtration and air cleaning, and more general options, such as building pressurization, envelope tightening, and isolating high risk areas. Persily *et al.* (2007) concluded that envelope tightening alone will not reduce long term exposure to contaminants. Envelope tightening reduces infiltration rates and less outdoor contaminant will enter the building. However, the lower infiltration rate will cause contaminants that enter the building to remain in the space longer, increasing long term exposure. Also, for building pressurization to be an effective measure, ventilation rates during operation must be compared to ventilation design rates.

Models and case studies investigating the effect of return air strategy on contaminant dispersion were not found. Models focused on the effect of recirculation on the spread of contaminants to connected zones. Klobut (1991) simulated dynamic contaminant concentrations, pressure distributions, airflows, and temperatures in a multizone building using Fortran 77. Each room was considered as one or more zones vertically stacked with a node in each zone. Differential equations for each zone were written to simulate temperature gradients and airflows as a result of wind pressure, fan operation, and buoyancy forces. Validation cases were simulated and solved analytically to verify the numerical stability of the program and ensure accurate results. The model results indicate that the worst air qualities occurred when the contaminant was released in the room with the highest thermal load, and that door position is of minor importance when recirculation is used to ventilate the building. However, the study only considered a HVAC system with a ducted return.

Summary and Conclusions

The impacts of ducted air distribution system design and performance on buildings, particularly residential structures in which ducts are frequently outside condition space, has received significant study. Duct leakage in unconditioned spaces wastes substantial energy and may entrain contaminants into a building. Less work relative to return systems non-residential buildings can be found in the literature. It is at least plausible that different return system types will have a significant effect on infiltration rates and internal air flow patterns in a building, thereby affecting energy consumption, air quality, and security. Some previous studies have considered the pros and cons of return system alternatives based on limited field measurements and experience; extensive analytical or controlled experimental studies providing a systematic quantitative energy and IAQ impact assessments for the various return strategies are very few.

Hydeman *et al.* (2003) state that systems utilizing unducted plenum returns will consume less energy compared to ducted returns because of lower static pressure drops; however, models and experiments confirming this claim were not found in the literature. When asked about the comparative energy use between ducted returns and unducted returns, the majority of designers agreed that unducted return systems would consume less fan energy than ducted returns. However, the difference was believed to be minimal and the belief was grounded in intuition, not calculations.

Literature regarding the impact of return air systems on indoor air quality is anecdotal. Numerous references suggest using ducted returns rather than plenum returns, because fan suction causes a greater negative pressure across the drop ceiling and building envelope with a plenum return (Harriman et al. 2001; Lstiburek 2002). Lstiburek (2002) advises designers to not use plenum returns, but if they are unavoidable, he lists some design rules to minimize the potential for unplanned airflows and moisture problems: do not connect drop ceiling return plenums to exterior walls, make sure intersecting interior walls do not contain or are not connected to leaking return ductwork or leaking exhaust chases or ducts, and extend interior wall cladding to underside of roof deck. Harriman *et al.* (2001) acknowledge that although both return air strategies allow opportunities for infiltration and moisture intrusion, the pressure difference across the envelope will be greater for a plenum return.

Although numerous references suggest using ducted return systems because unducted return systems have a greater potential for operating at negative pressure differentials, the literature lacks field measurements and analytical models investigating this phenomena. Cummings and Withers (1998) investigated uncontrolled air flow in 70 small commercial buildings in Florida. In 33 of the buildings, building cavities were used as part of the air distribution system. Building cavities characterized included enclosed air handler support platforms, mechanical closets, mechanical rooms, ceiling spaces, wall cavities, and chases. Seven of the seventy buildings used ceiling spaces as part of the thermal distribution system. The average ceiling plenum was found to be depressurized to 0.004 in. H_2O (1 Pa) with respect to the outdoors. Since the ceiling plenums operated at near neutral pressure differentials, the authors contend that the impact of ceiling space leakage may be negligible. More extensive measurements and data are needed to characterize return air systems on indoor air quality and infiltration.

Although advice and guidance aimed at reducing a building's susceptibility to a CBR attack is available, the literature lacks experimental studies characterizing the effect return air system design on building security performance. In large commercial buildings, separate heating, ventilation, and air conditioning (HVAC) systems often supply air to different zones and draw return air from a "common plenum" which mixes air from each zone before being redistributed by the HVAC system. With "common plenum" returns, the HVAC system will spread the contaminant as if the building was one ventilation zone. ASHRAE (2003) and NIOSH (2002) suggest routing ductwork to each air handler to avoid cross contamination between zones, but no studies compared ducted and unducted return system resistance to intentional or unintentional contaminant releases.

Chapter 3

OBJECTIVE AND METHODOLOGY

The discussion of the impact of return air system type on building energy consumption, IAQ, and resistance to a CBR attack in the open literature consists of anecdotes and advice, not field measurements and analytical proof. The objective of this thesis was to evaluate the differences in resistance to CBR attacks, and IAQ between unducted and ducted HVAC return systems through laboratory investigations at the Iowa Energy Center Energy Resource Station (ERS), and multizone model simulations.

Laboratory Experiments: Iowa Energy Center

The Iowa Energy Center Energy Resource Station (ERS), depicted in Figure 3-1, is a well instrumented demonstration and test facility built to combine laboratory testing capabilities with real building characteristics. The ERS facilities consist of four pairs of identical test rooms, shown in white, and a general service area with classrooms and offices, shown in gray. Each pair of test rooms represents a different location within the building (i.e. east, west, south, and interior) and therefore a different thermal load. The plenum level of the ERS facilities can be seen in Figure 3-2. Each test room plenum is separated from the adjacent test room plenum and general service area plenum by full height firewalls and the mechanical room and bathrooms are also separated by full height firewalls. Three variable air volume (VAV) air handling units serve the ERS. Two identical AHUs, designated as systems A and B, serve the pairs of test rooms, with each test room being served by its own VAV box. The layout of the test room ductwork can be seen in Figure 3-3. A separate AHU with a plenum return air system, shown in Figure 3-4, serves the general service area.

Table 3-1 contains ERS room and plenum dimensions.

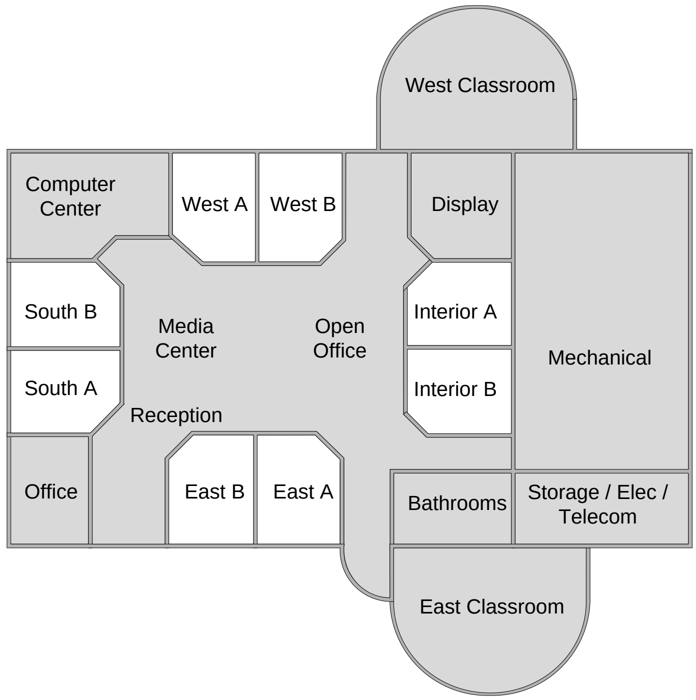


Figure 3-1: Iowa Energy Center ERS ground level

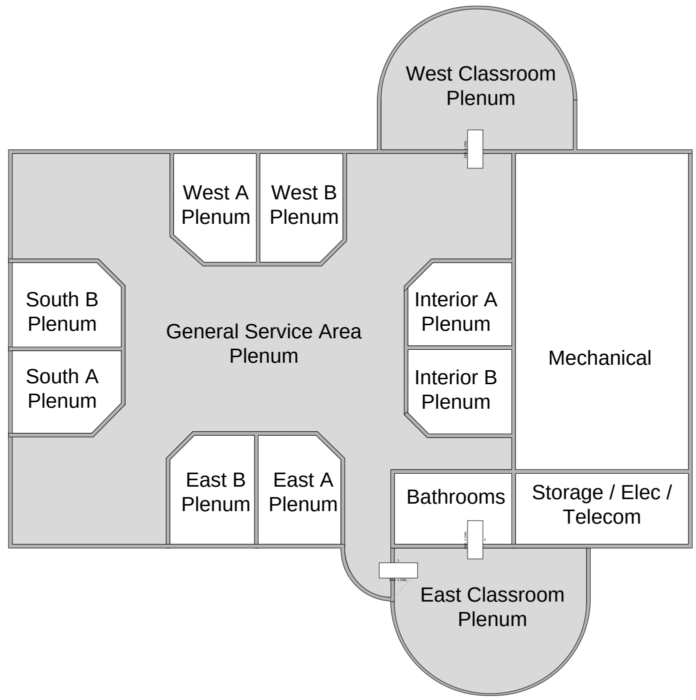


Figure 3-2: Iowa Energy Center ERS plenum level

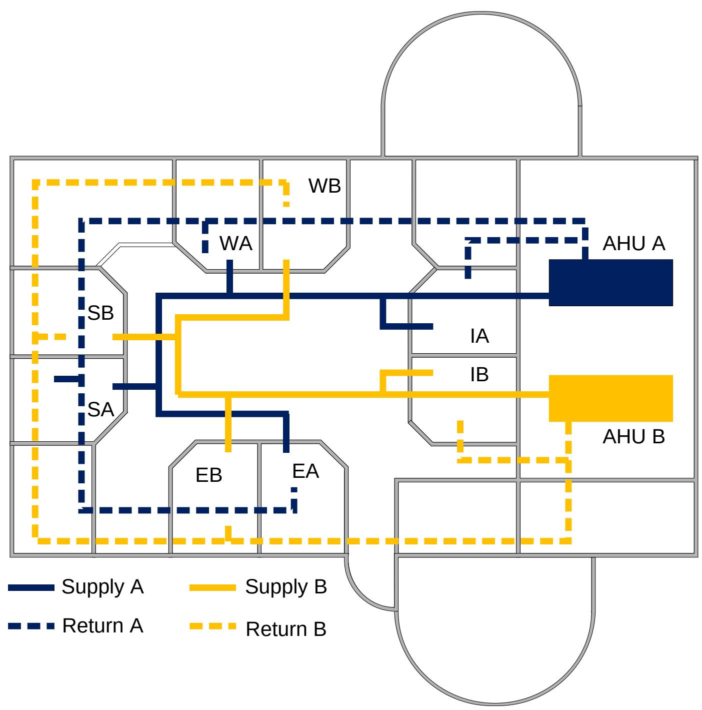


Figure 3-3: Iowa Energy Center ERS Test Room ductwork layout

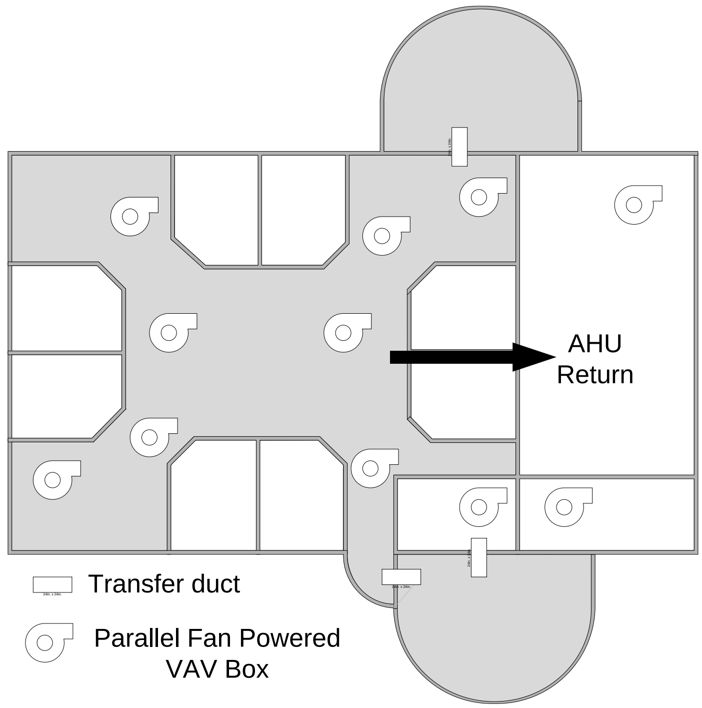


Figure 3-4: Iowa Energy Center ERS General Service Area plenum level

Table 3-1: Iowa Energy Center ERS dimensions

Room Name	Floor Area (ft^2)	Ceiling Height (ft)	Plenum Height (ft)	Exterior Wall Area (ft^2)	Exterior Window Area (ft^2)
Zones A & B					
Interior A & B	266 each	8.5	5.5	0	0
West A & B				137 each	74 each
East A & B					
South A & B					
General Service Area					
Mechanical	1764	14	0	1080	0
Storage / Elec. / Telecom	266	8	6	501	0
Media Center / Open office	1888	10	4	0	0
Bathrooms	390	8	6	499	0
Reception	178	8.5	5.5	75	40
Office	197	8.5	5.5	238	136
Display	319	8.5	5.5	0	0
Computer Center	415	8.5	5.5	383	197
East Classroom	769	9	1	762	70

West Classroom	796	9	1	762	70

ERS Test Room Experiments

The ERS test room pairs were used to compare ducted and plenum return performance with side-by-side controlled experiments. Table 3-2 contains the Test Room Experiment Protocol. Winter and summer tests were conducted by comparing different return air systems on AHU's A and B for approximately 1 week per test. Figure 3-5 shows an HVAC partial plan of a typical test room pair. Temperature, relative humidity, and differential pressure in the space and return air pathway were measured for each test. System schedules and control modes in the test plan were intentionally kept as simple as possible in order to facilitate comparison of results with model predictions. Constant heating and cooling thermostat set points were set at 70 ºF and 74 ºF respectively.

Table 3-2: Iowa Energy Center ERS Test Room Experiment Protocol

Test Case Description	Test Dates	Test Days Online	Test Room A Configuration	Test Room B Configuration
Test 1.1 Winter Testing				
Return Air Configuration	1/10/08 ~ 1/16/08	7 days	VAV Ducted	VAV Plenum
Fan Powered Box (FPB)			NO	NO
Test 1.2 Winter Testing				
Return Air Configuration	1/18/08 ~ 1/24/08	7 days	VAV Plenum	VAV Ducted
Fan Powered Box (FPB)			NO	NO
Test 1.3 Winter Testing				
Return Air Configuration	1/30/08 ~ 2/5/08	7 days	FPB Plenum VAV	VAV Ducted
Fan Powered Box (FPB)			YES	NO
Test 1.4 Winter Testing				
Return Air Configuration	2/7/08	7 days	FPB Plenum VAV	VAV Plenum

Fan Powered Box (FPB)	~ 2/13/08		YES	NO
Test 2.1 Summer Testing				
Return Air Configuration	8/13/08 ~ 8/17/08	5 days	VAV Ducted	VAV Plenum
Fan Powered Box (FPB)			NO	NO
Test 2.2 Summer Testing				
Return Air Configuration	8/19/08 ~ 8/23/08	5 days	VAV Plenum	VAV Ducted
Fan Powered Box (FPB)			NO	NO
Test 2.3 Summer Testing				
Return Air Configuration	8/28/08 ~ 9/1/08	5 days	FPB Plenum VAV	VAV Ducted
Fan Powered Box (FPB)			YES	NO
Test 2.4 Summer Testing				
Return Air Configuration	9/2/08 ~ 9/7/08	6 days	FPB Plenum VAV	VAV Plenum
Fan Powered Box (FPB)			YES	NO

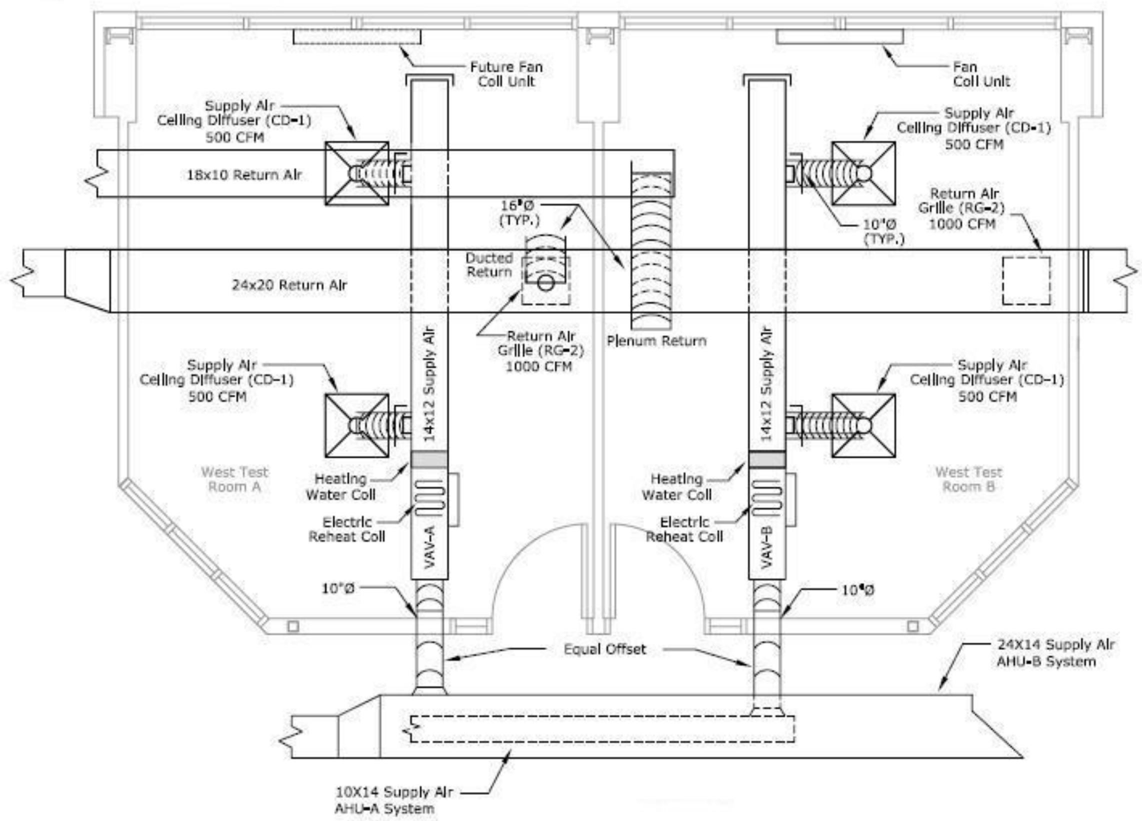


Figure 3-5: Typical Test Room pair – partial HVAC plan

To add an internal thermal load to a pair of the test rooms, two androids were used to simulate 4 people doing moderately active office work in each of South Test Rooms A and B. Each simulated person produces 250 Btu/h of sensible heat (ASHRAE 2007) for a total of 1000 Btu/h in each room. Each simulated person also releases 0.35 L/min of CO_2 for office work (ASHRAE 2007) for a total of 1.4 L/min of CO_2 generation per room. The internal load and CO_2 generation from the androids, and lighting were constant during the hours 6 a.m. – 6 p.m. and zero at other times. Note that for the plenum cases, the return duct shown was coiled up inside the plenum, as seen in Figure 3-6. The test room setup differs from a typical plenum, since each test room plenum is separated from the adjacent test room plenum and general service area plenum by full height firewalls to the roof.

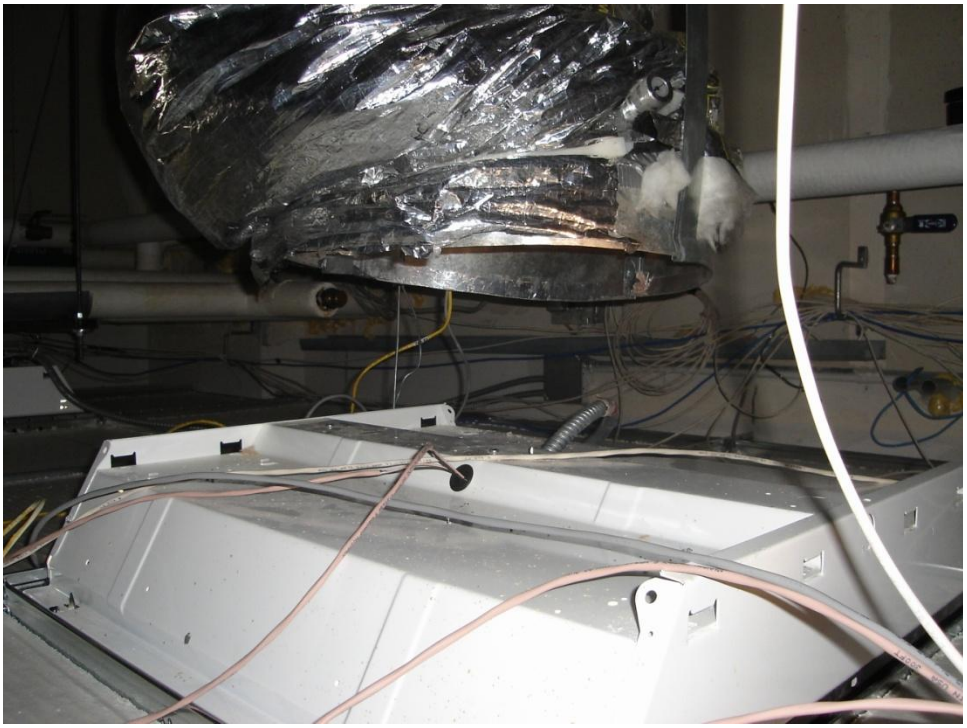


Figure 3-6: Iowa Energy Center ERS Test Room plenum configuration

Differential Pressure Measurements

During the Winter and Summer Test Room Experiments (Table 3-2), supply and return air balance for each test system was varied to compare the impact of return air system on differential pressure fields for positive, balanced and negative air handler operation. For each side-by-side comparison, return air for systems A and B were set at 80%, 100% and 120% of supply air. For example, in Test 1.1, ducted and plenum return systems were compared with return air for AHU A and B was set at 80% for 2 days, 100% for 3 days, 120% for 2 days. Differential pressures with an accuracy of ± 0.001 in. w.g. were measured in the locations seen in

Figure 3-7 for all four test rooms (south, east, west, and interior) for each minute. Differential pressure measurements for each Test Room and Test Room Plenum were taken with the low side referenced to the Media Center (with respect to the Media Center), and four exterior differential pressure measurements in the Media Center were taken with respect to the (w.r.t.) the outside at each wall.

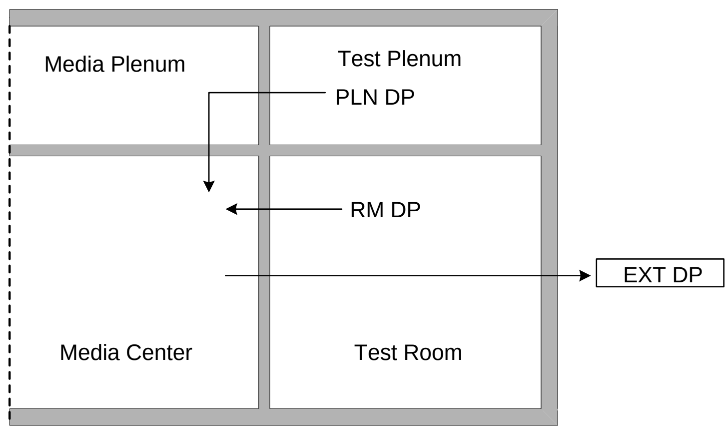


Figure 3-7: Measured differential pressure points – Test Room studies

Where:

RM DP = Measured Test Room differential pressure (Test Room w.r.t. Media Center)
PLN DP = Measured Test Plenum differential pressure (Test Plenum w.r.t. Media Center)
EXT DP = Measured Exterior differential pressure (Media Center w.r.t. Exterior)

Using the measured differential pressures, Test Room, Test Plenum, and Ceiling differential pressures were calculated, as seen below, with the sign convention seen Figure 3-8. Sign convention was chosen to have exfiltration from Test Rooms represented as positive differential pressure.

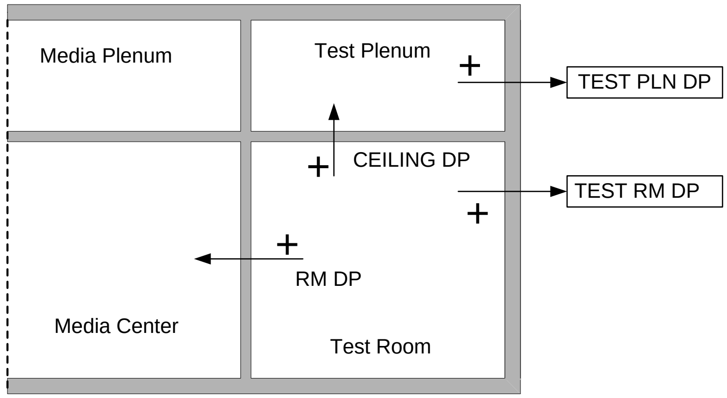


Figure 3-8: Calculated differential pressure points and sign convention

Where:

TEST RM DP = Calculated Test Room differential pressure (w.r.t. Exterior)
TEST PLN DP = Calculated Test Room Plenum differential pressure (w.r.t. Exterior)

Figure 3-9 shows measured room differential pressure with 15 minute average superimposed. Differential pressures were measured with an accuracy of ± 0.001 in. w.g. Figures comparing differential pressure contain 15 minute averages of calculated differential pressures taken after performing mathematical functions. For example, Test Room differential pressure was calculated using the measured Exterior and Room differential pressure for each wall.

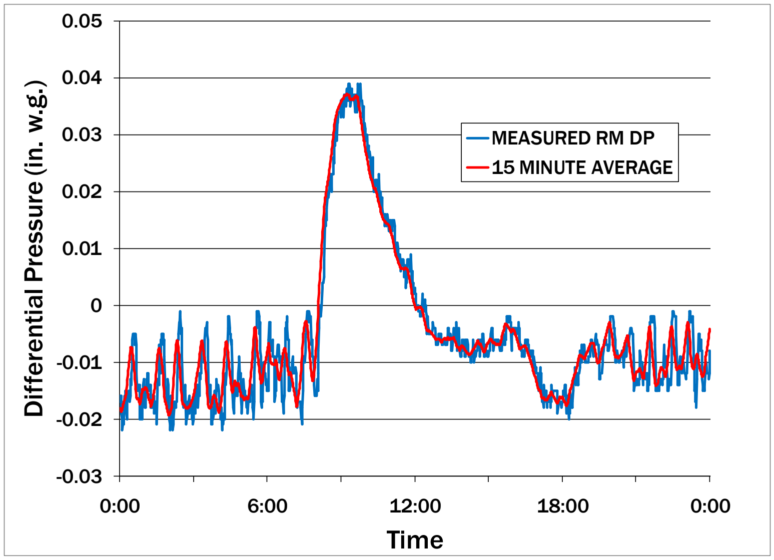


Figure 3-9: Measured and averaged differential pressure

General Service Area Tracer Gas Tests

Since the pairs of test rooms are isolated from each other by full height walls, using test rooms to characterize return air system resistance to inter-zonal contaminant transfer was not feasible. Therefore, CO_2 tracer gas tests were conducted in the general service area to compare resistance of ducted and plenum return air systems to interzonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space. To test the applicability of mutlizone model simulation for determining inter-zonal contamination vulnerability of each return air strategy, CO_2 tracer gas test results were compared to multizone model simulation results using the public domain software CONTAM (Walton and Dols 2005).

Tracer Gas Test Plan

The general service area, depicted as gray in Figure 3-1, is served by a separate VAV air handler with parallel fan powered boxes and a plenum return system, as seen in Figure 3-2. During the Tracer Gas Test, the system was operated in three modes: plenum return with parallel fan-powered VAV box fans on, plenum return with parallel fan-powered box fans off, and ducted return with parallel fan-powered box fans off. For the ducted return tests, a temporary return air system was constructed by routing 16” and 12” flex duct to each return grille. Airflows were controlled and logged so that conditions could be compared from one test to another. In addition to CO_2 sensors located at the room thermostats and AHU return, eight CO_2 sensors were placed in the plenum (seen in Figure 3-10) to track transient CO_2 migration through the plenum.

Two release locations were selected: the Office, which is far from the AHU return inlet, and the Display Room, which is close to the return inlet. Both are small rooms with a single return grille. Figure 3-11 shows the release locations and the anticipated return air pathways for a plenum return system. It was hypothesized that a release near the return inlet would result in a rapid, large increase in concentration throughout the general service area, while a release far from the return inlet would produce a later peak at a lower value because the tracer would be diluted in the plenum before reaching the AHU return. Release room doors were closed during testing so that tracer would enter the system predominantly through the ceiling return grille in each room. Releases were rapid discharges of 10 lb CO_2 cylinders lasting less than 5 minutes, mimicking an accidental contaminant spill or intentional CBR attack. The release quantity was selected to produce a significant increase above background concentration in the general service area and, as a result, caused initial concentrations to exceed the range of the CO_2 sensors in the release rooms and plenum. The estimated initial average concentration, based on an instantaneous release and well mixed assumptions, was 52,000 ppm in the Office, and 32,000 ppm in the Display Room.

Table 3-3 shows the General Service Area Tracer Gas Test Plan. Test 1.5 consisted of releasing CO_2 in both release locations to test the impact of parallel fan powered boxes in transporting contaminants from the plenum to conditioned spaces with a plenum return air system. Comparisons of multizone model simulations did not agree with tracer gas measurements, so the test protocol was altered for Test 2.5. It was hypothesized that as cold CO_2 was released, it fell to the ground and was stratified within the release zone. To approach well mixed assumptions inherent in multizone modeling and to test this hypothesis, mixing box fans aimed at the floor were placed in the release zone and additional CO_2 sensors with a 10,000 ppm range were placed in the release zone 1 foot from the ground and at the return grille. Test 2.5 consisted of releasing CO_2 in both release locations for ducted return, plenum return, and plenum return with parallel fan powered boxes with mixing fans and additional CO_2 sensors in the release zone. Test 2.5a consisted of repeating Test 1.5, with additional CO_2 sensors in the release zone and without release zone mixing, to measure the extent of stratification.

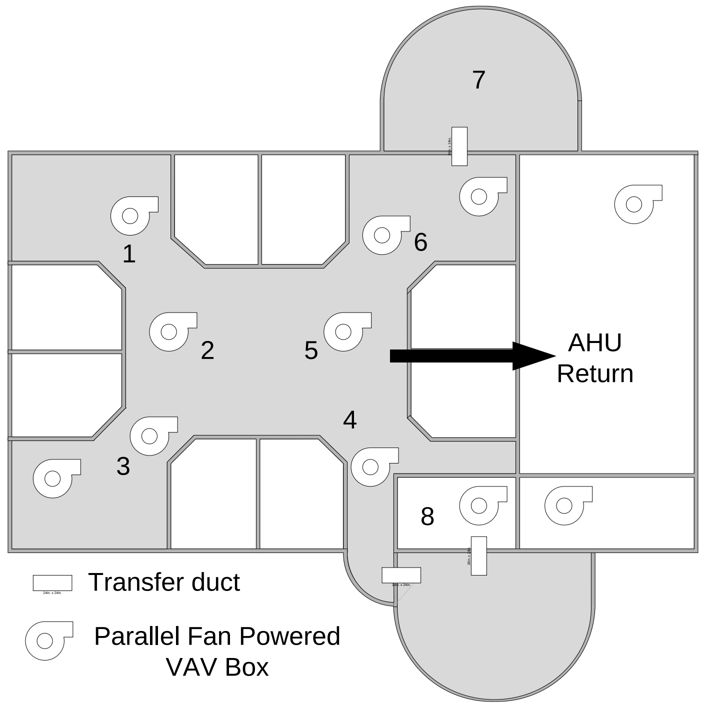


Figure 3-10: Location of General Service Area Plenum CO_2 sensors

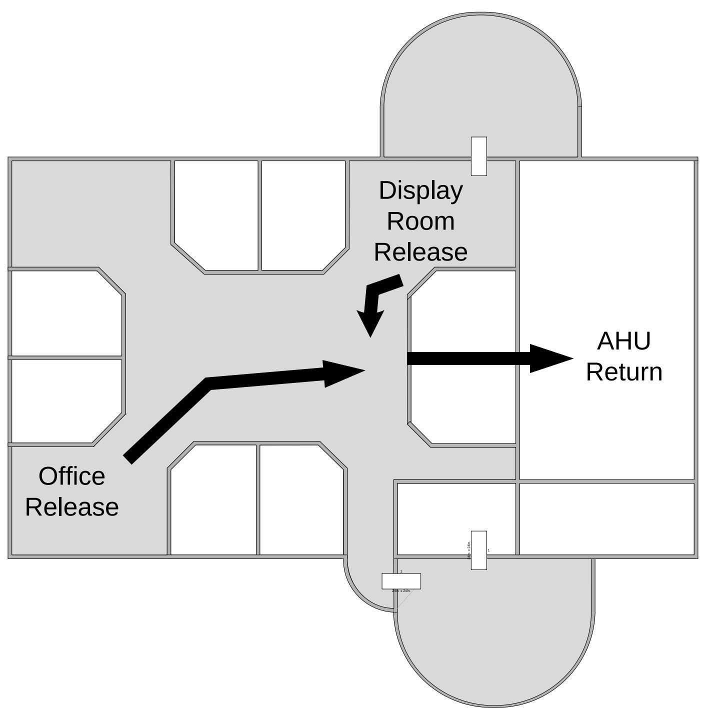


Figure 3-11: ERS Tracer Gas Test release locations and anticipated return air pathway

Table 3-3: General Service Area Tracer Gas Test Plan

Test Number	Release Date (night of)	Notes	Release Location	Return System	Fan Powered Box Operation	Release Zone Mixing
Test 1.5	2/21/2008	No release zone CO_2 sensors No mixing fans in release zone	Display	Plenum	ON	OFF
	2/22/2008		Display	Plenum	OFF	OFF
	2/23/2008		Office	Plenum	ON	OFF
	2/24/2008		Office	Plenum	OFF	OFF
Test 2.5	8/4/2008	Additional CO_2 sensors in release zone 1 ft from ground and at return grille Mixing fans in release zone	Display Room	Ducted	NONE	ON
	7/23/2008		Display Room	Plenum	OFF	ON
	7/24/2008		Display Room	Plenum	ON	ON
	8/1/2008		Office	Ducted	NONE	ON
	7/26/2008		Office	Plenum	OFF	ON
	7/25/2008		Office	Plenum	ON	ON
Test 2.5a	10/21/2008	Additional CO_2 sensors in release zone 1 ft from ground and at return grille No mixing fans in release zone	Office	Plenum	OFF	OFF
	10/22/2008		Office	Plenum	ON	OFF
	10/23/2008		Display Room	Plenum	OFF	OFF
	10/24/2008		Display Room	Plenum	ON	OFF

Multizone Modeling

To test the applicability of mutlizone model simulation for determining inter-zonal contamination vulnerability of each return air strategy, CO_2 tracer gas test results were compared to multizone model simulation results using the public domain software CONTAM (Walton and Dols 2005). In multizone modeling, a building is represented by well-mixed zones connected by airflow paths where the airflow between each zone calculated by conservation of mass and airflow-pressure relationships. Since zones are assumed to have uniform pressure and contaminant concentrations, multizone modeling is best suited for whole building simulations.

Multizone Model Simulations of the ERS Tracer Gas Tests

Building characteristics, such as room volumes, wall areas, and leakage characteristics of each surface were input into the graphical interface to create a multizone model representation of the ERS facilities, as seen in Figure 3-12 . In order to simulate the impact of parallel fan powered boxes on transport of contaminants from the plenum to local spaces and to compare ducted and plenum returns, a plenum level, as represented in Figure 3-13, was included with supply, return and outdoor air fans, and ductwork, diffusers and balancing dampers. For each test, airflow measurements were used to create supply, return and outdoor air constant volume fans. VAV airflows at each box were measured and were constant since the tests were completed overnight.

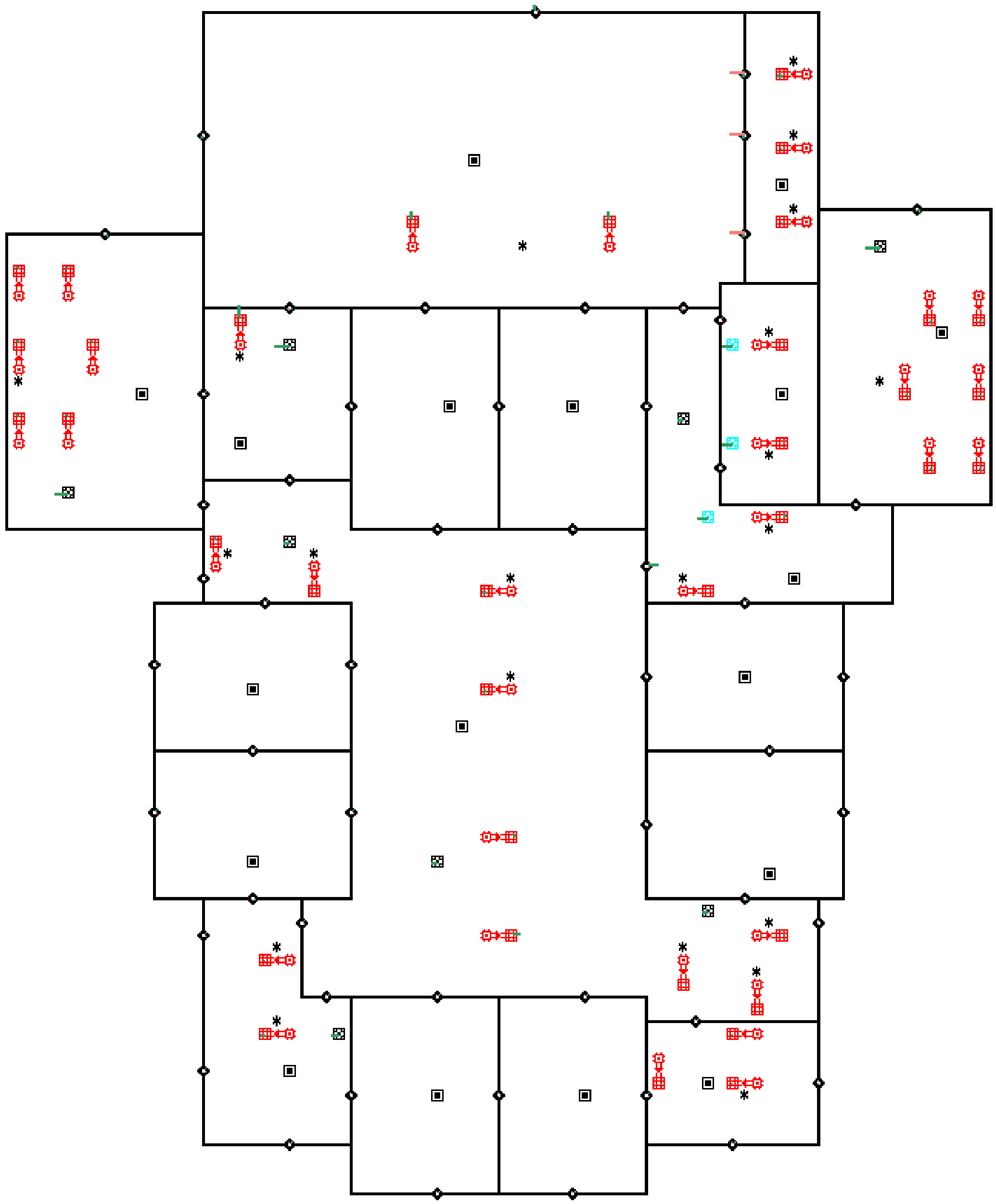


Figure 3-12: Multizone model representation of ERS ground level

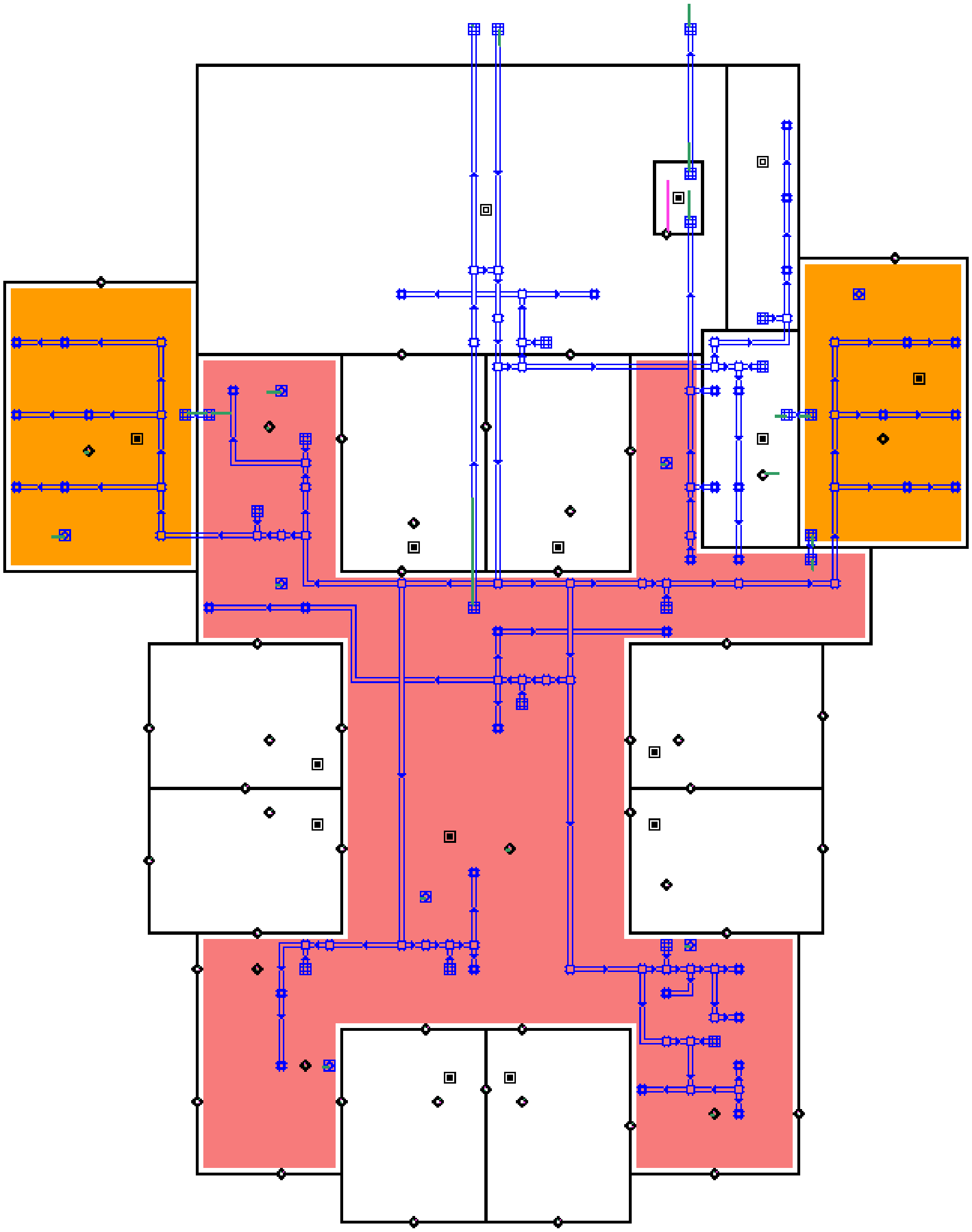


Figure 3-13: Multizone model representation of ERS plenum level

Multizone Model Simulations of Hypothetical Office Building

To assess the inter-zonal contamination resistance of different return air systems on a whole building level, contaminant dispersal of a generic gas and inter-zonal airflow was simulated in a hypothetical office building using multizone modeling (Walton and Dols, 2005). In multizone modeling, a building is represented by well-mixed zones connected by airflow paths where the airflow between each zone is calculated by conservation of mass and airflow-pressure relationships. Since zones are assumed to have uniform pressure and contaminant concentrations, multizone modeling is best suited for macro building simulations.

Hypothetical Office Building

Building characteristics, such as room volumes, wall areas, and leakage characteristics of each surface were input into the graphical interface to create a multizone model of the hypothetical building as seen in Figure 3-14. The hypothetical office building is a 2 story building with a floor to floor height of 13 ft. and a floor to ceiling height of 9 ft. with a footprint of 28,900 ft^2 and a total floor area of 57,800 ft^2. The floor plan consists of a lobby, corner conference rooms, individual perimeter office space, and an open office space in the core. In order to simulate the impact of parallel fan powered boxes on transport of contaminants from the plenum to local spaces and to compare ducted and plenum returns, a plenum level, seen in Figure 3-15 and Figure 3-16 was created with supply and return ductwork and parallel fan powered boxes.

It should be noted that since a plenum zone was created to compare ducted and plenum return air systems and to simulate interzonal transport of contaminant from plenum zones to occupies spaces by parallel fan powered boxes, a “complex duct system” was defined and the "simple AHU" option offered by CONTAM could not be used. In the "simple AHU" option, no plenum zone exists and supply and return airflow rates are specified at the zone level by placement of supply air diffusers and return air grilles. With the "simple AHU" option, supply and return airflow rates are calculated at the AHU level as the sum of all specified airflow rates at the zonal level. With a "complex duct system", an entire duct system is drawn and defined with duct sizes, lengths, friction factors, and duct leakage. The supply air system consists of supply air ducts and supply air balancing dampers, while the return air system consists of return air ducts and balancing dampers for ducted return cases and return air grilles connected to an open plenum for plenum return cases. An orifice resistance was placed in damper locations and zonal airflow rates were balanced to ± 0.5 cfm of intended values. Constant volume fans were placed in the duct system to simulate supply, return, and outdoor air fans.

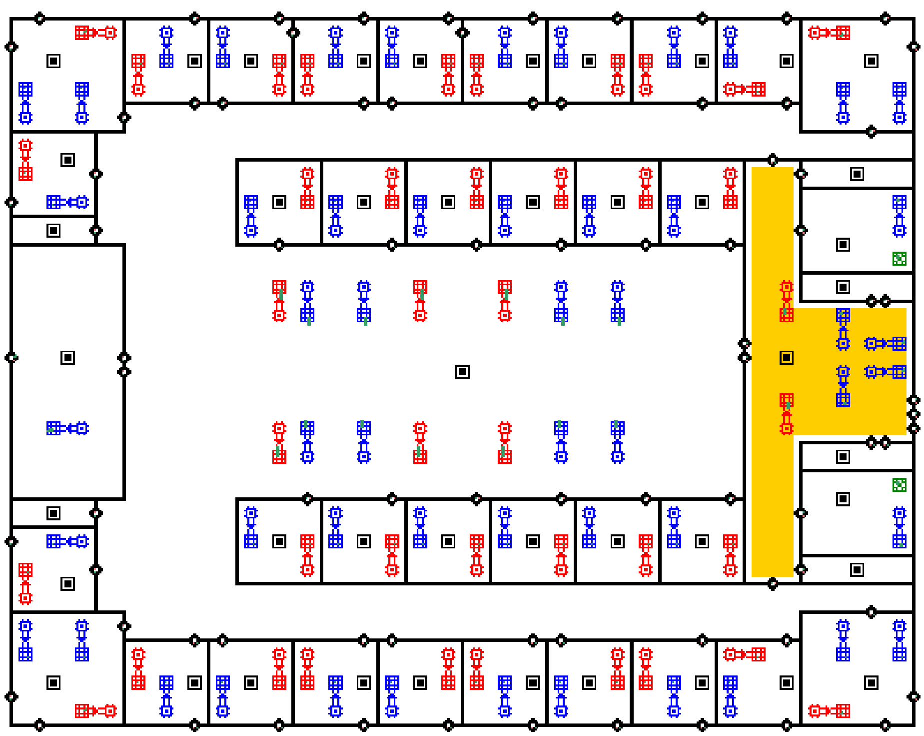


Figure 3-14: Multizone model representation of 1st floor of Hypothetical Office Building

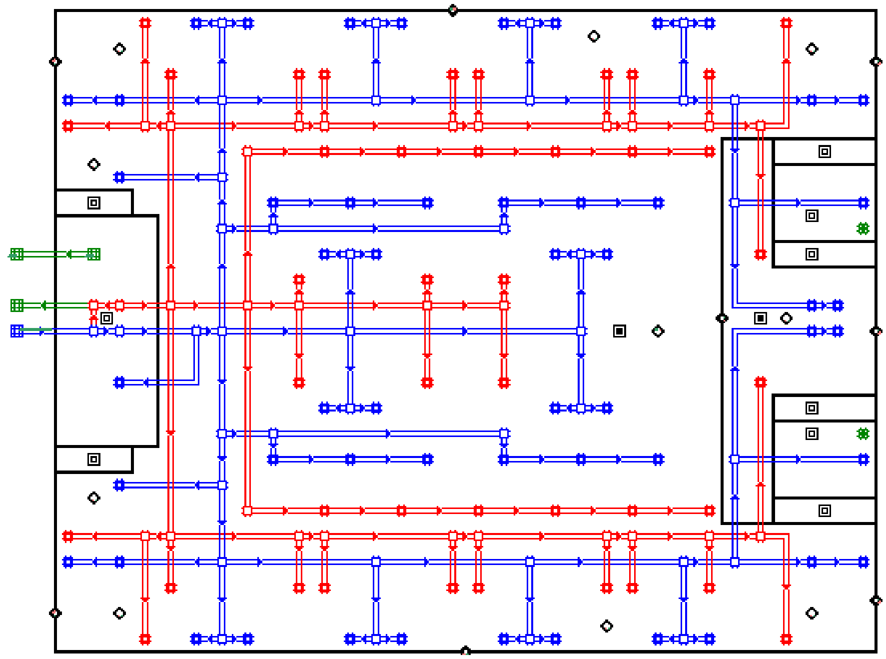


Figure 3-15: Multizone model representation of Hypothetical Office Building with ducted return

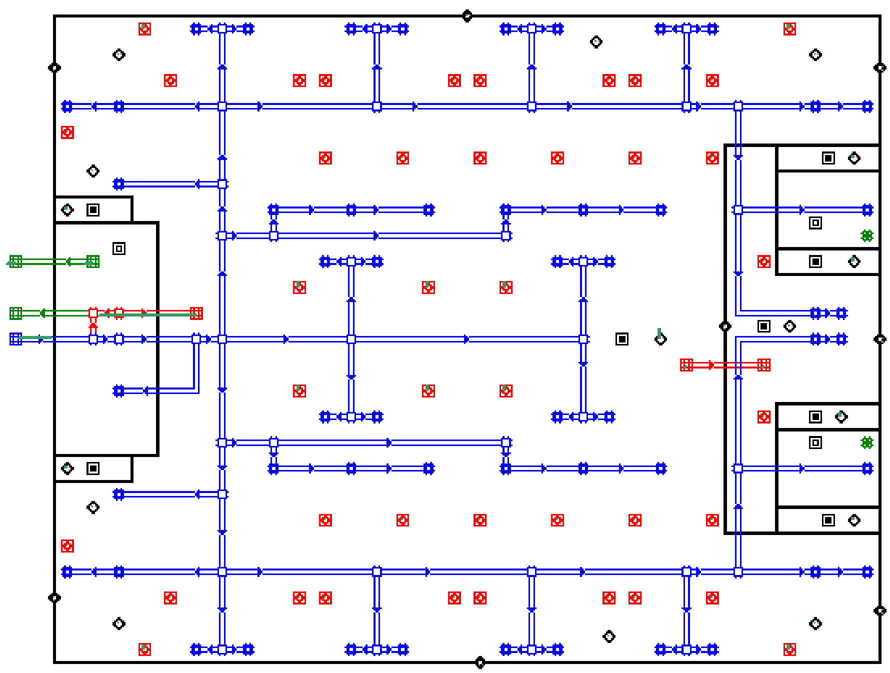


Figure 3-16: Multizone model representation of Hypothetical Office Building with plenum return

Parametric Matrix

A parametric matrix, seen in Table 3-4, was developed to isolate the impact of individual parameters on contaminant dispersal. Building and site parameters, such as climate, envelope air tightness and return air system type, and HVAC parameters, such as HVAC system type, zoning, and duct leakage, were varied and the results were compared to the base case to assess the impact of each parameter on inter-zonal contaminant transfer, inter-zonal airflow and moisture intrusion. The base building was defined as a pressurized building operating in neutral weather with average envelope tightness, floor-by-floor zoning, and ASHRAE recommended levels of duct leakage. Since CONTAM is a multizone modeling program without the ability to couple thermal and airflow calculations, constant zonal airflow rates were used to simulate a VAV system in steady-state operation. Buildings operate at part load conditions for the majority of the year, so zonal airflow rates of 0.5 cfm/ft^2 for part load conditions arising from neutral weather were used for the majority of the parametric runs. However, design heating and cooling zonal airflows were used to compare contaminant dispersal at design conditions. Airflow rates at design cooling and heating conditions were assumed to be 1.0 cfm/ft^2 and 0.35 cfm/ft^2, respectively. Outdoor airflow rates were held constant, at 0.2 cfm/ft^2 for each simulation.

Table 3-4: Parametric Matrix – Hypothetical Office Building

Focus Parameter	Building Characteristics									HVAC Characteristics											
	Climate			Envelope			Return System Type			HVAC Zoning				HVAC System		Air Balance		Duct Leakage			
	Neutral	Summer	Winter	Average	Tight	Leaky	Ducted	Plenum	Plenum with FPB	Floor-by-Floor	Perimeter/Core	Single Zone	Isolated Lobby	Steady State VAV	DOAS	Pressurized	Balanced	ASHRAE Fundamentals	Leaky	Water Vapor	Lobby Release - Generic Gas
Base Case	X			X			X			X				X		X		X			X
	X			X				X		X				X		X		X			X
	X			X					X	X				X		X		X			X
	X			X			X			X					X	X		X			X
Climate		X		X			X			X				X		X		X			X
		X		X				X		X				X		X		X			X
			X	X			X			X				X		X		X			X
			X	X				X		X				X		X		X			X
Envelope	X				X		X			X				X		X		X			X
	X				X			X		X				X		X		X			X
	X					X	X			X				X		X		X			X
	X					X		X		X				X		X		X			X
Zoning	X			X			X				X			X		X		X			X
	X			X				X			X			X		X		X			X
	X			X			X					X		X		X		X			X
	X			X				X				X		X		X		X			X
	X			X			X						X	X		X		X			X
	X			X				X					X	X		X		X			X
Leakage	X			X			X			X				X		X			X		X
	X			X				X		X				X		X			X		X

Table 3-4 continued: Parametric Matrix – Hypothetical Office Building

Focus Parameter	Building Characteristics									HVAC Characteristics											
	Climate			Envelope			Return System Type			HVAC Zoning				HVAC System		Air Balance		Duct Leakage			
	Neutral	Summer	Winter	Average	Tight	Leaky	Ducted	Plenum	Plenum with FPB	Floor-by-Floor	Perimeter/Core	Single Zone	Isolated Lobby	Steady State VAV	DOAS	Pressurized	Balanced	ASHRAE Recommended	Leaky	Water Vapor	Lobby Release - Generic Gas
Stack Effect			X	X			X			X				X		X		X			X
			X	X				X		X				X		X		X			X
Moisture Instrusion		X		X			X			X				X		X		X		X	
		X		X				X		X				X		X		X		X	
			X	X			X			X				X		X		X		X	
			X	X				X		X				X		X		X		X	
		X		X			X			X				X			X	X		X	
		X		X				X		X				X			X	X		X	
			X	X			X			X				X			X	X		X	
			X	X				X		X				X			X	X		X	
		X		X			X			X				X		X		X		X	
		X		X				X		X				X		X		X		X	
			X	X			X			X				X		X		X		X	
			X	X				X		X				X		X		X		X	
		X		X			X			X				X			X	X		X	
		X		X				X		X				X			X	X		X	
			X	X			X			X				X			X	X		X	
			X	X				X		X				X			X	X		X	

Chapter 4

RESULTS – LABORATORY EXPERIMENTS

The literature lacks experimental data quantifying the impact of return air system performance on building energy consumption and lacks studies comparing return air system resistance to an accidental spill or intentional CBR attack. Laboratory experiments were conducted to investigate the impact of different air return methods on IAQ and CBR agent dispersion resistance under controlled conditions in a well instrumented test facility. Return air strategies in the scope of work include overhead ducted and plenum return air systems and plenum return system with parallel fan powered VAV boxes.

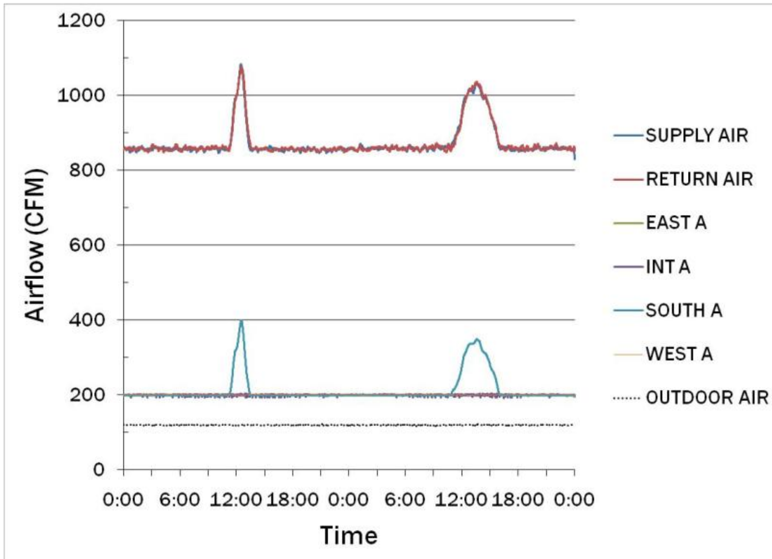
Test Room Experiments

The Iowa Energy Center Energy Resource Station (Lee *et al.* 1998, Price and Smith 2000) was used to conduct experiments comparing ducted and plenum return air systems. Since the Energy Resource Station (ERS) test room facilities allow simultaneous testing of two full scale building systems with identical thermal loads, side-by-side controlled experiments were conducted comparing the impact of return air system performance on AHU air flows and building pressurization.

Winter Test 1.1 - Differential Pressure Measurements

Along with supply, return and outdoor air measurements, VAV airflow measurements were logged for each Test Room VAV box for AHUs A and B. Figure 4-1 shows airflow measurements for AHU A with ducted return and AHU B with plenum return during Winter Test 1.1 with balanced airflow. Since an internal thermal load was used to simulate moderately active work in the South Test Rooms, the VAV airflow for South A and South B varied from the minimum box airflow of 200 cfm to approximately 400 cfm. The remaining rooms remained at their minimum box airflows for the entire test.

Figure 4-2 shows exterior differential pressure measurements w.r.t. the Media Center for ducted and plenum return systems during Winter Test 1.1 at balanced airflow. Even though the Test Room AHUs operated with balanced supply and return air, the building is pressurized by the AHU serving the General Service Area. The exterior differential pressure at the south wall varied from 0.03 in. w.g. to 0.07 in. w.g. and was higher than other exterior walls. Exterior differential pressure at the east and north walls tracked each other and was essentially equal for the balanced portion of Test 1.1 and with the exception of the West wall, the building was at positive pressures w.r.t. the exterior. The exterior differential pressure at the west wall was typically lower than the rest of the exterior walls and at one point was near neutral w.r.t. the Media Center.



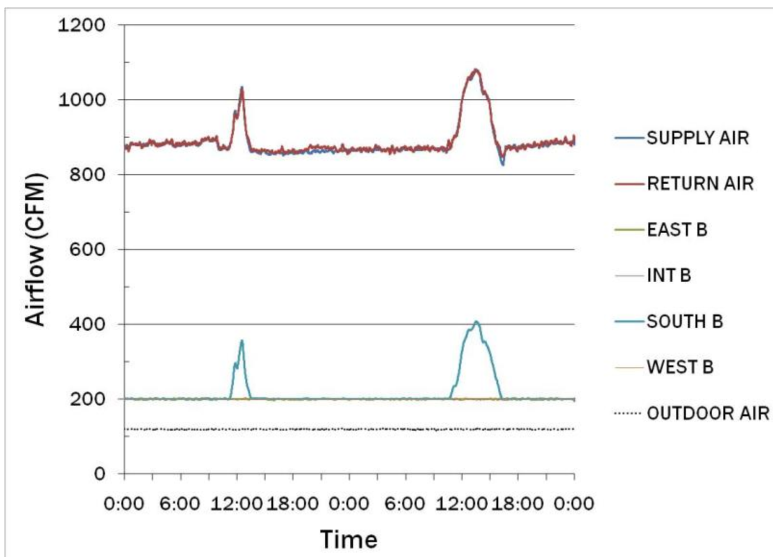


Figure 4-1: Airflow measurements for AHU A (ducted) & B (plenum) – Test 1.1 at balanced airflow

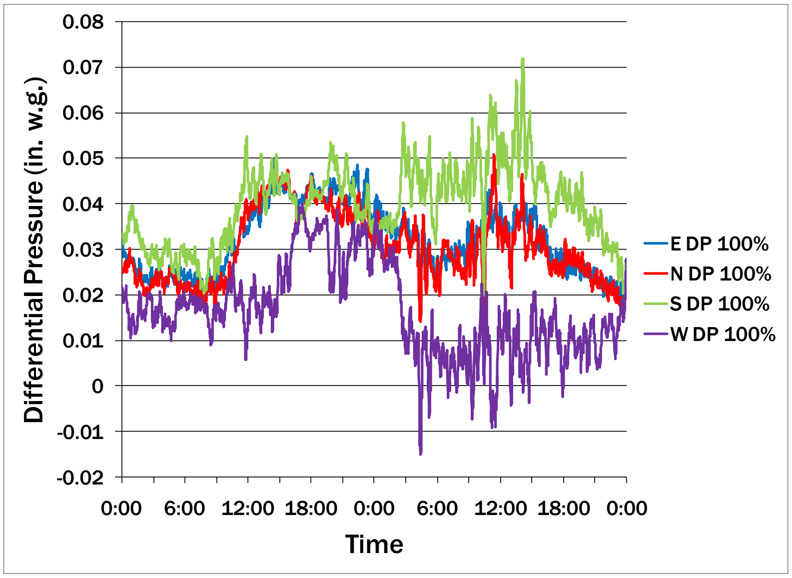


Figure 4-2: Exterior differential pressure (Media Center w.r.t. Exterior) – Test 1.1 at balanced airflow

Measured Test Room differential pressure during Winter Test 1.1, seen in Figure 4-3, was significantly different for ducted and plenum return systems. Test Room differential pressure w.r.t. the Media Center increased to 0.05 in. w.g. in South Test Room with ducted return, compared to 0.02 in. w.g. with plenum return. When the differential pressure in South Test Room with ducted return was 0.05 in. w.g., differential pressure w.r.t. the Media Center in West and East ducted Test Rooms was - 0.04 in. w.g, indicating positive pressurization in the South Test Room A and negative pressurization in the West and East Test Rooms. West and East Test Rooms with plenum return system (AHU B) also saw negative differential pressures w.r.t the Media Center when differential pressure in South B Test Room increased to 0.02 in. w.g., but the fluctuations were not as severe as with the Test Rooms with ducted return. Pressurization w.r.t. the Media Center presumably results from an increase in supply airflow to the room without an increase in return airflow. Even though supply and return airflow is balanced at the AHU, as seen in Figure 4-1, supply and return zonal airflows are not balanced in Test Rooms. At design airflows, both return air systems should preserve pressurization. With ducted return, zonal return airflow cannot track supply airflow changing at the VAV box, so the AHU draws equally from each Test Room, so Test Room pressurization varies more drastically. With plenum return, return airflow is presumably based on the zonal airflow, not the AHU return airflow, so Test Rooms are not pressurized and depressurized as VAV airflow changes.

To investigate the impact of return air imbalances on space pressurization for ducted and plenum return, return airflow was set at 80%, 100% and 120% of supply airflow at each AHU. Figure 4-4 and Figure 4-5 show impact of return air imbalance on Test Room differential pressure w.r.t. the Media Center for ducted return and plenum return during Winter Test 1.1. Please note that direct comparisons of differential pressures are not possible since tests investigating the impact of return air balance were conducted on separate days. However it is possible to draw qualitative comparisons of the changes in differential pressure for each return air fraction from overnight differential pressures.

Test Room differential pressure in rooms with ducted return was influenced by return air balance to a greater extent than rooms with plenum return. With ducted return, South Test Room differential pressure w.r.t. the Media Center increased to 0.07 in. w.g. at 80% supply airflow, compared to 0.05 in. w.g. at 80% supply airflow with plenum return. The same was true at all return air fractions: South Test Room A with ducted return was pressurized to a greater extent than with South Test Room B with plenum return. When space pressurization changed in South Test Room A with ducted return, East and West Test Room A space pressurization was influenced for all return air fractions. At 120% supply airflow, when South A Test Room with ducted return was pressurized to 0.03 in. w.g. w.r.t. the Media Center, East and West Test Rooms A with ducted return were depressurized to – 0.05 in. w.g. and – 0.07 in. w.g. respectively. The same relationship held true for 100% supply airflow: when South Test Room A with ducted return was pressurized to 0.05 in. w.g. w.r.t. the Media Center, East and West Test Rooms A with ducted return were depressurized to 0.04 in. w.g. w.r.t. the Media Center. However, at 80% the East and West Test Rooms A with ducted return were not depressurized significantly when supply airflow increased in South Test Room. The difference in supply and return airflow was large enough to negate any depressurization caused by ducted return's tendency to draw air in proportion to return air balance at design conditions. With plenum return, at return air fractions of 80% and 100%, East and West Test Rooms B were not depressurized significantly when VAV airflow in South Test Room B increased. Presumably return air is able to vary through an open return grille responding to differential pressure.

Using the differential pressure measurement at each wall (w.r.t. the Exterior) and the measured differential pressure measurement for each test room (w.r.t. the Media Center) measured in Figure 3-7, Test Room and Test Plenum differential pressure was calculated (w.r.t. the Exterior) as seen in Figure 3-8. Figure 4-6 compares Test Room differential pressure w.r.t. the Exterior for Test Rooms A with ducted return and Test Rooms B with plenum return for Winter Test 1.1 at balanced airflow. As the VAV air flows in the South Test Rooms increase from their minimum set points, the rooms become pressurized beyond the pressurization from the General Service Area AHU. As with the South Test Room differential pressures w.r.t. the Media Center, South Test Room A with ducted return was at a higher pressure w.r.t. the Exterior than South Test Room B with plenum return. In the East and West Test Rooms, the A Test Rooms with ducted return were at a lower pressure w.r.t. the Exterior than the B Test Rooms with plenum return. Figure 4-7 compares Test Plenum differential pressure w.r.t. the Exterior for ducted return and plenum return for Winter Test 1.1 at balanced airflow. Test Plenum differential pressure w.r.t. the Exterior followed the same relationship as with the Test Room differential pressure w.r.t. the Exterior. South Test Plenum A with ducted return was at a greater differential pressure w.r.t. the Exterior than South Test Plenum B with plenum return, and East and West Test Plenum A with ducted return was at a lower pressure w.r.t. the Exterior than East and West Test

Plenum B with plenum return. The relationship is in consistent with South Test Room A with ducted return being pressurized to a greater extent than South B with plenum return, and East and West A with ducted return being depressurized to a greater extent than East and West Test Rooms B with plenum return.

