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INDOOR AIRFLOW AND POLLUTANT REMOVAL IN A ROOM WITH FLOOR-BASED TASK VENTILATION: RESULTS OF ADDITIONAL EXPERIMENTS

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ABSTRACT

We have completed a laboratory-based study of the performance of a floor-based task ventilation system designed for use in office buildings. With the task ventilation system, occupants can adjust the flow rate and direction of air supplied to their work space through floor-mounted supply grilles. Air exits the ventilated space through a ceiling-mounted return grille. To study indoor airflow patterns, we measured the age of air at multiple indoor locations using the tracer gas step-up procedure. To study the intra-room transport of tobacco smoke particles, cigarettes were smoked mechanically in one workstation and particle concentrations were measured at multiple indoor locations. Test variables included supply flow rates, temperatures, supply directions, and internal heat loads. Multiple floor supply units were in operation simultaneously. During all tests, the ventilation system supplied 100% outside air. Our major findings are as follows: (1) Deviations from a uniform age of air, and a uniform particle concentration, were generally less than 30 percent. (2) With two floor-supply units operating and supply air directed toward the occupant, the age of air in the breathing zone was about 20 to 40 percent less than the age of air that would occur in the room if the air was perfectly mixed. (3) With two floor-supply units operating, the air appears to travel from the floor to the ceiling in a piston-like flow pattern. (4) With three floor-supply units operating, a two-zone flow pattern, with a piston-like flow in the lower region of the room and mixing in the upper region, was evident at some operating conditions. (5) A strong ($r^2 = 0.81$) correlation was found between the rate of change in the average age of air with height and two factors hypothesized to be determinants of the indoor airflow pattern. (6) Workstations without a cigarette smoking machine and with an operating task ventilation system, were not significantly protected from tobacco smoke in an adjacent workstation.

RESEARCH OBJECTIVES

The primary objectives of the research were to determine the spatial variability in ventilation and pollutant removal efficiency in a room ventilated with multiple floor-based task ventilation modules operating at lower flow rates than in previous tests. More specifically, we desired to compare the rate of ventilation (as indicated by an age of air) at the position of the occupant's breathing height to the rate of ventilation elsewhere in the room; to determine if the system resulted in a characteristic flow pattern such as displacement flow; and to determine the efficiency of removing tobacco smoke particles with a task ventilation system.

INTRODUCTION

We define "task ventilation" as a method of ventilation that provides for individual control of some local air supply parameters such as flow rate, temperature, or direction. We studied the Task Air™ system manufactured by Tate Architectural Products, Inc. This system has occupant-adjustable, floor-level air supply modules, has been installed in all or part of approximately 21 North American buildings [1] and is used extensively in South Africa.

The potential for improved thermal comfort, because occupants can (to some extent) adjust their local thermal environment, is a major impetus for the use of task ventilation. Improved indoor air quality is another potential benefit because the freshest (generally least polluted) air can be supplied more directly to the region around the occupant.

Task ventilation systems that supply cool air near the floor at a relatively low velocity and remove air near the ceiling have the potential to produce an indoor airflow pattern referred to as displacement ventilation. Displacement ventilation often results in two horizontal zones with different airflow patterns within the ventilated room. The lower zone contains cooler air flowing generally upward in a piston-like flow pattern. The flow in this region is not necessarily a perfect (i.e. unidirectional) piston flow. The air in the upper zone within the room is warmer and relatively well mixed. Scandinavian research [2, 3] on displacement ventilation indicates that the transition plane between the lower and upper zones occurs at a height where the total upward flow from warm plumes of air (generated by indoor sources of heat) and natural convection at walls becomes equal to the rate of air supplied by the ventilation system. The flow of air in a rising plume or boundary layer increases with height because of entrainment. Because of their impact on the height of the transition plane, the supply flow rate and the magnitude of thermal loads in the lower region of the room are expected to be parameters that impact the indoor airflow pattern. In some cases of displacement ventilation, the piston-like region extends to the ceiling, i.e., there is no upper well-mixed zone.

Other factors that are expected to impact the indoor air flow pattern, are the supply air velocity and the temperature difference between supply air and room air. Higher supply air velocities result in increased entrainment of air in the supply jets. This increased entrainment promotes mixing of the indoor air, i.e., inhibits perfect unidirectional piston flow. On the other hand, as the supply air becomes progressively cooler than the room air (on average), buoyancy forces become more important. Increased buoyancy forces cause the flow to be more piston-like. The supply velocity and temperature difference are inputs for the calculation of the Archimedes number (defined later) which is the ratio of buoyancy forces to momentum forces of the supply air jets.

In the portion of the room with a piston-like airflow pattern, the age of air (i.e., time elapsed since the air entered the building) will increase linearly in the direction of flow. With displacement flow and a transition plane above the breathing level, the age of air at the breathing level is lower relative to the same room with perfectly mixed air. In general, air with a greater age will contain a higher concentration of indoor-generated air pollutants; consequently, displacement flow can reduce occupant's exposure to indoor generated pollutants.

THE FLOOR-BASED TASK VENTILATION SYSTEM

With the Tate System, air is supplied by a conventional air-handling unit (AHU) to a sub-floor supply plenum maintained at approximately room air pressure. The AHU may supply some recirculated indoor air but, according to the manufacturer, often supplies 100% outside air. The supply plenum is the space beneath a raised access floor, i.e., a system of carpet-covered, removable floor panels supported on a metal framework approximately 30 to 60 cm above the permanent floor. Air supply modules, called task air modules (or TAMs), can be installed in place of any floor panel and easily moved to new positions. A TAM, depicted in Figure 1, contains a fan that draws air from the supply plenum and discharges air into the room through the slots (inclined 40° from vertical) in four plastic grilles each 13 cm in diameter. Using a recessed thumb wheel, the fan speed and, thus, air flow rate can be adjusted between approximately 0.04 m^3/s (lower flow rates were achieved for these tests by reducing the inlet opening) and 0.09 m^3/s, resulting in maximum air supply velocities of 1.9 to 6.1 m/s (or the fan may be turned off). The direction of air supply can be changed by rotating any or all of the four grilles. Occupants cannot control the supply air temperature which, to reduce the potential for cold drafts, is typically about 18 °C or 5 °C higher than the supply temperature of many conventional ceiling-based HVAC systems. The Tate System may include some floor-mounted supply-air modules that are not subject to occupant control but instead are controlled by thermostats and some supply modules may contain electric-resistance heating elements. Air is typically withdrawn from the occupied spaces through ceiling-level return grilles connected to return-air ducts or a return-air plenum located above a suspended ceiling.

Previous papers [4 - 9] provide a brief review of available published information on task ventilation. Recent tests by Bauman *et al.* [4 - 6] report the indoor thermal comfort conditions (velocities and temperatures) resulting from the use of the TAMs. Their recent investigations of thermal comfort [7], complement the research described in this paper and were performed coincident to our research in the same experimental facility.

