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VENTILATION EFFICIENCY TESTING: ANALYTICAL METHODS, SCALING THEORY AND EXPERIMENTAL MEASUREMENTS

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PREFACE

The United States and many other countries have made great strides in controlling outdoor air pollution caused by factory and automobile emissions, waste dumps and power plants. Yet, the greatest health risks from airborne pollution are found not in the outdoor atmosphere but in our homes, offices, and public gathering places. In fact, the risks we face from breathing indoor air may be compared, in some instances, to those taken by individuals working with chemicals and radiation in industrial settings. The major difference is that well established systems of monitoring and control are used in industry; whereas, no such systems exist for private residences, and little has been done to monitor and control indoor air quality in commercial buildings.

In a typical house, indoor air quality may be affected by aerosols from cigarette smoke; respirable particles and carbon oxides from heating and cooking appliances (those that burn natural gas, kerosene, oil, and wood); carbon monoxide from automobile exhaust; complex organic chemicals in building materials, furniture, cleaning fluids, and solvents; fibers of asbestos; airborne bacteria, fungi and house mites; and, of major concern in many parts of the United States, radon and its progeny.

Indoor air quality research has been spurred by the increase in energy conservation measures. The initial motivation was to evaluate the effect of reduced air exchange on indoor air quality. Conservation measures (the tightening of existing buildings against conditioned air loss) are often blamed for poor indoor air quality. However, several studies have shown that this is not the case, and that in some instances properly installed weatherization may actually reduce indoor pollution levels. Reduction of heat losses through more efficient (albeit decreased) ventilation does not automatically result in significantly higher levels of indoor air pollution.

The regulation of indoor air quality is no small undertaking. Different building structures (single family homes, apartment complexes, office buildings, hospitals, etc.) require different approaches and answers to their individual indoor pollution problems. The Department of Energy (DOE) through the Office of Buildings and Community Systems has undertaken the task of investigating and evaluating the reasons and possible cures for poor indoor air quality.

Simply stated, the goal of DOE's Indoor Environment Research Program is to develop advanced energy conservation technologies that maintain healthy and comfortable indoor environments. The results of ongoing research have evolved into the following hypotheses:

(1) Air quality in buildings is dominated by sources. Problems are more often related to strong sources (soil gas, construction materials, solvents, furniture materials, etc.) than to deficiences in ventilation.

(2) Air pollution is a buildings problem. Generally, the concentrations of pollutants observed in buildings are comparable to those outdoors; however, when major indoor sources are present, the concentrations indoors are substantially higher. Since people spend 70% to 90% of their time inside buildings, that is where the major portion of their exposure to air pollutants occurs. Because pollution sources and removal processes are often associated with building structure and operation, it follows that air pollution is a buildings problem.

(3) After source control, ventilation is the best control strategy for indoor pollution. Ventilation with outdoor air controls all indoor pollutants in a similar way. Therefore, it is the best single strategy to employ in buildings for pollution control. This assertion does not contradict the first hypothesis. Rather, it acknowledges that we cannot identify and remove all of the pollutant sources in a building. In those cases where a particular source is known to be a problem, it should be removed, if this can be done effectively. Because such information is usually lacking, ventilation remains the best general control strategy.

The research described in this report supports DOE program objectives by providing advanced techniques for evaluating the performance of ventilation systems with respect to control of indoor air pollutants. The objective of SERI's ventilation research is to use these techniques to compare the energy performance and air quality performance of different ventilation systems, so that a high level of air quality can be provided at minimum energy cost.

SUMMARY

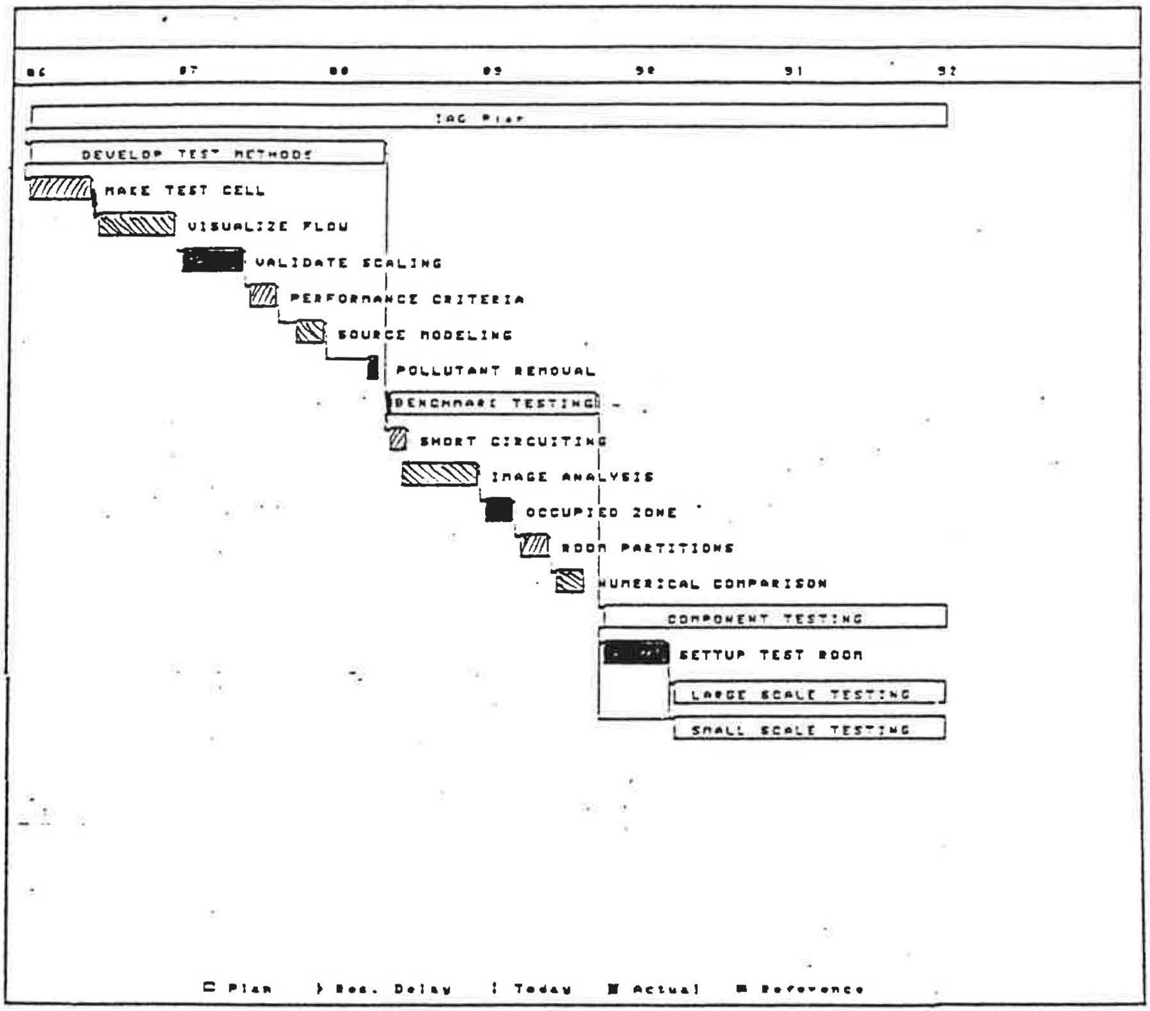
Ventilation systems have traditionally been designed to provide odor control and thermal comfort under the assumption that the air in a building is perfectly mixed. The advent of new ventilation technologies such as variable volume ventilation systems, displacement ventilation systems, and heat recovery systems have brought the usefulness of the perfect mixing assumption under question. In addition, increased concern over the health impacts of indoor air pollutants have led to the need for more accurate methods of determining the impact of ventilation system design on indoor pollutant transport and occupant exposure levels.

A recent revision of the ASHRAE ventilation standard 62-81 has recognized the need for understanding the link between ventilation air distribution and indoor air quality by including an appendix on ventilation efficiency for use in ventilation system design. Ventilation efficiency measures the ability of a ventilation system to deliver ventilation air to the building occupant as well as remove pollutants before they mix with air in the occupied zone. Knowledge of ventilation efficiency is required because local pollutant concentrations and occupant exposure levels in buildings are determined by the local ventilation rate and pollutant source strengths.