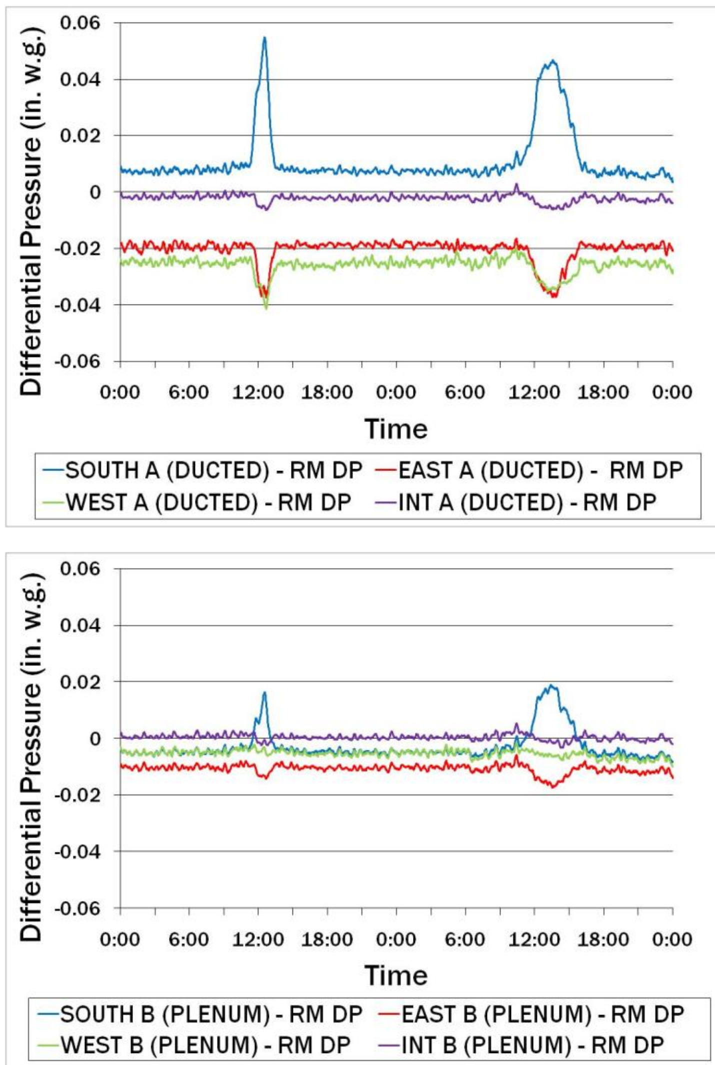


Figure 4-3: Test Room differential pressure (w.r.t. Media Center) – Test 1.1 at balanced airflow

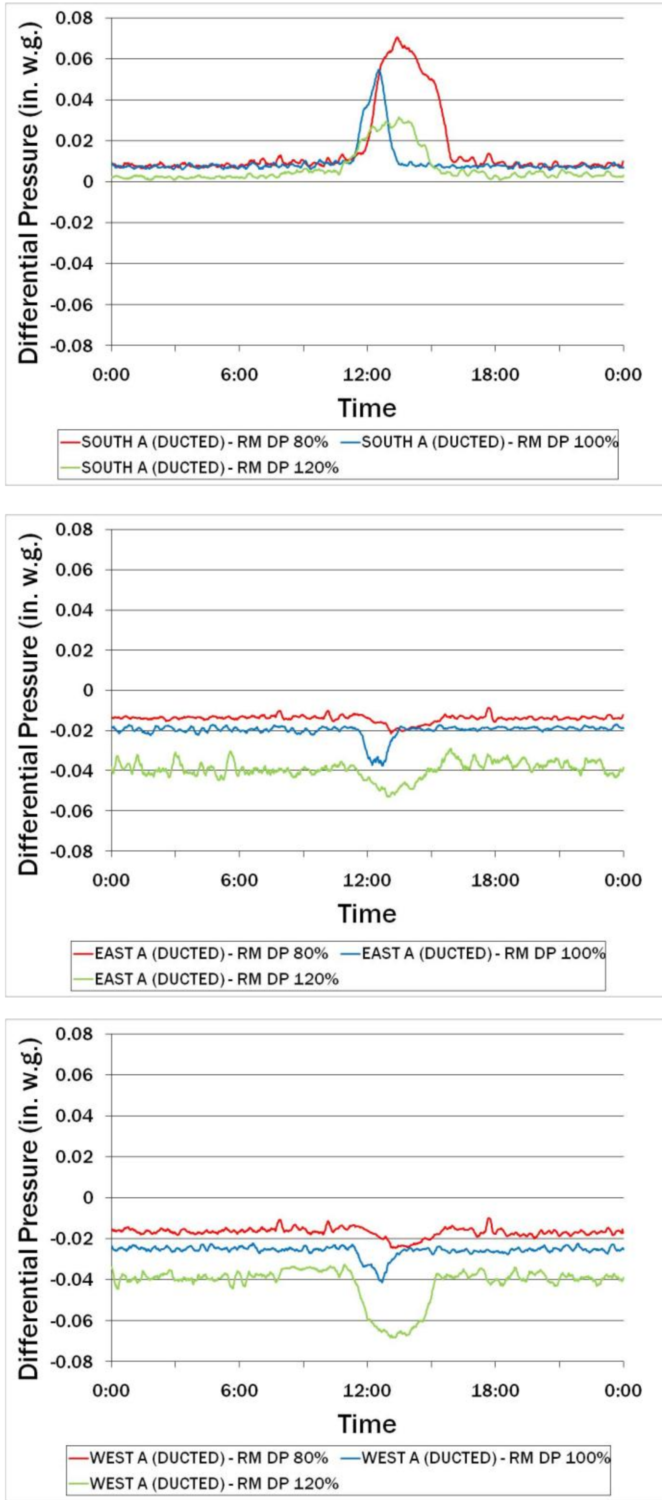


Figure 4-4: Impact of air balance on Test Room differential pressure (w.r.t. Media Center) with ducted return – Test 1.1

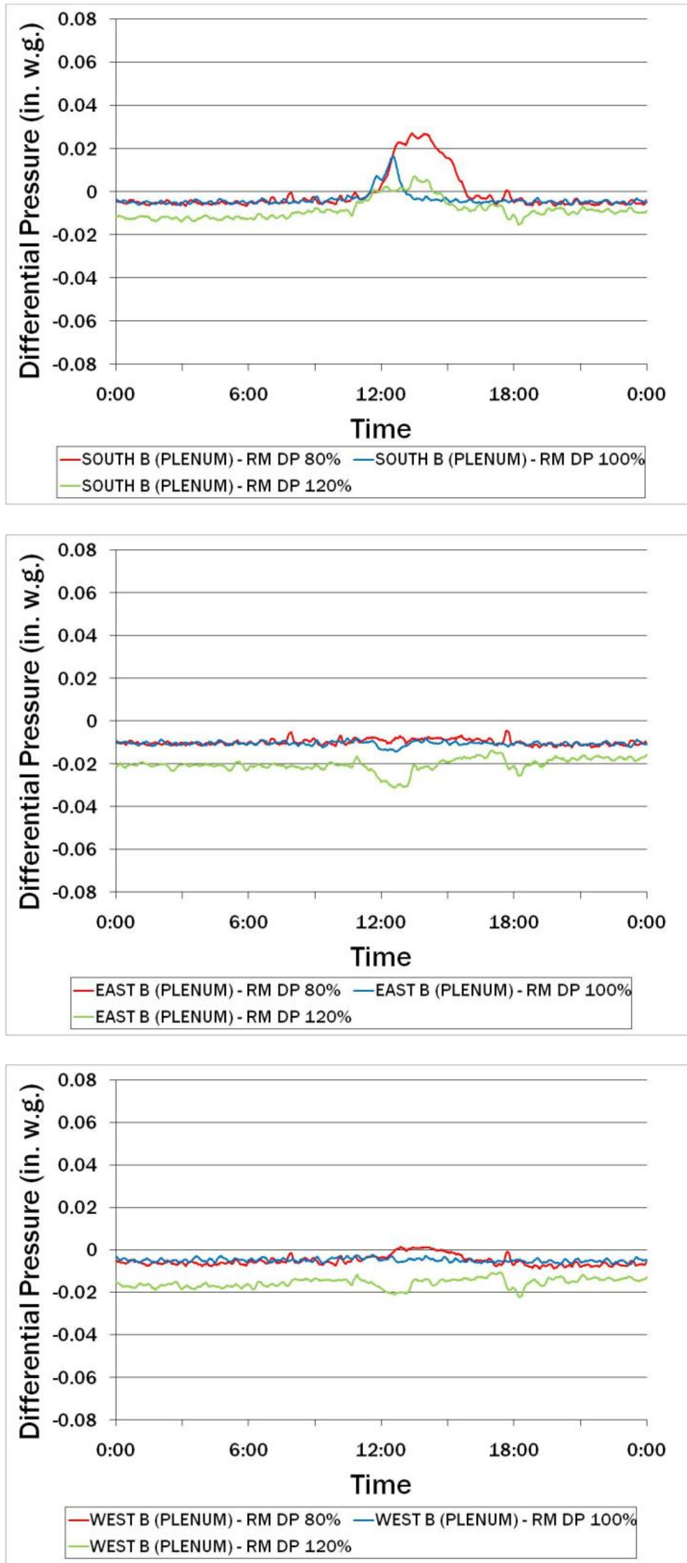


Figure 4-5: Impact of air balance on Test Room differential pressure (w.r.t. Media Center) with plenum return – Test 1.1

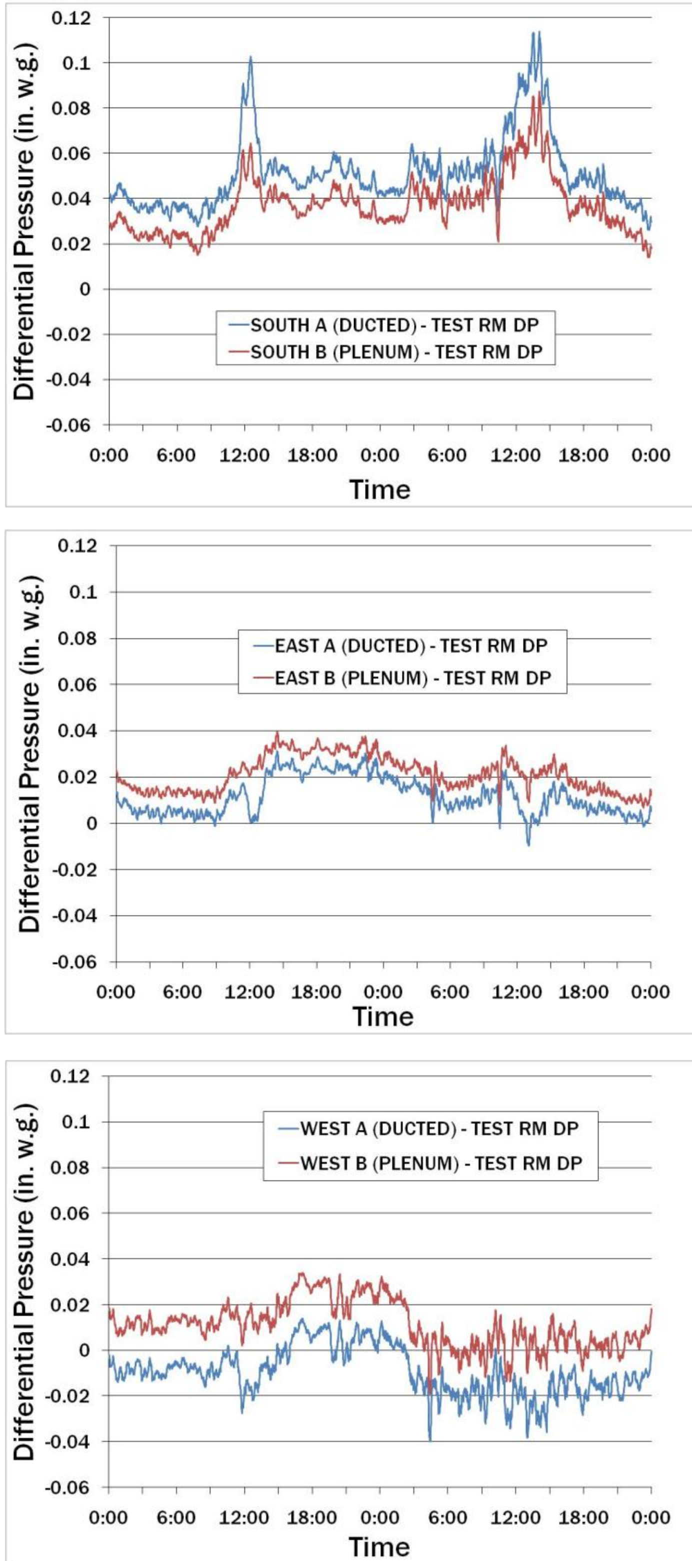


Figure 4-6: Test Room differential pressure (w.r.t Exterior) – Test 1.1 at balanced airflow

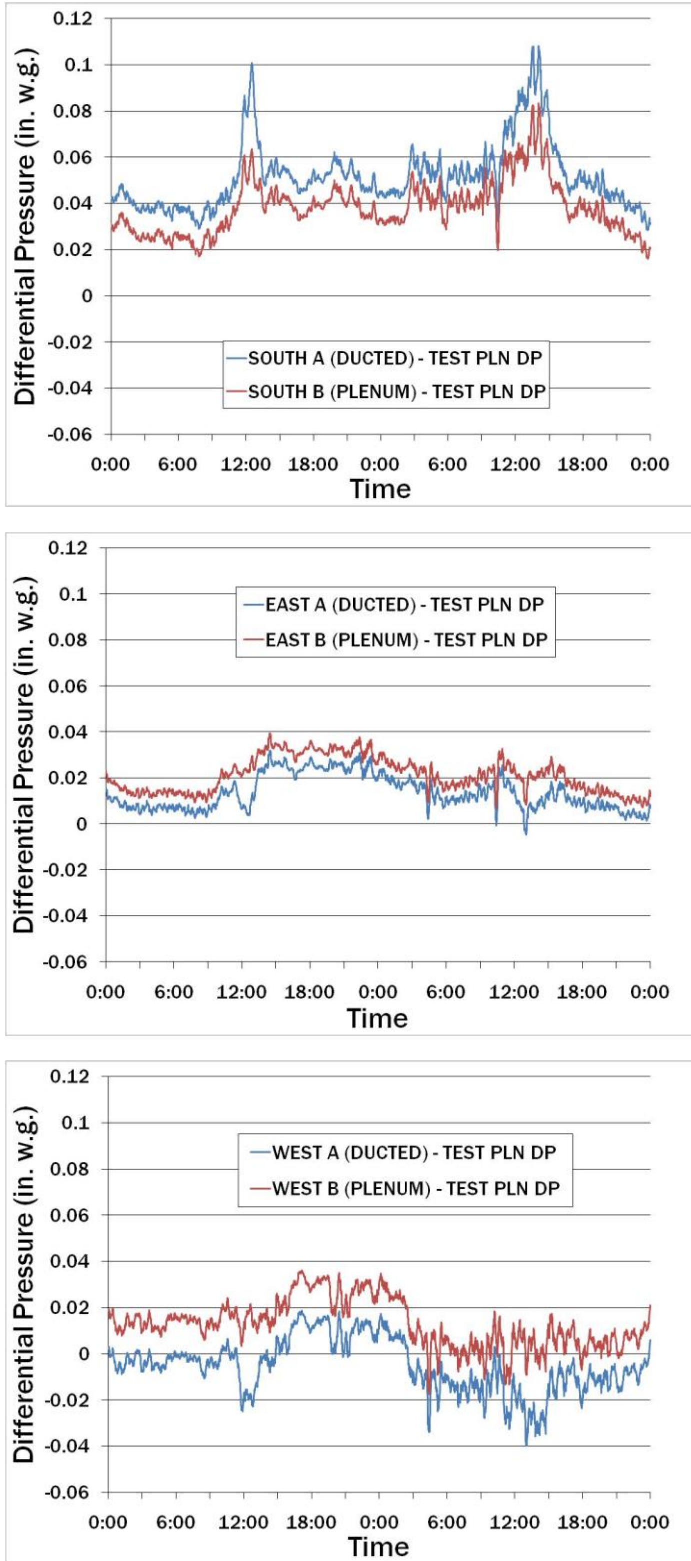


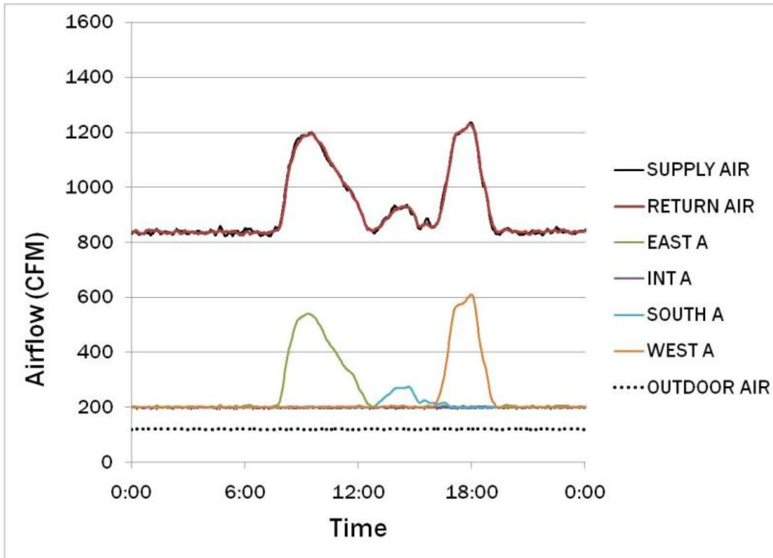
Figure 4-7: Test Room Plenum differential pressure (w.r.t. Exterior) – Test 1.1 at balanced airflow

Summer Test 2.1 - Differential Pressure Measurements

Figure 4-8 shows airflow measurements for AHU A with ducted return and AHU B with plenum return during Summer Test 2.1 for balanced airflow. In both cases, VAV airflow increases from the solar load in the East Test Rooms in the morning and West Test Rooms in the evening. However, VAV airflow increases in South Test Room A with ducted return and remains at the minimum set point of 200 cfm in South Test Room B with plenum return. With both ducted and plenum return, Interior Test Rooms A and B remain at their minimum VAV box airflows of 200 cfm.

Figure 4-9 shows exterior differential pressure measurements w.r.t. the Media Center for ducted and plenum return systems during Summer Test 2.1 at balanced conditions. Compared to Winter Test 1.1, the fluctuation of exterior differential pressure was smaller for Summer Test 2.1. The exterior differential pressure across all walls varied from 0.02 to - 0.01 in. w.g. for Test 2.1. Exterior differential pressure at all walls tracked each other. Since the exterior differential pressure w.r.t. the Media Center is nearly uniform across all walls, differences in pressure fields can be attributed to the impact of return air system rather than the impact of weather.

Figure 4-10 compares Test Room differential pressure w.r.t. the Media Center during Summer Test 2.1 for balanced airflow along with VAV airflows to each Test Room. For both ducted and plenum return, when all zonal airflows are at their minimum set points overnight, the Test Rooms are at equal pressurization w.r.t. the Media Center. As the VAV airflows change in the Test Rooms, the rooms become pressurized or depressurized w.r.t. the Media Center. Pressurization w.r.t. the Media Center presumably results from an increase in supply airflow to the room without an increase in return airflow. Even though supply and return airflow is balanced at the AHU, as seen in Figure 4-8, supply and return zonal airflows are not balanced in Test Rooms.



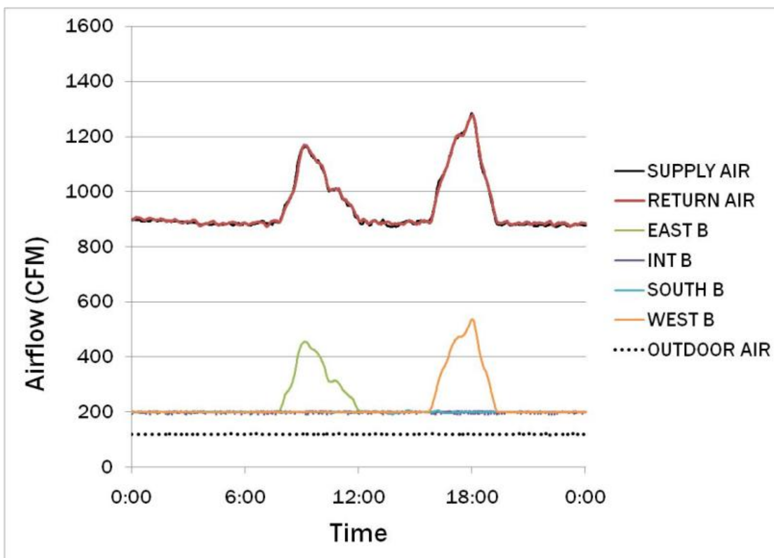


Figure 4-8: Airflow measurements for AHU A (ducted) and AHU B (plenum) – Test 2.1 at balanced airflow

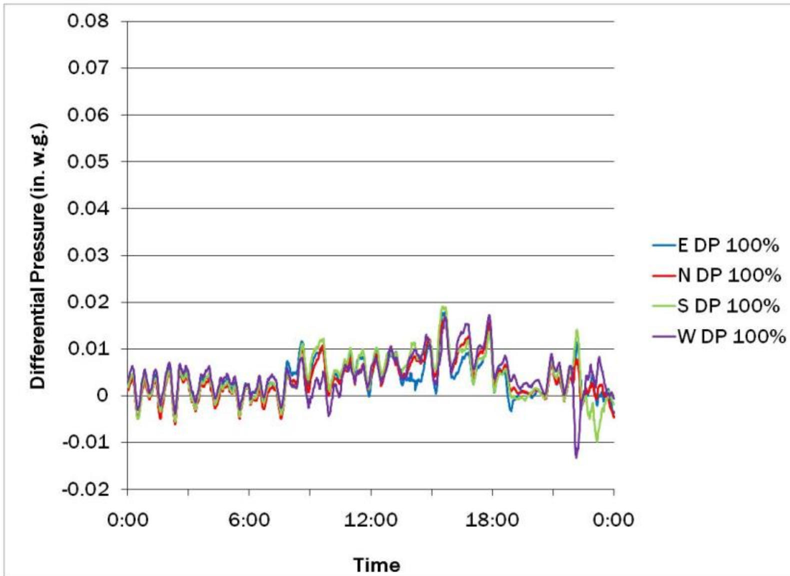


Figure 4-9: Exterior differential pressure (Media Center w.r.t. Exterior) – Test 2.1 at balanced airflow

As the VAV airflow in the East Test Rooms increased, East Test Room differential pressure w.r.t. the Media Center increased from nearly neutral to 0.04 in. w.g. with ducted return, compared to approximately 0.02 in. w.g. with plenum return. In West Test Room A with ducted return, differential pressure increased from nearly neutral to 0.05 in. w.g. compared an increase to 0.04 in. w.g. with plenum return. When the East Test Room with ducted return was at its highest differential pressure at 9:00 a.m. (pressurized w.r.t. the Media Center), the West Test Room with ducted return was at its lowest differential pressure of - 0.03 in. w.g. (depressurized w.r.t. the Media Center). However, with plenum return, West Test Room B differential pressure was nearly neutral as East Test Room B became pressurized w.r.t. the Media Center. As VAV airflow increased above the minimum set point in South Test Room A at 12:00 (with ducted return), the East and West Test Room differential pressure w.r.t. the Media Center decreased slightly. However, since zonal airflows were equal in East, West and South Test Rooms B (with plenum return) at 12:00, differential pressure in these spaces for this time period were nearly equal w.r.t. the Media Center.

Return air system did not impact Test Room differential pressure w.r.t. the Exterior as significantly as Test Room differential pressure w.r.t. the Media Center. Figure 4-11 compares Test Room differential pressure w.r.t. the Exterior during Summer Test 2.1 along with VAV airflows for ducted return and plenum return for balanced airflow. As East A and B VAV supply airflow increased, both East A and B were pressurized to approximately 0.04 in. w.g. w.r.t. the Exterior, and as West A and B VAV supply airflow increased, both West A and B Test Rooms were pressurized to approximately 0.06 in. w.g. w.r.t. the Exterior. Since the exterior walls are presumably tighter than interior walls, changes in Test Room pressure should impact differential pressure w.r.t. the Media Center more than differential pressure w.r.t. the Exterior. Figure 4-12 compares East and West Test Plenum differential pressure w.r.t. the Exterior for ducted and plenum return for Summer Test 2.1 with balanced airflow. Test Plenum differential pressure w.r.t. the Exterior is marginally higher for ducted return compared to plenum return in East and West Test Rooms, which is consistent with the hypothesis that ducted return does not balance return air at part load airflows.

Unlike Winter Test 1.1, during Summer Test 2.1 Test Room differential pressure w.r.t. the Media Center in rooms with ducted return and plenum return responded similarly to return air imbalance. Figure 4-13 and Figure 4-14 depict the impact of return air imbalance on Test Room differential pressure w.r.t. the Media Center for ducted and plenum return. As East Test Room VAV airflow increased to approximately 0.02 in. w.g. w.r.t. the Media Center for both return air systems and all return air fractions, South Test Rooms with both return air systems remained at near neutral pressure w.r.t. the Media Center for return air fractions of 80% and 100%, and decreased to – 0.04 in. w.g. for a return air fraction of 120%. Return air imbalance did impact West Test Room differential pressure w.r.t. the Media Center differently for ducted return and plenum return. As VAV supply airflow increase in West Test Rooms, West Test Room differential pressure w.r.t. the Media Center increased to 0.17 in. w.g. and 0.16 in. w.g. for 80% supply air flow, 0.14 in. w.g. and 0.13 in. w.g. for 100% supply airflow and 0.10 in. w.g. and 0.10 in. w.g. for ducted return and plenum return, respectively.

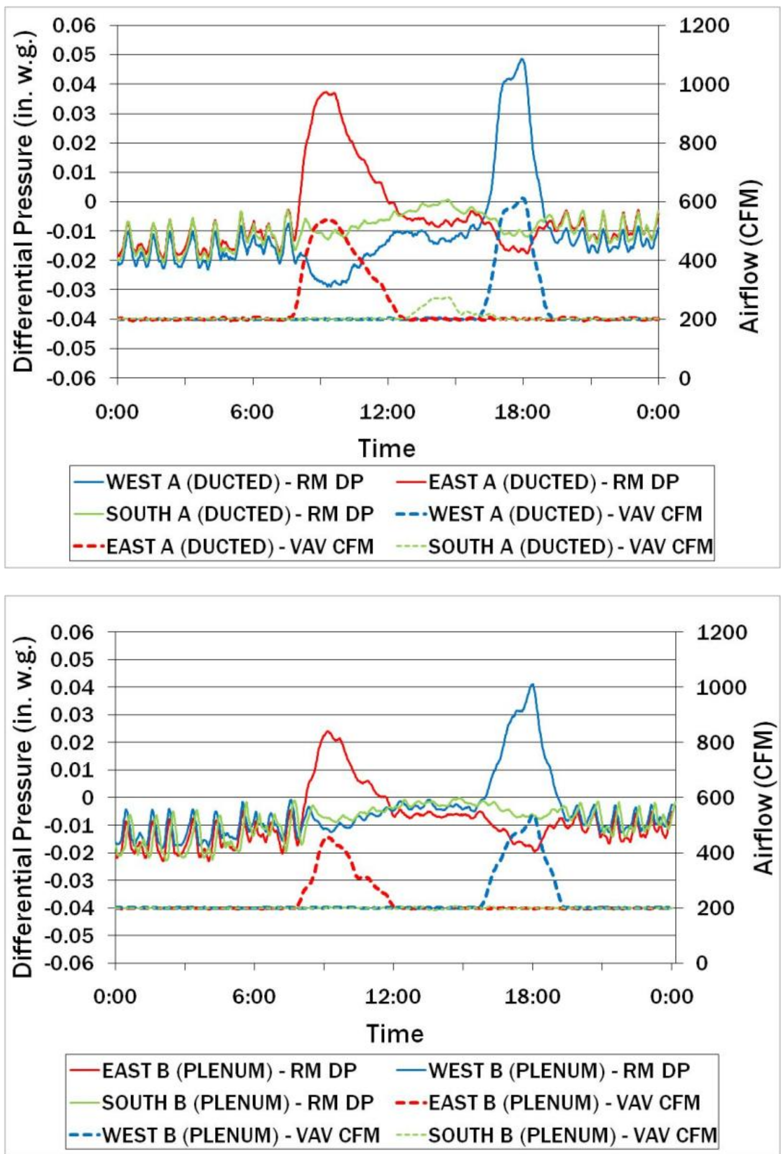
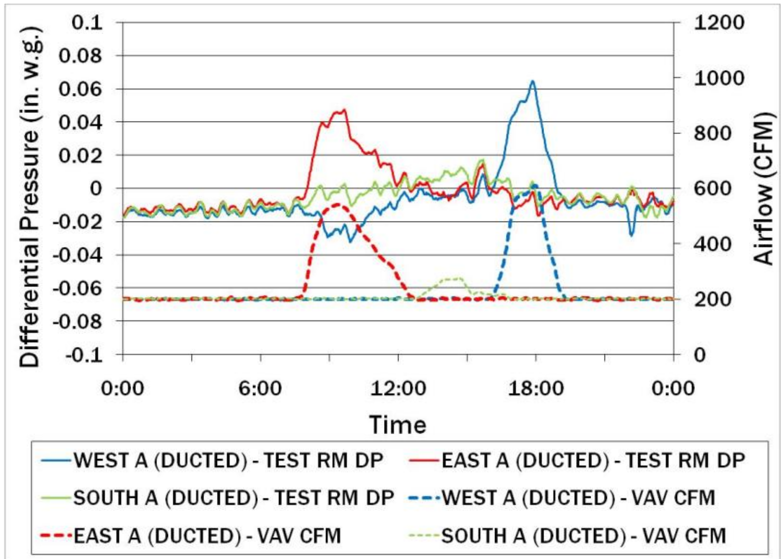


Figure 4-10: Test Room differential pressure (w.r.t. Media Center) and VAV CFM – Test 2.1 at balanced airflow with ducted return



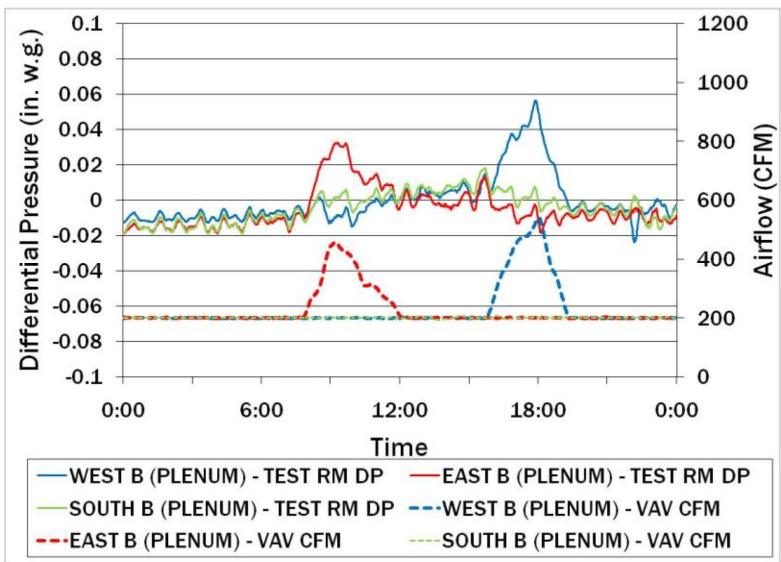


Figure 4-11: Test Room differential pressure (w.r.t. Exterior) and VAV CFM – Test 2.1 at balanced airflow with plenum return

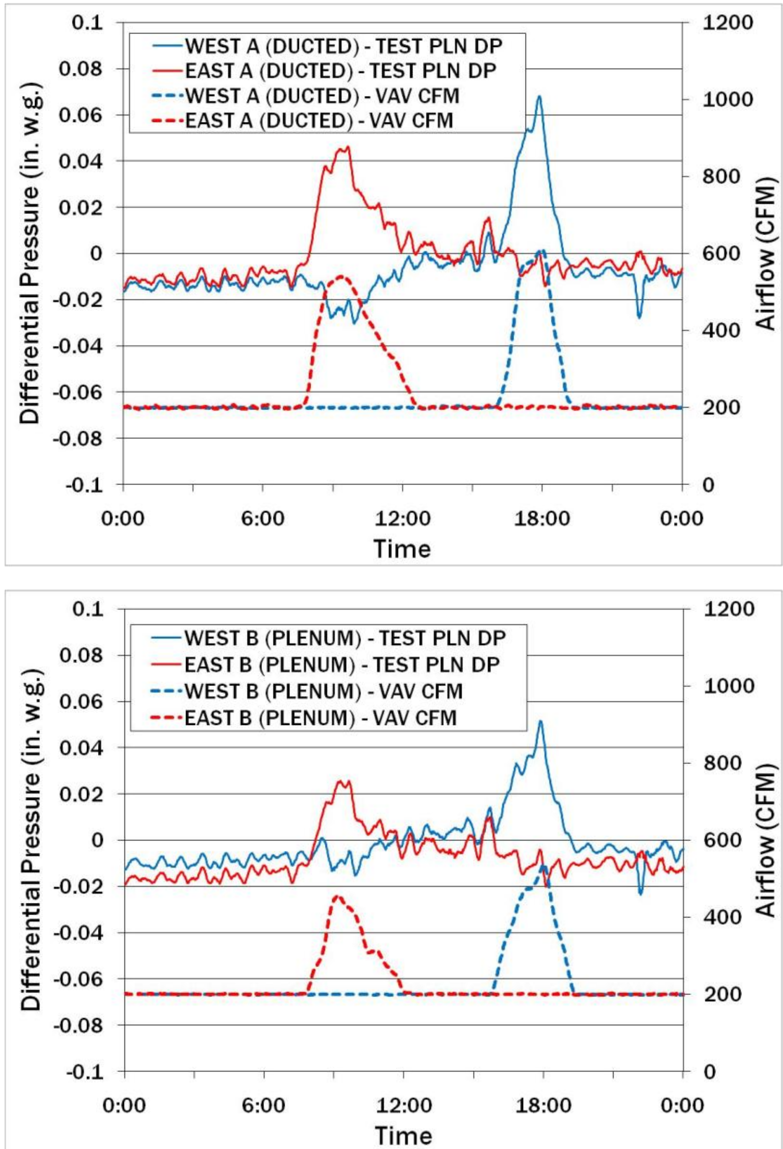


Figure 4-12: Comparison of Test Room differential pressure (w.r.t. Exterior) and VAV CFM – Test 2.1 at balanced airflow

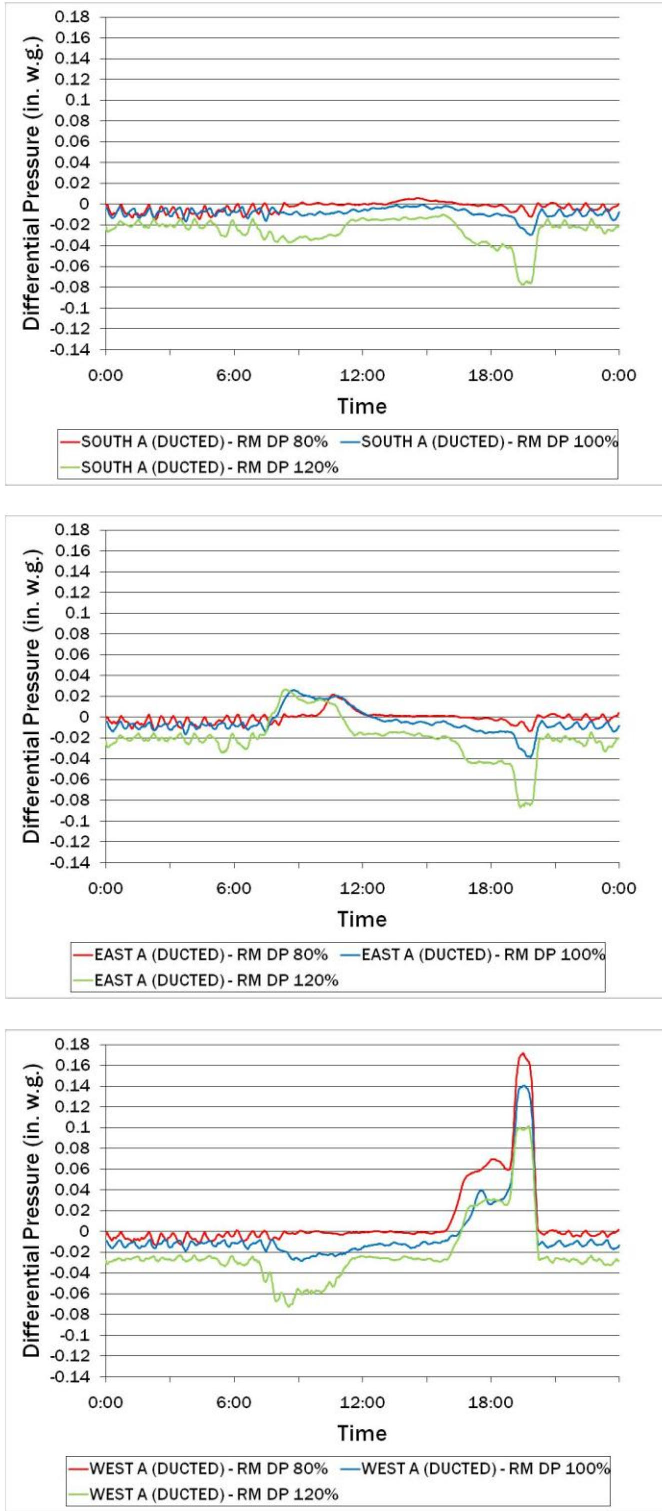


Figure 4-13: Impact of air balance on Test Room differential pressure (w.r.t. Media Center) with ducted return – Test 2.1

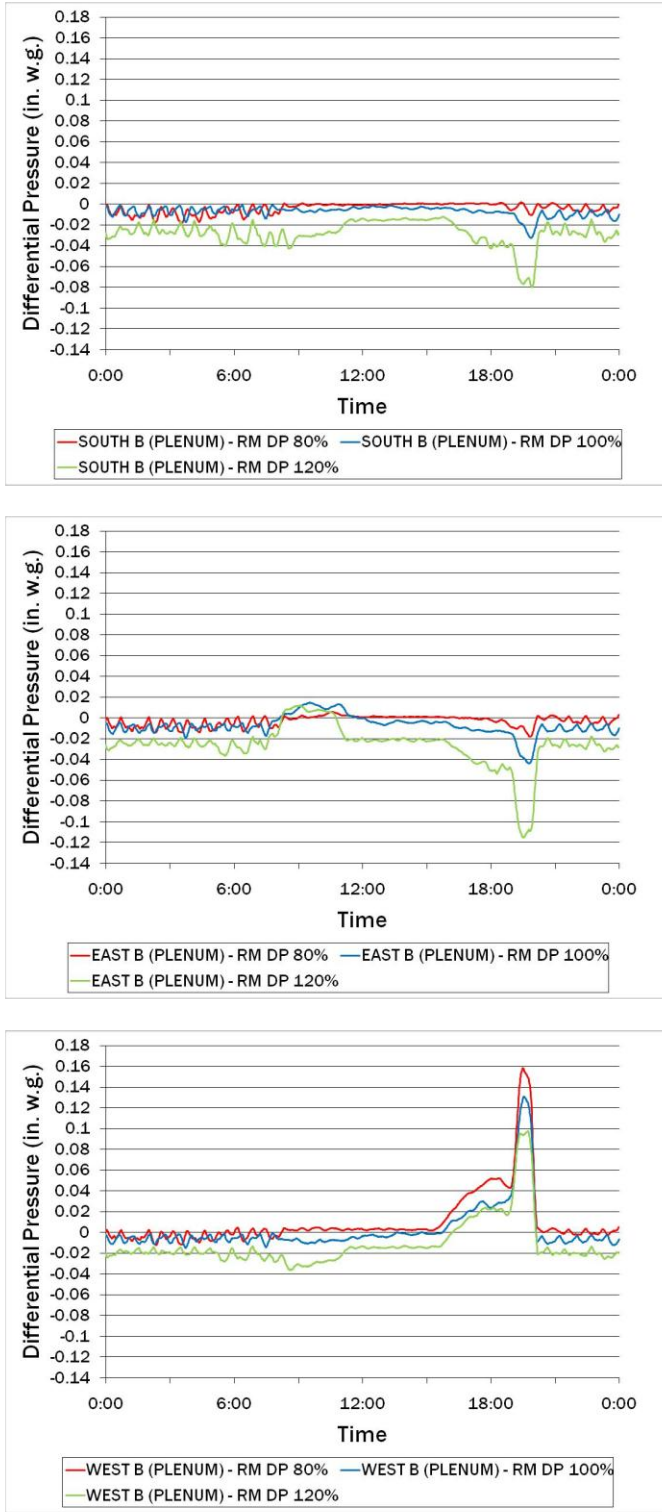


Figure 4-14: Impact of air balance on Test Room differential pressure (w.r.t. Media Center) with plenum return – Test 2.1

Discussion and Conclusions

The balanced portion of Winter Test 1.1 indicates that return airflow in ducted return systems does not respond to VAV supply airflow as it does in plenum return systems. Hydeman *et al.* (2003) assert that in VAV applications plenum returns self balance as supply air flow decreases at part load. With ducted return systems, return air flow does not track supply air flow changes to the zone and as a result, room pressurizations change in response to changes in supply air flow.

South Test Room with ducted return was pressurized w.r.t. the Media Center to a greater extent than South Test Room with plenum return, and East and West Test Rooms with ducted return were depressurized w.r.t. the Media Center to a greater extent than East and West Test Rooms with plenum return. During Winter Test 1.1, Test Room differential pressure in rooms with ducted return was influenced by return air balance to a greater extent than rooms with plenum return. Presumably with plenum return, return air is able to vary through an open return grille responding to differential pressure across the return grille, whereas with ducted return, return air is balanced for design conditions and is not able to vary in response to zonal supply airflow.

The balanced portion of Summer Test 2.1 is consistent with the hypothesis drawn from the results of Winter Test 1.1. As VAV supply airflow to a room increases with ducted return, the room becomes pressurized to a greater extent than with plenum return. For example, when VAV airflow increased in the East Test Rooms, East Test Room A with ducted return was pressurized w.r.t. the Media Center to a greater extent than East Test Room B with plenum return. As VAV airflow increases in a room, other rooms at their minimum VAV airflows depressurized to a greater extent with ducted return than with plenum return. When VAV airflow increased in East Test Rooms, West Test Room A with ducted return was depressurized more significantly than West Test Room B with plenum return. During Summer Test 2.1, return air balance had less of an impact on Test Room differential pressure. It is possible that the return air grilles in the Test Rooms with plenum return were not sized correctly to allow zonal return air to respond to Test Room and Test Plenum pressurization in Summer Test 2.1, most notably in the West Test Room. If this was the case, return air through return grilles with plenum return would be restricted which would result in Test Room pressurization.

General Service Area Tracer Gas Tests

Tracer gas releases were conducted in the Iowa Energy Center to compare resistance of ducted and plenum return air systems to interzonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space.

Tracer Gas Test Results with no Release Zone Mixing – Test 1.5

In Test 1.5, for each release zone, tests were performed to investigate the impact of parallel fan-powered VAV boxes on tracer dispersion in a plenum return system. VAV box fans were either all on or all off. Because they inject return air from the plenum directly into occupied space, fan-powered boxes have the potential to increase local space concentrations. The effect should be non-uniform, with fans that lie in the path of higher concentration return air creating a greater impact on space concentration.

Impact of Fan Powered Boxes with no Release Zone Mixing

Figure 4-15 shows transient room concentrations without release zone mixing for an Office release with parallel fan-powered boxes on and off. In each room, the peak CO_2 concentration with VAV box fans on is higher and occurs earlier than the peak CO_2 concentration with VAV box fans off. With VAV box fans on, the peak occurs roughly one hour after the release and the magnitude of the peak concentration in each room varies from 1000 ppm to 1400 ppm. With VAV box fans off, the peak occurs roughly four hours after the release and the magnitude of the peak concentration is nearly uniform at 800 to 900 ppm. With VAV box fans on, the Office concentration is out of range of the sensor for approximately 2 hours; however, with VAV box fans off the Office concentration is out of range of the sensor for more than 5 hours. Figure 4-16 shows transient plenum concentrations for the same Office release. As seen in Figure 3-10 and Figure 3-11, the Reception Plenum sensor (3), Media Center Plenum sensor (2), Open Office Plenum sensor (5) and the Break Room Plenum sensor (6) lie in the anticipated return air pathway for an Office release. Figure 4-16 confirms that fans lying in the return air pathway will have a greater impact on local space concentrations. In rooms not in the direct return air pathway from an Office release, i.e. the Computer Center or the West Classroom, tracer gas reaches the room via primary air only, which is indicated by the nearly equal space and plenum concentrations in those spaces. However, spaces in the return air pathway see greater increases in space concentration from higher concentration return air being injected into the space.

Figure 4-17 compares the total exposure (time integral of concentration) in different occupied spaces in the general services area without release zone mixing for an Office release with VAV box fans on and off. Results are presented in terms of "relative exposure", defined as the exposure with parallel fans on divided by the exposure with parallel fans off. Exposure results are not available for release zones since the concentration is out of range of the sensor for prolonged periods of time. Since VAV box fans serving the Media Center, Break Room, and Open Office, are directly in the return pathway from an Office release, the 15 minute exposures increase by 40%, 40%, and 55% respectively. In all spaces the 8 hour exposures with VAV box fans on and off are effectively equal. With VAV box fans on, the release zone concentration decays more rapidly since the box fan draws air from the plenum and depressurizes the plenum to a greater extent than with VAV box fans off. This increase in return air concentration delivered to the AHU Return causes a higher peak and faster decay in space concentrations throughout the building.

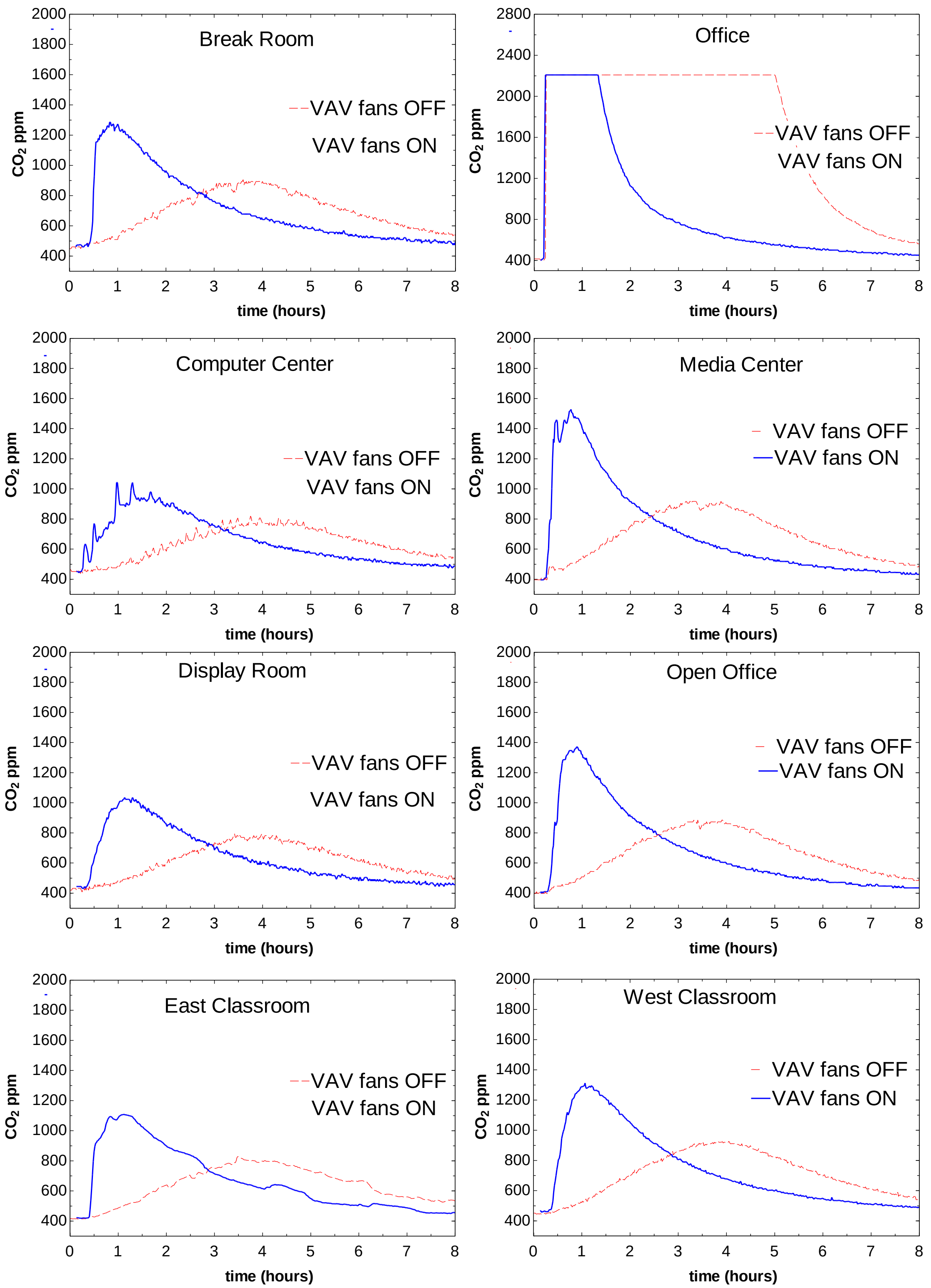


Figure 4-15: Room concentration with FPB on and off - Office release without release zone mixing

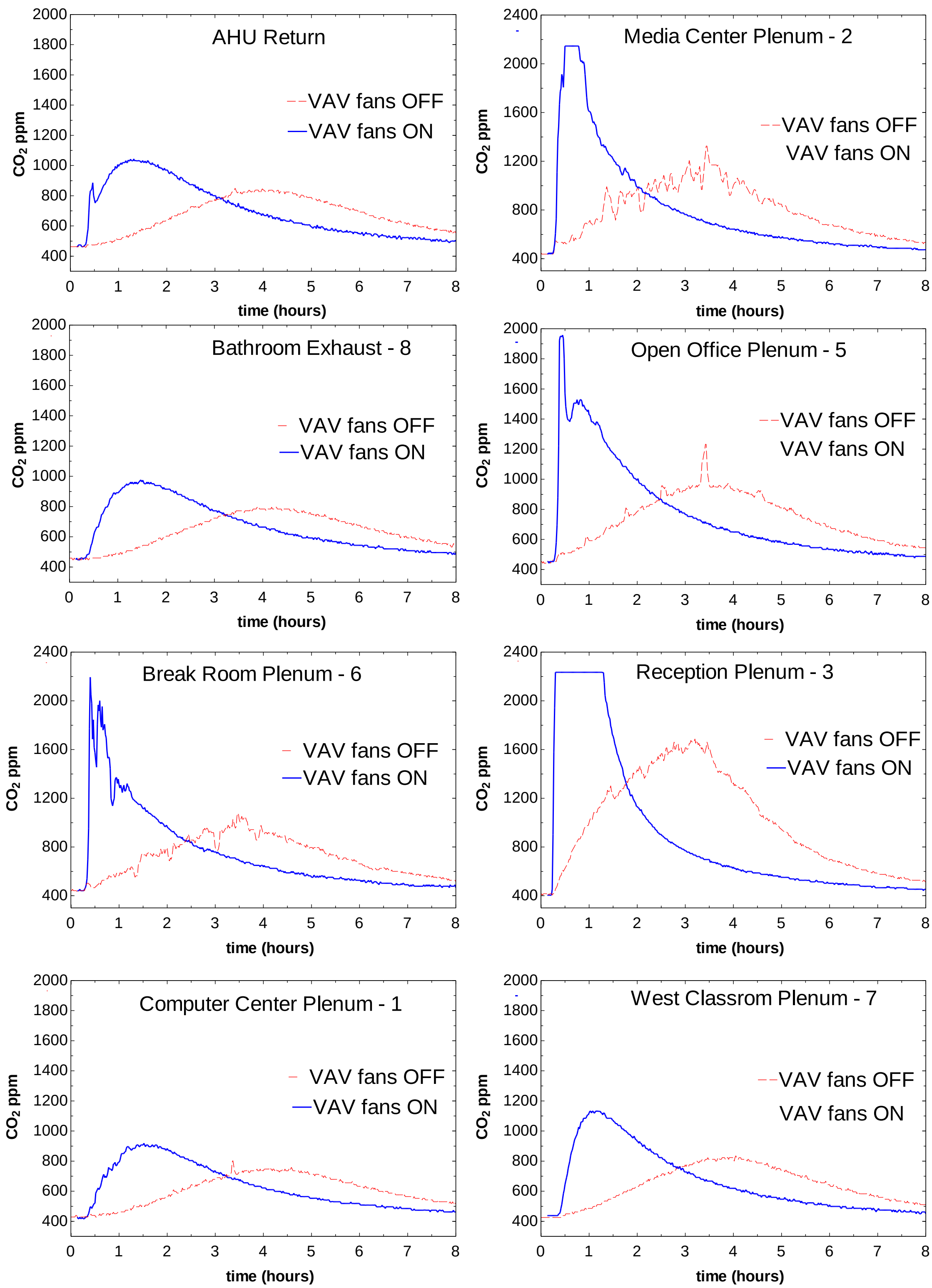


Figure 4-16: Plenum concentration with FPB on and off – Office release without release zone mixing

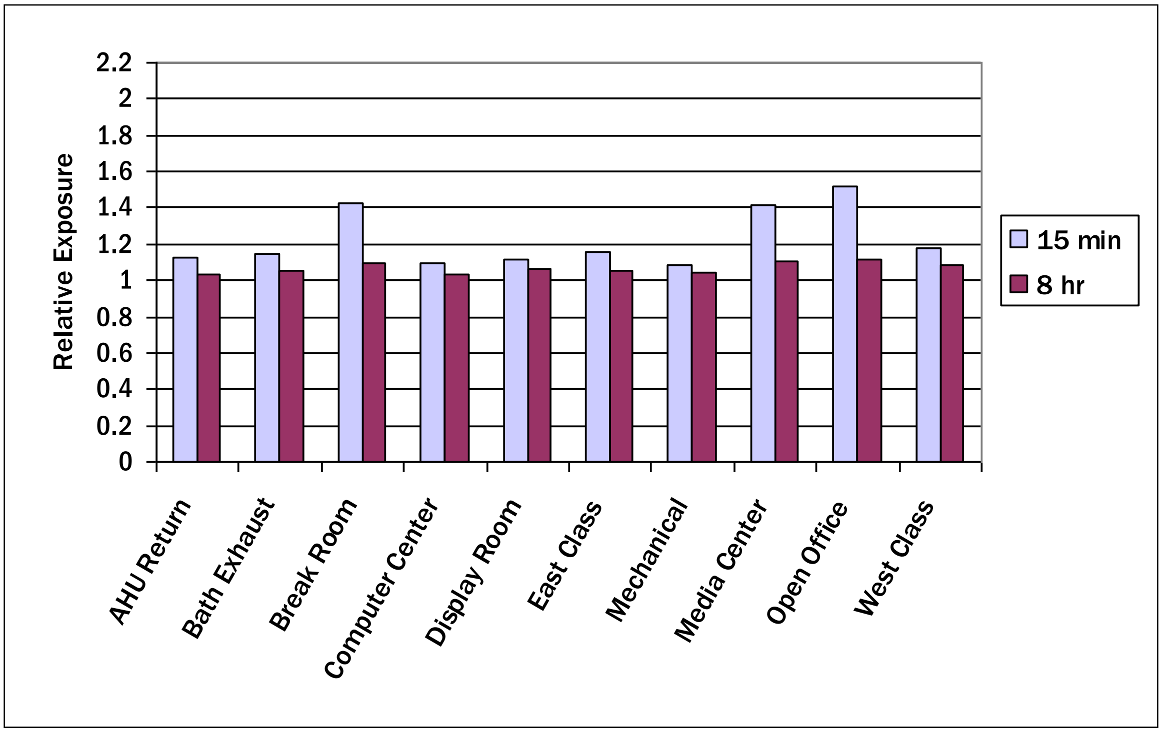


Figure 4-17: Exposure with FPB on relative to exposure with FPB off – Office release without release zone mixing

Figure 4-18 shows transient room concentrations without release zone mixing for a Display release with VAV box fans on and off. In each room, the peak CO_2 concentration with VAV box fans on is higher and occurs earlier than the peak CO_2 concentration with VAV box fans off. With VAV box fans on, the peak occurs within one hour after the release and the magnitude of the peak concentration in each room varies from 1000 ppm to 2000 ppm, compared to a peak of 800 to 900 ppm approximately 2 hours after the release. With VAV box fans on, the Display Room concentration is out of range of the sensor for approximately 30 minutes; however, with VAV box fans off the Display Room concentration is out of range of the sensor for 2 hours. Figure 4-19 shows transient plenum concentrations for the same Display Room release. As seen in Figure 3-10 and Figure 3-11 and, only the Display Room Plenum sensor (4) lies in the return pathway of a Display release. The VAV box fan serving the West Classroom, located near the

Display Room Plenum sensor (4), draws air from the high concentration return air and injects it into the space, increasing the concentration to 2000 ppm immediately following the release. The tracer short circuits the remaining VAV boxes in the plenum, reaches the AHU return inlet quickly and is delivered to spaces via primary air.

Figure 4-20 compares the total exposure (time integral of concentration) in different occupied spaces in the general services area without release zone mixing for a Display Room release with VAV box fans on and off. Results are presented in terms of "relative exposure", defined as the exposure with VAV fans on divided by the exposure with VAV box fans off. In every room except the East Classroom, the 15 minute exposure is higher with VAV box fans on. In the rooms served by VAV box fans not in the return pathway, the 15 minute exposure with VAV box fans on increased by 10 - 50%. In the West Classroom, the 15 minute exposure increased by 80% as a result of VAV box fan operation, since the West Classroom VAV box fan drew higher concentration air from the return air entering the plenum through the Display Room return grille. As with the Office release, the 8 hour exposure is effectively equal with VAV box fans on and off.

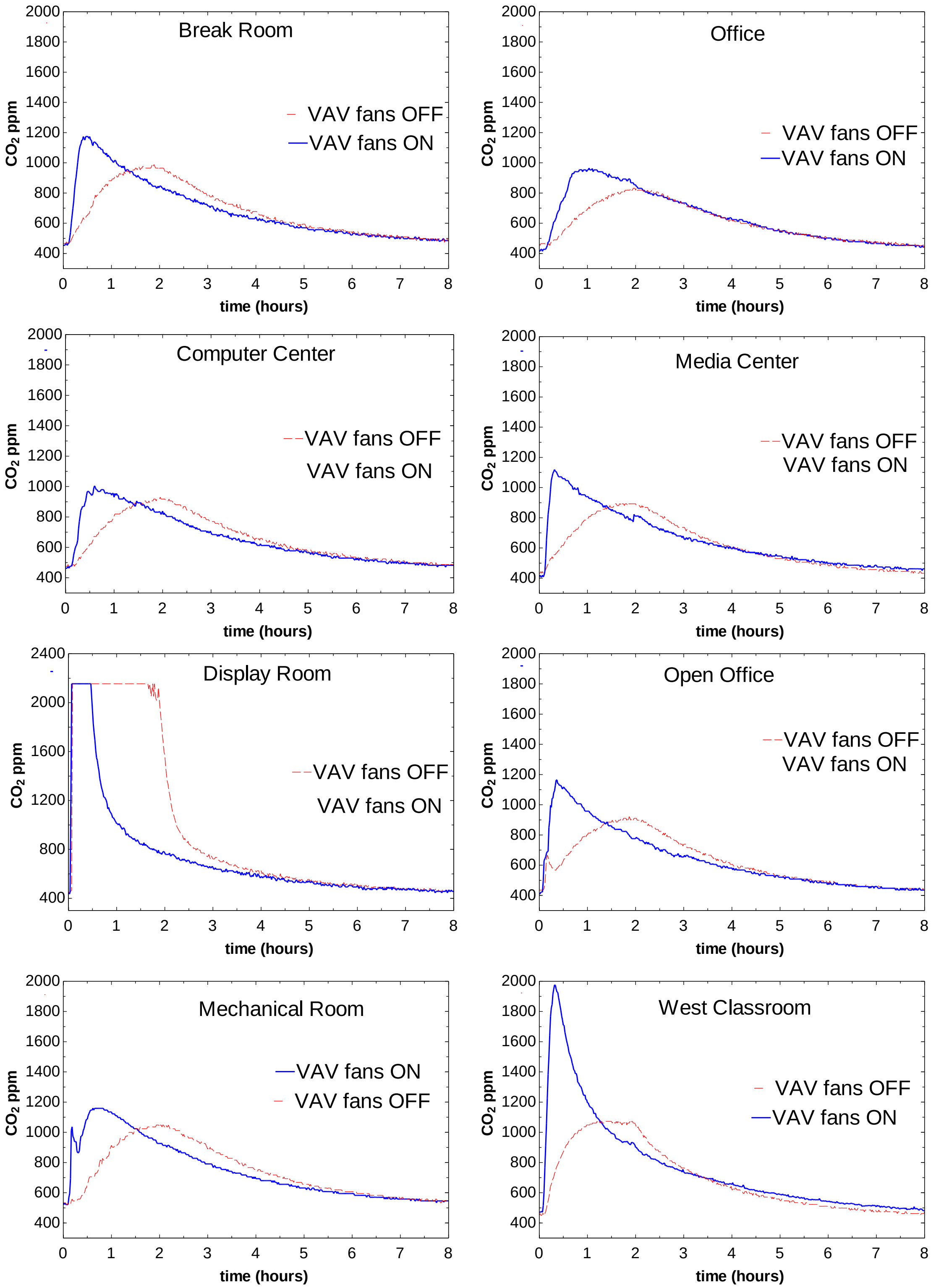


Figure 4-18: Room concentration with FPB on and off – Display Room release without release zone mixing

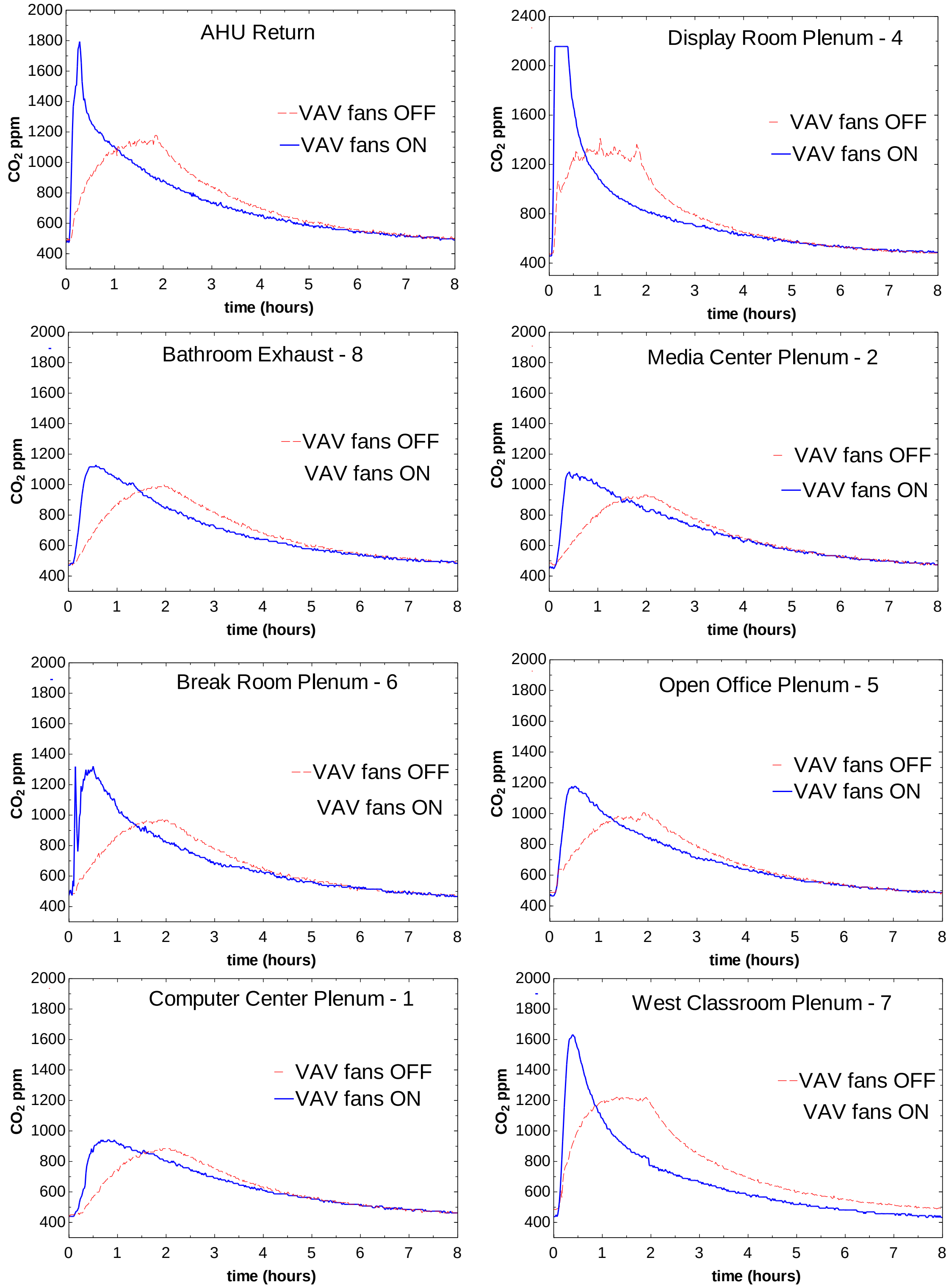


Figure 4-19: Plenum concentration with FPB on and off – Display Room release without release zone mixing

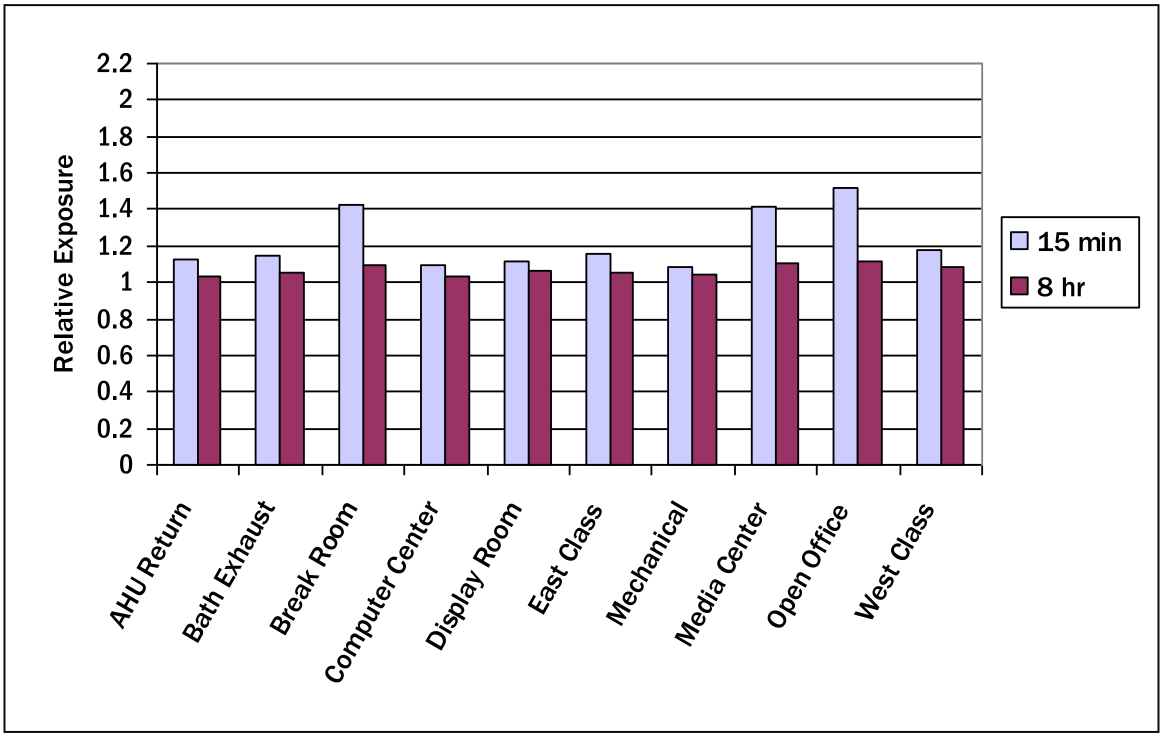


Figure 4-20: Exposure with FPB on relative to exposure with FPB off – Display Room release without release zone mixing

Multizone Model Simulations with No Release Zone Mixing

Figure 4-21 contains selected measured and modeled room concentrations after an Office release with plenum return and no release zone mixing. For brevity only four rooms are shown; however, the remaining rooms showed the same relationship. In each case, the modeled peak occurs roughly 1 hour after the release, whereas the measured peak occurs four hours after the release. The magnitudes of the modeled and measured peaks also differ significantly: the modeled peak concentration is between 1000 and 1200 ppm, whereas the measured peak concentration is between 800 and 900 ppm.

Figure 4-22 shows measured and modeled plenum concentrations after the same release. The measured plenum concentration at various plenum sensors, numbered as seen in Figure 3-10, are significantly different from the modeled plenum concentration. Since multizone modeling assumes that zones are well mixed, the entire plenum, depicted as pink in Figure 3-13, is represented by one concentration in the multizone model. Well mixed assumptions also include the assumption that zones are instantaneously mixed, so tracer that enters the plenum from the Office return grille is assumed to spread uniformly across the entire plenum volume, before reaching the AHU return inlet. The concentration at the AHU return fan, shown as red in Figure 4-22 peaks at roughly 800 ppm four hours after the release, whereas the modeled plenum concentration peaks at roughly 1700 ppm 30 minutes after the release.

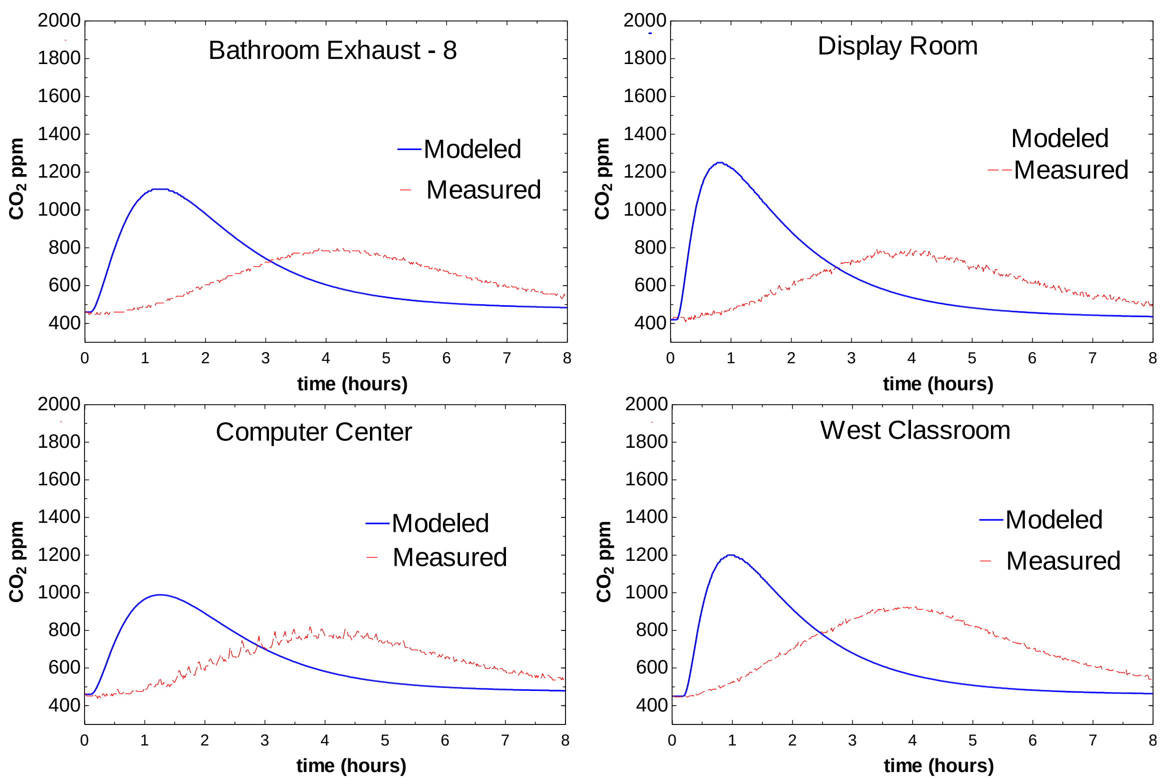


Figure 4-21: Measured and modeled room concentration with FPB off – Office release without release zone mixing

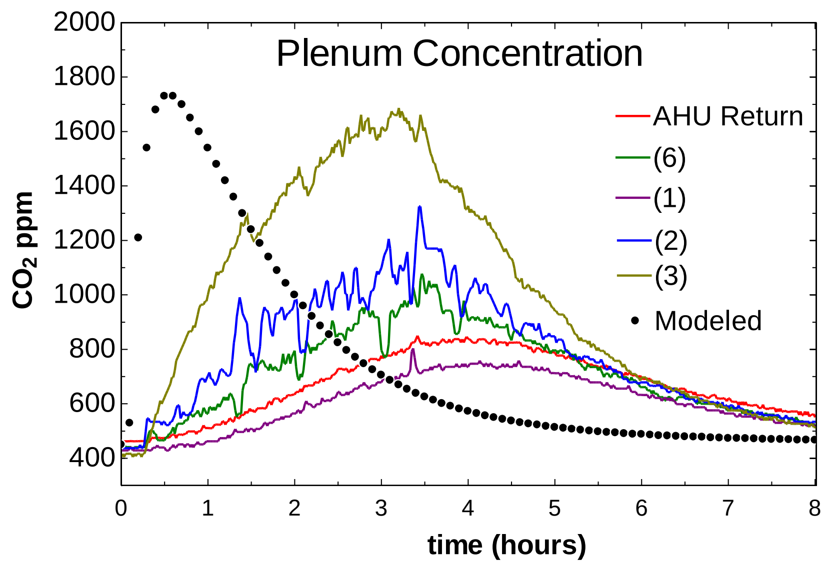


Figure 4-22: Measured and modeled plenum concentration with FPB off – Office release without release zone mixing

Figure 4-23 shows modeled room concentrations after an Office release with parallel fan powered boxes on and no release zone mixing. Even though the modeled concentrations differ from the measurements, the modeled peak magnitudes and peak times are closer to measurements than in the case with parallel fan powered boxes off, suggesting that the mixing provided by the parallel fan powered box fans starts to approach well mixed assumptions. With the fan powered boxes off, the peak concentration of 800 to 900 ppm occurred 4 hours after the release, whereas with the fan powered boxes on, the peak concentration varied from 1000 to 1300 ppm and occurred less than 1 hour after the release. Again, since multizone modeling assumes that zones are well mixed, the return air pathway cannot be traced from the Office and, therefore, all fan powered boxes draw air from the same high concentration air. Figure 4-24 shows measured and modeled plenum concentrations after the same release. The return air pathway from the Office can be seen by looking at the concentrations measured at plenum sensors 3, 2, and 6 (Figure 3-10), while the AHU return, shown as red, and the Computer Center plenum sensor (1), shown in purple, show peak concentrations of 1000 ppm. As a result of the well mixed assumptions, the modeled Computer Center concentration reaches 1600 ppm less than 30 minutes after the release, compared to a measured peak concentration of 1000 ppm 1 hour after the release. In reality, the Computer Center receives tracer from primary air only and the fan powered box injects plenum air of the same concentration into the space.

