VENTILATION
AIR FLOW MEASUREMENTS MADE WITH SULPHUR HEXAFLUORIDE

BY

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ABSTRACT

A tracer gas technique for heating, ventilating, and air conditioning (HVAC) system performance evaluation was developed and validated by a comparison to measurements made with a pitot tube and design specifications in an office building in Hull, Quebec . A method to balance local exhaust ventilation systems using the equilibrium concentration tracer gas method is also presented. The results found in a model of such a system were compared to results found with a hot wire anemometer. In both studies, tracer gas techniques proved to be a viable alternative to conventional methods used to balance ventilation systems and to ensure that these are performing satisfactorily. Furthermore, effective ventilation rates in the work places could be quantified using tracer gas techniques.

Presently, the method outlined for HVAC systems performance evaluation can be used to find fresh and primary air supply, recirculation, and effective ventilation rates.

RESUME

Une technique utilisant un gaz traceur pour l'évaluation du fonctionnement des systèmes de climatisation (HVAC) a été mise au point; une comparison avec les measures prises à l'aide d'une tube de pitot et avec les spécifications du concepteur dans un immeuble de bureau à Hull, Qué. a permis d'en vérifier la validité. L'autre présente également une méthode de réglage des systèmes de ventilation aspirants locaux à l'aide d'une technique reposant sur le point d'équilibre de la concentration de gaz traceur. Les résultats obtenus sur un modèle de ce système ont été comparés aux résultats obtenus à l'aide d'un anémomètre a fil chaud. Dans les deux cas, les techniques faisant intervenir un gaz traceur se sont avérées une option valable par rapport aux méthodes conventionnelles utilisées pour équilibrer les systèmes de ventilation et s'assurer qu'ils fonctionnent d'une manière satisfaisante. Par ailleurs, les taux de ventilation efficaces sur les lieux de travail pourraient être quantifiés à l'aide des techniques faisant intervenir les gaz traceurs.

Actuellement, la méthode indiquée pour l'évaluation du fonctionnement des systèmes HVAC peut être utilisée pour déterminer le taux d'alimentation en air primaire et frais, le taux de recirculation, et le taux de ventilation efficace.

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PREFACE

Although tracer gas techniques have been used in the past in a variety of studies, these have concentrated on one aspect of a ventilation system or another. For example, volumetric flow rate measurements in conduits have been found and effective ventilation rates have been determined to quantify air infiltration in a building. However, no attempts have been made to combine different aspects of the existing technology to evaluate the overall performance of a HVAC system nor to balance local exhaust ventilation systems. Research on these aspects of the use of tracer gases is reported herein.

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LIST OF SYMBOLS

The following define the symbols and their units used in this paper unless otherwise stated in the text.

A: area (m^2).

C: volume concentration (ppm, ppb).

C_d: coefficient of discharge.

C_e: coefficient of entry.

D: diffusion coefficient (cm^2/s).

H: enthalpy (J/kg).

h: height (m).

h_e: hood entry coefficient.

I_D: collision integral.

$J(\phi)$: angle of opening factor.

K: heat (J).

L: length (m).

M: hydraulic radius (m).

m: mass (kg).

MW: molecular weight.

O: perimeter (m).

P: flow work (J).

p: pressure (N/m^2).

Q: volumetric flow rate (m^3/s).

R: resistance factor (N/m^2).

R_e: Reynold's number.

R_r: release rate (m^3/s).

SP: static pressure (N/m^2).

T: temperature (^{o}C).

t: time (s).

TI: transfer index (s/m^3).

TP: total pressure (N/m^2).

v: velocity (m/s).

V: volume (m^3).

VP: velocity pressure (N/m^2).

VR: ventilation rate (ACPH).

w: work (J).

Δ: difference, e.g. Δp.

ϕ: diameter (m).

ε: energy of molecular interaction (erg).

μ: dynamic viscosity ($N.s/m^2$).

ν: kinematic viscosity (m^2/s).

GLOSSARY OF TERMS

AIR EXCHANGE RATE	The number of times room air is replaced by outside air in an hour (air changes per hour (ACPH)).
COEFFICIENT OF ENTRY	The square root of the ratio of velocity pressure inside the duct to the static pressure in a hood.
EFFECTIVE VENTILATION RATE	The air exchange or outside air supply rate at a given location.
FACE	A dead end underground tunnel.
FLOW WORK	The work required to move a mass of air through ducting.
FRESH AIR	Outside air used to ventilate work areas.
FRICTION LOSSES	Energy losses resulting from friction as a fluid flows through a conduit.
GENERAL VENTILATION	Ventilation achieved by dilution, i.e. supplying air to work places.
HERMETICALLY SEALED	Air tight.
HOOD ENTRY LOSS	Loss of energy of a flowing fluid as entering a hood, normally in the form of shock pressure losses.
HYDRAULIC RADIUS	The ratio of the cross sectional area of a conduit to the wetted perimeter as fluid flows through the conduit.
LINEAR RANGE	The response range of an analytical device up until detector saturation begins.
LOCAL VENTILATION	A form of ventilation that is used in more critical situations to either locally remove contaminants from the work environment or to locally dilute them to acceptable levels.
PRIMARY AIR	Air supplied to the work places through the ventilation system; therefore,

RECIRCULATION RATE	The percentage of recirculated room air being redistributed back to work areas as a part of the primary air.
SHOCK LOSSES	The resulting loss in energy encountered when a flowing fluid either expands or contracts.
STACK EFFECT	The net upward flow of air in a building because of temperature differences and consequently, density differences due to height.
STEADY FLOW SYSTEM	A flowing system characterized by equal intrusion and extrusion rates.
TRANSFER INDEX	The air transfer between two points.
VENTILATION RATE	Air exchange rate.
WIND EFFECT	The net influx of air into a building resulting from wind incidence on it.

1.0 INTRODUCTION

Governments, the American Conference of Governmental Industrial Hygienists (ACGIH), and the Occupational Health and Safety Administration (OSHA) all have guidelines or regulations regarding worker exposure to harmful contaminants. The aggressive and harmful natures of the pollutants generated by most industrial processes are obvious and hence, these limits were adopted. In most industrial settings, a variety of physical and chemical agents are present. Some of these include: dusts and fumes, noise heat, radiation, solvents and other chemicals, all of which are associated with the many and varied occupations found in, but not limited to, plants, factories, and mines. Even though office environments are typically characterized by lower pollution levels than those found in industry, the contaminants may be present at concentrations above sensory perception and synergistically could present a health hazard for some contaminants. This has led to the recent recognition that these environments may not be as comfortable and healthy as once believed.

In energy efficient, hermetically sealed buildings, air circulation has been decreased as a consequence of their air tight nature and complaints of stale air and lack of air motion have arisen (1). It is possible that the decreased air circulation has resulted in higher contaminant levels in these environments. This is supported by the fact that the occupants have complained about eye, nose, and throat irritation, headache, fatigue, sneezing, and contact lense problems. Such symptoms are typical of what is referred to as "Tight Building Syndrome" (TBS) (2). Some of the contaminants found in hermetically sealed buildings are listed in Table 1. As indicated, these can be divided into categories reflecting interior or exterior origin.

Hicks (3) notes that more than 30 different organic species, which do not exist outside, have been detected inside buildings. The internal sources of pollution include: construction materials like adhesives, particle board, concrete, etc.; tobacco smoke; cleaning and maintenance supplies; and office equipment. In fact for most pollutants, indoor values tend to be higher than outdoor values (4). This leads one to believe that supplying more outside air to the indoor environment would dilute the existing contaminants and result in a healthier, more comfortable environment. The study presented by Hicks shows that the incidence of TBS are considerably decreased when the amount of outside air supplied per person in an office environment is increased from about 2.4×10^{-3} m^3/s (five cfm) to about 11.8×10^{-3} m^3/s (25 cfm). The incidence dropped an average of about 26% in the two buildings studied. The latest American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) air requirement recommendations are based on the build-up of contaminants in the workplace and require a minimum of 0.01 m^3/s (20 cfm) of outside air per person where smoking is permitted.

ORIGIN	POLLUTANTS
Outdoor	sulphur oxides, ozone, pollens, lead, manganese, calcium chloride, silicone, cadmium, organics.
Indoor and Outdoor	nitric oxide, nitrogen dioxide, carbon monoxide, carbon dioxide, particles, water vapour, organics.
Indoor	radon, formaldehyde, asbestos, organics, ammonia, hydrocarbons, arsenic, nicotine, mercury, aerosols, allergens, organisms.

TABLE 1: INDOOR POLLUTANTS

The problem now facing engineers is to find an effective way to measure the amount of outside air supplied to a work station (the effective ventilation rate). Conventional pitot tube measurements can be used to estimate this but do not measure it directly. Proper air diffusion is assumed but does not necessarily exist where screens and mixed office designs characterize the interior office space, as is typical in many complexes. More fundamentally, the theory of air diffusion is not completely understood (5).

An alternative method to find effective ventilation rates in sealed buildings uses a tracer gas. Flooding the occupied space with a gas and monitoring its decay can be used to determine the amount of outside air being supplied at a given location, and gives better results than the the estimates now being used. This method has been used by several investigators to find air infiltration rates in houses for different meteorological conditions (6,7,8,9). Other researchers have used tracer gas techniques to observe volumetric flow rates or air velocities in closed conduits (10, 11, 12, 13). However, no attempts have been made to combine the available techniques to evaluate the overall performance of ventilation systems.

The purpose of the following research was to design a technique using a tracer gas (sulphur hexafluoride (SF_6)) to find volumetric flow rates in ducts and the effective ventilation rates at work locations. In particular, rates of fresh air supply, recirculation and effective ventilation were found. The testing was performed on a floor-by-floor basis in an office complex in Hull, Quebec, after trials of techniques and equipment. One floor was used to test the finalized procedure on five consecutive days.

At this stage, the technique developed does not save an investigator much time over conventional pitot tube traverses but does afford a more reliable measure of effective ventilation rates and volumetric flow rates in ducting. Furthermore, it can be adapted to the measurement of air infiltration in structures at least in part ventilated naturally. This could replace the empirically based and induced pressure techniques, the former being an estimate and the latter requiring large fans and elaborate field installations.

With further work in the field of equipment development for sampling and analysis, tracer gas techniques will facilitate the measurements used in ventilation studies. It is expected that an entire office complex could be evaluated in a matter of a couple of weeks rather than the months that are presently required.

2.0 VENTILATION PRINCIPLES

The absolute minimum requirement of any ventilating system is to sustain life, that is to provide necessary oxygen and remove carbon dioxide produced by respiration. However, it is unthinkable for ventilation design to consider this alone. Dilution of objectionable odours and contaminants and the control of temperature and humidity must also be considered. Generally, the purpose of ventilation is to provide a healthy, comfortable environment for those present.

Both natural and mechanical ventilation are found in practice. Natural ventilation depends on local meteorological conditions and their resulting or independent pressure differences. Consequently, control of this type of ventilation is limited, although the associated low capital and operating costs make it an attractive tool. For example, the pressure difference with respect to depth in an underground mine with a substantial geothermic gradient can induce a flow of outside air into the mine and can be used to reduce the workload of the existing mechanical system. This decreases operating costs and if considered in the original design, may also reduce capital costs. Similarly, open plan layouts in factories reduce the ventilating load to an extent that some smaller structures can be entirely ventilated by natural means (13, 14). This is achieved with windows and its effectiveness can be increased by proper placement of louvres in the structure.

Mechanical ventilation systems can be classified by one of three broad categories: push, pull, and push-pull. The difference between push or pull ventilation, as shown in Figure 1, lies in fan placement. Positioning the fan at the beginning of the distribution system supplies air under a positive pressure to work places, whereas placing the fan at the end creates rarefaction which induces a flow through them. Combining the two prevents a pressure build-up and consequently, noise caused by high velocity air escape or infiltration is eliminated. Designing the exhausted air volume to be 10% less than the amount of incoming air creates a slight positive pressure which can prevent dust and pollutants from entering through cracks and openings in the building.(13).

Mechanical ventilation can be further subdivided into either general or local ventilation. General ventilation is used to dilute contaminants and odours in a work area and replenish oxygen by supplying fresh air. Heating ventilating and air conditioning (HVAC) units serve to achieve these objectives. Local ventilation serves only a limited area. It is used to contain harmful contaminants generated by industrial processes, laboratories, etc. Laboratory hoods are the most effective type of local ventilation because these enclose the contaminant entirely when the sash is shut. Other designs do not necessarily enclose the process, but rather rely on capture velocities to remove the harmful substances from the work environment. Many industrial dust collectors are designed on this principle.