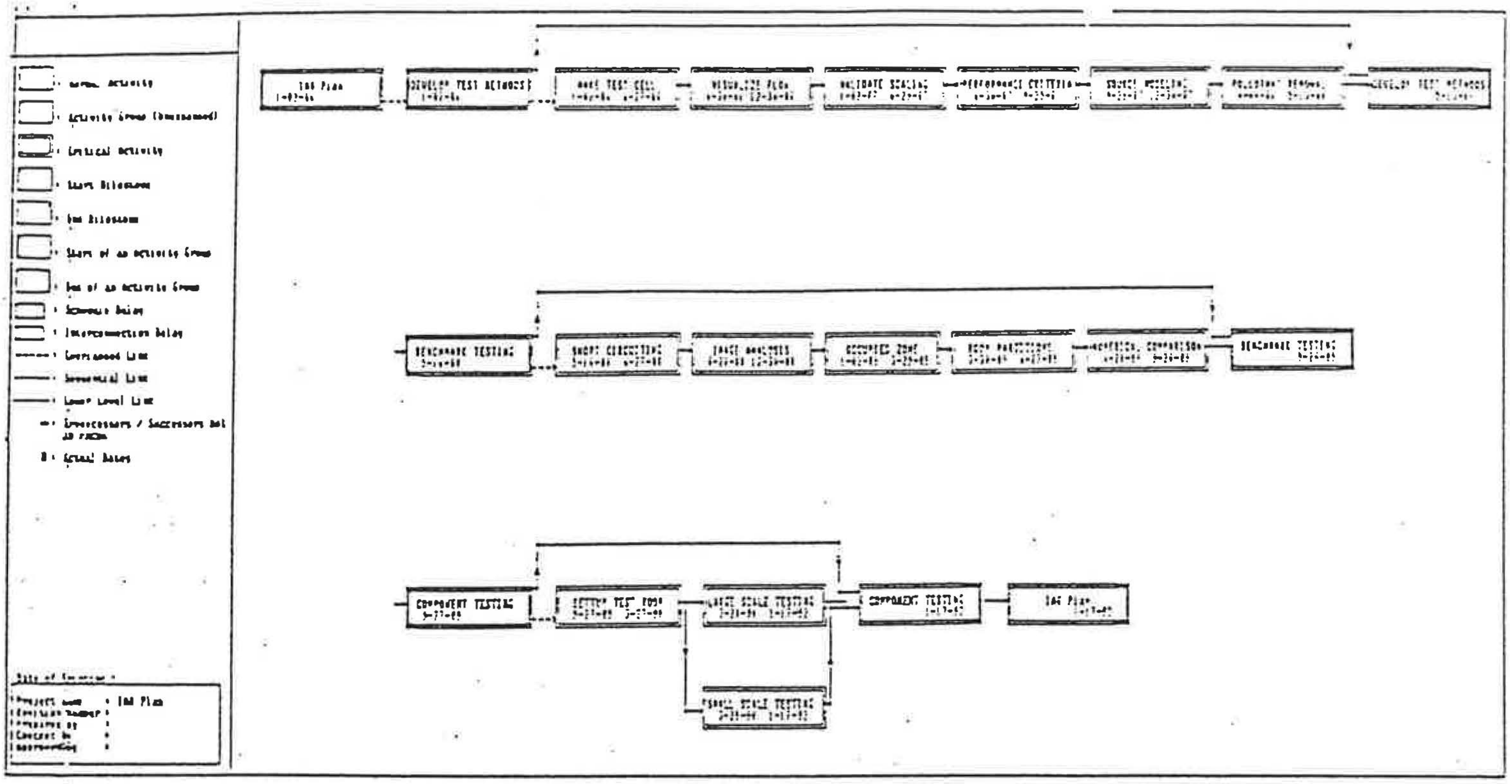
One of the primary problems facing the ventilation system designer is lack of control over the final operation and modification of his design. Building are often remodeled without regard for the impact of the modifications on ventilation system performance. Many indoor air quality problems can be traced to changes in building usage patterns or improper maintainenence. This implies that the sensitivity of performance to the presence or absence of disturbances such as interior room partitions (which may be added at a later date) is as important as performance under initial design conditions. In recognition of this fact, SERI has developed a multiyear testing program aimed at determining ventilation system performance, as seen by the building occupant, over a wide range of operating conditions.

During the initial phase of the research program it was recognized that existing point measurement techniques could not easily provide the resolution that is required to determine performance as a function of room location. As a result, flow visualization techniques and image-based concentration measurement techniques were developed which increase spatial resolution several orders of magnitude over conventional techniques. These advanced measurement techniques are designed to be used in full scale and small scale tests of ventilation system performance involving "benchmark" geometries (simple geometries designed to establish the range of expected performance variations), as well as tests involving real ventilation system components.

This report summarizes the results of benchmark tests designed to determine the effect of flow rate and thermal stratification on short circuiting of ventilation air between supply and return ducts in ceiling-based ventilation systems. The test results indicate that thermal stratification is the single most important parameter tested to date and underscore the need for the extension of system design techniques to include heating as well as cooling applications. The tests were conducted in an open room geometry and did not include the effects of room partitions and furniture. An overview of the SERI ventilation testing research plan is provided below.



SERI VENTILATION TESTING RESEARCH PLAN - GANTT CHART VIEW



SERI VENTILATION TESTING RESEARCH PLAN – PERT CHART VIEW

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NOMENCLATURE

c	concentration (kg/m^3)
Q	ventilation rate (m^3/s)
q	volumetric pollutant source strength (m^3/s)
V	room volume (m^3)

Greek

η_d	displacement efficiency nondimensional, Figure 7
η_r	removal efficiency nondimensional, Figure 8
τ	nominal room volume replacement time, V/Q (s)

Subscripts

o	condition at t=0
in	supply
out	return
s	pollutant source

DETERMINATION OF VENTILATION SYSTEM PERFORMANCE

Increased awareness of the potential health risks associated with indoor air pollutants [1-4] has stimulated interest in improving our understanding of how ventilation air is distributed and how pollutants are transported in buildings. The task of predicting the performance of ventilation systems with respect to control of indoor pollutants is not a simple one. Pollutant transport depends in general upon building geometry, pollutant source characteristics, and thermo/fluid boundary conditions such as flow rate, thermal stratification, duct location, and diffuser characteristics. If the air in a room is well mixed, then then local pollutant concentrations can be predicted based upon knowledge of the room ventilation rate, the pollutant source strength, and the pollutant concentration in the supply air. In situations where the well-mixed assumption does not apply, additional knowledge of the effect of ventilation system and building parameters upon local concentration distributions is required to determine ventilation system performance.

Because it is impractical or impossible to remove all pollutant sources, the building ventilation system must be designed to provide a reliable last line of defense against indoor pollutants. This implies that the ventilation system must provide an adequate balance between the ventilation rate and pollutant sources at all occupied building locations over a broad range of operating conditions. The ventilation system must be designed to account for worst case rather than average conditions because the sensitivity of concentration to flow non-uniformities can produce localized areas with unacceptably high concentration levels, even if an acceptable average building concentration can be achieved at a given ventilation rate. Finally, ventilation systems must be designed to be as robust as possible. Buildings are frequently remodeled without regard for the impact on ventilation performance that will be produced by the modifications or knowledge of the initial use for which the ventilation system was designed.

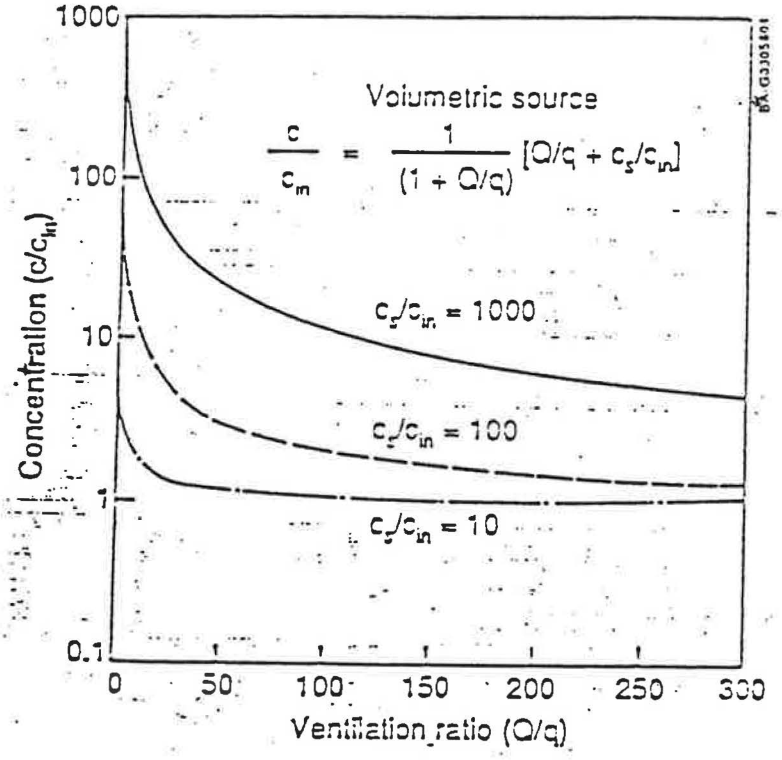


Figure 1 Sensitivity of concentration to local ventilation rate (uniformly distributed source with specified c_s/c_{in}). If local ventilation rates are allowed to produce low ventilation ratios, high pollutant concentrations will result.

A number of different ventilation efficiency measures have been proposed to provide a basis for ventilation system design[5,6]. These definitions can generally be categorized within the three dimensional matrix shown in Figure 2. The x-axis in Figure 2 defines the building subsystem that the definition is applied to, the y-axis defines the physical meaning attached to the definition (ventilation air delivery or pollutant removal), and the z-axis indicates whether the definition is based upon lab measurements, field measurements, or numerical calculations. Lab. measurements and numerical calculation can provide highly detailed information about transport phenomena while field studies provide valuable "in situ" measurements of performance.

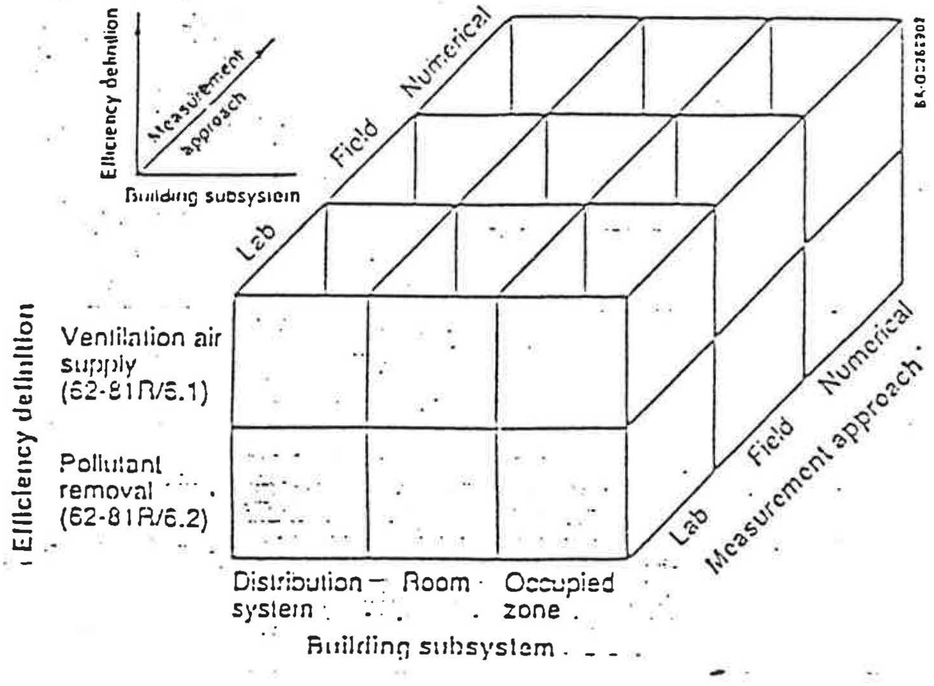


Figure 2 Major types of ventilation efficiency measures.