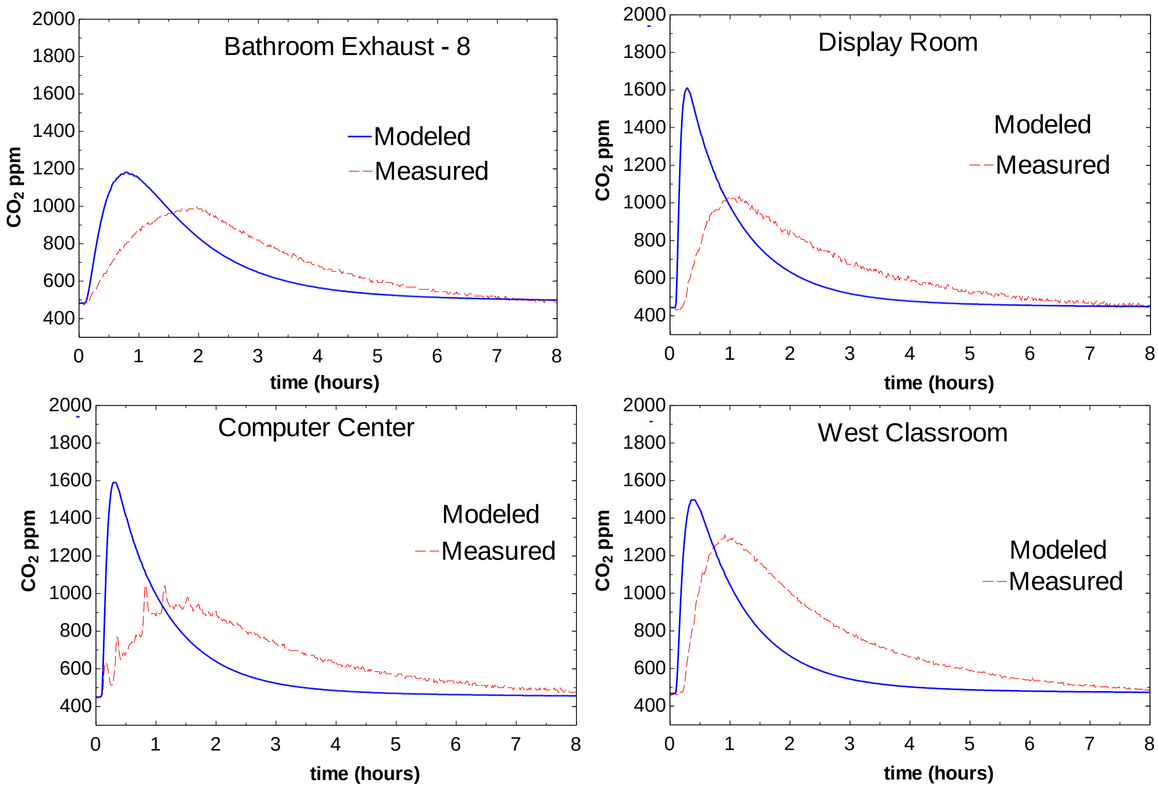


Figure 4-23: Measured and modeled room concentration with FPB on – Office release without release zone mixing

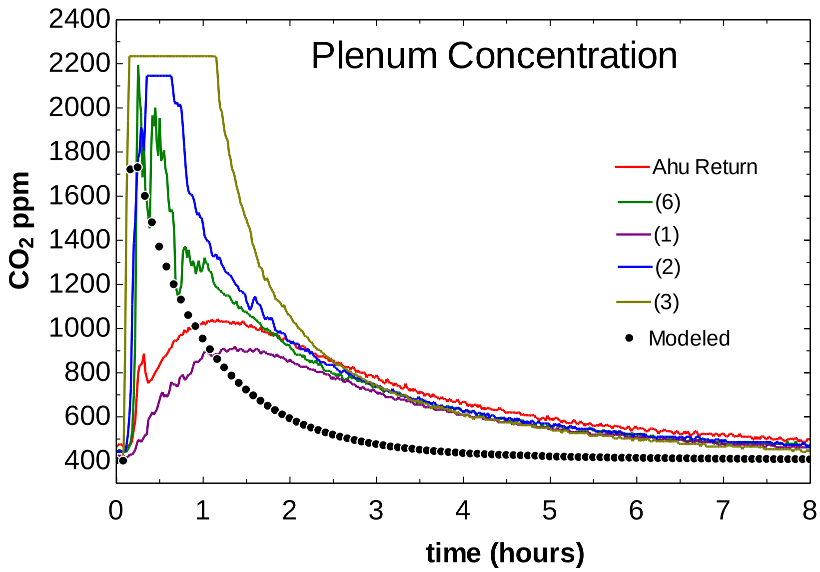


Figure 4-24: Measured and modeled plenum concentration with FPB on – Office release without release zone mixing

Figure 4-25 compares modeled and measured room concentrations after a Display Room release with plenum return and no release zone mixing. As in the previously discussed releases, the modeled and measured results do not agree. The modeled peak concentrations occur roughly 1 hour after the release and vary from 900 to 1300 ppm, whereas the measured peak concentrations occur roughly 2 hours after the release and are consistently 100 to 200 ppm lower than modeled peaks. Figure 4-26 compares modeled and measured plenum concentrations after the same release. Since the Display Room is near the AHU return inlet, tracer short circuits the majority of the plenum, and the interaction of the tracer with the plenum volume and the resulting time delay associated with an Office release far away from the AHU return has less of an impact. With this in mind, one would expect that the mutlizone model would predict room concentrations more accurately for a Display Room release; however, results indicate otherwise. The concentration measured at the Display Room Plenum sensor (4), shown in orange, peaks quickly following the release, but remains at nearly the same concentration for 2 hours before decaying to ambient concentrations. However, the modeled peak concentration peaks at 2400 ppm less than 1 hour after the release. The concentration profile of the Display Room plenum sensor (4) resembles a continuous release with a constant increase and a decay after reaching a steady state concentration. Another explanation for the discrepancy in measured and modeled concentrations could be stratification of tracer within the release room.

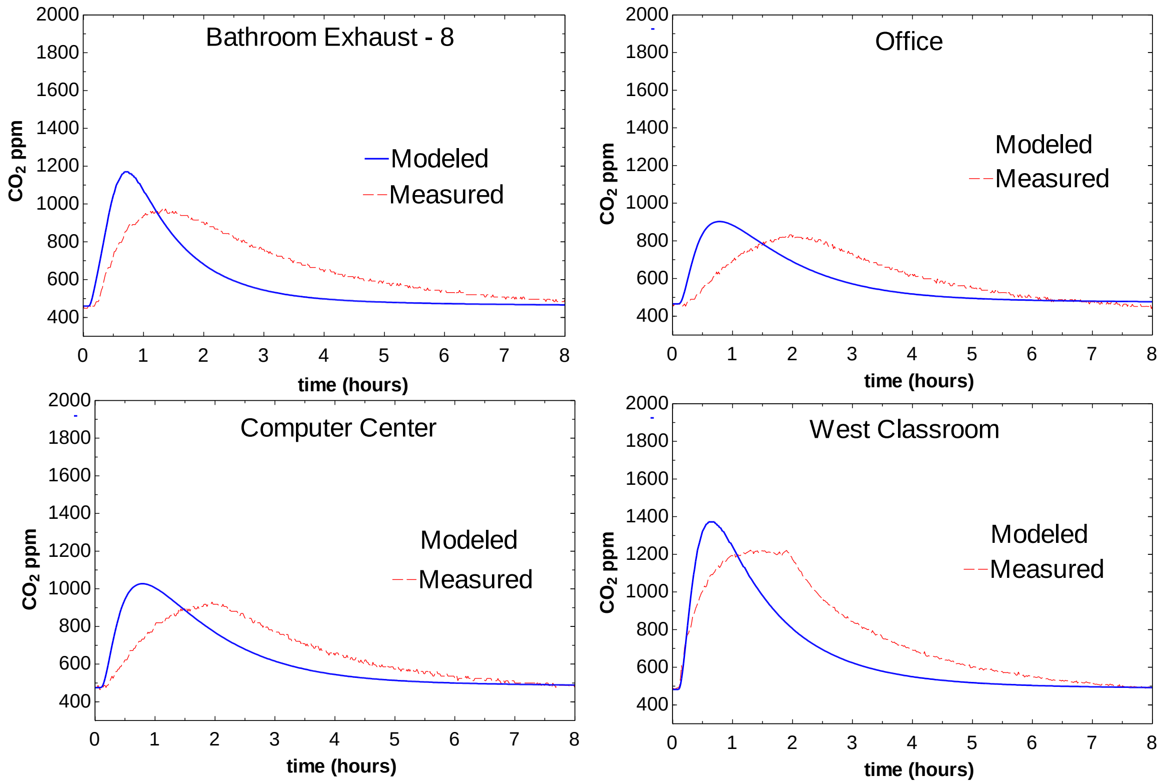


Figure 4-25: Measured and modeled room concentrations with FPB off – Display Room release without release zone mixing

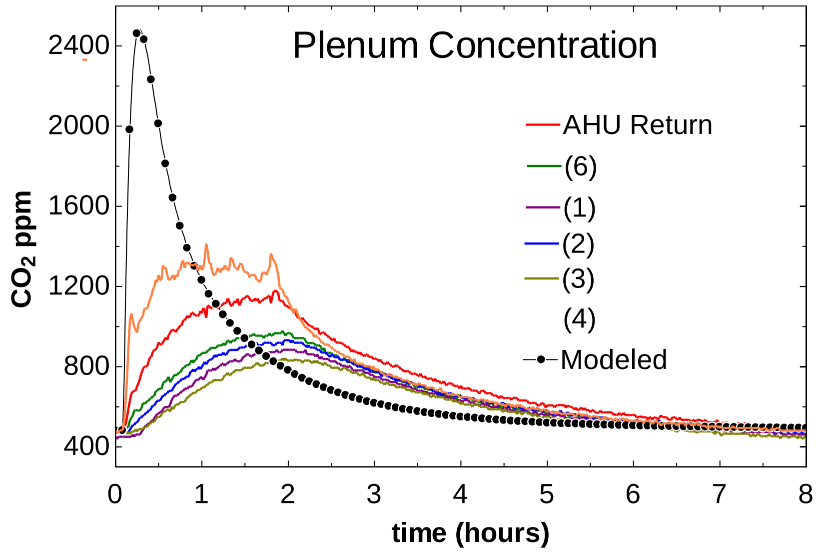


Figure 4-26: Measured and modeled plenum concentration with FPB off – Display Room release without release zone mixing

Figure 4-27 shows modeled and measured room concentrations after a Display Room release with the parallel fan powered boxes on. From looking at the Bathroom Exhaust and West Classroom, one would think that in this case the multizone model was more accurate in predicting room concentrations; however, as seen in the Computer Center and Office, the modeled and measured peak concentrations are significantly different. The modeled concentrations in the Computer Center and Office peak at 1800 ppm and 1600 ppm, respectively, compared to measured peaks of 900 ppm in both the Computer Center and Office. Figure 4-28 compares modeled and measured plenum concentrations after the same release. Since tracer released in the Display Room short circuits the majority of the fan powered boxes, the Computer Center and Office should receive tracer from primary air only. However, as mentioned above, since the return air pathway cannot be traced from the Display Room in the multizone model, every fan powered box draws air from the same high concentration plenum air. The modeled plenum concentration peaks rapidly to 2400 ppm, whereas the AHU return concentration at peaks at 1800 ppm. The Display Room Plenum sensor (4) peaks instantaneously, but is out of range of the plenum sensor for at least 30 minutes, so we cannot know what the peak plenum concentration is. Measured peak concentrations at the Computer Center Plenum sensor (1), shown in blue, and the Reception Plenum sensor (3), shown in tan, are essentially the same magnitude and occur at the same time as the respective room concentrations.

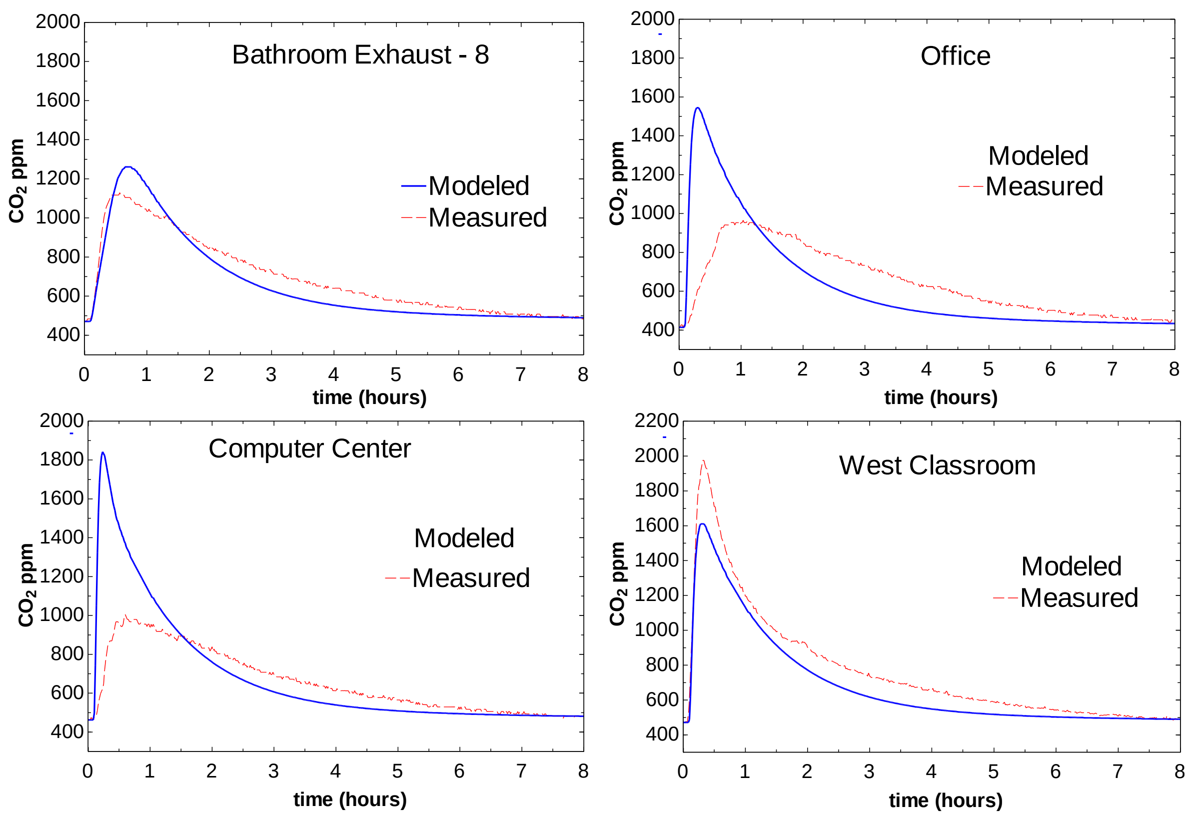


Figure 4-27: Measured and modeled room concentration with FPB on – Display Room release without release zone mixing

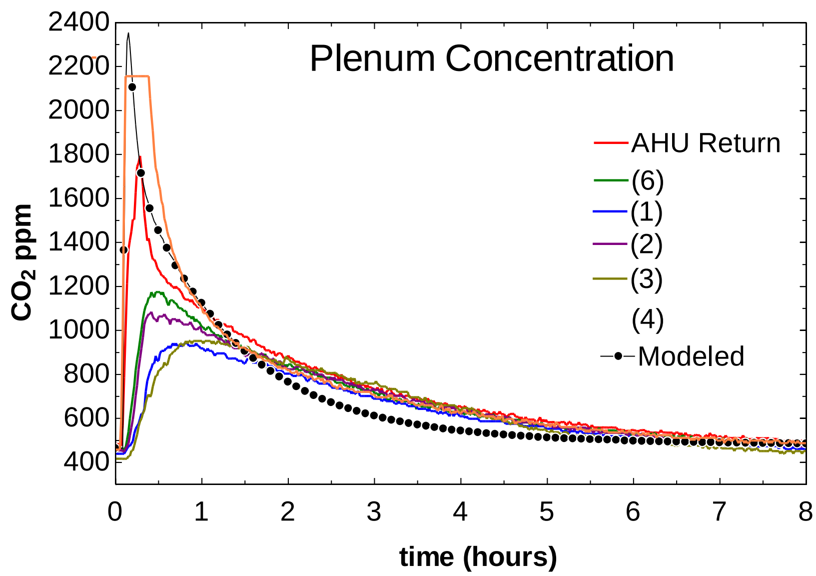


Figure 4-28: Measured and modeled plenum concentration with FPB on – Display Room release without release zone mixing

Tracer Gas Test Results with release zone mixing – Tests 2.5 and 2.5a

Since multizone modeling did not accurately simulate the general service area releases in Test 1.5, multizone modeling's limitations and methods aimed at increasing the accuracy of the simulations were discussed. One hypothesis for the inaccuracy was release zone stratification of cold CO_2 at the ground level. The release consisted of opening a valve on a pressurized cylinder of CO_2 with a known mass and emptying the cylinder in approximately 5 minutes. Since the CO_2 cools as it expands, cold CO_2 could potentially be dumped to the bottom of the release zone. Potential improvements to the testing procedure included placing an additional CO_2 sensor above the release room return grille to relate the concentration leaving the release zone to the amount of the release, measuring CO_2 concentration at several levels within the release zone to characterize any stratification, and placing mixing fans in the release room to ensure that the zone was well mixed. In Test 2.5, all three improvements were implemented: mixing box fans aimed at the floor were placed in the release zone and additional CO_2 sensors with a 10,000 ppm range were placed in the release zone 1 foot from the ground and at the return grille. Test 2.5 consisted of releasing CO_2 in both release locations for ducted return, plenum return, and plenum return with parallel fan powered boxes with mixing fans and additional CO_2 sensors placed in the release zone. Test 2.5a consisted of repeating Test 1.5, with additional CO_2 sensors in the release zone and without release zone mixing, to measure the extent of stratification.

Impact of Release Zone Mixing with Plenum Return

In Test 2.5 (see

Table 3-3), release zones were mixed by square box fans aimed at the floor to approach well mixed assumptions inherent in multizone modeling. Figure 4-29 shows transient room concentrations with and without release zone mixing for an Office release with plenum return. In each room, the peak CO2 concentration with release zone mixing is higher and occurs earlier than the peak CO2 concentration without release zone mixing. With release zone mixing, the peak occurs roughly one hour after the release and the magnitude of the peak concentration is nearly uniform at 1000 to 1100 ppm. Without release zone mixing, the peak occurs roughly four hours after the release and the magnitude of the peak concentration is nearly uniform at 600 ppm. Figure 4-30 shows transient plenum concentrations with and without release zone mixing for the same Office release. Plenum concentrations are higher with release zone mixing. With release zone mixing, the concentration at the Reception Plenum sensor (3) and the Media Center Plenum sensor (2) are out of range for almost two hours; however, without release zone mixing, the plenum concentration never exceeds the sensor range. Without release zone mixing, the concentration at the Reception Plenum sensor (3) and Media Center Plenum sensor (2) do not follow the expected transient profiles compared with the rest of the plenum concentrations.

The plenum concentrations along the return pathway peak and plateau multiple times following the release with no release zone mixing. Since the outdoor concentration is equal for both releases, the difference can only be a result of the tracer source in the release zone. For Test 2.5 and 2.5A, in addition to the sensor located at the thermostat 4 ft. from the ground, additional CO_2 sensors with a range of 10,000 ppm were placed in the release zone at the return grille and 1 foot from the ground. Figure 4-31 shows release room concentration at the thermostat, return grille, and ground of the Office. Without release zone mixing, the concentration at the ground is out of range of the 10,000 ppm sensor for over 3 hours, compared to one hour with release zone mixing. For the release without mixing, the concentration at the return grille peaks to over 10,000 ppm immediately following the release and falls to 6000 ppm for roughly 2 hours before peaking again. Without release zone mixing, the initial peak presumably results from the CO_2 being released from cylinder pointed at the ceiling and the following sharp decay presumably results from CO_2 being stratified within the room. The second peak, which occurs 2 hours after the release, could conceivably result from the CO_2 reaching room temperature as the room is mixed by the HVAC system. Since the concentration at the ground does not fall below 10,000 ppm, as it does at the return, the room is clearly stratified with higher CO_2 concentration at the floor level.

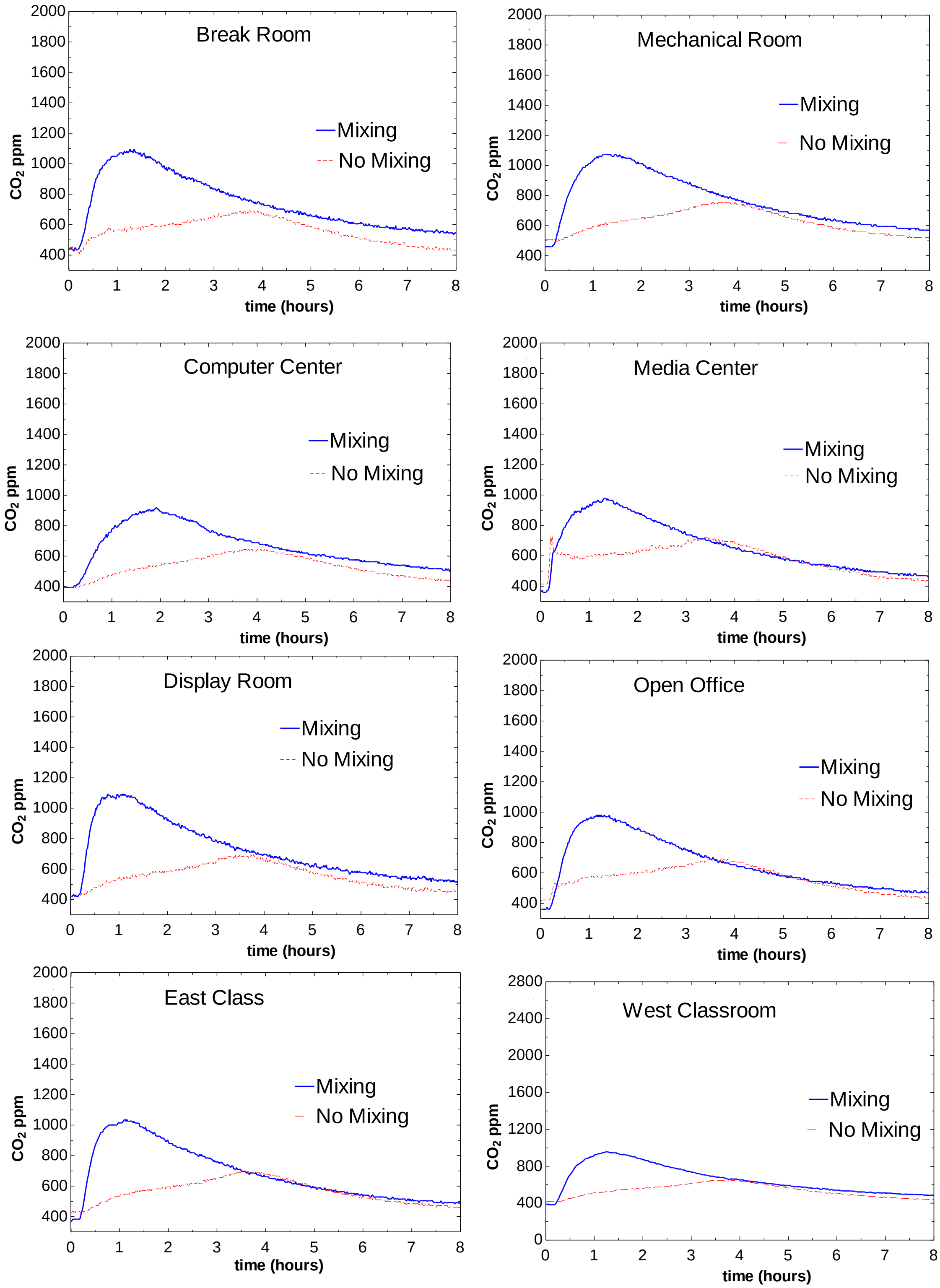


Figure 4-29: Room concentration with and without release zone mixing – Office release with plenum return

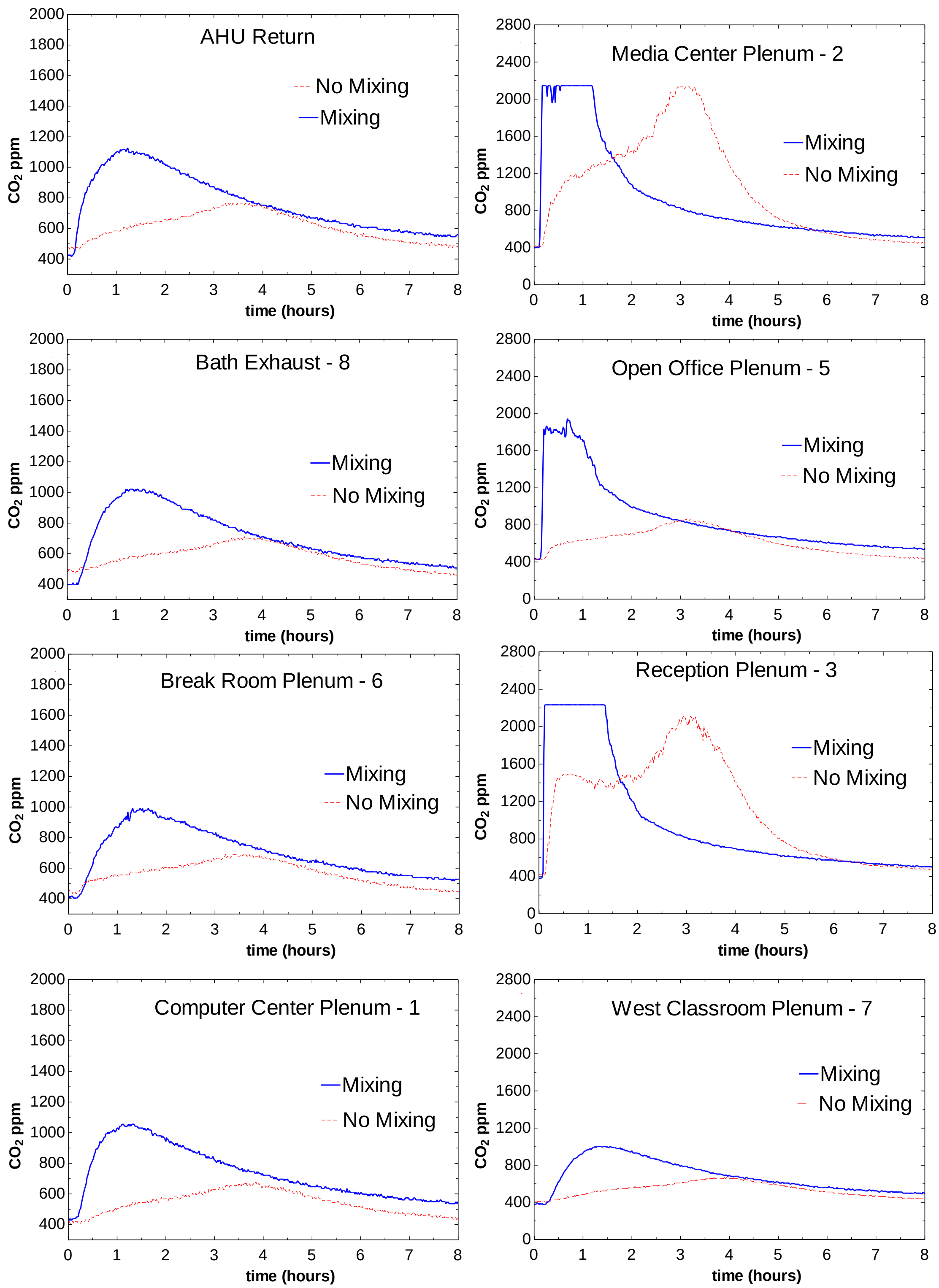


Figure 4-30: Plenum concentration with and without release zone mixing – Office release with plenum return

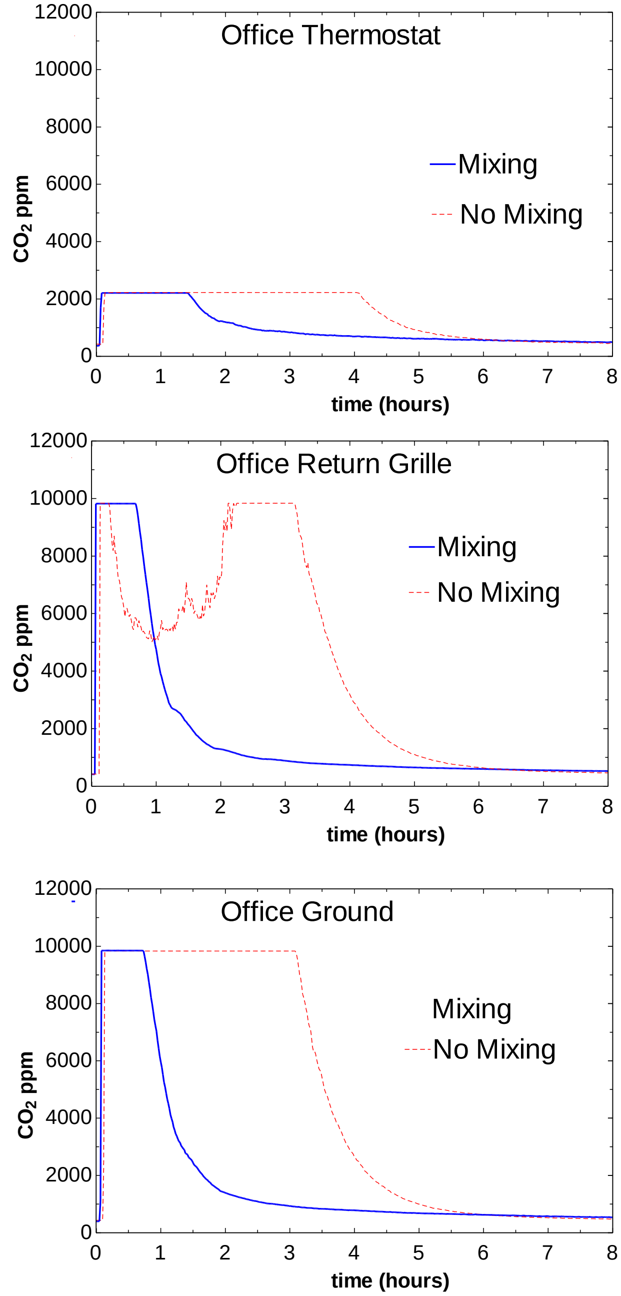


Figure 4-31: Release zone concentration with and without release zone mixing – Office release with plenum return

Figure 4-32 compares the total exposure (time integral of concentration) in different occupied spaces in the general services area with and without release zone mixing for an Office release with plenum return. Results are presented in terms of "relative exposure", defined as the exposure with release zone mixing divided by the exposure with no release zone mixing. In every room but the Media Center and Open Office, the 15 minute exposure with release zone mixing is greater than the 15 minute exposure without release zone mixing. Without mixing, the tracer has time to reach the Media Center and Open Office by diffusion across the Office door. The concentration at the Media Center and Open Office, which are both connected to the Office (Figure 3-1), peak from CO_2 leaking under the release zone door. In rooms not directly connected to the Office, the 15 minute exposures were 10 to 20% higher with release zone mixing. The 8 hour exposure with release zone mixing is 15 to 40% higher than the 8 hour exposure without release zone mixing.

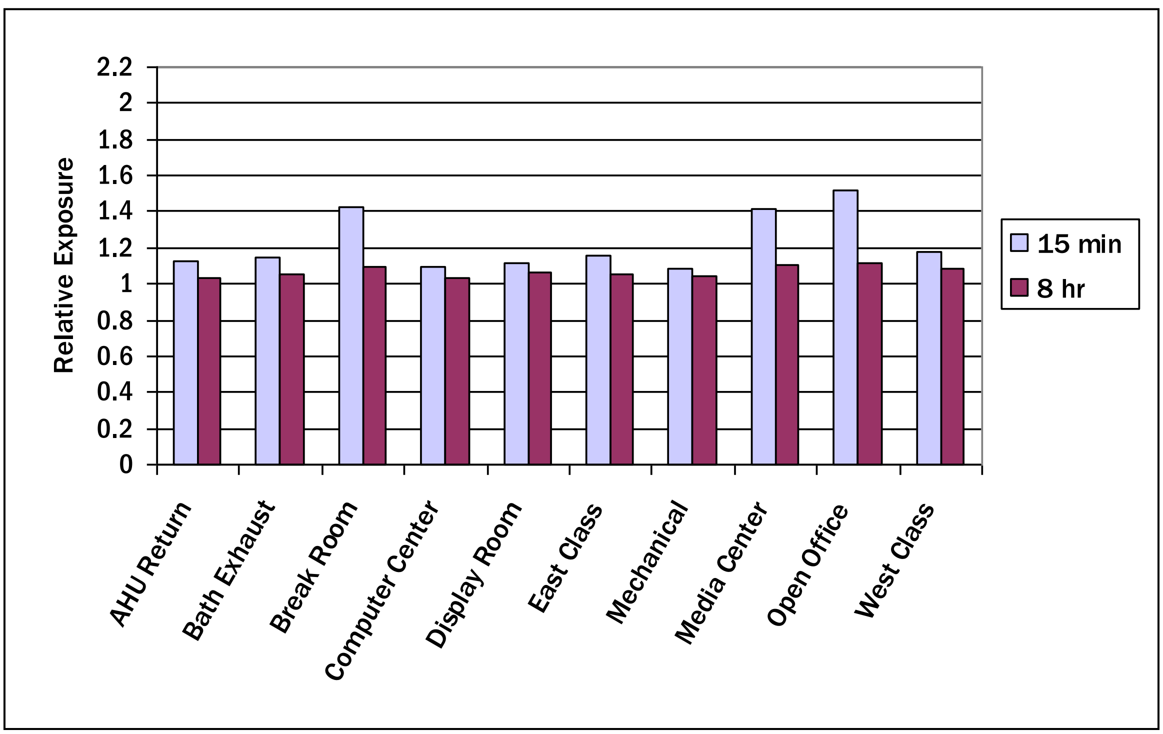


Figure 4-32: Exposure with release zone mixing relative to exposure without release zone mixing – Office release with plenum return

Figure 4-33 shows transient room concentrations with and without release zone mixing for a Display Room release with plenum return. In every room except the Media Center and Open Office, tracer peaks at a higher concentration and decays more rapidly with release zone mixing. The higher peak and faster decay with release zone mixing result from the HVAC system receiving higher concentrations since the CO_2 is not stratified in the release zone. Since the Media Center and Open Office are connected to the Display Room (Figure 3-1), the tracer has time to reach the Media Center and Open Office by diffusion or across the Display Room door.

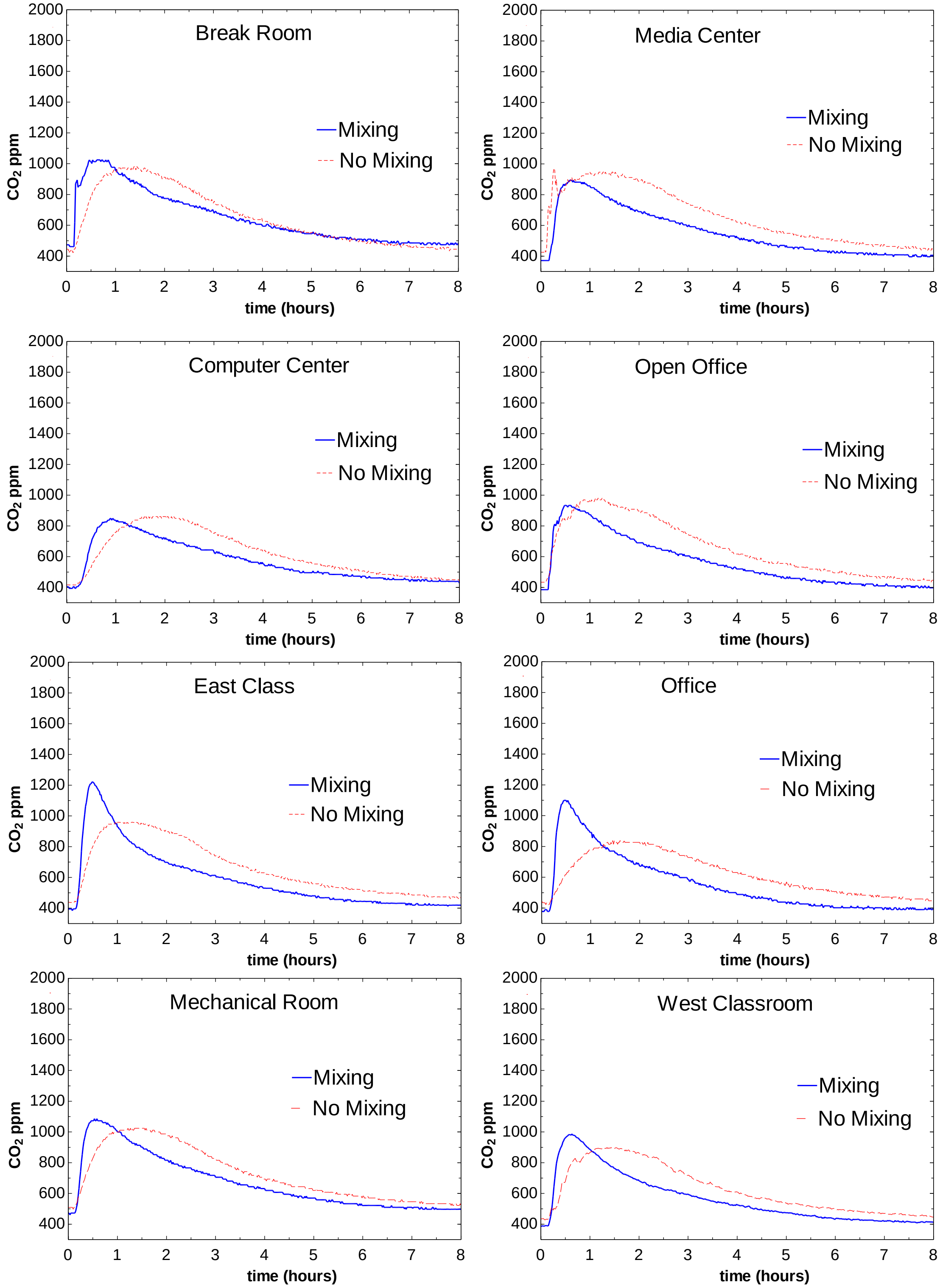


Figure 4-33: Room concentrations with and without release zone mixing - Display release with plenum return

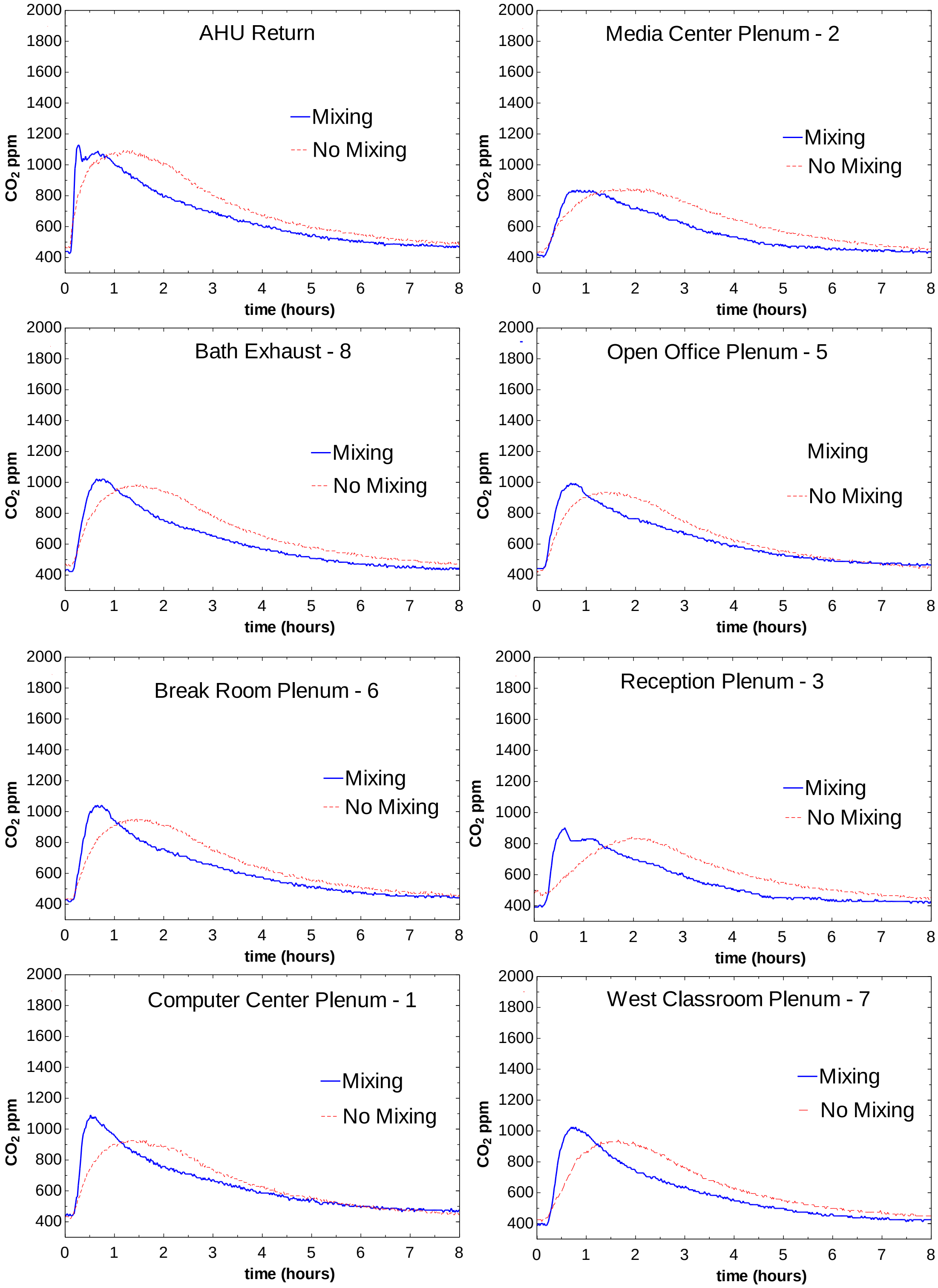


Figure 4-34: Plenum concentration with and without release zone mixing – Display release with plenum return

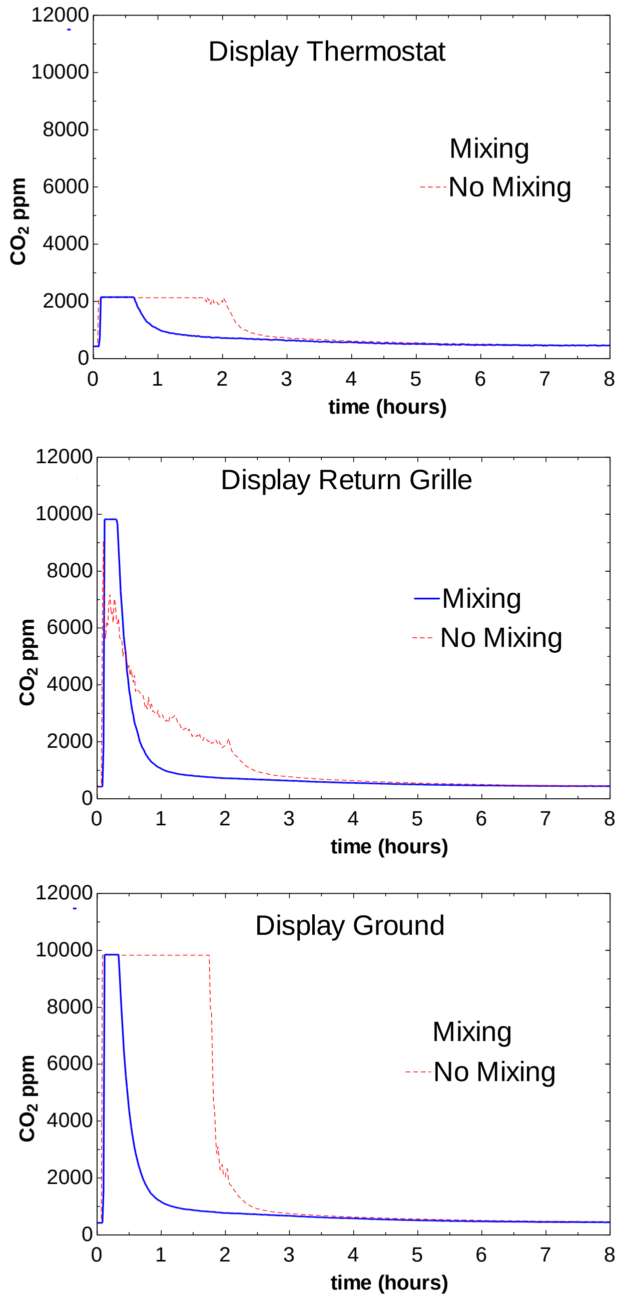


Figure 4-35: Release zone mixing with and without mixing – Display Room release with plenum return

Figure 4-35 shows release room concentration at the thermostat, return grille, and ground of the Display Room. With release zone mixing, the concentration at the ground peaks and decays rapidly, out of range of the 10,000 ppm sensor for less than 30 minutes, compared to 2 hours without release zone mixing. After examining the release room concentration at different sensors, one might conclude that the concentration at the return grille without release zone mixing does not peak multiple times as it did in the Office release. However, as seen in Figure 4-36, with no release zone mixing the concentration at the return grille peaks immediately following the release falls, presumably from CO_2 stratification, and peaks slightly before decaying from room mixing by the HVAC system. Figure 4-37 compares the total exposure (time integral of concentration) in different occupied spaces in the general services area with and without release zone mixing for a Display Room release with plenum return. Results are presented in terms of "relative exposure", defined as the exposure with release zone mixing divided by the exposure with no release zone mixing. In every room except the Media Center and Open Office, tracer peaks at a higher concentration and decays more rapidly with release zone mixing. The higher peak and faster decay with release zone mixing result from the HVAC system receiving higher concentrations since the CO_2 is not stratified in the release zone. Since the Media Center and Open Office are connected to the Display Room (Figure 3-1), the tracer has time to reach the Media Center and Open Office by diffusion or across the Display Room door. In rooms not directly connected to the Display Room, the 15 minute exposure increased by 10-40% as a result of release zone mixing. In all rooms except the Media Center the 8 hour exposure was nearly equal with release zone mixing and without release zone mixing.

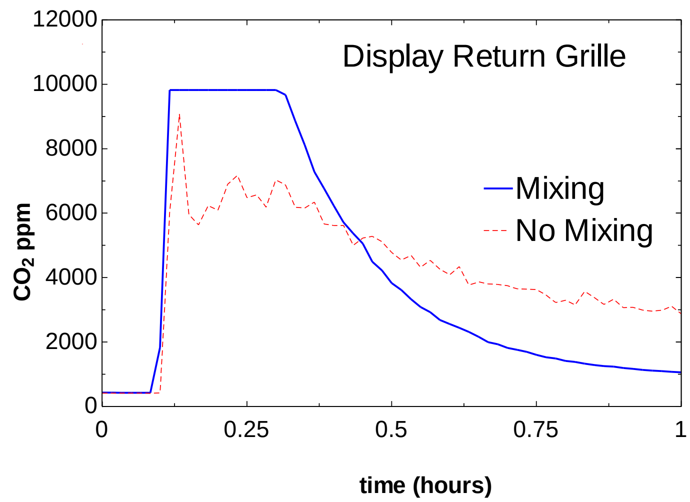


Figure 4-36: Return grille concentration with and without release zone mixing – Display Room release with plenum return

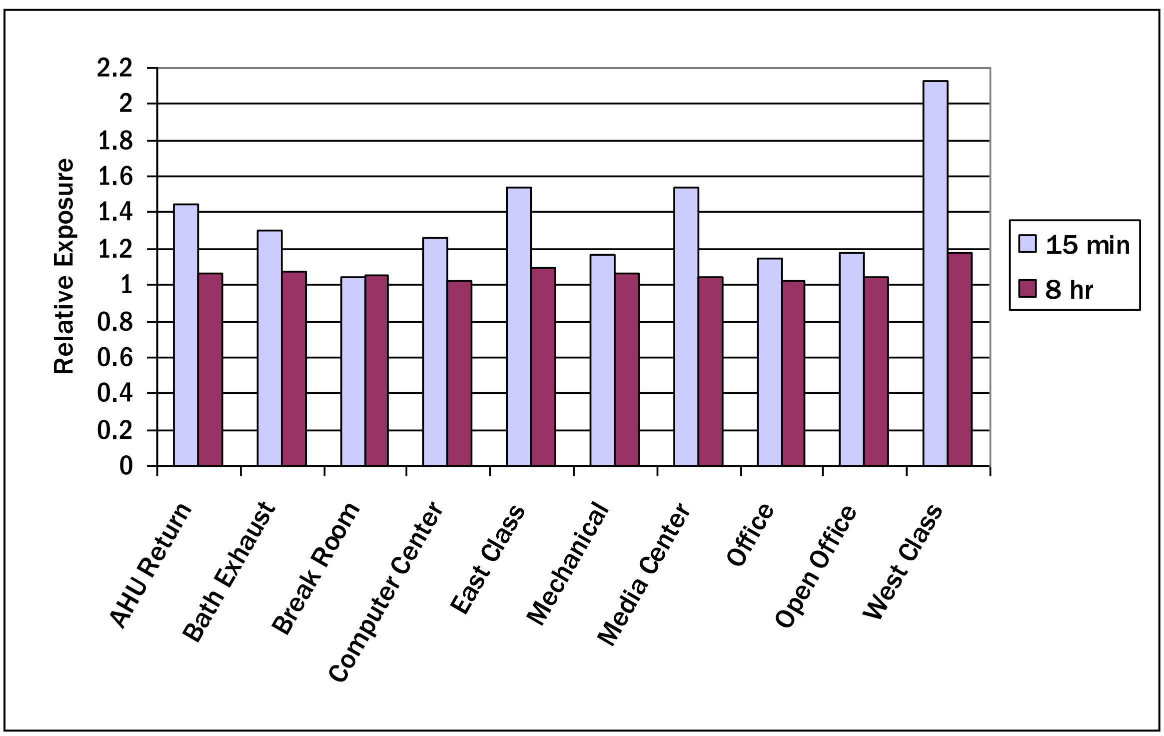


Figure 4-37: Exposure with release zone mixing relative to exposure without release zone mixing – Display Room release with plenum return

Impact of Return Air Strategy with Release Zone Mixing

Figure 4-38 shows transient room concentrations for an Office release with ducted and plenum return air systems, with release zone mixing. With ducted return, tracer moves directly from the Office release zone to the AHU and is distributed to all spaces connected to that system. The peak room concentrations occur roughly 30 minutes after the start of the release and decay rapidly thereafter. With plenum return, arrival of the tracer at the AHU is delayed by its relatively slow spread across the plenum. Figure 4-39 shows concentrations in the plenum after the same release. By looking at concentrations within the plenum, the return air pathway can be seen. Tracer enters the return air grille in the Office and passes across Plenum Sensors 3, 2, and 5 before reaching the AHU return.

Plenum concentration is much higher in the plenum return case. In the ducted return case, the plenum concentrations increase following the release, presumably due to a combination of leakage from the supply ducts and leakage from positively pressurized spaces across the suspended ceiling, which affords little resistance to flow. Since the range of the sensors was 2000 ppm, concentrations in the release zone and release path were above the range of CO_2 sensors for up to 2 hours. The estimated initial average concentration, based on an instantaneous release, was 52,000 ppm in the Office and 32,000 ppm in the Display Room.

Figure 4-40 compares the total exposure (time integral of concentration) in different occupied spaces in the general services area for ducted and plenum return after an Office release. Results are presented in terms of "relative exposure", defined as the exposure for the plenum return case divided by the exposure for the ducted case. Over a 15 minute period, exposures in the plenum return case are mostly lower by 40-60% than exposures with ducted return. Over a longer period, however, the entire building, including the plenum, becomes mixed to a nearly uniform concentration, so at 8 hours, the exposures are essentially the same.

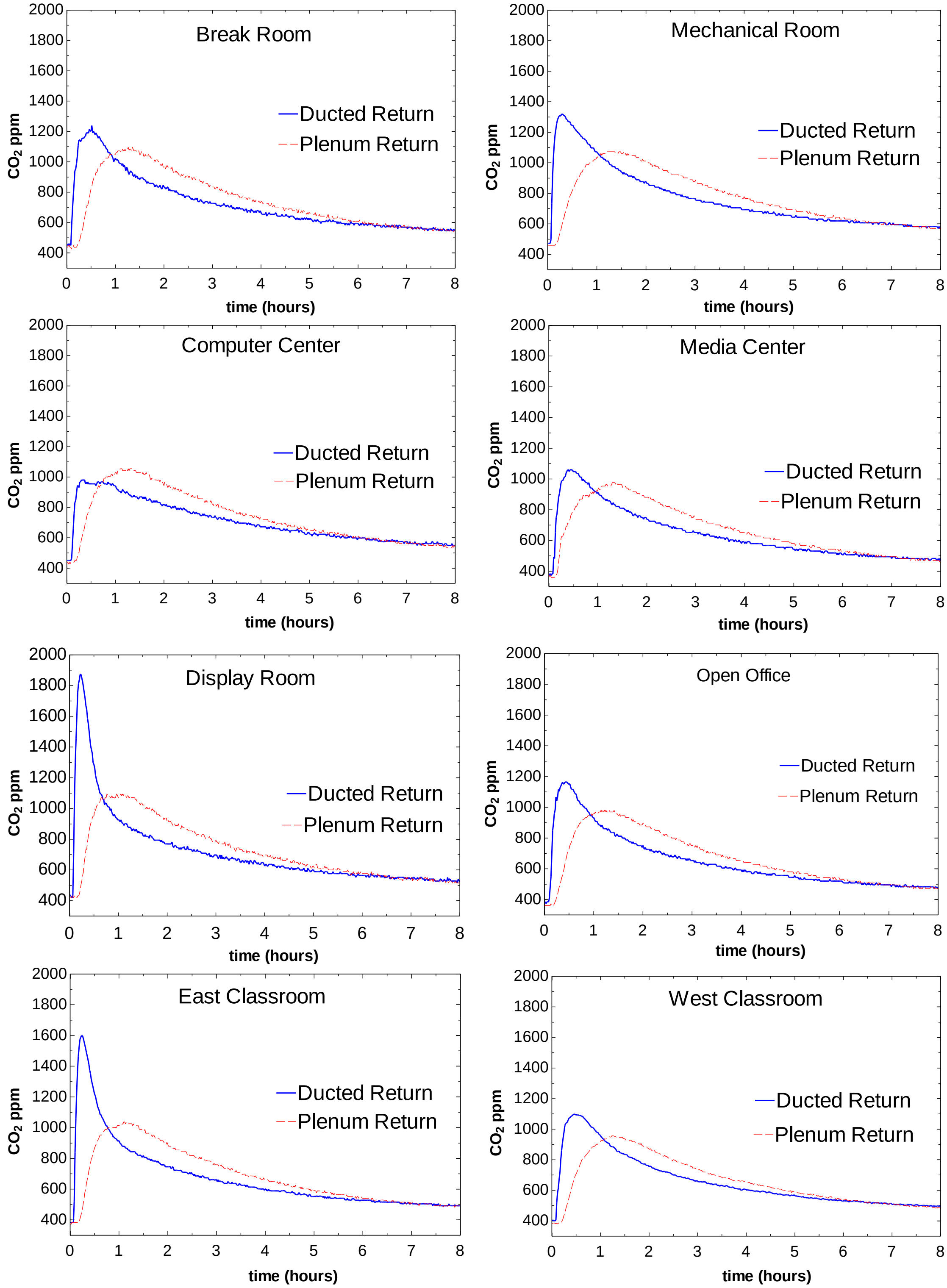


Figure 4-38: Room concentration with ducted and plenum return – Office release with release zone mixing

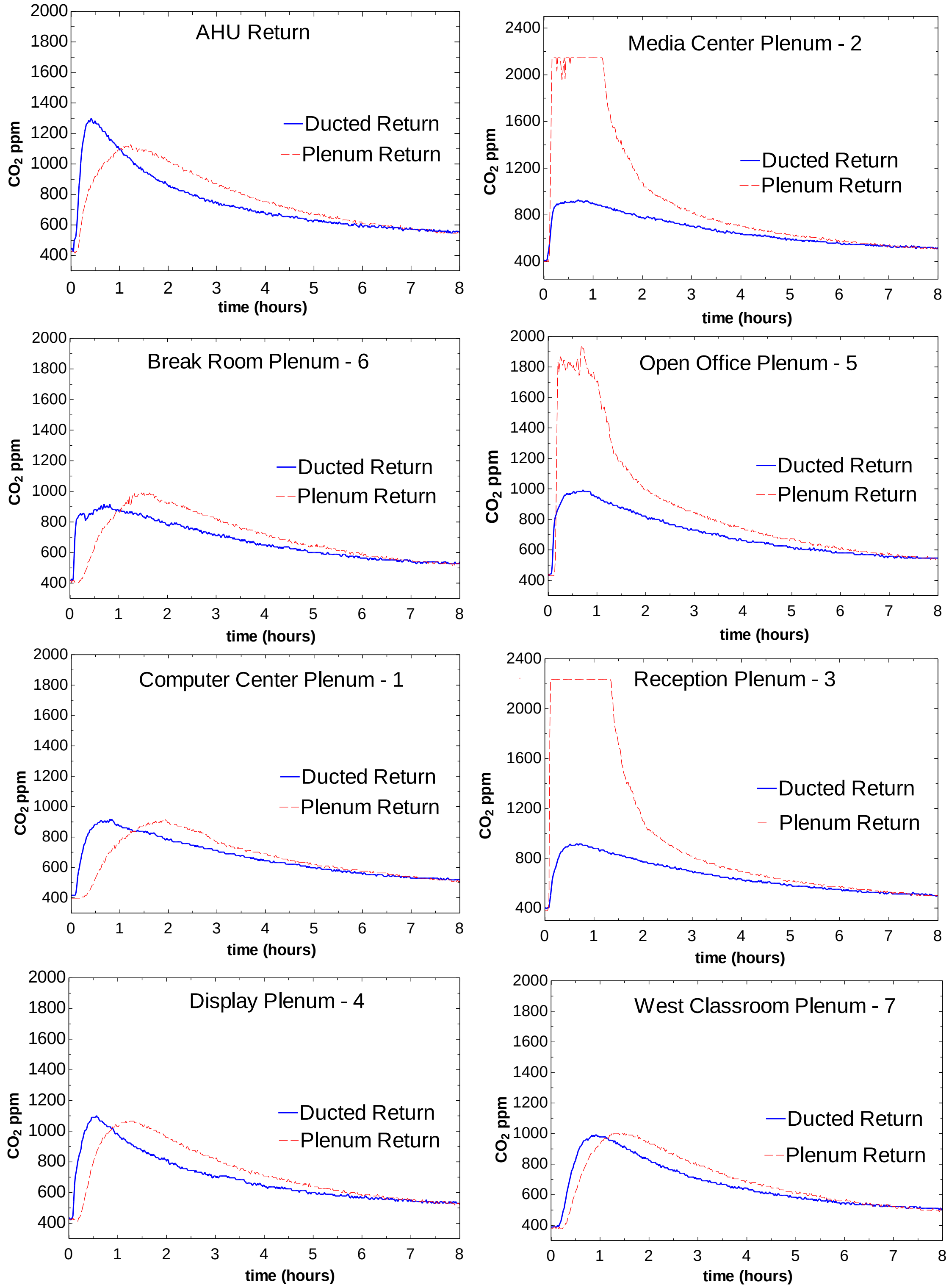


Figure 4-39: Plenum concentration with ducted and plenum return – Office release with release zone mixing

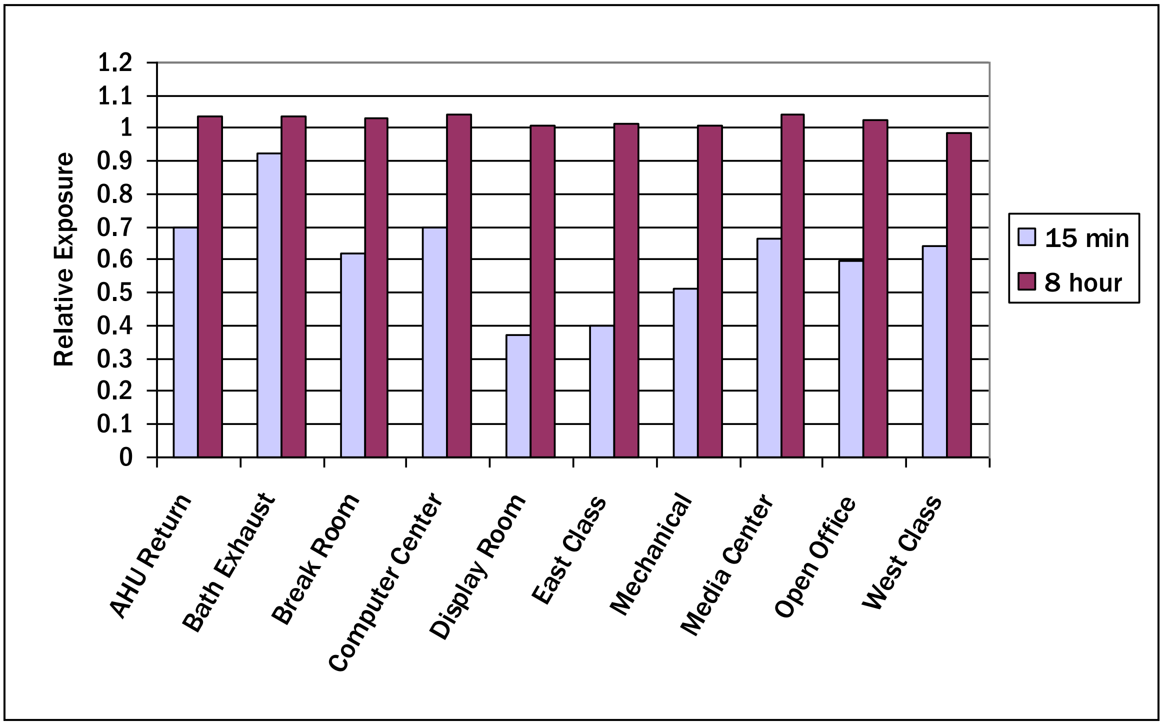


Figure 4-40: Exposure with plenum return relative to exposure with ducted return – Office release with release zone mixing

Transient room concentrations after a Display release with ducted and plenum return systems are shown in Figure 4-41. With the exception of the Office and West Classroom, the transient room concentrations are essentially the same. Figure 4-42 shows transient plenum concentrations after the same release. AHU Return concentration profiles are essentially the same, peaking at the same time and at the same tracer concentration. Clearly this is due to short-circuiting from the release zone to the AHU return inlet; there is little opportunity for the tracer to disperse throughout the plenum as in the Office release. However, since the West Classroom Plenum and the plenum above the Display Room are connected by a fire wall and return air transfer duct, tracer does migrate in the ducted return case. Presumably, this is due to a depressurized West Classroom drawing tracer from the plenum above the release zone, through the return air transfer duct, and across the suspended ceiling. Since the doors were closed in the test, the least resistance to unbalanced airflow in the West Classroom was through the suspended ceiling.

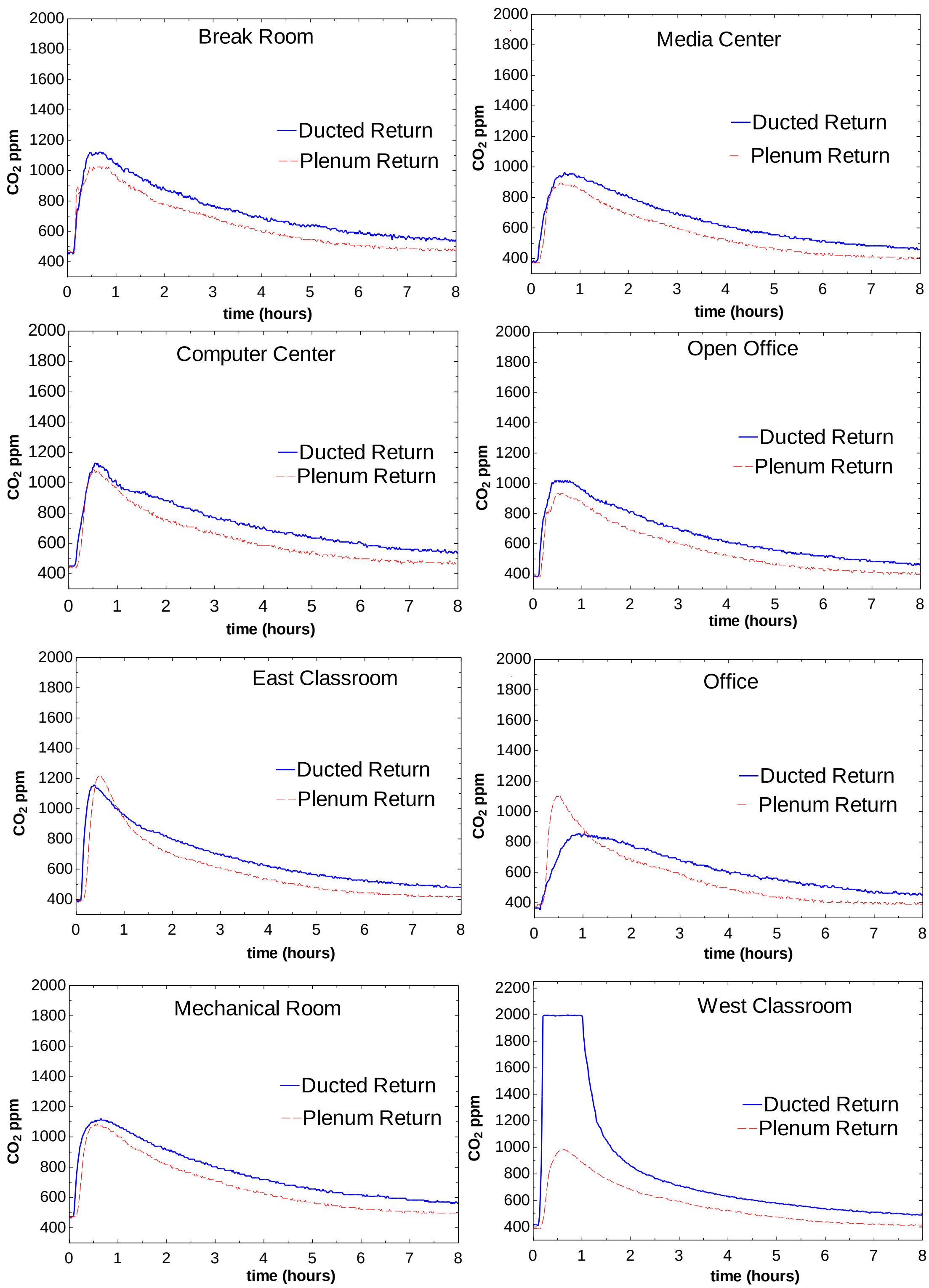


Figure 4-41: Room concentrations with ducted and plenum return – Display Room release with release zone mixing

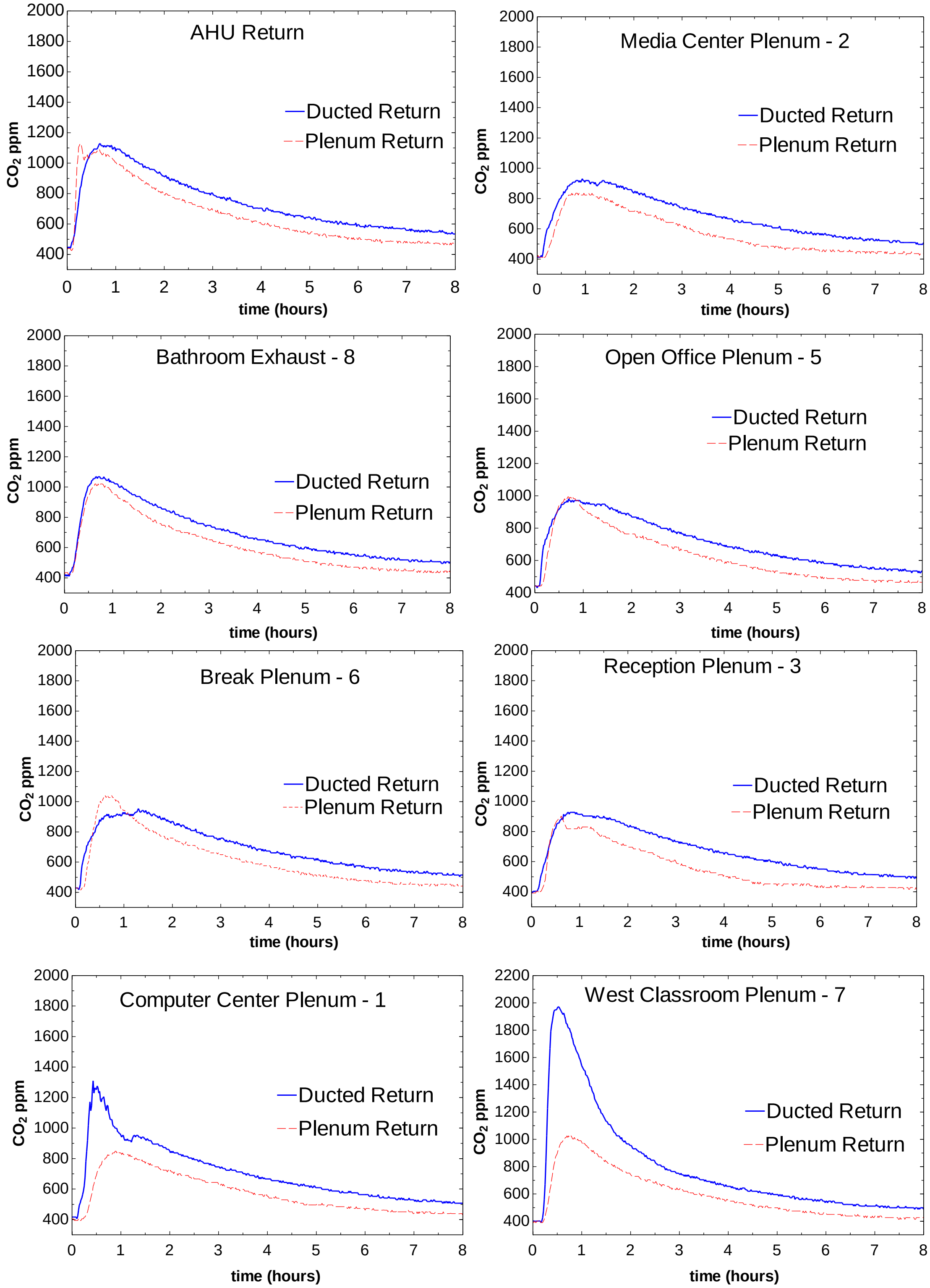


Figure 4-42: Plenum concentration with ducted and plenum return – Display Room release with release zone mixing

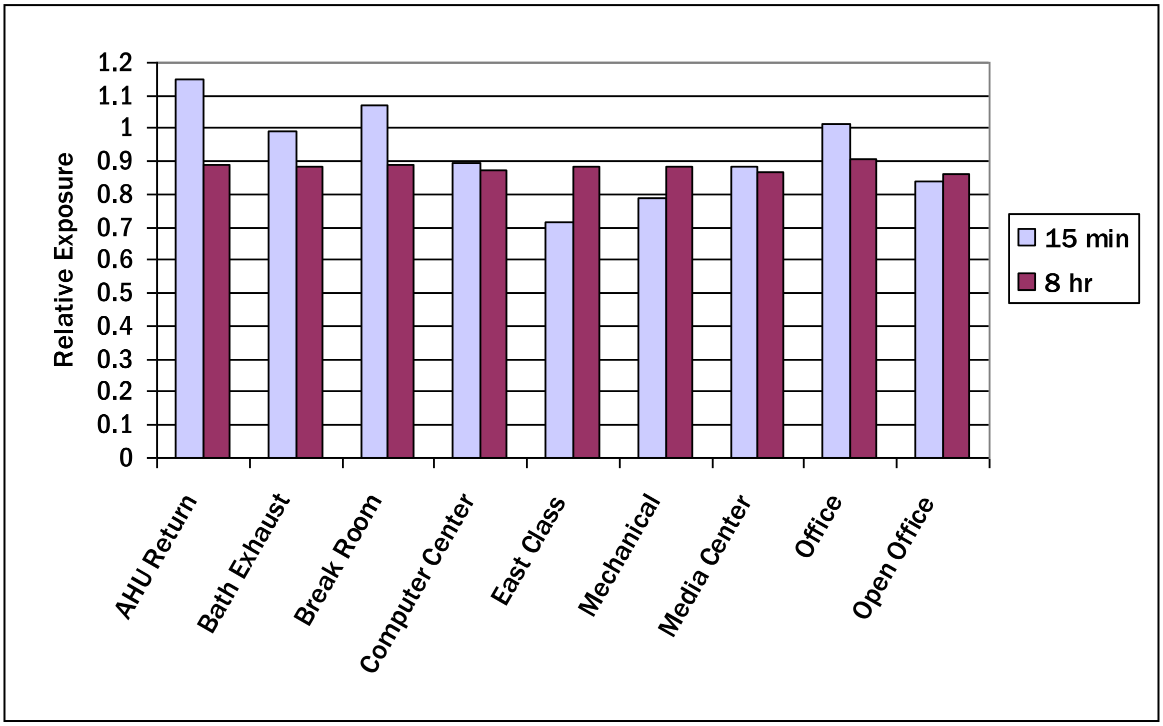


Figure 4-43: Exposure with plenum return relative to exposure with ducted return – Display Room release with release zone mixing

Impact of Fan Powered Boxes with Release Zone Mixing

Additional tests were performed to show the impact of parallel fan-powered VAV boxes on tracer dispersion in a plenum return system. Because they inject return air from the plenum directly into occupied space, fan-powered boxes have the potential to reduce the buffering effect of the plenum shown in the results above. The effect should be non-uniform, with fans that lie in the path of higher concentration return air creating a greater impact on space concentration.