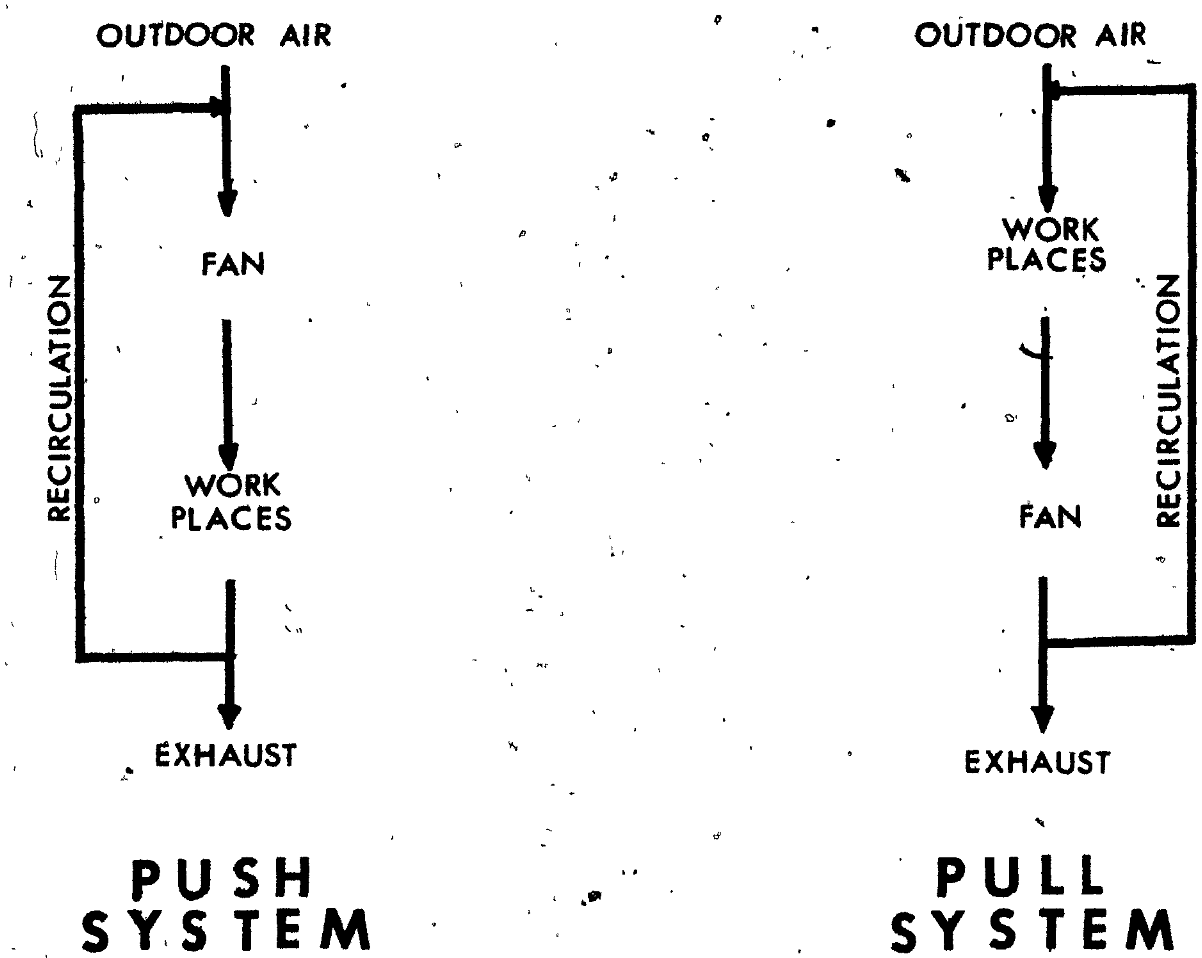


FIGURE 1: TYPES OF VENTILATION

The effectiveness of the above types of ventilation systems must be periodically checked to ensure a high quality work environment. Large building systems have to be balanced so that proper air distribution is obtained not only through the duct network, but also in the work areas. The effects of natural ventilation often have an influence on the functioning of a mechanical system when these are used together; therefore, its characteristics need to be known. Proper operation of local ventilation systems is very important because these are responsible for the removal of harmful contaminants from the work environment. All of the above can be determined using tracer gas techniques.

The remainder of this chapter outlines the theory behind air flow and air distribution through all parts of general and local ventilation systems. These are the characteristics measureable by the tracer gas techniques outlined and in some cases, validated in this paper.

2.1 PRINCIPLES OF GENERAL BUILDING VENTILATION

General building ventilation falls into two categories: mechanical or natural. These must supply air to occupied spaces at a specified ventilation rate in order to maintain a healthy, comfortable environment. Typical air requirements for an office complex as outlined by the ACGIH (15) are given in Figure 2. With the advent of the recent energy crisis, air tight office buildings have become popular. These rely solely on mechanical ventilation.

2.1.1 THEORY OF NATURAL VENTILATION IN BUILDINGS

Natural ventilation was the first type of ventilation found in practice because there is no need for any infrastructure. Presently, it is still used as the sole means of ventilation in many dwellings found in warm climates, but it is normally found in combination with mechanical ventilation in colder climates and larger buildings where air conditioning and better air distribution are required.

In natural ventilation, ventilating air enters a building through cracks and openings. The equation governing the flow of air through a crack is:

$$Q = Lk(\Delta p)^n \tag{2.1}$$

where: n has been experimentally found to be between 0.6 and

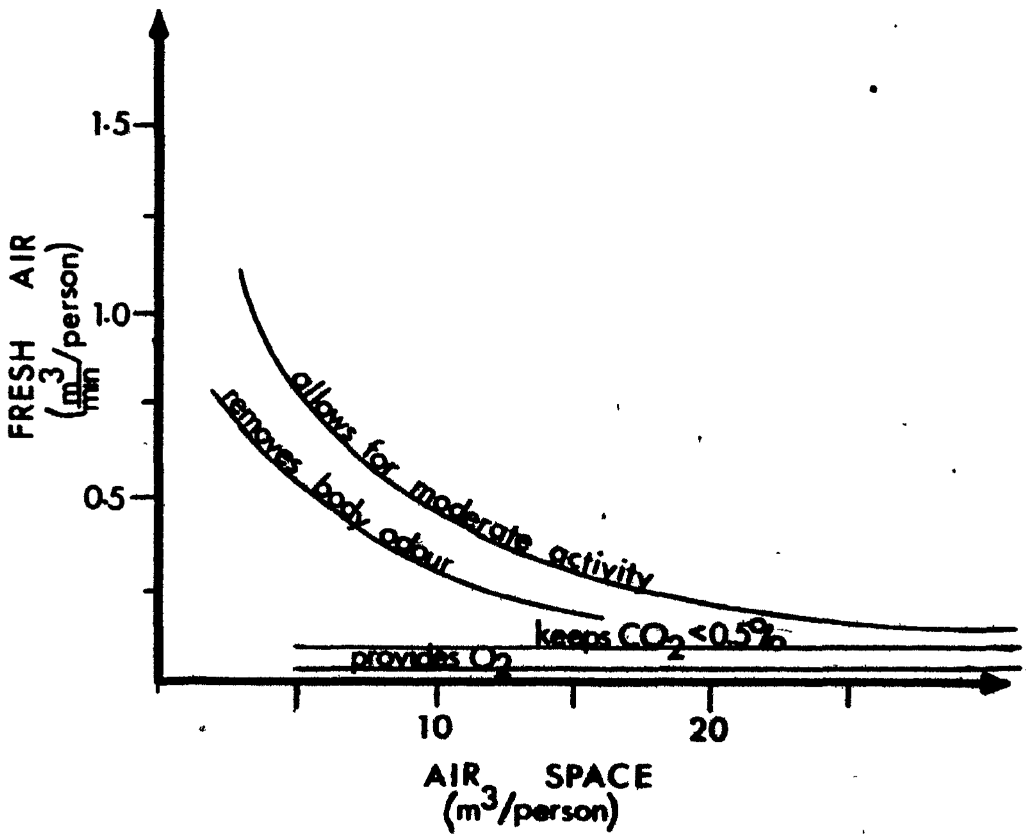


FIGURE 2: INDOOR GENERAL VENTILATION REQUIREMENTS (after ACGIH (15))

0.7, Q is the volumetric flow rate (m^3/s), L is the crack length (m), Δp is the pressure difference across the opening (N/m^2), and k is a factor that depends on the window type as outlined in Table 2.

The flow rate across an opening like a window has been determined by dimensional analysis and is given by:

$$Q = \left(\frac{g\Delta Th}{T}\right)^{1/2} \left(A\bar{Q}\left(\frac{\Delta Tgh^3}{T\nu^2}, \frac{h}{b}\right)\right) \tag{2.2}$$

where: g is the gravitational constant (m^2/s), h is the height of the opening (m), ν is the kinematic viscosity of air (m^2/s), A is the area of the opening(m^2), $\bar{Q}$ is a function of the Grashof (GR) number, $\frac{\Delta Tgh^3}{T\nu^2}$ and h/b, the aspect ratio, and ΔT is the temperature difference across the opening (°C). Croome and Roberts(13) indicate that the Grashof number is equal to 1/3 C_d where C_d is the coefficient of discharge through the opening. This is valid if the viscous forces of the system are small in comparison to the buoyancy forces and horizontal velocities are predominant.

For windows other than sliding windows, an angle of opening factor, $J(\phi)$, must be introduced so that:

$$Q = (1/3C_d\ AJ(\phi))\left(\frac{g\Delta Th}{T}\right)^{1/2} \tag{2.3}$$

characterizes flow through the opening. It is evident that $J(\phi) = 1$ for sliding windows as these do not obstruct flow.

WINDOW TYPE	k (0.001 $m^3/s/m$ of crack @ $p = 1\ N/m^2$)	
	AVERAGE	RANGE
Sliding	0.08	0.02 - 0.30
Pivoted	0.21	0.06 - 0.80
Weather Stripped Pivoted	0.08	0.01 - 0.20

TABLE 2: k FACTORS FOR DIFFERENT WINDOWS (after Croome and Roberts (13))

Figure 3 shows the factors for another type of window.

The above analysis has been extended to include multiple or a series of openings (13). For two openings in series with their centres h metres apart , the following equation describes the volumetric flow rate across both of the openings:

$$Q = 2AC_d\left(\frac{A_1/A_2}{(1 + A_1/A_2)(1 + (A_1/A_2)^2)^{1/2}}\right)\left(\frac{g\Delta Th}{T}\right)^{1/2} \qquad (2.4)$$

Therefore, if the sliding windows were the same size, the formula reduces to 3/2 times Equation 2.3.

2.1.1.1 WIND AND STACK EFFECTS

Air can either infiltrate through openings in a structure as a result of wind or pressure differences due to height as is possible in multi-storey buildings. These two effects act in conjunction with one another as shown in Figure 4.