The operating conditions chosen for tests summarized in this paper were suggested by results from previous tests [6]. Previous tests at relatively high supply-air flow rates and one TAM operating indicated a relatively well-mixed airflow pattern throughout the ventilated space. At relatively low supply-air flow rates and with more than one TAM operating, the previous data indicated significantly enhanced breathing zone ventilation and a displacement flow pattern.

EXPERIMENTAL FACILITY, INSTRUMENTATION AND PROCEDURES

Facility

All experiments were performed in a controlled environment chamber (CEC) with a 5.5 x 5.5 m floor and a 2.5 m high ceiling. The CEC resembles a modern office space and has provisions for a high degree of control over the method of ventilation and indoor thermal environment [10]. Figure 2 illustrates the air flow configuration for the tests, with supply air directed into the sub-floor plenum and delivered to the room via TAMs installed in the access floor. During all of tests, the CEC was subdivided into three workstations by 1.65 m tall partitions, with furnishings typical of those in offices as shown in Figure 3. A duct connected a ceiling-level return grille (located in place of a ceiling tile) to the HVAC system.

The furnished chamber contained sources of heat and air motion typical of real offices including: overhead lights (with a total power of 500 W of which roughly 100 W directly entered the chamber); 75 W task lights in each workstation; and a personal computer containing a small cooling fan and a monitor in each workstation (90 W each). Two workstations were occupied by a seated mannequin. Electric resistance heating elements wrapped around the mannequins released 75 W (a typical rate of release of sensible heat by an office worker). During a few tests, internal loads were increased by combinations of the following: operation of extra task lights; operation of a 200 W radiant heater beneath a desk; operation of mixing fans within the chamber; and operation of particle sampling and counting instrumentation within the chamber.

The CEC's HVAC system provides a separate stream of conditioned air that is directed through a plenum in the two exterior walls and between the inner two window panes called the annular space, see Figures 2 & 3. This system maintained the temperature of the interior window pane at approximately the average indoor temperature. Consequently, the exterior walls and windows were not a source of strong natural-convection airflow, but affected indoor airflow much like interior walls.

Tracer Gas Measurements

The tracer gas step-up procedure [11, 12] was used to study indoor airflow patterns and the spatial variability of ventilation. In this procedure, the supply air was labeled with a tracer gas and the rate of increase of tracer gas concentration at a location indicated how rapidly the indoor air was replaced with "new" air that entered the building since the start of tracer gas injection. During the step-ups, a mixture of 1% sulfur hexafluoride SF_6 was injected at a constant rate into the supply airstream. A peristaltic pump drew the tracer/air mixture from a storage bag and directed the mixture through a flowmeter and tubing and into the supply duct. The tracer injection rate was monitored using rotameters calibrated with a bubble flowmeter and was generally stable within 2%. During the tests, air samples were drawn continuously through copper tubes from six total locations to two gas chromatographs (GCs) equipped with electron capture detectors. Two of these samples originated from within the chamber at a subset of the locations illustrated in Figure 3 and four samples originated within the HVAC system. The GCs were able to analyze a sample from each location at a frequency of once every three minutes. Peristaltic pumps also directed air/tracer samples at a constant rate into 1 liter sample bags. Bag sampling commenced at the start of tracer gas injection and continued until tracer gas concentrations were stable, at which time syringe samples were collected manually from the same locations. The bag samplers collected samples from all of the locations within the chamber depicted in Figure 3. Air samples were collected and analyzed from 17 unique locations within the CEC. Bag and syringe samples were analyzed using the GCs immediately after completion of the tests. Equipment and procedures are similar to those used previously and described by Fisk *et al.* [11, 12].

The GCs were calibrated after each test using thirteen different concentrations of SF_6 from 0 ppb to 180 ppb. Measurements of tracer gas concentrations were generally repeatable within two ppb.

Tobacco Smoke Particle Measurements

The efficiency of removing tobacco smoke particles, and intra-room particle transport, were investigated during some of the tests. A cigarette was smoked by a cigarette-smoking machine located on the desk in workstation number 3 (WS3) and particle concentrations were measured as a function of time during and after the period of smoking at four locations within the CEC (identified in Figure 3 and in Table 3) and also in the supply duct and at the return grille. A factory calibrated optical particle counter (OPC), measured particle number concentrations in 15 size bins ranging from 0.09 to 3.00 microns. Air samples were drawn (at a rate of 5 L/min) to the optical particle counter through lengths of 1.3 cm diameter copper tubing connected to electrically actuated ball valves mounted on a copper manifold. The OPC drew an air sample from this manifold at a rate of 3 ml/min.

TEST CONDITIONS

Table 1 provides test conditions and some ratios of average ages of air. The tests are sorted by number of TAMs operating, then by overall flow rate. Test 89 is separated because the air supply directions were different than during all other tests. The well mixed test (85W) is also separated from the other tests.

TAMs were installed in each the three workstations at the locations indicated on Figure 3. During the tests with two TAMs operating, the third TAM was removed and replaced with a solid floor tile. Air supply directions include "toward" and "inward". "Inward" refers to the nozzles pointed inward toward the center of the TAM and also upward at an angle of 50° from the floor. "Toward" refers to air supply from all four supply grilles directed toward the mannequin and at an angle of 50° from the floor. The heated mannequins were always seated in workstations 1 & 3. During test 85W, designed to determine measurement precision by comparing the results of measurements at different locations, the air within the chamber was mixed vigorously with fans.

Table 1. Test conditions and age of air ratios for tests in the CEC. Age of air ratios with an asterisk are considered statistically different from unity from a perspective of measurement precision.

Test	TAM loc.[b]	Grille Dir.[c]	Room Temp(°C)	Supply Temp(°C)	Internal Loads(W/m^2)	Flow rate[d] (m^3/s)	Ratios of Average Ages of Air[e] R/BLV	BLU/BLV	CLA/BLA	KLA/BL
79	1, 3	T	25.7	22.9	17.8	0.027	1.26*	1.21*	1.06	0.89*
84	1, 3	T	28.4	18.9	43.4	0.049	1.18*	1.28*	1.09*	0.86*
83	1, 3	T	28.8	18.5	43.5	0.049	NA	NA	NA	NA
82	1, 3	T	28.2	18.8	38.2	0.050	NA	NA	NA	NA
81	1, 3	T	24.1	18.2	29.2	0.067	1.36*	1.31*	1.24*	0.87*
80	1, 2, 3	T	26.3	21.1	26.7	0.035	1.10	1.18*	1.08*	0.80*
87	1, 2, 3	T	24.7	17.0	23.8	0.067	0.91	1.14*	1.02	0.50*
86	1, 2, 3	T	25.0	17.0	21.2	0.067	0.87*	1.09*	1.00	0.47*
88	1, 2, 3	T	24.6	16.2	33.9	0.082	1.08	0.96	1.28*	0.68*
89	1, 2, 3	I	24.4	15.9	23.5	0.064	1.07	1.36*	1.09*	0.65*
85W[a]	1, 2, 3	T	24.7	19.4	29.5	0.044	1.02	1.03	1.01	0.98

a. W indicates a well-mixed test in which fans vigorously mixed the chamber air.

b. Numbers indicate the workstation in which TAMs were operating.

c. T = supply air directed toward occupant; I = supply air directed inward and toward center of TAM.

d. Total rate of air supply from all TAMs operating.

e. R = age of air in the return duct; BLV = average age of air at the desk at breathing level in the ventilated workstations (with TAM); BLU = average age of air at the breathing level in the unventilated (without TAM) workstation (the average age of air at location 4 in Figure 3 is always included); CLA = average age of air near the ceiling level above all workstations; BLA = average age of air at the breathing level in all workstations; KLA = average age of air at the knee level in all workstations.