Figure 4-44 contains transient room concentrations after an Office release with the fan-powered VAV boxes on and off. As seen in Figure 3-2, Figure 3-10, and Figure 3-11, the fan-powered boxes serving the Media Center (plenum sensor 2), Open Office (plenum sensor 5), Break Room (plenum sensor 6), and West Classroom (plenum sensor 4) lie in the return pathway from the Office release. The Computer Center (plenum sensor 1) and the Display Room are in corners of the general service area plenum where air from the Office return would not be expected to migrate. Figure 4-45 shows transient plenum concentrations after an Office release. Plenum air in the vicinity of plenum sensors 3, 2 and 5 has a high concentration of tracer, so the operation of parallel VAV fan powered boxes has a dramatic effect. In the case of the Computer Center, the impact on local concentration is much smaller because the local plenum concentration (plenum sensor 1) is close to the space concentration.

Figure 4-46 shows relative exposure for plenum return tests with parallel fan-powered VAV box fans on and off for the Office release. In this case, relative exposure is defined as the ratio of exposure with fans on to exposure with fans off. Over an 8 hour period, the exposures with the fans on and off are essentially the same. However, the impact of the fan powered box operation is clear and consistent for 15 minute exposures. During the Office release, 15 minute exposures increased by 40-55% in the Media Center, Open Office, and Break Room. The parallel fan powered VAV box fans serving these rooms are in the return air pathway of an Office release. The tracer gas bypasses the remaining parallel fan-powered VAV box fans and reaches the room via primary air. The impact of fan powered box operation can also be seen in the transient concentrations of the Bathroom and the Mechanical Room. Since air is not returned from either the Mechanical Room or the Bathroom and the fan powered VAV box fans serving the spaces is surrounded by full height fire walls, tracer reaches these spaces via primary air only.

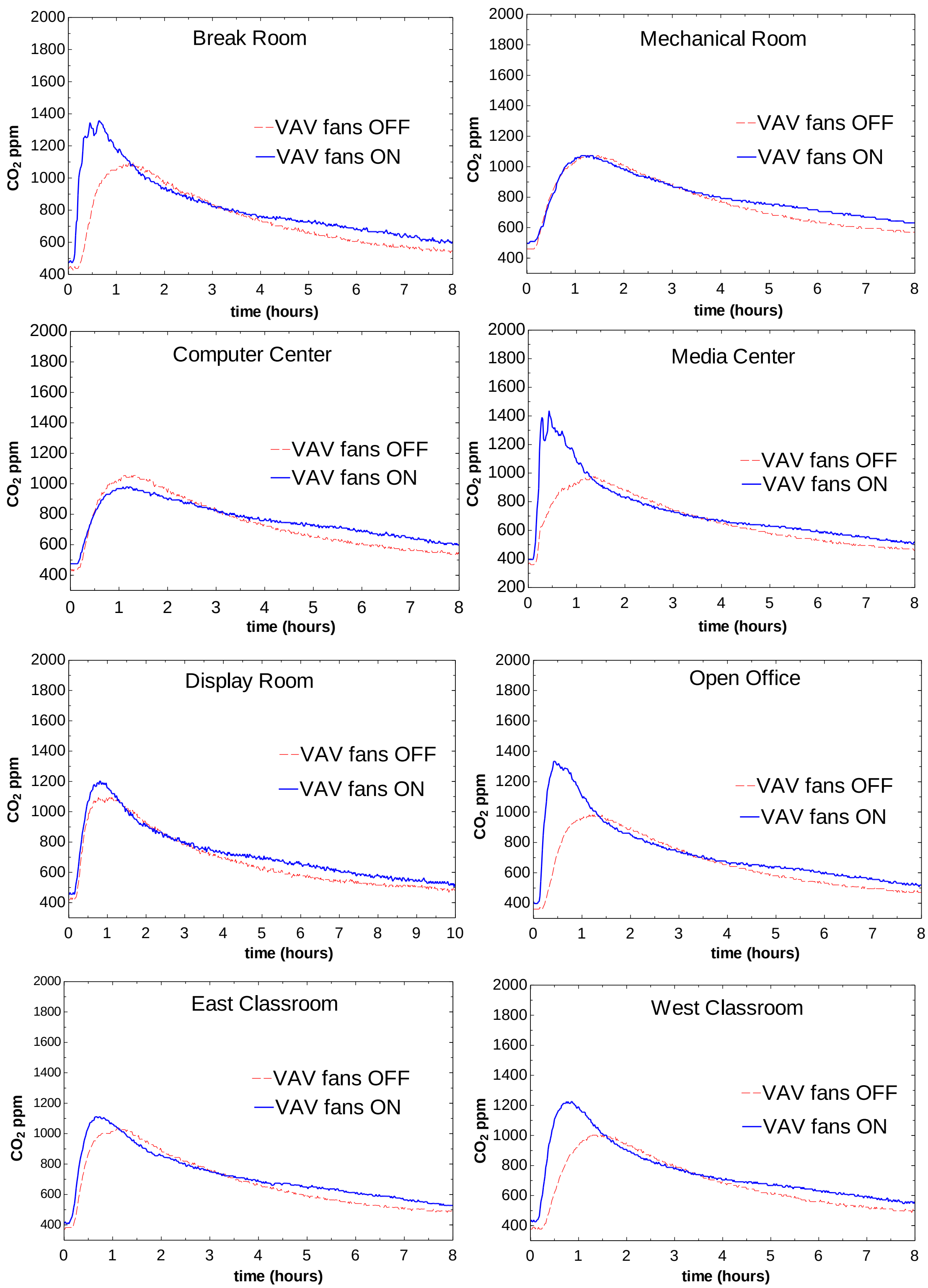


Figure 4-44: Room concentration with FPB on and off – Office release with release zone mixing

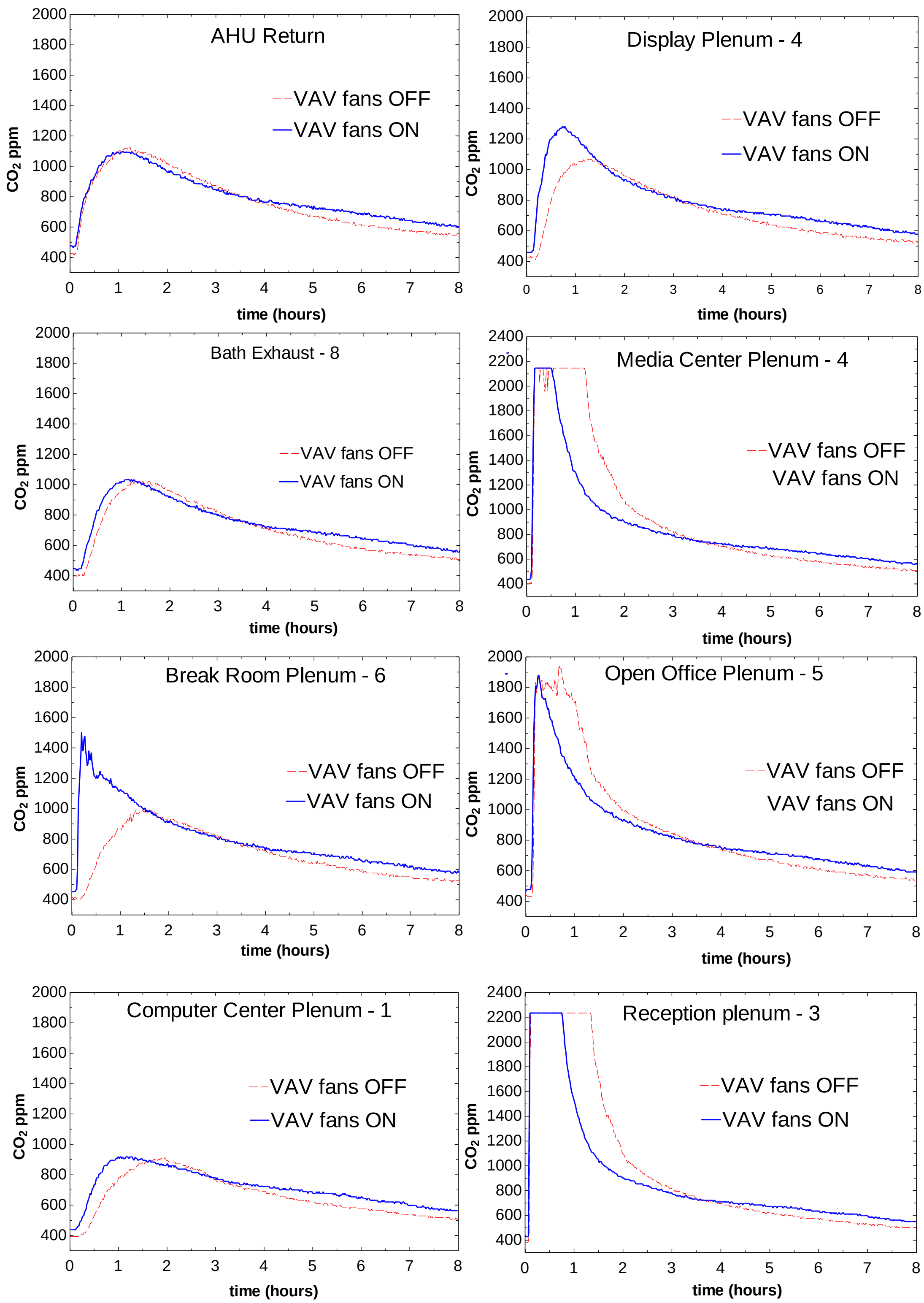


Figure 4-45: Plenum concentration with FPB on and off – Office release with release zone mixing

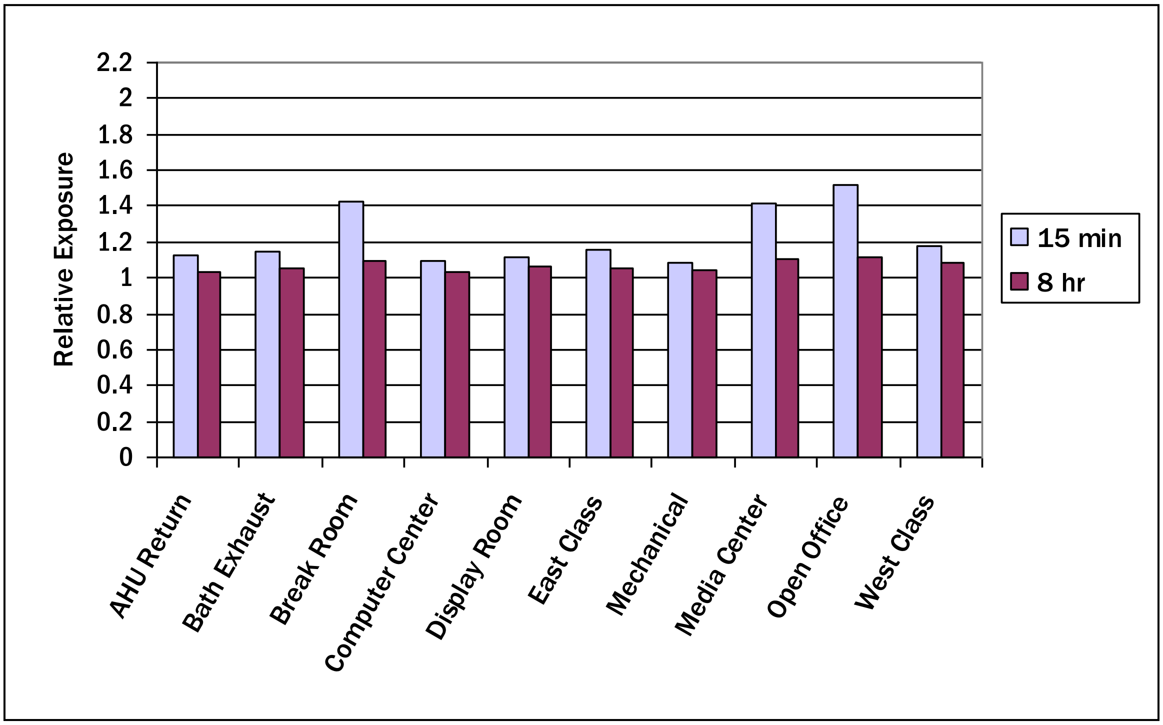


Figure 4-46: Exposure with FPB on relative to exposure with FPB off – Office release with release zone mixing

Figure 4-47 shows transient room concentrations after a Display Room release with VAV box fans on and off. With the exception of the West Classroom and Office, the transient room concentrations are similar in time and magnitude of peak. The higher room West Classroom concentration with the VAV box fans on is justifiable, since in this release scenario, only the VAV box serving the West Classroom lies in the return pathway. All other rooms receive tracer via primary air only, so the transient concentration are similar in time and magnitude of the peak. However, the Office concentration is higher with the VAV box fans off, which suggests that the Office received a different amount of primary air in each release. As seen in Figure 4-48, with the exception of the West Classroom Plenum sensor (7), the transient plenum concentrations are similar between the two release scenarios, which confirms that rooms receive tracer via primary air.

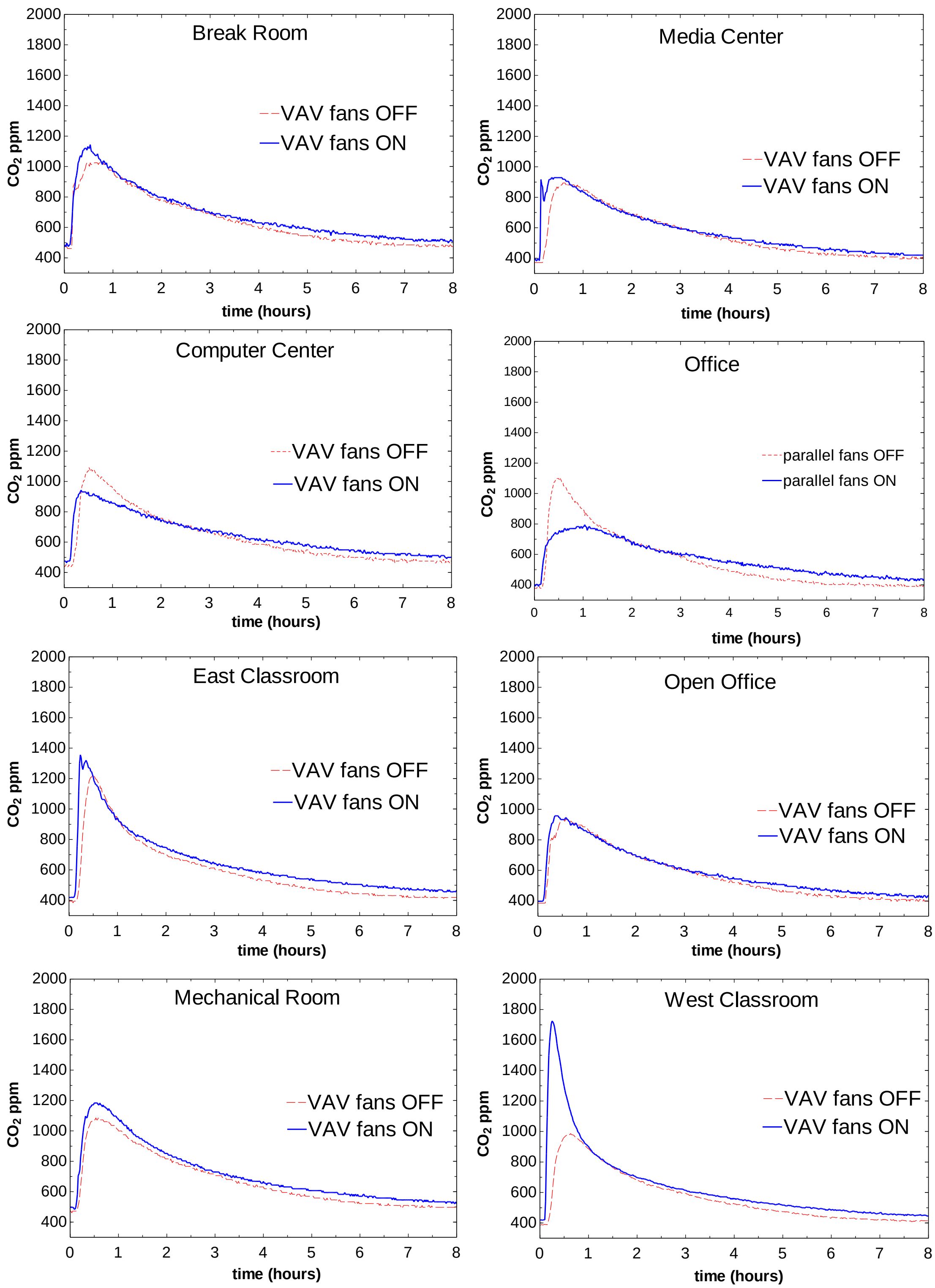


Figure 4-47: Room concentration with FPB on and off – Display Room release with release zone mixing

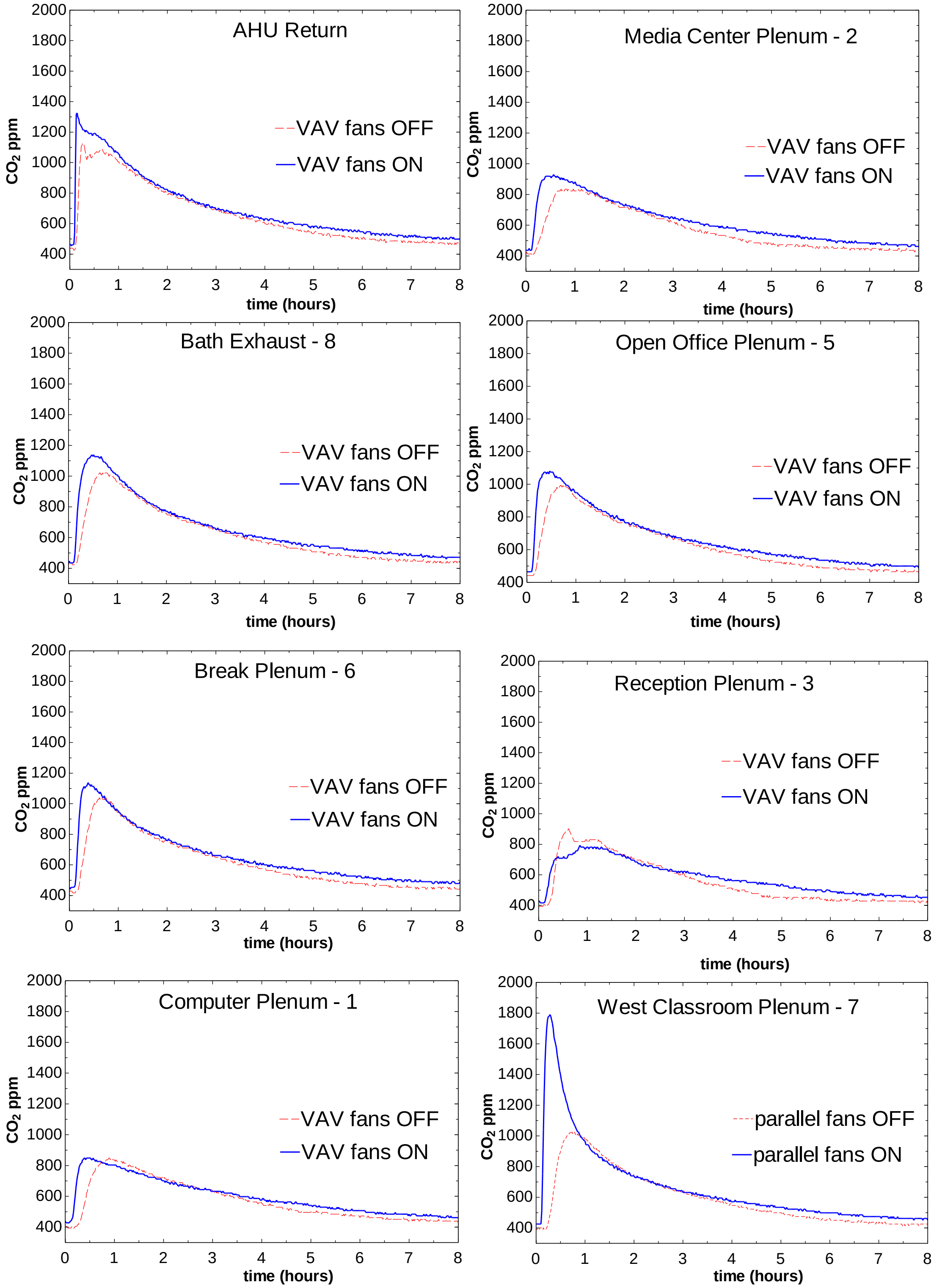


Figure 4-48: Plenum concentration with FPB on and off – Display Room release with release zone mixing

Figure 4-49 shows relative exposure for plenum return tests with parallel fan-powered VAV box fans on and off. Glancing at the transient room concentrations in Figure 4-49 might lead one to believe that the exposures for the two release scenarios would be nearly equal. However, during the Display release, 15 minute exposures were 20 to 50% higher for rooms served by VAV box fans not in the return air pathway. Since the West Classroom VAV box fan was in the return air pathway, operation of the VAV box fan increased the 15 minute exposure by more than 100%. The 8 hour exposures were nearly equal with the exception of the West Classroom, which saw a 20% increase in 8 hour exposure by operation of the VAV box fans.

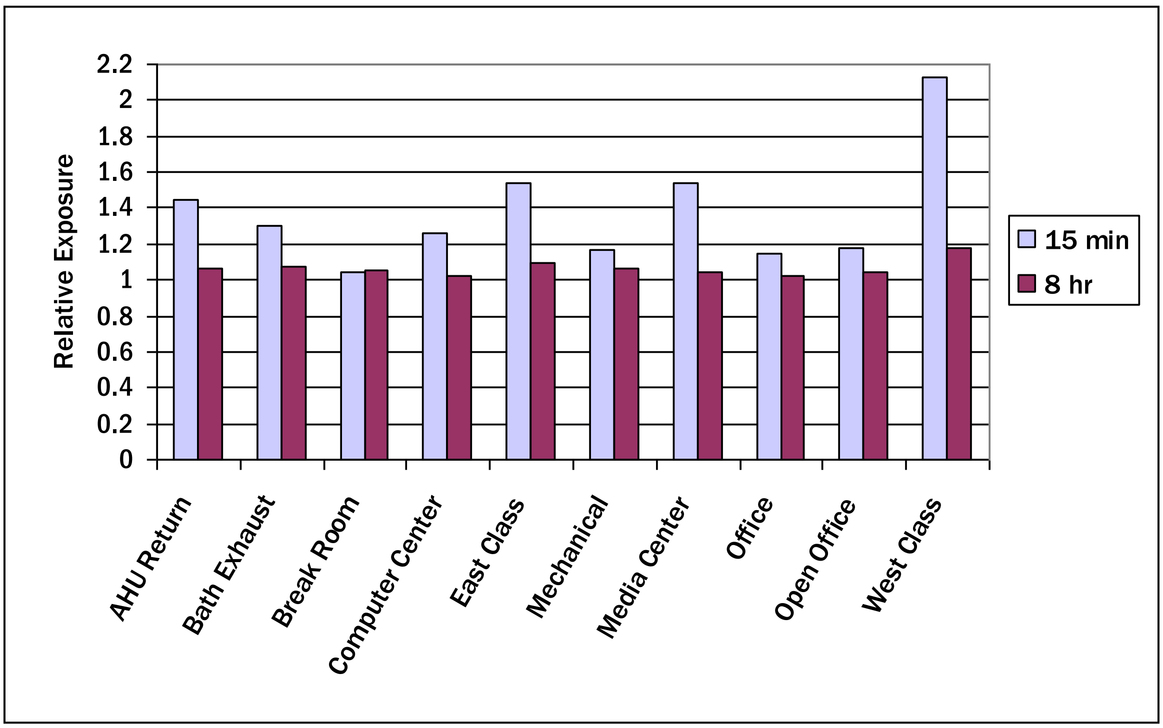


Figure 4-49: Exposure with FPB on relative to exposure with FPB off – Display Room release with release zone mixing

Multizone Model Simulations with Release Zone Mixing

To test the hypothesis that release zone stratification lead to inaccurate simulations of Test 1.5 releases, airflow measurements at the VAV boxes and the AHU fans measured during Test 2.5 were used in the same multizone model discussed above. As well as simulating a release in both locations with plenum return and plenum return with parallel fan powered boxes, a ducted return system was also simulated. The ducted return simulations consisted of placing dampers at the return registers and balancing the zonal return air flows to those measured prior to the simulations. Technicians at the ERS measured return airflows with airflow hoods and balanced the zonal return airflows to equal that of the supply airflows to each zone.

Figure 4-50 compares modeled and measured room concentrations after an Office release with plenum return and release zone mixing. The modeled and measured concentration profiles with release zone mixing show agreement in both the magnitude and timing of the peak in each room. In both modeled and measured cases, the peak occurs roughly 1 hour after the release and with the exception of the West Classroom, the modeled and measured peak magnitudes in each room are within 50 to 100 ppm of each other. However, in each room the modeled concentrations decay more rapidly than the measured concentrations.

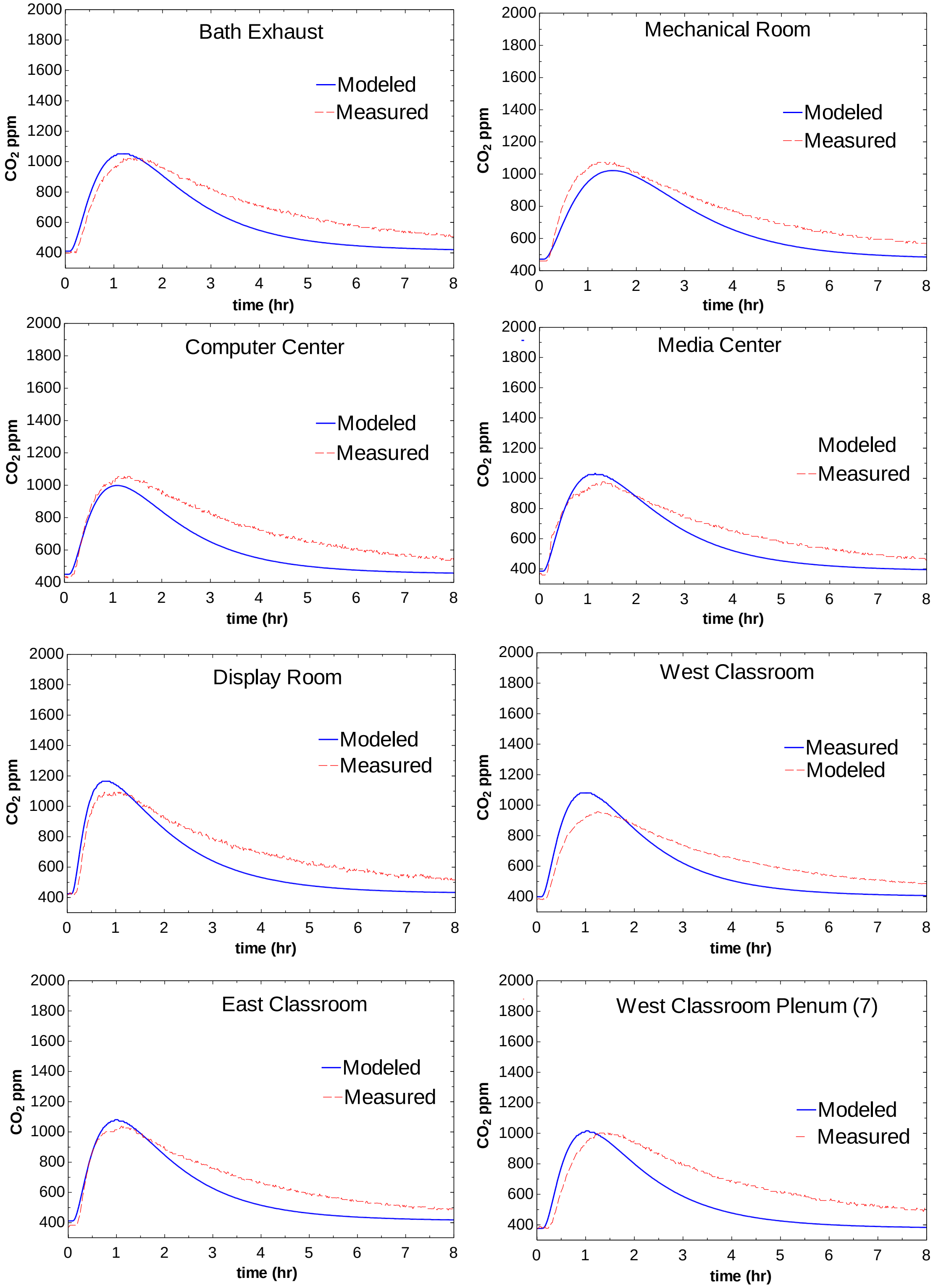


Figure 4-50: Measured and modeled room concentration with plenum return – Office release with release zone mixing

Even though the modeled and measured room concentrations agreed reasonably, the multizone model did not model the plenum concentrations accurately (as seen in Figure 4-51). Since the mixing boxes mixed the tracer throughout the room, the concentration measured at the Reception Plenum sensor (3) spiked instantaneously and was out of range of the plenum sensor. Since zones are assumed to be well mixed, the multizone model did not capture the propagation of tracer across the plenum. However, the profile of the modeled plenum concentration is closer to the profile of the measured plenum concentrations, namely the timing of the modeled peak concentration. In Test 1.5, without release zone mixing (Figure 4-22), the modeled and measured peaks differed by more than 3 hours. Clearly, the comparisons of measured and modeled room concentrations in Tests 1.5 (Figure 4-21) and 2.5 (Figure 4-50) indicate that since multizone modeling does not treat the plenum as a true plenum, it is of more importance to model the timing of the peak rather than the magnitude of the peak. That said, perhaps it is of more importance that the room concentrations were modeled accurately.

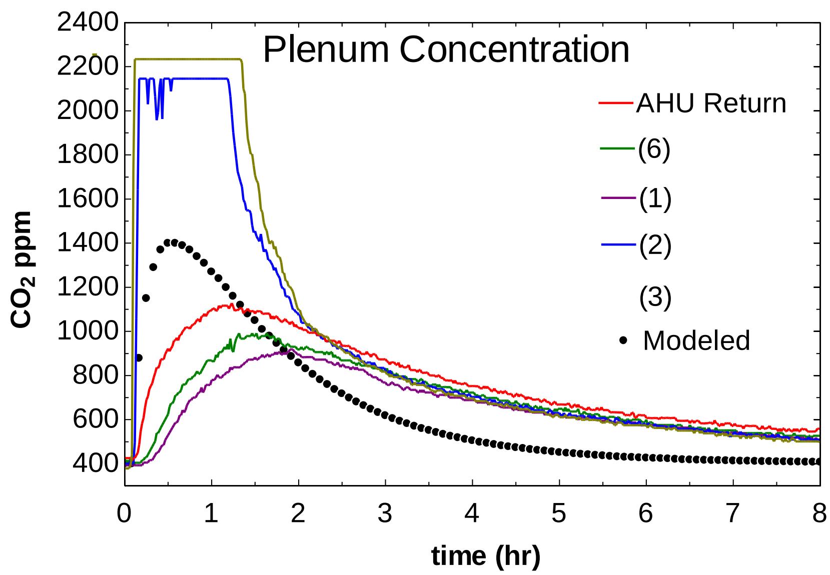


Figure 4-51: Measured and modeled plenum concentration – Office release with release zone mixing

Figure 4-52 compares measured and modeled room concentrations after an Office release with ducted return and release zone mixing. Again, with the exception of the West Classroom, the modeled and measured concentrations are similar in timing and magnitude. The measured and modeled peak concentrations and the timing of the peaks in the Bathroom Exhaust, Computer Center, and Media Center are essentially the same. In the Mechanical Room and East Classroom, the model simulated the timing of the peak concentration accurately, but the measured peak concentration is roughly 100 ppm greater than the modeled peak concentration. The model simulated the timing of the peak concentration in the Display Room accurately, but the modeled concentration is roughly 200 ppm greater than the measured concentration. However, in the West Classroom, the measured peak concentration was 1000 ppm compared to a modeled peak concentration of 1500 ppm, and the timing of the measured and modeled peaks was essentially the same at 30 minutes after the release. As with the Office release with plenum return, the modeled concentrations decayed more rapidly than the measured concentrations.

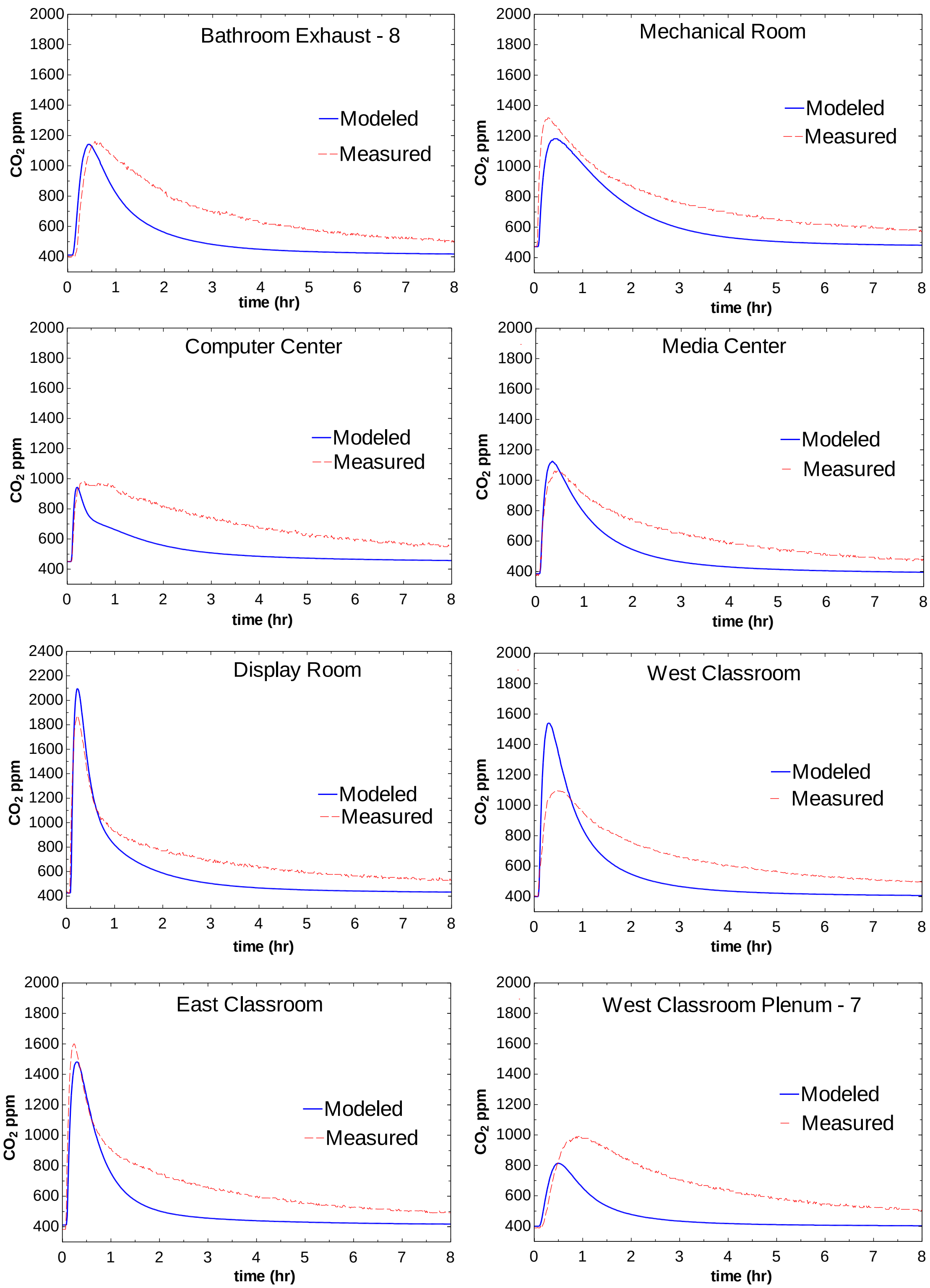


Figure 4-52: Measured and modeled room concentration with ducted return – Office release with release zone mixing

The results from the modeled and measured plenum concentrations, specifically the West Classroom and West Classroom Plenum Sensor (7), may offer a reason for the discrepancy. Figure 4-53 compares measured and modeled plenum concentrations after an Office release with ducted return. Since the tracer is conveyed to the AHU by return ducts, the concentration in the plenum never exceeds the range of the sensor, as it did along the return air pathway in the plenum return tests. The modeled concentration was consistently lower than the measured plenum concentration. As seen in Figure 4-52, the measured peak concentration in the West Classroom Plenum is 200 ppm greater than the modeled peak concentration, which implies that the room pressurization and the leakiness of the suspended ceiling in the West Classroom were not modeled accurately. Since the multizone model treats tracer passing through the return grille the same as tracer leaking across the suspended ceiling with a plenum return, modeling the leakage characteristics of the suspended ceiling was of less importance in the plenum return cases. However, in the ducted case, tracer in the plenum results from either duct leakage or positive room pressurization. Taken alone, the discrepancy in measured and modeled concentrations in the West Classroom could lead one to believe that multizone modeling does not accurately simulate ducted return system, but if the leakage characteristics of the suspended ceiling were modeled more accurately in the West Classroom, the modeled and room concentrations could conceivably be comparable.

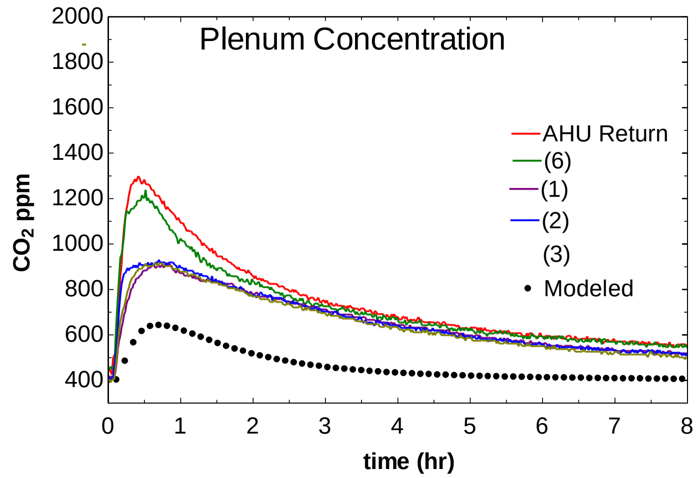


Figure 4-53: Measured and modeled plenum concentration with ducted return – Office release with release zone mixing

Figure 4-54 compares measured and modeled room concentrations after a Display release with plenum return and release zone mixing. In every room, the multizone modeled simulated the timing of the modeled concentration accurately, and with the exception of Media Center and the West Classroom, the measured and modeled peak concentrations differed by less than 100 ppm. In the both the Media Center and West Classroom, the measured and modeled peak concentrations differed by 400 ppm. Figure 4-55 compares measured and modeled plenum concentrations after the same release. As with the Office release with plenum return, the measured and modeled plenum concentrations did not agree. However, the profile of the modeled plenum concentration is closer to the measured plenum concentrations with release zone mixing. Without mixing (Figure 4-26), the concentration measured at the Display Room Plenum sensor (4), shown in orange, peaks quickly following the release, but remains at nearly the same concentration for 2 hours before decaying to ambient concentrations. With mixing, the concentration at the Display Room Plenum sensor (4) is out of range of the sensor for roughly 30 minutes, so we cannot know what the peak concentration was, but the multizone model simulated the timing of the peak more accurately than with no release zone mixing.

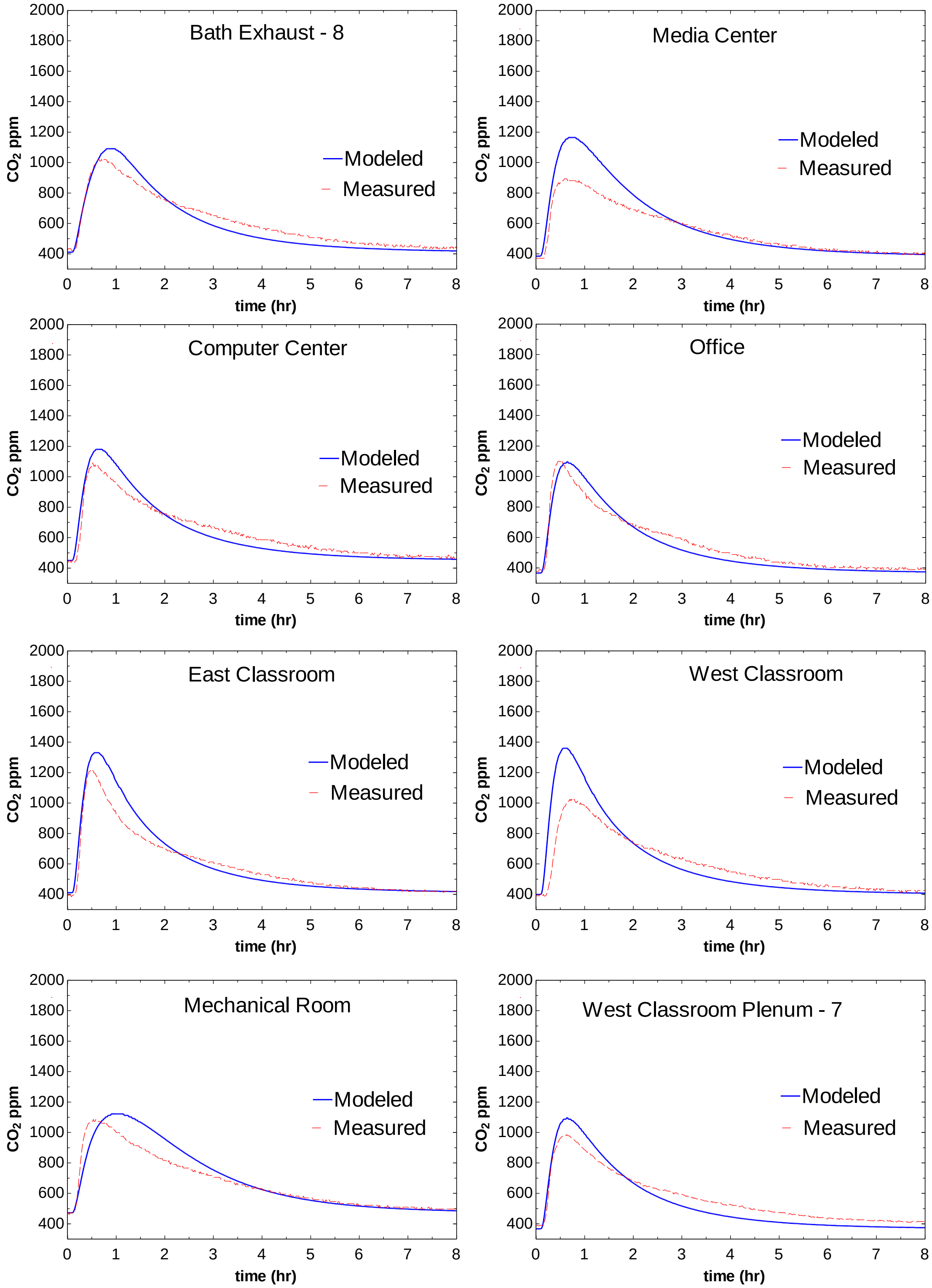


Figure 4-54: Measured and modeled room concentration with plenum return – Display Room release with release zone mixing

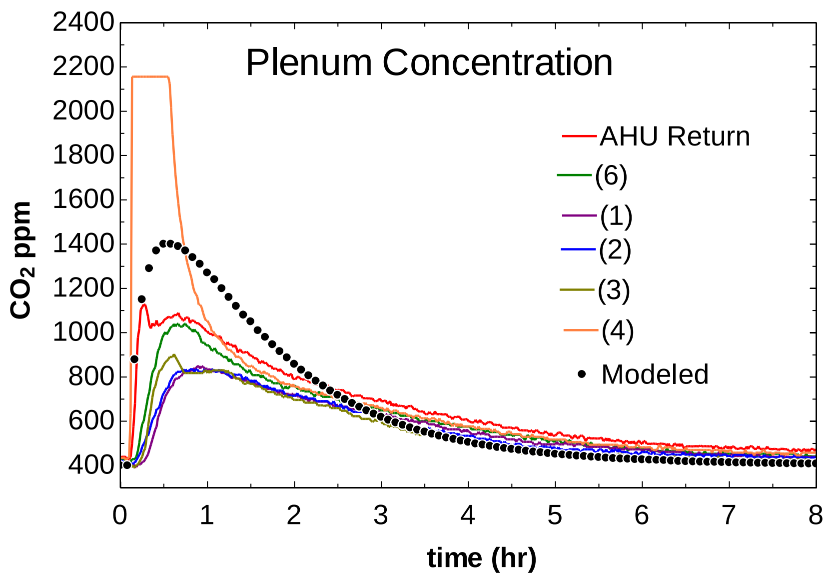


Figure 4-55: Measured and modeled plenum concentration with plenum return – Display Room release with release zone mixing

Figure 4-56 compares modeled and measured room concentrations after a Display Room release with ducted return and release zone mixing. The multizone model simulated both the magnitude and the timing of the peak concentration in the Bathroom Exhaust, Computer Center, East Classroom, and the Mechanical Room. However, in the Media Center, Office, and West Classroom, the multizone model did not simulate the concentration profiles accurately. The measured peak concentration in the Media Center of 900 ppm occurred approximately one hour after the release, whereas the modeled peak concentration was 200 ppm higher and occurred 30 minutes earlier. In the Office, the measured and modeled peak concentration was essentially equal, but the modeled peak concentration occurred approximately 30 minutes earlier. The measured and modeled concentrations in the West Classroom and West Classroom Plenum were significantly different, leading one to believe that a leakage path existed between the Display Room and the West Classroom. In the West Classroom, the measured concentration was out of range of the sensor for approximately one hour, but the modeled peak concentration was 1300 ppm. The measured concentration in the West Classroom Plenum peaked at 2000 ppm, whereas the modeled concentration peaked at only 600 ppm. Figure 4-57 compares measured and modeled plenum concentrations after the same release. Based on results from previous tests, the West Classroom Plenum (7) and Display Room Plenum (4) concentration profiles, are unusually high for a ducted return system, which suggests leakage or a considerable release room over-pressurization.

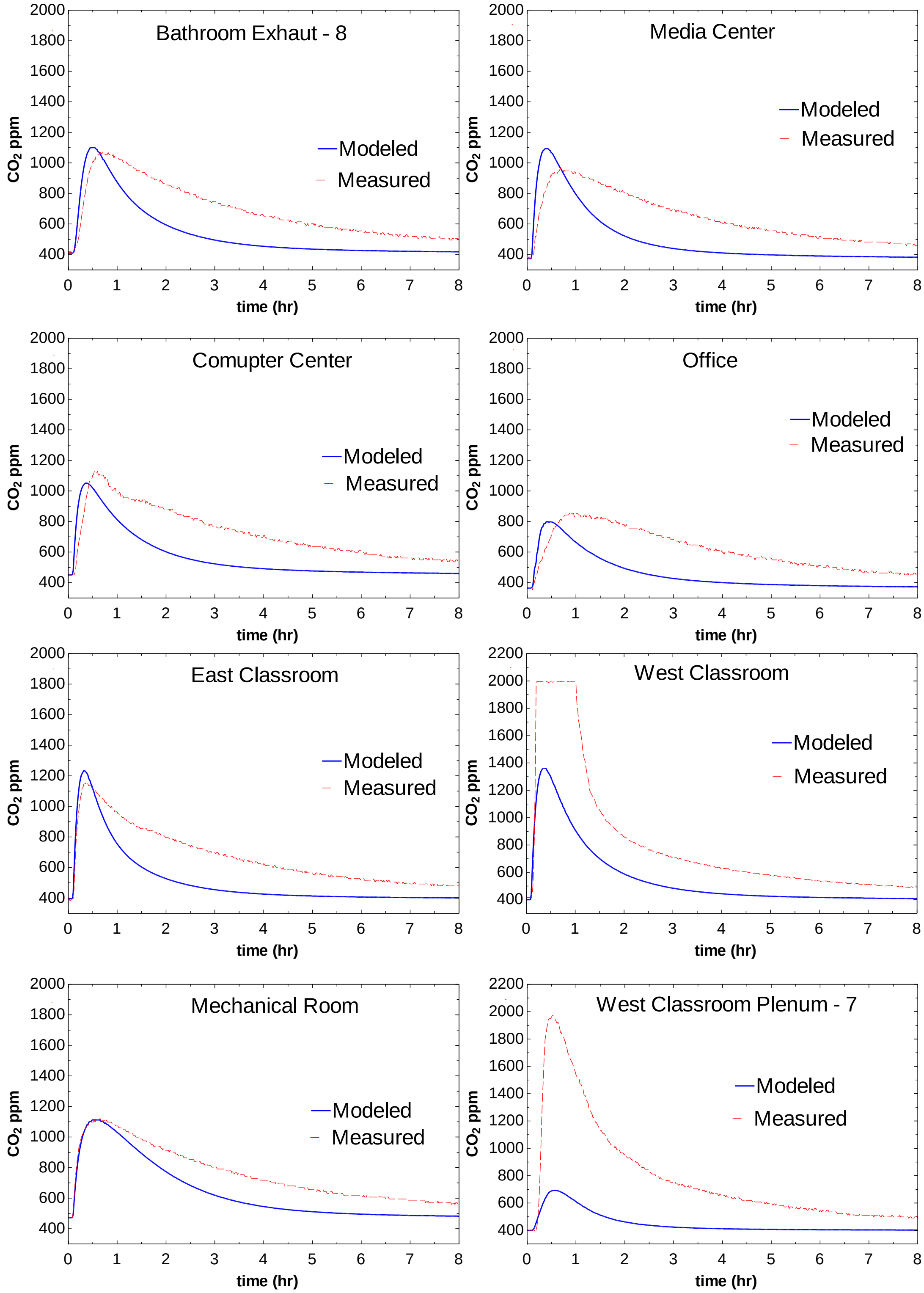


Figure 4-56: Measured and modeled room concentration with ducted return – Display Room release with release zone mixing

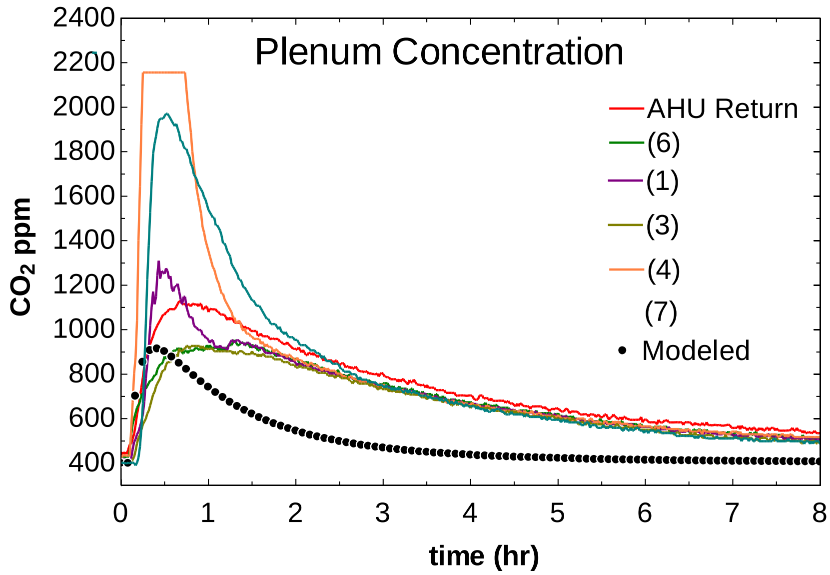


Figure 4-57: Measured and modeled plenum concentration with ducted return – Display Room release with release zone mixing

As with the measured results without release zone mixing, the multizone model did not accurately simulate the impact of parallel fan powered boxes in transporting tracer from the plenum to conditioned spaces.

Figure 4-58 compares measured and modeled room concentrations after an Office release with VAV box fans on and release zone mixing. The inaccuracy can most clearly be seen in the results of the Computer Center. Since the mutlizone model assumes that the plenum is well mixed, every VAV box fan draws air from the same high concentration return air. However, the measured results from an Office release with the VAV box fans on and off (Figure 4-44) show that the impact of the VAV box fans is non uniform, with fans lying in the path of higher concentration return air creating a greater impact on space concentration. The measured results from the Office release with VAV box fans on and off are the same for the Computer Center, Display Room, and East Classroom, which indicates that in both cases tracer reaches these spaces via primary air only. The VAV box fan serving the Computer Center, Display Room, and East Classroom do not lie in the return air pathway from the Office (Figure 3-10 and Figure 3-11), so tracer short circuits these boxes. As a result of the well mixed assumption, modeled concentrations peak at higher magnitudes and earlier than the measured concentrations. The modeled Computer Center concentration peaks instantly at 1700 ppm, whereas the measured concentration peaks at 1000 ppm approximately one hour after the release. In the Display Room, the modeled concentration peaks at 1400 ppm less than 30 minutes after the release, whereas the measured concentration peaks at 1200 ppm approximately 1 hour after the release, and in the East Classroom, the modeled concentration peaks at 1300 ppm less than 30 minutes after the release, whereas the measured concentration peaks at 1100 ppm, less than 1 hour after the release.

The results are similar for the Display Room release with VAV box fans on and release zone mixing. Figure 4-59 shows modeled and measured room concentrations after a Display Room release with VAV box fans on and release zone mixing. Even though the VAV box fans serving the Media Center, Office and Computer Center, are not in the return air pathway of the Display Room release (Figure 3-10 and Figure 3-11), the modeled results show instantaneous increases in these spaces. Measured results (Figure 4-47) show that spaces not in the path of high concentration return receive tracer via primary only. The modeled Computer Center concentration peaks instantly at 1700 ppm, whereas the measured concentration peaks at 900 ppm approximately less than 30 minutes after the release. In the Media Center, the modeled concentration peaks at 1400 ppm less than 30 minutes after the release, whereas the measured concentration peaks at 900 ppm approximately 30 minutes after the release, and in the Office, the modeled concentration peaks at 1500 ppm less than 30 minutes after the release, whereas the measured concentration peaks at 800 ppm, approximately 1 hour after the release.

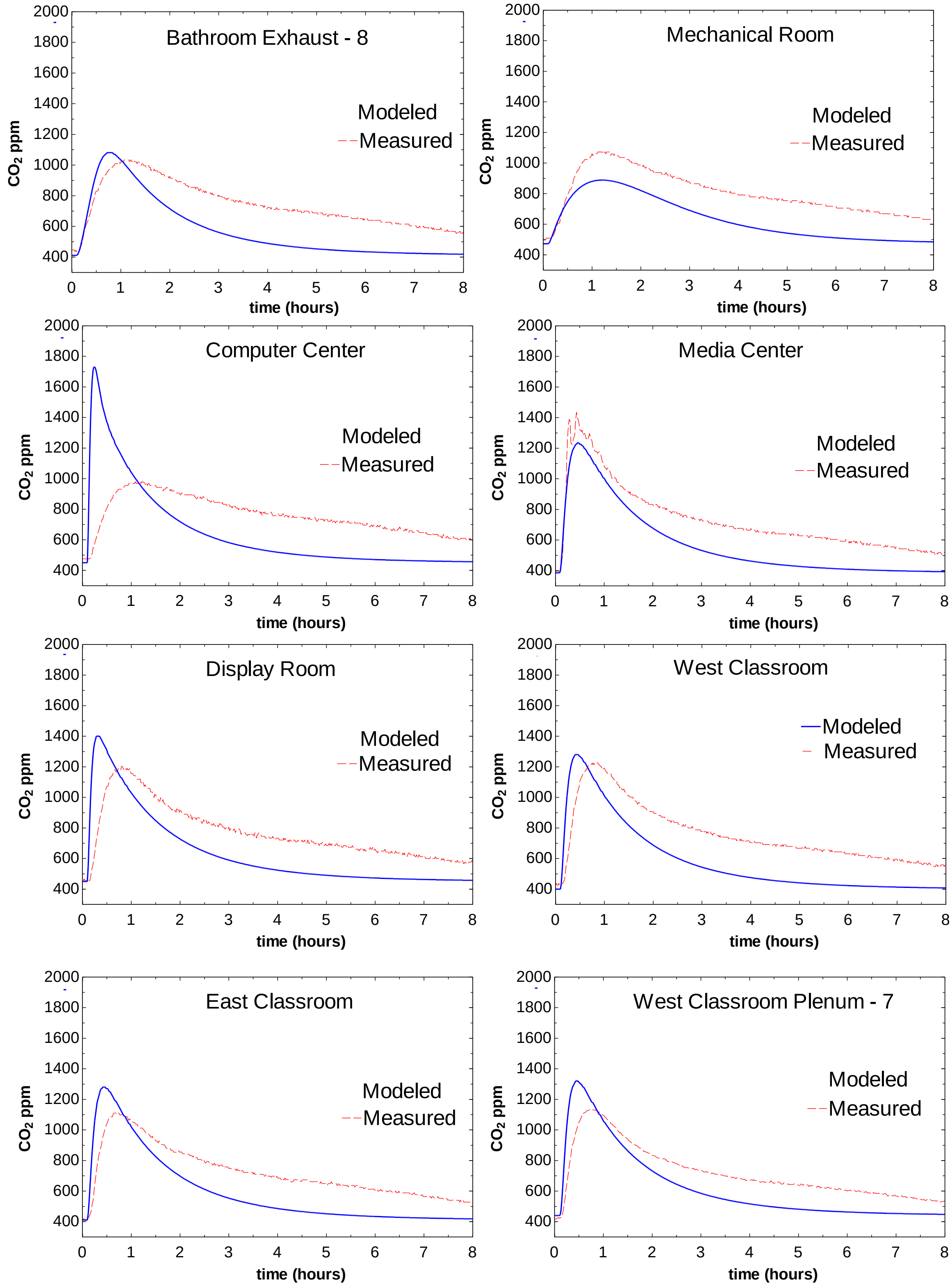


Figure 4-58: Measured and modeled room concentration with FPB on – Office release with release zone mixing

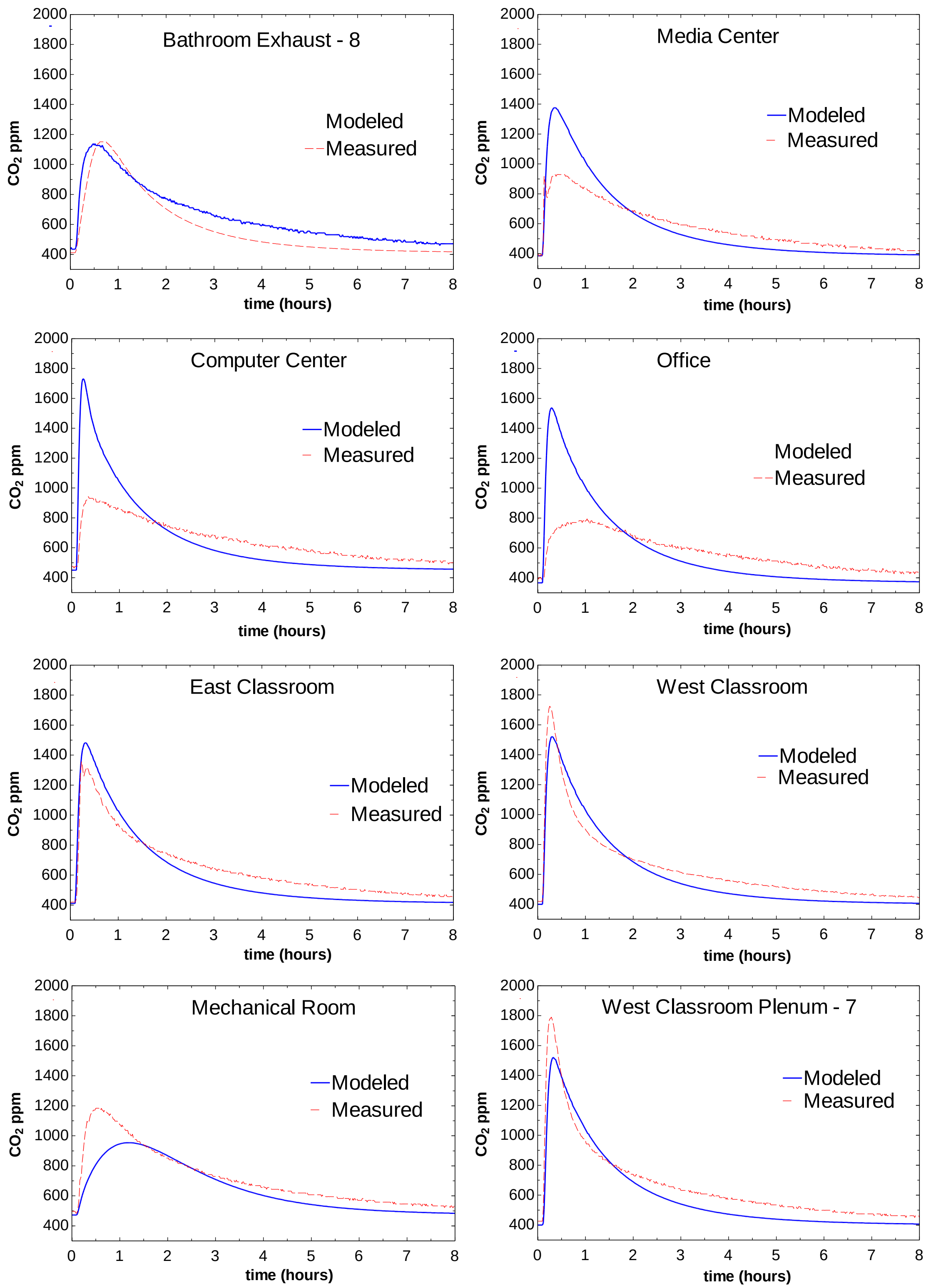


Figure 4-59: Measured and modeled room concentration with FPB on – Display Room release with release zone mixing

Discussion and Conclusions

CO_2 tracer gas tests were conducted in the general service area to compare resistance of ducted and plenum return air systems to interzonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space. To determine inter-zonal contamination vulnerability of each return air strategy, multizone model results were compared to tracer gas measurements. Based on the results presented above, the following conclusions may be drawn.

- Contrary to recommendations found in much building security literature, plenum return does not inherently pose a greater risk of exposure to building occupants. Plenum return, in some cases, may provide greater protection to occupants during the time immediately following a contaminant release, during which evacuation can take place by delaying the entry of contaminants into occupied spaces.
- The impact of parallel fan powered boxes is non-uniform with fans lying in the path of higher concentration return air creating a greater impact on space concentration. Fan powered VAV boxes tend to diminish the buffering effect of the plenum because they may inject highly contaminated return air into occupied spaces.
- The differences in cumulative exposure between plenum and ducted return in the event of a transient exposure diminishes with time.
- For releases with release zone mixing, plenum and concentrations peak at higher concentrations sooner following a release and decay to ambient levels

more rapidly to ambient levels compared to releases without release zone mixing.

- Assumptions inherent in multizone modeling, most notably well mixed zones with uniform contaminant concentrations, restrict multizone modeling's applicability in determining inter-zonal contamination vulnerability of return air strategy. Since the model assumes a well mixed plenum, simulating the transport of contaminants from the plenum to conditioned spaces by parallel fan powered boxes was not possible. Although there were instances in which multizone modeling accurately simulated inter-zonal contaminant concentration with release zone mixing, simulations were not consistent for different release zone locations and return air strategies.

The results reported here come from a limited study in a single building. The data obtained in this study does not support definitive conclusions regarding whether plenum return is comparable to or superior to ducted return. However, it does clearly cast doubt on the rather categorical statements found in many published sources that ducted return is inherently superior than plenum return (ASHRAE 2003, NIOSH 2002, FEMA 2003, USACE 2001). As in many facets of engineering, the merits of one approach or the other vary with the situation.

Chapter 5

RESULTS – PARAMETRIC MULTIZONE MODEL

To assess the inter-zonal contamination resistance of different return air systems on a whole building level, contaminant dispersal of a generic gas and inter-zonal airflow was simulated in a hypothetical office building using multizone modeling (Walton and Dols, 2005). In multizone modeling, a building is represented by well-mixed zones connected by airflow paths were the airflow between each zone is calculated by conservation of mass and airflow-pressure relationships. Since zones are assumed to have uniform pressure and contaminant concentrations, multizone modeling is best suited for macro building simulations.

Parametric Matrix

A parametric matrix, seen in Table 3-4, was developed to isolate the impact of individual parameters on contaminant dispersal. Building and site parameters, such as climate, envelope air tightness and return air system type, and HVAC parameters, such as HVAC system type, zoning, and duct leakage, were varied and the results were compared to the base case to assess the impact of each parameter on inter-zonal contaminant transfer, inter-zonal airflow and moisture intrusion. The base building was defined as a pressurized building operating in neutral weather with average envelope tightness, floor-by-floor zoning, and ASHRAE recommended levels of duct leakage. Since CONTAM is a multizone modeling program without the ability to couple thermal and airflow calculations, constant zonal airflow rates were used to simulate a VAV system in steady-state operation. Buildings operate at part load conditions for the majority of the year, so zonal airflow rates of 0.5 cfm/ft^2 for part load conditions arising from neutral weather were used for the majority of the parametric runs. However, design heating and cooling zonal airflows were used to compare contaminant dispersal at design conditions. Airflow rates at design cooling and heating conditions were assumed to be 1.0 cfm/ft^2 and 0.35 cfm/ft^2, respectively. Outdoor airflow rates were held constant, at 0.2 cfm/ft^2 for each simulation.

Base Case

Using a part load primary airflow of 0.5 cfm/ft^2, 0.2 cfm/ft^2 outdoor airflow rate and a burst release in the 1st floor lobby, seen in orange in Figure 3-14, CONTAM simulations of the base case were run. The building was pressurized by varying return airflow to maintain a 0.02 in. w.g. pressure differential w.r.t. the exterior. For ducted return and DOAS, return airflow was balanced for each room and for plenum return, return grilles were placed throughout the building to equalize ceiling pressure differential in each room. Primary air and outdoor air fraction for each return system was consistent with exception of the DOAS system. In a dedicated outdoor air system (DOAS), the sensible and latent loads are decoupled, so the supply airflow is assumed to be 0.15 cfm/ft^2, the same outdoor air flow as in the other base cases. With the DOAS system, the remaining sensible load is assumed to be served by a parallel system. With the fan powered box case, primary air was the same as the ducted and plenum return cases, with the parallel fan powered box delivering the 0.35 cfm/ft^2 of plenum air.