The matrix shown in Figure 2 demonstrates that ventilation performance is determined by system design as well as room air distribution. For example, the fraction of ventilation air that is delivered to a building occupant depends in general upon two factors:

(1) the fraction of the air delivered to a room that short circuits directly to the return duct,

(2) and the fraction of this short circuited air that is recirculated to the room by the ventilation system via the return air.

Sensitivity to flow short circuiting can be reduced by using large recirculation rates, at the risk of reintroducing pollutants to the building rather than exhausting them directly to the outside. The impact of recirculation rate on per cent delivery of ventilation air is shown in Figure 3. Some caution is required before using Figure 3 as the basis of ventilation system design because large recirculation rates also reduce the ratio of the source to supply concentration ratio (c_s/c_{in}) previously shown in Figure 1. This reduction tends to uniformly elevate the concentration of the pollutant in the building, at the same time that it reduces concentration variations to a smaller range of ventilation ratios (Q/q). Because c_{in} has been increased relative to a system with a low recirculation rate, the margin for error can actually be reduced in systems with large recirculations rates. A small variation in c/c_{in} with high recirculation rates (high c_{in}) has the potential to expose a large number of building occupants to an unacceptably high pollutant concentration. Conversely, a large variation in c/c_{in} may be acceptable in systems with low recirculation rates, because of the increased "headroom" provided by reducing the value of c_{in}. An additional conclusion that can be drawn from our discussion of Figure 1, is that uniform concentration distributions can occur in systems with high recirculation rates, even when room airflow is not well mixed.

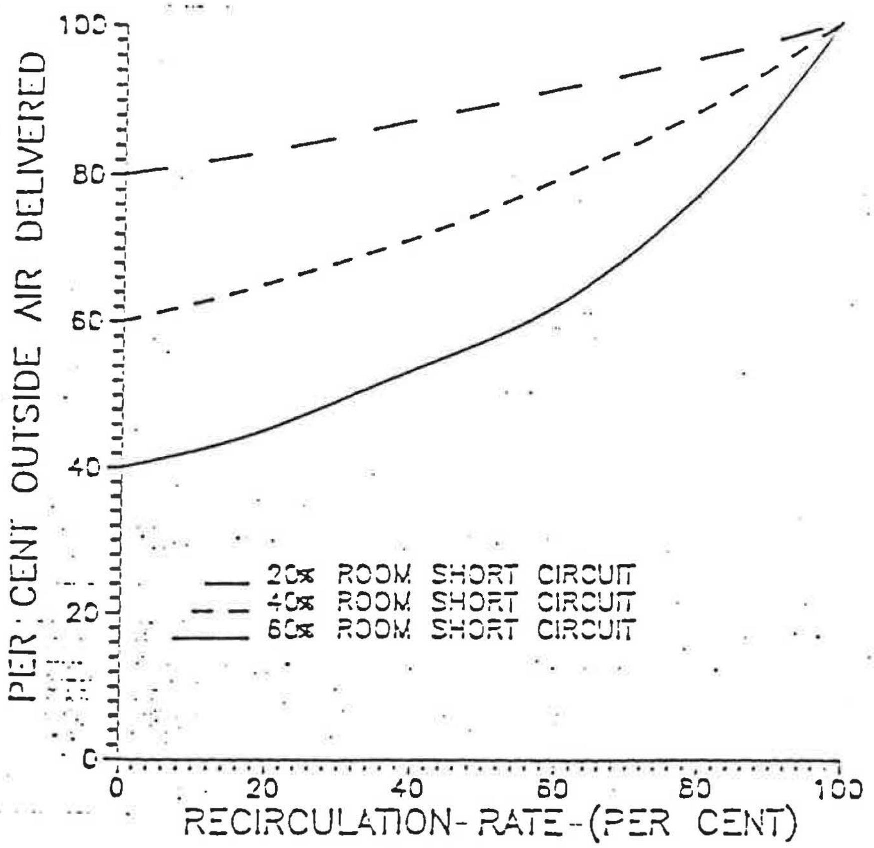


Figure 3 Impact of system recirculation rate on per cent delivery of ventilation air, as a function of room short circuiting level. The assumptions used in the development of this figure are the same as those in references 12-15.

Several different methods of measuring ventilation system performance have been evaluated to determine their usefulness in meeting the objectives of SERI's ventilation testing research program. Age of air methods[7-10] can be used to detect spatial variations in air delivery by comparing the residence time of the air as a function of room location. When normalized with respect to the shortest possible residence time, the spatial average age of room air can be used to define a measure of air exchange efficiency[11].

If the room subvolume of interest can be approximated as being well mixed, then the short circuiting of ventilation air with respect to that subvolume by measuring the effective ventilation rate within that subvolume using tracer decay techniques and comparing this with the nominal ventilation rate.[12-15]. The impact of system recirculation on air delivery can then be calculated using Figure 3.

no vent

The measurement techniques described above are limited to measurement of ventilation air delivery. As shown in Figure 2, room concentrations in the presence of pollutant sources are also a function of the ability of the ventilation system to remove pollutants before they mix with room air. Ventilation systems that selectively remove pollutants will have higher average concentrations in the exhaust than in the room. Systems that are not very efficient at removing pollutants will have lower average concentrations in the exhaust than in the room. To quantify this effect, Rydberg and Kulmar[16] defined removal effectiveness to be the ratio of the concentration in the exhaust to the average room concentration at steady state. This ratio is one for a perfectly mixed system and can range in value from zero to infinity for systems that are less efficient or more efficient than a perfect mixing system. An example of a ventilation strategy that has been designed to selectively remove buoyant pollutants is shown in Figure 4.

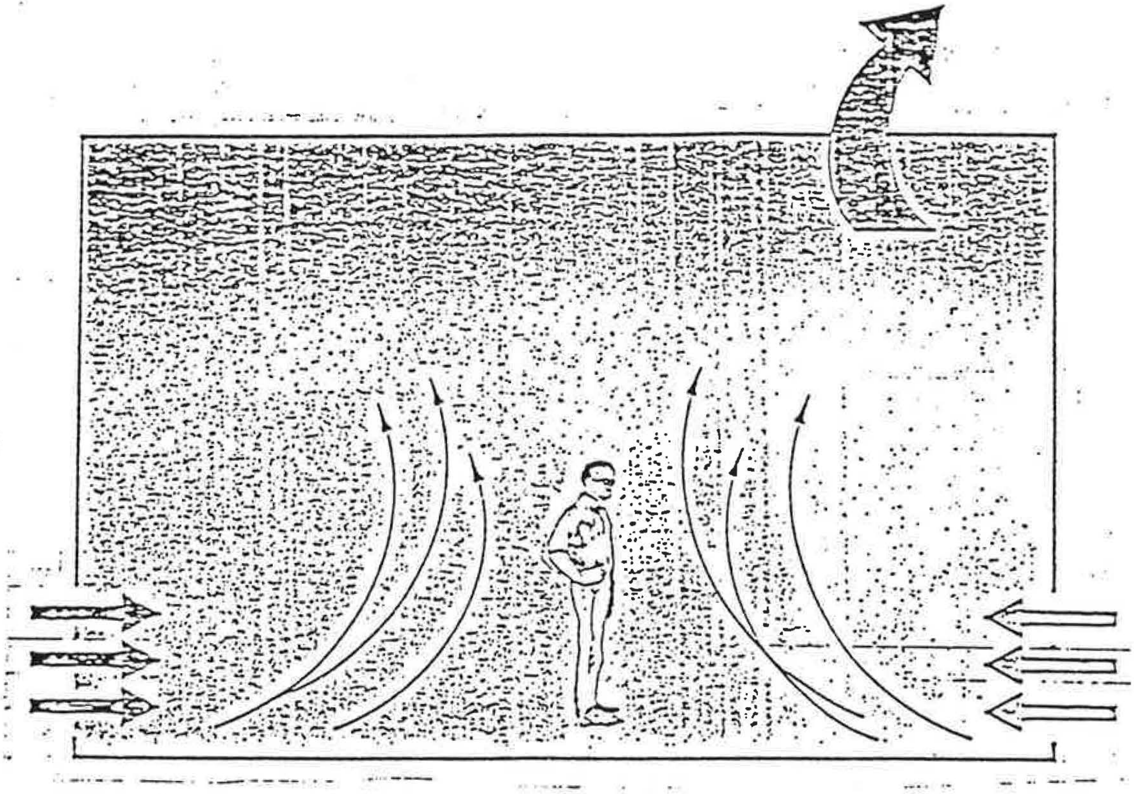
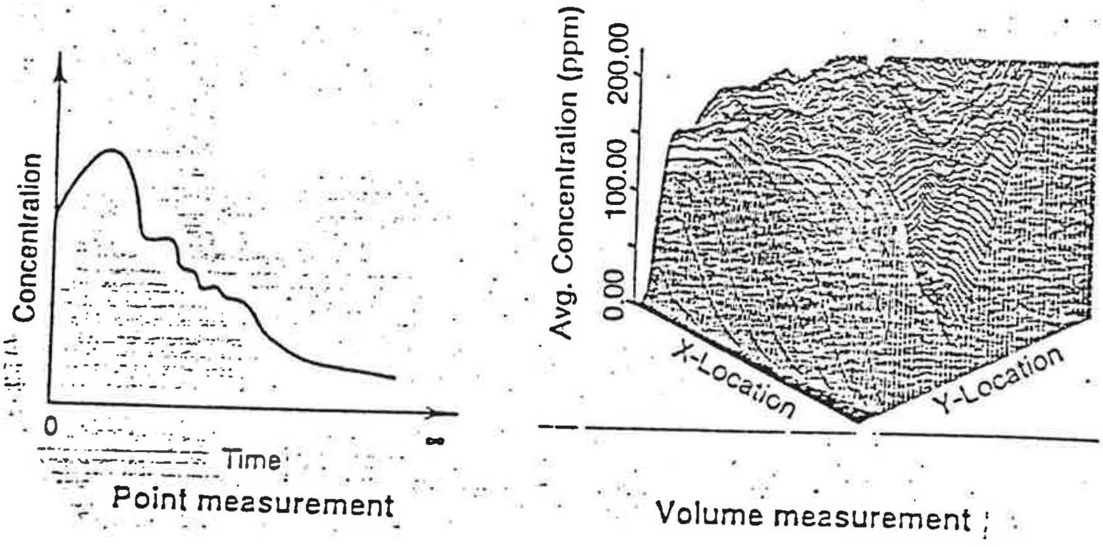


Figure 4 Displacement ventilation systems use thermal stratification to selectively control buoyant pollutant sources.