The amount of air entering a building because of wind is given by:

$$Q = 0.5kAv \qquad (2.5)$$

where: k is a factor reflecting the ratio of the areas of free inlets and outlets as shown in Table 3, and v is the wind velocity (m/s). A perpendicular relationship between wind

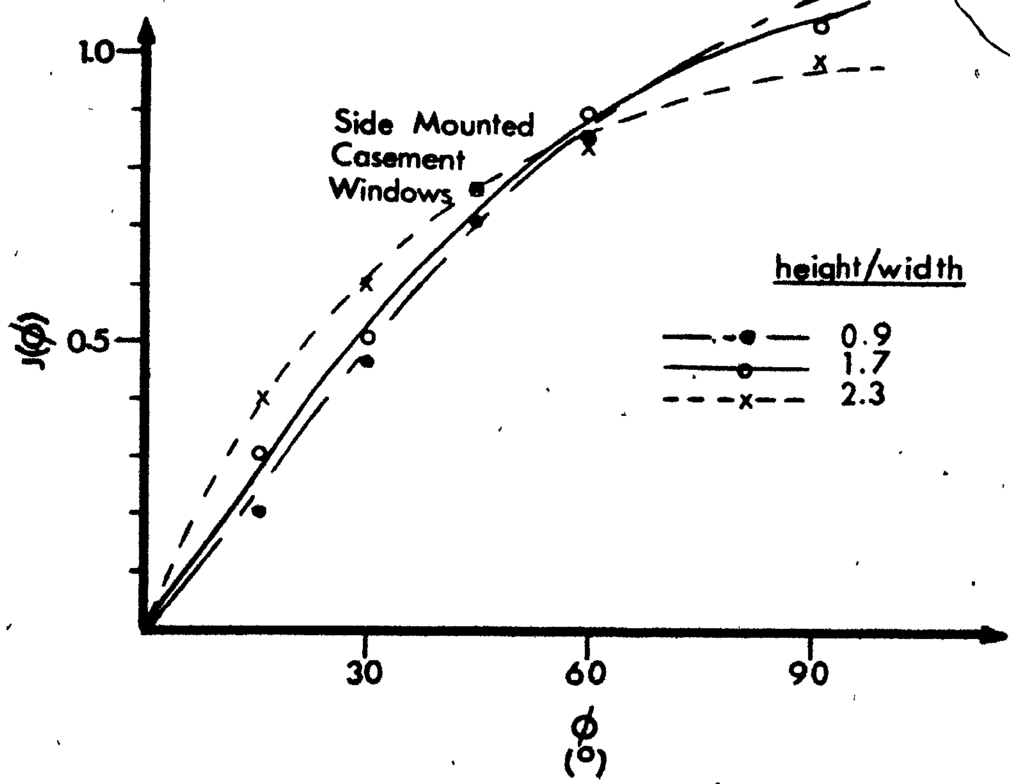


FIGURE 3: DIFFERENT ANGLE OF OPENING FACTORS (after Croome and Roberts (13))

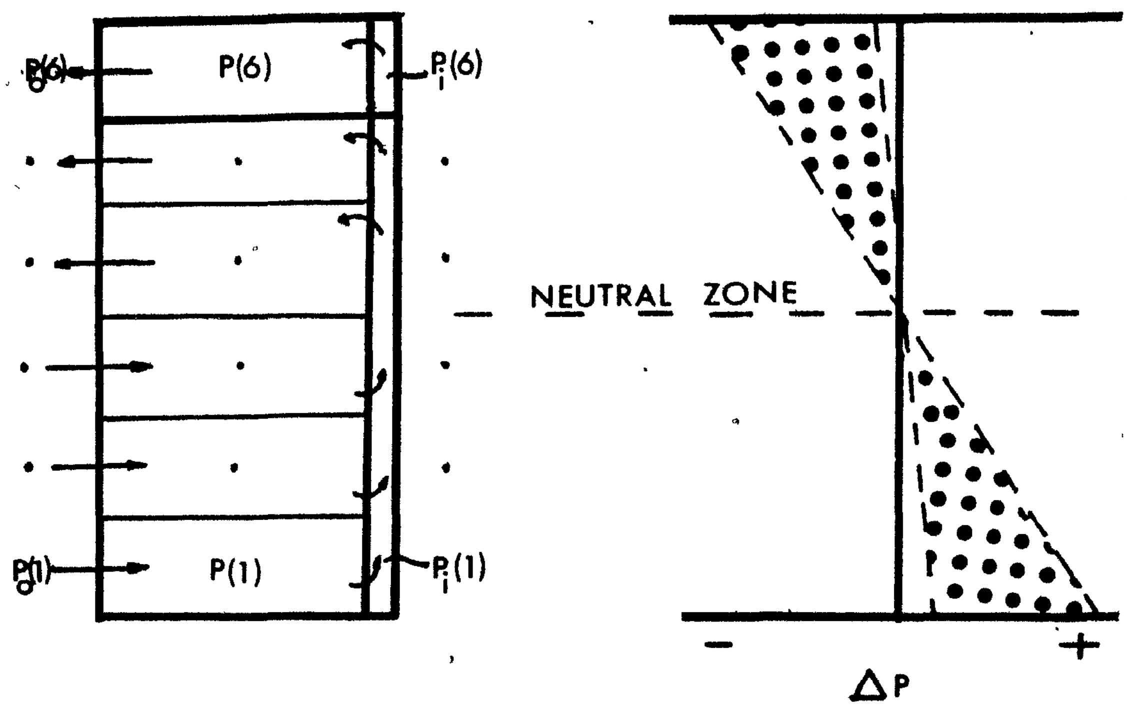


FIGURE 4: THE WIND AND STACK EFFECTS

$\frac{A_{outlets}}{A_{inlets}}$	k
0.25	0.21
0.50	0.38
0.75	0.51
1	0.60
2	0.76
3	0.81
4	0.82
5	0.83

TABLE 3: FREE INLETS TO FREE OUTLETS FACTORS (after Croome and Roberts (13))

direction and the side of the building is assumed.

Another approach to quantifying air infiltration due to wind is to use a relationship which reflects the pressure differences caused by it, such as:

$$Q = \frac{A\Delta p^{1/2}}{R} \qquad (2.6)$$

where R is the resistance factor of the opening (N/m^2). This can be expressed as:

$$Q = 0.827\Delta p^{1/2}\, \Sigma A \qquad (2.7)$$

and

$$Q = 0.827(\Delta p_1 + \Delta p_2)^{1/2}\left(\frac{A_1 A_2}{(A_1{}^2 + A_2{}^2)^{1/2}}\right) \qquad (2.8)$$

for openings in parallel and series respectively. Although the above equations are correct in the ideal case, wind profiles change with respect to height, which complicates the analysis. Croome and Roberts (13) outline this.

The stack effect results from warm air rising in a building because of its relative density. The phenomenon is so named because it is the principle governing the design of emission stacks found in industry, household chimneys, etc.. In order that a stack be effective, the driving force, which is a function of the pressure difference between air masses of differing temperatures, must induce an upward flow (16).

In a building environment, as the warm air rises, it is replaced by cooler outside air through doors, windows, and cracks. Hence, the stack effect is enhanced by cold outdoor environments.

Infiltration at the bottom of a building by cold air is given by:

$$Q = C_d \frac{A(2\Delta p_b)^{1/2}}{\rho i} \tag{2.9}$$

and similarly, the amount existing at the top is:

$$Q = C_d \frac{A(2\Delta p_t)^{1/2}}{\rho o} \tag{2.10}$$

where: ρ is the air density (kg/m^3), and pressure differences are derived from indoor (i) and outdoor (o) values. All openings that are actively allowing air into the building should be included. Knowing that the air pressure at ground level is equal to the air pressure at a height plus ρgh, where ρ is the average indoor or outdoor air density, the resulting equations can be solved for the indoor air pressure at the top and bottom of a building to give:

$$p_t + p_b = gh(\rho_o - \rho_{avg}) \tag{2.11}$$

Solving Equations 2.9 and 2.10 for p_t and p_b and substituting the solutions into Equation 2.11, and assuming mass conservation ($m = \rho_i Q_i = \rho_o Q_o$) yield the relationship:

$$Q = C_d \frac{(2\Delta\rho g h)^{1/2}}{T} \left(\frac{A_i A_r}{(1 + A_r^2)^{1/2}} \right) \qquad (2.12)$$

where: A_r is the ratio of outlet area to inlet area and $\Delta\rho$ is the density difference between the top and the bottom of the building. Using the ideal gas law, $\Delta\rho = -\frac{\Delta T \rho_o}{T}$, and substituting this and $C_d = 0.6$, $\rho = 1.2$, $g = 9.8$, $T = 293^\circ K$ into Equation 2.12, we get:

$$Q = 0.17(\Delta T h)^{1/2} \left(\frac{A_i A_r}{(1 + A_r)^{1/2}} \right) \qquad (2.13)$$

which is the flow rate into a building as a result of the stack effect. In essence, only the temperature difference between the incoming and outgoing air and the areas of the openings need be known for the calculation.

Figure 5 shows the infiltration rate resulting from the wind and stack effects acting in combination.

2.1.2 THEORY OF MECHANICAL VENTILATION IN BUILDINGS

Mechanical ventilation is achieved by supplying air to workplaces with a fan via ducting. The purpose of the fan is

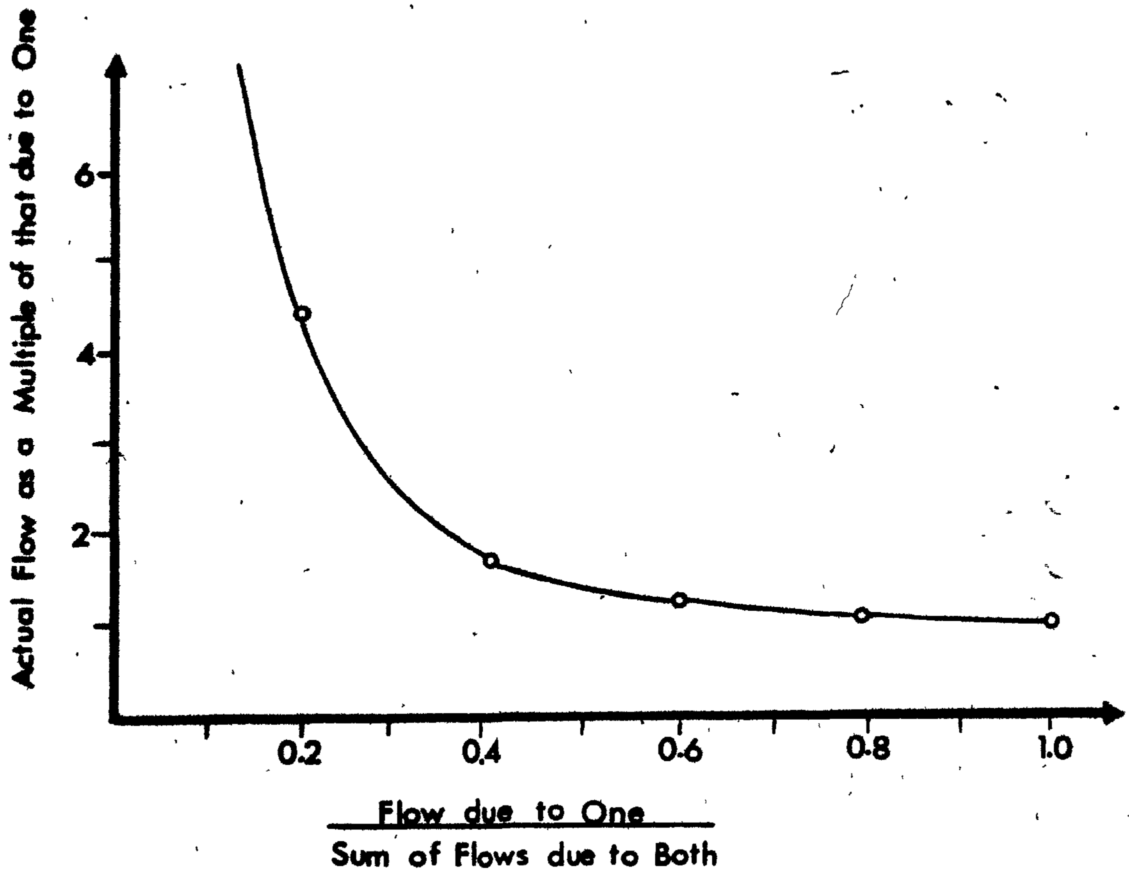


FIGURE 5: COMBINED EFFECTS OF THE WIND AND STACK EFFECTS
(after Croome and Roberts (13))

to supply energy to the air so that it can flow through the distribution system. Normally in large office complexes, centrifugal fans are used to overcome the losses encountered as air flows through the ducting. These are capable of generating high static pressures at relatively low noise levels. To ensure that the ventilating air is uniformly distributed, the duct network must be designed so that the losses, which are a function of fluid velocity (described in Section 2.1.3.1), encountered in each branch allow the desired volume of air to flow through; hence, duct diameter can be used to increase losses by increasing the fluid velocity. This can be a delicate balance and therefore, adjustable dampers or baffles are often installed at the time of construction to allow for subsequent corrections and changes. Once through the distribution system, the ventilating air is supplied to work places via diffusers to ensure proper mixing.

Three types of HVAC systems are commonly found in practice: continuous air supply, variable air volume (VAV), and more recently, heat reclaim types. A continuous air supply system supplies a given amount of ventilating air to work areas and is often found in conjunction with natural ventilation. Normally, the air is centrally treated and cooling and/or heating coils are activated by thermostats. Multiple zone systems are also found in practice. Here, a number of thermostats are used to monitor different areas in a building. Ventilating air is treated according to the zones' needs.