Figure 5-1 compares maximum lobby concentration as a function of time for each return air system. Since the primary air change rate for the DOAS system is lower than the other systems and since DOAS systems are one-pass systems, the majority of the contaminant remains in the release zone. With the ducted, plenum and plenum with fan powered box (w/fpb) systems, contaminant reaches the AHU and is recirculated to the rest of the building. However, DOAS does offer one advantage compared to other HVAC systems with recirculation. Since the DOAS system is a one-pass system, contaminant released in the lobby is exhausted and reaches the rest of the building through zonal pressurization and air leakage. Figure 5-2 compares 1st floor concentration normalized by maximum lobby concentration for each return air system. 1st floor concentration peaks at 4%, 3%, and 2.75% of the maximum lobby concentration for ducted return, plenum return with fan powered boxes, and plenum return systems, respectively. Since the DOAS system is a one-pass system with the lobby at a lower pressure relative to the rest of the floor, contaminant does not reach the rest of the floor.

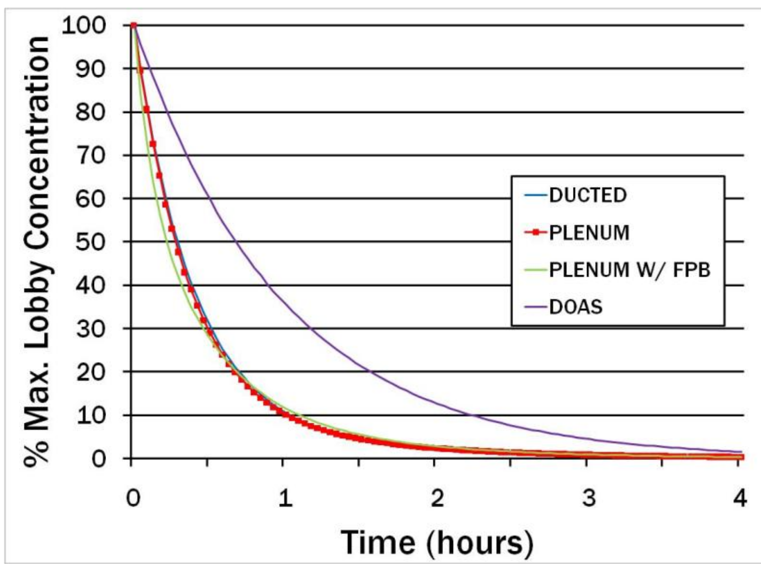


Figure 5-1: Normalized Lobby Concentration – Base Case

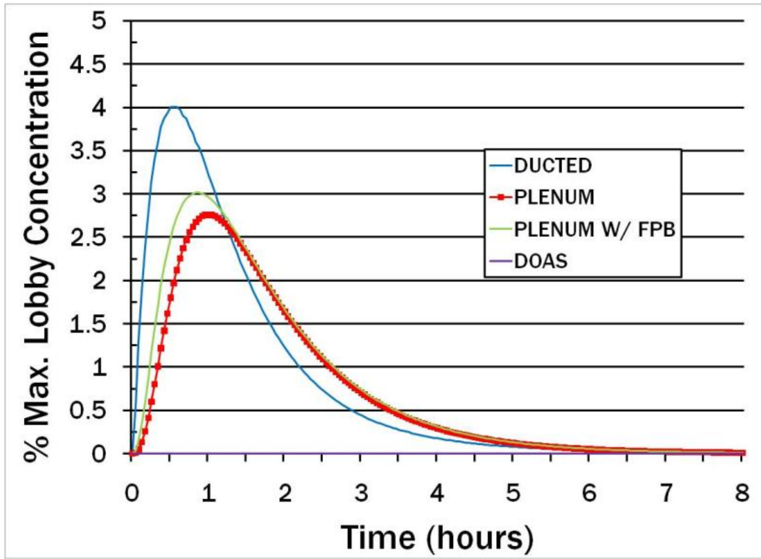


Figure 5-2: Normalized First Floor Office concentration – Base Case

Even though the ducted return, plenum return and plenum return with fan powered box systems receive the same primary supply air and outdoor air, the 1st floor concentration is different for each return case. Figure 5-3 and Figure 5-4 show the Normalized Lobby Plenum and Normalized Open Plenum concentrations, respectively, for each return air system. For both plenum return systems, immediately following the release, the lobby plenum concentration increases to close to 50% of the maximum lobby concentration, compared with fractions of a percent of the maximum lobby concentration for the ducted return and DOAS systems. With the ducted return and DOAS systems, contaminant is returned or exhausted through ductwork and contaminant reaches the plenum through zonal pressurization. As seen in Figure 5-4, Open Plenum concentration for the plenum return systems increase to approximately 4% of maximum lobby concentration compared 2% of maximum lobby concentration for ducted return and DOAS systems. The multizone model indicates that the plenum zone acts as a buffer, in which the contaminant is diluted by lower concentration return air before being recirculated by the AHU.

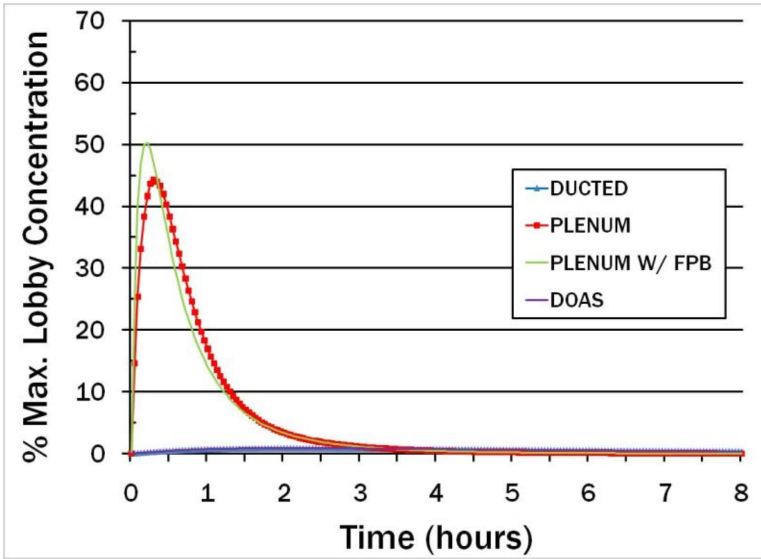


Figure 5-3: Normalized Lobby Plenum concentration – Base Case

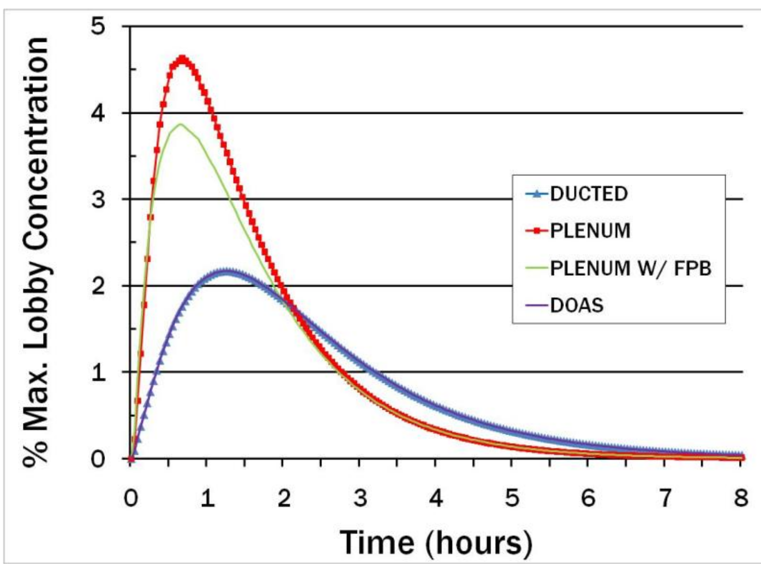


Figure 5-4: Normalized Open Plenum concentration – Base Case

15 minute and 8 hour Lobby and 1st floor exposures are compared in Figure 5-5 for each return system. In this case, exposures are relative to the ducted case for each time period and each zone. For example, the relative lobby exposure for the plenum return system was calculated by dividing the lobby exposure with plenum return by the lobby exposure with ducted return. 15 minute lobby exposures are essentially equal for ducted and plenum return systems, and 15 minute lobby exposure with fan powered boxes is approximately 90% of 15 minute lobby exposure with ducted return. With DOAS, the 15 min lobby exposure is 20% higher than with ducted return. Since DOAS has a lower air change rate, after 8 hours the lobby exposure for the DOAS system is twice that of ducted return and plenum return w/fpb systems. After 8 hours, exposure with both plenum return systems is equal to exposure with ducted return.

The difference in 1st floor exposure is more significant. 15 minute 1st floor exposure is 10% and 25% of the 15 minute exposure with ducted return for plenum return and plenum return w/fpb, respectively. 8 hour exposure with plenum return is approximately 90% the exposure of ducted return. Operation of the fan powered boxes increases the 8 hour exposure to 95% that of the exposure with ducted return. Since the DOAS system is a one-pass system, contaminant does not reach the 1st floor office area.

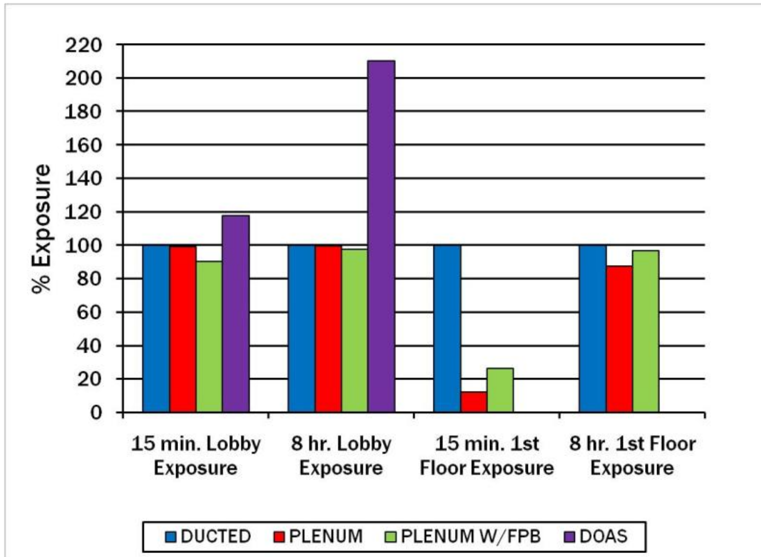


Figure 5-5: Lobby and First Floor exposure (relative to ducted) – Base Case

Climate

The impact of climate on contaminant dispersal was investigated by varying design heating and cooling zonal airflows from the base case assumption of 0.5 cfm/ft^2. Primary airflow rates at design cooling and heating conditions were assumed to be 1.0 cfm/ft^2 and 0.35 cfm/ft^2, respectively. In each case, outdoor airflow rates were assumed to be constant at 0.2 cfm/ft^2. Figure 5-6 and Figure 5-7 show First Floor Office concentration for the different airflow rates with ducted return and plenum return, respectively. 1st floor concentration with ducted return peaked at 6%, 4%, and 2% of maximum lobby concentration for summer, neutral, and winter airflow rates, respectively. With plenum return, 1st floor concentration peaked at approximately 5%, 3%, and 1% of maximum lobby concentration for summer, neutral, and winter climates, respectively. Peak concentrations occurred approximately 30 minutes after the release for ducted return systems for each climate, but the plenum return system introduced a time delay. Peak concentrations occurred approximately 30 minutes, 1 hour, and 1.5 hours after the release, for summer, neutral and winter airflow rates, respectively.

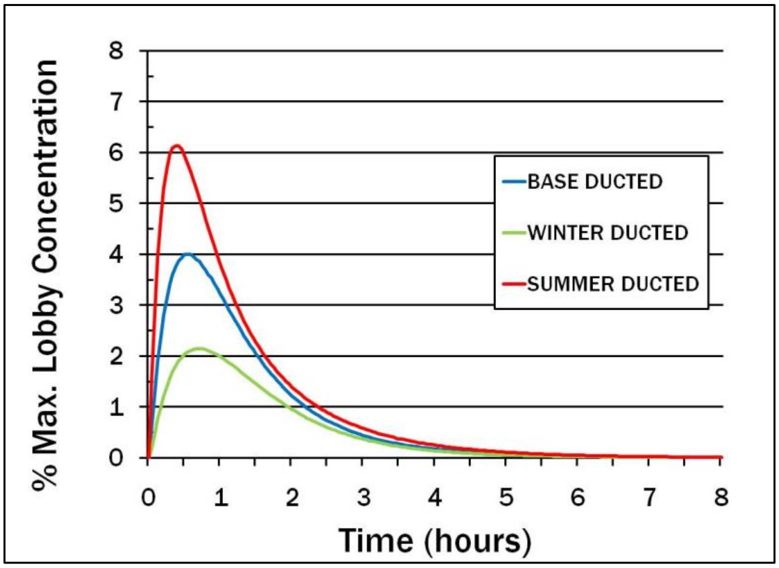


Figure 5-6: First Floor Office concentration with ducted return – Climate

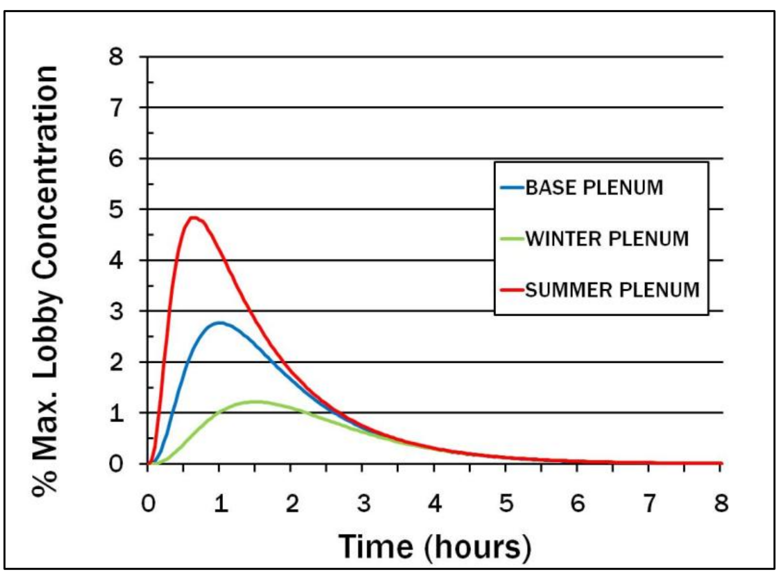


Figure 5-7: First Floor Office concentration with plenum return – Climate

Figure 5-8 and Figure 5-9 show First Floor Office exposure relative to the base case for ducted and plenum return air systems. In this case, exposure results are presented in the form of exposure with summer and winter climates relative to the base case for each return system (i.e. ducted return systems are being compared with ducted return systems). With ducted return, 15 minute exposure with summer and winter air flow rates was 200% and 50% of exposure with neutral airflow rates, respectively. 8 hour exposure with summer and winter airflow rates was 130% and 60% of exposure with neutral airflow rates, respectively. Since the plenum return system introduced time lag to the peak concentrations, 15 minute exposures increased from summer airflow rates and decreased from winter airflow rates by a significant amount. 15 minute exposure with summer airflow rates was close to 500% that of exposure with neutral airflow rates, while 15 minute exposure with winter airflow rates was less than 25% that of exposure with neutral airflow rates. The impact of airflow rates on 8 hour exposure was not as significant and similar in magnitude to the 8 hour relative exposures with ducted return. Figure 5-10, a comparison of 1st floor exposure with plenum return relative to exposure with ducted return for each climate, indicates that the plenum acts as a buffer between the release zone and space for all airflow rates. 15 minute exposure with plenum return was 30%, 10%, and 5% of exposure with ducted return for summer, neutral and winter airflow rates, respectively. 8 hour exposure with plenum return was between 95% and 80% of exposure with ducted return for summer, neutral and winter airflow rates.

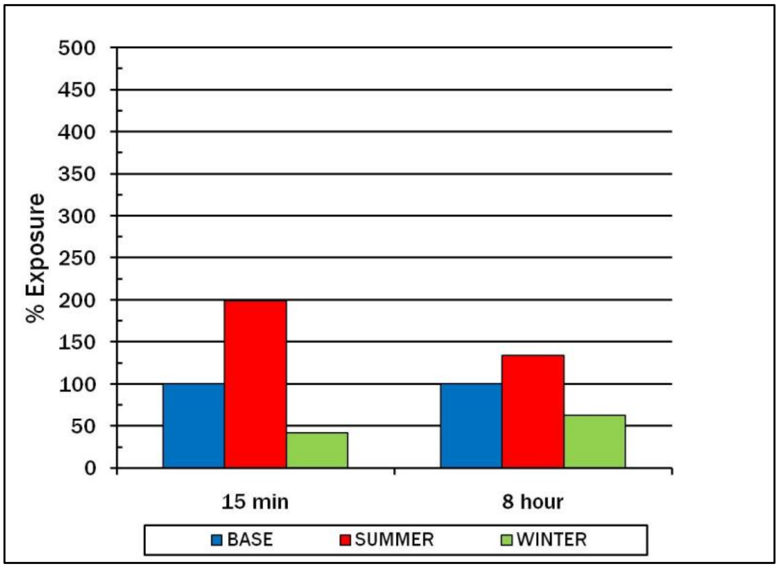


Figure 5-8: First Floor Office exposure with ducted return (relative to Base case with ducted return) - Climate

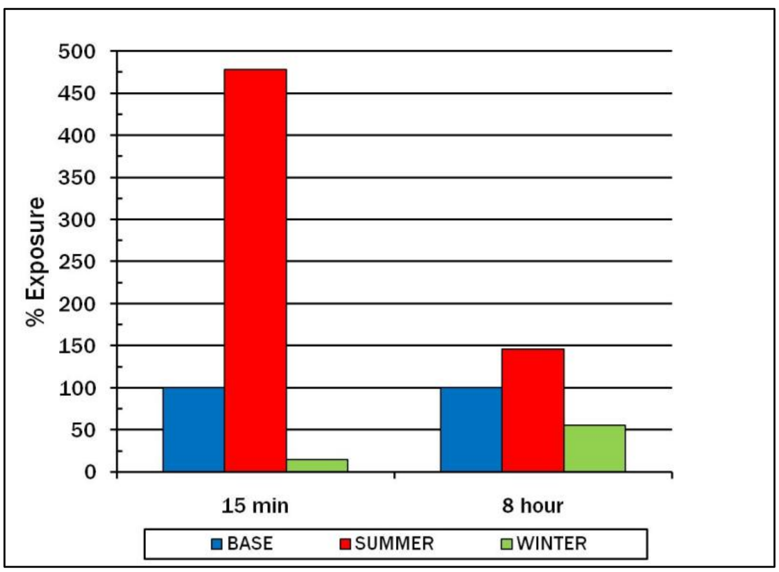


Figure 5-9: First Floor Office exposure with plenum return (relative to Base Case with plenum return) - Climate

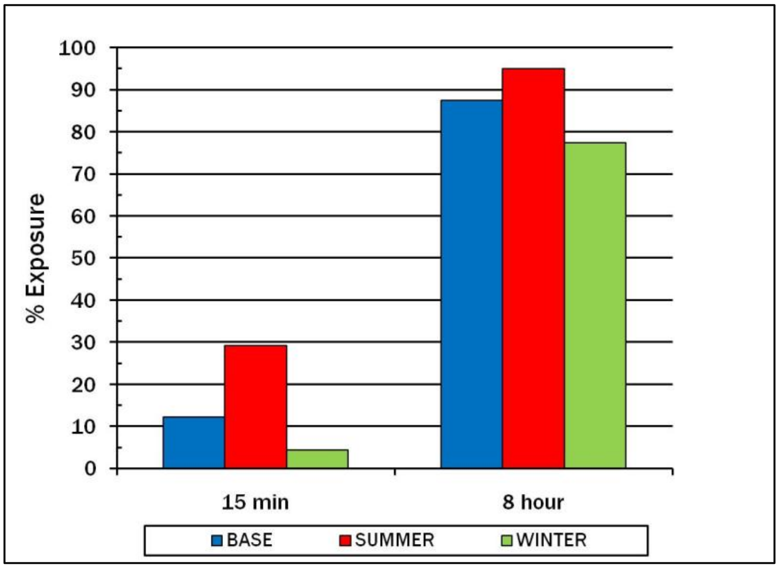


Figure 5-10: First Floor Office exposure with plenum return (relative to ducted return for each climate) - Climate

Envelope

The impact of building envelope tightness on contaminant distribution and building exposure was investigated by comparing results with a tight and leaky envelope with results with an average envelope tightness assumed in the base case. Persily (1999) collected data on the air tightness of 139 commercial buildings, including office buildings, schools, retail buildings, industrial buildings, collected from published literature. To determine the air tightness of a building, the building is pressurized during a series of tests, generally from 10 Pa to 75 Pa, and the air flow required to induce each level of pressurization is measured. Once the results are fitted to the curve represented in Equation 2-1, and the coefficient, C, and the empirical flow exponent, n, are determined, leakage at any pressure difference can be determined.

Building envelope tightness will affect envelope and space pressurizations in buildings, so buildings will be modeled using leaky and tight values found in the literature. An example of leaky and tight ceilings used in office buildings are gypsum board and suspended tile ceilings. Withers and Cummings (2000) measured air tightness directly of suspended tile ceilings in two buildings and found that the suspended tile ceilings were approximately 10 times leakier than gypsum board ceilings. The suspended tile ceilings had an air tightness of 5.0 cfm / ft^2 ceiling area at 0.2” w.g., equivalent to an effective leakage area of 19 cm^2/m^2 at 4 Pa. Average effective leakage areas of office exterior walls measured by Persily and Ivy (2001) was 4.8 cm^2/m^2 at 4 Pa. For this study, leaky walls have an effective leakage area of 7.8 cm^2/m^2 at 4 Pa, which is mean air tightness plus one standard deviation, and tight walls will have an effective leakage area of 0.4 cm^2/m^2 at 4 Pa, which is mean air tightness minus one standard deviation. For each envelope tightness, supply and outdoor airflow were held constant and return airflow was varied to maintain a pressure difference of 5 Pa (0.02” w.g.).

15 minute and 8 hour exposure in the 1^{st} floor office are shown in Figure 5-11 and Figure 5-12 with ducted and plenum return for each envelope tightness. Both 15 minute and 8 hour exposure was approximately 10% higher with a leaky envelope compared to an average envelope. With a leaky envelope, a greater difference between supply and return airflow is needed to maintain the pressure difference than with an average envelope. With less return airflow in each zone, less contaminant is returned to the HVAC system and therefore, less contaminant is exhausted. Surprisingly, with a tight envelope and ducted return, 15 minute and 8 hour exposure was essentially the same compared to an average envelope, though why this is the case is not apparent. Following the logic assumed in comparing results from an average and leaky building, one would assume that with a tight envelope, a smaller difference between supply and return airflow is needed to maintain the same pressure difference when compared to an average envelope tightness. With more contaminant returned to and therefore exhausted by the HVAC

system, one would expect the exposure with a tight envelope tightness to be lower than with an average envelope tightness. Figure 5-12 compares 15 minute and 8 hour exposure in the 1st floor office with plenum return for each envelope tightness. With a leaky envelope, 15 minute exposure and 8 hour exposure was 80% and 90% that of exposure with an average envelope. With a leakier building, more contaminant leaves the building through exfiltration in the zone and in the plenum and less contaminant leaves the building through the exhaust at the HVAC system. With a tight building, 15 minute and 8 hour exposure was 90% that of exposure with an average envelope. Since a smaller difference between supply and return airflow is required to maintain the same pressure difference as with the average envelope, more return airflow leaves the zone and contaminant reaches the HVAC system and is exhausted at a higher rate. Figure 5-13 shows 15 minute and 8 hour exposure with plenum return relative to ducted return for each envelope tightness. 15 minute and 8 hour exposure with plenum return were approximately 15% and 80% that of exposure with ducted return across the range of envelope tightness. When comparing plenum return to ducted return with the same envelope, the impact of the plenum volume is consistent in providing a short term protection in the form of a buffer between the release zone and the remaining building occupants.

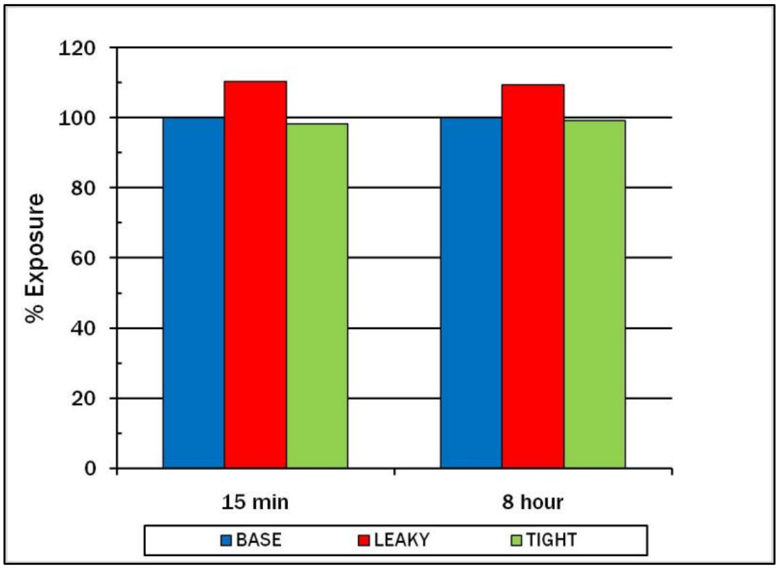


Figure 5-11: First Floor Office exposure with ducted return (relative to Base Case with ducted return) - Envelope

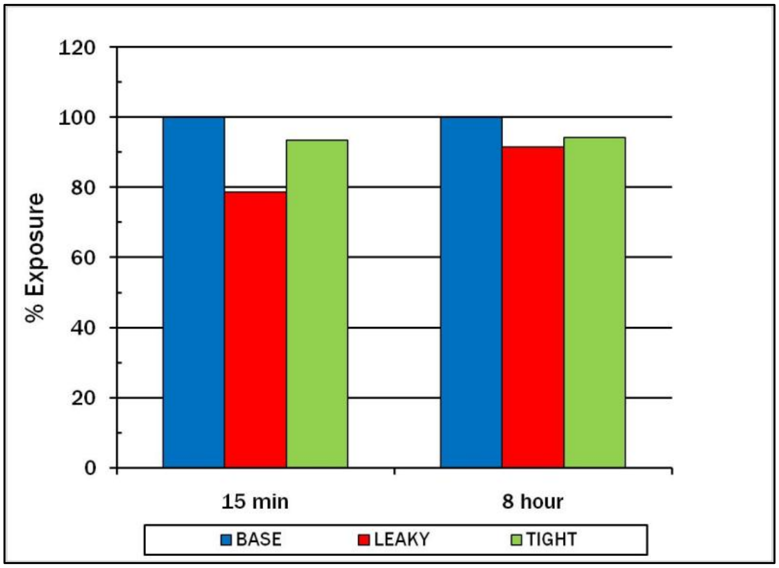


Figure 5-12: First Floor Office Exposure with plenum return (relative to Base Case with plenum return) - Envelope

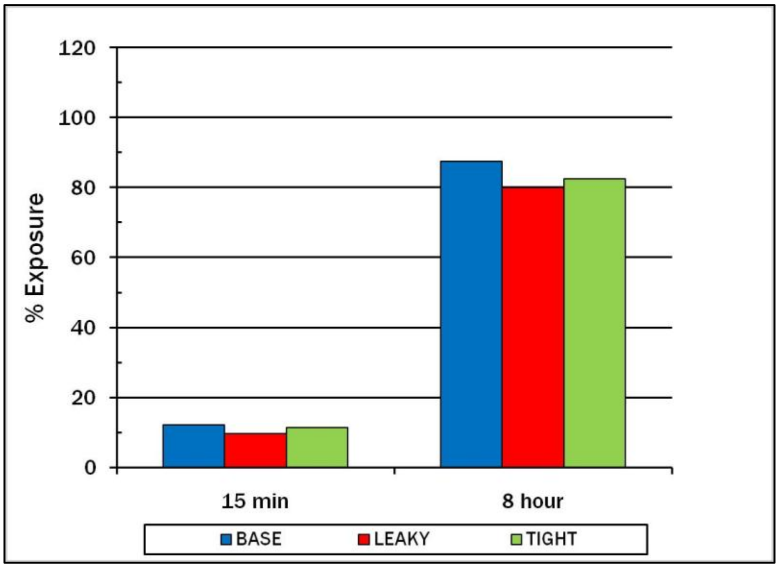


Figure 5-13: First Floor Office exposure with plenum return (relative to ducted return) - Envelope

Zoning

To investigate the impact of HVAC zoning on contaminant dispersal, zoning was varied for ducted and plenum return air systems. In the following discussion, zoning refers to HVAC system zoning and not VAV box zoning within each HVAC system. Besides floor-by-floor HVAC zoning assumed in the base case, in which each floor is served by a separate HVAC system, perimeter/core HVAC zoning on each floor, isolated lobby zoning and one HVAC zone for the entire building is considered. For all zoning options, primary and outdoor airflow is equal to the airflows in the base case and the building is pressurized to 0.02” w.g. w.r.t. the exterior. Figure 5-14 shows a representation of perimeter/core zoning, with the perimeter zone shaded in tan and the core zone shaded in white.

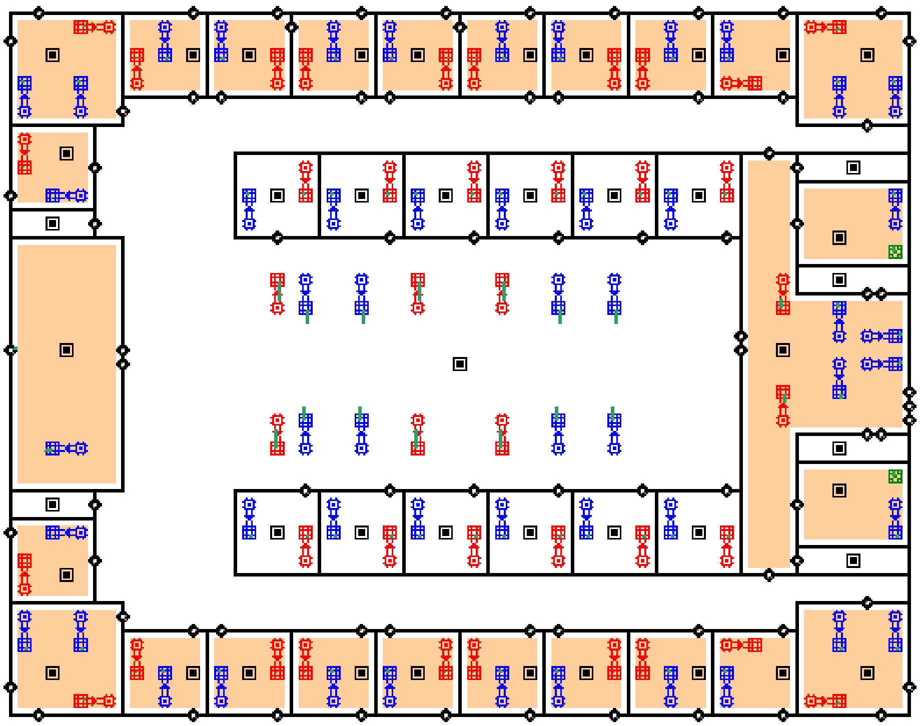


Figure 5-14: Representation of perimeter/core zoning of hypothetical office building

Figure 5-15 and Figure 5-16 compare 1st floor perimeter office concentration for each zoning strategy for ducted and plenum return systems, respectively. With perimeter/core zoning and ducted return, contaminant released in the lobby would be expected to remain in the first floor perimeter spaces at higher concentrations and reach the first floor core zone primarily through air leakage and pressurization. However, with perimeter/core zoning and plenum return, contaminant released in the lobby would enter the "common plenum" and be distributed by both HVAC systems relatively uniformly. With ducted return, the perimeter office concentration increases to 9% of the maximum lobby concentration with perimeter/core zoning compared to 4% of the maximum lobby concentration with floor-by-floor zoning. Since contaminant is mixed in the common plenum and is distributed by both HVAC systems, with plenum return the perimeter office concentration increases to 2% of the maximum lobby concentration with perimeter/core zoning compared to 3% with floor-by-floor zoning. For both return air systems, the perimeter office peak concentration with one zone is less than the perimeter office peak concentration with floor-by-floor zones. With ducted return, the perimeter office concentration peaks at 4% of maximum lobby concentration with floor-by-floor zoning compared to 2% with one zone, and with plenum return, the perimeter office concentration peaks at 3% of the maximum lobby concentration with floor-by-floor zoning compared to 2% with one zone.

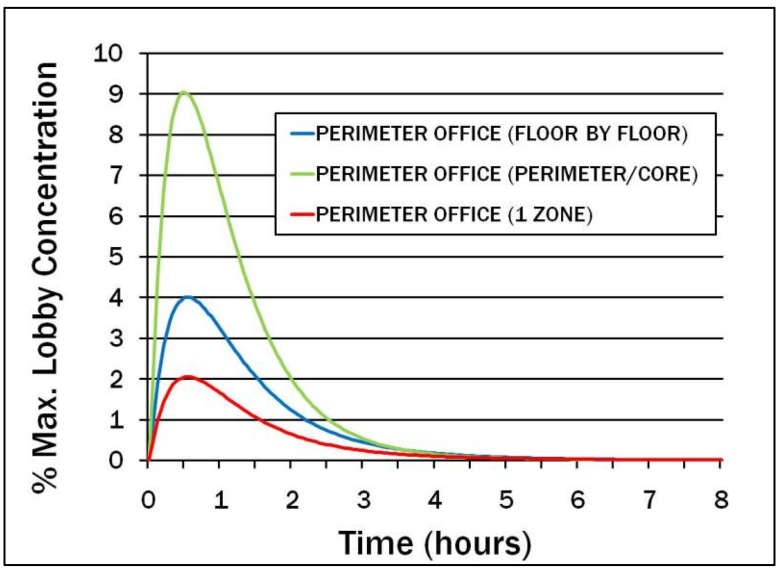


Figure 5-15: First Floor Perimeter Office concentration with ducted return - Zoning

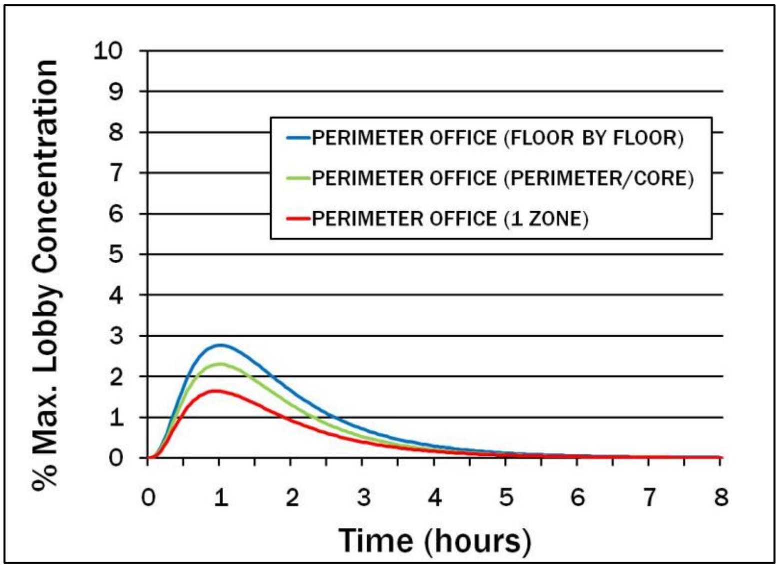


Figure 5-16: First Floor Perimeter Office concentration with plenum return - Zoning

Figure 5-17 and Figure 5-18 compare the core office concentration for each zoning strategy with ducted return and plenum return, respectively. With both return systems, the perimeter and core office concentration are equal for floor-by-floor zoning. However, since the lobby is isolated from the core HVAC zone, perimeter/core zoning with ducted return offers protection for core office spaces. With perimeter/core zoning and ducted return, the peak perimeter office concentration is 9% of maximum lobby concentration and the core office peak concentration is significantly less than the perimeter office concentration (fractions of a percent of the maximum lobby concentration). With perimeter core zoning and plenum return, both the perimeter and core office peak concentrations are nearly 2% of maximum lobby concentration, since contaminant mixes in the “common plenum” and is distributed by both HVAC systems uniformly. For both ducted and plenum return, the first floor perimeter and core office concentrations are equal with 1 building zone. Concentrations are lower with 1 building zone since contaminant is distributed to both floors; however, exposure extends to a greater portion of the building.

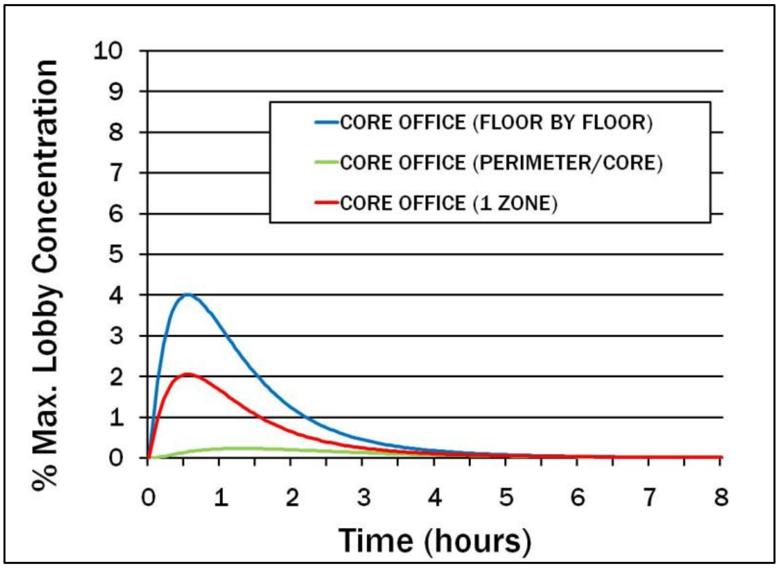


Figure 5-17: First Floor Core Office concentration with ducted return - Zoning

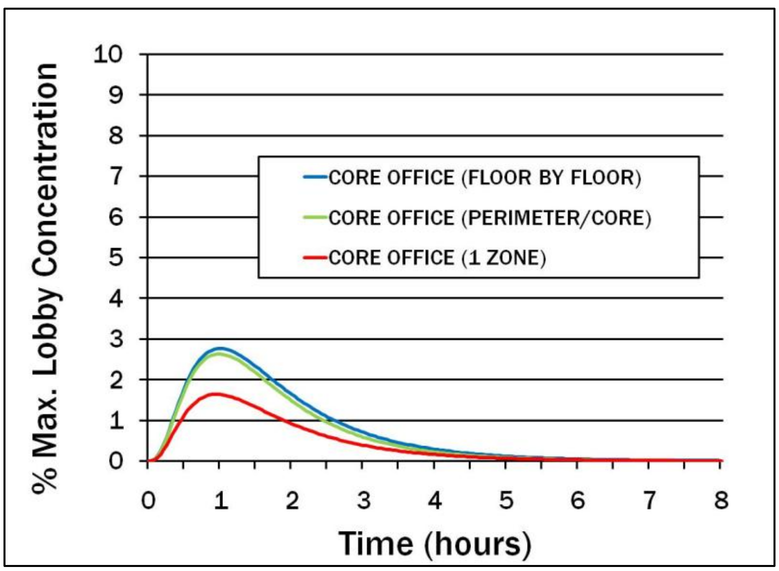


Figure 5-18: First Floor Core Office concentration with plenum return - Zoning

Examining first floor perimeter and core office concentrations alone do not illustrate the spatial variation of contaminant concentration for the entire building. Figure 5-19 and Figure 5-20 show spatial variations in contaminant concentration for the entire building for ducted and plenum return 15 minutes after a lobby release. In these figures, results are presented in the form of percentage of floor area exposed to percentage of maximum lobby concentration. After 15 minutes with 1 building zone, close to 100% of the floor area is exposed to 1% and 0.1% of the maximum lobby concentration for ducted and plenum return, respectively. With 1 building zone, the majority of the building is exposed to uniform concentration, since contaminant is distributed evenly by the single HVAC system. As seen in Figure 5-19, after 15 minutes with perimeter/core zoning and ducted return, 20% of the floor area is exposed to higher concentrations than with the other zoning options, and the 80% of floor area is exposed to lower concentrations since a greater portion of the area is isolated by HVAC zoning. However, as seen in Figure 5-20, after 15 minutes with plenum return, the spatial variation of contaminant concentration for floor-by-floor zoning and perimeter/core zoning is essentially equal. With plenum return and perimeter/core zoning, contaminant released in the lobby enters the “common plenum” and is distributed by both HVAC systems.

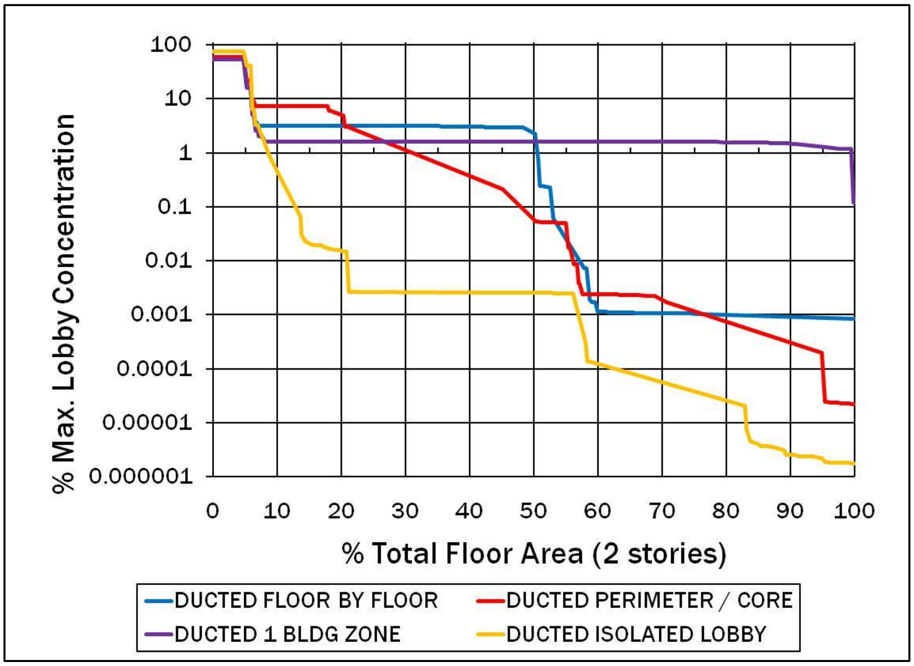


Figure 5-19: Spatial variations in concentration after 15 minutes with ducted return – Zoning

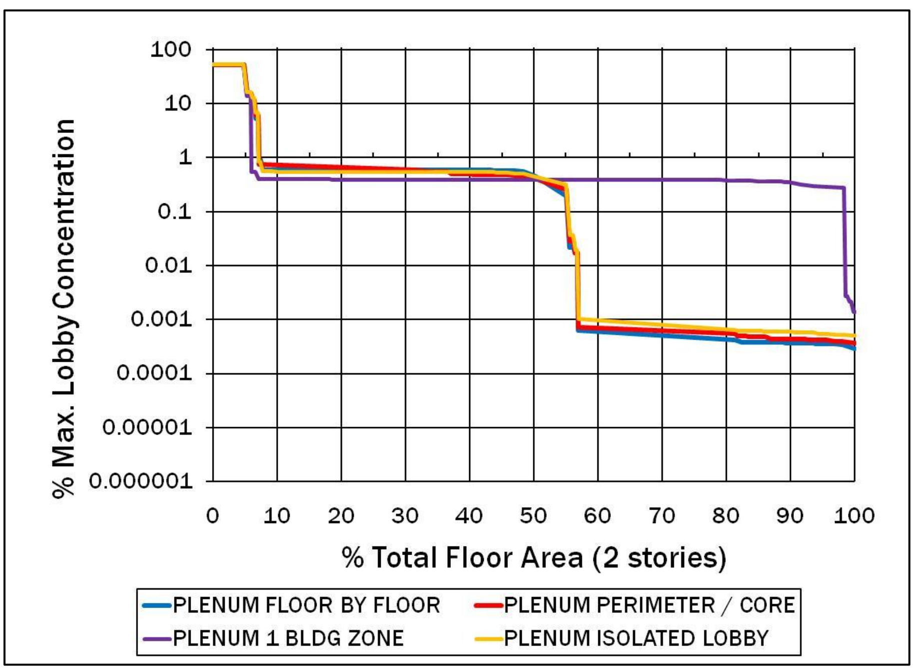


Figure 5-20: Spatial variations in concentration after 15 minutes with plenum return - Zoning

To further investigate the impact of zoning on contaminant dispersal, 15 minute and 8 hour exposures in first and second floor perimeter and core offices is compared for each return air strategy and zoning option in Table 5-1, Table 5-2, and Table 5-3. Each table presents a different metric. Table 5-1 presents results in the form of exposure for each zone and each zoning strategy with ducted return relative to 1st floor perimeter office exposure with ducted return and Floor-by-Floor zoning. Table 5-2 presents results in the form of exposure for each zone and each zoning strategy with plenum return relative to 1st floor perimeter office exposure with plenum return and Floor-by-Floor zoning. Table 5-3 presents results in the form of exposure with plenum return relative to ducted return for each zoning strategy and zone.

As seen in Table 5-1, HVAC zoning strategy with ducted return has a significant impact on spatial distribution of exposure. With Floor-by-Floor zoning and ducted return, 1st floor perimeter and core office exposure is equal, while 2nd floor perimeter and core office exposure is 0.02% and 5% that of the 1st floor perimeter office exposure for 15 minutes and 8 hours, respectively. Since the lobby release zone is served by the perimeter HVAC system, 15 minute and 8 hour exposures in the 1st floor perimeter office with Perimeter/Core zoning are approximately double that of exposures with Floor-by-Floor zoning. Since the core zones are isolated from the lobby release by Perimeter/Core zoning, 15 minute and 8 hours exposures in the 1st floor core office decrease to 1% and 11% of exposure in the 1st floor perimeter office, respectively. Exposure in the 2nd floor perimeter and core spaces follow the same relationship as in the 1st floor: exposure in the 2nd floor perimeter office increased, while exposure in 2nd floor core office decreased when compared to Floor-by-Floor zoning. As expected, when the building is served by one HVAC system, contaminant is distributed within the building uniformly at lower concentrations. Therefore, with one building zone, 15 minute and 8 hour exposures equal to half the exposure of the 1st floor perimeter office exposure with Floor-by-Floor zoning for all 1st and

2nd floor offices. When the lobby is served by a separate HVAC system, 15 minute and 8 hour exposures in the building decreases significantly compared to Floor-by-Floor zoning.

Table 5-1: Exposure with ducted return relative to Base Case with ducted return

% Exposure with Ducted Return (relative to 1st floor perimeter office with Ducted Return and Floor by Floor zoning)								
Zone	**Floor by Floor (Base Case)**		**Perimeter/Core**		**1 Zone**		**Isolated Lobby**	
	15 min.	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**
1st floor Perimeter	100	100	233	193	51	52	0.05	2
1st floor Core	100	100	1	11	51	52	0.05	2
2nd floor Perimeter	0.02	5	0.04	8	51	52	0.00004	0.2
2nd floor Core	0.02	5	0.004	0.08	51	52	0.0003	0.2

Not surprisingly, with plenum return, the impact of zoning on spatial distribution of exposure was less significant than with ducted return. When HVAC systems share a "common plenum", contaminants are mixed and distributed by the connected HVAC system as if the building were a single zone. As seen in Table 5-2, 15 minute and 8 hour 1st floor exposure with plenum return and Perimeter/Core zoning is 80% to 90% that of exposure with plenum return and Floor-by-Floor zoning. However, since the 2nd floor plenum is not connected to the 1st floor plenum in Floor-by-Floor and Perimeter/Core zoning, 2nd floor occupants would be protected in both cases. With one building zone, 15 minute and 8 hour exposures are 60% to 70% of the 1st floor perimeter office exposure with Floor-by-Floor zoning for all 1st and 2nd floor offices. Isolating the lobby from the rest of the building with a plenum return system is not possible since contaminant returned from the lobby plenum mixes with return air from the rest of the floor. With plenum return and Isolated Lobby Zoning, 15 minute and 8 hour exposure on the 1st floor is 90% of exposure with plenum return and Floor-by-Floor zoning.

Table 5-2: Exposure with plenum return relative to Base Case with plenum return

% Exposure with Plenum Return (relative to 1st floor perimeter office with Plenum Return and Floor by Floor zoning)								
Zone	**Floor by Floor (Base Case)**		**Perimeter/Core**		**1 Zone**		**Isolated Lobby**	
	15 min.	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**
1st floor Perimeter	100	100	83	79	67	58	92	93
1st floor Core	100	100	94	90	66	58	90	93
2nd floor Perimeter	0.1	9	0.1	8	66	58	0.1	11
2nd floor Core	0.1	9	0.1	10	66	58	0.1	12

In the preceding discussion concerning Table 5-1 and Table 5-2, exposures in each zone were taken relative to the 1st floor perimeter office to illustrate the impact of zoning on spatial distribution of exposure. In order to compare ducted and plenum return system resiliency directly, exposure with plenum return relative to ducted return is tabulated in Table 5-3 for each zoning strategy and corresponding zone. For example: in Table 5-3, 1st floor perimeter office exposure with ducted return is compared to 1st floor perimeter office exposure with plenum return for each zoning strategy.

Results indicate that with floor by floor zoning, plenum return offers a significant reduction in 15 minute exposure compared to ducted return. With floor-by-floor zoning, 15 minute exposure with plenum return is 12% and 29% of 15 minute exposure with ducted return, for 1st and 2nd floor, respectively. 8 hour exposure with plenum return decreased by 13% in the 1st floor and increased by 60% in the 2nd floor when compared to 8 hour exposure with ducted return. It is not immediately apparent as to why 8 hour exposures increased on the 2nd floor compared to ducted return. With perimeter/core zoning and plenum return, 15 minute exposure is 4% and 960% that of 15 minute exposure with ducted return for 1st floor perimeter and core offices respectively. With plenum return, contaminant released in the lobby perimeter zone enters the "common plenum" and is distributed uniformly by both HVAC systems. Similarly, with perimeter/core zoning on the 2nd floor, 15 minute exposures with plenum return decrease in perimeter zones and increase in core zones when compared to ducted return. Since the building shares a "common plenum" with 1 building zone, 15 minute and 8 hour exposures are 16% and 96% of exposures with ducted return, respectively. Not surprisingly, using plenum return to isolate the lobby is not an effective measure to reduce occupant exposure. 15 minute exposure with plenum return is 200 to 300 times higher than exposure with ducted return and 8 hour exposure with plenum return is 50 to 60 times higher.

Table 5-3: Exposure with plenum return relative to ducted return for each zoning strategy

% Exposure with Plenum Return (relative to corresponding office with Ducted Return for each zoning option)								
Zone	**Floor by Floor**		**Perimeter/Core**		**1 Zone**		**Isolated Lobby**	
	15 min.	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**	**15 min.**	**8 hr.**
1st floor Perimeter	12	87	4	46	16	96	21000	5000
1st floor Core	12	87	960	750	16	96	21000	5000
2nd floor Perimeter	29	160	15	95	16	96	25000	6000
2nd floor Core	29	163	1920	1030	16	96	32000	6000

Duct Leakage

The Sheet Metal and Air Conditioning Contractors National Association (SMACNA) introduced the concept of defining duct leakage as a function of pressure in the duct and surface area of the duct because specifying leakage as a percentage of fan air flow rate does not take into account the size of the duct system and the pressure in the ducts (SMACNA 1985). The leakage class, C_L, calculated from xxxx is defined as is the air leakage rate per 9.3 m^2 of duct surface area with a 250 Pa pressure difference across the leaks, expressed in cfm. ASHRAE (2007) estimates that leakage classes of 3-12 are attainable for "commonly used duct construction and sealing practices," and estimates that leakage classes of 30-48 are attainable for unsealed ducts. Connections to diffusers and grilles or duct mounted equipment, such as VAV boxes, are not included in these estimates.

To gauge the impact of duct leakage on contaminant distribution and occupant exposure levels, simulation results with a leakage class rating of 48 were compared with the base building results, in which the duct leakage was assumed to be the ASHRAE recommended level of 12. Figure 5-21 and Figure 5-22 show 1st floor office space and plenum contaminant concentrations for the tight and leaky ducts. With leaky ducts and ducted return, the difference in peak concentration was less than 0.5% of the maximum lobby concentration with tight ducts. Since the supply air quantity was lower and the plenum concentration was higher with a higher rate of duct leakage, space concentration was marginally lower. With plenum return, however, peak contaminant concentration was higher with tight ducts. Leaky supply ducts seem to offer another "buffer" between the release zone and occupants in the remaining zones. Since a portion of the contaminant that leaks out of supply ducts into the return air stream is exhausted, less contaminant reaches the space.

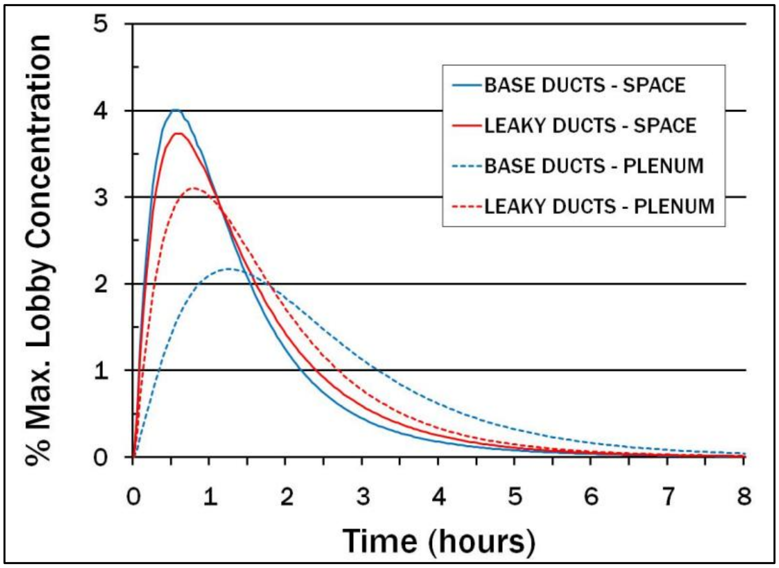


Figure 5-21: First Floor Office and Open Plenum concentration with ducted return – Duct Leakage

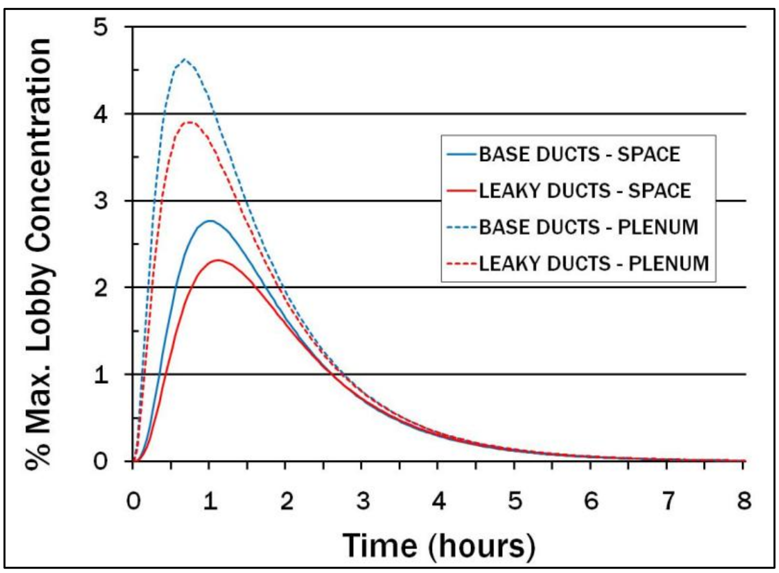


Figure 5-22: First Floor Office and Open Plenum concentration with plenum return – Duct Leakage

Figure 5-23 and Figure 5-24 compare 15 minute and 8 hour relative exposure for ducted and plenum return systems with leaky and tight ducts. With leaky ducts and ducted return, 15 minute exposure was approximately 90% that of exposure with tight ducts. 8 hour exposure with leaky ducts was essentially equal to that of exposure with tight ducts. With plenum return, leaky ducts reduced the 15 minute and 8 hour exposures to 70% and 90%, respectively, compared with tight ducts. Figure 5-25 shows 15 minute and 8 hour exposure with plenum return relative to ducted return for tight and leaky ducts. With tight ducts, as discussed previously, the plenum acted as a "buffer" between the release zone and remaining spaces, reducing the 15 minute and 8 hour exposures by 85% and 25%, respectively. Leaky supply ducts in a plenum return system added another level of protection, reducing the 15 minute and 8 hour even further compared to ducted return.

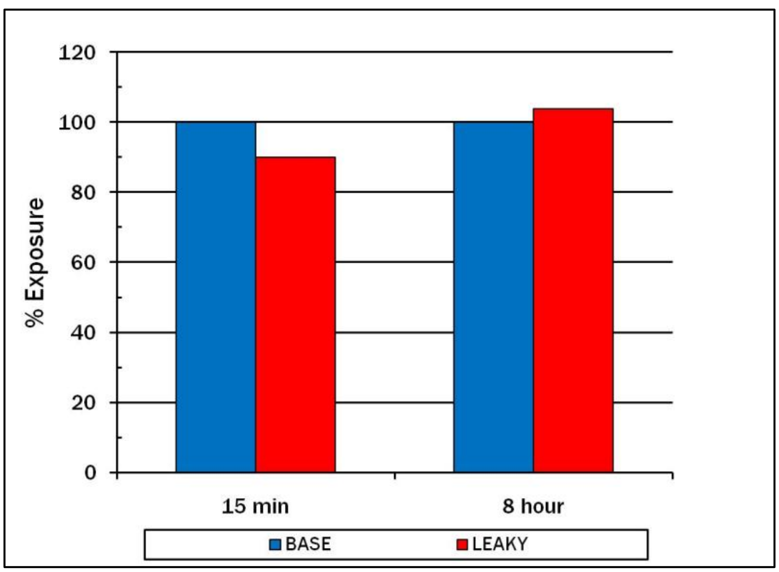


Figure 5-23: First Floor Office exposure with ducted return (relative to Base Case) – Duct Leakage

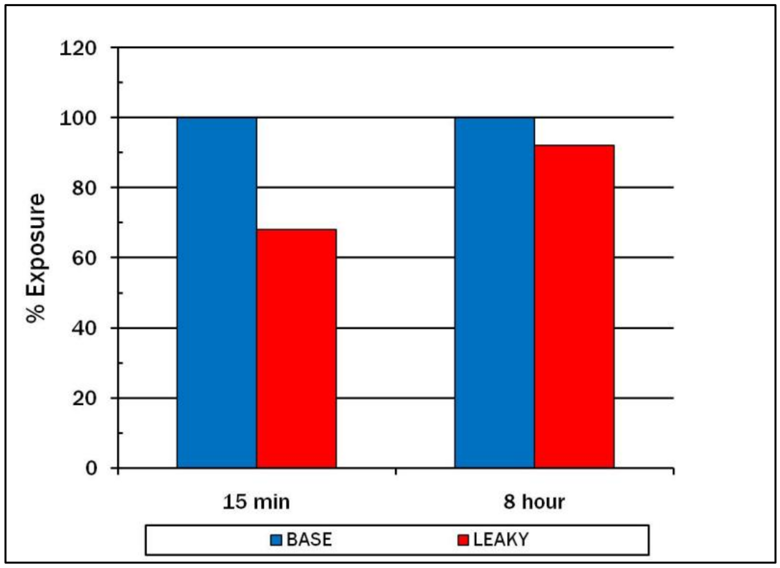


Figure 5-24: First Floor Office exposure with plenum return (relative to Base Case) – Duct Leakage

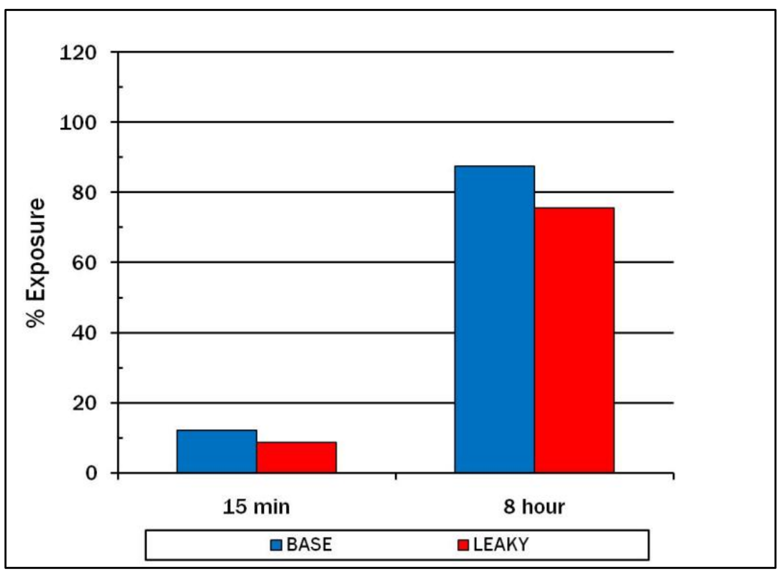


Figure 5-25: First Floor Office concentration with plenum return (relative to ducted return)

Stack Effect

To investigate the impact of return air system on contaminant distribution induced by stack effect, the 2 story hypothetical building was expanded to 6 stories. Infiltration of colder ambient air into a multistory building causes warmer air to rise in elevator and stair shafts to upper stories. Stack effect was induced by specifying a 77ºF temperature difference between the building and outdoors (keeping the building at 73ºF with an ambient temperature of - 4ºF, the ambient temperature in Minnesota in January according to TMY2 weather data). Each floor is a copy of the first floor, and is served by a separate AHU with the same supply, return, outdoor air and exhaust air. For both return air systems, contaminant was released in the 1st floor lobby with and without stack effect. Figure 5-26 shows the 1st floor lobby release location in yellow and the location of elevators and stairs in blue. Each lobby has 2 elevator shafts with 2 elevator doors, and 2 stair shafts, each with a plan area of 100 ft^2. Each office area has 2 stair shafts with the same characteristics as the lobby stairs. CONTAM library elements (Persily and Ivy, 2001) were chosen for elevator and stair doors, and are represented by leakage areas of 150 cm^2 and 187.5 cm^2, respectively, at 4 Pa with a discharge coefficient of 1 and a flow exponent of 0.65. Since buildings are generally pressurized to avoid infiltration, for simulations with and without stack effect, each floor was pressurized to 0.02" w.g. with respect to the outdoors by reducing return airflow at each AHU.

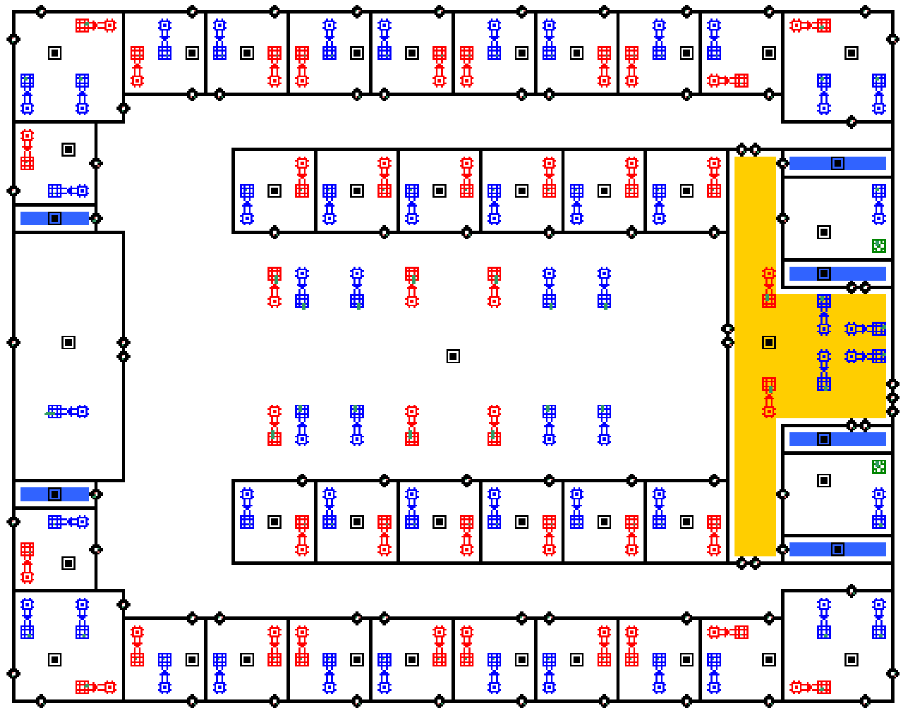


Figure 5-26: Hypothetical Building Elevator and Stair Location – Stack Effect

Stack Effect with Plenum Return

To determine the impact of stack effect in distributing contaminant in buildings with plenum return air systems, simulations were run in which contaminant was released in the 1st floor lobby of a 6 story building, with and without stack effect. Figure 5-27 shows differential pressures between the occupied areas and the exterior and between the lobby and elevator and stair shafts generated by stack effect. Even though the building is pressurized to 0.02" w.g. with respect to the exterior in the building without stack effect, stack effect reverses air flow into the 1st floor lobby and office and brings the lobby and office areas to near neutral with respect to the exterior. Colder ambient air is drawn from the exterior into the lobby and elevator and stair shafts connected to the 1st floor lobby. At the first floor lobby, the differential pressure across the shaft is -0.055" w.g. with respect to the lobby. As the air flows up through the lobby shafts, differential pressure between the upper floor lobbies and lobby shafts change, eventually forcing air across the shaft to the 6th floor lobby. Air is drawn from the 1st, 2nd, and 3rd floor lobbies and enters the 4th, 5th, and 6th floor lobbies. Since each floor is pressurized or depressurized to a different extent by the vertical air flow through the shafts, differential pressure between the occupied spaces and exterior changes for each floor, from near neutral at the 1st floor to 0.066" w.g. with respect to the exterior. At each floor the lobby area and office area is separated by a full height wall and return air transfer duct, so differential pressure between the areas and the exterior differential pressure between the areas and the exterior is equal.

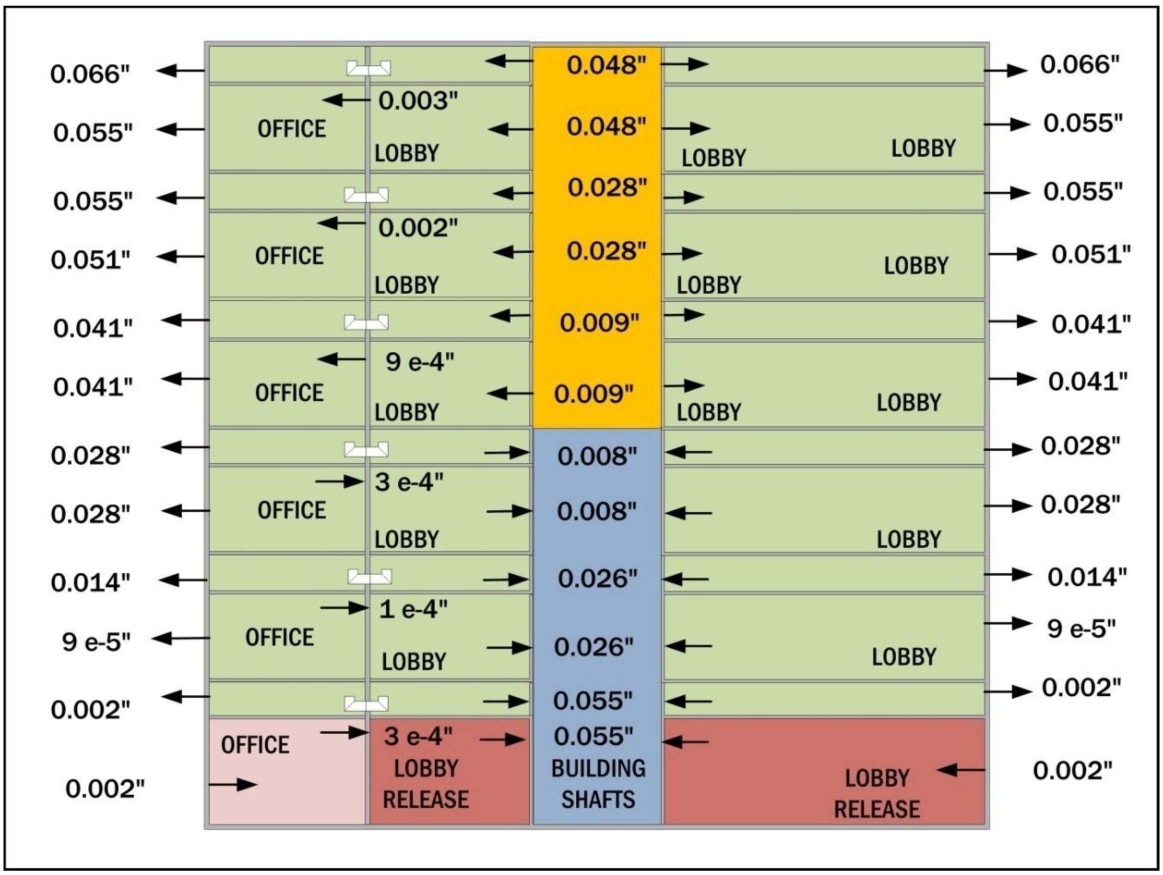


Figure 5-27: Differential Pressure with plenum return – Stack Effect

Figure 5-28 shows stack induced airflows and lobby supply and return airflows with plenum return air system. Supply air for the simulations investigating stack effect was 1560 cfm or 0.4 cfm/ft^2 (the minimum airflow setting in most office type VAV applications). Stack effect forced nearly 1200 cfm from the lobby into the 1st floor shafts, vertical air flow forced nearly 1100 cfm into the 6th floor lobby. Even though return fan airflow with and without stack effect was equal, stack effect reduced 1st, 2nd, and 3rd floor lobby return air from 1060 cfm to 242 cfm, 586, and 840 cfm respectively, while increasing 4th, 5th, and 6th floor lobby return air to 1348 cfm, 1614 cfm and 1830 cfm, respectively. Presumably, lobby return air was drawn through the shafts in the lower floors and forced into the shafts in the upper floors, eventually entering the upper story plenums through the low resistance return air grilles.