MEASUREMENTS OF VENTILATION EFFICIENCY BASED UPON CONTROL VOLUME ANALYSIS

The ventilation performance concepts described above involve compromises that are linked in part to the limitations in spatial resolution that can be achieved using conventional point measurement techniques. Rydberg's definition of pollutant removal effectiveness does not provide information about local pollutant concentrations, and requires measurements to be made after steady state conditions have been achieved. Age of air techniques provide a method of detecting flow nonuniformities, but require long time integrals that may be difficult to evaluate[8] and lose physical meaning when interpreted in terms of local ventilation rates[10]. The short circulting analysis developed in references 12-15 provide a powerful method for examining the link between local ventilation rate and system recirculation rate, but do not measure pollutant removal rates.

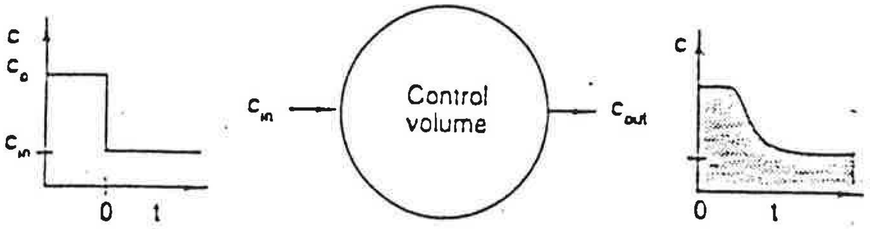
To overcome the limitations in spatial resolution associated with the use of conventional point measurement techniques, SERI researchers have developed flow visualization and digital image analysis concentration measurement techniques that produce spatial resolutions several orders of magnitude larger than conventional approaches. These methods make it possible to accurately determine the link between the ventilation system design and local air quality as seen by the occupant of a building.[17,18] To limit costs during the initial phases of the research project, Initial benchmark tests of simple ventilation systems have been conducted using a unique small scale test cell. The small scale tests use water as the transport fluid. The use of water rather than air in small scale tests has the advantage that velocity scales and length scales can be reduced by the same amount, so that convective time scales remain unscaled (ie, the small scale tests occur in real time). Water tests can be used to study non-isothermal flows, provided that the difference in Prandtl number between air and water is properly accounted for.[19,20] Heavy gases such as Freon can be used to reduce Prandtl number differences, but will incorrectly scale radiant effects.[21] Radiant effects do not have to be considered in water tests because water is opaque to infrared radiation.



Point measurement

Volume measurement

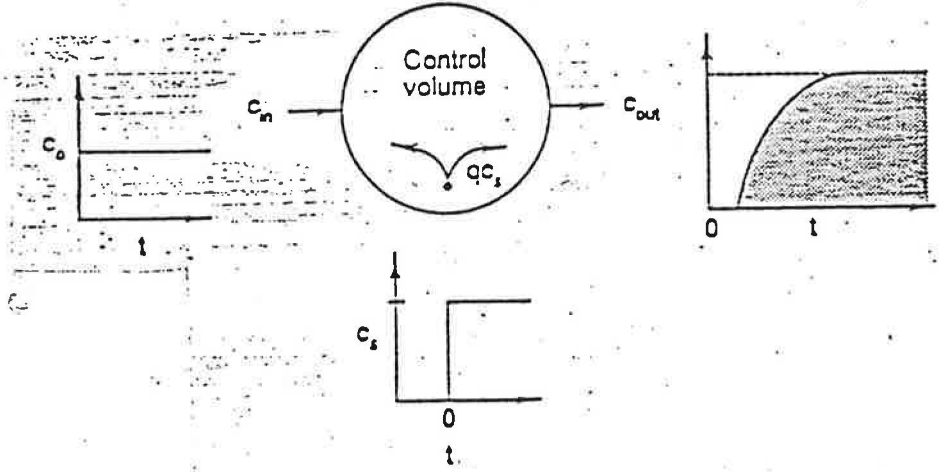
Figure 5 Conventional point measurement techniques cannot provide the spatial resolution required to accurately measure ventilation system performance with respect to room subvolumes



$$\eta_d = \frac{\text{(actual system)}}{\text{(perfect system)}} = 1/\tau \int_0^{\infty} \frac{c_{out} - c_{in}}{c_o - c_{in}}\, dt$$

$$\tau = V/Q$$

Figure 6 Determination of Displacement Efficiency, η_d, Based on Knowledge of Flow and Concentration on Boundaries of Control Volume.



$$\eta_r = \frac{\text{(actual system)}}{\text{(perfect system)}} = 1/t \int_0^{t} \frac{(Q + q)\, c_{out} - c_{in} Q}{\bar{q} c_s}\, dt$$

Figure 7 Determination of Removal Efficiency, η_r, Based on Knowledge of Flow and Concentration on Boundaries of Control Volume.

Two short term measures of ventilation efficiency have been developed to take advantage of the spatial resolution provided by the image analysis system (see Figures 6 and 7). The displacement efficiency, η_d, measures the ability of the ventilation system to deliver ventilation air to a specified control volume, and the removal efficiency, η_r, measures the ability of the ventilation system to remove pollutants before they mix with room air. Both measurements are based upon mass balances on a specified room subvolume and therefore have a direct physical interpretation that can be easily understood and applied by ventilation system designers. The displacement efficiency measures the fraction of room air that is replaced during the time that one room volume is supplied by the ventilation system and the removal efficiency measures the fraction of a specified pollutant source that is removed by the ventilation during the time that one air change is supplied by the ventilation system. (Figures 8 and 9).

These ventilation efficiency measures have been developed so that they can be applied to both full scale and small scale tests. Because the ventilation efficiency and displacement efficiency are based upon mass balances, they both have well defined limits as the elapsed time from the begining of a test approaches infinity. These limiting values provide extremely sensitive calibration points for detection of experimental errors.

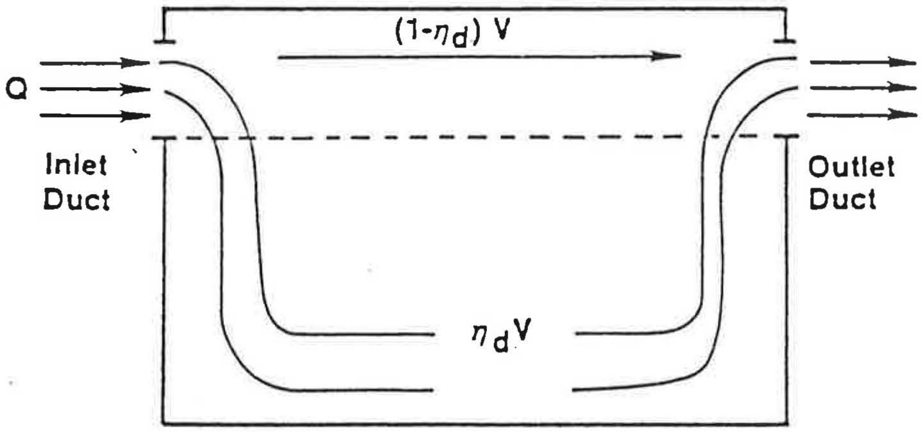


Figure 8 Control volume showing physical meaning of Displacement Efficiency

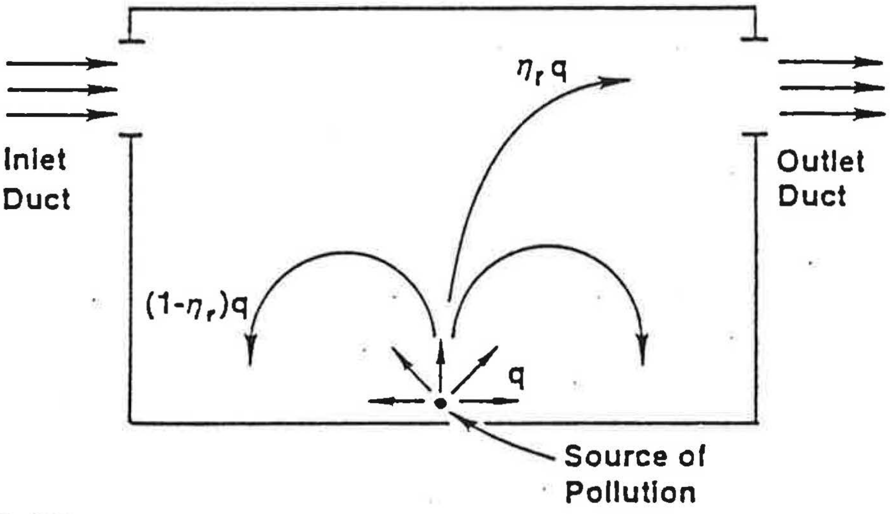


Figure 9 Control volume showing physical meaning of Removal Efficiency

Although the integrals in Figures 6 and 7 look similar to the integrals that are evaluated during age of air calculations, they are in fact fundamentally different. The age of air is essentially a statistical weighting function which can be used to provide a relative measure of the average time before air is replaced at a given point measurement location, based on evaluation of an infinite time integral. Age of air calculations do not provide any information on pollutant removal rates or physical ventilation rates unless the flow is well mixed. The displacement efficiency and removal efficiency measure air delivery and pollutant removal based upon short term mass balances on well defined control volumes (not point locations).