DATA ANALYSIS METHODS

Tracer Gas Data

Equations based on age distribution theory [14] are used to calculate the ages of air. Using tracer gas concentrations as a function of time, the following equation was employed

$$A = \int_0^{t_{SS}} \left(1 - \frac{C(t)}{C(t_{SS})}\right) dt \tag{1}$$

where: A is the local age of r; t is the time variable set equal to zero at the start of tracer gas injection; $C(t)$ is the tracer gas concentration at time t, and t_{ss} is the time when concentrations have stabilized. The integral is evaluated numerically. As discussed above, the local age of air at a location can be computed from air samples collected in bags and syringes. Using the tracer gas concentrations in bag and syringe samples, C_{bag} and C_{syr}, respectively, the local age of air was determined using the equation

$$A = t_{SS} \left(1 - \frac{C_{bag}}{C_{syr}}\right) \tag{2}$$

Where C_{bag} is the time-averaged concentrations at a location and C_{syr} is the steady state concentration. We also compute the room-mean age of air, A_{RM}, i.e., the spatial average age of air in the room, based on the equation

$$A_{RM} = \frac{\int_0^{t_{SS}} t\left(1 - \frac{C(t)}{C(t_{SS})}\right) dt}{\int_0^{t_{SS}} \left(1 - \frac{C(t)}{C(t_{SS})}\right) dt} \tag{3}$$

These integrals are evaluated numerically.

To indicate the spatial variability in the age of air, we use various ratios based on the ages. The age of air in the return duct, which equals the nominal time constant (i.e., indoor air volume divided by rate of outside air entry), is often used as a reference age. For example, the age of air in the return duct divided by the age of air at breathing level in the "ventilated" workstation (with operating TAM) is an indicator of the efficiency of the ventilation pattern--higher values (greater than one) of this ratio indicate more efficient airflow patterns with increased ventilation (lower ages) at the location of the occupant. When ratios contain an average of the age measured at several locations, we use volume-weighted averages assuming that each measurement is representative of a volume that extends half way to adjacent measurement points and/or to the edge of the workstation.

Particle Data

To evaluate the particle data collected at the different sample locations, we compute total particle number concentrations (for all size bins) less the "background" particle concentration (i.e., the concentration before the cigarette is smoked and after an extended period of ventilation). To indicate the spatial variability of particle concentration and the efficiency of particle removal, we compare time-average values of these background-corrected particle concentrations measured at different indoor locations. Concentrations are averaged over the time period between the start of smoking and the time when particle concentrations have returned to the background concentration (i.e., over the period of tobacco smoke exposure).

RESULTS

Data Precision

During test 85W, the chamber air was well-mixed which ideally should produce the same local age of air at every point in the chamber. However, due to measurement imprecision and errors (and possible imperfect mixing despite the operation of mixing fans) all of the measured ages of air are not equal. We assume that our measurement of the local age of air at a single point is normally distributed. Thus, for a 95% confidence interval of the measurement of age of air at a single point we use twice the coefficient of variation in the ages of air measured during the test with mixing fans. The resulting coefficient of variation is 4.76% yielding a 95% confidence intervals of $\pm$ 9.5%. Consequently, smaller differences between two ages of air are not considered significant from the measurement-precision perspective. Previous tests with mixing fans yielded similar 95% confidence intervals [6, 15].

The above estimates for the precision of a single point measurement of age of air are not directly applicable for the ratios in Table 1, which are based upon multi-point measurements. Using propagation of error analysis [13], we combined the precision values to determine the estimated precision of each ratio. The ratios marked with an asterisk in Table 1 are significantly different from unity with 95% confidence.

Age of Air Results

Table 1 provides test conditions as well as age-of-air ratios from the tests. A large majority of the ratios are within 0.3 of unity; therefore, in most tests, the deviation from uniform ventilation (well mixed) is at most 30%.

Enhancement of Ventilation at the Breathing Level:
As mentioned above, a potential goal in using task ventilation is to provide air to an occupant's breathing zone that is younger (e.g., generally fresher) than well-mixed air typically resulting from a conventional office ventilation system. A measure of this enhanced ventilation is the ratio of the age of air in the return duct to the average age of air at the breathing height. The age of air in the return duct is the age of air that would result at every location in the room, if the air in the room was perfectly mixed. Thus, enhanced breathing-zone ventilation is indicated by the above-mentioned ratio being significantly greater than 1.00. In Table 1, all tests (79, 81 & 84) with two TAMs operating exhibit significant enhanced breathing zone ventilation. None of the comparable test with three TAMs operating showed this same enhanced breathing zone ventilation. We have no explanation why three operating TAMs do not provide the same or better enhanced breathing zone ventilation than two operating TAMs while operating at the same supply air flow rate per TAM. But this result is consistent with the analysis of the data, given in the next section, regarding the location of the transition layer in displacement flow.

Displacement Flow Pattern:
In previous tests using the TAMs [6], we found indications of displacement flow during tests with low supply flow rates; however, the number of relevant tests was too small for conclusions. The test data in this paper were acquired, in part, to verify whether displacement flow occurs and the extent to which it occurs while using the TAMs at low flow rates.

Two indicators of the extent to which indoor air flows in a displacement pattern, rather than being perfectly mixed, are the height of the transition plane between zones and the rate of change (slope) of age of air with height. Due to practical limitations in the number of age-of-air measurements, it is difficult to determine the height of the transition plane. However, the average slope is readily determined. To calculate slopes, we average all the ages of air measured within workstations at the knee height and average all ages of air at ceiling height. Then differences between those average ages of air is divided by the difference in normalized chamber height, which is the measurement height divided by the distance from the floor to the ceiling.

Table 2 lists the measured slopes. Figures 4 and 5 show the average ages of air in all workstations, normalized by the age of air at the return duct, plotted versus normalized chamber height. The average age of air increases significantly with height in all tests except Test 85W conducted with mixing fans. The shape of the age of air versus height curves provide some information on the height of the transition between zones. The curves on Figure 4 are based on tests with two TAMs operating. In the three tests without operation of mixing fans (Tests 79, 81 and 84), the age increases almost linearly with height. In these tests, there is no evidence of a two-zone flow pattern. One test with three TAMs operating (Test 88 on Figure 5) also yielded a nearly linear curve of the average age of air versus height. However, in other tests with three TAMs operating, the age increases substantially between the knee-level and breathing-level measurement heights and then much more slowly between the breathing level and the ceiling level. This type of curve is evidence of a two-zone flow pattern with the transition plane being below the breathing level; however, the height of the transition plane can not be precisely determined because measurements were made at only three heights.