With the advent of the energy crisis, VAV units became popular because of their characteristic energy efficiency. These supply ventilating air based on the heat requirements in a given area. Therefore, as the temperature rises in a given zone, more air, which is cooler than the work room air, is supplied. This reduces the work load of the ventilation system at times when full air conditioning is not required. VAV systems are by definition multiple zone. Recirculation of room air can also be used to further reduce the work load.

The last system to be outlined is the heat reclaim type. It is also considered an energy efficient system. Heat pumps or other heat reclaim devices are used to recover excess heat found in the work areas (interior) and transfer it to the areas of a building exposed to outdoor weather conditions (exterior). It is best to have two independent air handling units serving the two distinct zones. Heat ~~can~~ be transferred from the interior to the air handling unit supplying the exterior zones via a refrigerant.

2.1.2.1 FLOW THROUGH CLOSED CONDUITS

The movement of air through a closed conduit results in pressure losses, which are a function of fluid velocity, viscosity, density, temperature, and pressure, and the interior surface and geometry of the duct through which the fluid flows.

Below a critical velocity, fluid flow is said to be laminar; otherwise it is turbulent for which eddy and cross currents are characteristic. In laminar flow, pressure or head losses result from the fluid particles shearing against one another in parallel planes if the run is straight and of uniform geometry (17). The boundary layer (next to the interior surface) clings to the duct and is characterized by the lowest velocity. As the distance increases from the wall, so does the velocity. This defines a velocity profile as shown in Figure 6. For circular ducts, the Poiseuille - Hagen relationship:

$$\Delta p = \frac{32\mu L v}{\phi^2} \qquad (2.14)$$

gives the pressure drop where: μ is the absolute viscosity ($N.s/m^2$) and ϕ is the duct diameter (m). If bends, contractions, and other variations in duct geometry exist, these are accounted for using the equivalent length method (see Appendix I). This expresses the variation as an equivalent length of straight duct so that Equation 2.14 can be used to calculate the resultant pressure drop.

Turbulent flow is usually encountered in practice. Unlike laminar flow, pressure losses are caused by friction on the interior duct surface. The resulting pressure drop is given by:

$$\Delta p = \frac{2fL\rho v^2}{\phi} \qquad (2.15)$$

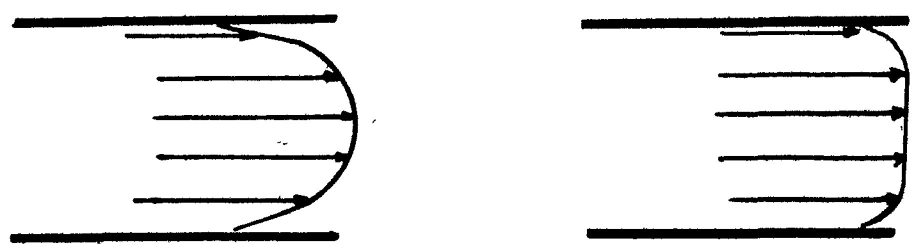


FIGURE 6: VELOCITY PROFILES FOR FLUID FLOW

where: f is a friction factor. Again, the equivalent length method can be used to account for irregular duct geometries.

An important criterion used to distinguish turbulent from laminar flow is Reynold's number:

$$Re = \frac{\rho V \phi}{\mu} \qquad (2.16).$$

Above a given Reynold's number (>2300), which varies with pipe roughness, laminar flow becomes turbulent because of the frictional effects of the contact surface.

Friction factors for turbulent flow can be found for different Re's from the graph shown in Figure 7. Friction factors are smallest when a small contact surface is associated with a large cross-sectional area; therefore, rectangular and square ducts have higher friction factors than do circular ducts. However, Jennings (17) notes that a rectangular duct with an aspect ratio not exceeding 8:1 will have the same static frictional loss and mean fluid velocity as a circular duct of the same material and hydraulic radius.

A more general approach to Equations 2.14 and 2.15 accounts for ducts other than circular ones. In these instances, the two equations can be used if the hydraulic radius, M, is considered. This is the ratio of the cross sectional area of the conduit to the wetted perimeter and four times this value can be inserted for .

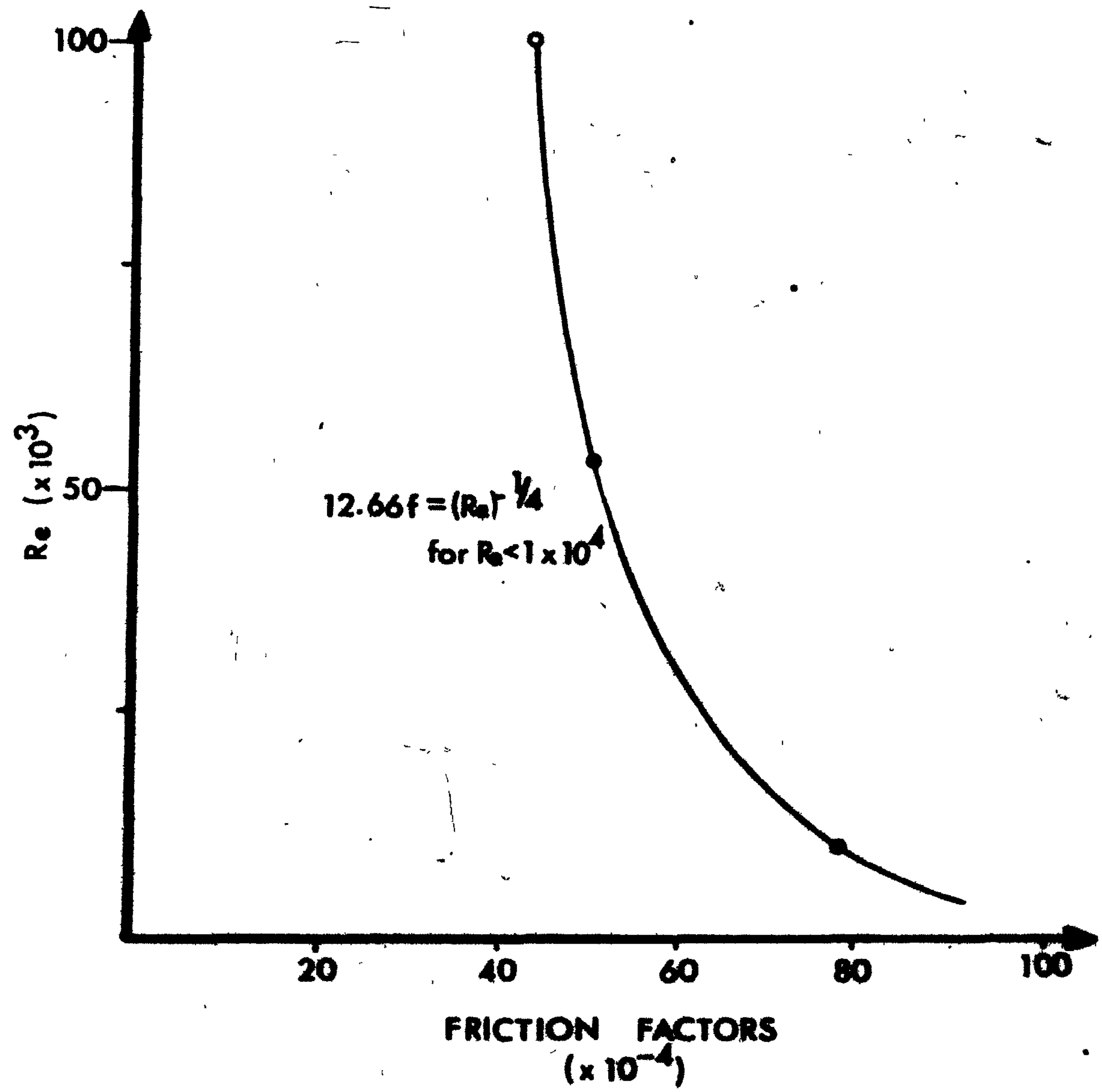


FIGURE 7: FRICTION FACTORS FOR FLUID FLOW

2.1.2.2 FLUID FLOW THEORY AS APPLIED TO VENTILATION

Ventilation is considered an open system. Mass can flow into or out of the system at given rates. Ventilation is also considered steady flow. This means that the rates of flow into and out of the system are always equal. Typically, work is performed on the incoming air by a fan and heat may be added or subtracted by air conditioning units; therefore, the air is at a new energy level. Nonetheless, energy is conserved. Keeping these principles of the conservation of mass and energy in mind, Bernoulli developed a steady flow energy equation:

$$\int v\,dp + \frac{v^2}{2} + gh = \text{constant} \qquad (2.17).$$

This implies that the energy throughout the system remains constant, neglecting friction and assuming the medium is homogeneous. Referring to Figure 8, heat and energy are added at point A; hence, Bernoulli's equation for this system becomes:

$$gh_i + \frac{v_i^2}{2} + H_i + W_{i-f} + K_{i-f} = gh_f + \frac{v_f^2}{2} + H_f \qquad (2.18)$$

where: H is enthalpy (J/kg), W is work done by the shaft (J) and K is the heat added to the system at A (J).

The above analysis changes somewhat to describe the flow of air through ducting. The potential energy term can be ignored and consequently:

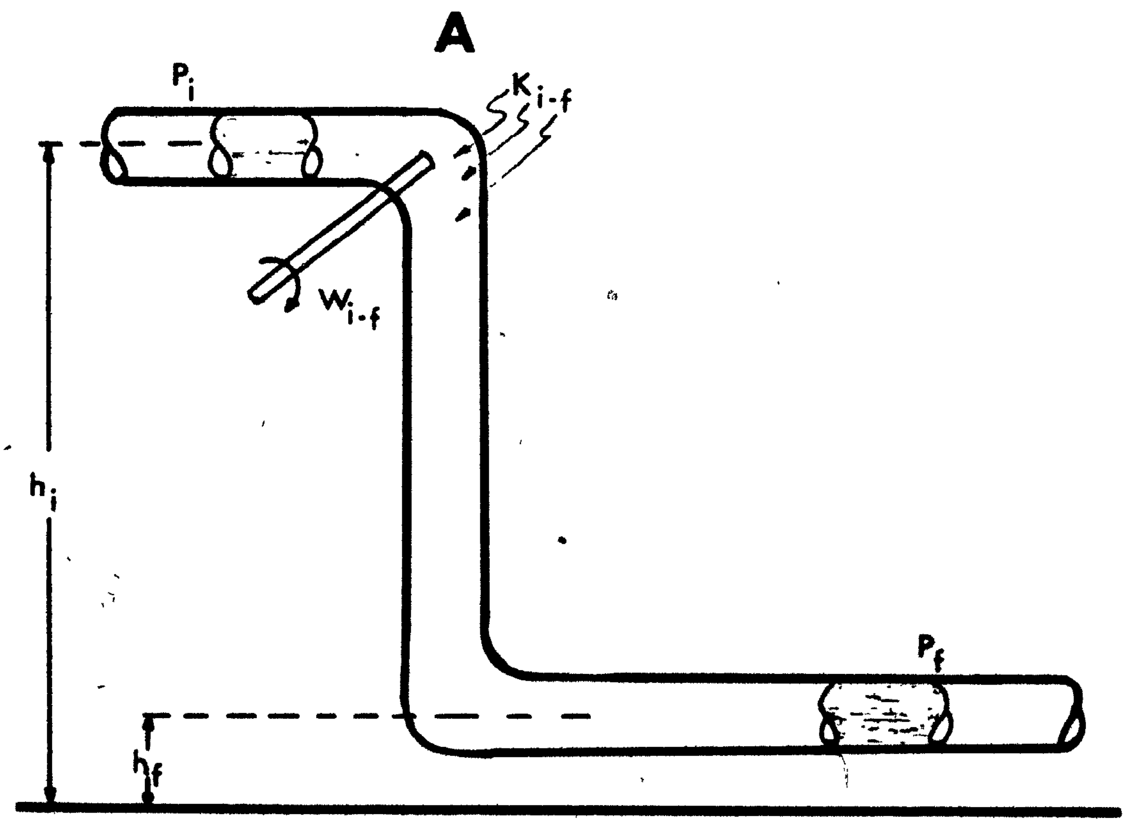


FIGURE 8: ILLUSTRATION FOR BERNOULLI'S EQUATION

$$\frac{v_i^2}{2g} + \frac{H_i}{g} = \frac{v_f^2}{2g} + \frac{H_f}{g} + \Delta p \qquad (2.19)$$

which can be written:

$$\frac{v_i^2}{2g} + \frac{P_i V_i}{g} = \frac{v_f^2}{2g} + \frac{P_f V_f}{g} + \Delta p \qquad (2.20)$$

where: V is the specific volume (m^3/kg) and P has the units of work and PV is considered flow work; can be used for Equation 2.18. The pressure loss (Δp) is a result of internal energy losses.