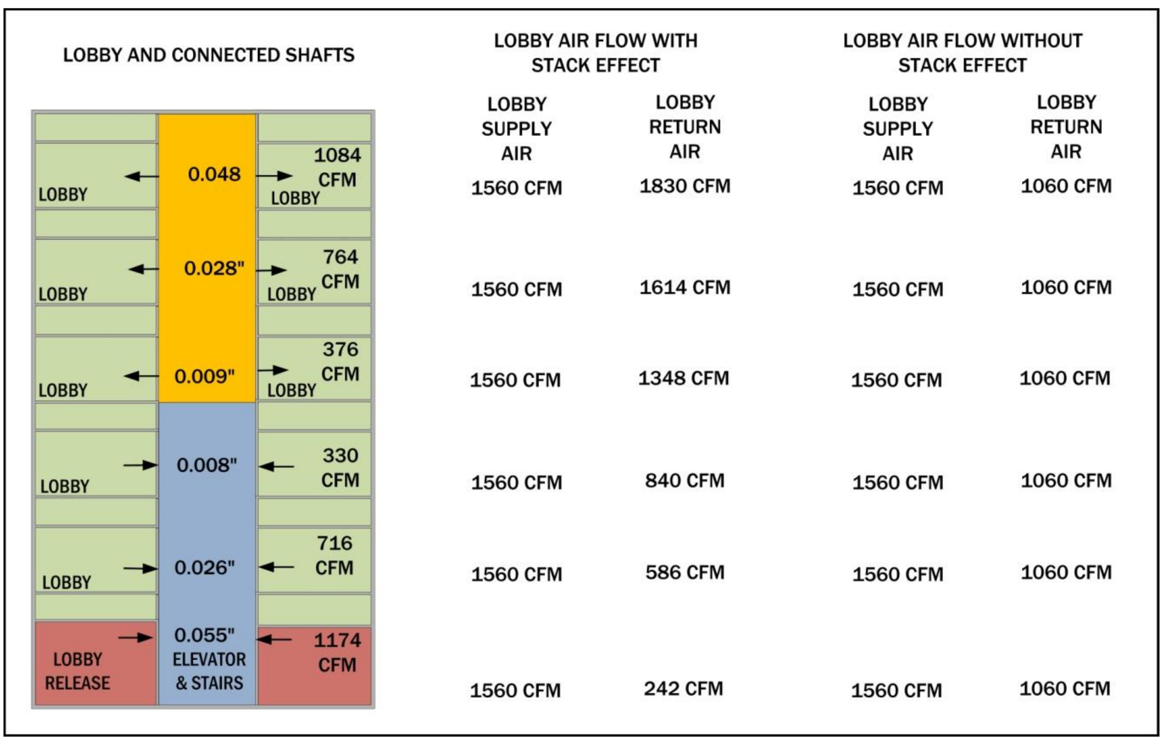


Figure 5-28: Stack induced airflow and lobby airflow with plenum return – Stack Effect

Figure 5-29 shows the 1st floor Lobby concentration with plenum return, with and without stack effect. Contaminant concentration is essentially equal in the release zone; however, as seen in Figure 5-30, stack effect has a significant impact on 1st floor Office peak contaminant concentration and concentration profile. Since 1st floor lobby return air flow with stack effect is a fraction of that without stack effect, 1st floor office peak concentration is 4% of maximum 1st floor lobby concentration, whereas with stack effect, peak concentration is only 0.5% of maximum lobby concentration. Figure 5-31 and Figure 5-32 show upper floor lobby concentration with and without stack effect. With stack effect, contaminant reaches the 4th, 5th, and 6th floor lobbies from elevator and stair shafts connected to the 1st floor lobby, but does not leave the shafts into either the 2nd or 3rd floors. With stack effect, peak contaminant concentration is 9%, 7%, and 4% of maximum 1st floor lobby concentration for the 6th, 5th and 4th floors, respectively. Without stack effect, contaminant concentrations in the upper floor lobbies are essentially zero, since the floors are neutral with respect to each other. Figure 5-33 and Figure 5-34 show upper floor office concentration with and without stack effect. With stack effect inducing air flow to the upper three floors, peak contaminant concentration was between 0.5 and 1.5% of maximum 1st floor lobby concentration, compared to less than 0.001% of maximum 1st floor lobby concentration without stack effect. Since the 3rd floor and 2nd floor lobbies were not contaminated, 3rd and 2nd floor office concentration with stack effect was zero.

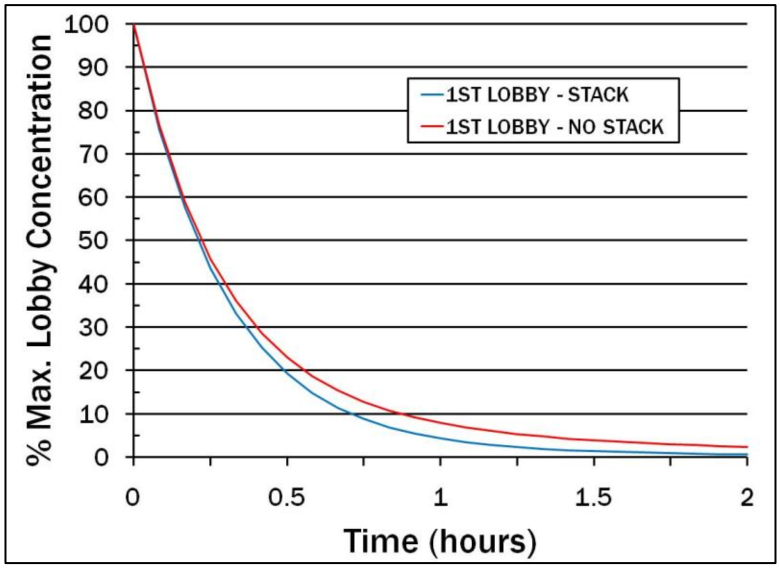


Figure 5-29: First Floor Lobby concentration with plenum return – Stack Effect

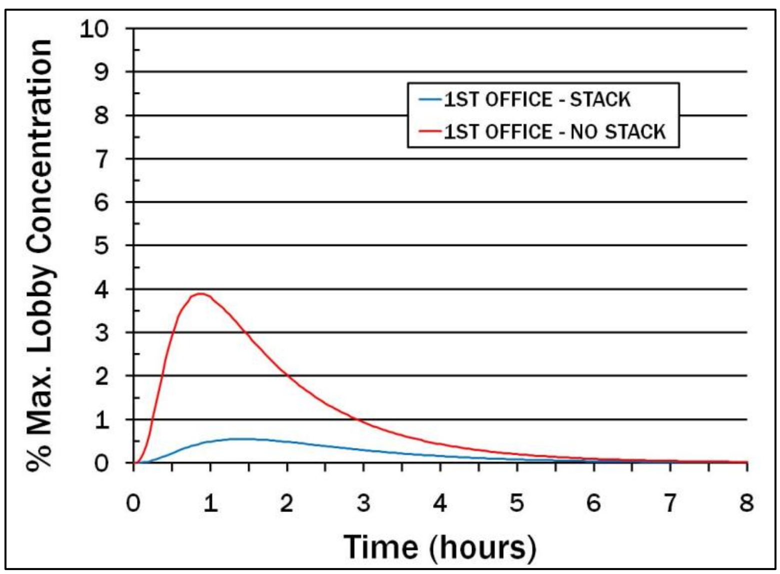


Figure 5-30: First Floor Office concentration with plenum return – Stack Effect

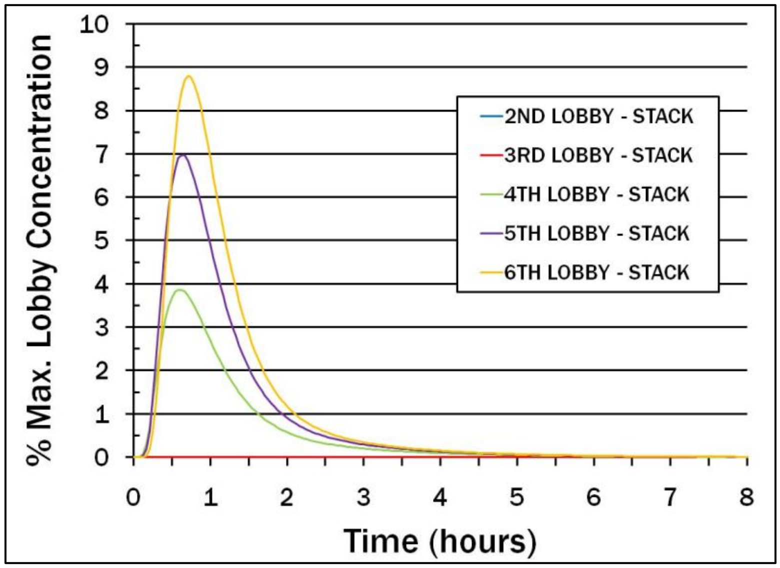


Figure 5-31: Upper Floor Lobby concentration with plenum return and stack effect

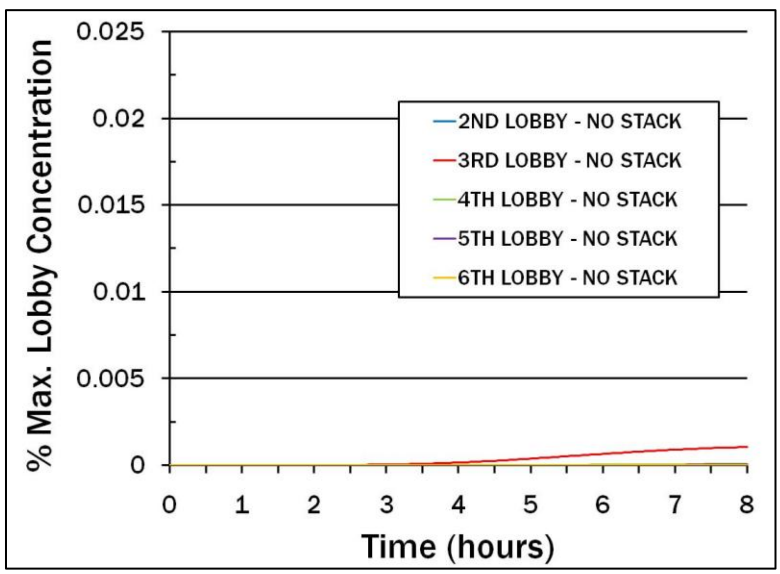


Figure 5-32: Upper Floor Lobby concentration with plenum return and no stack effect

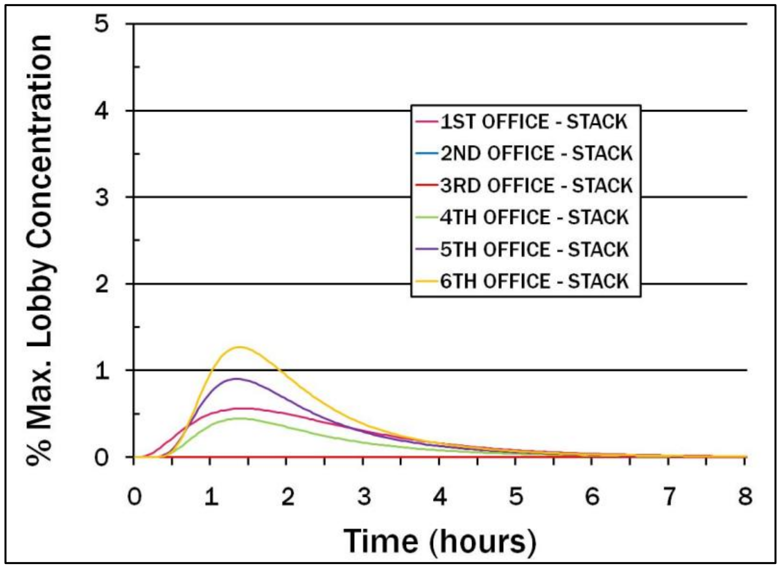


Figure 5-33: Upper Floor Office concentration with plenum return and stack effect

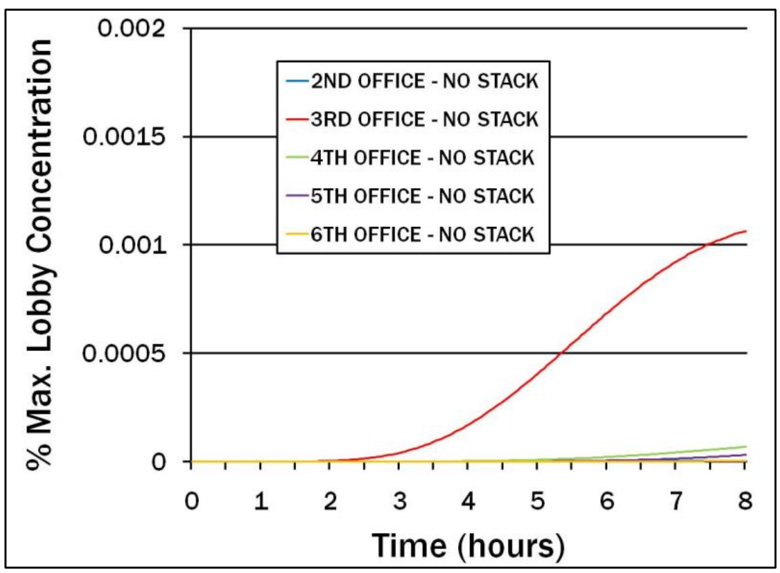


Figure 5-34: Upper Floor Office concentration with plenum return and no stack effect

Stack Effect with Ducted Return

In order to compare the impact of ducted return and plenum return air systems in distributing contaminants in a building with stack induced differential pressures and airflows, the 1st floor lobby release scenario was simulated with the same 6 story hypothetical building with ducted return. Differential pressures generated by stack effect were significantly different with ducted return and plenum return. Figure 5-35 shows differential pressure between occupied zones and the exterior and between occupied zones and shafts connected to the 1st floor lobby for the 6 story building with ducted return. With ducted return, stack effect depressurizes the 1st floor lobby to -0.033" w.g. with respect to the exterior, compared to -0.002" w.g. with plenum return. As seen in Figure 5-27, with plenum return differential pressures between the occupied lobby and office areas and the exterior were uniform, since the lobby and office areas are connected by a transfer return grille at the full height wall separating the zones. However, with ducted return, differential pressure across the exterior envelope is not uniform. At the first floor, the lobby is depressurized by 0.033" w.g. with respect to the exterior while the office area is depressurized by 0.003" w.g, and at the 6th floor, the lobby is pressurized by 0.1" w.g. with respect to the exterior while the office area is pressurized by 0.046" w.g. With ducted return, stack effect causes unintended depressurization between the office and lobby zones throughout the building. The 1st, 2nd, and 3rd floor lobbies are depressurized by 0.037" w.g., 0.018" w.g. and 1E-4" w.g. with respect to the office areas, respectively and the 4th, 5th, and 6th floor lobbies are pressurized by 0.019" w.g., 0.037" w.g., and 0.057" w.g., respectively.

Another difference between ducted and plenum return is the differential pressure between the plenum zones and the exterior. With plenum return, differential pressure across the plenum envelope is essentially equal to the differential pressure across the envelope of the zone below. With ducted return, however, differential pressure across the plenum envelope and the envelope in the zone below are not equal throughout the building. In fact, as the differential pressure across the exterior envelope changes, the relative difference in pressure across the plenum and space envelopes remains relatively constant for both office and lobby areas. For example, the 1st floor lobby is depressurized by 0.033" w.g. with respect to the exterior and the 1st floor lobby plenum is depressurized by 0.018" w.g. with respect to the exterior, a difference of 0.015" w.g. The same difference of 0.015" w.g. exists between the 6th floor office area envelope and plenum envelope above.

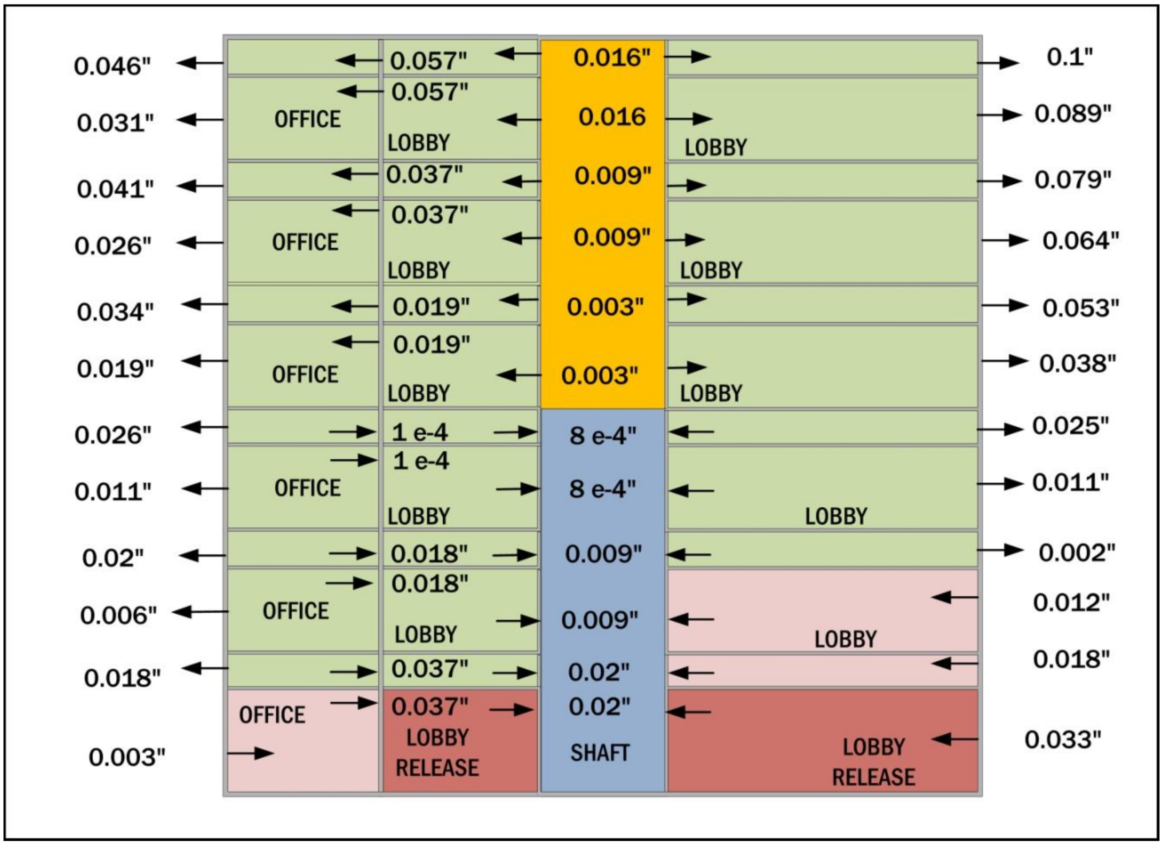


Figure 5-35: Differential Pressure with ducted return – Stack Effect

Lobby airflow and stack induced airflow was also significantly different with ducted and plenum return. Figure 5-36 shows stack induced airflow through shafts connected to the 1st floor lobby and lobby supply and return air throughout the building with ducted return. With ducted return, flow into shafts at the 1st floor lobby is 610 cfm, and lobby return air is 1222 cfm, compared to 1174 cfm of airflow into shafts and 242 cfm of lobby return air with plenum return, as seen in Figure 5-28. Presumably, return air with ducted return is more controlled, so vertical airflow through the shafts is made up from the from the exterior and office area connected to the lobby, rather than the lobby return air. "Make up air" entering the 1st floor lobby depressurizes the lobby by 0.033" w.g. with respect to the exterior and depressurizes the 1st floor office area by 0.037" w.g. with respect to the lobby. Lobby return air with ducted return is more consistent floor to floor than with plenum return, varying from 1222 cfm to 1416 cfm compared to a variation of 242 cfm to 1830 cfm with plenum return. With plenum return, lobby return air with plenum is greater than lobby supply air on the 5th and 6th floors, however, with ducted return, lobby return air is less for each floor.

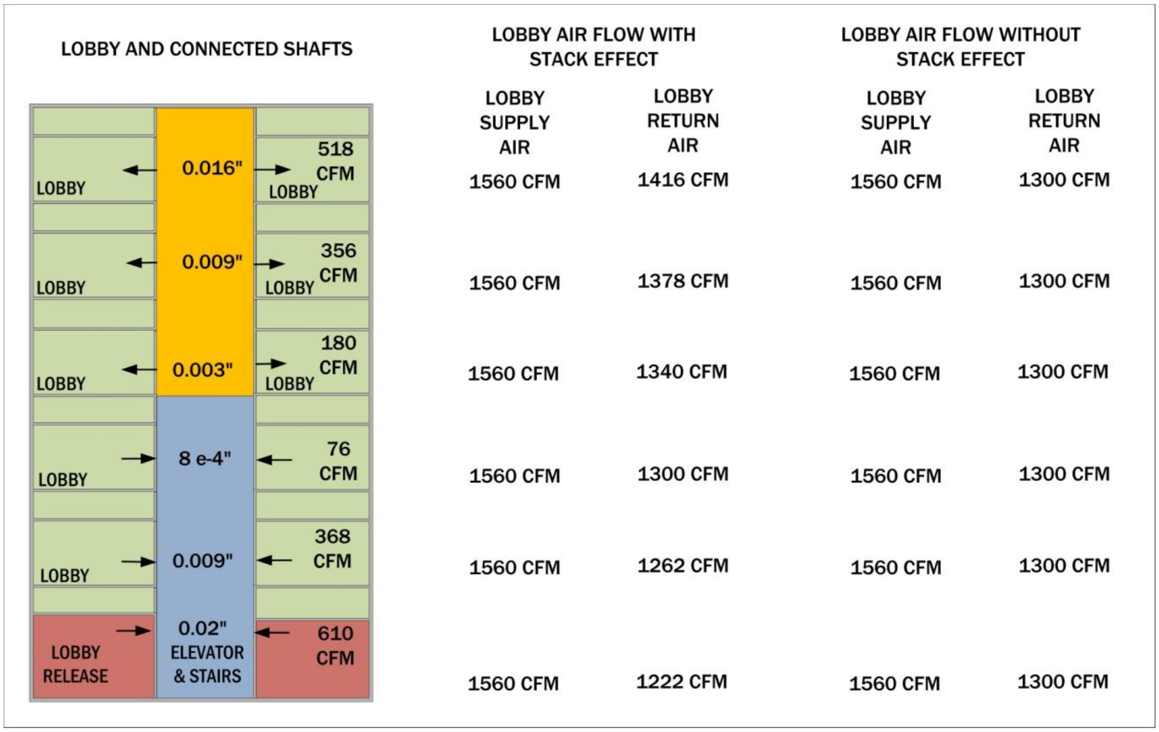


Figure 5-36: Stack induced airflow and lobby airflow with ducted return – Stack Effect

Figure 5-37 shows 1st floor lobby concentration with and without stack effect with ducted return. Release zone concentration profiles are similar with and without stack effect since lobby airflows are similar, as seen in Figure 5-36. However, since lobby return air was 1222 cfm with ducted return compared to 242 cfm with plenum return, 1st floor office concentration with stack effect was significantly different. Figure 5-38 compares 1st floor office concentration with and without stack effect with ducted return. Peak 1st floor office concentration without stack effect is approximately 4.5% of maximum release zone concentration compared to 4% with stack effect, a difference of 0.5%. On the other hand, as seen in Figure 5-30, with plenum return peak 1st floor office concentration was 4% of maximum release zone concentration without stack effect and 0.5% with stack effect, a difference of 3.5%.

Since vertical airflow is lower with ducted return, stack effect transfers less contaminant to upper floor lobbies compared to plenum return. Figure 5-39 shows upper floor lobby concentration with stack effect and ducted return. Peak concentration in 6th, 5th, and 4th floor lobbies reaches 4.5%, 3.5%, and 2% of maximum release zone concentration, respectively, compared 9%, 7%, and 4% of maximum release zone concentration with plenum return. In both cases, stack effect draws air from 2nd and 3rd floor lobbies and pushes air into the 4th, 5th, and 6th floor lobbies, so 2nd floor and 3rd floor spaces are not contaminated by the 1st floor release.

Figure 5-40 shows office concentration with stack effect throughout the building. With ducted return, occupants in 1st floor office area are exposed to significantly greater contaminant concentrations than the upper floor offices. Peak concentration in the 1st floor office area is 4% of maximum release zone concentration, while peak concentration in the upper floor offices is less than 0.5%. As seen in Figure 5-31, with plenum return, 1st floor and upper floor office occupants are exposed to similar contaminant concentrations. With plenum return, peak concentration is 0.5% in the 1st floor office area, and 1.25%, 1%, and 0.5% of maximum release zone concentration in the 6th, 5th, and 4th floor office areas, respectively.

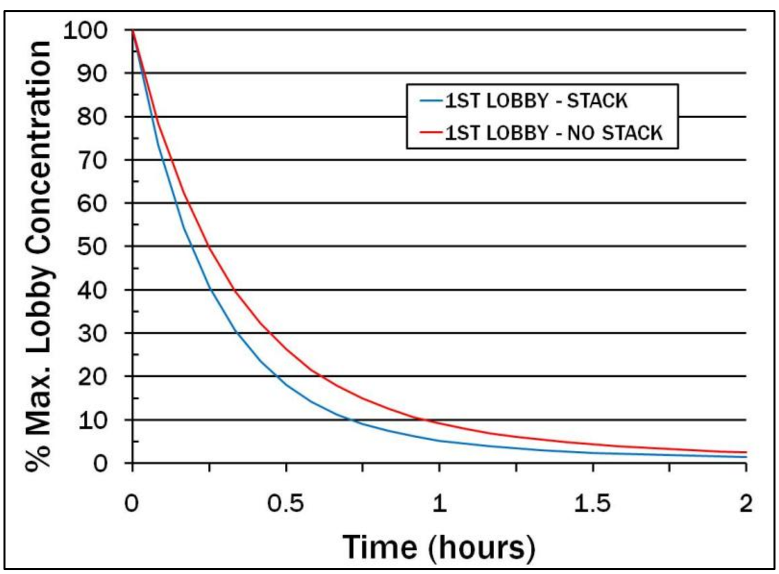


Figure 5-37: First Floor Lobby concentration with ducted return – Stack Effect

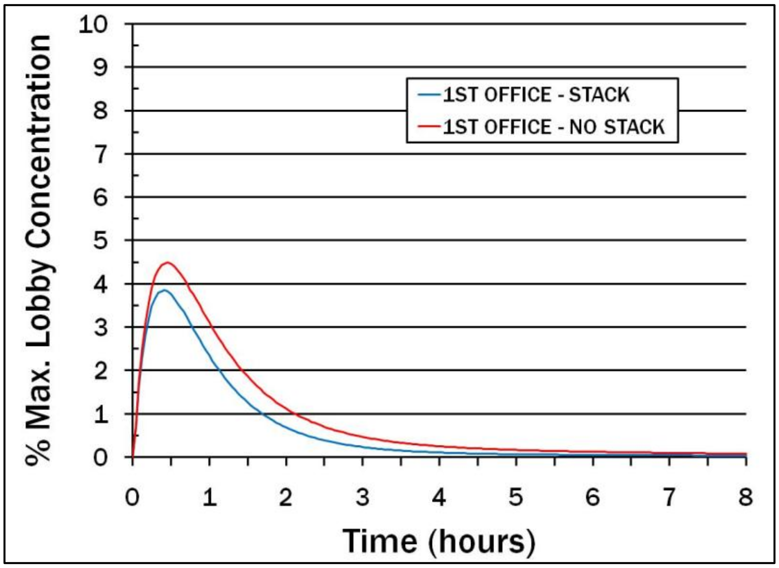


Figure 5-38: First Floor Office concentration with ducted return – Stack Effect

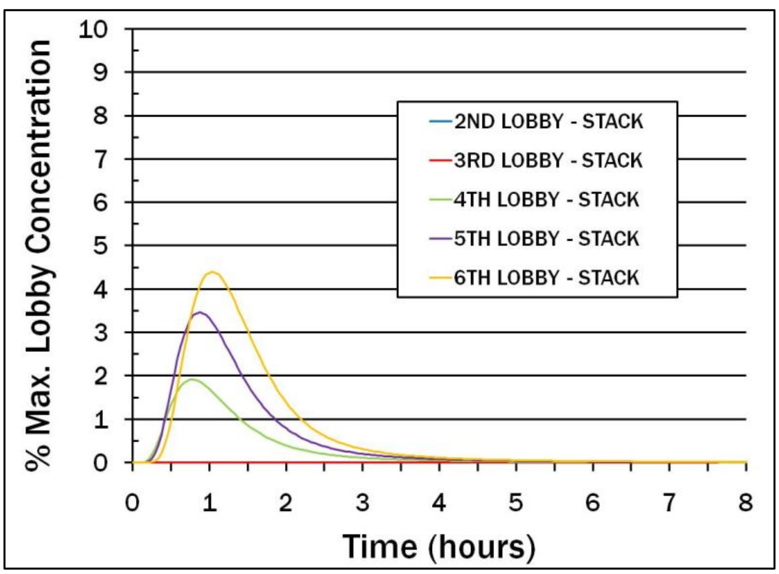


Figure 5-39: Upper Floor Lobby concentration with ducted return and stack effect

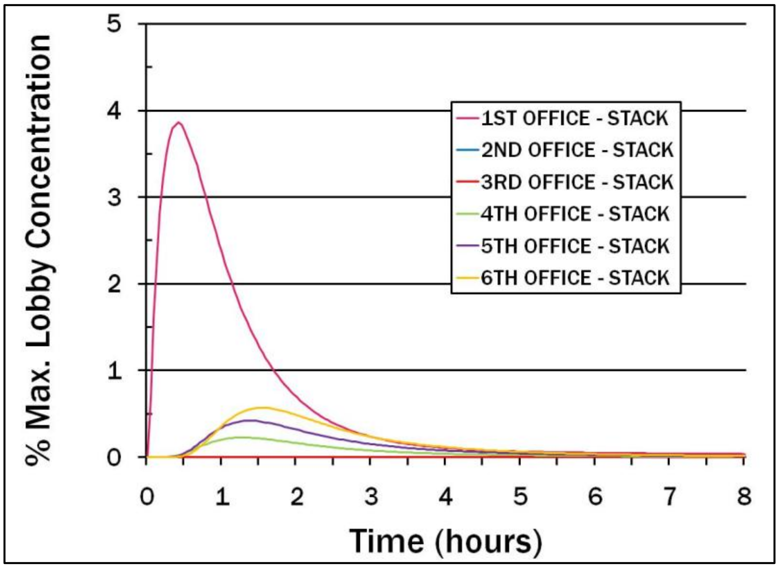


Figure 5-40: Upper Floor Lobby concentration with ducted return and stack effect

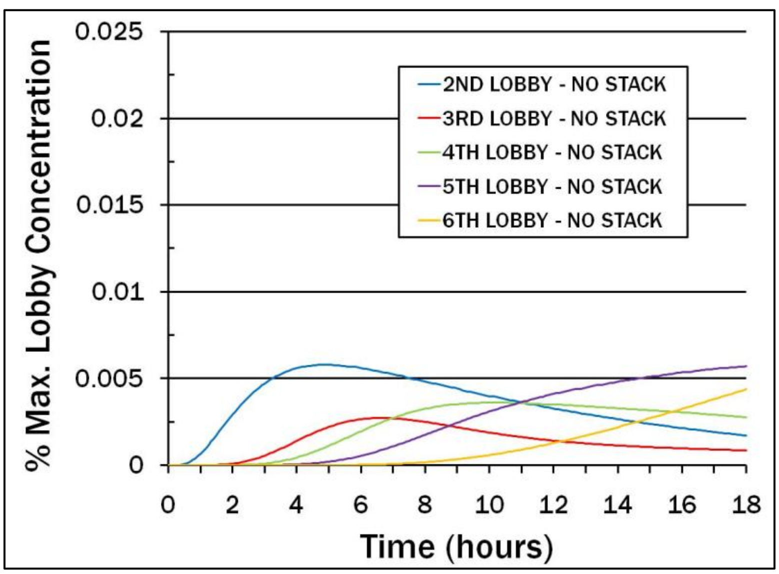


Figure 5-41: Upper Floor Lobby concentration with ducted return and no stack effect

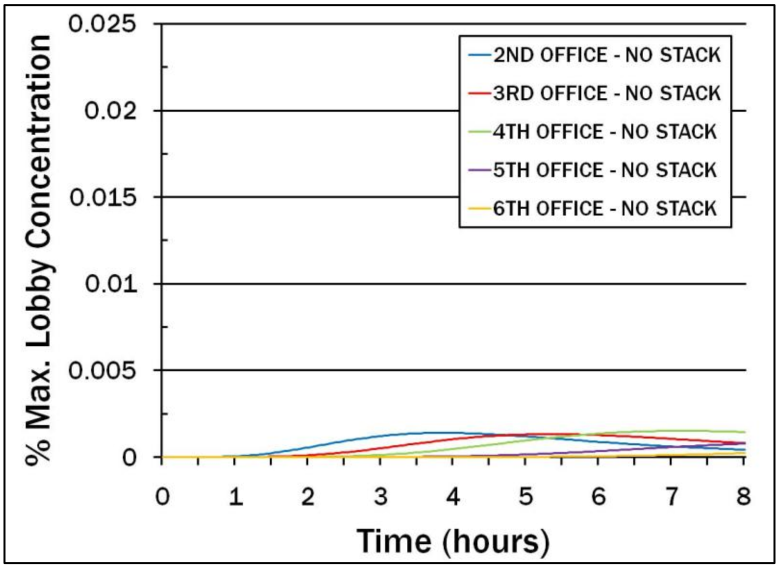


Figure 5-42: Upper Floor Office concentration with ducted return and no stack effect

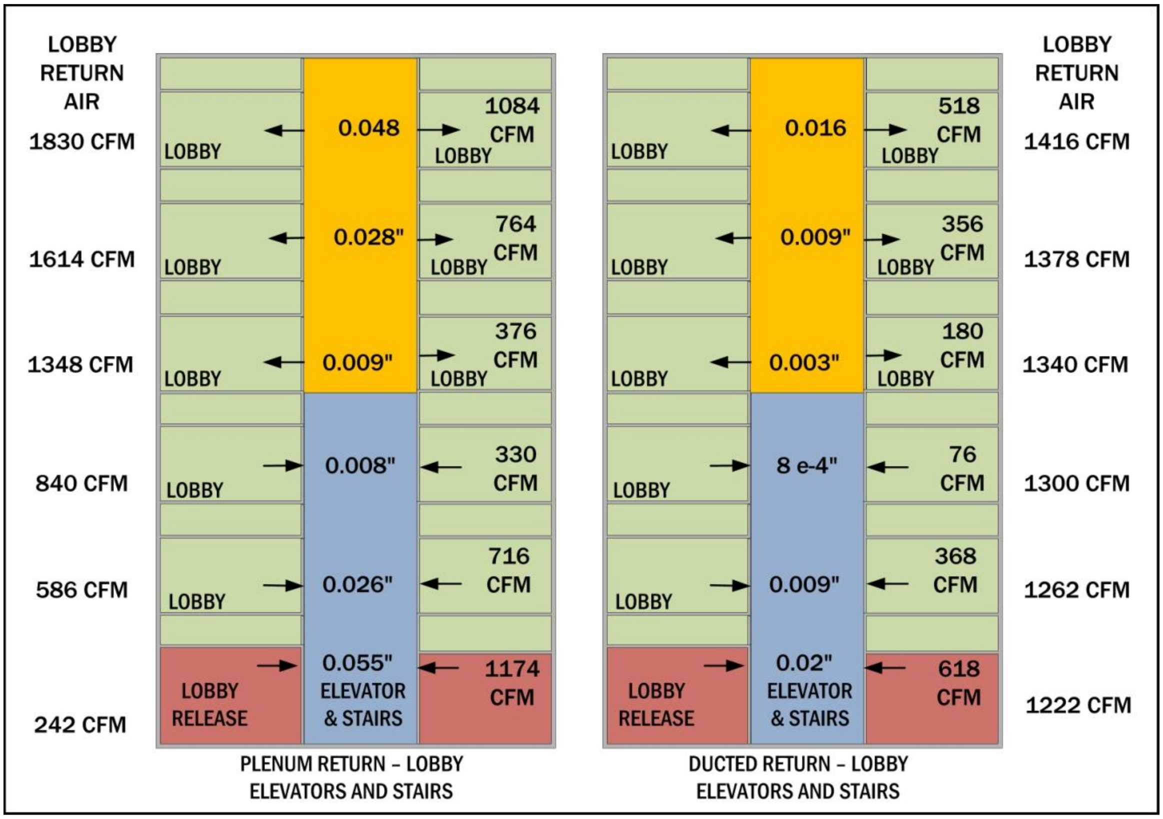


Figure 5-43: Stack induced airflow with ducted and plenum return – Stack Effect

Moisture Intrusion

To compare the potential for moisture infiltration in ducted and plenum return buildings, water vapor was tracked as a contaminant. No internal moisture sources were placed in the space, so any variation in humidity ratio in the building results from infiltration. To model dehumidification at a cooling coil, a 100% efficient filter removed water vapor from the supply air and a water vapor source was introduced into the supply air to bring the supply air to saturation at 55 °F. As a result, the space humidity ratio was controlled at 0.009 kg/ kg for all summer simulations. Simulations were run with a balanced and pressurized building. In the balanced building, return air flow was equal to supply air flow minus exhaust air flows from bathrooms and in the pressurized building, return air flow was selected to pressurize the building to 0.02” w.g. with respect to outside. TMY2 data from Houston, TX and Minneapolis, MN was selected to represent summer and winter weather conditions, respectively, such as ambient humidity ratio, wind speed and wind direction.

Figure 5-44 and Figure 5-45 show simulated summer humidity ratios in a balanced building during with ducted and plenum return systems. With a balanced building and a ducted return air system, the simulation results suggest that although the space humidity ratio is controlled at 0.009 kg/kg by dehumidification, wind pressure drives the plenum humidity ratio closer to 0.014 kg/kg, the ambient humidity ratio. However, with a balanced building and a plenum return system, the simulation results suggest that the plenum humidity ratio tracks the space humidity ratio as the space air enters the return plenum before being returned to the AHU.

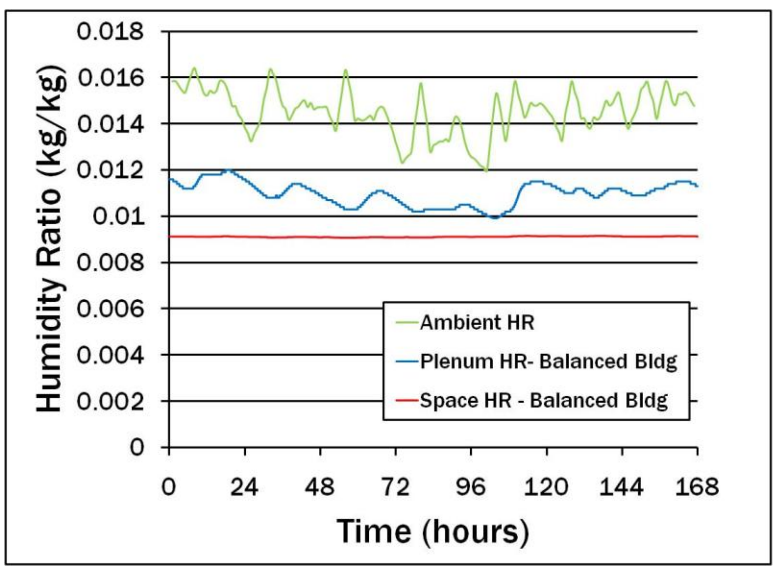


Figure 5-44: Simulated summer humidity ratio for a balanced building with ducted return

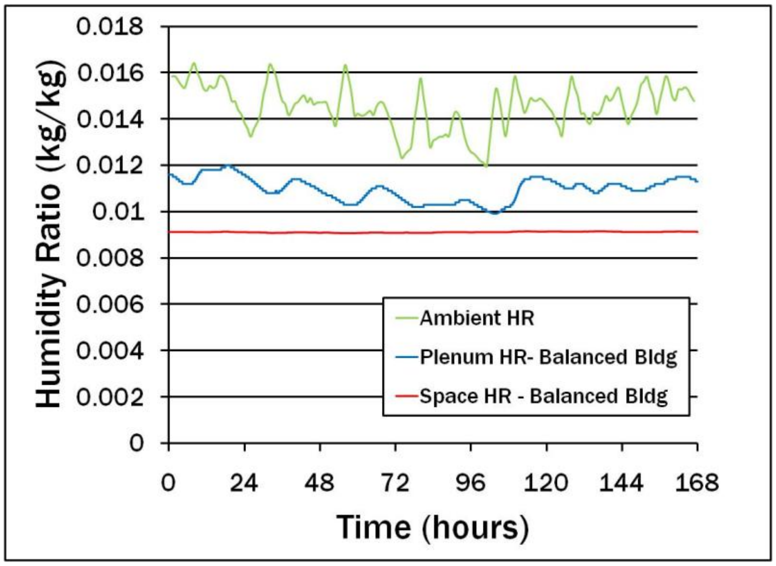


Figure 5-45: Simulated summer humidity ratio for a balanced building with plenum return

Figure 5-46 and Figure 5-47 and compare simulated plenum humidity ratios for the balanced and pressurized hypothetical building for each return configuration. Pressurizing the building with the ducted return air system reduced the plenum humidity ratio to levels equal to the space humidity ratio. Since flow paths modeling suspended ceiling tiles were placed between the space zones and the plenum zones, the zone and plenum were pressurized to approximately the same differential w.r.t. the exterior. However, pressurizing the building with the plenum return system did change the plenum humidity ratio when compared to the balanced building because air from the space enters the return plenum in both the balanced and pressurized cases.

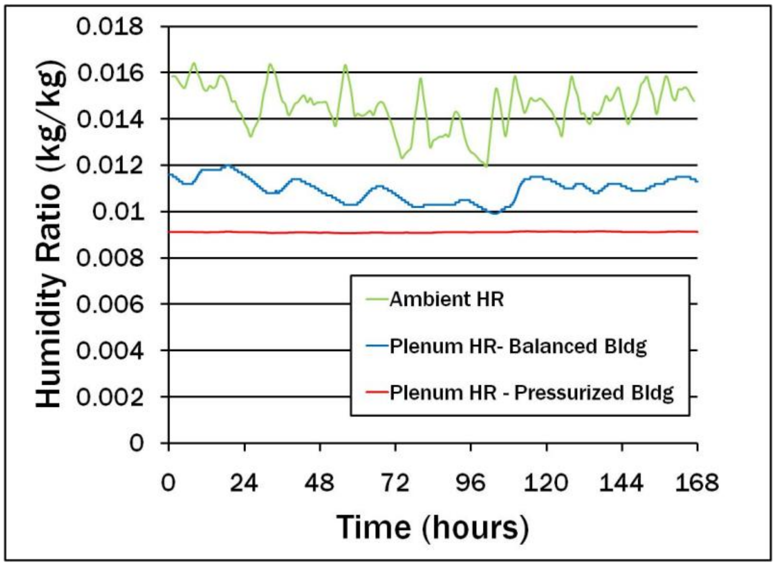


Figure 5-46: Simulated summer humidity ratio for balanced building and pressurized building with ducted return

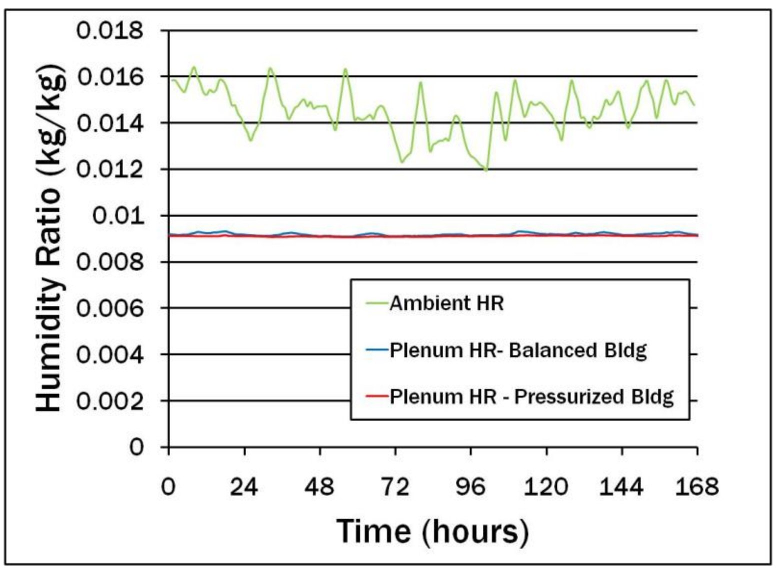


Figure 5-47: Simulated summer humidity ratio for a balanced and pressurized building with plenum return

Figure 5-48 and Figure 5-49 show simulated winter humidity ratios in a balanced building with ducted and plenum return systems. As with the summer simulations, the supply air humidity was assumed to be 0.009 kg/kg. Simulation results indicate that for a balanced building with ducted return, plenum humidity ratio is influenced by ambient humidity ratio. Since the space and plenum are only connected by a leakage pathway representing leaky suspended ceiling tiles, wind pressure drives the plenum humidity ratio closer to ambient levels. However, with a plenum return system, return air from the space enters the plenum so with a balanced building, plenum humidity ratio tracks space humidity ratio to a greater extent. Figure 5-50 and Figure 5-51 show simulated ambient and plenum humidity ratio for balanced and pressurized buildings with both return air systems. As seen in Figure 5-50, with a pressurized building and ducted return system, the plenum humidity approached the space humidity ratio, since pressurizing the space causes air to enter the plenum through the suspended ceiling tiles. As with the summer results, simulation results suggest that pressurizing a building with a plenum return system does not change the plenum humidity ratio since return air from the space enters the plenum before reaching the AHU.

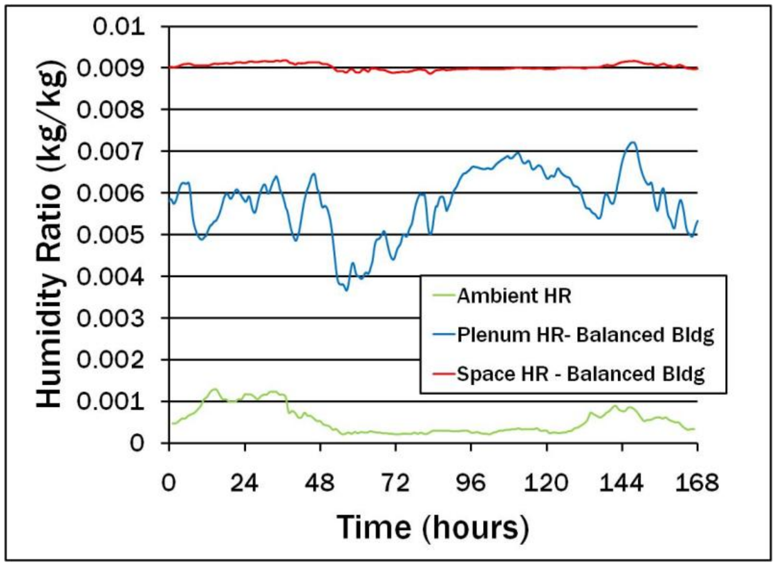


Figure 5-48: Simulated winter humidity ratio for a balanced building with ducted return

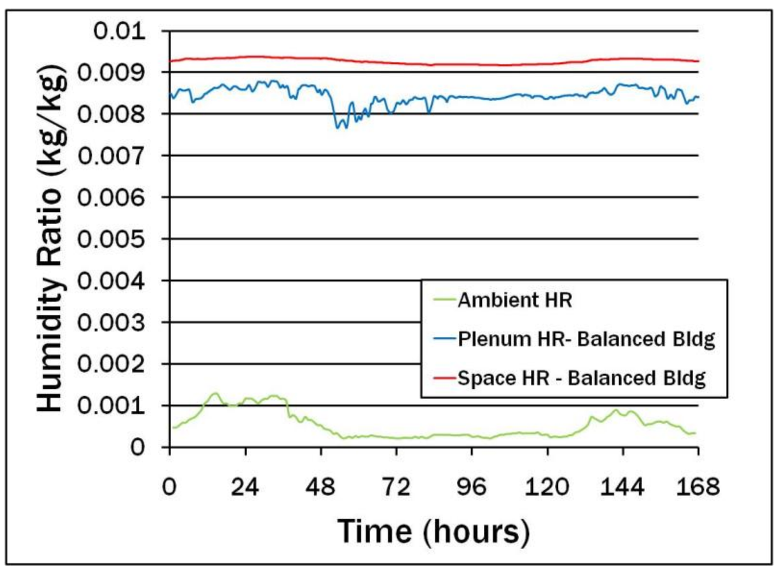


Figure 5-49: Simulated winter humidity ratio for a balanced building with plenum return

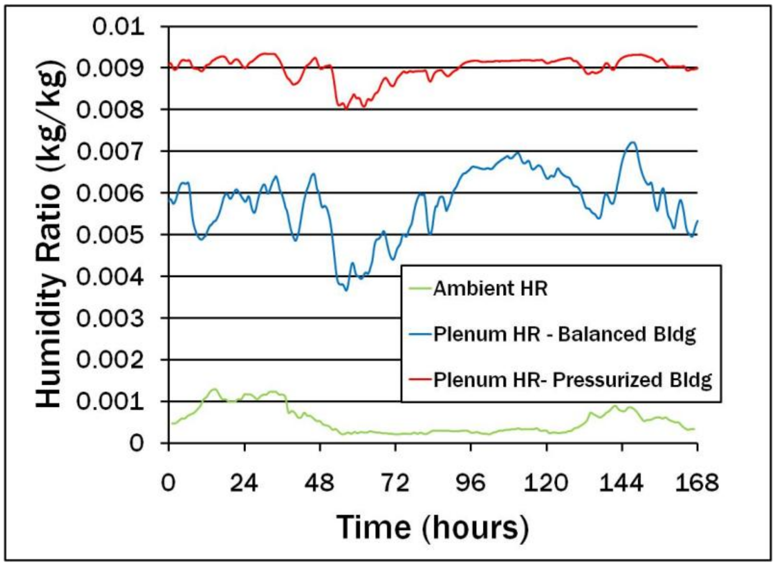


Figure 5-50: Simulated winter humidity ratio for a balanced and pressurized building with ducted return

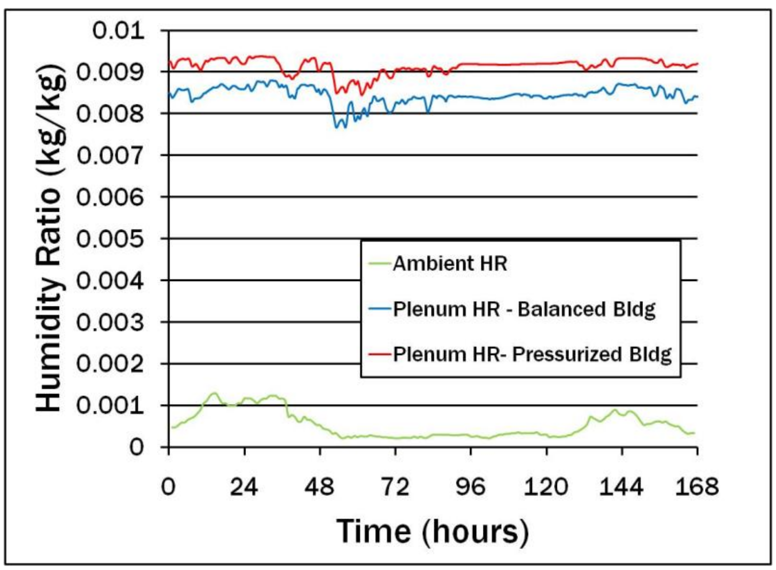


Figure 5-51: Simulated humidity ratio for a balanced and pressurized building with plenum return

Discussion and Conclusions

On the basis of this parametric study, several useful comparisons can be made between ducted and plenum return system performance relative to an indoor burst release of a contaminant. First, the observation from laboratory experiments at the Iowa Energy Center ERS that the plenum functions as a buffer zone that can delay and flatten the peak concentration in occupied space following a release held true in these simulations. Exposure results indicate that plenum return systems have the potential to significantly reduce short term occupant exposure to contaminants released in occupied spaces. Since the DOAS utilizes lower air change rates than recirculating air systems, occupant exposure with the DOAS system was significantly higher in the release zone; however, exposure was isolated to the release zone due to the "single pass" air system.

Differences in climate (weather) and zoning changed the magnitude of exposure, but not trends related to return system type. The most interesting and difficult to interpret results were those obtained when envelope leakiness was varied. In some cases, higher leakage resulted in somewhat increased exposure while in others exposure decreased. More importantly, however, relative to the objectives of this study, leakage did not change the trend to delayed, lower peak exposure with ducted return. Stack effect air flows were significantly impacted by return system type with the pressurization inside the building with ducted systems more non-uniform than with plenum return. However, vertical air flows were greater in the case of plenum return, resulting in greater vertical transfer in the direction of the stack-induced air flow.

Chapter 6

Discussion and Conclusions

The impacts of ducted air distribution system design and performance on buildings, particularly residential structures in which ducts are frequently outside conditioned space, has received significant study. Duct leakage in unconditioned spaces wastes substantial energy and may entrain contaminants into a building. Less work relative to return systems in non-residential buildings can be found in the literature. Some previous studies have considered the pros and cons of return system alternatives based on limited field measurements and experience; extensive analytical or controlled experimental studies providing a systematic quantitative energy and IAQ impact assessments for the various return strategies are very few.

Laboratory Experiments

Laboratory Experiments were conducted to investigate the impact of different air return methods on IAQ and CBR agent dispersion resistance under controlled conditions in a well instrumented test facility. Return air strategies in the scope of work included overhead ducted and plenum return air systems and plenum return system with parallel fan powered VAV boxes. The Iowa Energy Center Energy Resource Station (Lee *et al.* 1998, Price and Smith 2000) was used to conduct experiments comparing ducted and plenum return air systems.

Tracer Gas Tests

Tracer gas releases were conducted in the Iowa Energy Center to compare resistance of ducted and plenum return air systems to interzonal contaminant transfer and to investigate the impact of parallel fan powered VAV boxes on transport of contaminants from the plenum to conditioned space. Contrary to recommendations found in building security literature (ASHRAE 2003, NIOSH 2002, FEMA 2003, USACE 2001), plenum return does not inherently pose a greater risk of exposure to building occupants. Plenum return, in some cases, may provide greater protection to occupants during the time immediately following a contaminant release, during which evacuation can take place by delaying the entry of contaminants into occupied spaces. Results indicate that the impact of parallel fan powered boxes is non-uniform with fans lying in the path of higher concentration return air creating a greater impact on space concentration. Fan powered VAV boxes tend to diminish the buffering effect of the plenum because they may inject highly contaminated return air into occupied spaces.

Assumptions inherent in multizone modeling, most notably well mixed zones with uniform contaminant concentrations, restrict multizone modeling's applicability in determining inter-zonal contamination vulnerability of return air strategy. Since the model assumes a well mixed plenum, simulating the transport of contaminants from the plenum to conditioned spaces by parallel fan powered boxes was not possible. Although there were instances in which multizone modeling accurately simulated inter-zonal contaminant concentration with release zone mixing, simulations were not consistent for different release zone locations and return air strategies.

Differential Pressure Measurements

Since the Energy Resource Station (ERS) test room facilities allow simultaneous testing of two full scale building systems with identical thermal loads, side-by-side controlled experiments were conducted comparing the impact of return air system performance on AHU air flows and building pressurization. Differential pressure measurements and VAV airflows were logged for every minute with an accuracy of ± 0.001 in. w.g.

Results from the balanced portion of Winter Test 1.1 seems to confirm the assertion from Hydeman *et al.* (2003) that in VAV applications plenum returns self balance as supply air flow decreases at part load. With ducted return systems, return air flow does not track supply air flow changes to the zone and as a result, room pressurizations change in response to changes in supply air flow. Test Room differential pressure in rooms with ducted return was influenced by return air balance to a greater extent than rooms with plenum return. Presumably with plenum return, return air is able to vary through an open return grille responding to differential pressure across the grille, whereas with ducted return, return air is balanced for design conditions and is not able to vary in response to zonal supply airflow.

Parametric Multizone Modeling Study

On the basis of this parametric study, several useful comparisons can be made between ducted and plenum return system performance relative to an indoor burst release of a contaminant. First, the observation that the plenum functions as a buffer zone that can delay and flatten the peak concentration in occupied space following a release held true in these simulations. Differences in climate (weather) and zoning changed the magnitude of exposure, but not trends related to return system type. The most interesting and difficult to interpret results were those obtained when envelope leakiness was varied. In some cases, higher leakage resulted in somewhat increased exposure while in others exposure decreased. More importantly, however, relative to the objectives of this study, leakage did not change the trend to delayed, lower peak exposure with ducted return. Stack effect air flows were significantly impacted by return system type with the pressurization inside the building with ducted systems more non-uniform than with plenum return. However, vertical air flows were greater in the case of plenum return, resulting in greater vertical transfer in the direction of the stack-induced air flow.

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Appendix A

SUMMARY OF REFRENCES

Reference \ Category	Building Energy Use	Security and Contaminant Dispersal	IAQ	Design and Construction Methods	Repairs and Retrofits	Leakage Measurements	Analytical Model	Experimental Study	Residential	Commercial
ASHRAE (2003)		X		X						X
ASHRAE (2007)			X	X		X			X	X
ASTM (2000)						X				
ASTM (2003a)						X				
ASTM (2003b)			X			X			X	X
Bahnfleth et al. (2007)	X	X	X	X		X				X
Brennan *et al.* (2002)			X	X					X	X
Carrie *et al.* (2002)					X	X		X		X
Conat *et al.* (2004)	X				X	X		X		X
Crawley (2001)	X						X		X	X
Crawley *et al.* (2000)	X						X		X	X
Crawley *et al.* (2001)	X						X		X	X
Cummings (1989)						X			X	
Cummings and Withers (1998)	X		X	X		X		X		X
Cummings *et al.* (1990)	X				X	X		X	X	
Cummings *et al.* (1996)	X		X	X	X	X		X		X
Davis and Roberson (1993)	X				X	X		X	X	
Delp *et al.* (1998a)						X		X		X
Delp *et al.* (1998b)						X		X		X
FEMA (2003)		X		X						X
Fisk *et al.* (2000)						X		X		X
Franconi *et al.* (1998)	X						X			X
Guntermann (1986)				X			X			X
Harriman *et al.* (2001)			X	X						
Hydeman et al. (2003)	X			X						X

Reference \ Category	Building Energy Use	Security and Contaminant Dispersal	IAQ	Design and Construction Methods	Repairs and Retrofits	Leakage Measurements	Analytical Model	Experimental Study	Residential	Commercial
Jump *et al.* (1996)	X				X	X		X	X	
Klobut (1991)		X	X				X			X
Lee *et al.* (1998)	X	X	X				X			
Lstiburek (2002)			X	X					X	X
Lstiburek *et al.* (2002)	X		X	X	X	X		X	X	X
Modera *et al.* (1999)	X					X		X		X
Modera *et al.* (1996)	X				X			X	X	
Modera *et al.* (2002)						X		X		X
NIOSH (2002)		X		X						X
O'Neal *et al.* (2002)	X						X	X	X	
Parker *et al.* (1993)	X				X	X	X	X	X	
Persily (1999)										
Persily and Ivy (2001)		X	X			X	X		X	X
Persily *et al.* (2007)		X			X		X			X
Price and Smith (2000)	X	X	X				X	X		
Price *et al.* (2003)		X			X					X
Proctor (1997)						X		X	X	
Rock and Wolfe (1997)	X						X			X
SMACNA (1985)				X		X				X
Siegel and Walker (2003)				X		X	X	X	X	
Spengler and Chen (2000)		X	X	X						
Swim and Griggs (1995)				X		X	X	X		X
USACE (2001)		X		X						X
Walton and Dols (2005)		X					X		X	X
Withers *et al.* (1996)	X				X	X		X		X
Withers and Cummings (2000)			X	X	X	X		X	X	X
Wray (2003)	X						X			X
Wray and Matson (2003)	X						X			X
Wray *et al.* (2005)						X		X		X
Xu *et al.* (1999)					X	X	X	X		X
Zuraimi *et al.* (2004)			X					X		X

Reference: American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). (2003). "Report of Presidential Ad Hoc Committee for Building Health and Safety under Extraordinary Incidents." Atlanta.

1. Scope and content:
This report addresses risk management in industrial, commercial, institutional, educational and public use/assembly buildings. Topics discussed include evaluating the risk to a facility, assessing the vulnerability of a facility based on risk, determining acceptable vulnerability, determining infrastructure constraints and vulnerability, and protective measures for new and existing buildings.
2. Relevance to return systems:
• Providing areas of refuge with fire, smoke and particulate separation with no cross contamination of return air minimizes the area of dispersion and provides short term protection for occupants • Mail handling should be done in a room or building with a separate ventilation system and separate return air pathway • Return duct work should be routed to avoid cross contamination of air (unducted returns should not be used)
3. Significant findings:
Since the time that buildings operate under normal operation far exceeds the time under extraordinary incidents, nothing should be done to reduce vulnerability that reduces air quality, comfort or health of a building environment under normal operating conditions.
4. Limitations and assumptions:
Buildings not considered industrial, commercial, institutional, educational, or public/assembly are outside the scope of this report.
☐ Building Energy Use ☒ Security / Contaminant Dispersal ☐ Indoor Air Quality ☒ Design & Construction Methods ☐ Repairs & Retrofits ☐ Leakage Measurements ☐ Analytical Model ☐ Experimental Study ☐ Residential ☒ Commercial & Institutional

Reference: American Society for Testing and Materials, International (ASTM). (2000). *Standard E 741-00, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution.*

1. Scope and content:
This reference describes tracer gas dilution, a test for determining a single zone's air change with the outdoors. Three techniques are described: (1) concentration decay, (2) constant injection, and (3) constant concentration. The required equipment and capabilities of each technique are discussed.
2. Relevance to return systems:
The reference does not address return air systems.
3. Significant findings:
To obtain the air change rate, use the tracer gas decay technique. To obtain the air change flow, use the constant injection or constant concentration techniques. Sources of bias are listed for each technique. Uncertainties zone volume measurements affect conversion between air change rates and air change flows, and vice versa.
4. Limitations and assumptions:
The test method applies only to single zone systems. Since the test methods require uniformity of the tracer gas within the zones, multizone buildings are difficult to treat as a single zone.

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☐ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☐ Commercial & Institutional

Reference: American Society of Testing and Materials, International (ASTM). (2003a). *Standard E 779-03, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization.*

1. Scope and content:
This reference describes a test method that determines a building envelope's air leakage. The air leakage characteristics can be determined from the relationship between airflows and pressure differences due to mechanical pressurization and depressurization.
2. Relevance to return systems:
The reference does not address return air systems.
3. Significant findings:
Air tightness of the building envelope determined by this method can be used to compare the relative tightness of similar buildings, to indentify leakage sources and rates, and to determine the leakage reduction of incremental repairs.
4. Limitations and assumptions:
This test method does not determine air change rate directly. The tracer gas dilution method should be used to measure air change rate directly (ASTM 2000).

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☐ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☐ Commercial & Institutional

Reference: American Society of Testing and Materials, International (ASTM). (2003b). *Standard E 1554-03, Standard Test Method for Determining External Air Leakage of Air Distribution System by Fan Pressurization.*

1. Scope and content:

This reference covers two methods to measure air leakage of duct systems that pass outside conditioned spaces in low-rise residential and small low-rise commercial buildings. The techniques use airflow and pressure measurements to determine leakage and include distinct measurements for supply and return air leakage.

2. Relevance to return systems:

When the air handler is turned on, mechanically driven air leakage is significantly larger than wind and infiltration driven leakage. Since supply and return air leakage impact the system differently, the two leakage paths and characteristics should be determined separately.

3. Significant findings:

- Test Method A is a leakage test in which envelope pressure differences are generated by a separate fan and the envelope is pressurized and depressurized. Test Method A will have lower operating condition airflow leakage uncertainties for leaky systems since results from Test Method B are converted to operating system pressures.
- Test Method B is a leakage test in which the distribution system and at the same time as the envelope to isolate the leaks in communication with the exterior of the building. System operating pressures are used to estimate the leakage under typical operating conditions. Test Method B is preferred for houses or businesses with leaky envelopes.
- This standard should be used to: compare relative air leakage from similar air distribution systems, identify leakage sources and leakage rates of different components in system, determine air leakage reduction from individual retrofit measures applied incrementally

4. Limitations and assumptions:

- The proper use of these methods requires a knowledge of the principles of air flow and pressure measurements

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Reference: Brennan, T., J.B. Cummings, and J. Lstiburek. (2002). “Unplanned Airflows & Moisture Problems.” ASHRAE Journal **44**(11): 36-41.

1. Scope and content:
This reference focuses on moisture related problems resulting from unplanned airflows. The authors describe how air moves through buildings due to pressure differences and describe the driving forces behind those pressure differences (fans, stack effect, wind). After discussing how unplanned airflows cause condensation problems, design and construction methods are suggested to prevent moisture problems.
2. Relevance to return systems:
The reference describes how wall and ceiling cavities become depressurized by the return-side of the air handler. Hot and humid air outdoor air can be drawn through crawl spaces or exterior walls by depressurized return plenums. Air can be drawn across suspended ceiling tiles by depressurized return plenums. In cooling conditions outdoor air or unconditioned attic air drawn into the building may condense on cold surfaces. In heating conditions warm indoor air drawn into unconditioned attic spaces may condense on cold surfaces.
3. Significant findings:
Suggestions to prevent moisture problems include: ▪ Avoiding plenum returns or operate return plenums at positive pressure relative to outdoors and at negative pressure relative to room air ▪ Include air tightness specifications in construction documents ▪ During TAB stage, create a pressure map for all probable modes of HVAC system operation ▪ Avoid more than one vapor barrier in assembly ▪ Pressurize buildings for hot and humid climates and depressurize buildings for cold climates ▪ Place air and thermal barriers together as dual-purpose material or in parallel
4. Limitations and assumptions:
The reference did not present simulations, and focused on describing moisture related problems from unplanned airflows.

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Reference: Carrie, F.R., R.M. Levinson, T.T. Xu, D.J. Dickerhoff, W.J. Fisk, J.A. McWilliams, and M.P. Modera. (2002). "Laboratory and field testing of an aerosol-based duct-sealing technology for large commercial buildings." ASHRAE Transactions **108**(2): 316-326.

1. Scope and content:
Carrie *et al.* investigated sealing ducts in commercial buildings by blowing an aerosol sealant through pressurized duct systems. The sealing technique was used on isolated duct sections of two commercial buildings and the ASHRAE leakage class and the effective leakage area of the duct systems were measured. The ASHRAE leakage classes (cfm/100 ft^2 at 1 in. H_2O) were reduced from 657 to 103 and from 40 to 3. The effective leakage areas (cm^2 at 25 Pa) were reduced from 544 to 95 and 45 to 3. The authors also quantified losses of sealant near the aerosol generator, evaluated the ability of the seals to withstand high pressures encountered in commercial duct systems, evaluated new procedures to speed up the sealing rates and conducted field experiments assessing the feasibility of sealing large leaks and long duct runs.
2. Relevance to return systems:
The reference does not specifically address return ducts and plenums; however, the same sealing technique could potentially be used for return air ducts.
3. Significant findings:
The reference investigates the potential of using an aerosol-based duct-sealing technology, previously developed for residential applications, in large commercial buildings. Major obstacles in sealing ducts include running diagnostic tests to find leaks, interrupting building operation, and sealing ducts in spaces with limited access. Since the ducts are pressurized and registers are blocked, particles "automatically" find the leaks, and diagnostic tests required to find the leaks can be avoided. Also, time spent sealing ducts in inaccessible spaces can be reduced. The authors performed a crude cost analysis on a hypothetical large office building with a C_L = 200 duct system. Franconi *et al.* (1998) predicted 30% savings of fan energy use as a result of reducing supply duct leakage. Assuming typical sealing rates encountered, typical commercial fan energy use, and market experience of aerosol sealing in residences, the simple payback period was estimated to be one to two years.
4. Limitations and assumptions:
Although the bursting pressure of seals measured in the laboratory indicate that the strength of seals is adequate for the pressures ducts systems experience in commercial buildings, longevity of seals should be tested before the sealing technique is commercialized.

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Reference: Conat, A., M. Modera, J. Pira, J. Proctor and M. Gebbie. (2004). *Comprehensive Diagnostic and Improvement Tools for HVAC-System Installations in Light Commercial Buildings, Final Report to United States Department of Energy*. San Rafael: Proctor Engineering Group, Ltd.

1. Scope and content:
Diagnostic and improvement tools were developed to address airflow, refrigerant charge, economizer operation, and duct leakage and conduction in light commercial buildings. The authors refined aerosol-based duct sealing technology, computer driven diagnostic and improvement tracking tools, and an integrated human/computer diagnostic verification process. Site monitoring was conducted to measure the energy savings for particular cases of HVAC system repair. 25 sites were visited, 16 of these sites received diagnostic measurements, and 8 sites received repairs to their HVAC systems. Pre and post-repair measurements included duct leakage at 25 Pa, refrigerant charge added, airflow through evaporator at 25 Pa, supply and return dry bulb temperatures, return wet bulb temperatures, condenser air entering air temperature, evaporator and condenser saturation temperatures, and suction and liquid line temperatures.
2. Relevance to return systems:
Return duct heat gain, characterizing the effect of return duct sealing, and sensible steady state EER, reflecting the effect of increased refrigerant charge and return duct sealing were calculated from pre and post repair measurements using linear regressions. Return duct heat gain was defined as the temperature gain between the return grille and return plenum as a function of outside to inside temperature difference. Sensible steady state EER was defined as amount of sensible cooling (Btu/h) per watt at steady state. The calculation did not include the impact of supply side sealing.
3. Significant findings:
5. At 16 sites, duct leakage at 25 Pa was an average of 22% of evaporator air flow at 25 Pa. 6. At 3 sites, sealing return ducts decreased average return duct heat gain by the equivalent of 12.4% of the system's sensible capacity at a 30 °F outside-inside ΔT. The amount of savings increased as the outside-inside ΔT increased. 7. At 2 sites, correcting the refrigerant charge and sealing return ducts improved the sensible steady state EER by an average of 18% at a 30 °F outside-inside ΔT. Improvements increased as outside-inside ΔT increased.
4. Limitations and assumptions:
The sites visited were light commercial buildings (less than 10,000 ft^2 floor area) with constant air volume (CAV) rooftop HVAC systems.

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Reference: Crawley, D.B. (2001). "EnergyPlus: The Future of Building Energy Simulation." Heating, Piping & Air Conditioning Engineering **73**(11): 65-67.

1. Scope and content:
Crawley describes the background of EnergyPlus's predecessors, DOE 2 and BLAST, and discusses the birth and structure of EnergyPlus.
2. Relevance to return systems:
The reference does not address return ducts and plenums; however, ventilation systems can be simulated in EnergyPlus.
3. Significant findings:
▪ EnergyPlus uses an integrated simulation for loads and systems, so accurate prediction of temperature and other comfort parameters is possible ▪ The modular structure of EnergyPlus allows users to create modules to keep up with new building technologies
4. Limitations and assumptions:
The EnergyPlus team focused first on writing the simulation engine, so EnergyPlus does not have a graphical user interface. Third parties are developing user-friendly interfaces for input and output of data.