Table 2. Factors indicative of displacement ventilation.

TEST	Flow rate/Loads[a]	Archimedes No.[b]	Measured slope[c]	Predicted[d] slope	AEE_G[e]	AEE_{BL}[f]
79	6.1E-5	0.13	0.32	0.28	1.37	1.14
80	4.9E-5	0.32	0.43	0.42	1.27	1.05
81	6.3E-5	0.04	0.22	0.20	1.26	1.18
84	4.1E-5	0.13	0.24	0.22	1.16	1.04
86	1.2E-4	0.14	0.48	0.44	1.14	0.85
87	1.1E-4	0.13	0.46	0.40	1.15	0.88
88	9.0E-5	0.09	0.27	0.31	1.14	1.09
89	1.1E-4	0.16	0.35	0.41	1.15	0.98

a. Total loads less 100W for the lights; $m^3/s/W$.

b. Archimedes No = $g\ \Delta T\ L\ /\ T\ v^2$

c. Slope based on difference between average ages of air at ceiling and knee height in all workstations divided by normalized height difference; hr / normalized height

d. Based on a least squares fit;
Predicted Slope = 2.59E3*(Flow rate / Loads) + 0.95*(Archimedes No.); $r^2 = 0.81$

e. Global air exchange effectiveness = Local age of air at Return grille / Room mean age of air

f. Breathing level air exchange effectiveness = Local age of air at Return grille / Average age of air at breathing height

One factor that should influence the degree to which the indoor airflow pattern resembles displacement ventilation, is the ratio of the buoyant forces to the momentum forces in the supply air jets. The Archimedes number, a nondimensional number that quantifies this ratio, is equal to

$$Ar = \frac{g\Delta TL}{Tv^2} \tag{4}$$

where g is the acceleration due to gravity (m/sec^2), ΔT is the temperature difference between the room air and the supply air (°C), L is a characteristic length (m) equal to the diameter of the air supply grilles, T is the room air temperature (°K), and v is the velocity of supply air (m/sec) exiting the TAM. The room air temperature was measured on a wall at a height of about 1.5 meters from the floor. The Archimedes numbers for each test are provided in Table 2. A least squares fit shows a correlation ($r^2 = 0.30$, $p = 0.16$) between the Archimedes number and the slope of the average age of air versus height.

We also determined the correlation ($r^2 = 0.33$, $p = 0.14$) between the slope of the average age of air with height and the ratio of supply flow rate to internal heat loads. The balance between supply flow rate and internal loads is expected to impact the height of the transition plane in displacement flow. The heat load at the ceiling, due to the overhead lights, was not included in the ratio since heat release at ceiling height does not cause warm plumes of air that cause mixing.

The two factors, Archimedes number and the ratio of the supply air flow rate to internal heat load were combined, in a multiple least squares regression fit, to predict the slope of the average age of air versus height, see Figure 6. The goodness of fit ($r^2 = 0.81$, $p = 0.01$) indicates that most of the variance in the slope is explained by the two factors.

Two other values listed in Table 2 that are indicative of the indoor air flow pattern in the room, are the global air exchange effectiveness (AEE_G) and the breathing level air exchange effectiveness (AEE_{BL}) [15]. The first parameter, AEE_G, is defined as the local age of air at the return grille divided by the room-mean age of air. AEE_G is the most commonly used measure of air exchange effectiveness. The range of values for AEE_G are: zero if the supply air entirely short-circuits to the return, one if the room air is perfectly well mixed, and two if the air travels in a perfect piston flow from the floor to the ceiling. AEE_G values in Table 2 are consistent with other indicators that the air flow pattern in the room was an imperfect displacement type flow.

The second parameter, AEE_{BL}, is defined as the local age of air at the return grille divided by the average of the measured ages of air at breathing height. A theoretical maximum value of AEE_{BL} can be determined for pure piston flow, but these values are dependent upon flow rate as well as measurement and ceiling heights, thus each set of test conditions will produce a different maximum. However, as with AEE_G, values greater or less than unity indicate a tendency toward a displacement or a short-circuiting air flow pattern, respectively. Most values (except tests 86, 87, & 89) for AEE_{BL} are greater than unity. All of the values of AEE_{BL} are less than AEE_G which is consistent with a two zone displacement flow pattern, as described in the introduction, with the transition plane below the breathing level. At similar test conditions as those listed in Table 1, Bauman *et al.* [7], made detailed velocity and temperature measurements, at six heights and concluded that the transition plane, was below the breathing level for most test conditions.

<u>Particle Removal Experiments</u>

Table 3 contains the time-average particle number concentrations from all tests with tobacco smoking. During test 85W, the air within the chamber was vigorously mixed with fans. To determine the measurement precision of the particle number concentration data in Table 1, we used the same methodology as for the measurement precision of the age of air. Thus, the measurement precision of the particle number concentration at a single point is ± 8.4%, with 95% confidence.

Table 3. Total (for all size bins) time-average particle number concentrations (particles/cm^3) during the test, minus the background concentrations measured before and long after cigarette smoking.

				LOCATIONS[b]			
TEST	2A	2B	3B	3A	RETURN	SUPPLY	AVG[c]
80	2230	2220	2790	2590	2360	110	2440
82	1540	NA	1410	1590	1430	100	1490
83	1520	1430	1540	1770	1470	40	1550
84	2590	2500	2500	2610	2330	180	2500
85W[a]	2510	2630	2390	2540	2680	220	2550
86	1440	1110	1650	1510	1210	70	1380
87	1620	1420	1610	1790	1120	230	1510
88	1520	1430	1260	1580	1280	130	1420
89	1180	1210	970	1950	1560	90	1370

a. W indicates a well-mixed test in which fans vigorously mixed the chamber air.
b. Locations: 2A = ceiling level, WS2; 2B = breathing level, WS2; 3B = breathing level, WS3; 3A = ceiling level, WS3; RETURN = return grille; SUPPLY = supply duct.
c. AVG = average concentration, excluding concentration in supply duct.

For all tests, excluding test 89, the locally measured particle concentrations were within ± 20% of the average total concentration at all measurement locations (excluding the supply). This result indicates relatively little spatial variability in the time-average particle concentration; however, the number of measurement locations is limited and all measurements within the room were at the breathing level or higher. The data do show some consistent spatial patterns of particle concentrations. The total particle concentration above the workstation with the cigarette smoking machine was always greater than the average total particle concentration of all sample locations. Thus the buoyant tobacco smoke plume had a tendency to rise and not disperse fully before reaching the measurement point above the cigarette. Also, the breathing zone tobacco smoke concentration in WS2 without the smoking machine was nearly always lower, but by a small amount, than the room average particle concentration.