Conventionally for air flow, the flow work is referred to as the static pressure (SP) and the term $v^2/2g$ is called the velocity pressure (VP). The total pressure (TP) is the sum of these at any point in the system. Bernoulli's equation can then be expressed as:

$$SP_i + VP_i = SP_f + VP_f + \Delta p \qquad (2.21).$$

2.1.2.3 FAN AND SYSTEM CHARACTERISTIC CURVES

Fans are characterized by a set of curves as shown in Figure 9. Although information concerning many different variables is shown, the curve most relevent to this paper relates fan static pressure to volumetric flow rates. The static pressure of the air leaving the fan results from the work the fan does on the air. In ventilation design, the fan's static

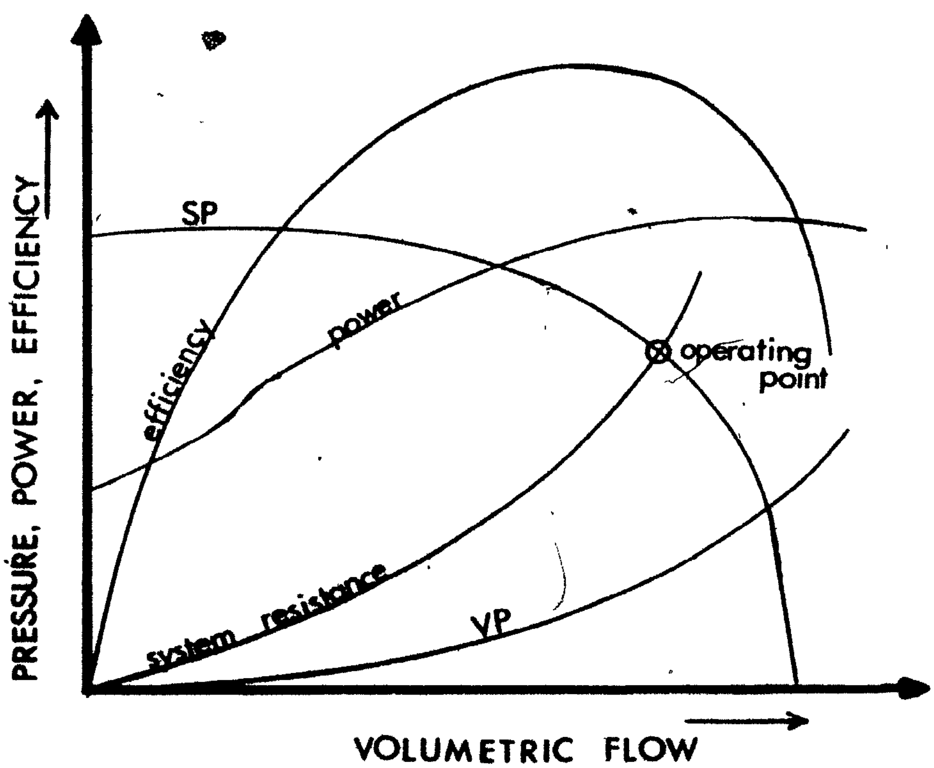


FIGURE 9: FAN AND SYSTEM CHARACTERISTIC CURVES

pressure just equals or is slightly higher than the expected pressure drop across the system, which is a function of the system's resistance.

The resistance of a system is a function of shock and frictional losses. The basic equation relating resistance (R), volumetric flow rates, and pressure loss is:

$$p = RQ^2\left(\frac{\rho}{1.2}\right) \tag{2.22}$$

where:

$$R = \frac{kLO}{A^3} \tag{2.23}$$

and k is a roughness factor (kg/m^3) and O is the perimeter of the interior surface(m). Figure 9 also shows the operating point of a fan, which is the intersection of a fan's static pressure curve and the system's resistance curve.

There are many laws governing the operation of a fan that can be used to change the operating point in a given system. These relate different fan parameters to one another and are called fan laws. These are outlined in Appendix II. These laws can be applied if some operating parameters or a system is changed. This adds a degree of flexibility to ventilation design.

2.1.2.4 AIR DIFFUSION IN VENTILATED ROOMS OR SPACES

Once ventilating air is conditioned to the desired temperature and humidity levels, air diffusion is the mechanism responsible for ensuring that all parts of a room are maintained at these levels. The theory or science of air diffusion has not yet been thoroughly investigated; however, a considerable amount of knowledge has been obtained in the field (5). Investigations at the University of Illinois have shown that the placement of air diffusers greatly affects the overall ambient conditions of a room. Five types of diffusers were studied:

1) horizontally discharging outlets near or on the ceiling,
2) vertically discharging outlets near or on the floor (non-spreading jet),
3) vertically discharging outlets near or on the floor (spreading jet),
4) horizontally discharging outlets near or on the floor,
5) vertically discharging outlets near or on the ceiling.

Figure 10 indicates the air flow patterns generated by the different diffusers.

It is evident that there are differences between heating and cooling regardless of the method of diffusion.

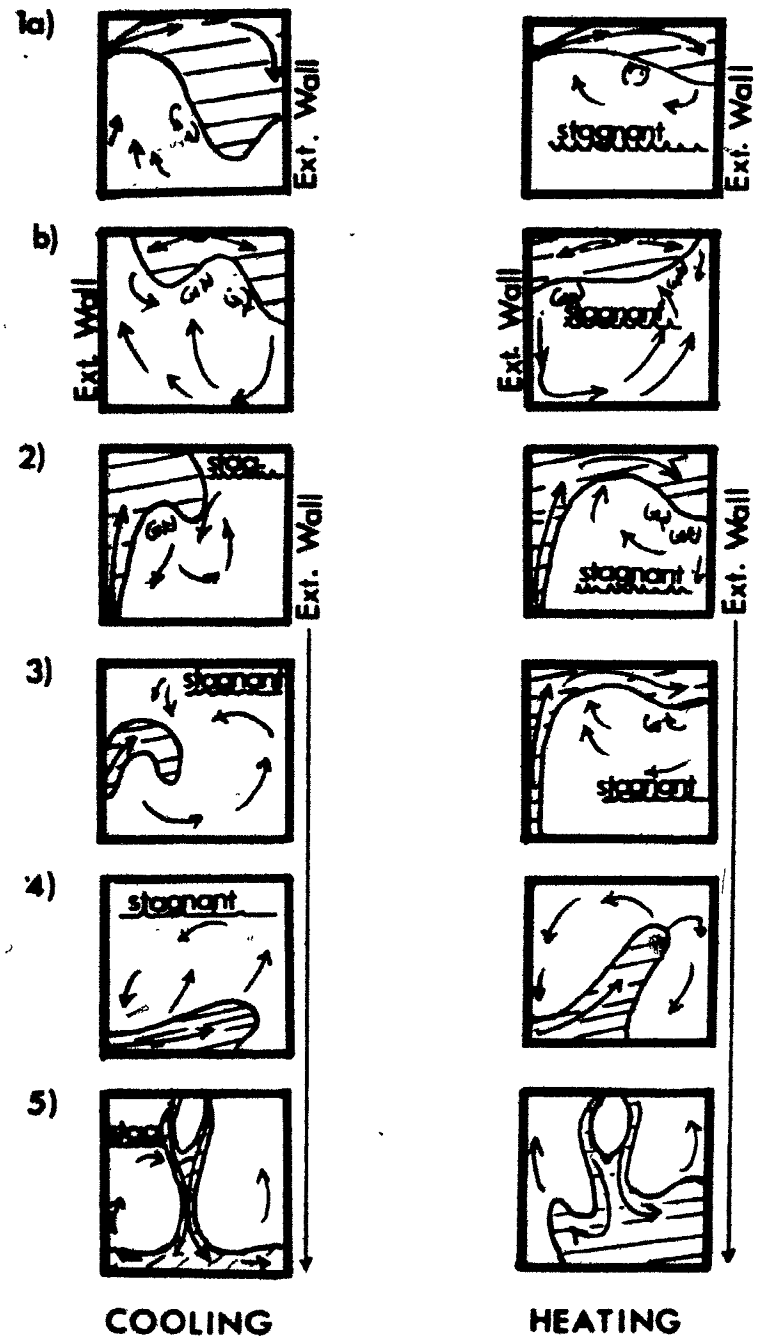


FIGURE 10: AIR FLOW PATTERNS GENERATED BY VARIOUS DIFFUSERS (after ASHRAE (5))

Natural convection tends to cause the total air envelope, which is the primary air (air delivered to the room) and the entrained air (room air trapped in the primary airstream), to rise more during heating than during cooling. The movement of the primary air has been modeled analytically from the outlet to a distance where its velocity drops to 0.76 m/s, and shows the same characteristics for heating and cooling even though the movement of the total air envelope does not (5).

An important feature of air diffusion is that a stagnant zone is present in most situations. This is a result of natural convection and will form in a room from the ceiling down during heating and from the floor up during cooling (5). Return air outlets affect only a limited area and should be placed near or at the level of the stagnant zone to prevent its build-up. However, while not all of the aforementioned methods of air diffusion completely prevent stagnant zones, these may not be required to do so. Proper placement of diffusers and sufficient primary air velocities, in combination with compatible architectural layouts, can ensure that the stagnant zone forms out of the breathing zone of workers. Nonetheless, caution must be exercised so that air velocities do not create uncomfortable drafts.

2.2 PRINCIPLES OF LOCAL VENTILATION

The need for local ventilation in a building environment arises when the general ventilation does not sufficiently dilute a contaminant in the atmosphere. In general, dilution ventilation is not as satisfactory for health control as local ventilation. Common examples of local ventilation are industrial dust collectors and laboratory fume hoods.

Much of the relevent theory regarding local ventilation design and operation has been presented in early sections of this chapter; in particular, a knowledge of the flow through closed conduits and fan selection is required in local ventilation design. The following subsections cover additional principles of local ventilation.

2.2.1 THE CAPTURE OF CONTAMINANTS

Not all local ventilation systems enclose the contaminant generating area entirely as do laboratory hoods. Therefore, it is often necessary to rely on capture velocities to entrain the pollutant and carry it from the room. Capture velocities differ according to the contaminant being controlled as outlined in Table 4. Figure 11 shows the relationship between the designed duct velocity and the capture velocity at a distance from the hood. This relationship is true for circular hoods and square and rectangular hoods with a small aspect

PROCESS	CAPTURE VELOCITY (m/s)
Evaporation from Tanks	0.25 - 0.51
Spray Booths, Low Speed Conveyor Transfer, Welding, Plating	0.51 - 1.02
Spray Painting in Shallow Booths, Conveyor Loading, Crushing	1.02 - 2.54
Grinding, Abrasive Blasting, Tumbling	2.54 - 10.16

TABLE 4: REQUIRED CAPTURE VELOCITIES (after ACGIH (15))