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Reference: Crawley, D.B., L.K. Lawrie, F.C. Winkelman, and C.O. Pedersen. (2000). "EnergyPlus: Energy Simulation Program." ASHRAE Journal **42**(4): 49-56.

1. Scope and content:
Crawley *et al.* describe the development and structure of EnergyPlus, a new building energy simulation program developed to take advantage of improvements in analysis and computational methods within the last 2 decades. EnergyPlus resolves many of the shortcomings of BLAST and DOE-2 by calculating building loads and system/plant response simultaneously and iteratively. BLAST and DOE-2 simulates and calculates building loads and distribution and plant response sequentially with single pass calculations. Also, the modular structure of EnergyPlus allows the addition of user-defined HVAC components and links to other programs.
2. Relevance to return systems:
The Airflow Network Model allows simulation of air distribution systems with supply and return leaks, and multizone air flows.
3. Significant findings:
The reference is a helpful introduction to EnergyPlus. The author includes a table that compares the capabilities of DOE-2, BLAST, IBLAST and EnergyPlus.
4. Limitations and assumptions:
EnergyPlus is a simulation engine without a graphical user interface.

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Reference: Crawley, D.B., L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, R.K. Strand, R.J. Liesen, D.E. Fisher, M.J. Witte, and J. Glazer. (2001). "EnergyPlus: creating a new-generation building energy simulation program." Energy and Buildings **33**: 319-331.

1. Scope and content:
Crawley *et al.* describe the history of EnergyPlus's development, and present an overview of the capabilities and structure of EnergyPlus.
2. Relevance to return systems:
The reference does not address return ducts and plenums; however, ventilation systems can be simulated in EnergyPlus.
3. Significant findings:
The reference describes how EnergyPlus overcomes the shortcomings of DOE 2 and BLAST. Significant improvements include integrated simulation of building load calculations and heating/cooling systems and plant /electric systems responses, and the modular structure allowing users to add HVAC components and other features. Also, graphical representations clarify the explanations of the structure and organization of EnergyPlus.
4. Limitations and assumptions:
As of yet EnergyPlus does not have a graphical user interface for data input. Third party programs are being developed.

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Reference: Cummings, J.B. (1989). *Tracer Gas as a Practical Field Diagnostic Tool for Assessing Duct System Leaks*. Cocoa: Florida Solar Energy Center, FSEC-PF-195-90.

1. Scope and content:
Cummings presents a method of testing homes to detect and quantify duct leakage using tracer gas analysis. By measuring the infiltration rate of the house with the air handler on and measuring the infiltration rate again with the air handler off, duct leakage can be estimated.
2. Relevance to return systems:
The return leak fraction can be calculated from the tracer gas concentration at three locations: 1) in the room near the return grille, 2) in the supply air stream, and 3) near the location of the return leak. The return leak fraction can be multiplied by the supply air flow rate to get a return leak air flow rate. The return leak air flow rate can be compared to the infiltration air flow rate to characterize the distribution of leakage between the supply and return sides.
3. Significant findings:
The test for return leak fraction, completed in 15 minutes, can be used to ensure that duct leaks have been repaired and can indicate whether repairing duct leaks will be cost effective.
4. Limitations and assumptions:
The reference describes a tracer gas test in a house, but the same method can be used in commercial buildings.

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Reference: Cummings, J. B., and C.R. Withers. (1998). "Building cavities used as ducts: air leakage characteristics and impacts in light commercial buildings." ASHRAE Transactions **104**(2): 743-752.

1. Scope and content:
Cummings and Withers investigated uncontrolled air flow in 70 small commercial buildings in Florida. In 33 of the buildings, building cavities were used as part of the air distribution system. Building cavities characterized included enclosed air handler support platforms, mechanical closets, mechanical rooms, ceiling spaces, wall cavities, and chases. Seven of the seventy buildings used ceiling spaces as part of the thermal distribution system. The average ceiling plenum was found to be depressurized to 0.004 in. H_2O (1 Pa) with respect to the outdoors.
2. Relevance to return systems:
The paper refers to plenums in a general sense by focusing on building cavities used as part of the air distribution system. Leakage characteristics and pressure differences of the building cavities are reported in more detail in "Uncontrolled Air Flow in Non-Residential Buildings, Final Report FSEC-CR-878-96."
3. Significant findings:
The amount of air leakage depends on the pressure differential across the leak and the area of the leak. Since the average ceiling plenum was depressurized to 0.004 in. H_2O (1 Pa) with respect to the outdoors, the authors contend that "Consequently, return air leakage associated with ceiling space plenums may be small or negligible" (p. 751). The authors point out that "The magnitude of the impacts is a function of the amount of air leakage but also a function of the location of those leaks." (p. 749) The authors suggest placing both the primary air and thermal barriers at the roof deck, so the plenum is considered part of the conditioned space.
4. Limitations and assumptions:
Leakage in the building cavities was not measured separately from the air distribution system, but qualitative evidence is presented that building cavities leak. Also, the authors' discussion of the impacts of return air leakage on energy use, infiltration, and indoor humidity assumed that the buildings were located in a hot and humid summer climate, that the leak originated from the ceiling or attic space, and that the HVAC system was in air conditioning mode. The discussion of placement of barriers and impacts of return air leakage may not be relevant for buildings in cold and dry winter climates or with buildings in heating mode.

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Reference: Cummings, J.B., J.J. Tooley, N.A. Moyer, and R. Dunsmore. (1990). "Impacts of duct leakage on infiltration rates, space conditioning energy use, and peak electrical demand in Florida homes." In *Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings, 9.65-9.76.* Washington, D.C.: American Council for an Energy Efficient Economy.

1. Scope and content:
Cummings *et al.* tested 150 homes in Florida for evidence of duct leakage using tracer gas dilution and blower door tests. 25 homes were selected for duct repair and 24 homes were monitored for air conditioning energy use before and after repairs. Tracer gas dilution was used to measure the return leak fraction (RLF), the portion of the air returning to the air handling unit (AHU) from outside the conditioned space. The average RLF measured in 91 homes was 10% of air handler flow, and 30% of the homes had a RLF greater than 10%. After repairing ducts in 25 homes, ACH50 was reduced from 12.30 to 11.13, indicating that 68% of the leaks were repaired. In the 25 homes selected to have duct repairs, the average RLF was reduced from 16.7% to 4.5%.
2. Relevance to return systems:
The reference focuses on residential air distribution systems. The main source of return leaks was found to be the return plenum, usually the support platform for the AHU. The metric used to compare leakage between homes was the return leak fraction.
3. Significant findings:
In 24 homes, cooling energy use was reduced 18%, from 41.3 kWh/day to 34.2 kWh/day. Assuming a repair cost of $200, an average cooling savings of 7.1 kWh/day, and modest heating season savings of $25, Cummings *et al.* found that the simple payback period of duct repair to be on the order of 2 years. Duct repair would not only reduce residential electrical use, but could reduce peak demand on the electrical grid. Assuming that the distribution of duct leaks in Florida mimicked the distribution found in their study, Cummings *et al.* presented a theoretical calculation on the impact of return duct leakage on winter peak demand of an example house and on the state of Florida. The house was assumed to be heated with a heat pump sized for cooling mode, and a supplemental electric resistance heater. Typical duct repair reduced the winter peak demand per house by 1.6 kW, and reduced Florida's state wide demand by 13%. Duct repair costing $600 million avoided $3.5 billion in new electrical generation, at $700/kW new electric generation.
4. Limitations and assumptions:
The study focuses on residential air distribution systems. Leakage fractions in the residential data are not comparable to leakage measurements in commercial distribution systems because of the larger loads and larger air handling equipment.

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Reference: Cummings, J.B., C.R. Withers, N. Moyer, P. Fairey, and B. McKendry. (1996). *Uncontrolled air flow in non-residential buildings.* Cocoa: Florida Solar Energy Center, FSEC-878-96.

1. Scope and content:
Cummings *et al.* investigated uncontrolled airflow, which included duct leakage, return air imbalances and exhaust air/intake air imbalances, in 70 small commercial buildings in Florida. Measurements taken included building air \`1\`, outdoor air and make-up airflows. 7 ceiling space configurations were defined based on the location of the primary thermal and primary thermal barriers. The impact of duct leakage to and from these ceiling spaces on energy use and indoor air quality was discussed based on the ceiling space configuration. The authors suggest placing both the primary thermal and primary air barriers at the roof deck, so the ceiling space is within the conditioned space. Repair of uncontrolled airflow included sealing duct leakage, turning off attic fans, air tightening the building envelope and reducing outdoor air flow. Reductions of energy use and peak electrical demand were determined for buildings which received repair.
2. Relevance to return systems:
The majority of repairs consisted of sealing duct leaks. Supply and return leaks were included together.
3. Significant findings:
Repairs were made in 20 of the 70 buildings: ▪ Average cooling energy use was reduced from 87.4 kWh/day to 75.1 kWh/day, a reduction of 14.7%. In the 18 buildings that showed energy savings, reductions varied from 4.3% to 36%, and in one building energy use increased by 6.7%. ▪ Average peak electrical demand was reduced from 7.61 kW to 6.90 kW, a reduction of 9.4%. In four buildings peak electrical demand was increased. In the buildings that showed a reduction in demand, reductions varied from 1.4% to 28%.
4. Limitations and assumptions:
The buildings were located in Florida, so discussion of impact of unplanned airflows on energy use, indoor air quality and infiltration assumed summer conditions and cooling mode.

- ☒ Building Energy Use
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- ☒ Indoor Air Quality
- ☒ Design & Construction Methods
- ☒ Repairs & Retrofits
- ☒ Leakage Measurements
- ☐ Analytical Model
- ☒ Experimental Study
- ☐ Residential
- ☒ Commercial & Institutional

Reference: Davis, B.E., and M.R. Roberson. (1993). "Using the "pressure pan" technique to prioritize duct sealing efforts: a study of 18 Arkansas homes." Energy and Buildings **20**(1): 57-63.

1. Scope and content:
Davis and Roberson identified duct leaks using a "pressure pan" technique, sealed the leaks, and measured energy consumption before and after sealing ducts for 17 Arkansas homes. The building is depressurized to -30 Pa using a blower door. The air handler is turned off, the filter is removed, and all registers are opened fully. A micromanometer is attached to a pan and placed over each supply and return register, one at a time. The resulting pressure difference is a measurement of the pressure in the duct with respect to the space. If the pressure in the duct is the same than the space, there is no duct leakage near that register, and if the pressure in the duct is significantly different from the room pressure, a substantial duct leak is assumed to be near that register. The process gives no measurement of duct leakage, only an indication that a leak exists. A pressure difference of 0.1 to 1 Pa indicates a small duct leak, and pressure differences greater than 1 Pa indicate a moderate to large duct leak.
2. Relevance to return systems:
The authors determined what portion of the leakage in the supply and return was sealed and what portion was left unsealed.
3. Significant findings:
Twenty four hour electric and gas energy use was plotted against average hourly temperatures for each day. The average temperature over the 74 day recording period was used for reduction in average energy use. The average reduction in energy consumption was 31.3% for houses with heat pumps and 19.7% for houses with gas furnaces. The authors asserted that based on the results of this study on heating and another study on cooling, the average Arkansas home could save $130/yr with gas heat and electric cooling, and $160/yr for electric heat pump heating and cooling, and that the cost of the duct repair including costs, profit and overhead would be approximately $500 per house. The simple payback period would be 3.9 years for gas/electric and 3.2 years for electric/electric.
4. Limitations and assumptions:
The study focused on the impacts of duct leakage on heating energy use in residences.

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Reference: Delp, W.W., N.E. Matson, D.J. Dickerhoff, and M.P. Modera. (1998a). "Field investigation of duct system performance in California small commercial buildings (round II)." In *Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings, 3.105-3.116.* 1998. Washington, D.C.: American Council for an Energy Efficient Economy.

1. Scope and content:
Delp et al., from Lawrence Berkeley National Laboratory (LBNL), characterized HVAC systems, duct leakage, and duct thermal losses in sixteen buildings containing twenty-five packaged rooftop HVAC systems. The data from the LBNL study was compared to data from Florida Solar Energy Center's (FSEC) 1996 study, titled "Uncontrolled Air Flow in Non-Residential Buildings."
2. Relevance to return systems:
The reference does not address return ducts and plenums. Combined effective leakage areas (ELA's) are reported, but a method of splitting ELA's between supply and return systems is outlined in the appendix.
3. Significant findings:
Delp *et al.* measured the effective leakage area (ELA) of the air distribution system, by sealing supply and return registers, pressurizing the ducts using a calibrated fan, and measuring the flow through the system at a range of pressures. The ELA is the area (cm^2) of a single orifice that would produce the same flow as the leaks in a portion of a duct system at a reference pressure difference, typically 25 Pa. The authors normalized leakage measurements in order to compare leakage data from different systems and different studies by comparing combined ELA (cm^2) to unit size (tons) and combined ELA (cm^2) to floor area (m^2). The average normalized ELA for the LBNL data was 3.7 cm^2/m^2 floor area, 2.8 times greater than the residential data, and the average normalized ELA for the FSEC data was 2.7 cm^2/m^2 floor area, 2 times greater than the California residential data measured by Jump *et al.* 1996.
4. Limitations and assumptions:
The reference reports combined supply and return ELA.

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Reference: Delp, W.W., N.E. Matson, E. Tschudy, M.P. Modera, and R.C. Diamond. (1998b). "Field investigation of duct system performance in California light commercial buildings." ASHRAE Transactions **104**(2): 722-732.

1. Scope and content:
Delp et al., from Lawrence Berkeley National Laboratory (LBNL), characterized HVAC systems, duct leakage, and duct thermal losses in sixteen buildings containing twenty-five packaged rooftop HVAC systems. The data from the LBNL study was compared to data from Florida Solar Energy Center's (FSEC) 1996 study, titled "Uncontrolled Air Flow in Non-Residential Buildings."
2. Relevance to return systems:
The reference does not address return ducts and plenums. Combined effective leakage areas (ELA's) are reported, but a method of splitting ELA's between supply and return systems is outlined in the appendix.
3. Significant findings:
Delp *et al.* measured the effective leakage area (ELA) of the air distribution system, by sealing supply and return registers, pressurizing the ducts using a calibrated fan, and measuring the flow through the system at a range of pressures. The average normalized ELA for the LBNL data was 3.7 cm^2/m^2 floor area, 2.8 times greater than the residential data measured by Jump *et al.* 1996 and the average normalized ELA_{25} for the FSEC data was 2.7 cm^2/m^2 floor area, 2 times greater than the California residential data measured by Jump *et al.* 1996. ▪ 50% of the buildings had insulation at the roof deck, 38% had insulation on ceiling tiles, and the remainder had insulation at both places ▪ 38% of the buildings had the ceiling cavity purposely vented to the outside ▪ 56% of the buildings had the primary thermal barrier located at the ceiling tiles (ductwork was outside the conditioned space), 19% had the primary thermal barrier at the roof, and the remainder had the primary thermal barrier in between
4. Limitations and assumptions:
The reference reports combined supply and return ELA.

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Reference: Federal Emergency Management Agency (FEMA). (2003). "Reference manual to mitigate potential terrorist attacks against buildings." *FEMA 426*, Washington, D.C.

1. Scope and content:
The manual offers design measures intended to reduce physical damage to structural and non-structural building components in the event of a blast explosion or to reduce casualties from bomb explosions and releases of CBR agents. The manual is organized in the following chapters: 8. Chapter 1 presents methodologies to integrate threat/hazard, asset value, and vulnerability 9. Chapter 2 discusses architectural/engineering design measures for the building property 10. Chapter 3 discusses architectural/engineering design measures for the building itself 11. Chapter 4 provides a discussion of blast theory 12. Chapter 5 presents CBR design measures to mitigate vulnerability and reduce risk
2. Relevance to return systems:
The manual suggests separating ventilation zones by avoiding unducted return plenums and limiting shared returns. A CBR agent released above an unducted return plenum will most likely reach the HVAC unit and will be redistributed throughout the building; however, ducted returns offer limited access points to the return air system.
3. Significant findings:
Other HVAC system design measures include: ▪ Elevating fresh air intakes ▪ Secure mechanical rooms and systems ▪ Isolate high risk areas (lobbies, mailrooms, and loading docks) by operating these areas at a negative pressure relative to the rest of the building and a positive pressure with respect to outdoors
4. Limitations and assumptions:
The manual acknowledges that the guidance and advice is most applicable to commercial office facilities, retail commercial facilities, light industrial facilities, health care facilities, local schools, and higher education facilities. The information in the manual is also not mandatory, not applicable to all buildings, and not applicable when it other hazards.

☐ Building Energy Use	☐ Leakage Measurements
☒ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☐ Experimental Study
☒ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Fisk, W.J., W. Delp, R. Diamond, D. Dickerhoff, R. Levinson, M.P. Modera, M. Nematollahi, and D. Wang. (2000). "Duct systems in large commercial buildings: physical characterizations, air leakage, and heat conduction gains." Energy and Buildings **32**(1): 109-119.

1. Scope and content:
Effective leakage areas (ELA's), air-leakage rates, and heat conduction gains of supply ducts in large commercial buildings were compared. Also, different methods of measuring air leakage rates were compared, and large inconsistencies suggest the need for further development of accurate testing methods. The authors physically characterized 6 buildings and their supply duct systems from building plans and walkthroughs. In two buildings, 4 sections of supply ductwork were isolated, and ELA's and air leakage rates were measured. The leakage classes in the supply systems ranged from 60 to 270, much higher than the range of 3 to 12 ASHRAE cites for quality duct construction and sealing practices, and higher than the range of 30 to 48 ASHRAE assumes for unsealed ductwork.
2. Relevance to return systems:
The reference does not address return ducts and plenums. ELA's and air leakage rates were measured for subsections of supply ducts.
3. Significant findings:
The reference presents physical characterization of large commercial buildings and their supply duct systems, ELA's and air leakage rates of supply ducts, and heat conduction gains of supply ducts. The leakage classes in the supply systems ranged from 60 to 270, much higher than the range of 3 to 12 ASHRAE cites for quality duct construction and sealing practices, and higher than the range of 30 to 48 ASHRAE assumes for unsealed ductwork. The large inconsistencies of air leakage rates measured by different methods illustrate the need for further research on leakage measurements and techniques.
4. Limitations and assumptions:
The reference did not investigate the ELA's or air leakage rates of return ducts or plenums.

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Franconi, E., W.W. Delp, and M.P. Modera. (1998). *Impact of duct air-leakage on VAV system energy use.* Berkeley: Lawrence Berkeley National Laboratory, LBNL-42417 Draft Report.

1. Scope and content:
Franconi *et al.* evaluated the impact of supply duct leakage on VAV-system energy use in a typical office building using TRNSYS to model system components and DOE 2 to calculate load profiles. The impact of leakage upstream and downstream of VAV boxes is discussed. Three leakage levels are considered: (1) 10% upstream & 10% downstream, (2) 5% upstream and 5% downstream, and (3) no leakage.
2. Relevance to return systems:
The paper does not consider return duct or return plenum leakage. The TRNSYS component models are not published in this reference, but can be found in Wray and Matson (2003). The component models can be used to model return duct leakage.
3. Significant findings:
For 10% upstream and 10% downstream leakage fan energy increases by 55%, coil load increases by 9% and reheat energy decreases by 8% compared to a distribution system with no leakage.
4. Limitations and assumptions:
Although the plenum temperature was determined from a plenum energy heat balance, no adjustments were made to zone loads to account for changes in plenum temperatures that occur as a result of leaky supply ducts.

- ☒ Building Energy Use
- ☐ Security / Contaminant Dispersal
- ☐ Indoor Air Quality
- ☐ Design & Construction Methods
- ☐ Repairs & Retrofits
- ☐ Leakage Measurements
- ☒ Analytical Model
- ☐ Experimental Study
- ☐ Residential
- ☒ Commercial & Institutional

Reference: Guntermann, A.E. (1986). “VAV system enhancements.” Heating, Piping & Air Conditioning **58**(8): 67-78.

1. Scope and content:
Guntermann discusses the pitfalls of VAV-systems in providing acceptable indoor relative humidity levels at part load. A solution to this problem is using plenum generated heat to increase supply air temperatures and supply air airflow rates without increasing the relative humidity. VAV-systems discusses include VAV with reheat, fan powered VAV terminals, and dual duct VAV.
2. Relevance to return systems:
For a one story building, an analysis of the ceiling plenum heat balance for ducted returns and plenum returns is presented. Lighting levels were varied from 1 to 5 W/ft2, with 65% of the lighting heat gain going to the plenum, and room and outdoor temperatures were set at typical values.
3. Significant findings:
Internal heat gains, plenum airflow rates, plenum temperatures, ceiling heat gains, total and space sensible loads, sensible heat ratios, supply air temperatures, and supply airflow rates are tabulated for lighting levels of 1 to 5 W/ft^2 for ducted returns and plenum returns. With a plenum return air system, the analysis showed part of the lighting heat gain going to the return air and being conditioned by the HVAC system. With a ducted return, the lighting heat gain increased the temperature of the plenum and was radiated back into the conditioned space through the suspended ceiling. Since VAV-systems vary airflow rates to meet space loads, the heat load from the increased temperatures in the plenum increased airflow rates by 20 – 50%.
4. Limitations and assumptions:
13. Roof and wall solar heat gains were neglected for all outdoor temperatures except the design condition of 90 F 14. Return duct leakage and heat gain were neglected 15. Supply and return fan heat gains were neglected 16. The supply air temperature was assumed to be constant, so temperature reset was not considered

- ☐ Building Energy Use
- ☐ Leakage Measurements
- ☐ Security / Contaminant Dispersal
- ☒ Analytical Model
- ☐ Indoor Air Quality
- ☐ Experimental Study
- ☒ Design & Construction Methods
- ☐ Residential
- ☐ Repairs & Retrofits
- ☒ Commercial & Institutional

Reference: Harriman, L., G. Brundrett, and R. Kittler. (2001). Humidity Control Design Guide for Commercial and Institutional Buildings. Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

1. Scope and content:
Harriman *et al.* provide a comprehensive guideline for controlling humidity in commercial and institutional buildings for owners, architectural designers, HVAC designers, contractors and building operations staff. After discussing basic humidity control, psychrometrics, and human comfort, system design and equipment and controls, the authors focus on different applications, such as schools, office buildings, and hospitals. Although the reference assumes the reader has a basic understanding of HVAC terminology, the discussion is accessible to architects, owners and building contractors.
2. Relevance to return systems:
The reference discusses the impact of return air leakage from ducted returns and plenum returns on indoor air quality and moisture intrusion through the building envelope through clear discussion and informative illustrations.
3. Significant findings:
The authors recommend using ducted return rather than plenum return because fan suction causes a greater negative pressure across a plenum return. Although both strategies allow infiltration, a plenum with ducted return will have a smaller pressure difference across the building envelope.
4. Limitations and assumptions:
The guide emphasizes low-rise construction, humidity control by dehumidification, and controlling humidity between 30% and 60%.

☐ Building Energy Use	☐ Leakage Measurements
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☒ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Hydeman, M., S. Taylor, J. Stein, and K. Kolderup. (2003). *Advanced Variable Air Volume System Design Guide, #P500-03-082 (Attachment A-11 Product 3.6.2).* California Energy Commission.

1. Scope and content:
This HVAC design guide focuses on integration of fans, air handlers, ducts, terminal units and controls of built up VAV systems in multi-story large commercial buildings. The authors seek to advance the standard of practice while achieving cost effective energy savings. The report is divided into the following chapters: (1) early design issues, (2) zone issues, (3) VAV box selection, (4) duct design, (5) supply air temperature reset, (6) fan size, type and control, (7) coils and filters, and (8) outdoor air, return air, and exhaust air control.
2. Relevance to return systems:
The design guide recommends using return air plenums when possible because both energy and first costs are reduced. Three return air options are defined: (1) fully unducted, using both the ceiling cavity and architectural air shaft as return air plenums, (2) partially ducted from fan down riser and part way to local plenum returns, and (3) fully ducted.
3. Significant findings:
Advantages of plenum returns: 17. Lower energy use because reduced fan static pressure (0.25” – 0.75” w.g. for plenum returns compared to 1” – 2” w.g. for ducted returns) 18. Lower installed mechanical cost because return ductwork is eliminated 19. Self-balancing (for VAV systems individual spaces will not be pressurized at supply air flows change) 20. Reduced ceiling space depths Disadvantages of plenum returns: 21. Possibility of plenum depressurization 22. Individual space pressurization not possible 23. Dust accumulated in ducts is easier to clean than dust accumulated in return plenums
4. Limitations and assumptions:
The authors stress that the advice in this design guide applies to multi-story commercial buildings located in California or similar climates.

☒ Building Energy Use	☐ Leakage Measurements
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☐ Indoor Air Quality	☐ Experimental Study
☒ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Jump, D.A., I.S. Walker, and M.P. Modera. (1996). "Field measurements of efficiency and duct retrofit effectiveness in residential forced air distribution systems." In *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, 1.147-1.155.* Washington, D.C.: American Council for an Energy Efficient Economy.

1. Scope and content:
Jump *et al.* tested 24 houses in Sacramento before and after duct retrofits to estimate the magnitude of duct leakage and conduction and their impact on HVAC energy consumption. HVAC systems in the houses included conventional air conditioning, gas furnaces, electric furnaces and heat pumps. Retrofits included adding extra insulation to the exterior of ducts, and using mastic to seal duct leaks.
2. Relevance to return systems:
Testing of the houses included measuring duct leakage before and after duct retrofit. Average supply leakage was reduced from 18% to 8% and average return leakage was reduced from 17% to 7%.
3. Significant findings:
As a result of the retrofits, the average normalized power consumption was reduced by 18%. However, there was a large range of leakage flows between systems, so not all houses would receive the same benefit of duct sealing. Prior to sealing the ducts, supply leakage fractions ranged from 2% to 38% and return leakage fractions ranged from 0% to 35%. The reduction of normalized power consumption ranged from 5% to 57%, so diagnostic tests should be developed to indicate which houses have the potential for improvement. Jump *et al.* estimated the cost of retrofitting the duct system and found a large variation in costs. The labor cost, reflecting the time required finding duct leaks and repairing ducts in inaccessible spaces, dominated the material cost.
4. Limitations and assumptions:
All ducts tested were located in unconditioned attic spaces. The impact of duct leakage on HVAC energy consumption will depend on the location of the ducts with respect to the conditioned space. Even though the reference focuses on residential air distribution systems, evidence is presented that sealing and insulating ducts located in unconditioned spaces can reduce HVAC energy consumption considerably. A similar reduction in energy consumption could apply to commercial distribution systems.

☒ Building Energy Use	☒ Leakage Measurements &
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☒ Residential
☒ Repairs & Retrofits	☐ Commercial & Institutional

Reference: Klobut, K. (1991). *Distribution of Contaminants in Buildings by Air Recirculation and Other Airflows*. Helsinki: Helsinki University of Technology.

1. Scope and content:
Klobut simulated dynamic contaminant concentrations, pressure distributions, airflows, and temperatures in a multizone building using Fortran 77. Physical coupling between thermal behavior of the building and interzonal airflows was modeled. Each room was considered as one or more zones vertically stacked with a node in each zone. Differential equations for each zone were written to simulate temperature gradients and airflows as a result of wind pressure, fan operation, and buoyancy forces. Validation cases were simulated and solved analytically to verify the numerical stability of the program and ensure accurate results. An example building with a corridor and four rooms was simulated with different door positions, different amounts of return air, and different thermal loads for each room. When contaminant sources were expressed as kg/s, L/h, or olfs, contaminant concentrations were expressed as kg/m^3, ppm, and pols, respectively. The perceived air quality was calculated in terms of Predicted Percentage Dissatisfied.
2. Relevance to return systems:
The simulation modeled a ventilation system with supply ducts, return ducts, and an exhaust fan in the corridor.
3. Significant findings:
The worst air qualities (highest contaminant concentrations) occurred when the source was in the room with the highest thermal load. When return air is used, the position of the door is of minor importance, since the contaminant enters the return air system and is redistributed through the HVAC system
4. Limitations and assumptions:
24. The report did not consider plenum returns 25. Perfect mixing of air and contaminants within a zone 26. Thermal capacity of building partitions was constant 27. No heat exchange or leakage between ducts and their adjacent zones

☐ Building Energy Use	☐ Leakage Measurements
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☒ Indoor Air Quality	☐ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Lee, S., G. Maxwell, and C. Klaassen. (1998). "Building Description for Energy Modeling of the Energy Resource Station." Energy Resource Station, Iowa Energy Center: Ankeny, Iowa.

1. Scope and content:
This reference was created to provide energy modelers and other interested parties with a building description of the Iowa Energy Center Energy Resource Station.
2. Relevance to return systems:
The reference does not specifically mention return air systems.
3. Significant findings:
The building description includes roof, exterior wall, interior wall partition, door, ceiling, interior glass, and floor construction layers. Layers are described from inside to outside with the thickness, conductivity, density, specific heat and thermal resistance. Each window has information about the number of panes, window width, window height, shading coefficient and heat conductance of the total window. Each space is described and each of the six surfaces of each space is tabulated with areas and windows and doors associated with that space.
4. Limitations and assumptions:
The reference does not include drawings or construction specifications. However, when viewed with a floor plan, the information provided is a specific and comprehensive of the ERS. Architectural components are described in an organized tabular format. See Price and Smith (2000) for a more detailed description of the building, mechanical systems, and purpose of the ERS.

☒ Building Energy Use	☐ Leakage Measurements
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Reference: Lstiburek, J. (2002). "Investigating & Diagnosing Moisture Problems." ASHRAE Journal **44**(12): 36-41.

1. Scope and content:
Lstiburek describes evaporation, condensation, capillary suction, gravitational flow, vapor diffusion and mass flow of moist air inside building cavities and materials. After a discussion of the rules of water movement based on first principles, examples of common moisture problems are presented.
2. Relevance to return systems:
The reference describes how plenum returns can draw moist air out of exterior walls and lists design rules to avoid moisture problems.
3. Significant findings:
28. Drop ceiling return plenums should not be connected to exterior walls 29. Interior gypsum should extend to underside of roof deck and be sealed 30. Make sure intersecting interior walls do not contain or are not connected to leaking return ducts or leaking air chases
4. Limitations and assumptions:
The reference describes moisture problems but does not compare humidity levels and return air temperatures between return air strategies.

- ☐ Building Energy Use
- ☐ Security / Contaminant Dispersal
- ☒ Indoor Air Quality
- ☒ Design & Construction Methods
- ☐ Repairs & Retrofits
- ☐ Leakage Measurements
- ☐ Analytical Model
- ☐ Experimental Study
- ☒ Residential
- ☒ Commercial & Institutional

Reference: Lstiburek, J., K. Pressnail, and J. Timusk. (2002). "Air Pressure and Building Envelopes." Journal of Thermal Environment & Building Science **26**(1): 53-91.

1. Scope and content:
Lstiburek *et al.* describe how indoor air quality, smoke and fire spread, durability, comfort and energy use are affected by unintended airflows and moisture problems in five case studies. Unintended airflows occurred from a lack of understanding of how HVAC systems interact with the building envelope and structure. Diagnostic tools and rehabilitation measures are described for each case study.
2. Relevance to return systems:
31. One case study describes how plenum returns and exhaust fans become driving forces for unintended airflow in buildings and how the unintended airflows cause indoor air quality problems 32. Another case study describes how return leakage in a single family residence lead to high utility bills and decreased cooling efficiency
3. Significant findings:
33. Occupants of a single story school with a ventilated crawl space complained about poor indoor air quality. Poor building design and construction created an air path from a crawl space to the return air plenum. Exhaust fans and operation of the air handling unit in the return plenum depressurized the classrooms and the return plenum with respect to outdoors. Warm saturated air was drawn from the crawl space to the classroom areas through joints between the interior walls and foundations. The air cooled and moisture condensed in the wall cavities, which lead to decay and odor. 34. A single family residence with a heat pump in the attic was experiencing high utility bills due to return air leakage. Return leakage was revealed when noticeably warm air exited the supply diffusers when the air handler was turned on without the compressor. The repair strategy included relocating the air pressure boundary so the attic was part of the conditioned space. The attic vents were sealed, the insulation was moved to the roof, and the attic space was vented to the living space. Supply leakage would no longer be wasted to the attic, and return leakage would no longer draw unconditioned air into the air handler.
4. Limitations and assumptions:
The reference describes how indoor air quality and energy use are affected by unintended airflow, but does not include measurement of humidity, temperatures, or energy use before or after buildings have been repaired.

☒ Building Energy Use	☒ Leakage Measurements
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☒ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Modera, M.P., D. Dickerhoff, O. Nilssen, H. Duquette, and J. Geyselaers. (1996). "Residential field testing of an aerosol-based technology for sealing ductwork." In *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, 1.169-1.17.* Washington, D.C.: American Council for an Energy Efficient Economy.

1. Scope and content:
Modera *et al.* recruited home owners served by Florida Power and Light (FPL) to have their duct systems sealed with an innovative aerosol-based duct sealing technology. The time required to seal the ducts using the aerosol-based sealant process was compared to the time required using conventional duct sealing practices estimated by Florida Power and Light's (FPL) standard audit. The sealing rates for ducts composed of common materials, including sheet-metal, plastic flexduct, and ductboard were also recorded. Utility bill analysis from July, August, September, and October indicate that the aerosol-based sealing reduced the electric consumption by 10% of the average air-conditioning electricity consumption.
2. Relevance to return systems:
The majority of duct systems sealed were on the supply side, because most of the homes had platform returns, which were sealed with mastic and fiberglass tape. In 6 homes more than 80% of return-side leakage was sealed by the aerosol.
3. Significant findings:
The time required for sealing the first half of the houses using the aerosol-based sealing process was 6.1 labor-hours compared to 9.5 labor-hours for the conventional sealing process, resulting in a 35% reduction in labor. For the second half of the houses sealed, the aerosol-based sealing process required 4.4 labor-hours compared to 11.5 labor-hours for the conventional sealing process, resulting in a 60% reduction in labor.
4. Limitations and assumptions:
The study focused on sealing residential duct systems; however, Carrie *et al.* (2002) and Modera *et al.* (2002) have modified the sealing process for commercial duct systems and have shown that sealing multiple duct sections simultaneously and increasing the aerosol production rate reduces duct leakage by over 80%.

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Reference: Modera, M., T. Xu, H. Feustal, N. Matson, C. Huizenga, F. Bauman, E. Arens, and T. Borgers. (1999). *Efficient Thermal Energy Distribution in Commercial Buildings: Final Report to California Institute for Energy Efficiency*. Berkeley: Lawrence Berkeley National Laboratory, LBNL 41365.

1. Scope and content:
Modera *et al.* focused on thermal energy distribution systems comprised of fans, pumps, ducts, and pipes used to transport heating, cooling, and ventilation air throughout commercial buildings. The authors characterized the stock of existing US commercial buildings, the prevalence of common types of thermal distribution systems, and their energy consumption in California. Supply duct leakage was modeled in a prototypical office building located in California in DOE 2. A case study investigated thermal losses in commercial packaged rooftop systems. Measurements included total duct leakage, duct leakage to outside, supply and return fractions, fan consumption, duct and plenum pressures during normal operation and airflows through diffusers. Statewide savings opportunities were identified and efforts required to realize these savings were discussed for each type of thermal energy distribution system.
2. Relevance to return systems:
In the two commercial packaged rooftop units, return leakage fractions were 24% of fan airflow in one store and 51% of fan airflow in another.
3. Significant findings:
Adding 30% supply duct leakage (uniformly distributed) to a thermally-perfect system increased perimeter fan consumption by 11%, perimeter fan peak demand by 13%, core fan consumption by 12%, and core fan peak demand by 15%.
4. Limitations and assumptions:
The energy analysis focused on supply duct leakage.

☒ Building Energy Use	☒ Leakage Measurements
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☐ Indoor Air Quality	☒ Experimental Study
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☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Modera, M.P., O. Brzozowski, F.R. Carrie, D.J. Dickerhoff, W.W. Delp, W.J. Fisk, R. Levinson, and D. Wang. (2002). "Sealing ducts in large commercial buildings with aerosolized sealant particles." Energy and Buildings **34**:705-714. LBNL-42414, Lawrence Berkeley National Laboratory.

1. Scope and content:
Modera *et al.* tested a method of sealing ducts in 2 large commercial buildings using aerosolized sealant particles. One building had a constant-air-volume (CAV) system and the other had a variable-air-volume (VAV) system. The leakage class (cfm/100 ft^2 at 1 in. H_2O) and the effective leakage area (cm^2 at 25 Pa) of the duct systems were measured before and after sealing. The leakage classes were reduced from 230 to 80 cfm/100ft^2 and 60 to 8 cfm/100 ft^2, and the effective leakage areas were reduced from 320 to 110 cm^2 and 190 to 24 cm^2.
2. Relevance to return systems:
The reference does not specifically address return ducts and plenums; however, the same sealing technique could potentially be used for return air ducts.
3. Significant findings:
This reference illustrates that using aerosolized sealant particles to seal duct leaks is promising. Challenges commercial buildings pose to the use aerosol sealant technology include the time required for repairing longer duct runs and potential to impact the sensitive electronic equipment, such as VAV boxes. In the first building tested, 66% of the leakage area was sealed within 2.5 hours, and in the second building, 88% of the leakage area was sealed within 5 hours. To investigate whether or not aerosolized particles would impact the calibration and operation of VAV boxes, the performance and calibration of a VAV boxes was tested after blowing the aerosol sealant particles through the ducts. The flow meter calibrations were performed by simultaneously measuring velocity with a hot-wire anemometer downstream of the VAV box and the pressure signal from the VAV sensor. Calibrations did not change before and after the particles were injected and damper operation remained normal.
4. Limitations and assumptions:
The study only presented 2 field trials. More buildings need to be tested to ensure that all types of duct systems can be sealed using aerosol particles.

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Reference: National Institute for Occupational Safety and Health (NIOSH). (2002). "Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks." *Publication No. 2002-139,* Cincinnati.

1. Scope and content:
The reference identifies actions that building owners can take to improve building security. High risk facilities and single and multi-family residences are beyond the scope of the guide. The guide is arranged in four sections: (1) things not to do, (2) physical security, (3) ventilation and infiltration, and (4) maintenance, administration, and training.
2. Relevance to return systems:
The reference suggests using ducted returns over plenum returns to avoid inter-zonal transfer of contaminants.
3. Significant findings:
35. Ducted returns offer limited access points to introduce chemical, biological, or radiological (CBR) agents 36. CBR agents released above the drop ceiling in an unducted ceiling plenum will likely reach the HVAC system and be redistributed 37. CBR agents are likely to enter the building through lobbies, mailrooms, and loading docks, so these spaces should not share return air systems or ceiling plenums, and should be 100% exhausted
4. Limitations and assumptions:
The guide is not meant to be comprehensive, and the authors stress that actions should be based on analysis of risk and assessment of building security and that HVAC systems should not be modified without knowing how occupants and the building will be affected.

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Reference: O'Neal, D.L., A. Rodriguez, M. Davis, and S. Kondepudi. (1992). "Return air leakage impact on air conditioner performance in humid climates." Journal of Solar Energy Engineering **124**: 63-69.

1. Scope and content:
O'Neal *et al.* used a psychrometric room to experimentally test the effect of return air leakage from a hot, humid attic on the performance of a split-system residential air conditioner. Conditions to the evaporator were changed to simulate hotter and more humid air that would result from return air leakage in a residential attic. The outdoor temperature was assumed to be 38.7°C (100°F), the attic temperatures were assumed to vary between 54.4°C (130°F) and 65.6°C (150°F), and attic humidity was assumed to vary between 10% and 35% for these attic temperatures. For return leakage fractions between 4% and 20%, values found in existing literature, the authors simulated air conditioner performance using capacity, coefficient of performance, power consumption, and sensible heat ratio.
2. Relevance to return systems:
Return air leakage of hot, humid air in residential attics is investigated through experimental studies.
3. Significant findings:
The effect of return air leakage on air conditioner performance has received less attention than the effects of supply air leakage. Effective capacity and effective coefficient of performance decreased significantly as return air leakage increased. At an ambient outdoor temperature of 37.8 °C (100°F), 54.4°C (130°F) attic temperature, and 10% attic relative humidity, the capacity dropped 19.2% as the attic leakage rate increased from 0% to 13%. At 10% leakage, depending on the attic conditions, an air conditioner would have as much as 40% less capacity. At an ambient outdoor temperature of 37.8°C (100°F), 54.4°C (130°F) attic temperature, and 10% attic relative humidity, the effective coefficient of performance dropped 1.53% as the attic leakage rate increased from 0% to 9.1%. Although the power consumption due to return air leakage was constant for all conditions, a decrease in capacity and coefficient of performance would increase run times for air conditioners operating simultaneously, and increase the demand for electric utilities during the hottest part of the day.
4. Limitations and assumptions:
The study focused on residential air conditioning performance in hot and humid climates.

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Reference: Parker, D., P. Fairey, and L. Gu. (1993). “Simulation of the effects of duct leakage and heat transfer on residential space-cooling energy use.” Energy and Buildings **20**: 97-113.

1. Scope and content:
Parker *et al.* have developed a model that predicts impacts of duct leakage and duct heat transfer on the performance of a residential air conditioner. Input parameters include supply and return duct leakage area, supply and return operating pressures, and the air handler run time. The model includes duct interaction with natural infiltration, by comparing supply and return side duct leakage. Measurements of duct leakage and electrical demand in a house were taken before and after duct repair to compare to modeled results.
2. Relevance to return systems:
The simulation explicitly considers the source of return air leak. If the return air leak originates in the conditioned zone, the impact may be negligible. However, if the return leak originates in the attic zone, the enthalpy of the return air may increase significantly.
3. Significant findings:
Parker *et al.* modeled a typical house in Florida, and found that with no duct leakage or conduction losses, the AC energy consumption was reduced by 24% and the peak cooling electrical demand was reduced by 30%. Comparing return leakage fractions of 3%, 10.7%, 25% and 40% indicated that AC electric consumption increased drastically as return leakage increased. Increasing the return leakage fraction from 10.7% to 40% increased the AC electrical consumption by 59%. After repairing ducts in a typical Florida home, the AC energy consumption was reduced by 19% for a group of days with similar interior to exterior temperature differences. The cooling energy use was measured before and after retrofit for the two hottest days in the analysis period. Daily consumption was reduced by 41%, from 58.4 kWh to 34.2 kWh. The peak electrical demand was reduced by nearly 2.2 kW.
4. Limitations and assumptions:
Even though the reference focuses on residential air distribution systems, evidence is presented that sealing and insulating ducts can reduce HVAC energy consumption considerably. The same reduction in energy consumption should apply to commercial distribution systems.

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Reference: Persily, A.K. (1999). "Myths About Building Envelopes." ASHRAE Journal 41(3): 39-47.

1. Scope and content:

Persily presents envelope leakage data from 139 buildings around the world, with 90 buildings from the United States, that challenge the prevailing belief that commercial buildings are air tight. The data, which is organized by building age, size and construction, challenges the discussions in press and technical literature that blame "tight buildings" for the rise in indoor air quality complaints and "sick-building syndrome" complaints of building occupants.

2. Relevance to return systems:

The reference does not mention plenum or ducted return air systems.

3. Significant findings:

- In terms of leakage per unit envelope area, the air tightness of commercial buildings fall in the range of typical to leaky houses
- There was no correlation between
  - year constructed and envelope leakage
  - wall construction and envelope leakage
  - age of building when tested and envelope
- The average envelope tightness of offices, schools and industrial building types were all in the same range of 25 $m^3/hr\text{-}m^2$ at 75 Pa
- The average envelope tightness of restaurants, assembly buildings, and hotels were all in the same range of 40 $m^3/hr\text{-}m^2$ at 75 Pa
- Taller buildings appear to be tighter than shorter buildings and shorter buildings cover the entire spectrum of envelope leakage values

4. Limitations and assumptions:

Persily states that the available air tightness sample size is small and not random, so conclusions from this reference cannot be generalized over broad sections of the building stock.

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Reference: Persily, A.K., and E.M. Ivy. (2001). "Input Data for Multizone Airflow and IAQ Analysis, NISTIR 6585." Gaithersburg: National Institute of Standards and Technology.

1. Scope and content:
NISTIR 6585 is a database of input data for performing multizone airflow and IAQ analysis. The reference describes the data that can be contained in CONTAM library files and introduces several libraries contained in CONTAM as project libraries and describes data not contained in CONTAM libraries and provides resources for finding this data.
2. Relevance to return systems:
3. Significant findings:
Types of data found in libraries include: ▪ Levels ▪ Zones ▪ Flow paths, air handling systems, and ducts ▪ Wind pressure coefficients ▪ Weather ▪ Contaminants ▪ Source/sinks ▪ Filters ▪ Occupants ▪ Schedules
4. Limitations and assumptions:
The reference is an introduction to the libraries contained in CONTAM, and is not a user manual. Read Walton and Dols (2005) for an introduction to multizone modeling, specifically CONTAM.

☐ Building Energy Use	☒ Leakage Measurements
☒ Security / Contaminant Dispersal	☒ Analytical Model
☒ Indoor Air Quality	☐ Experimental Study
☐ Design & Construction Methods	☒ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Persily, A., R.E. Chapman, S.J. Emmerich, W.S. Dols, H. Davis, P. Lavappa, and A. Rushing. (2007). *Building Retrofits for Increased Protection Against Airborne Chemical and Biological Releases, NISTIR 7379.* Gaithersburg: National Institute of Standards and Technology.

1. Scope and content:
This reference identified building retrofit options to protect occupants from chemical and biological releases in and around buildings, and evaluated retrofit options' impact on occupant exposure using multizone modeling. CONTAM was used to simulate airflow and contaminant transport in three buildings. A case study was conducted in two buildings to calculate the first costs of implementing specific retrofits. Retrofits discussed and modeled included air cleaning and filtration, HVAC system operation, envelope tightening and building pressurization, and local options such as shelter-in-place.
2. Relevance to return systems:
One retrofit considered was recommisioning an HVAC system to ensure that it operates as intended. Recommissioning includes balancing supply and return airflow rates to ensure proper pressurization.
3. Significant findings:
38. For filtration or air cleaning to be effective, bypass must be eliminated and infiltration through the building envelope should be minimized 39. Other retrofits, including purging or HVAC shutdown, require sound decisions and understanding of how the HVAC system operates
4. Limitations and assumptions:
The reference focused on building retrofits and protective measures and did not discuss architectural and HVAC design decisions. The cases discussed are generic and specific building types, such as educational, health care, and retail facilities, are unique and should be discussed in more detail.

- ☐ Building Energy Use
- ☐ Leakage Measurements
- ☒ Security / Contaminant Dispersal
- ☒ Analytical Model
- ☐ Indoor Air Quality
- ☐ Experimental Study
- ☐ Design & Construction Methods
- ☐ Residential
- ☒ Repairs & Retrofits
- ☒ Commercial & Institutional

Reference: Price, B.A., and T.F. Smith. (2000). "Description of the Iowa Energy Center Energy Resource Station: Facility Update III." Technical Report: ME-TRS-00-001. Department of Mechanical Engineering, University of Iowa.

1. Scope and content:
This reference is an in depth description of the Iowa Energy Center Energy Resource Station. The document presents an overview of the design, equipment, control systems, and outlines the capabilities of the HVAC systems serving the laboratory. The report contains chapters including Building Structure, Mechanical Equipment, Energy Management and Control Systems and several Appendices relating to specific point names and equipment specifications.
2. Relevance to return systems:
The reference does not specifically mention plenum return or ducted return systems.
3. Significant findings:
The reference contains descriptions of the building layout, laboratory purpose and objectives as well as detailed information such as mechanical equipment control diagrams, mechanical equipment specifications, room dimensions, mechanical system and control systems capabilities. When combined with the description provided by Lee et al. (1998), an energy modeler or air flow modeler of the ERS has all the information necessary to create an accurate representation of the facilities.
4. Limitations and assumptions:
The reader and user of information contained in this report are cautioned that numbers within the document are estimates from information available at the time of publications. The values may have changed as exact specifications are received from manufacturers.

☒ Building Energy Use	☐ Leakage Measurements
☒ Security / Contaminant Dispersal	☒ Analytical Model
☒ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☐ Commercial & Institutional

Reference: Price, P.N., M.D. Sohn, A.J. Gadgil, W.W. Delp, D.M. Lorenzetti, E.U. Finlayson, T.L. Thatcher, R.G. Sextro, E.A. Derby, and S.A. Jarvis. (2003). *Protecting Buildings from a Biological or Chemical Attack: actions to take before or during a release.* Berkeley: Lawrence Berkeley National Laboratory, LBNL-51959.

1. Scope and content:
This reference provides advice on how to operate a building to reduce casualties from biological and chemical attacks and how to alter a building and its HVAC systems to make it more secure. Advice is given depending on whether the release is biological or chemical and whether the source is indoors or outdoors.
2. Relevance to return systems:
The reference comments on how HVAC systems with common returns mix air from separate ventilation zones and spreads contaminants as if one air handler were operating.
3. Significant findings:
The authors suggest: 40. Isolating zones by providing separate air handlers and return systems for zones to minimize the spread of contaminant 41. Eliminating return air and exhausting 100% air for high risk areas such as mailrooms, loading docks and public access areas
4. Limitations and assumptions:
The authors stress that the reference is advice for design and operation of "typical large commercial buildings with fairly ordinary HVAC systems," not an extensive how-to manual. Topics not discussed include crowd control, medical treatment, evidence gathering, decontamination methods, and rescue gear.

- ☐ Building Energy Use
- ☒ Security / Contaminant Dispersal
- ☐ Indoor Air Quality
- ☒ Design & Construction Methods
- ☐ Repairs & Retrofits
- ☐ Leakage Measurements
- ☐ Analytical Model
- ☐ Experimental Study
- ☐ Residential
- ☒ Commercial & Institutional

Reference: Proctor, J. P. (1997). "Field measurements of new residential air conditioners in Phoenix, Arizona." ASHRAE Transactions **103**(2): 406-415.

1. Scope and content:
Proctor measured airflow through the air handler, refrigerant charge, size of air conditioners, and duct leakage in 22 newly built residences in the Phoenix, AZ area containing 28 air conditioning systems. Three duct leakage measurements were made at a test pressure of 0.1 in. H_2O (25 Pa): total leakage, exterior leakage, and normal operating leakage split between supply and return. The average total duct leakage was 310 cfm, the average duct leakage to the outside was 193 cfm, the average supply leakage was 9% of airflow on the supply side, and the average return leakage was 5% of airflow on the return side. The average supply and return leakage at operating flow agreed with residential data from California and Nevada (Siegel and Walker 2003).
2. Relevance to return systems:
The reference focuses on residential air distribution systems. Supply systems consisted of a rigid metal supply plenum with helix core flex duct take-offs and smaller runs to the registers. Common return systems included helix core flex duct connected to the air handler without a return plenum. Five systems used platform returns with a grille mounted on the platform or ducted returns connected to the platform.
3. Significant findings:
This paper presents evidence that residential air distribution systems are not installed properly. The paper reports three measurements of duct leakage. A fan/measurement device was mounted at the air handler's blower door to test duct leakage. Total duct leakage was measured by sealing all the registers and pressurizing the ducts to 0.10 in. H_2O (25 Pa). Leakage to the outside was measured by pressurizing the house and ducts simultaneously using a blower door and fan/measurement device. The supply and return leakage during operating pressures was also measured by adjusting the test leakage measurements to operating pressures.
4. Limitations and assumptions:
The study focused on residential systems, so leakage measurements are not comparable to return systems in commercial buildings.

☐ Building Energy Use	☒ Leakage Measurements
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Reference: Rock, B.A, and D.J. Wolfe. (1997). "A sensitivity study of floor and ceiling plenum energy model parameters." ASHRAE Transactions **103**(1): 16-30.

1. Scope and content:
The authors characterized the sensitivity of floor and ceiling plenum heat transfer parameters on transient energy models. The parameters of interest were plenum radiation, plenum surface emissivity, convection coefficients, floor thickness, raised floor material, and the number of nodes in the plenum. HLITE was used to find cooling loads in typical offices and VLITE was used to solve for the radiant view factors. As the parameter was varied, the sensitivity was defined as the percent difference in the maximum and minimum cooling load relative to the maximum cooling load. The energy model was not sensitive to the heat transfer parameters; however, simplifying assumptions limit the relevance of the study on existing buildings.
2. Relevance to return systems:
The authors modeled six ventilation configurations, two of these being ducted supply with ducted return, and ducted supply with plenum return.
3. Significant findings:
The authors sought to improve understanding of the heat transfer in floor and ceiling plenums, and the impact of floor and ceiling configuration on peak cooling load. However, simplifying assumptions listed below limit the relevance of the data. The authors also mention that "load calculation models used for design purposes (as opposed to research purposes) need to include the effect of different types of ceiling and floor plenums." The paper takes a first step that may lead to the inclusion of plenum configurations in design software.
4. Limitations and assumptions:
42. The model was developed with the following simplifying assumptions that restrict the relevance of the study on existing buildings: 43. duct and plenum leakage were neglected 44. exfiltration and infiltration were neglected 45. air was dry at sea level 46. rooms and plenums modeled were adjacent to spaces with similar conditions, so heat transfer between adjacent rooms, and heat transfer between the space and outside were neglected 47. solar radiation was not modeled 48. rooms and plenums were assumed to be well-mixed so a nodal model could be used 49. the cumulative effect of varying multiple variables was not modeled 50. only the cooling load was modeled

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Reference: Sheet Metal and Air Conditioning Contractors National Association (SMACNA). (1985). "HVAC Air Duct Leakage Test Manual."

1. Scope and content:
The manual contains construction, installation, and testing methods for assessing duct leakage. SMACNA states that the document is not an endorsement for routine use of testing and that leakage testing is generally an unjustified expense where proper methods of assembly and sealing are used. The manual states that all ductwork shall be constructed for the pressure classification specified on the contract drawings and contains acceptable duct sealing materials.
2. Relevance to return systems:
The paper does not specifically address return air ducts, but designer specifications can include return air ducts.
3. Significant findings:
▪ For pressure classifications of 4" w.g. and higher, Seal Class A is required (all transverse joints, longitudinal seams, and duct wall penetrations) and Leakage Class 6 is attainable ▪ For pressure classifications of 3" w.g., Seal Class B is required (all transverse joints and longitudinal seams) and Leakage Class 12 is attainable ▪ For pressure classifications of 2" w.g and lower, Seal Class C is required (transverse joints) and Leakage Class 24 is attainable ▪ When pressure classification is not specified, 1" water gauge pressure is the basis of compliance regardless of velocity in the duct, except when the duct is variable air volume: the basis of compliance for ducts upstream of VAV boxes is 2" water gauge when designers do not specify a pressure classification on contract drawings. ▪ SMACNA states that differences of the fan delivery and summation of airflows at terminals of ±10% do not necessarily indicate leakage, due to potential inaccuracy of airflow measurement devices
4. Limitations and assumptions
SMACNA assumes that for duct systems constructed to 3" w.g. pressure classification or lower, leakage testing is an added expense and is not cost effective. For duct systems constructed to 4" w.g. pressure classification and greater, the designer must determine if leakage testing is justified.

☐ Building Energy Use	☒ Leakage Measurements
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Reference: Siegel, J., and I. Walker. (2003). "Integrating ducts into the conditioned space: Success and challenges." In *Building Integration Solutions: Proceedings of the Architectural Engineering 2003 Conference, 129-133.* Austin: American Society of Civil Engineers.

1. Scope and content:
Siegel and Walker (2003) monitored eleven residences in California and Nevada and sought to show that ducts located in conditioned spaces have improved efficiencies compared to ducts located outside the conditioned space. For the 5 houses with unvented attics the delivery efficiency was slightly higher than the 4 houses with ducts in exterior locations. Also, during this study, the authors measured duct leakage using two fan pressurization tests proposed in ASHRAE Standard 152P. First the authors pressurized the duct system and determined the total duct leakage. Second the authors pressurized the house and ducts to determine the duct leakage to the outside. Duct leakage was reported as a leakage fraction: the ratio of the leakage flow at operating conditions to the air flow through the air handler. The greatest supply and return leakage fractions to the outside occurred in the same house, 15% and 16% respectively. The smallest supply and return leakage fractions occurred in the same house, 2% and 1% respectively. The average supply and return leakage fractions to the outside were 6% and 4% respectively. The average total supply and return leakage fractions were 10% and 6% respectively.
2. Relevance to return systems:
The reference focuses on residential air distribution systems. Measurements of total supply and return leakage fractions and supply and return leakage fractions to the outside at typical operating pressures are reported.
3. Significant findings:
Previous papers have mentioned that the impact of leaks on energy use depends on the origin of the duct leaks. Moisture problems arising from warm humid air leaking from a space and condensing on a cold attic surface are prevented by ventilating attics to the outside. The paper refers to two interior locations for ducts: cathedralized attics and floor cavities. A simulation was conducted that compared ducts in conventional attics ventilated to the outside, and attics ventilated to the conditioned space (cathedralized) for a residence in Sacramento. On the summer design day, the air temperature in the conventionally ventilated attic was 20 °C (36 °F) hotter than the cathedralized attic, and cooling energy use was reduced 25-50% for the cathedralized attic.
4. Limitations and assumptions:
The study focused on residences, but the authors mention that a similar study could be conducted on commercial buildings.

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Reference: Spengler, J.D., and Q.Y. Chen. (2000). "Indoor air quality factors in designing a healthy building." Annual Review of Energy and the Environment **25**: 567-601.

1. Scope and content:
Discussion includes: ▪ Trends in public perception of indoor air quality (IAQ), ventilation design philosophy and litigation as a result of poor IAQ ▪ How buildings and their IAQ adversely impact occupants' health. ▪ How the traditional design-bid-build construction process contributes to poor IAQ ▪ Design guidance and evaluation tools to advance state of practice for good IAQ
2. Relevance to return systems:
Spengler and Chen state that surface area in contact with air in an unducted ceiling plenum can be twice the floor areas. Ceiling plenums contain unfinished wallboard, fireproofing, fiberglass, acoustical insulation, power and communication cables, and topsides of ceiling tiles that contribute to VOC emissions. Although emissions of individual materials are known from chamber tests, knowledge of how emissions interact with each other is limited.
3. Significant findings:
The reference was a review of IAQ and no significant findings were presented regarding return air systems.
4. Limitations and assumptions:
The reference focuses on the public's perception of IAQ, ventilation design philosophy and litigation as a result of poor IAQ.

☐ Building Energy Use	☐ Leakage Measurements
☒ Security / Contaminant Dispersal	☐ Analytical Model
☒ Indoor Air Quality	☐ Experimental Study
☒ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☐ Commercial & Institutional

Reference: Swim, W. B., and E.I. Griggs. (1995). "Duct leakage measurement and analysis." ASHRAE Transactions **101**(1): 274-291.

1. Scope and content:
This paper is a continuation of the ASHRAE Research Project R308. The complete set data of collected is contained in the Final Report on ASHRAE Research Project 447. Leakage measurements were made on different sizes of rectangular and round sheet metal ducts with different types of seals and joints for both positive and negative internal pressures. The duct sizes and specific types of joints and seams tested are listed in detail in the paper. Five samples containing one duct section were tested to produce multiple data points, and then sections were tested as units with two duct sections and one joint. Leakage rates for joints and seams were also measured: leakage rates for seams were measured by sealing joints, and leakage rates for joints were measured by sealing seams. Leakage rates were measured by measuring the makeup air required to maintain a specified internal pressure across the duct, over a range of 1 in. H_2O (250 Pa) to 3 in. H_2O (750 Pa) for both positive and negative pressures. The measurements followed a power law model and the authors tabulated power law constants, C and n, for various combinations of ducts and joints.
2. Relevance to return systems:
Return ducts and plenums are not specifically addressed. Duct leakage rates for rectangular and round ducts, and popular joint and seam combinations are presented.
3. Significant findings:
Leakage rate constants were lower for round ducts than rectangular ducts. The reference not only tabulates power law constants, but measured the percent contribution of seams and joints to duct leakage rates. Seam leakage contributed 12-25% of the leakage in two sizes of rectangular duct and 10-38% of the leakage in round ducts. This analysis shows that joints make the main contribution to duct leakage, and that improvement in duct construction need to focus on better joints. Data also shows that slip-and-drive joints used on rectangular ducts are harder to seal than round duct joints. A design methodology is also presented to predict the leakage of a duct system prior to construction.
4. Limitations and assumptions:
Leakage data was obtained in a laboratory setting and different levels of workmanship may change leakage characteristics. Since the test duct sections were constructed by the same workers, the data can best be used to compare the leakage characteristics of rectangular and round ducts, and different types of seams and joints.

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☒ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☒ Design & Construction Methods	☐ Residential
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Reference: United States Army Corps of Engineers (USACE). (2001). "Protecting Buildings and Their Occupants from Airborne Hazards." *TI 853-01*, Washington, D.C.

1. Scope and content:
The reference suggests actions designed to "prevent, protect against and reduce the effects of outdoor and indoor releases of hazardous materials." Measures discussed include high-efficiency filters for removing gases and aerosols from makeup air, recirculating filter units, physical security and entry screening measures, architectural and mechanical design measures, and protective-action plans covering sheltering, evacuation, purging, and protective masks.
2. Relevance to return systems:
The only discussion of return systems consists of how contaminants can reach HVAC systems through return ducts and be redistributed to zones via supply ducts once contaminants have been introduced indoors.
3. Significant findings:
▪ Use exhaust fans to create negative pressure differentials in locations where deliberate internal release of hazardous materials is a concern (lobbies, mailrooms, and loading docks) ▪ Separate zones to minimize the spread of contaminant and limit the effect of a single release to an isolated portion of the building ▪ Separate zones by using separate HVAC systems for each zone and designing full height walls between zones and hallway doors
4. Limitations and assumptions:
Protective-action plans, such as shelter-in-place, evacuation, and purging and the training needed to implement the plans are discussed in more detail than architectural and mechanical design measures aimed minimizing inter-zonal contaminant transfer.

☐ Building Energy Use	☐ Leakage Measurements s
☒ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☐ Experimental Study
☒ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Walton, G.N., and W.S. Dols. (2005). *CONTAM 2.4 User Guide and Program Documentation, NISTIR 7251*. Gaithersburg: National Institute of Standards and Technology.

1. Scope and content:
CONTAM allows you to determine airflows and pressures, contaminant concentrations, and personal exposure of occupants within multizone buildings. CONTAM is introduced, and the new capabilities of Version 2.4 are discussed. Five tasks are required for users to model airflow and contaminant transport in buildings: (1) building idealization, (2) schematic representation, (3) data entry, (4) simulation, and (5) review & record results. The steps required to complete each task are described in detail. Next, special applications of CONTAM are described and the theoretical background and model assumptions are discussed. The appendices contain an example project file and the program structure of the solver.
2. Relevance to return systems:
When sketching a building within CONTAM, ducted and plenum return air systems can be modeled.
3. Significant findings:
Some improvements of Version 2.4 include: ▪ Automated duct balancing ▪ New contaminant filter models ▪ Deposition sink models ▪ Increased limit on number of building components that can be created within one project
4. Limitations and assumptions:
☐ Building Energy Use ☐ Leakage Measurements ☒ Security & Contaminant ☒ Analytical Model ☐ Indoor Air Quality ☐ Experimental Study ☐ Design & Construction Methods ☒ Residential ☐ Repairs & Retrofits ☒ Commercial & Institutional

Reference: Withers, C. R., J.B. Cummings, N.A. Moyer, P.W. Fairey, and B.B. McKendry. (1996). "Energy savings from repair of uncontrolled airflow in 18 small commercial buildings." ASHRAE Transactions **102**(2): 549-561.

1. Scope and content:
This paper includes findings and data from a Florida Solar Energy Center (Uncontrolled Air Flow in Non-Residential Buildings, Final Report FSEC-CR-878-96) investigation of uncontrolled air flow in 70 small commercial buildings in Florida. In 14 out of the 18 buildings monitored, the duct system was repaired by people with considerable experience in repair of residential duct leakage. Energy use was monitored for 5-7 weeks before and after repair during the summer when ambient temperatures were assumed to be similar. To filter out inconsistencies, kWh energy usage was plotted against temperature difference between outdoors and indoors. Reductions in air conditioning energy use ranged from -6.7% to 36%, with an average of 15.1%. Daily kWh savings averaged 12.5 kWh. The authors compared repair costs with energy savings (at $0.075/kWh) and concluded that average repairs cost $455, with a simple payback period of 3 years. FSEC-CR-878-96 includes data on pre repair and post repair peak electric demand. As a result of uncontrolled airflow, peak electrical demand was reduced by an average of 0.71 kW, or 9.4%.
2. Relevance to return systems:
Some of the repairs included sealing return ducts and plenums, but measurements of duct and building leakage and cooling energy use pertain to combinations of repairs. In many cases, repair was not delineated between supply and return ducts. Details of repairs in each building are included in the paper.
3. Significant findings:
This paper illustrates that repair of uncontrolled airflow can provide significant energy savings and reductions in peak electrical demand. However, some repairs were limited by time, interference with business operation, and money available in the project budget. Also, not all duct leaks were repaired. Even with the limitations, air conditioning energy use and peak electrical demand was reduced. Given more resources, improved diagnostic tools, and more access to buildings, the authors expect a greater reduction in air conditioning use and peak electrical demand.
4. Limitations and assumptions:
Since combinations of repairs of uncontrolled airflow were made on the buildings, the impact of return duct and return plenum leakage on air conditioning energy use and peak electrical demand was not determined.

☒ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☒ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Withers, C.R., and J.B. Cummings. (2000). *Building Envelope Air Leakage Failure in Small Commercial Buildings Related to the Use of Suspended Tile Ceilings*, Final Report, PF-398-00.

1. Scope and content:
This reference presents measurements of two building's suspended ceiling tile ceilings and data and observations from three buildings showing the impact of a leaky ceiling will have as a result of wind and temperature differences, duct leakage, restricted return air, and unbalanced exhaust air. The authors cite two other Florida Solar Energy Center reports (FSEC-CR-397-91 and FSEC-CR-878-96) and state that after screening data for small commercial buildings and residences of similar construction (single story, slab on grade, concrete block or wood frame, with ventilated attic or ceiling spaces), small commercial buildings are twice as leaky. Since the primary difference is the use of suspended ceiling tiles in small commercial buildings, compared to gypsum board ceilings, the authors suggest that suspended ceilings constitute the majority of envelope leakage in small commercial buildings.
2. Relevance to return systems:
The reference does not specifically mention plenum return and ducted return air systems, but the discussion and information presented is relevant to both systems.
3. Significant findings:
The authors state that even through there may be significant pathways across a ceiling, the severity of the impact depends on the amount, direction, and quality of airflow. Four primary driving forces cause uncontrolled airflow in small commercial buildings: ▪ Driving forces such as wind or temperature differences ▪ Duct leakage ▪ Restricted return air ▪ Unbalanced exhaust air The authors measured suspended ceiling leakage directly at 5.0 cfm/ft^2 at 50 Pa pressure difference across the ceiling, which is approximately 10 times leakier than a typical gypsum board ceiling.
4. Limitations and assumptions:
The reference focuses on small commercial buildings.

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☒ Indoor Air Quality	☒ Experimental Study
☒ Design & Construction Methods	☒ Residential
☒ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Wray, C.P. (2003). *Duct thermal performance models for large commercial buildings*. Berkeley: Lawrence Berkeley National Laboratory, LBNL-53410.

1. Scope and content:
California's Title 24, Energy Efficiency Standards for Non-Residential Buildings, gives no credit to buildings with energy-efficient duct systems and the lack of modeling capability is a primary reason. Wray reviewed past modeling efforts related to duct thermal performance and recommended near and long term modeling approaches for analyzing duct leakage and conduction in large commercial buildings in order to include duct performance in California Title 24. Wray also provided an overview of duct air leakage, fan performance, and duct surface heat transfer and their effects on constant air volume (CAV) and variable air volume (VAV) systems. Models reviewed included DOE-2.1E, DOE-2.2, Energy Plus, and TRNSYS. Wray also outlined future work needed in order to include duct performance in California Title 24's provisions for large commercial buildings.
2. Relevance to return systems:
▪ DOE-2.1E does not model the effects of return duct leakage and return duct heat transfer ▪ DOE-2.2 models the effects of return duct leakage, but not return duct heat transfer ▪ As of 2003, EnergyPlus does not model duct thermal performance, but modular nature allows integration of duct performance models
3. Significant findings:
▪ Appendix II contains 7 TRNSYS component models (supply fan, return fan, cooling coil, zone return air mixing, economizer, ceiling return plenum, upstream ducts, and downstream ducts) used by Franconi *et al.* (1998) to model the effects of supply duct leakage upstream and downstream of VAV terminal boxes. ▪ Short-term recommendation: build upon work done by Franconi (1998) that used DOE-2 and TRNSYS ▪ Long-term modeling recommendation: assuming EnergyPlus could be certified as a compliance tool for the 2008 revisions to California Title 24, Wray recommends integrating duct thermal performance models with EnergyPlus
4. Limitations and assumptions:
The discussion of the effects of duct air leakage, fan performance, and duct surface heat transfer on CAV and VAV system operation is focuses on supply ducts.

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Reference: Wray, C.P., and N.E. Matson. (2003). *Duct Leakage Impacts on VAV System Performance in California Large Commercial Building.* Berkeley: Lawrence Berkeley National Laboratory, LBNL-53605.

1. Scope and content:
Wray and Matson modeled the annual energy use of a low-pressure terminal-reheat variable-air-volume (VAV) HVAC system with 6 supply duct leakage configurations in 9 office buildings representing three California climates. DOE-2.1E and custom TRNSYS component models developed by Franconi (1998) were used to model the buildings. The distribution system simulation is uncoupled from the load and plant simulations performed by DOE-2.
2. Relevance to return systems:
The buildings modeled utilize ceiling return plenums, but return plenum and return duct leakage are not modeled. The same strategy could be used to model return leakage.
3. Significant findings:
Adding 19% supply leakage increased fan power by 40-50% compared to a relatively tight duct system (5%). Annual cooling plant consumption increased by 7-10% and reheat energy reduced by 3-10%. Total HVAC site energy, which includes supply and return fan electricity consumption, chiller and cooling tower electricity consumption, boiler electricity consumption and boiler natural gas consumption, increased by 2-14%.
4. Limitations and assumptions:
▪ Return air leakage was not modeled ▪ The HVAC system modeled had perfectly insulated ducts, so the effect of duct surface heat transfer was not considered ▪ The VAV system maintained constant static pressure upstream of the VAV box and had a constant supply air temperature at the air handler. ▪ The authors suggest future modeling efforts should include parallel fan-powered VAV boxes, duct surface heat transfer, and static pressure and supply air temperature reset strategies

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☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Wray, C.P., R.C. Diamond, M.H. Sherman. (2005). *Rationale for Measuring Duct Leakage Flows in Large Commercial Buildings*. Berkeley: Lawrence Berkeley National Laboratory, LBNL-58252.