For example, a local value of the displacement efficiency, η'_d, can be calculated based upon knowledge of the local concentration at elapsed time $t=\tau$ after a step change in concentration has been applied to the air which is supplied to a room.

$$\eta'_d = (c-c_o)/(c_{in}-c_o) \text{ at } t=\tau \qquad (1a)$$

$$c=c_o \text{ for } t<0 \qquad (1b)$$

$$c=c_{in} \text{ for } t>0 \qquad (1c)$$

In equation (1a), τ refers to the time scale associated with the overall ventilation rate and volume of the room (not the time scale associated with the local ventilation rate and local volume element) and c refers to the local concentration.

An overall value for η_d can be calculated by averaging the local value η^l_d over the room volume, or by integrating the concentration with respect to time in the exhaust duct as has been previously discussed. A relative measure of displacement efficiency η^{rel}_d can be determined by calculating the ratio of the local displacement efficiency to the room average displacement efficiency. Values of η_d can also be calculated for finite room subvolumes. The displacement efficiency η^{oz}_d is the efficiency obtained by averaging η^l_d over the occupied zone.

If the integral method of calculating η_d is extended to the upper limit $t \to \infty$, it is equivalent to the definition of local age of air divided by τ. The theoretical limiting value of the integral as $t \to \infty$ is 1.0. When η_d measurements are being used in field studies, this limiting value can be used during initial calibration tests to determine the errors associated with unspecified interzonal airflows and infiltration. If these sources of error are too large, they can be corrected for or controlled.

Limiting values of η_d for perfectly mixed and perfect displacement flows are shown in Figures 10 and 11. Real flows include a combination of displacement and mixing, with the displacement fraction being determined primarily by the time of flight between the supply diffuser and exhaust duct (Figure 12).

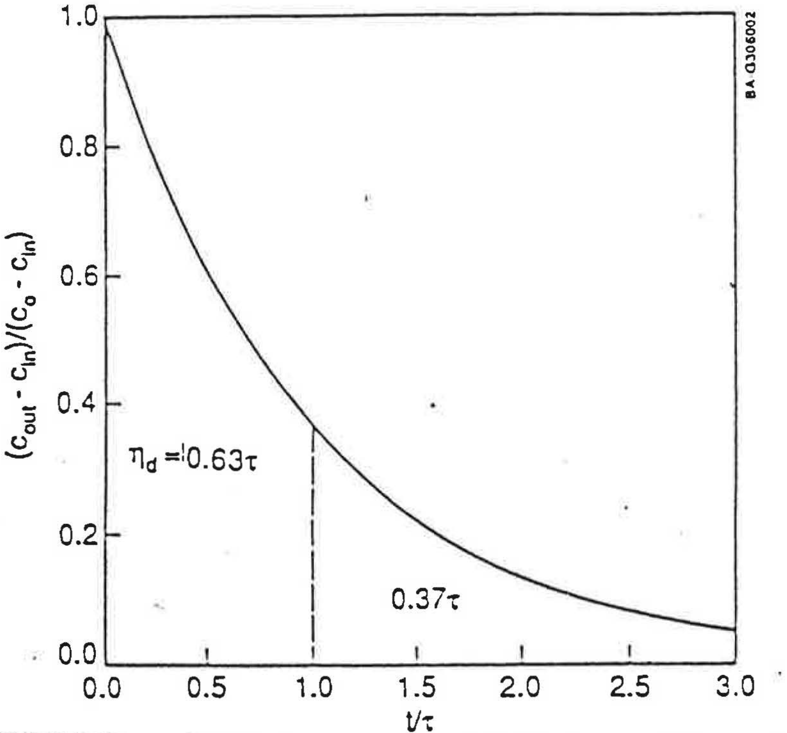


Figure 10 Average η_d for perfectly mixed flow.

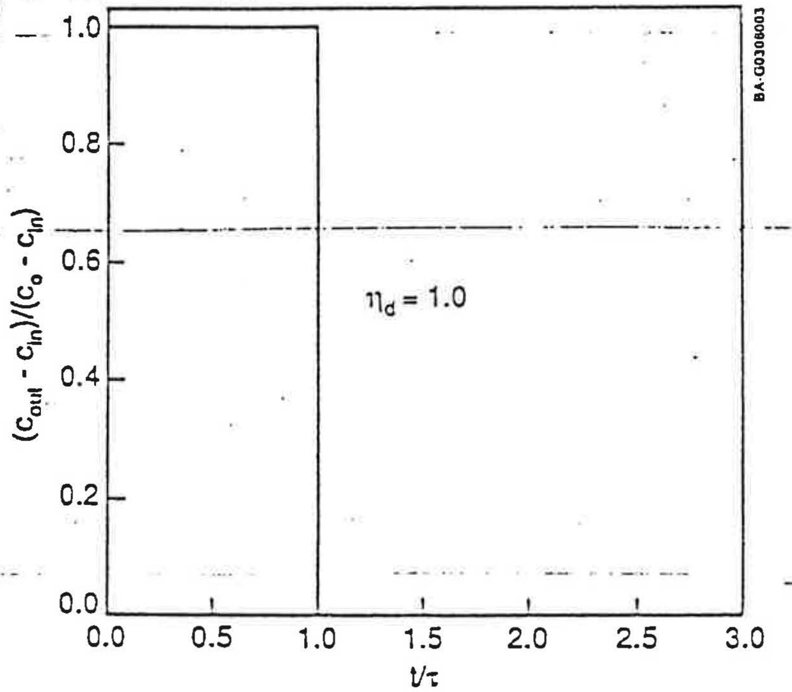


Figure 11 Average η_d for perfect displacement flow.

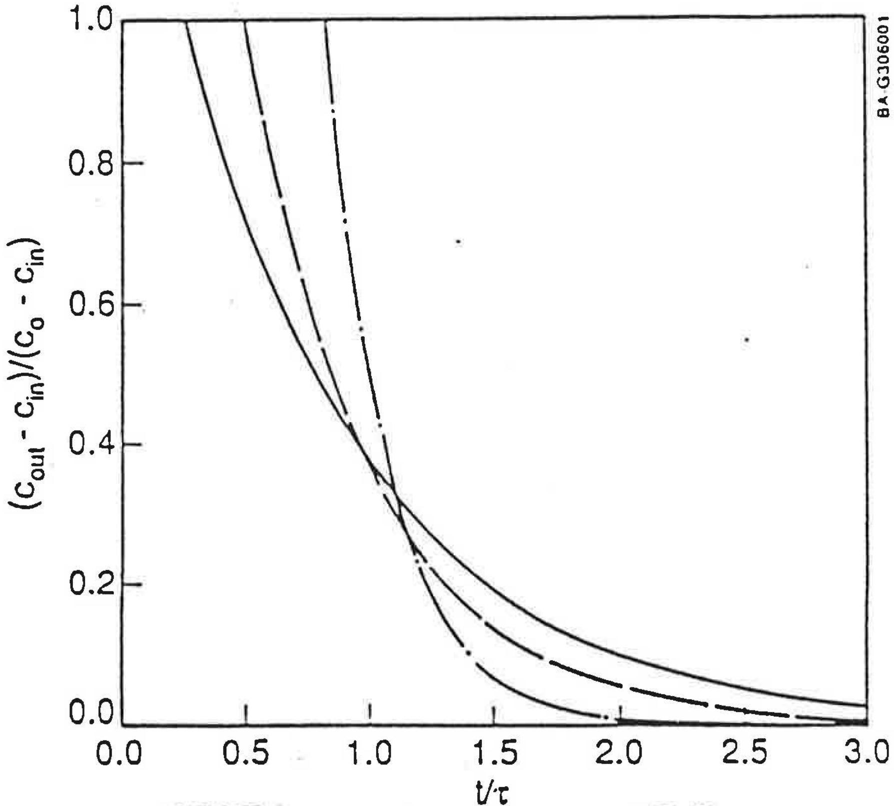


Figure 12 Average η_d for real flows.

One of the primary problems associated with the modeling of HVAC system performance is determining the fraction of air provided at the supply diffuser that is actually delivered to a given room location. Multizone mixing models have been used by several authors to differentiate between performance in different room subvolumes. In this section a modified two-zone analysis will be used to demonstrate the relationship between η_d and short circuiting between the supply and return ducts in ceiling based systems where the return duct is located in the jet mixing zone. Because one of the primary objectives of diffuser design is to provide adequate mixing of the ventilation jet before it enters the occupied zone it is convenient to divide the room into the jet mixing zone with volume $V-V_{oz}$, and the occupied zone with volume V_{oz}. The jet produces mixing by entraining air from the occupied zone at the rate Q_{ent}. By continuity, this is also the rate at which air is supplied to the occupied zone. If $(V-V_{oz})/(Q+Q_{ent}) << V_{oz}/Q_{ent}$ then a steady-state approximation can be applied to the jet mixing zone, resulting in a concentration at the return duct equal to

$$c_{out} = (Qc_{in}+Q_{ent}c_{oz})/(Q+Q_{ent}) \qquad (2)$$

For the system shown in Figure 8, this is also the concentration of the air that is delivered to the occupied zone. If we assume that the occupied zone is well mixed, then the differential equation describing the rate of change of concentration in the occupied zone is

$$dc_{oz}/dt=(1/V_{oz})[Q_{ent}Q/(Q+Q_{ent})]\{c_{in}-c_{oz}\} \qquad (3)$$

This is identical to the equation that would result if the ventilation jet was added directly to the occupied zone with the ventilation rate

$$Q_{ent}Q/(Q+Q_{ent}) \qquad (4)$$

If $Q_{ent}/(Q+Q_{ent})$ is not equal to V_{oz}/V, η^{oz}_{d} will differ from 0.63 even though the occupied zone is well mixed. Solving equation (3) one finds

$$\eta^{oz}_d = 1-\exp(-\tau/\tau_{oz}) \qquad (5a)$$

$$1/\tau_{oz} = (1/V_{oz})Q_{ent}Q/(Q+Q_{ent}) \qquad (5b)$$

Equation (5a) provides a method for calculating τ/τ_{eff} if η^{oz}_d is known from short term experimental measurements. Evaluating equation (5) we find

$$\tau/\tau_{oz} = -\ln(1-\eta^{oz}_d) \qquad (6)$$

A graph of equation (6) is shown in Figure 13. The fraction of ventilation air that short circuits to the return duct relative to what would have been supplied to the occupied zone if the entire room was well mixed is

$$s_a = (1-\eta^{oz}_d/0.63) \qquad (7)$$

Examples of η_r calculations for perfect mixing and perfect displacement flows are shown in Figures 14 and 15. The removal efficiency does not make physical sense when applied to subvolumes of a room which do not contain pollutant sources. However, it is possible to define a pollutant delivery efficiency η_p, which measures the fraction of a pollutant source which is added to a room subvolume during the time that one volume change is supplied to the room. The pollutant delivery efficiency for a room is