SUMMARY OF MAJOR FINDINGS

Our experiments have shown that the use of this floor-based task ventilation system, with 100% outside air directed toward the occupants, resulted in a modest (20 to 40%) decrease in age of air at the breathing zone, compared to the reference case with perfect mixing. In buildings with substantial recirculation of air by the central air-handing system, the enhancement of ventilation rate at the breathing zone is expected to be smaller. The optimum improvements in breathing zone ventilation with a displacement air flow pattern will be realized when the transition layer is above the breathing height.

The particle smoke concentration data gives similar results to the local age of air data. A slightly lower (about 10%) particle concentration was measured at the breathing level, as compared to the average room concentration, in a workstation with a TAM and without the cigarette smoking machine. As stated above, less improvement will be realized with a HVAC system with substantial recirculation, but more improvement will be realized if the transition layer in a displacement flow pattern is above the breathing height.

An upward displacement air flow pattern results from operation of this task ventilation system with low supply velocities. By multiple linear regression, a good fit was found between the change in of age of air with height (between tests) versus the Archimedes Number of the supply jets and the ratio of total supply flow rate divided by the magnitude of internal heat loads. These same factors have been indicated to be important determinants of the performance of conventional displacement ventilation technologies used primarily in Scandinavia.

During many tests, the age of air at breathing locations (and also above breathing height) is approximately equal to the nominal time constant--the age that would occur throughout the room if the air was perfectly mixed. The piston-like flow, limited to the region near the floor, does not substantially benefit the occupants. In these situations, the commonly-used global air exchange effectiveness can still be significantly above unity, falsely suggesting an indoor air flow pattern superior to complete mixing. As an alternative to the global air exchange effectiveness, we recommend the breathing level air exchange effectiveness or other ratios based on the age of exhaust air and ages of air at breathing locations. These parameters are better indicators of the impact of indoor air flow patterns on pollutant exposure and health.

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Table 1. Test conditions and age of air ratios for tests in the CEC. Age of air ratios with an asterisk are considered statistically different from unity from a perspective of measurement precision.

Table 2. Factors indicative of displacement ventilation.

Table 3. Total (for all size bins) time-average particle number concentrations (particles/cm^3) during the test, minus the background concentrations measured before and long after cigarette smoking.

Figure 1. Cutaway diagram of a task air module (TAM).

Figure 2. Cross section of CEC. Numbered items are: 1 = floor panel; 2 = TAM; 3 = return grille; 4 = suspended ceiling; 5 = subfloor plenum; 6 = ceiling plenum; 7 = light fixture; 8 = annular space between windows; 9 = air supply to subfloor plenum; 10 = air return to HVAC system; 11 = conditioned air supply to annular space; 12 = air return from annular space to HVAC system. The return-air grille is centered between the front and back walls.

Figure 3. Plan view of CEC with workstations denoted WS1, WS2, and WS3. Tracer gas was sampled at points 1 - 4 (0.4 m, 1.1 m and 2.1 m above floor), and at points 5 & 7 (1.1 m above floor), at point 6 (1.1 m and 2.1 m above floor), and at point 8 (2.1 m above floor). Particles were sampled at points 2 and 3 (1.1 m and 2.1 m above floor).

Figure 4. Normalized height versus normalized age of air from tests with TAMs operating in WS1 and WS3.

Figure 5. Normalized height versus normalized age of air from tests with TAMs operating in WS1, WS2 and WS3.

Figure 6. Measured versus predicted slope of age of air versus normalized height. Prediction based upon multiple linear regression with Archimedes number and ratio of supply flow rate to internal heat load as variables. Test numbers shown.