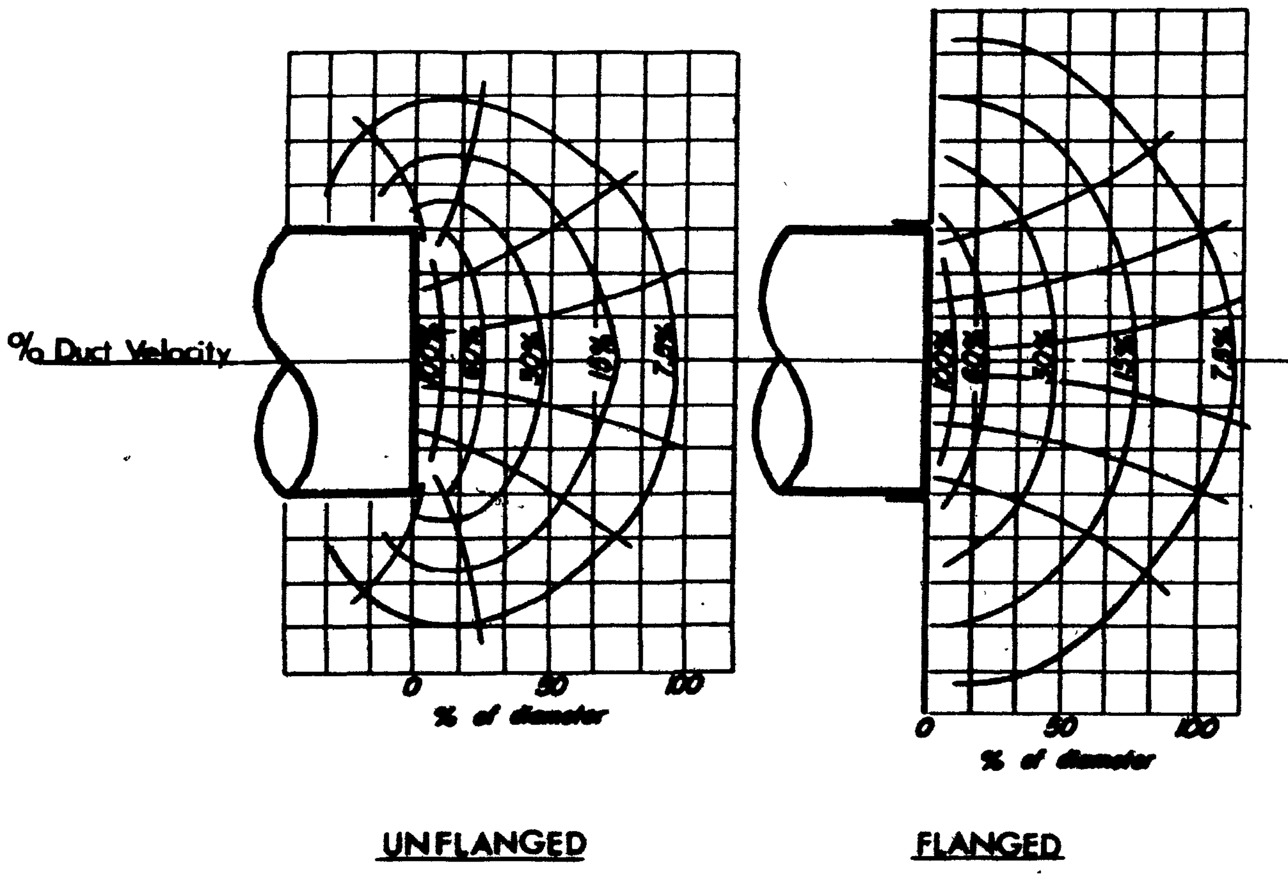


FIGURE 11: CAPTURE VELOCITIES AT A DISTANCE FROM A HOOD
(after ACGIH (15))

ratio. It is evident that this distance is of prime concern in the design of local exhaust systems. As the distance between the hood and the process increases, the required air volume also increases in order to achieve the desired capture velocity. Another method of ensuring sufficient capture velocities would be to use smaller ducts, thereby increasing the duct velocity.

2.2.2 HOODS AND DUCT VELOCITY REQUIREMENTS

Associated with every hood is a hood entry loss which is a result of the conversion of static pressure to velocity pressure inside the duct, where approximately 2% of the static pressure is lost (15). The coefficient of entry, C_e, is given by:

$$C_e = \sqrt{\frac{VP}{SP}} \tag{2.24}$$

therefore;

$$Q = 4.043A\sqrt{VP} = 4.043AC_e\sqrt{SP} \tag{2.25}$$

at standard density and pressure (mm of H_2O). The pressure loss as a result of entry is reflected in the following equation:

$$SP = VP + h_e \tag{2.26}$$

where h_e is the pressure head (mm of H_2O). Substituting Equation 2.26 into Equation 2.24 and solving for h_e gives:

$$h_e = \frac{(1 - C_e^2)VP}{C_e^2} \quad (2.27).$$

Figure 12 illustrates the coefficient of entry for different hoods.

The above analysis, in particular Equation 2.25, is very crucial to ensure the proper design of a local exhaust system. Having decided upon a capture velocity and a particular hood it is necessary to meet the guidelines in Table 5 for duct velocities. This is easily achieved with the proper selection of duct size. Entry losses must be added to frictional and shock pressure losses when selecting a fan.

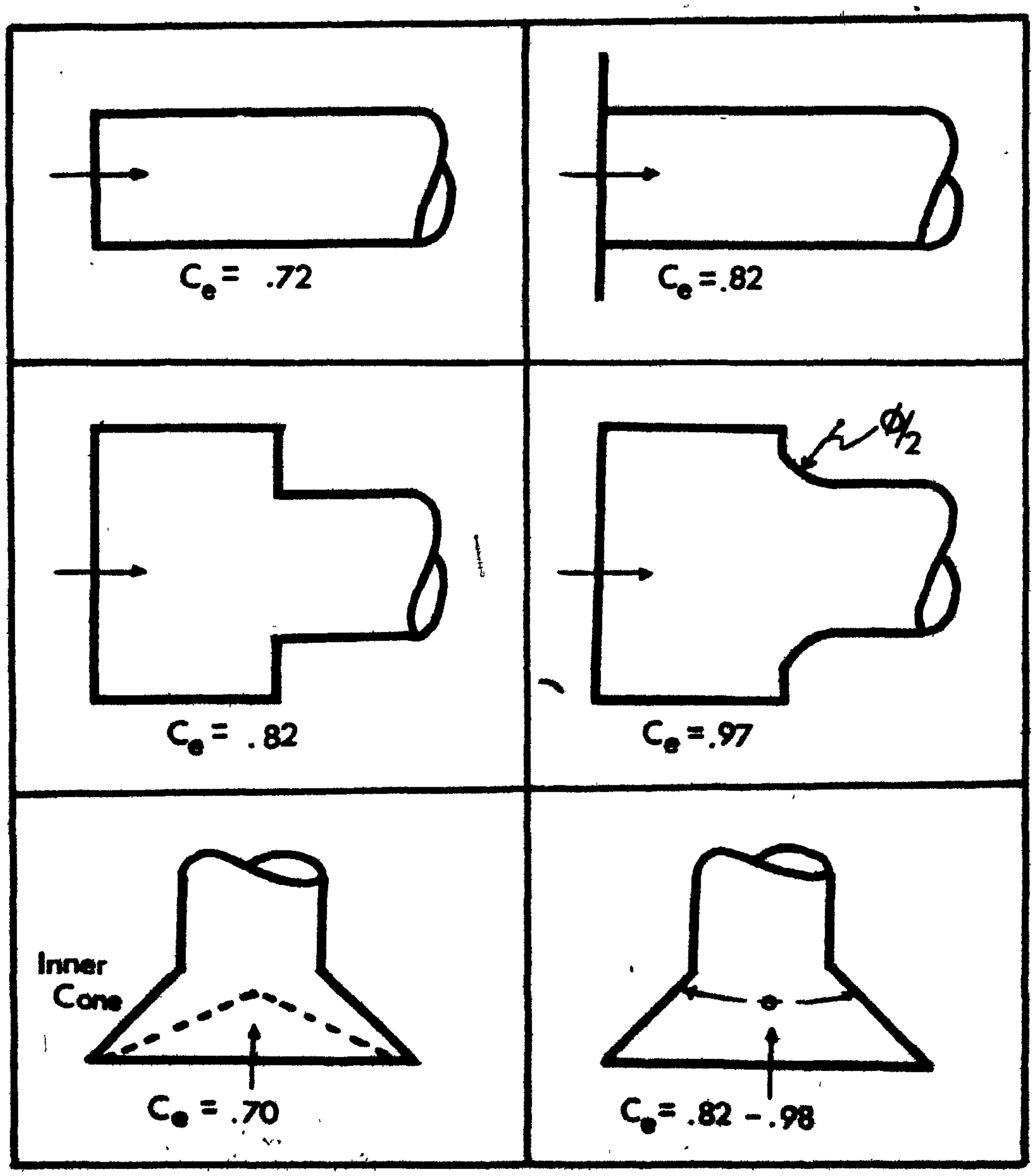


FIGURE 12: COEFFICIENTS OF ENTRY (after ACGIH (15))

CONTAMINANT	DUCT VELOCITY (m/s)
Vapours, Smoke, Gases	5.59
Fumes	7.11 - 10.16
Fine Light Dusts	10.16 - 12.70
Average Industrial Dust	17.78 - 20.32
Heavy Dusts	20.32 - 22.86
Very Heavy Dusts or Moist Dusts	22.86

TABLE 5: DUCT VELOCITY REQUIREMENTS (after ACGIH (15))

3.0 TRACER GASES AND VENTILATION EVALUATION

Traditionally, volumetric flow rate measurements with pitot tubes or other air velocity measuring devices have been used to balance and to calculate the number of air changes per hour (ACPH) or the ventilation rate of a given mechanical system. Other methods of finding ventilation rates have been used in the case of natural ventilation. The "crack or component method", which determines air leakage as described in Section 2.1.2, is one such method. Another involves the pressurization of a building with a fan and measuring the volumetric flow through it, which in turn reflects the ventilation rate.

Although these and other techniques have all been used in the past, each has its associated problems. For example, extending volumetric flows in ducting to an open space for the determination of the ventilation rate assumes that ventilating air mixes perfectly with room air, which is not true. Hitchin and Wilson (18) found this not only to be misleading but also stated that even if perfect mixing did occur, only 63% of the room would be changed after what is normally considered a complete air change. To apply duct measurements to calculations of the ventilation rate with any accuracy at all, ventilating air would have to push the existing air out of the area much like a piston would. The component method for finding the ventilation rate in a closed space, which is based on the identification and approximation of all cracks in a structure, also leaves considerable room for error. Some cracks may go unnoticed and it may be difficult to approximate equivalent lengths for others. Finally, the pressurization technique employed by Stricker (19) and Tamura (20) calculates the ventilation rate at a given pressure drop. Houses are not necessarily subjected to equal pressures on all sides under normal conditions and therefore, this technique does not adequately reflect true ventilation rates. In any case, the balancing of local exhaust and other ventilation systems can be cumbersome and time consuming using conventional tools. Corrections have to be made for air densities and turbulence acts to reduce accuracy. Frequent calibration of secondary air flow measuring instruments is also a problem.

In practice, most ventilation systems are characterized by dead pockets, short circuiting, and recirculation, which are not readily identified by the methods and tools outlined above. Smoke tubes can sometimes be used to qualitatively indicate these problems in given circumstances. An alternative method for evaluating ventilation system performance, which eliminates most of these shortcomings, uses a tracer gas.

3.1 PREVIOUS WORK

Tracing techniques have long been used to determine air mass movement using aerosol or gaseous tracers. Deuble (12) lists the following shortcomings of aerosol tracers:

- the need for proper dispersion and sampling,
- atypical diffusion in an atmosphere,
- losses from settling and impaction,
- instability in the atmosphere,
- statistical sampling error,

when using them to quantify air movement. Gaseous air tracers overcome most of these problems and consequently have been adopted more frequently.

Tracer gases have been used for pollution transport, building ventilation including laboratory hoods and local exhaust systems, mining ventilation, and rock porosity and permeability studies.

The following references, although not complete, represent a thorough examination of the publications related to tracer gases and the types of studies performed.

Pollution studies have been performed both indoors and outdoors. Lidwell and Williams (1960), Foord and Lidwell (1975), Lidwell (1981), and Schmidt (1975) studied indoor migration of bacteria and smoke in hospitals, the former being a concern because of infection and the latter in cases of emergency where asphyxiation can be a problem. The studies performed outdoors deal mostly with plume tracking and dispersion, but the Occupational Health Unit, Medical Services Branch, Health and Welfare Canada (unpublished, 1980) and Lamb et al. (1980) look at the possibility of contaminants re-entering buildings. Brown et al. (1975), Cohen et al. (1969), Collins et al. (1965), Dietz et al. (1973, 1976), Drivas and Shair (1974), Deuble and Broce (1979), Ferber and List (1973), Giroux et al. (1974), Lamb and Shair (1977), Niemeyer and McCormick (1968), Orgill et al. (1974), Shair et al. (1977), and Start et al. (1974, 1977) have all published reports of atmospheric pollution transport studies with tracer gases. These studies, although not directly related to the present research, outline different gases and techniques associated with the use of tracers.