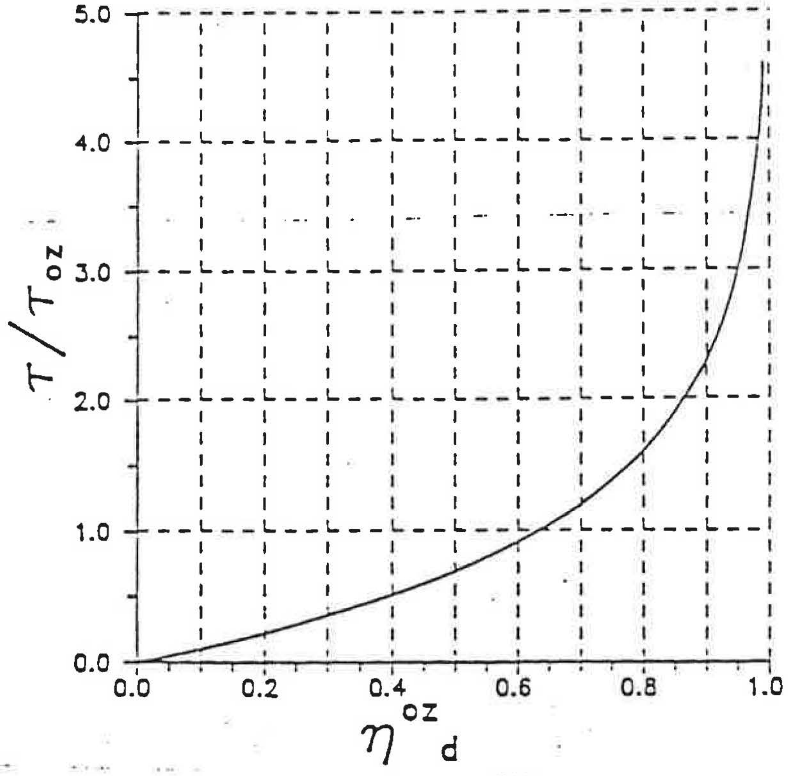


Figure 13 τ/τ_{oz} as a function of η^{oz}_d

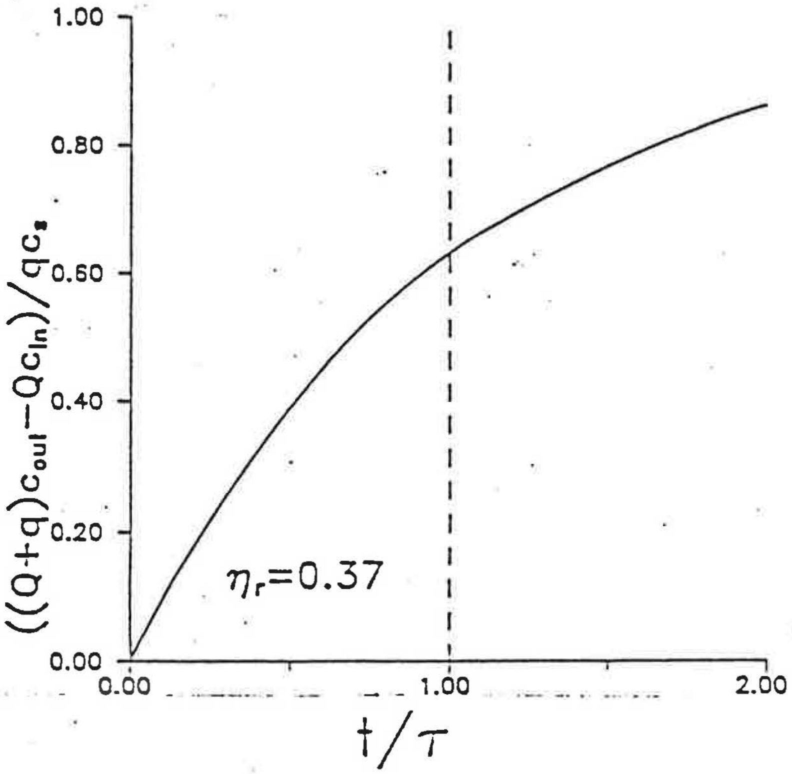


Figure 14 Removal efficiency for perfectly mixed flow.

$$\eta_p = 1-\eta_r = (c-c_o)Q/qc_s \qquad (8)$$

where c is the average concentration in the room at $t=\tau$.

The pollutant delivery efficiency for the occupied zone is

$$\eta^{oz}{}_p = [(c_{oz}-c_o)Q/qc_s](V_{oz}/V) \qquad (9)$$

In equation (10), c_{oz} is the average concentration in the occupied zone at time $t=\tau$. For a room in which the entire volume is perfectly mixed,

$$\eta^{oz}{}_p = 0.63(V_{oz}/V) \qquad (10)$$

For a ventilation system with the same two zone structure as was used in the derivation of equation (5),

$$\eta^{oz}{}_p = (\tau_{oz}/\tau)[1-\exp(-\tau/\tau_{oz})] \qquad (11)$$

As in the case of air delivery. a stratification factor can be defined for pollutant delivery that measures the the effective pollutant source strength in the occupied zone relative to the source strength for a perfectly mixed flow.

$$s_p = (1/0.63)(V/V_{oz})\eta^{oz}{}_p \qquad (12)$$

Solving for the steady state concentration in the occupied zone for the two zone flow described above and simplifying with the use of equations (7), (11), and (12) produces the result

$$(c_{oz}-c_o)Q/qc_s = s_p/(1+s_a) \qquad (13)$$

Equation (13) demonstrates that s_p and $(1+s_a)$ provide a direct measure of the effective source strength and the effective ventilation rate relative to a room that is perfectly mixed.

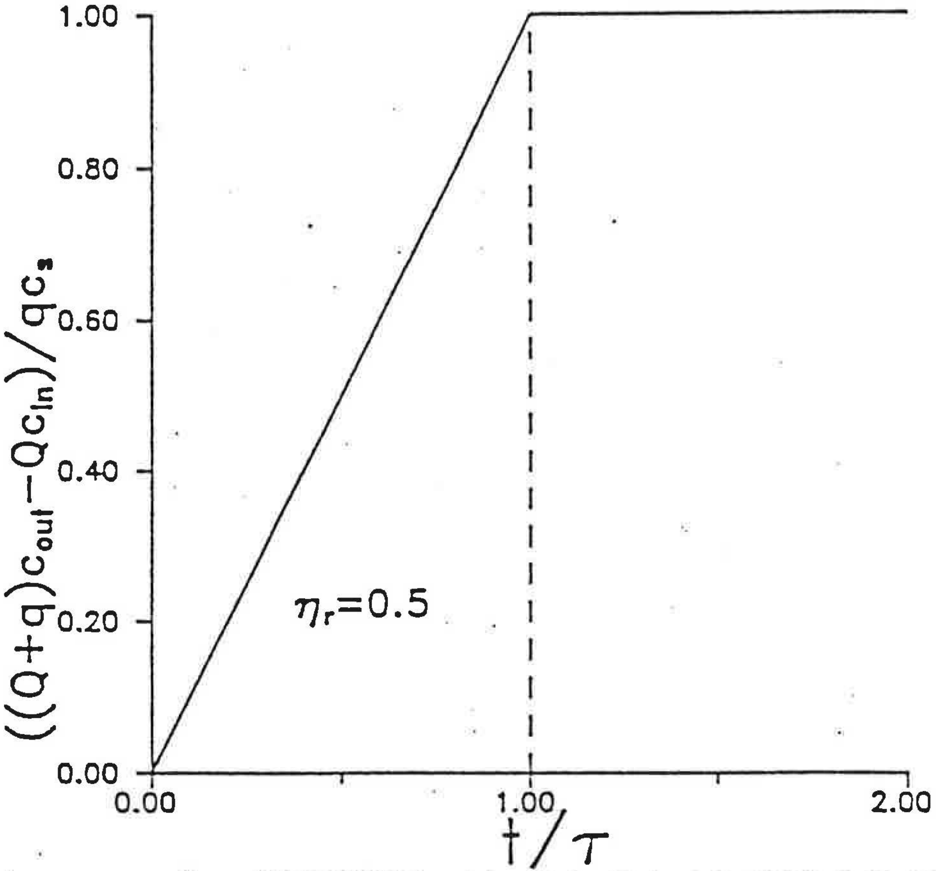


Figure 15 Removal efficiency for perfect displacement flow

EXPERIMENTAL RESULTS

Measurements of average room values of the displacement efficiency have been conducted for the simple ceiling based ventilation system shown in Figure 8. Parameters which were measured during the experiments included flow rate (Reynolds number), supply duct diameter, and thermal stratification (Rayleigh number). The Rayleigh number is used rather than the Grasof number to provide a first order correction for bouyancy effects due to the difference in Prandtl number between air and water [19-21].

The length scale used in the definition of the Reynolds number is the supply duct diameter. The length scale and temperature difference used in the definition of the Rayleigh number is the temperature difference between the supply and the test cell and the height of the test cell. A detailed description of the experimental apparatus has been previously given in reference 17. The supply duct consisted of a single slot diffuser that extended across the entire width of the test cell, as did the return duct. The tests were conducted with a completely open room volume, and therefore did not include the impact of partitions or furniture on ventilation performance.