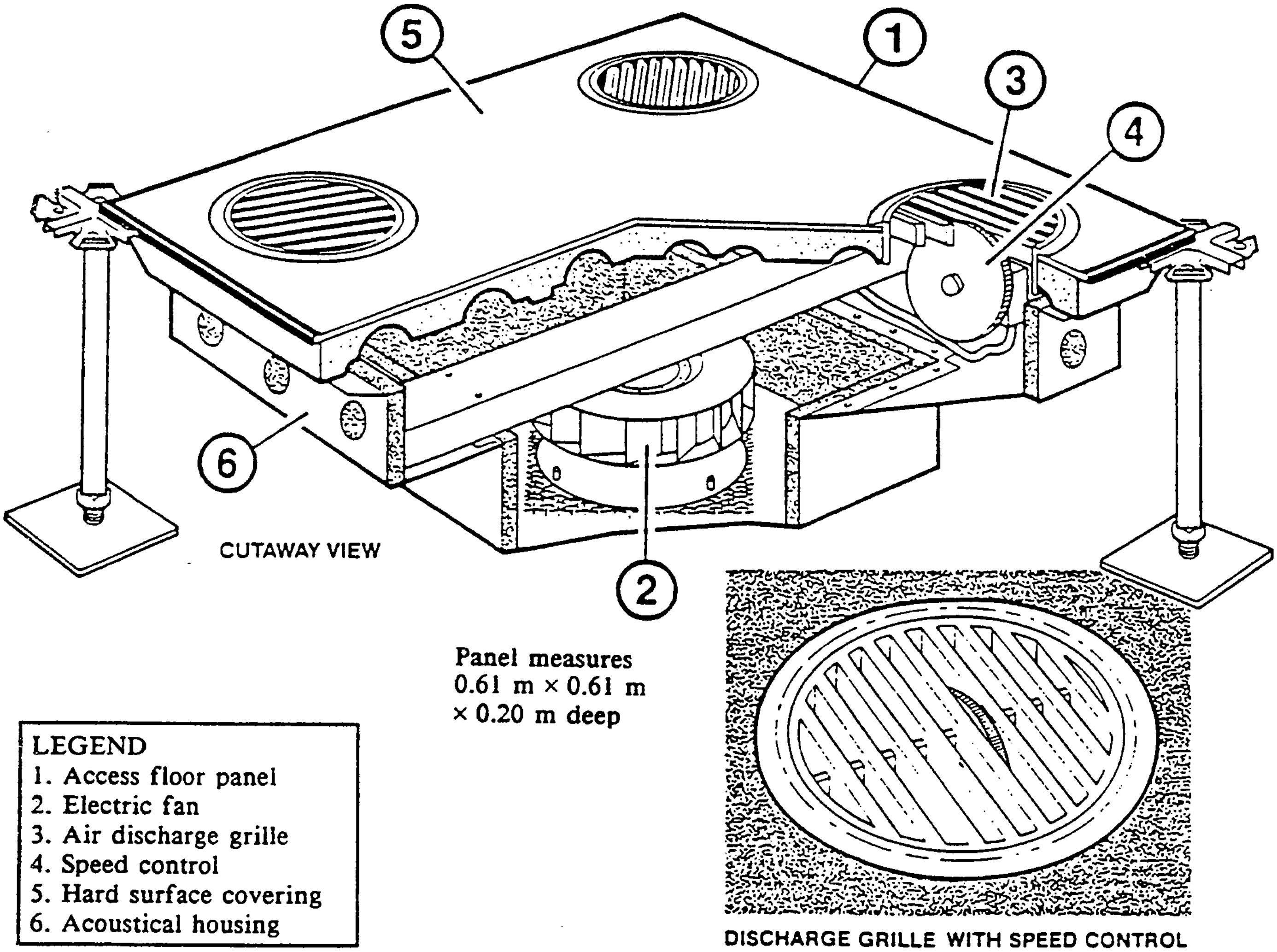
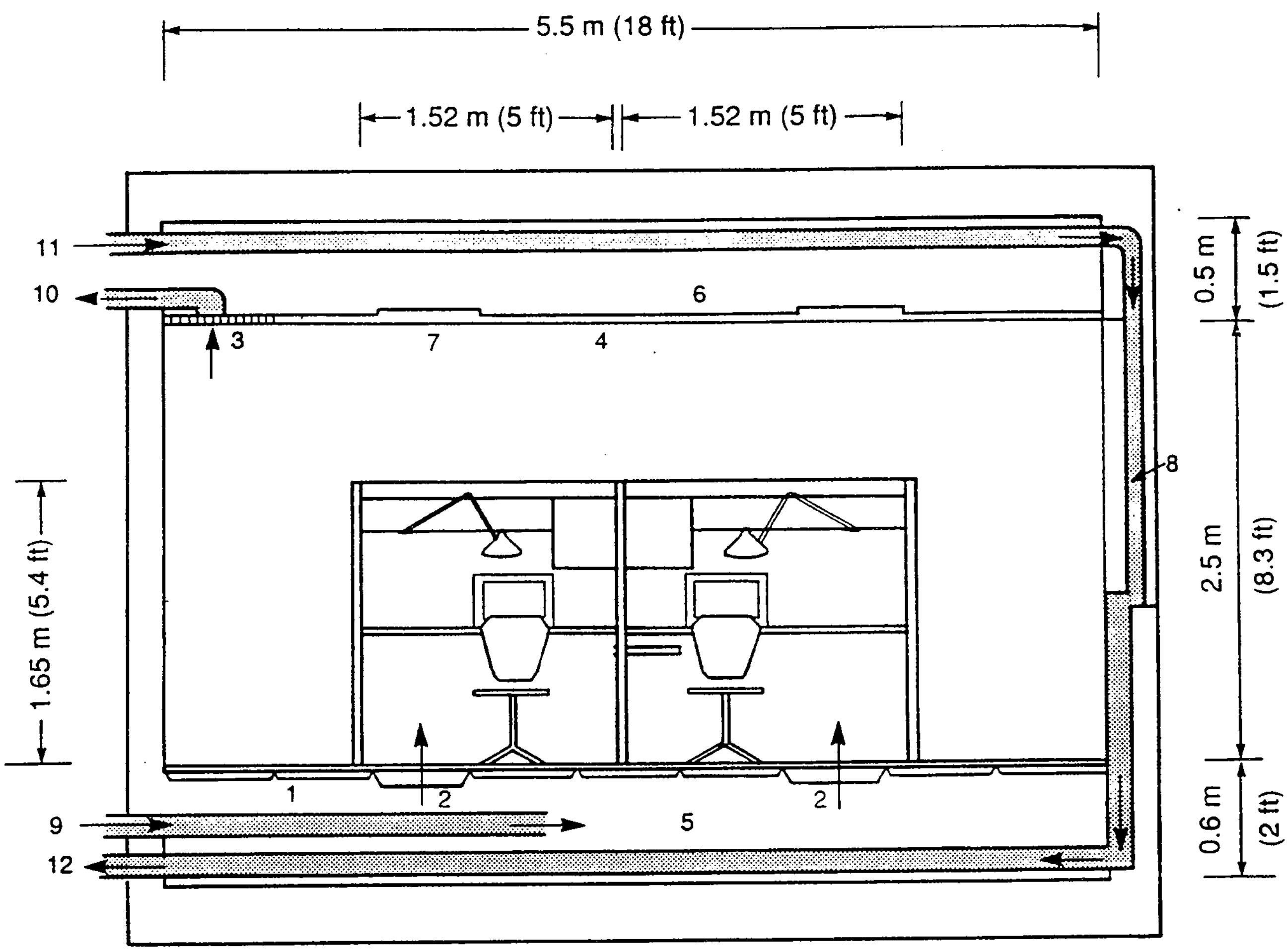


Figure 1. Cutaway diagram of a task air module (TAM).



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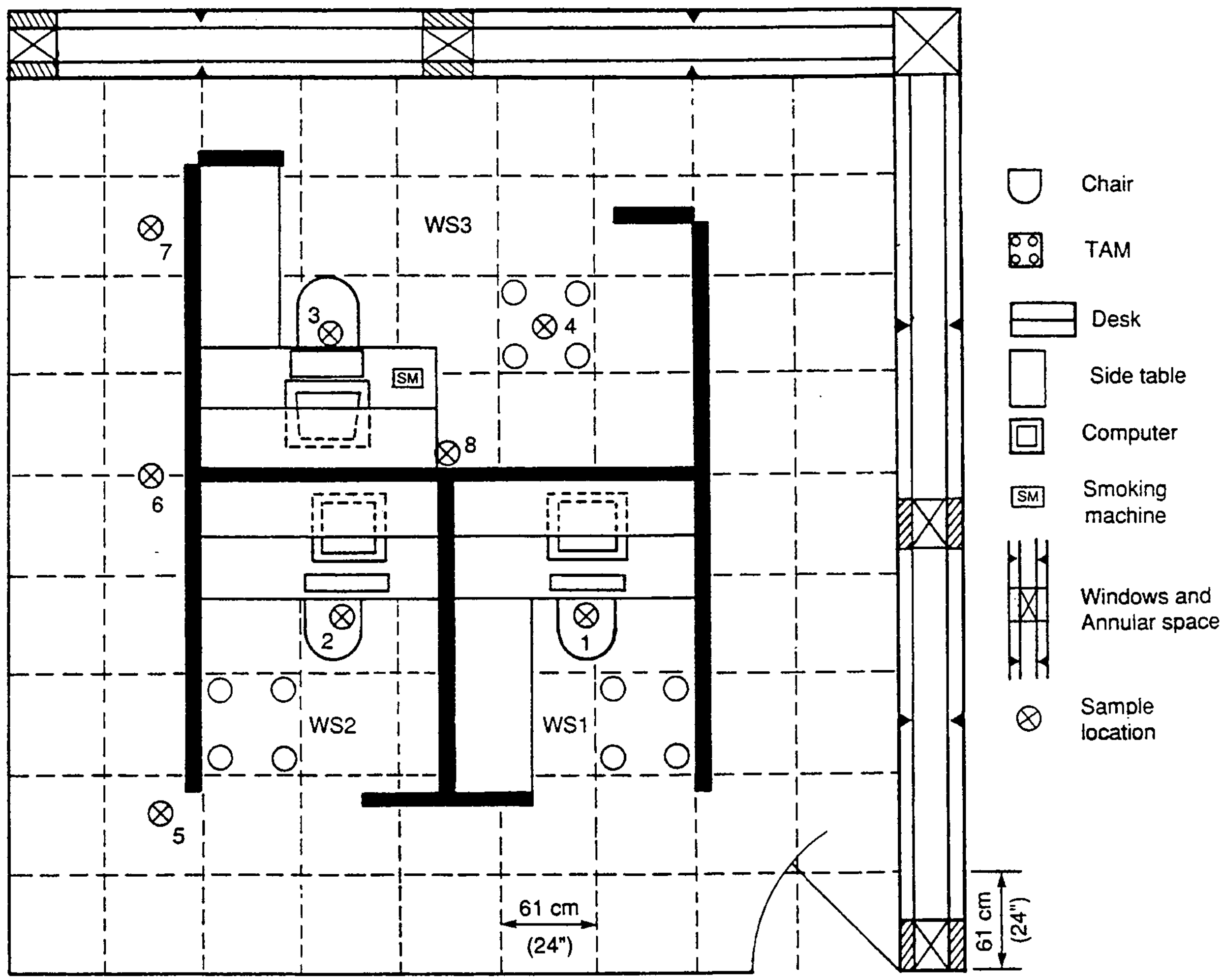