The majority of building ventilation studies to date, have used the rate of decay method (see Section 3.2.1) for determination of the ventilation rate or the number of ACPH. Other investigators, e.g. Lamb et al (1980), have used tracer gases for local exhaust system performance evaluation. Knoepke (1977) and Owen and Scott (1967) used a tracing technique to determine the volumetric flow rates in closed conduits. Laboratory hood system efficiencies have been determined by Caplan and Knutson (1982) and Cottman and Walcott (technical bulletin). Nonetheless, ventilation rate or air infiltration investigations have dominated studies involving tracer gases in buildings. These studies have been carried out or investigated by Coblentz and Achenbach (1963), Hill and Kusuda (1975), Hunt et al. (1976), Kallioski et al. (1980), Lagus (1977, 1978), Tamura and Wilson (1963), and Warner (1940). In all cases, the studies deal with the rate of decay as a function of the effects of natural ventilation.

Tracer gases and techniques have also been used in mine ventilation studies. The aims of the studies were to find volumetric flow rates in underground roadways, the effectiveness of face ventilation, recirculation of contaminated mine air, leakage through mine stoppings and bulkheads, and the extent of migration of pollutants underground. Kissel and Bielicki (1974), Matta et al. (1978, 1980), Thimons et al. (1974, 1974) Timko et al. (preprint), and Vinson et al. (1980) have all performed mining studies. The determination of the residence time of ventilating air in uranium mines is outlined by Brossard and Associates (1980) and by a study performed in Agnew Lake Mines, Agnew Lake, Ontario (1978).

Many of the methods used were combined and adapted to produce a method of evaluating the performance characteristics of a ventilation system in an air tight building.

3.2 TRACER GASES: PROPERTIES AND CHARACTERISTICS

There seems to be general agreement on the desired properties of a tracer gas. Collins et al. (30) describe the following requirements:

- nontoxic, odorless, and colorless even at relatively high concentrations;
- gaseous at temperatures well below ambient and possessing a low molecular weight to provide rapid mixing with air;
- not likely to be found in the atmosphere of concern even in the parts per trillion range;
- chemically stable towards hydrolysis, oxidation, and photolysis;
- capable of being easily dispersed into the atmosphere of concern at a measured rate;
- samples easily collected by unskilled workers;
- capable of being detected in the parts per billion or trillion range.

Simply stated, a tracer gas is any gas that can be mixed with air and measured at very low concentrations to yield air flow patterns and measurements. An additional dimension therefore exists in comparison to conventional ventilation measurement methods; the ability to measure air movement and transfer in open spaces.

Extensive use of tracer gases, including hydrogen, helium, carbon monoxide, carbon dioxide, sulphur hexafluoride (SF_6), ethane, nitrous oxides, freons, and others, dates from the 1960's. Table 6 is a summary of the characteristics of some of the gases. Of these, SF_6 and freons have most of the desired qualities. However, the extensive use of freons as refrigerants, combined with decreased detectability and higher ambient concentrations, make it somewhat less attractive. On the other hand, SF_6 is used as an electrical insulator; therefore, there may be a background concentration in the vicinity of high power voltage facilities. One other possible disadvantage of SF_6 is that it decomposes into more toxic, lesser fluorides of sulphur at temperatures in excess of 550 ^{o}C.

3.2.1 SULPHUR HEXAFLUORIDE (SF_6)

SF_6 was discovered by Moissan and Lebeau in approximately 1900 (2) and was first used as a tracer gas in 1965 (61). Its physical and chemical properties are outlined in Table 7. Atmospheric concentrations of SF_6 are less than two ppt by volume. Teflon, a substance used for its inertness in many analytical chemistry devices, has been found to absorb SF_6 (31).

SF_6 is considered inert, odorless, colorless and non-toxic. Studies have been performed on rats where the nitrogen in their atmosphere was replaced with SF_6 (approximately 80% SF_6) and no side effects were noticed (10). The gas has also been used in pulmonary function tests where humans had their

TABLE 6: CHARACTERISTICS OF DIFFERENT TRACER GASES (after Lagus, 1978)

GAS	MEASUREMENT APPARATUS	TLV (vol/vol)	DETECTION LIMIT (ppm)	TOXICITY	CHEMICAL INERTNESS	COMMENTS
H_2	katharometer	4% (LEL)	200	nontoxic	reacts to oxygen, heat, flame	flammable, explosive
He	katharometer	-	300	nontoxic	nonreactive	nonreactive
CO	IR absorption, GC with FID	50ppm	5	asphyxia	reacts to flame	can react to O_2 in high concentrations and may explode
CO_2	IR absorption, GC with TCD	5,000ppm	1 70	nontoxic	water soluble	-
SF_6	GC with ECD	1,000ppm	$.02 \times 10^{-3}$	nontoxic	inert	may produce toxic agents at > 550°C
N_2O	IR absorption	25ppm	1	nontoxic	water soluble	can form explosive mixtures in air
ETHANE	GC with FID	3% (LEL)	5	nontoxic	burns in air	may explode in O_2 and heat or flame
FREON	GC with ECD	1,000ppm	1×10^{-3}	nontoxic	stable	

TLV - Threshold Limit Value
IR - Infrared spectroscopy
ECD - Electron capture detector
GC - gas chromatography
TCD - thermal conductivity detector
FID - flame ionization detector

MOLECULAR WEIGHT	146.07	SUBLIMATION POINT	-64 °C
DENSITY GAS	6.60	DENSITY LIQUID	1.67
FREEZING POINT	-51 °C	LOW TOXICITY	

TABLE 7: PROPERTIES OF SULPHUR HEXAFLUORIDE

lungs filled with an 80% mixture of SF_6; again, no side effects were noticed. However, at elevated temperatures (>550 °C), SF_6 decomposes into sulphur tetrafluoride, which is an extremely toxic substance with an ACGIH recommended Short Term Exposure Limit of 0.4 mg/m^3.

Electronegative gases like SF_6 are particularly well suited to detection by electron capture (EC) gas chromatography (GC). Infrared (IR) spectrometry can also be used.

3.3 TRACER GAS METHODS FOR VENTILATION EVALUATION

Hitchin and Wilson (18) outlined four tracer gas methods:

- rate of decay,
- equilibrium concentration,
- transfer index, and
- steady concentration.

Table 8 outlines these methods and lists their advantages and disadvantages. Although these are the main techniques used in tracer gas studies, hybrids of these have also been developed and tested. For example, the Occupational Health Unit, Medical Services Branch, Health and Welfare Canada (26) used a dilution factor to estimate contaminant concentrations in a building in case of a chemical spill. This is a hybrid of the transfer index technique. Lamb et al. (27) use a modified form of the transfer index to determine the efficiency of pot gas collectors in the aluminium industry. The equilibrium concentration and transfer index methods can be further used to measure volumetric flow rates in closed conduits as Knoepke (9) and Thimons et al (10) showed. Caplan and Knutson (47) describe a method for evaluating the efficiency of laboratory hoods. Nonetheless, this section concentrates on the techniques outlined by Hitchin and Wilson (18) because these represent the basis to all studies involving tracer gases for the purpose of ventilation evaluation.

TECHNIQUE	ADVANTAGES	DISADVANTAGES
RATE OF DECAY	- simple analysis. - reasonable sampling period.	- possible non-exponential decay. - difficulty getting uniform ambient conditions.
EQUILIBRIUM CONCENTRATION	- single measurement. - transfer index can be calculated. - can be used to measure volumetric flow rated in closed conduits. - perfect mixing is not required.	- long period to get equilibrium in an open system. - requires a sophisticated release device.
TRANSFER INDEX	- perfect mixing is not required. - can be used to measure volumetric flow rates in closed conduits. - can readily indicate recirculation.	- long sampling period or frequent sampling is required.
STEADY CONCENTRATION	- no mixing hypothesis. - equilibrium concentration is achieved more rapidly	- sophisticated release device. - assumption or measurement of source concentration.

TABLE 8: SUMMARY OF ADVANTAGES AND DISADVANTAGES OF TRACING METHODS

3.3.1 THE RATE OF DECAY METHOD

The rate of decay method has been one of the more extensively used tracer gas techniques. In this method, the gas is released to achieve a nearly uniform concentration throughout the area of concern so that the effects of diffusion are minimal. One way to ensure proper mixing and the desired initial condition is to release the gas through the ventilation system with all doors between rooms open. Other techniques, especially point releases, may require some manual mixing. Once the uniform concentration has been achieved, the decay of the gas is monitored.

Decay will occur according to:

$$C_t = C_o e^{-VRt} \tag{3.1}$$

where: Ct is the measured concentration, Co is the initial concentration, and VR is the ventilation rate (ACPH). Solving this equation for VR gives:

$$VR = 1/t \ln C_o/C_t \tag{3.2}$$

Plotting the measured concentration versus time on semi-logarithmic graph paper should yield a straight line whose slope is equal to the ventilation rate if perfect mixing exists. If perfect mixing does not exist, the function may not be linear. Hence, phenomena like recirculation and short circuiting should be investigated. These phenomena can be more easily identified if sampling is performed at several locations, which also allows the determination of the effective ventilation rate at the different positions. For instance, if an entire floor in a building is being investigated, multi-point sampling for the decay of a tracer gas can yield the effective ventilation rate for each sampling site as well as the overall ventilation rate for the floor by averaging all results.

3.3.2 THE EQUILIBRIUM CONCENTRATION METHOD

The principle underlying the equilibrium concentration method is that releasing a gas at a continuous rate gives an equilibrium concentration throughout a ventilation system. The concentration reflects the amount of ventilating air by the equation:

$$Q = R_r/C_{eq} \tag{3.3}$$

where: R_r is the rate of emission (m^3/s) and C_{eq} is the equilibrium concentration. If measurements were to be made throughout the area being evaluated, effective ventilation rates could be determined. Furthermore, this method lends itself to the determination of volumetric flow measurements in closed conduits where the gas is released into the conduit and measured further downstream. Q, as found by Equation 3.3, represents the volumetric flow rate. The equilibration period is much decreased in this instance.

The major disadvantage of this method, especially when dealing with a relatively expensive gas like SF_6, is that equilibrium concentration takes a long time to achieve when finding effective ventilation rates and consequently, a lot of gas is used (18).

3.3.3 THE TRANSFER INDEX METHOD

The transfer index method vies with the rate of decay method in popularity. It has been used in a variety of ventilation studies ranging from cross infection studies in hospitals (22) to volumetric flow rate measurements in underground mines (12). This method involves the release of a known amount of gas and the measurement of the time integral concentration at points throughout the system being studied. The transfer index (TI) is expressed as:

$$TI = 1/Q_R \int C_t \partial t \tag{3.4}$$

where: Q_R is the amount of gas released (m^3). The effective ventilation rate (m^3/s) is given by the reciprocal of the TI. Equation 3.4 can be reduced to a form which Thimons and Kissel (12) used to find volumetric flow rates in underground mines:

$$Q_R = Q \int C_t \partial t \tag{3.5}$$

which is equivalent to:

$$Q_R = Q.C_{avg}.t \tag{3.6}$$

where; Q represents the volumetric flow rate.

Taking samples at given intervals and averaging them for the calculation may tell an investigator more about the ventilation system in question than one time-weighted average sample. For instance, it indicates the amount of time required for the tracer gas to reach a particular area or when recirculation begins in a ventilation system characterized by it.

3.3.4 THE STEADY CONCENTRATION METHOD

The steady concentration method combines the transfer index and equilibrium concentration methods. The tracer gas is released at a controlled rate, which results in a known concentration at the source, and the gas concentration is measured at other points. When the concentration at any point becomes steady, the transfer index can be calculated by a simple ratio of the two concentrations. Again, the TI can in turn be used to find the effective ventilation rate (m^3/s).

Controlled injection of the tracer is very important when using this method, which consequently requires a sophisticated release apparatus.

3.4 CONVENTIONAL METHODS USED IN EVALUATING VENTILATION

In the past, standard methods have been adopted by different professional organizations for the testing of ventilation systems. Three such organizations are ASHRAE, ACGIH, and the British Standards Institute. Although the adopted practices may not always be the same, these usually agree fairly well. Only the more widely used methods are presented below.

3.4.1 PITOT TUBES AND AIR FLOW MEASUREMENTS IN CLOSED CONDUITS

Although pitot tubes are not the only instruments available for air flow measurements in ducting, these are a primary measuring device and the theory behind their use extends to the other instruments used. Various electronic and mechanical instruments which serve the same purpose exist. However, these are secondary measuring instruments and require calibration. Their main advantage is that instantaneous readings can be obtained.