The volumetric flow rate during the tests was varied from 5.1 volume changes per hour (Reynolds = 500) to 12.4 volume changes per hour (Reynolds = 1200). The supply duct to test cell height ratio (d/H) was varied from 0.026 to 0.127. As can be seen from examination of Figures 16 and 17, duct diameter and flow rate had very little impact on the measured value of the displacement efficiency, with average values of about 0.5. This value is 20% lower than would be expected for a perfectly mixed flow.

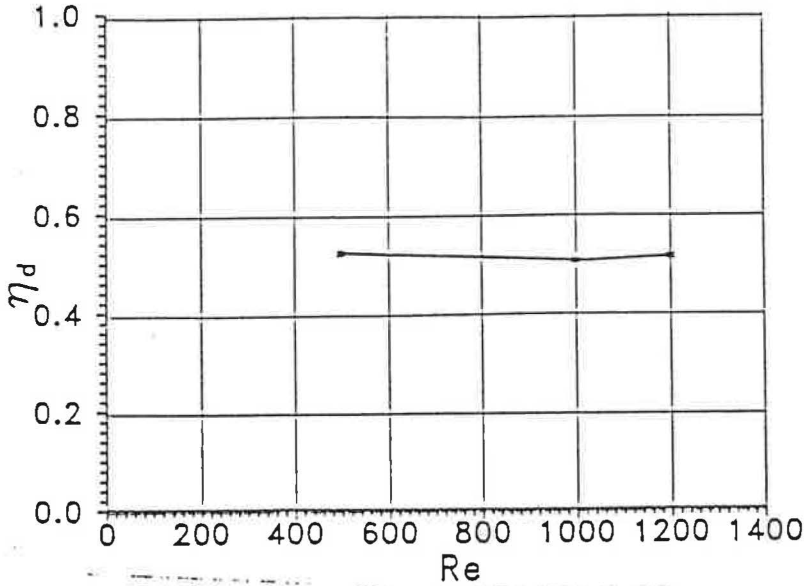


Figure 16 Impact of Reynolds number on displacement efficiency. Rayleigh=0. d/H=0.1.

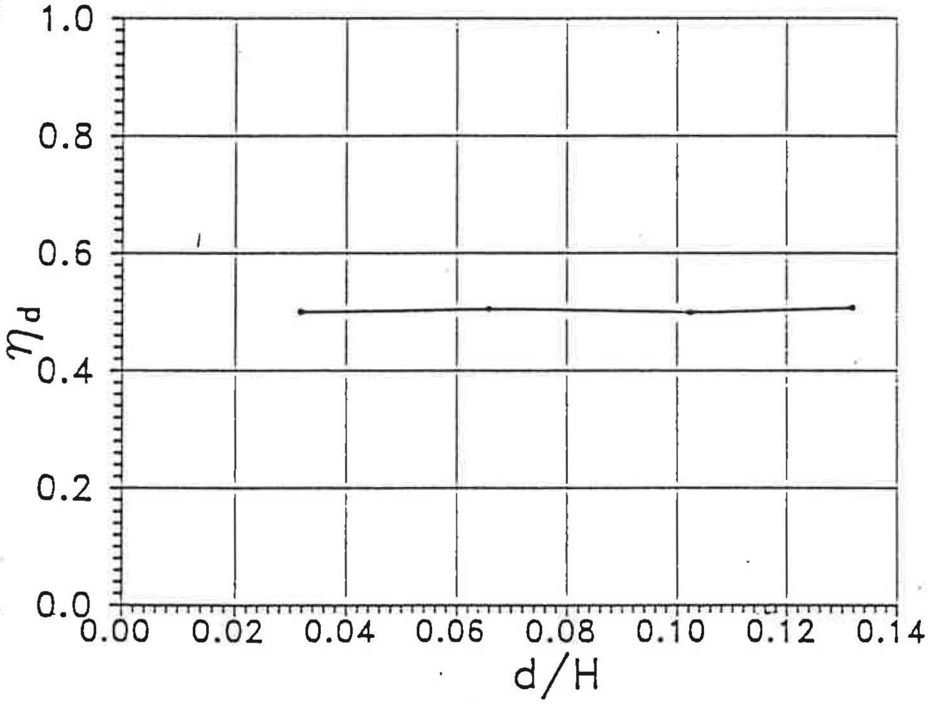


Figure 17 Impact of supply duct diameter on Displacement Efficiency.Reynolds=1000. Rayleigh=0.

Rayleigh numbers were varied between $3x10^9$ to $-3x10^9$, with negative values denoting a supply temperature that is lower than the test cell. The corresponding variations in the displacement efficiency are shown in Figure 18. The displacement efficiency varied between a low of 0.2 (68% lower than a perfectly mixed system) to a high of 0.78 (24% larger than would be expected in a perfectly mixed flow. Visual summaries of the test results for different test conditions are shown in Figures 19-21. Note that during both isothermal (Rayleigh=0) and cold (Rayleigh<0) tests, there is a region on the right side of the test cell that receives little or no ventilation air. This is a demonstration of the type of local variation in ventilation rate that can lead to air quality problems if there are strong local pollutant sources. The hot jet (Rayleigh>0) test results demonstrate that very careful design is required if ceiling based systems are used in heating applications.

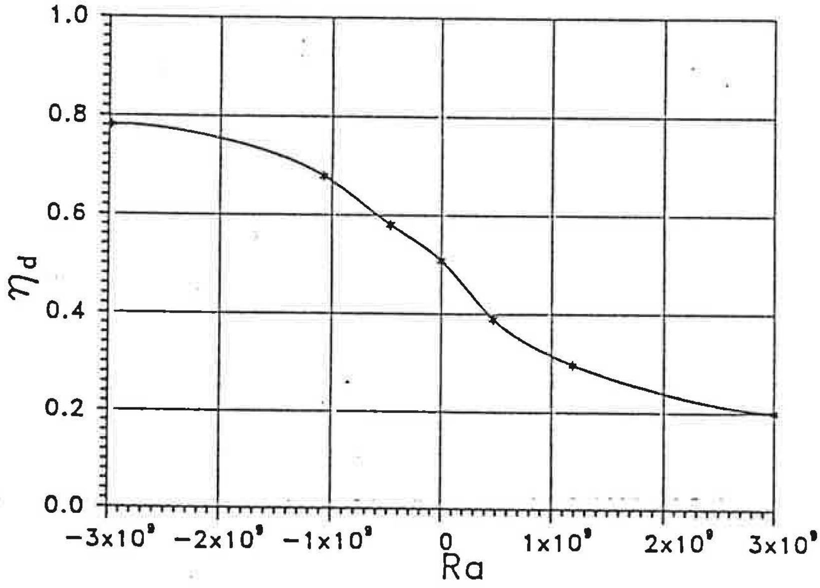


Figure 18 Impact of Rayleigh number on displacement efficiency

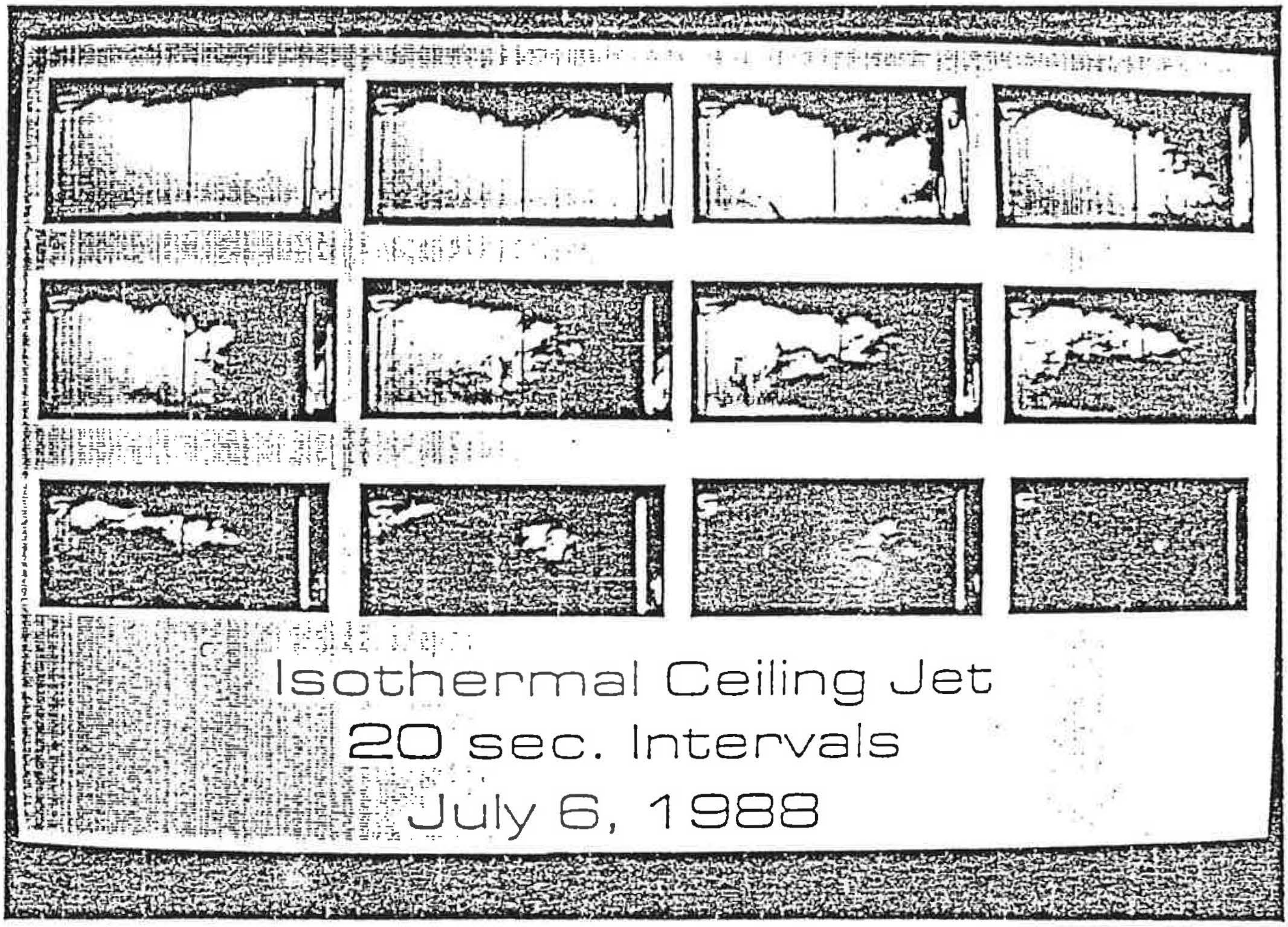


Figure 19 Visual summary of isothermal jet tests.