Figure 3. Plan view of CEC with workstations denoted WS1, WS2, and WS3. Tracer gas was sampled at points 1 - 4 (0.4 m, 1.1 m and 2.1 m above floor), and at points 5 & 7 (1.1 m above floor), at point 6 (1.1 m and 2.1 m above floor), and at point 8 (2.1 m above floor). Particles were sampled at points 2 and 3 (1.1 m and 2.1 m above floor).

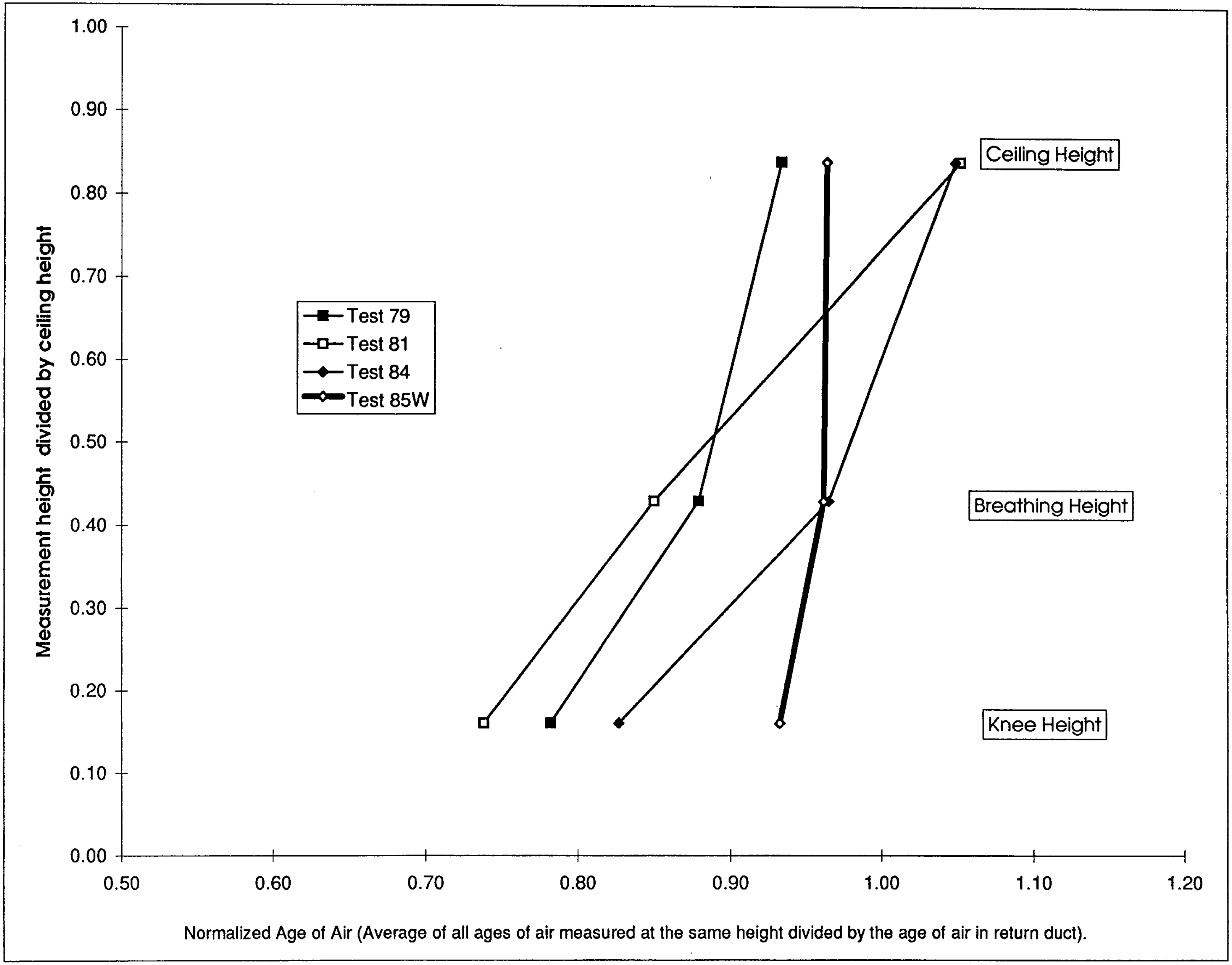


Figure 4. Normalized age of air versus normalized height from tests with TAMs operating in WS1 and WS3.