1. Scope and content:
Wray *et al.* describe common leakage metrics and duct leakage test methods used to characterize air distribution systems and compiled duct pressurization data from large commercial buildings tested by LBNL. Leakage at operating conditions was found by measuring the airflow out of each supply grille and the supply fan airflow. The difference between the sum of supply grille airflows and the supply fan airflow was the leakage. The measured leakage fraction was compared to the leakage that would be implied by duct pressurization tests. The buildings contain VAV, CAV, and dual duct systems. Data for “high pressure” ducts, upstream of VAV boxes, and “low pressure” ducts, downstream of VAV boxes, are included.
2. Relevance to return systems:
Return air leakage is not reported, but the methods described can be used to measure return air leakage by separating the supply and return sides of the distribution system.
3. Significant findings:
There were significant discrepancies between estimated duct leakage and measured duct leakage. The discrepancies illustrate that duct leakage determined from duct pressurization tests do not accurately predict leakage at operating conditions, because the standard duct pressurization test assumes that all leaks experience the average duct static pressure. Results from duct pressurization tests should be used to compare air distribution systems, not to predict duct leakage at operating conditions.
4. Limitations and assumptions:

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Xu, T., O. Bechu, R. Carrie, D. Dickerhoff, W. Fisk, E. Franconi, O. Kristiansen, R. Levinson, J. McWilliams, D. Wang, M. Modera, T. Webster, E. Ring, Q. Zhang, C. Huizenga, F. Bauman, and E. Arens. (1999). *Commercial Thermal Distribution Systems: Final Report for CIEE/CEC.* Berkeley: Lawrence Berkeley National Laboratory, LBNL-44320.

1. Scope and content:
Xu *et al.* characterized the performance of thermal distribution systems in large and light commercial buildings in California, analyzed the potential for including duct performance in the non-residential portion of California's Energy Efficient Standards for Residential and Non-Residential Buildings, Title 24 and conducted laboratory and field experiments of sealing ducts through aerosol injection. Supply duct effective leakage areas, air leakage classes, operating pressures, air leakage ratios, and heat conduction losses were found for 5 light and 5 large commercial buildings. Also the authors include a discussion of the keywords, modeling options and limitations of duct leakage models in DOE 2.1E.
2. Relevance to return systems:
For the 5 large systems, effective leakage areas and static pressures were measured in supply ducts, and for the 5 light commercial systems, effective leakage areas and static pressures were measured in both supply and return ducts and plenums.
3. Significant findings:
1. In the 5 large commercial buildings, ASHRAE leakage classes (cfm/100 ft^2 at 1" H_2O) ranged from 34 to 246 for main supply branches (upstream of VAV boxes) and from 58 to 606 for downstream branches. In the 5 small commercial buildings, total ASHRAE leakage classes (supply, return, air handler) ranged from 244 to 414, with an average of 333. 2. DOE 2.1E has numerous shortcomings when modeling duct thermal losses: lacks the capability to model return duct losses/gains, use of fixed supply leakage ratio even with VAV systems, assumption of all supply leakage occurring at end of duct run, and inability to model supply-return air imbalances and the resulting infiltration/exfiltration.
4. Limitations and assumptions:
Even though the study focused on supply duct leakage, supply and return ducts were constructed with the same workmanship so return duct leakage could be as prevalent as supply leakage. Conclusions about the population of commercial buildings in California and the U.S. cannot be drawn from the limited data collected, but significant duct leakage existed.

☐ Building Energy Use	☒ Leakage Measurements
☐ Security / Contaminant Dispersal	☒ Analytical Model
☐ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☒ Repairs & Retrofits	☒ Commercial & Institutional

Reference: Zuraimi, M.S., K.W. Tham, and S.C. Sekhar. (2004). "A study on the identification and quantification of sources of VOCs in 5 air-conditioned Singapore office buildings." Building and Environment **39** (2): 165-177.

1. Scope and content:
Zuraimi *et al.* identified and quantified VOC sources in 5 air conditioned buildings in Singapore. A mass balance model was used to separate the sources into 3 categories: building materials, ventilation systems, and occupants and their activities, and to find area-specific steady state emission rates of the sources. To separate the sources of VOCs, the global return air was sampled in three combinations of building cycles - 1) ventilation system on and normal occupancy, 2) ventilation system on and no occupancy, 3) ventilation system off and no occupancy. Thirty seven VOCs were monitored, and additional VOCs were monitored to determine TVOC area-specific emission rates. The average contribution of each source to TVOCs was 39% from ventilation systems, 37.3% from occupants and their activities, and 23.7% from building materials.
2. Relevance to return systems:
In all buildings studied, conditioned air was delivered by supply ducts above the ceiling, while air was returned either by return ducts or return plenums. Emission rates from ventilation systems with ducted returns and plenum returns were compared, and generally the emission rate of each VOC did not differ. However, emission rates of 4 compounds (dodecane, tetradecane, toluene, and styrene) were significantly higher in ventilations systems with ducted return. TVOCs in the conditioned space were higher in buildings utilizing plenum returns. The authors contend that in a plenum return system, "the return air is exposed to a bigger area (equivalent to twice the floor area of the building) and to a host of other VOCs sources which includes the underside of the ceiling tiles and outer duct liners," and that return air in ducted return systems is exposed to less area. (p. 172)
3. Significant findings:
The age of buildings tested ranged from 6 months to 10 years. The emission rates pentadecane, hexadecane, 2-propanol, and hexanal from ventilation systems were found to be consistently higher in established buildings. Previous chamber studies identified pentadecane, hexadecane, 2-propanol, and hexanal as emissions of ceiling tiles. The authors contend that higher emission rates of these compounds in established buildings may be explained by the age of materials used in ventilations systems.
4. Limitations and assumptions:
Measured area-specific emission rates are net rates because removal factors other than ventilation such as sinks are not considered. Also, the indoor space was assumed to be well-mixed.

☐ Building Energy Use	☐ Leakage Measurements
☐ Security / Contaminant Dispersal	☐ Analytical Model
☒ Indoor Air Quality	☒ Experimental Study
☐ Design & Construction Methods	☐ Residential
☐ Repairs & Retrofits	☒ Commercial & Institutional

Appendix B

SUPPLEMENTAL QUESTIONAIRES

Designer Questions

3. Please provide your name, employer, job title, and city/state below. The responses will be edited for confidentiality.
4. If you are willing to discuss your responses or participate in an expert panel, please provide your email address and/or phone number (optional).
5. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space?
6. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality?
7. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns?
8. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization?
9. Do you expect a higher energy use associated with ducted return or plenum return? Why?
10. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why?
11. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how?
12. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how?
13. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how?
14. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts?
15. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier?

16. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented?
17. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents?
18. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure?
19. Would you be willing to participate in a future survey regarding return air systems?
20. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer Responses

Designer 1

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Type of system and available clearances above the ceilings. Critical spaces in labs and hospitals do not allow R/A plenums. Sometimes we have a say, mostly the cost of the building and the ceiling heights dictated by the architect limit the plenum depth. The architect and owner determine if the ductwork can be exposed or not. We have utilized exposed fabric ductwork on some projects.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? Yes we have designed exposed ductwork. The architect and owner determine if the ductwork can be exposed or not. We have utilized exposed fabric ductwork on some projects. Many manufacturing facilities, gymnasiums and aquatic areas have exposed ductwork. Most offices, schools and labs do not. The exposed ductwork decision is usually based on the look the architect or client are trying to achieve.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes. The cost of the ductwork and labor to install, but also the fan horsepower is greater with return ductwork.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? The quantity and location of return registers is based on the requirement to allow the R/A to get back into the ceiling plenum, we

do not match the quantity of R/A grilles to S/A diffusers. Typically you still need at least one R/A grille per room, depending on the size of the room and the quantity of return air light fixtures. The R/A grilles are located so that they are not near or adjacent to other R/A grilles in neighboring offices, to reduce sound or noise transmission from office to office.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Higher energy use with a ducted return due to increased static pressure. The A/C unit will also have a lower entering air temperature with ducted return and thus operate slightly less efficiently.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Not in a typical office application. If space is designed for humidity control needs, the return air plenum has to be sealed to the outdoors and a vapor barrier is required on all outside walls.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Yes. Spatial pressurizations are required to maintain positive and negative areas for migration and control of airflow. Thus the systems have to be fully ducted to the spaces. The system may require filtration at the room level for both S/A and R/A.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Typically, 5 to 10% leakage is anticipated and compensated during the balancing stage of the project. S/A quantity should be increased slightly to compensate for leakage when the S/A ductwork is not within the conditioned space. Plenum leakage is usually not a factor since the pressure is low.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Typically SMACNA and ABBC and NEBB standards apply. Leakage is only verified on projects where the system designs are more critical such as labs and hospitals. The ASHRAE handbooks provide recommendations; Fundamentals book chapter 35 and HVAC Systems & Equipment book chapter 16.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? We specify them to be insulated for all system types. For cost cutting reasons, the insulation is typically deleted in return air plenum applications, by the owner. The energy code requires the ductwork to be insulated where the temperature difference of the supply air is 20F or greater than the space where it is located. This typically requires ducted return system to have insulated supply ductwork and the area below the roof in plenum return systems, to have insulated supply ductwork. We prefer external wrap insulation.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? The insulation should be on the roof deck. Insulation on the ceiling tiles means that all sprinkler piping above the ceiling is subjected to freezing. The ceiling is the plenum barrier between conditioned space and R/A path.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor

retardation is implemented? A very small DP is expected (hundreds of an inch of W.C.). The water vapor barrier is the same for all construction, regardless of R/A type.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? No, the plenum is part of the conditioned space.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? SMACNA standards note the sealant requirements. Duct materials typically depend on the environment it's being installed in or the systems that it is serving. Typical applications are galvanized steel, kitchen hoods are welded black steel or stainless steel, showers or wet areas are aluminum, buried ductwork is fiberglass and lab hoods can be PVC or coated metal depending upon the chemicals utilized in the hoods.
16. Would you be willing to participate in a future survey regarding return air systems? Yes.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. For a standard office application, ducted returns require greater ceiling plenum depths, which can cause a building to be higher and more costly. Ducted returns are more expensive (sheet metal and labor), use more energy (fan HP), require more balancing and more design/installation coordination.

Designer 2

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Plenum returns are only used where there are no cross contamination issues between rooms and room pressurizations are non-issues. 95% of the jobs going through our office utilize ducted return and a great deal of work has "once-through" ventilation, meaning all the air is 100% exhausted. Laboratories, hospitals, research facilities all require ducted exhausts. Plenum space is negotiated between architects & engineers. Architects like less space to offer higher ceilings where as engineers would like more plenum space.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? I've only done exposed ductwork once and that was a chemistry building for Boston College. It is usually owner requested.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? The first cost difference would be buying duct for ducted return, possible larger motor due to increased static. For plenum return everything in the plenum will need to be plenum rated. Not the case for ducted return. Plenum return also requires more full height walls.

5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization?

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? I expect plenum return to see a savings in energy due to requiring less static pressure on the return system.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Plenum return will produce lower IAQ due to dust and particles picked up in the plenum.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? If airborne chemical or biological releases are a concern then a return system cannot be utilized. The system will need to be 100% exhausted through a high plume dilution exhaust fan. Each area will be pressurized to contain chemicals and releases within their work areas.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? No.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Leakage can be verified in a return air system. Significant drafts above plenums indicate leakage.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Supply ducts are always insulated to keep the air at discharge temperature. Insulation is wrapped on the exterior of the duct. Insulation also keeps the plenum air from condensing on the duct. Return/exhaust air is typically not insulated. The only time it is insulated is if it is returning cold air, i.e. ventilation from environmental rooms at below freezing.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? Plenums are not typically insulated.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Ducted return/exhaust typically runs around 2.5-3.0” external static pressure. Not familiar with plenum return but would guess around 2.0” E.S.P.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? I do not vent plenum spaces to the outdoors.

15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? We do not specify duct sealants or sealing methods.

16. Would you be willing to participate in a future survey regarding return air systems? Yes

17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer 3

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Usually, it is the client. More specifically, it's the client's budget. A plenum return system has a lower initial HVAC cost which makes it appealing for bidders to give the client a low cost of installation. (Although the cost of the electrical system goes up due to use of plenum rated wiring) Balancing a plenum return system is very difficult and the pressure difference between the plenum space and condition space is usually small resulting in low infiltration. If a plenum system is to be used, I usually have to work with whatever space I have left between the roof and ceiling. If the space is terribly ineffective, I sometimes can alter the dimensions a little by collaborating with the Architect. I have a stronger position when it comes to say for where the ducts are going. I try to keep every inch of ductwork inside conditioned space so to keep energy costs down and to also keep installation costs down. Insulation for ducts becomes rather expensive quickly so it is always in my best interest to avoid exposing duct work to the elements.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? I do design exposed ductwork, and there are many occasions that the owner requests it. It gives and industrial look to there location which seems to be a trend lately (a lot of stores in malls are doing this.) If an owner does request exposed ductwork, it usually has to be round (spiral type) instead of rectangular. Besides practicality of easy access/ installation, it does help because the ductwork is directly inside the conditioned space which does make the system a little bit more efficient. But for the most part, it is mostly about looks.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Absolutely. The plenum return system is much more inexpensive than the ducted return because with the ducted return, a mechanical contractor has to fabricate all the return ductwork, dampers, etc. With a plenum system, that is not included. But as I mentioned previously the electrical cost increase. Also, some codes do not allow exposed PVC vent piping in the open air plenums. The plumbing contractor would be forced to insulate it or utilize cast iron.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? I usually do try to match return registers with supply registers, and yes, it is to avoid pressurizations and depressurizations. If a showroom for a retail store has 1200 CFM supply, I will put about 1200 CFM return to balance the room. As a basic setup, I will put supply registers on the outside of the room and have the return positioned in the middle of the room to have the air circulate. I will try to put the minimum amount of return registers to retrieve the air

flow at a NC level at or below 30. Also, I will adjust the return so to have a slight pressurization (about 250 CFM).

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Usually there is a higher energy cost associated with plenum return. When you have plenum return, the system is not exactly in balance. When this happens, rooms with pressurizations and depressurization that are not desired occur and put extra stress on the air handling unit. This in turn results in a higher energy cost.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Depending what the application is. If it is a restaurant, moisture and contaminants in a kitchen have to be exhausted correctly. If you have a ducted return, one can easily balance out a return register to a certain CFM so not to interfere with exhaust fans and kitchen hoods. (You want to have a negative pressure so kitchen air is sucked out of the kitchen and doesn't seep into the dining room.) With a plenum return, this is much more difficult and moisture and contaminated air complaints will arise. This is why I try to avoid using them.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? These situations have to be assessed accordingly. Usually, these areas do not get a return duct and most, if not all, of the supply air is exhausted. For ventilation rates in these situations, I consult the International Mechanical Code and ASHRAE standards.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? I usually design HVAC systems for smaller buildings so my runs of ductwork do not get much larger than 100 feet. So as a rule of thumb I use 0.1" w.g. per 100' of duct for supply and 0.05" w.g. per 100' of duct for return. If I do design a larger building, duct leakage should be assessed more effectively.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Duct efficiency has to be within 10% of design and the system has to be tested after construction. Due to the size of the systems we are typically designing (small) we do not take this into consideration.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? If ductwork is exposed to unconditioned space, ductwork has to be insulated (supply and return unless designing a 100% outdoor air system then just supply.) They have to be insulated to increase efficiency and lower energy costs. Insulation methods vary so the mechanical contractor consults the SMACNA manual.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? The insulation goes in the roof to the plenum air is not unconditioned. Usually ceiling tiles are the only barrier in the plenum but it can also be gypsum board or other paneling.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Pressure difference is usually not too high because of

the efficiency of the plenum return. Normal pressure differences are only 0.03" w.g. but that can vary. It would be appropriate to correctly seal openings and create vapor barriers but unfortunately that is more expensive and sometimes I do not get that luxury.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? I usually don't use a plenum system but if I did, it should be vented in some manner and a louver with a built in exhaust fan would work correctly. To size it, I usually consult the International Mechanical Code and ASHRAE 62.1.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? The duct-mate system is usually specified in most of our projects. But, mechanical contractors are instructed to consult SMACNA policies to ensure proper duct installation and sealing for certain applications.
16. Would you be willing to participate in a future survey regarding return air systems? Absolutely.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. Plenum systems are an inexpensive way to return air from a building, but not the most efficient. Although the ducted return's cost is more, the energy savings, ease of use and performance far exceeds that of a plenum return system.

Designer 4

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? The main criteria for determining whether a plenum return is acceptable, is the space criteria for pressurization. If the spaces served by the system require consistent space pressure relationships, then a plenum return will not work. Next, considering the type of facility, lab, or hospital, then areas adjacent to critical areas will not have plenum returns, since the potential would exist to "draw" air from the plenum of adjacent areas. Finally, if a return plenum is an acceptable approach, then cost would play a factor. Return plenums are typically less expensive since the ductwork is reduced. Working in an A/E firm, we would have a say in how deep the plenum is. Similarly, we would have a say in whether duct was exposed in the conditioned space, however; ultimately, the Architect drives the finish criteria.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? Very rarely, only if there is an Architectural style and element that considers exposed ductwork.

4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes, plenum returns will be less expensive. Could be approximately $5/CFM less for plenum return.

5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? With plenum returns, you can not maintain pressurization within each space no matter how the return grilles located. Return grilles are located within each space with full height partitions, with adequate transfer ducts (if partitions extend to structure). In open areas, returns are typically sized for the maximum tile grid size, 22x22 for a 24x24 grid. The quantity is determined by the total supply CFM using about 1400 CFM per return grille.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? We expect a lower energy use with plenum returns, since the duct friction loss is less, and return fans can be sized slightly smaller for lower pressure drop.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? No different than duct systems. As long as the cooling coils are sized properly, to account for added heat gain to the return plenum, there should be no particular issue.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? It will depend on the potential location of the release. If we have a more “exposed” area, more prone to such release, such as the mail room, or loading dock, we would typically 100% exhaust those spaces. Another consideration would be to sequence the air handling unit to a 100% purge cycle, to prevent recirculation of chemical/biological agents. In general, a release in a recirculated air system, plenum or ducted, will have the same result.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? We typically allow for 5-10% leakage in supply and return distribution.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? We reference SMACNA HVAC Duct Leakage Test Manual and SMACNA Standards for duct construction. We establish the minimum pressure class and seal class for all duct systems on our drawings. This establishes the leakage criteria. Our specifications require all ductwork to be leak tested in the field. All tests are to be witnessed and documented.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Yes, Supply ducts are insulated, to prevent condensation on the outer surface of the duct, as well as to prevent heat loss through the duct. Return ductwork is typically only insulated in ceilings with a roof above, and in mechanical rooms, for the same reasons as why supply duct is insulated.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? Return plenum is not insulated. Ceiling tiles and upper floor construction serve as an adequate insulation for the interior of the plenum. Plenums

with roofs above, will typical provide additional rood insulation above what we normally provide for ducted return.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? The DP from the plenum to the outside is typically very low, and will vary greatly depending on the wind movement around the building. The return plenum will typically be negative 0.12-0.15 inches. Since the area of the actual return plenum is a relative small percentage of the area that is within the occupied building envelope, which is held at a positive pressure, we don't take special measures for the return plenum. Typical envelope construction has suitable air and moisture barriers that will not be impacted whether the building has plenum return or ducted return.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? No.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Duct materials and sealing methods are standard industry construction. We do not allow duct tape as a sealing method. Typically, only water based mastics and caulk seals are used. Sealing methods will change based on system pressure, or type of transported medium, i.e. wetted ductwork will have welded joints (stainless steel).
16. Would you be willing to participate in a future survey regarding return air systems? No thank you.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer 5

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? The number one answer is cost. The price of Sheet metal has risen significantly in the last 2 years. If we can reduce the total quantity of ductwork in a bldg this helps to keep the construction cost down. Typical the floor to floor height is 13'-4". Unless the building type required a lot of services to be run in the ceiling (Hospital or Laboratory) we use 13'-4 and generally the engineers input is not considered. We are seeing concrete plank being used as opposed to steel beams and this helps with plenum space tremendously. Generally we are asked to conceal most ductwork because of aesthetic reasons.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? I use exposed ductwork in assembly spaces that do not have ceilings or

the ceiling system is composed of an architectural cloud layout. (Gymnasiums, wrestling rooms, pools, auditoriums). If there is a condition where there is no plenum space and we are commented to condition the room by using forced air then exposed ductwork is generally the easiest, cheapest solution. Some owners like the look of fabric duct in high volume no ceiling spaces. Some school districts color the fabric ducts to match school colors to accent a gymnasium.

4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes, for the obvious reasons on more material being used. Occasionally you will have an architect try to reduce the floor to floor height and use the "extra" space between items in the plenum for the return air path. But I have never seen a cost savings going this route.

5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? I typical try to limit the areas where we have plenum returns to just corridors. I do not want the plenum air exposed to exterior walls where the average temperature of the plenum is reduced. In the rooms where I have a plenum return I size the return air grille on a maximum velocity and pressure drop. If the volume of return air is high and the maximum velocity or pressure drop is exceeded, then I use more than one grille.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? I would say it all depends on quality of construction. You can have a crowed plenum with obstructions blocking good airflow and thus driving up the static pressure the fan must overcome versus a ducted return system where the contractor has installed square elbows without turning vanes at all changed in direction.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Plenums tend to be dirty. The filter in an air handling piece of equipment tends to load up faster in plenum return systems. Indoor air quality can be better in ducted system for the simple fact you can trace a return air path from room mounted grille back to air handling equipment. Moisture should be removed from the outside air before it reached the space. If the air is dry when it conditions the space, the return air will be dryer as well (assuming you don't have any high moisture gains in the space, other than the design occupancy). Ducted returns will help contain this dry air and not allow infiltration to occur, which is the other significant source of moisture in a building.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? I have never been given the opportunity to design such a system. I would think ducted return would be the way to go because you can trace the entire return air path.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? I once had an "old" engineer tell me never design to a gnat's ass. Now that is not so say you over design, but typically I allow some growing room in main duct risers or trunks. SMACNA allows for ±10% when you are balancing a system. HVAC is not an exact science. It is common practice to have some extra capacity in the air handling equipment to allow for leakage. I wait for the testing and balancing report to see the quality of ductwork construction. If you

have leaky ductwork the T&B report will show 100% airflow at a duct traverse and less than 100% at the terminal units.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? I use the Sheet Metal and Air conditioning Contractors national Association (SMACNA) HVAC Air duct leakage Test Manual. I require the contractor to inspect for audible leaks and submit a Testing and Balancing report to the engineer for review.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? I do insulate both the supply and return ductwork. You are spending money to heat or cool air and transport it to different locations in the building, you should try to minimize the loss of energy (and money) during the transport and insulation does that. I typically use either 1-1/2" foil faced flexible fiberglass blanket or rigid fiberglass board insulation applied to the outside of the ductwork. Downstream of the terminal equipment I use internally insulated ductwork. This is for thermal as well as for acoustically treatment.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? I have found that it is easiest and cheapest to apply the insulation at the roof deck. If the building envelope is well insulated and construction quality is good you can minimize the energy lost in return air plenum. It also helps to limit the area of the return air plenum. Try not to locate the plenum adjacent to exterior walls and other unconditioned spaces.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? The pressure drop across the plenum is anybody's guess. I use 1 inch water gage. This number comes from engineering judgment and experience. I don't think there is an easy way to measure this. You never want the interior of your building under negative pressure. I always return less air than I supply. I usually supply air to the corridors and don't return any of that air. Most of the air is transferred for toilet exhaust but typically I try to keep a couple hundred cfm on the floor to positively pressurize the building to help prevent infiltration. I recently read an article about an air barrier for buildings (Building Design and Construction Jan. 2007, "Air Barriers, The latest tool in moisture control.").

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? No I don't vent plenum space. The two sources for moisture generation in a building are people and infiltration. If you control the amount of moisture in the outside air you will not have a problem with excessive moisture in a building, unless there is a specific process or activity that generates high moisture levels and this is a separate issue.

15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? The duct sealing method and materials do change with building type and with different owners. Most schools I design are all low velocity systems with a ductwork pressure class of 2" w.g. We use a seal class C, which calls for

only the transverse joints to be sealed. In hospital work we use 2" w.g. ductwork pressure class downstream of the terminal equipment and a 3" or 4" w.g. upstream of the terminal equipment, with a seal class B. This calls for all transverse and longitudinal seams to be sealed. On all of our projects we use a duct mate style connector or a transverse duct flange (TDF) connection. I don't allow slip and drive due to leaky joints.

16. Would you be willing to participate in a future survey regarding return air systems? Yes I would.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. I think I have exhausted my little knowledge on the previous 17 questions; I have no more to give.

Follow up questions

1. Do you have an estimate of the difference in first cost ($/cfm or $/ft^2) between the use of plenum return and ducted return? No I don't. It is extremely hard to convince architects to increase the floor to floor height when designing around a ducted return. The only place where we can make a strong argument is in healthcare work, the AIA guidelines required ducted return systems.
2. What is the maximum ΔP or velocity for a return grille? I design around Titus, Model 50F or Model 350R and I try to keep the velocity thru the grille at about 500 fpm and less than 0.1 "w.g. static pressure drop thru the face of the grille.
3. You stated that you, "Try not to locate the plenum adjacent to exterior walls and other unconditioned spaces." Won't plenums always be adjacent to exterior walls? I limited the plenum areas to just above corridors. The corridor does touch the outside wall at the ends of the building, but this area is typically a lot loss area than having the plenum extended above rooms adjacent to the corridor and these rooms have an exterior wall exposure.

Designer 6

2. What factors determine whether you use a ducted return or plenum return? – Project type and owner. I would say that plenum design is standard. Ducted return is used when required by the Owner or where required by the application. Do you have any say in how deep your plenum space is? –Yes and no. If we are involved early enough in the design, we can make recommendations on what space is required. I've had projects where the structure was increased for more plenum space and I've had projects where we had to find a way to make do with what was available. Do you have any say in whether or not the supply ducts and return system is in the conditioned space? – I would say that supply/return systems are usually located in ceiling plenums unless requested otherwise by the architect/owner.

3. Do you ever design exposed ductwork? - Infrequently, but yes. Does an architect or owner ever request exposed ductwork? Yes Are there any reasons for exposed ductwork besides practicality? – Exposed ductwork is normally used where the architect is going for an "industrial" look.

4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes there is. In addition to having more ductwork to duct the return from each space, more plenum space is often required as the supply/return ducts will often have to cross. Deeper plenum increases structural, architectural and envelope costs.

5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? Location is determined by trying to promote good air distribution within the space. Highest part of the ceiling for coffered ceilings so there are not "hot pockets" at the top. In a flat ceiling, opposite of the supply to promote good distribution. Each space that has a door needs a return. Large open spaces returns are distributed but sized for the quantity of air being returned.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? – Would expect minimally higher energy use with ducted return due to somewhat higher static pressure losses in a ducted system. A ducted system will have a balance damper to balance the return device that wouldn't be present in a plenum return. Duct losses would be somewhat higher than plenum losses.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? – While there is better opportunity for being able to clean return air ductwork, a return air plenum system will generally move at a low enough velocity that it is not entraining dirt from the plenum. And if it were entraining dirt from the plenum, proper filtration would take care of that. – However, poor envelope sealing can allow moisture to migrate from the exterior into the plenum where plenty of food sources for mold can be found. The question of IAQ relative to plenums is not mutually exclusive of other components/systems in the building.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? – Yes, if this issue is a concern for the building owner, then a ducted return would be recommend. This allows for monitoring and filtering of the air as well as ease in cleaning the ductwork after an incident.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? - Not normally assumed to be significant in commercial systems that are properly sealed.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? - Medium pressure systems are specified to be leak tested with leakage reports submitted for review and approval.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? – Supply ducts are required to be insulated by code. Either

external or internal insulation is used depending on whether acoustical control from mechanical equipment is required. Return air duct is not normally insulated unless exposed on the roof, etc.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? – Plenums are not normally insulated except where they butt up at the envelope. Standard plenum would be exposed structure and exposed ceiling tiles or gypboard.
13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented?- We normally design building for a slight positive pressure with respect to outside. A return air plenum would be slightly negative with respect to the occupied space, so it would be relatively close to neutral with respect to outside. – Vapor barrier requirements are provided by the architect and are independent of the use of a return plenum.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? - return air plenums are not normally vented to the outside.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? We specify duct sealing in compliance with SMACNA standards. Duct sealing requirements do change with pressure class and with Owner requirements.
16. Would you be willing to participate in a future survey regarding return air systems? yes
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. The general experience used to answer these questions is based on commercial design/construction, not residential of any sort. Return air plenum was taken to mean the space between the structural deck and architectural ceiling and was not taken to mean attics, crawl spaces, etc.

Designer 7

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Our designs typically do not utilize a ducted return air system with the exception of health care, pharmaceutical packaging, and research laboratory work. We do have some influence as to the ceiling plenum height. We are usually involved in the preliminary discussions regarding steel dimensions, ceiling heights, and steel elevations. We usually react to the aesthetic designer’s preference as to whether the ductwork is exposed or hidden.

3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? Certainly there are applications for exposed ductwork and we have incorporated exposed ductwork in many designs. Deleting the cost of the duct insulation is a consideration.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? I have not priced systems both ways to ascertain the exact cost, but logic says that additional material and fan horsepower must cost more. With the costs of material, I would expect that added cost to be significant.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? I prefer to keep the return air grille size to work within a 2’x2’ ceiling grid. This allows for a discreet maximum airflow per grille. For a large space, I would keep adding grilles as necessary to accommodate the room airflow. I will also try to locate the grilles to minimize thermal stratification and to minimize the temperature difference within a room. For instance, I like to locate the return air grille at the exterior wall to draw the conditioned room air past the building envelope. For interior spaces, I prefer to install the grille in the vicinity of the thermostat.
6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Intuition tells me that the ducted system should use more energy due to the higher restriction in airflow through the ductwork, but I have not done an actual analysis to confirm/deny this.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? That depends on your definition of IAQ in this instance. If you are referring to particulate matter within the occupied zone, I would hope that the AHU filters would remove a majority of the dust entrained within the ceiling plenum and that the ceiling plenum would not adversely impact the occupied zone air quality. If you are referring to thermal comfort, I believe that the ducted return would have an impact on the room air quality. I would expect that the ducted return would require additional airflow within each zone, since the associated roof load would be introduced to the occupied zone instead of the ceiling plenum. It is possible that the additional airflow might cause localized drafts.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Certainly. Location of intakes is very important as well as proper treatment (filtration, etc.) of the return airstream prior to recirculation.
9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? I am more concerned with supply air duct leakage than return air duct leakage. I specify specific duct construction (pressure class and leakage class) and duct pressure testing for some of the more important duct systems.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? See above.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Depends on the location of the ductwork and what temps of air they are conveying. I have a project that supplies neutral temperature ventilation air. This supply ductwork is not insulated because it is installed within a return air plenum. Conditioned supply air is always insulated per the energy code unless the ductwork is exposed within the conditioned space. I usually do not specify return air duct insulation unless it is required for acoustical reasons or installed directly beneath a roof surface. The ductwork is either wrapped or lined to meet the heat transfer requirements per code.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? I am not typically involved with the design of the building envelope. If someone asked me for my opinion, I would suggest that the insulation be installed at the roof surface. The ceiling is typically the air barrier.
13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? I usually design the pressurization system to maintain between 0.05” and 0.10” w.c. difference. This is balanced either by relief fan modulation, or counterbalanced dampers on the relief air openings. I do not design the building façades. In this geographic area, the building should have a continuous air barrier and a continuous water barrier anyway.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? Please elaborate on this question. Do you mean vent ceiling return air plenum spaces, or unconditioned attic/crawlspaces?
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Ducts are constructed of various metals depending on end use. Pressure class and leakage class are specified for each duct system. The sealing methods certainly change based upon system pressure and type of system.
16. Would you be willing to participate in a future survey regarding return air systems? Yes.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer 8

2. What factors determine whether you use a ducted return or plenum return? The type of space, the type of building, the construction budget, the building codes. Do you have any say in how deep your plenum space is? Usually not. Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Usually not.

3. Do you ever design exposed ductwork? Yes. Does an architect or owner ever request exposed ductwork? No. Are there any reasons for exposed ductwork besides practicality? Yes, some projects make a point to display the ductwork to send a message of the high quality of mechanical systems. E.g. UofM Mechanical Engineering building and the Ellerbe Becket offices.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes.
5. How do you determine the number and location of return registers in a system with plenum return? Number of registers depends upon the size and shape of the space served plus the volume of air to move. The location depends upon the ceiling layout, the thermostat location and the type of ceiling system. Do you match return registers with supply registers to avoid pressurization or depressurization? Not sure of the question. If you mean are there always at least one return register in a room with supply registers then yes.
6. Do you expect a higher energy use associated with ducted return or plenum return? Higher with ducted. Why? Plenums have lower pressure drops.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Yes. Why? Plenums perform very poorly in air distribution so stagnant air is common. Plenums often cause excess infiltration at the exterior boundary and draw in hot moist air from the outside.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? Yes. If so, how? Some return registers must be located low on the side wall.
9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Not duct leakage as much as plenum leakage. Since plenums leak a lot, the consideration is to make sure the architect details the plenum boundaries to be air tight.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? SMACNA duct leakage testing. Specified to be from 1% to 3% of total air flow.
11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Yes. For sound and for thermal. Supplies insulated on the outside and returns on the inside.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? Don’t insulate the plenum, only rely on the perimeter wall insulation and the roof deck insulation. Yes.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? No expectations. Only try to impress upon the architect to seal the perimeter for both air and moisture.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? No.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Use SMACNA seal classes. No.
16. Would you be willing to participate in a future survey regarding return air systems? Sure.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. Plenum returns are now prohibited in all health care occupancies.

Designer 9

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? I prefer plenum return over ducted return in all cases. However, some Owners require ducted return. In these cases, I will provide a ducted return system.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? I have had several projects with no ceiling or partial ceilings where the ductwork is exposed. In these cases, the Architect was looking for a certain aesthetic look.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? The cost for ducted return is definitely higher, but I do not have a guess as to $/CFM.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? I typically use 24 x 24 egg crate grilles and place at least one in each space with a supply diffuser(s). I do not match one for one as the capacity of a 24 x 24 egg crate grille is many times higher than the supply diffusers I use.
6. Do you expect a higher energy use associated with ducted return or plenum return? Why? I would expect that ducted return systems have a slightly higher energy cost, but nothing significant.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Properly designed, I wouldn't expect either system to draw more IAQ complaints or have more moisture controls problems than the other.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Rooms with airborne chemical or

biological releases are typically exhausted. Most codes specifically prohibit return air for spaces with these concerns.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? I know that duct leakage exists but do not provide a safety factor in fan or air handling system calculations for it. I have plenty of additional safety factors in my calculations that make up for leakage.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? I specify that all ductwork shall be sealed. I also specify leakage testing in accordance with SMACNA (Class 12 for 2" static and smaller, Class 6 for 3-6" static).
11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? I insulate only supply ductwork with external fiberglass blanket insulation. I do not use lined duct.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? I rely on the architect to insulate the plenum. This is typically accomplished with roof insulation.
13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Using CFM offset (outside air intake vs. exhaust), I positively pressurize the building to the tune of approximately 500-1000 CFM per floor. I rely on the Architect for vapor barriers and good envelope construction.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? No.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Typically, all ductwork is galvanized steel with sealed joints regardless of operating pressure. See answer to Item 11.
16. Would you be willing to participate in a future survey regarding return air systems? Yes.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. None.

Designer 10

2. What factors determine whether you use a ducted return or plenum return? Type of project, code requirements, and sensitivity to pressure gradients between spaces. Do you have any say in how deep your plenum space is? Yes, however, there are several factors that go into this decision. Among them, cost of construction, type of project, and whether or not we are trying to tie to an existing building that already has floor-to-floor heights established. Do you have any say in whether or not the

supply ducts and return system is in the conditioned space? Yes, on our projects it would be the exception to run ductwork outside of the conditioned space.

3. Do you ever design exposed ductwork? Yes. Does an architect or owner ever request exposed ductwork? Yes. Are there any reasons for exposed ductwork besides practicality? The aesthetics. For example, some architects want to create a more “exposed” feel for a space. We have been involved in retail, commercial and cultural arts projects that included exposed ductwork.

4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? “Significant” is relative. The cost difference is dependent on several factors, including available space, size of system, and location of primary fans.

5. How do you determine the number and location of return registers in a system with plenum return? Two factors are considered: pressure drop and acoustics. Do you match return registers with supply registers to avoid pressurization or depressurization? If you are asking, “would we have the same quantity or size?”, the answer is usually no. The supply distribution in a room or space is more critical than the return path. For example, a space might have four supply diffusers and only one return air grille. Acoustics, or sound transmission between spaces, is also a necessary consideration. In some return air plenum applications, we might design the return air grille with a short section of ductwork and at least one 90 degree turn to minimize the sound transmission to an adjacent space.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? I would expect a **slightly** higher energy usage with a ducted return system due to an increased system static pressure. However, in the overall scheme of things, I would consider this minor.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? No, not if the system is designed properly. Indoor air quality is a function of the quality of supply air being provided, the air change rate, and the percentage of outside air in relation to total air quantity. Both plenum and non-plenum return systems can address IAQ and moisture control.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? Yes. If so, how? Generally these are “dedicated” systems and are single pass (100% exhaust, 100% outside air systems).

9. Do you consider supply and return duct leakage and plenum leakage during your design? Yes If so, how? First, we specify ductwork to be sealed in compliance with minimum ASHRAE standards for the pressure classification being designed. Secondly, in the selection of HVAC equipment and design of ductwork, we will add a factor (usually in the range of 5% to 10%) to cover system loss due to leakage.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? ASHRAE Standards. As part of duct construction, we require the contractor to test sections of the duct system depending on the pressure classification requirements. Test reports are submitted to the owner’s representative as part of the contractor’s construction requirements.

11. Do you insulate supply and return ducts? Why or why not? All supply ducts are insulated. Generally we do not insulate return duct. In addition to the fact that most state energy codes require this, we need to deliver the supply air temperature to the space. Surface temperature of supply air duct providing cool air (air conditioned) may have a surface temperature below dew point, resulting in condensation. Additionally, there may be acoustical considerations to either insulate or line both supply and return ducts. How do you insulate supply and return ducts? Generally with exterior foil faced fiberglass. Ducts can also be lined with a non-eroding fiberglass of equivalent "R" value.

12. How do you insulate the plenum? Generally, the plenum is within the building envelope and is specified by the architect to meet minimum energy code standards. Do you place the insulation above the ceiling tiles or at the roof deck? Generally at the roof deck. Do you rely on the suspended ceiling tiles to be the primary air barrier? Yes.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? 0.05 to 0.10 inches of water. How is this estimated? Previous experience for the type of construction. If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? None. All heated and air conditioned buildings in the Pacific Northwest would be designed with a vapor barrier on the warm side of the insulation.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? I am not sure I understand your question. Return air plenum spaces are not vented to the outside and depend on the mechanical ventilation system to control moisture. Ceiling cavities outside of the thermal envelope are vented to atmosphere to control and minimize moisture from being trapped in the building construction. These vents are generally sized by the architect and provided by the general contractor.

15. What, if any, duct materials or duct sealing methods do you specify? Generally, all of our ductwork is metal (galvanized sheet metal, aluminum, or stainless steel). On some occasions we have used fiberglass when products in the air stream dictate its use. There are several commercial products available on the market for duct sealing; generally we specify a non-water soluble mastic that is field applied. Do duct material and duct sealing methods change with building type or operating system static pressure? For our type of projects, generally no.

16. Would you be willing to participate in a future survey regarding return air systems? Sure.

17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. Project type and budget are two very important factors in determining if a plenum return is appropriate for a particular project. For example, plenum return systems would not be considered for the majority of our healthcare projects because of concerns for cross-contamination.

Follow up questions

1. Do codes require the use of ducted returns for health care projects, or is the decision left up to the designer?

    Hospitals will:

(1) Meet all the general design elements in this section for patient care and support areas as described in WAC 246-320-535 through 246-320-99902;

(3) Provide heating, ventilation, and cooling including:

(a) A heating and cooling system with capacity to maintain a temperature range in accordance with Table 525-3;

(b) Insulated piping and duct systems;

(c) Air balancing of distribution systems to maintain air changes, ventilation requirements, and pressure relationships meeting requirements in Table 525-3;

(d) An air handling duct system meeting requirements in WAC 246-320-99902(5) with:

(i) Fiberglass-lined ducts, if installed, serving sensitive areas with ninety percent efficiency filters installed downstream of the duct lining;

(ii) Fiberglass-lined ducts, if installed, meeting the erosion test method described in UL Publication #181; and

(iii) Fiberglass-lined ducts, if installed, will not be located downstream of humidification units;

(e) Use of space above ceilings for return plenums only in non-sensitive areas where exhaust and return plenums are allowed with:

(i) Exposed insulation on pipes and ducts meeting requirements of American Society for Testing and Materials C107; and

(ii) Cementitious fire proofing used on structure;

2. You stated that the architect specifies that the plenum meet minimum energy code standards. To which standards are you referring? International Energy Conservation code, 2006 edition, Section 503.2.7 Duct and plenum insulation, and sealing.

503.2.7 Duct and plenum insulation and sealing. All supply and return air ducts and plenums shall be insulated with a minimum of R-5 insulation when located in unconditioned spaces and with a minimum of R-8 insulation when located outside the building. When located within a building envelope assembly, the duct or plenum shall be separated from the building exterior or unconditioned or exempt spaces by a minimum of R-8 insulation.

Exceptions:

1. When located within equipment.
2. When the design temperature difference between the interior and exterior of the duct or plenum does not exceed 15°F (8°C).

3. For which pressure classifications do you specify leakage testing? The following is from our master specification:

DUCT LEAKAGE TESTING:

Ductwork of 2.00 Inch w.g. or Less:

All visible and audible leaks perceptible to Owner's Representative shall be sealed.

Ductwork Over 2.00 Inch w.g.:

Testing Requirements: Upon completion of installation and prior to balancing, insulating, and acceptance, subject system to leakage testing as indicated in SMACNA – HVAC Air Duct Leakage Test Manual and based on the following requirements:

Test pressure (P_T): 3.0, 4.0, 6.0, 10.0 w.g.

Duct Construction Pressure Class (P_C): 3.0, 4.0, 6.0, 10.0 w.g.

Leakage Class (C_L): 3, 6, 12, 24.

Test pressure and duct construction pressure class are the same as duct pressure-velocity classification; i.e. 4.0. Leakage class is found in Table 4-1 of HVAC Air Duct Leakage Test manual. 6 is leakage class for 4.0 inches rectangular metal ductwork and 3 is leakage class for 4.0 inches round metal ductwork.

Maximum Leakage Allowed: (As calculated by the following formula from HVAC Air Duct Leakage Test Manual: F = CL x PT 0.65, where F is leakage rate in cfm per 100 sq.ft. of duct surface.)

Test Report: Upon completion of test, Contractor to submit Air Leakage Test Summary Report (see sample at end of this section) for Engineer's review. Orifice tube data entries may be eliminated if a different type of test apparatus is used. In such case, record type of meter on test report.

Testing Agenda: Submit a testing agenda which describes test method and sequence in which various areas of ductwork shall be tested (i.e., all at once or 1 floor at a time). Tests shall be performed on as large a section of duct system as practical.

Leak Testing: Smoke bombs shall not be used to locate leaks. Soap solution shall be used on exterior of duct to locate leaks. Leaks, which do not form bubbles, but rather displace solution, shall be considered major and shall be sealed. In addition, all audible leaks perceptible to Owner's Representative shall be sealed.

Fume Exhaust Ductwork:

Fume exhaust duct leakage shall not exceed 0.1 cfm/100 sq.ft. of duct surfaces at 6.00 inch w.g.

Designer 11

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? To determine if a return air plenum is used there are three primary items that are considered. 1. What is the building type from an occupancy and use standpoint? For example a hospital with surgery suites or a lab clean room will each have specific design criteria that a strip mall would not have. 2. How much space is available in the ceiling plenum and what the building construction is? Obviously if you do not have space to cross ductwork it is difficult to provide a ducted return air system. Similarly there are building materials such as wood that prohibit the use of a plenum design. 3. Cost is also a determining factor since the design must be within the project budget and a plenum design is less expensive than a ducted design. Yes, on each project we discuss the plenum depth and the location of the duct. Plenum depth is often reduced to minimize the building height and thus the overall cost of the building.

3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? The largest percentage of projects we design have concealed ductwork. However there are some specific project types where exposed ductwork is common. (Natatoriums; Exhibition Halls; Lofts; etc.) I would say that practicality is rarely the determining factor for exposed ductwork. Most commonly it is the aesthetic of the space and interior design concept that will determine if exposed ductwork is an acceptable choice. For example I developed the design concept for the first six Chipotle Restaurants and part of the "look" and design concept was to make the duct exposed and be an active part of the aesthetics.

4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Yes, however the cost will vary by building type. Buildings with many individual zones will have a higher density of return air duct and thus a higher cost.

5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? The number of individual zones will affect the number of return air devices. Since each zone will need some method of return. Within each zone the number of devices is based on the size and capacity of each return air device being used. The larger the capacity of each device the fewer the quantity needed.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Lower fan energy should result from a plenum system design since there is less static pressure to overcome and the resulting fan HP should be lower. The other energy factor is the possible loss through the plenum construction to the exterior. If the exterior wall construction is fairly tight and well insulated the losses are not significantly more than a ducted system. Unless the plenum height is extremely large and there is in turn a substantial amount of additional wall area associated with the plenum height.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? There definitely can be problems with plenum return if the building envelope is not designed properly. It is important to remember that the plenum return is not the source of the problem it simply compounds an existing problem. The key is to have an envelope designed properly to avoid moisture infiltration and the potential for moisture related contaminants such as mold. We can aid in this practice by designing our systems to slightly pressurize the building so that they exfiltrate rather than have infiltration issues.

8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Yes, I would say that this would push us to use a ducted system to minimize the potential areas for induction of the contaminant into the system. It will also allow for easier use of sensors for detection of dangerous constituents in the air stream since they can be mounted in main ducts directly in the air stream with no need to monitor the larger plenum.

9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Yes, we have leakage test requirements in our specification that must be performed to ensure the integrity of the system. The Testing and Balancing contractor must seal and pressurize sections of duct to ensure that the meet the leakage criteria. If they fail they must be re-sealed and re-tested until they meet the criteria. This is used on larger, more complex systems and usually not on the simple single zone systems.

10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Leakage tests are performed during construction by the Testing and Balancing contractor according to ASHRAE / IESNA 90.1 – 2004. The tests are often observed by an owner's representative or the engineer of record.

11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Yes, supply and return systems are insulated externally if they are not provided with internal acoustical liner. All dedicated outdoor air system supply ductwork is insulated (no liner allowed). All ductwork that is exposed on a roof or located in an attic is insulated. The insulation is used to avoid the loss or gain in temperature from the plenum or surrounding ambient conditions. It saves energy and on the supply side ensures delivery of air at the temperature that is required for conditioning of the space.

12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? In a plenum the exterior walls are insulated and if it is an upper level then the insulation usually occurs at the bottom chord of the roof truss if it is an attic or within the roof assembly if it is a flat roof construction. Yes, the ceiling tiles are the primary air barrier.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? We do not design plenums to be at negative pressure relative to the exterior since it will cause problems as mentioned in item 8 above. As far as pressure loss goes if it is a very large open plenum the losses are the return

air grille pressure loss, which is published, and the entrance losses to the ductwork which can be calculated from many reference manuals. IF it is a segregated plenum with many spaces there will be additional factors that need to be included in the pressure loss and will be specific to the type of items the air is passing through.

14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? In general I would say no. This is because of how we design our systems. Since we pre-treat all of our outside air to a space neutral condition for both humidity and temperature it is not a significant source of moisture. Additionally, since we try to exfiltrate in all areas we do not have a significant amount of moisture entering the facility through the skin of the building. That leaves only internal latent gains which in most occupancy groups is a small amount of moisture that can be addressed with the mechanical cooling the system. Most of the occupancies we work with do not require that the moisture be isolated to one area and not be allowed to migrate with the air. There are exceptions such as Natatoriums where we try to contain the moisture and relive part of it to the exterior via exhaust and treat the rest with specialized equipment. Conversely, in Museum Galleries we try not to make the air migrate if each gallery has differing moisture and / or temperature requirements. In this case we keep the space neutral (pressure) and try to contain the moisture with vapor barriers and special systems that can either remove or add moisture as needed.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? SMACNA is the standard that defines the requirements for joint types and seal classes and each are directly related to the operating pressure within the ductwork. We require mastic sealants to be used on all joint of ducts.
16. Would you be willing to participate in a future survey regarding return air systems? Yes.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Follow up questions

1. Do you have approximate numbers or evidence of higher fan HP associated with the use of ducted plenums, or is it your intuition and expectation? It is a calculation that we run. The number will be job specific. For example it is easy to visualize a large central AHU for say a 500,000 sq ft, single story, building with a fully ducted return with as much ductwork on the return as on the supply. Compare that to the space above the ceiling being one large open plenum with only a short piece of duct from the AHU to the plenum. In this case you are comparing hundreds of feet of ductwork and air devices with friction loss to a large open plenum with only friction loss at the air devices and minimal entry losses at the return duct at the AHU. Here the additional static pressure is appreciable resulting in additional HP. Now compare this to a 10,000 sq ft building. The amount of ductwork is less as is the total friction loss and therefore the disparity between ducted and plenum will not be as large as the 500,000 sq ft bldg.
2. Do you have an estimate of the difference in first cost ($/cfm or $/ft^2$) between the use of plenum return and ducted return? Sorry, but this too is job specific. As you can see I do not like to rule-of-thumb things since people tend to use the information

incorrectly. It is completely different from say a hospital to a best buy. You could range anywhere from $3 per sq ft to $10 per sq ft depending on the level of complexity of the system. The more zones the higher the cost will be.

3. When you are sizing return grilles, is there a maximum size grille before you add another return grille to a space? Do you always use the maximum size return grille within a space, or do you distribute the return air requirements to smaller grilles? On many of our projects we tend to be very sensitive to the aesthetics of the space and we select the grilles to blend into the ceiling grid by using 2'x2' grilles and then distributing them evenly to get even airflow. Airflow through each grill is selected to perform at a maximum NC level. However, if you were to take the Best Buy example from before you will rarely see more than one large return location per RTU. Occupancy and space function will have a large effect on the number and size.

Designer 12

2. When you are sizing return grilles, is there a maximum size grille before you add another return grille to a space? Do you always use the maximum size return grille within a space, or do you distribute the return air requirements to smaller grilles? On many of our projects we tend to be very sensitive to the aesthetics of the space and we select the grilles to blend into the ceiling grid by using 2'x2' grilles and then distributing them evenly to get even airflow. Airflow through each grill is selected to perform at a maximum NC level. However, if you were to take the Best Buy example from before you will rarely see more than one large return location per RTU. Occupancy and space function will have a large effect on the number and size.
3. Do you ever design exposed ductwork? Yes. Does an architect or owner ever request exposed ductwork? Yes. Are there any reasons for exposed ductwork besides practicality? It may be an aesthetic preference (e.g. no suspended ceiling system). It may be for fuller accessibility in a high-bay lab area.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Enough so that cost-driven projects don't go ducted unless they are mandated.
5. How do you determine the number and location of return registers in a system with plenum return? Factors include distance, plenum velocity / pressure drop, sound barriers, register noise generated, architectural compatibility with other ceiling components. Do you match return registers with supply registers to avoid pressurization or depressurization? Air balance relationships depend on the project needs.
6. Do you expect a higher energy use associated with ducted return or plenum return? Plenum returns *may* yield a small savings. Why? Lower air pressure drop.

7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? There could be some difference in some climates.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? Yes. If so, how? It would depend on the project and the threats addressed.
9. Do you consider supply and return duct leakage and plenum leakage during your design? Yes, depending on project size and type. If so, how? It may be a percentage of fan flow correlated to the applicable duct testing specification.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? We typically refer to SMACNA duct construction standards according to pressure classification. If so, how? Fan test and adjusting may reveal an issue.
11. Do you insulate supply and return ducts? It depends on their location with respect to conditioned space, concealed space, outdoors. Why or why not? Energy conservation (avoiding an entropy loss) and condensation prevention. How do you insulate supply and return ducts? Most often externally.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? At the deck. Do you rely on the suspended ceiling tiles to be the primary air barrier? Never.
13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? Depends on the project. How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented?
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Typically not. Why or why not? Loss of control of infiltration. If so, how do you size these vents?
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Yes, typically following SMACNA standards.
16. Would you be willing to participate in a future survey regarding return air systems?
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer 13

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Answer: Building operation and applications can determine whether you use a ducted return or plenum return. Same time mechanical engineer involved in discussion about plenum space. Supply duct must be insulated in the conditioned space.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? Answer: Yes, I designed exposed ductwork in industrial and commercial buildings. Same time architect request exposed ductwork. You are correct, no reasons for exposed ductwork besides practicality and mechanical convenience.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Answer: Yes. But remember electrical lights must be plenum rated with proper conduits, and ceiling must be air tight, no leaks.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? Answer: You selecting return registers base on amount of air and return registers performances. You not matching return registers with supply registers.
6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Answer: Yes. More static pressure will be with ducted return.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Answer: No. I did not expect any difference in indoor air quality complaints.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Answer: Using ducted return system.
9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Answer: No. Ductwork must meet ASHRAE and industry standards requirements for leakage.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Answer: SMACNA. Specifications section - 15 direct contractors.
11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Answer: Yes. Our specifications direct contractor base on ASHRAE recommendations to provide insulation.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? Answer: We don’t insulate plenum. Same time we rely on the suspended ceiling tiles to be the primary air barrier.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Answer: We don't estimating ΔP across the plenum.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? Answer: We don't vent plenum spaces to the outside.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? Answer: No. Contractors must meet ASHRAE and SMACNA requirements.
16. Would you be willing to participate in a future survey regarding return air systems? Answer: No. Sorry no time.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Designer 14

2. What factors determine whether you use a ducted return or plenum return? Do you have any say in how deep your plenum space is? Do you have any say in whether or not the supply ducts and return system is in the conditioned space? One significant factor is the cost. Ducted returns cost money but allow for increased air circulation that is a necessity in healthcare, education, and laboratory type projects. The depth of the plenum return is related to the amount of air being drawn back to the system, the depth of steel members above the ceiling, and the amount of mechanical and electrical work planned for installation in the ceiling which leads to the question of whether or not there is raised floor planned for the project. Last but not least, there may be an acoustical concern as well.
3. Do you ever design exposed ductwork? Does an architect or owner ever request exposed ductwork? Are there any reasons for exposed ductwork besides practicality? There is no problem with exposed ductwork and we regularly encounter it in retail applications and gymnasiums.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? Depending on the extent of the ducted return distribution and the size of the system in cfm one would expect a premium in the range of $7.50/cfm to $15.0/cfm. To determine the number exactly one needs the duct layout including duct sizes, duct routing, and the number of return registers.
5. How do you determine the number and location of return registers in a system with plenum return? Do you match return registers with supply registers to avoid pressurization or depressurization? Return registers are generally matched to supply registers on a cfm basis.

6. Do you expect a higher energy use associated with ducted return or plenum return? Why? I think ducted returns will have increased static pressure drop due to ductwork and registers and possibly require larger horsepower return fan motors.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? Ducted return systems provide better indoor air quality due to increased circulation with return registers.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? This is most appropriately responded to by a design engineer but in the post 9/11 world the criteria are always changing.
9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Duct leakage is considered and allowed for in accordance with SMACNA standards for all medium pressure supply ducts. Tests are conducted in the field with results confirmed and documented. Return and exhaust ducts are tested if they are concealed and inaccessible in the same manner.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? Refer to above – SMACNA.
11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Supply ducts are always insulated while return ducts are generally not. Supply ducts are insulated to conserve energy and avoid condensation.
12. How do you insulate the plenum? Do you place the insulation above the ceiling tiles or at the roof deck? Do you rely on the suspended ceiling tiles to be the primary air barrier? Generally ceiling plenum returns are not insulated.
13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Please get this response from an HVAC design engineer.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Why or why not? If so, how do you size these vents? It has not been my experience. I have not encountered a situation where these plenum return spaces are vented.
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure? All design engineers generally reference SMACNA standards for each pressure classification with the added caveat to meet UL and NFPA.
16. Would you be willing to participate in a future survey regarding return air systems? Not at this time.
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems. Refer to above.

Designer 15

2. What factors determine whether you use a ducted return or plenum return? Type of building and client. Research labs, healthcare, etc must be ducted. Do you have any say in how deep your plenum space is? Yes, we negotiate with the architects and structural engineers. Do you have any say in whether or not the supply ducts and return system is in the conditioned space? Yes, we negotiate with the architects and structural engineers.
3. Do you ever design exposed ductwork? Yes Does an architect or owner ever request exposed ductwork? Yes Are there any reasons for exposed ductwork besides practicality? Yes, as and architectural statement/look.
4. Is there a significant difference in first cost ($/cfm) between systems with ducted and plenum returns? sometimes
5. How do you determine the number and location of return registers in a system with plenum return? Based on pressurization, walls that go to deck, control zoning, Do you match return registers with supply registers to avoid pressurization or depressurization? Not all the time. Some positive pressure is a good thing. In large rooms with multiple supply registers there may only be one or two return registers because you could move more air through the return grille.
6. Do you expect a higher energy use associated with ducted return or plenum return? Why? Ducted return. Higher fan energy than the potential heat gain from the plenum. Especially if you're in a high rise building.
7. Do you expect any difference in indoor air quality complaints or moisture control associated with ducted return or plenum return? Why? NO. moisture control is at the cooling coil and the plenum shouldn't impact this. IAQ is based on % OA, air changes per hour, etc. again no impact by plenum.
8. Do you design return systems differently if protection from airborne chemical or biological releases is a concern? If so, how? Yes, these spaces are ducted exhaust systems with HEPA filtration.
9. Do you consider supply and return duct leakage and plenum leakage during your design? If so, how? Yes. Estimate 1-5% for duct leakage based on the building type and function. Lower numbers for healthcare/science facilites. Higher for conference spaces, office bldgs, etc.
10. What standards, if any, do you specify for duct leakage, and is leakage verified after construction? If so, how? See above. We require pressure testing on all ductwork to verify leakage rate in accordance with Specifications or SMACNA.
11. Do you insulate supply and return ducts? Why or why not? How do you insulate supply and return ducts? Yes. Concern of condensation in humid climates and energy code requirements. Insulate with batt or rigid insulation pending on location in building.
12. How do you insulate the plenum? Depends on architecture of building. Do you place the insulation above the ceiling tiles or at the roof deck? I like roof deck. Do you rely on the suspended ceiling tiles to be the primary air barrier? Yes.

13. When using a plenum return system, what is the expected ΔP across the plenum (with respect to outside)? This varies on building type and envelope. Solid vs. glazing. How is this estimated? If the plenum is depressurized with respect to the outside, what, if any façade improvements or water vapor retardation is implemented? Get vapor barrier in the right place in the wall, caulk and seal all the openings. This really is an architectural question.
14. Do you vent plenum spaces to the outside to control vapor diffusion or air transported moisture? Not in Florida/south east. Why or why not? Too humid, moisture migration. If so, how do you size these vents?
15. What, if any, duct materials or duct sealing methods do you specify? Do duct material and duct sealing methods change with building type or operating system static pressure?
16. Would you be willing to participate in a future survey regarding return air systems? sure
17. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Contractor Questions

1. Please provide your name, employer, job title, and city/state below. The responses will be edited for confidentiality.
2. If you are willing to discuss your responses or participate in an expert panel, please provide your email address and/or phone number (optional).
3. Do you consider the difference in first cost between ducted returns and unducted plenum returns when bidding for a project? Do you have an estimate of the difference in first cost in $/cfm or $/ft^2 floor area between ducted returns and unducted plenum returns?
4. As a mechanical contractor, what is your role in constructing a suspended ceiling? Do you install the building envelope and air barrier associated with suspended ceiling? Do your methods of installation and construction depend on whether the HVAC system utilizes a ducted return configuration or unducted plenum return configuration?
5. When constructing a drop down ceiling for a plenum, does the designer/owner/architect specify the materials of the ceiling, or do you choose the construction materials? Do you prefer gypsum board or ceiling acoustical tiles? Why?
6. Does the owner require testing for duct leakage and quality assurance for all types of projects? When quality assurance is required, how is allowable duct leakage specified and what is a typical value for allowable duct leakage? When quality assurance is required, is the ceiling plenum tested for leakage?

7. What measures do you take to ensure that a return air plenum located above a drop down ceiling is as tight as possible?
8. What duct sealing materials and methods do you use? Do you prefabricate and pre-seal your ducts, or do you fabricate and seal your ducts in the field?
9. Please provide any other information you deem important in characterizing ducted return and plenum return systems.

Contractor Responses

Contractor 1

2. Do you consider the difference in first cost between ducted returns and unducted plenum returns when bidding for a project? Do you have an estimate of the difference in first cost in $/cfm or $/ft^2 floor area between ducted returns and unducted plenum returns? Yes, we do this frequently. But, no, there are too many variables for us to consider using parameter costs for this value engineering option. It is easier and less risky to estimate the difference on a project-by-project basis.
3. As a mechanical contractor, what is your role in constructing a suspended ceiling? Do you install the building envelope and air barrier associated with suspended ceiling? No. Do your methods of installation and construction depend on whether the HVAC system utilizes a ducted return configuration or unducted plenum return configuration? N/A
4. When constructing a drop down ceiling for a plenum, does the designer/owner/architect specify the materials of the ceiling, or do you choose the construction materials? Do you prefer gypsum board or ceiling acoustical tiles? Designer/Architect/Owner in most cases. Some are open to contractor suggestions, some are not. Why?
5. Does the owner require testing for duct leakage and quality assurance for all types of projects? No – Usually only on healthcare or pharmaceutical grade projects, unless they are seeking LEED certification. When quality assurance is required, how is allowable duct leakage specified and what is a typical value for allowable duct leakage? Usually in terms of percentage loss. When quality assurance is required, is the ceiling plenum tested for leakage? None that I can remember.
6. What measures do you take to ensure that a return air plenum located above a drop down ceiling is as tight as possible? Visual inspection. If a problem develops, we might start spot measurement of differential pressures.

7. What duct sealing materials and methods do you use? Study the SMACNA standards for answers to this question. Do you prefabricate and pre-seal your ducts, or do you fabricate and seal your ducts in the field? Both. Project-specific.
8. Please provide any other information you deem important in characterizing ducted return and plenum return systems. When comparing one to another you must consider acoustical impacts. Also, by creating an air plenum in the ceiling cavity, PVC piping and other combustibles are not allowed… possibly adding cost.

Facility Operator Questions

1. Please provide your name, employer, job title and city/state below.
2. If you are willing to discuss your responses, please provide your email address and/or phone number (optional).
3. Do you prefer one type of return system over another or do you leave the choice up to the designer?
4. Have you found significant differences in energy use between similar buildings using ducted return or plenum return systems? If so, how do they compare?
5. Do you experience different maintenance issues (e.g., moisture problems or mold growth) and associated costs for ducted return and plenum return systems? If so, have these differences lead you to specify one return system over another?
6. Are there differences in complaints of poor indoor air quality or comfort in your buildings with ducted returns and plenum returns?
7. Is there a difference in building security in the event of a hazardous airborne chemical or biological release associated with ducted return or plenum return systems?
8. Do you require quality assurance from a mechanical designer regarding the construction of your duct system or plenum system? Do you require the system be commissioned after construction and tested for leakage?

Facility Operator Responses

Facility Operator 1

2. Do you prefer one type of return system over another or do you leave the choice up to the designer? The ducted return air system is preferred. The choice of using a return air plenum vs. ducted is probably an issue of cost of both design and construction. The advantages to the customer on noise reduction, control could be substantial depending on the installation. The cost could also be quite significant. The designer needs to hit a budget for both design and construction. If the project is underfunded the designer may not have much of a choice. If the designer is just pumping out the design they may tend toward plenum return just to make it simple.

3. Have you found significant differences in energy use between similar buildings using ducted return or plenum return systems? If so, how do they compare? No I have not found significant difference in energy. But we normally are into large systems that need return fans. When a plenum return is used the pressure loss in the plenum is quite low and directly affects the suction pressure of the fan. Also for small constant volume systems there could be energy differences if the designer could work the system so a return air fan would not be needed. In many cases a return air fan can be avoided in smaller systems, however if the return duct is too long with too large of a pressure drop they will need this. This could be a cost savings for plenum return in smaller constant volume systems.

4. Do you experience different maintenance issues (e.g., moisture problems or mold growth) and associated costs for ducted return and plenum return systems? If so, have these differences lead you to specify one return system over another? This is a little more complex. The return temperature is normally quite high compared to the supply air temperature so I would not expect much problem with mold or moisture problems. There could be minor balancing problems that could result in pressurization issues for select areas of a building with ducted return which have been closed off by dampers with doors closed but I think this is rare.

5. Are there differences in complaints of poor indoor air quality or comfort in your buildings with ducted returns and plenum returns? Again if the system is non-ducted noise could be a problem especially near the mechanical rooms. This could also be a problem with ducted but would probably be less. IAQ could be affected if the return air system with balancing dampers is installed; the occupant closes the damper, closes the door to this room and the supply air is reduced as a result of overpressure of the room. I have had some minor problem like this but mostly minor.

6. Is there a difference in building security in the event of a hazardous airborne chemical or biological release associated with ducted return or plenum return systems? I do not know but to me it would be reasonable to assume that more return air would be routed through the occupied space in a non-ducted plenum system then in a ducted return air system. I would therefore assume that there is somewhat more hazards in the non-ducted than the ducted return air system. I do not think anyone

has validated this. However this is only academic because the time to identify the hazard is probably the most critical part of this type of assessment.

7. Do you require quality assurance from a mechanical designer regarding the construction of your duct system or plenum system? Do you require the system be commissioned after construction and tested for leakage? The mechanical engineer who designs the duct system is generally not involved in the construction of the duct unless there is a problem. The commissioning process does not deal well with duct leakage. Generally this is tested during the duct installation for leakage. We in ___ do have a duct leakage test but that is during the T&B process.

Facility Operator 2

2. Do you prefer one type of return system over another or do you leave the choice up to the designer? No preference unless the design or need for ducted is a must.

3. Have you found significant differences in energy use between similar buildings using ducted return or plenum return systems? If so, how do they compare? No

4. Do you experience different maintenance issues (e.g., moisture problems or mold growth) and associated costs for ducted return and plenum return systems? If so, have these differences lead you to specify one return system over another? No, however we have about 100 buildings with a mixture of different types of equipment.

5. Are there differences in complaints of poor indoor air quality or comfort in your buildings with ducted returns and plenum returns? No they run about the same.

6. Is there a difference in building security in the event of a hazardous airborne chemical or biological release associated with ducted return or plenum return systems? Yes with a ducted and dampers you can isolate with open air plenums you cannot.

7. Do you require quality assurance from a mechanical designer regarding the construction of your duct system or plenum system? Do you require the system be commissioned after construction and tested for leakage? Yes, we have just started this process.

Facility Operator 3

2. Do you prefer one type of return system over another or do you leave the choice up to the designer? We typically leave the choice up to the designer. We have no strong preference for a ducted system over a plenum system. However, if cost and space were not an issue we would probably use ducted systems in all buildings. A ducted system will make air balancing a little easier, and better ensure the air flow in each room.

3. Have you found significant differences in energy use between similar buildings using ducted return or plenum return systems? If so, how do they compare? We have not checked to determine if there is a difference between energy use of ducted versus non-ducted return air system.

4. Do you experience different maintenance issues (e.g., moisture problems or mold growth) and associated costs for ducted return and plenum return systems? If so, have these differences lead you to specify one return system over another? We have not experienced maintenance differences between ducted and non-ducted return air systems. This is another reason we have no strong preference for one system over the other.

5. Are there differences in complaints of poor indoor air quality or comfort in your buildings with ducted returns and plenum returns? We do not have complaints of poor air quality or comfort that can be attributed to ducted or non-ducted return air system. These complaints are due to other reasons.

6. Is there a difference in building security in the event of a hazardous airborne chemical or biological release associated with ducted return or plenum return systems? There certainly could be a difference. A ducted system would reduce the possibility of contaminated air being drawn through an adjacent space on its way back to the air handling unit. However, this would really be a moot point since an air system with return air would eventually distribute the contaminant throughout the entire building (or area served by the air handling unit), unless an economizer/purge cycle could be initiated to clear the spaces.

7. Do you require quality assurance from a mechanical designer regarding the construction of your duct system or plenum system? Do you require the system be commissioned after construction and tested for leakage? The Contractor is the only one that can provide quality assurance regarding the construction of the building systems. The designer really has no control over this aspect of the project, even though the designer can inspect and approve or disapprove the construction. Also, the ductwork is constructed by one Contractor and the ceiling plenum is constructed by a different Contractor (or Contractors). Quality assurance of a plenum system is much more difficult than a ducted return system. We often require commissioning of our systems, especially new ones and/or large ones. Duct systems are usually tested for air leakage, while plenum systems are almost never tested for air leakage.

Facility Operator 4

2. Do you prefer one type of return system over another or do you leave the choice up to the designer? Having been a designer for 20 years from an effort point having a non ducted return is less work (greater profits from a fee standpoint) due to minimum duct calculations, no routing of duct work in the overhead, coordination limited, and cost estimating to list a few. From a preference stand point a ducted return.
3. Have you found significant differences in energy use between similar buildings using ducted return or plenum return systems? If so, how do they compare? It would be very difficult to determine a difference let alone a "significant" difference. One would have to have to similar buildings located near each other and monitor them closely. Fan energy is more than likely slightly reduced in un-ducted systems.
4. Do you experience different maintenance issues (e.g., moisture problems or mold growth) and associated costs for ducted return and plenum return systems? If so, have these differences lead you to specify one return system over another? Being that we are discussing return ducts where temperatures are 70F and above mold growth is unlikely.
5. Are there differences in complaints of poor indoor air quality or comfort in your buildings with ducted returns and plenum returns? Non ducted returns tend to have noise issues near the inlet if not designed correctly due to the large amount of air being pulled from the plenum, this can lead to comfort concerns. I don't know of any of our buildings that have experienced IAQ issues due to being either ducted or non-ducted.
6. Is there a difference in building security in the event of a hazardous airborne chemical or biological release associated with ducted return or plenum return systems? We have no protocol that I am aware of that differentiates between ducted and non-ducted systems.
7. Do you require quality assurance from a mechanical designer regarding the construction of your duct system or plenum system? Do you require the system be commissioned after construction and tested for leakage? Generally the mechanical engineer is not involved in the QA for his design this is a function of the construction contractor. The engineer will respond to RFI's (Request for Information) if his design is found to contain errors or omissions. The duct systems in themselves are not commissioned but the component installed such as VAV boxes, fire and smoke dampers. As for leakage testing they are done in accordance with SMACNA tables. Most of our return air systems are low pressure and would not require pressure testing.