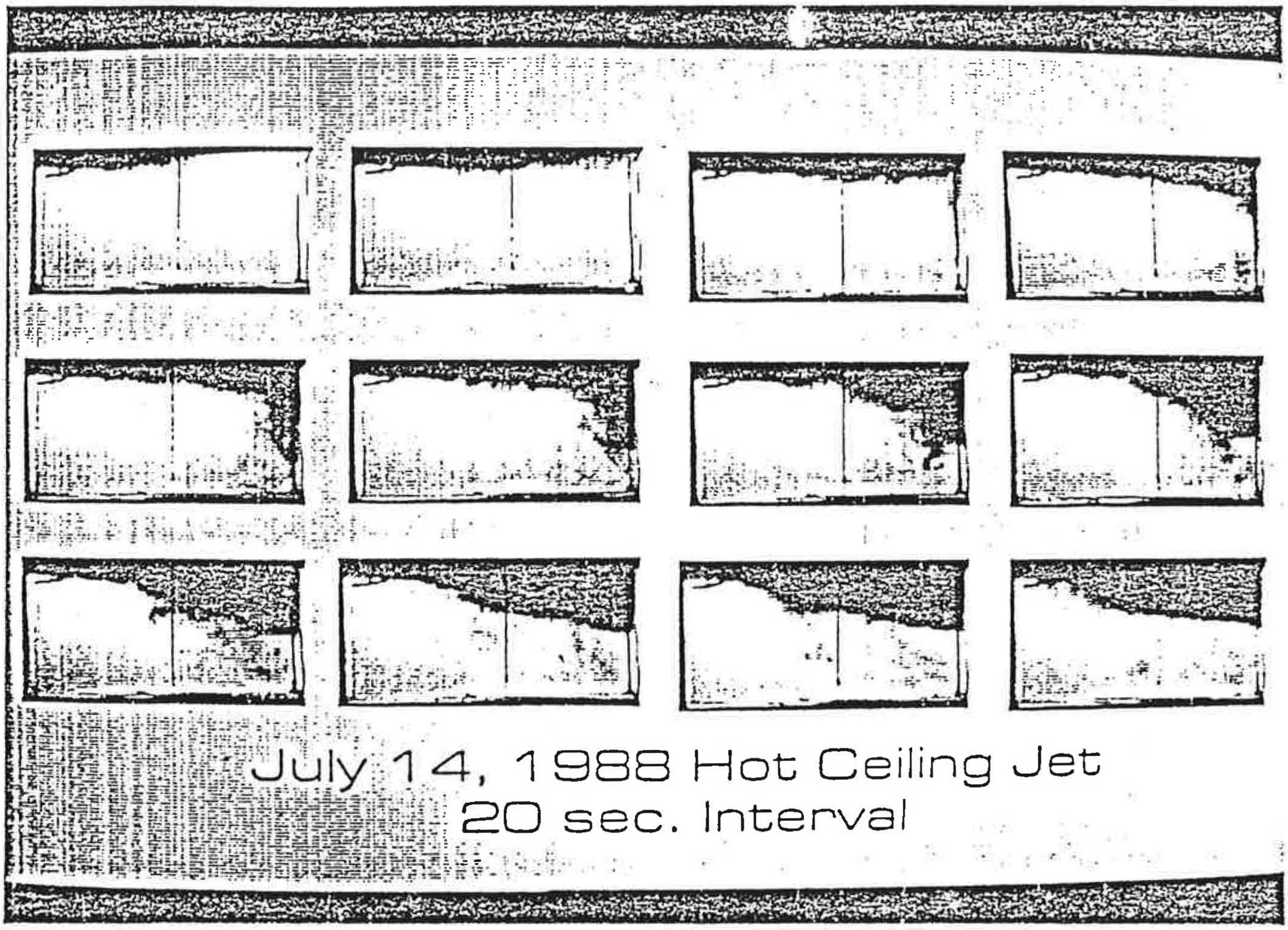
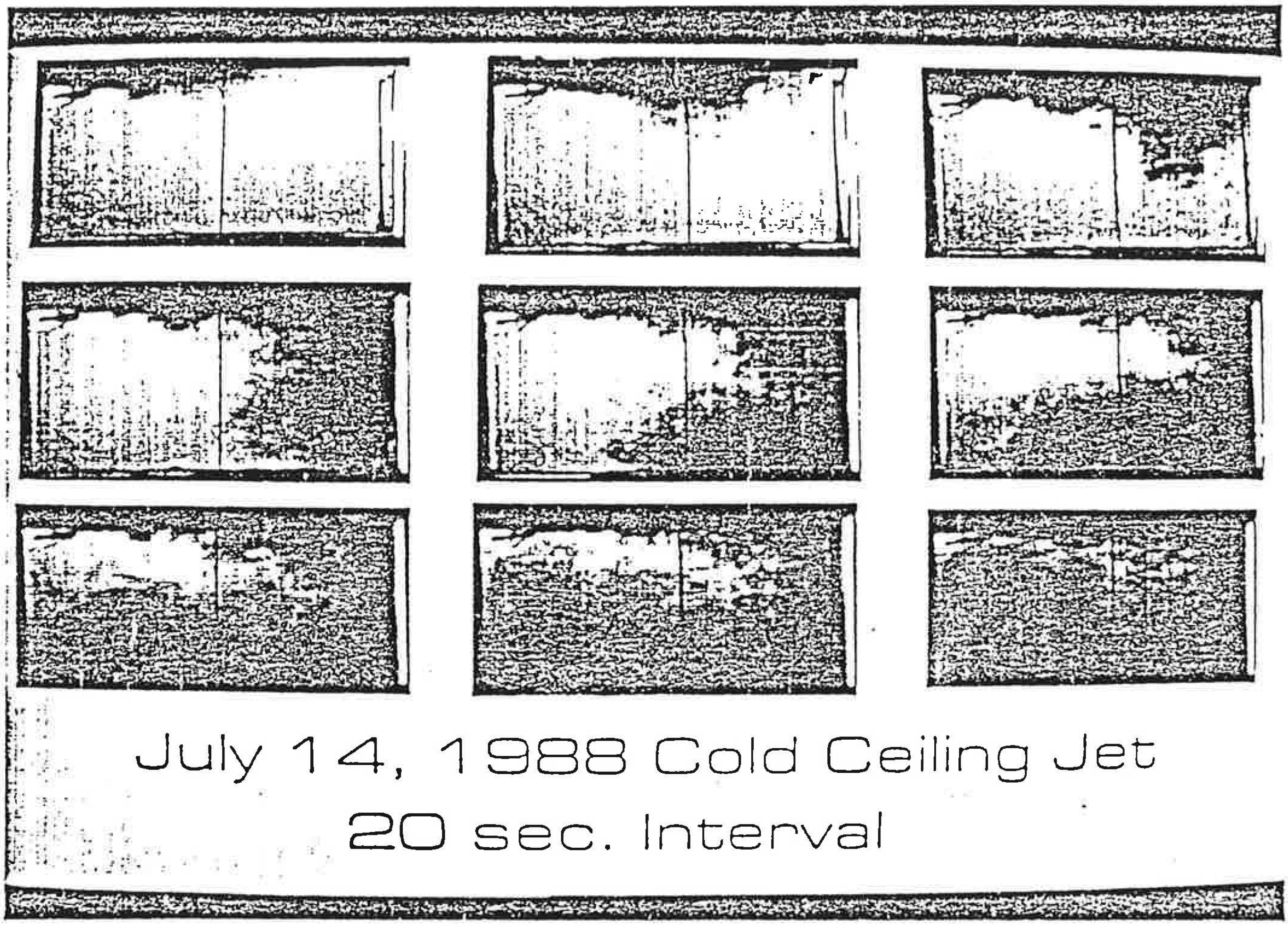


Figure 20 Visual summary of hot jet tests.



July 14, 1988 Cold Ceiling Jet
20 sec. Interval

Figure 21 Visual summary of cold jet tests

CONCLUSIONS

The performance of different ventilation systems cannot be accurately evaluated unless measurements can be made at a large enough number of points to measure local concentration distributions. Optical measurement and digital image analysis techniques can be used to provide spatial resolutions several orders of magnitude larger than can be provided using conventional point measurement techniques. Two new definitions of ventilation efficiency have been developed to take advantage these high spatial resolutions. The ventilation efficiency definitions are suitable for both laboratory and field studies, have well defined limits which can be used for calibration purposes, and can be interpreted in terms of effective ventilation rates and pollutant source strengths, thereby providing direct physical insight into ventilation system performance. Benchmark tests of displacement efficiency for a simple ceiling based ventilation system indicate the presence of flow short circulting and flow nonuniformities in a single zone without internal partitions. These effects were found to be relativly independent of supply duct diameter and flow rate, and highly dependent upon the temperature difference between the supply and the test cell. A simple analysis has been made demonstrating that systems with high recirculation rates are less sensitive to local variations in ventilation rates than systems with low recirculation rates. However, this reduced sensitivity is attained at the cost of increaseing average pollutant concentrations, and may in fact lead to a higher level of exposure.

Future tests will focus on determination of the impact of system design on supply of ventilation air to the occupied zone and the impact of room partitions on ventilation system performance, based upon the performance measurement techniques developed in the present report. Component tests with real diffusers and industry participation are scheduled to begin during the last quarter of 1989.

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