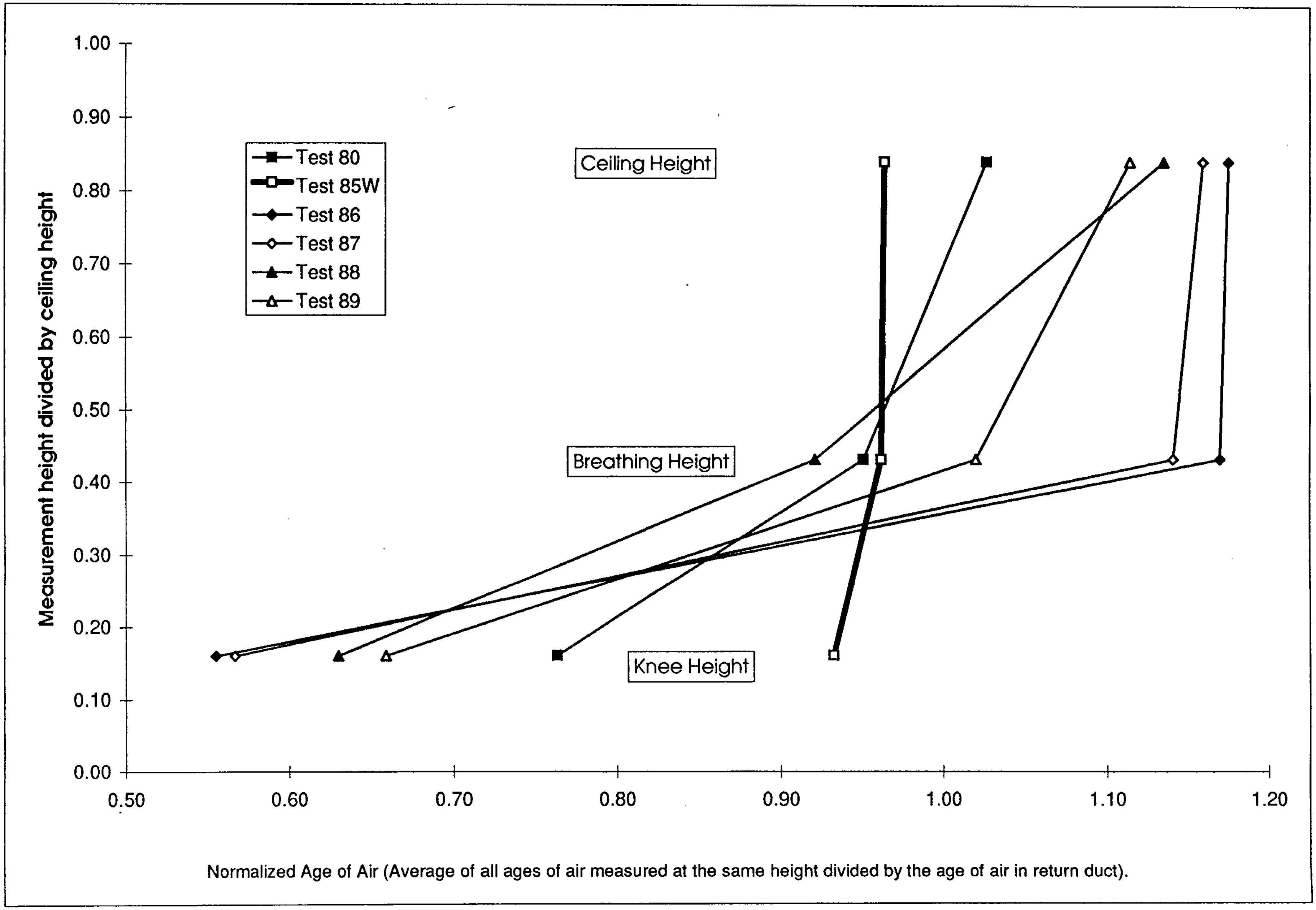
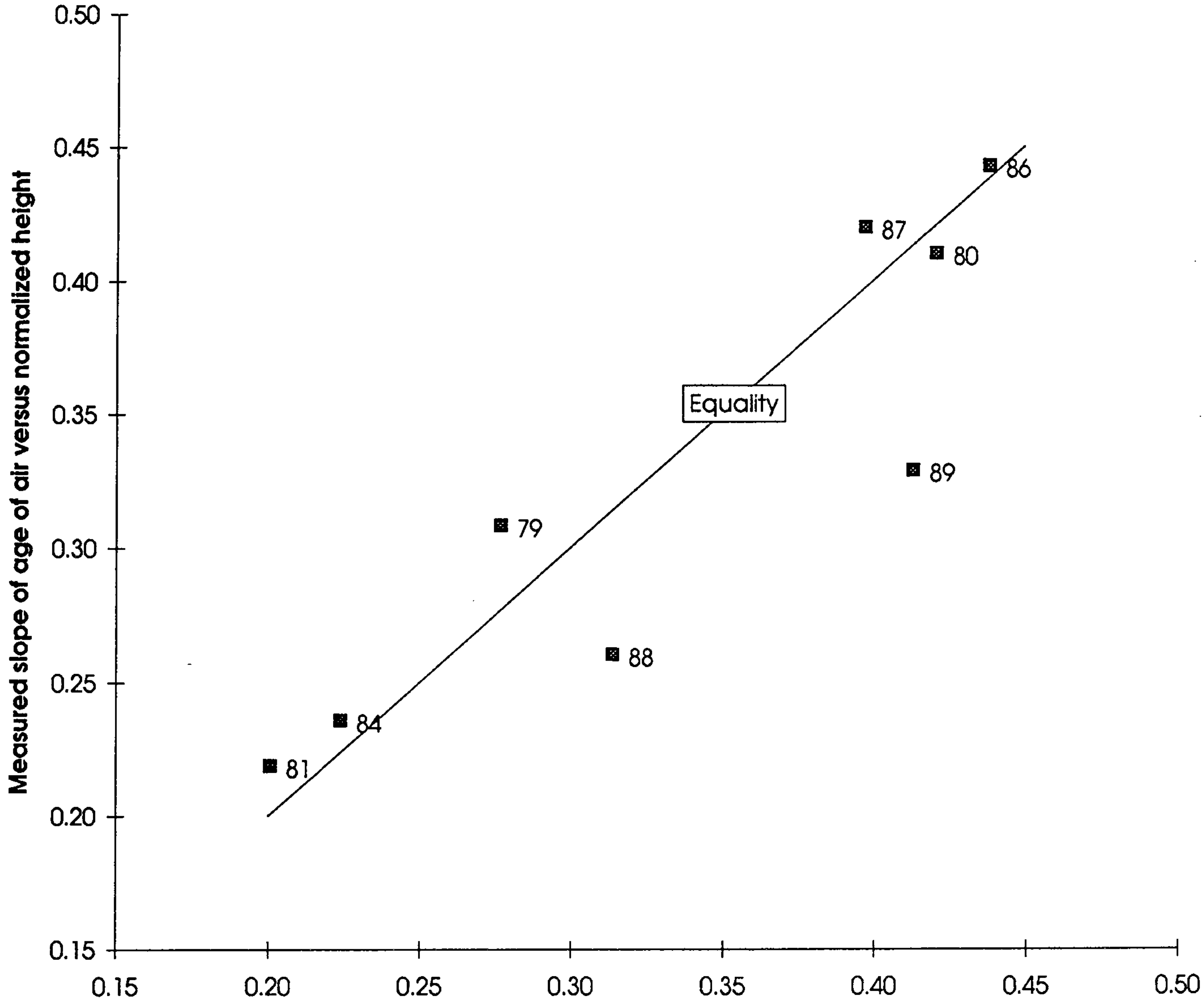


Figure 5. Normalized height versus normalized age of air form tests with TAMs operating in WS1, WS2, and WS3.



Predicted slope = 2.59E3 * FlowRate(m^3/s)/Loads(W) + 0.95 * (Archimedes); $r^2 = 0.81$

Figure 6. Measured versus predicted slope of age of air versus normalized height. Prediction based upon multiple linear regression with Archimedes number and ratio of supply flow rate to internal heat load as variables. Test numbers shown.

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