A pitot tube is used in conjunction with a manometer to give pressure measurements inside of closed conduits where the velocity is greater than 3.05 m/s. It is inserted into a duct so that the measuring end is parallel to air flow. Total, static, and velocity pressures can be measured; however, velocity pressure is used for volumetric flow rate determination. Once this is measured, the velocity can be found using Equation 2.25.

Often, centreline measurements are made and a percentage (80 to 90%) of the value is applied as an approximation of the average duct velocity pressure. If more accurate results are required, then a traverse should be made and results averaged. Figure 13 shows traverse points for both circular and square ducting as outlined by the ACGIH.

3.4.2 AIR EXCHANGE RATES IN OPEN SPACES

The number of ACPH in a structure can be determined in a variety of ways, some being more empirical than others. The most empirical method is described in the ASHRAE Book of Fundamentals (62). In this technique, a ventilation rate of a room is assumed according to its relative position in the structure and the number of doors and windows associated with it. The average air exchange rate of all rooms can then be applied to the building to give an overall ventilation rate.

The crack, or component, method is another technique used to determine ventilation rates. Here, the investigator locates all cracks or openings in a structure and expresses these as an equivalent length. The amount of infiltration through each crack is then calculated (19). The total amount of infiltration gives the ACPH for the structure.

The last method, sometimes called the Equivalent

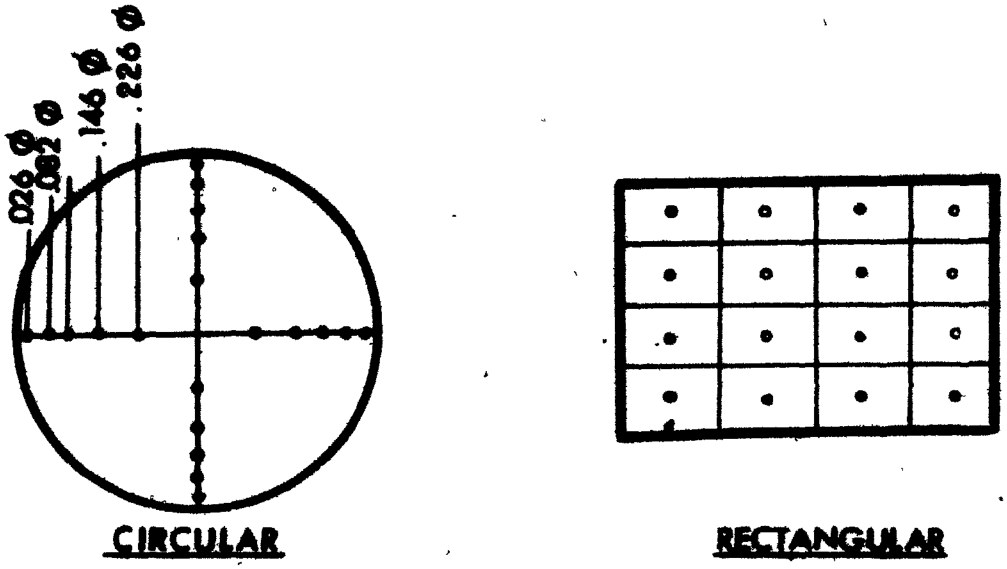


FIGURE 13: TRAVERSE POINTS FOR CIRCULAR AND RECTANGULAR DUCTING (after ACGIH (15))

Leakage Area (ELA) method, is quite sophisticated and requires proper instrumentation. A large fan is placed in a window or another opening in the building and all cracks and openings are sealed. The fan is started and set at a given pressure. With the pressure constant, as the seals are removed, the increased flow rate through the fan represents the infiltration through cracks. Consequently, the extent to which a crack or a set of cracks contribute to the overall infiltration rate can be determined. Having all the seals removed yields the ventilation rate for the entire building. On the other hand, the flow rate with all seals in place gives the infiltration through walls, building materials, etc.

The methods described above can only be used in the case of natural ventilation. The only conventional way of determining ventilation rates in a hermetically sealed building is to measure the amount of fresh air entering the mechanical system assuming even distribution. This quantity divided by the volume of occupied space, including the plenum, gives the ACPH.

4.0 TRACER GAS STUDIES AND METHODOLOGIES

Although tracer gas techniques have been widely used in a variety of building ventilation studies, as a rule, only one aspect of a system has been evaluated. Knoepke (9) found the flow of flue gases in an industrial setting and compared the results obtained with results of pitot tube tests. The average difference was 4% but only five tests are reported in the publication. The rate of decay method has been used frequently to find ventilation rates, and Coblentz and Achenbach (6), Hill and Kasuda (49), and Tamura and Wilson (8) have compared this method to those outlined by ASHRAE with various conclusions. As yet, no work has been done combining these two types of studies to give a more detailed description of the performance of a given ventilation system.

To arrive at a procedure that would combine the rate of decay, transfer index, and equilibrium concentration methods for a more thorough examination of a building ventilation system, both laboratory and preliminary field investigations were necessary. The laboratory work involved the release of a gas into a duct system to ascertain volumetric flow rates. The experiments were repeated until reasonable confidence in a method of release and sampling was assured. The preliminary field work was performed as part of a much larger study which dealt with, in part, finding decay rates of a tracer gas in an office environment. This provided a forum for working out details and discovering field related problems to be anticipated and accounted for in the final protocol. Not all the results of the preliminary work are presented, but those that exemplify the critical phenomena encountered in tracer gas studies are given in Chapter 5. Once the procedure was finalized, it was tested five times.

4.1 VOLUMETRIC FLOW RATE MEASUREMENTS IN LABORATORY DUCTING

The objective of laboratory studies was to develop and validate a procedure using the equilibrium concentration method and SF_6 to measure volumetric flow rates in ducts. Once developed, this would be adapted and used to measure flow rates in ducting in a building.

The investigation concentrated on the methods of release and sampling. The low volumetric flow rates in the laboratory system required a SF_6 standard of about 12 ppm to be used as the tracer. This ensured that the release rate could be well quantified. Pure SF_6 required release rates that were too low to be accurately measured with available equipment. Two types of samples were collected initially; syringe and bag samples. The syringe samples represented point or instantaneous measurements and the bag samples a two minute time weighted average. The syringe method was quickly discarded as time dependent errors became evident.

The flow rates obtained with SF_6 were checked against those found with a hot wire anemometer. Although it would have been better to use a primary air velocity measuring device, low duct velocities made it impossible to use pitot tube traverses. The hot wire anemometer was calibrated against a pitot tube in a laboratory wind tunnel at velocities in excess of 3.05 m/s and this calibration factor was assumed for the lower velocities measured.

4.1.1 EQUIPMENT

The laboratory duct system (Figure 14) was made of galvanized 0.15 m (6") diameter stove pipe with all joints caulked with silicone to prevent leakage. It consisted of four branches, all of which were under negative pressure when operating. The fan was a 7457 W (10 hp), 1500 rpm, 0.18 m (7") diameter centrifugal type. The air was exhausted from the laboratory through a corrugated plastic tube to prevent any SF_6 contamination of room air. Sampling ports were installed as indicated in the figure.

For SF_6 release, a 0.1 m^3 plastic bag of an approximately 12 ppm standard was used along with a Gillian high/low flow personal sampling pump. Tygon tubing connected the bag standard to the pump and fed the SF_6 into one end of the duct system.

Sampling was carried out with Gillian pumps and aluminized gas sampling bags. An Alnor hot wire anemometer was used before and after the tracer gas tests to determine air velocities for comparison.

The SF_6 analysis was performed using a Varian 3700 gas chromatograph with an EC detector (ECD) and a 0.5 nm molecular sieve column. Syringe injections were used. A Hewlett Packard 3390A Integrator resolved the GC response into interpretable results.

For standard generation of both the release and

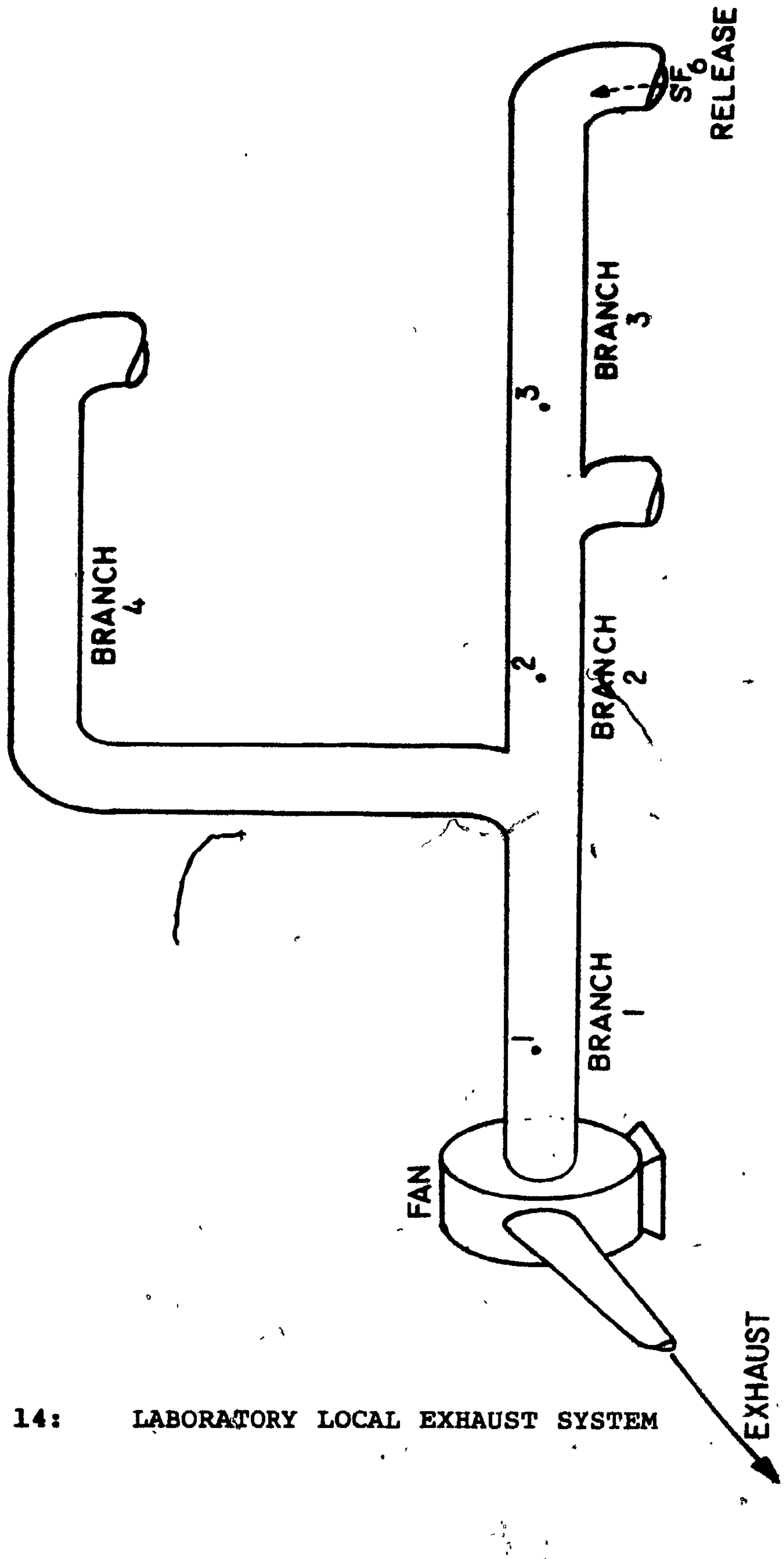


FIGURE 14: LABORATORY LOCAL EXHAUST SYSTEM

calibration standards, a Metronics Dynacalibrator 340 standard generator outfitted with SF_6 permeation devices was used.

4.1.2 PROCEDURE AND INTERPRETATION

The procedure arrived at through initial testing involved:

- release standard preparation (Appendix III),
- GC calibration (Appendix IV),
- actual testing,
- analysis.

The release standard was generated over a period of three days at an approximate flow rate of 3.67×10^{-7} m^3/s (22 ml/min) which was checked five times. A time weighted average flow was used to calculate the final concentration of 11.8 ppm. The Gillian pump used to release SF_6 into the laboratory system was calibrated at 1.67×10^{-5} m^3/s (one lpm). Between the initiation of the release and sampling, the hot wire anemometer was used to make a five point traverse at the three sample locations while the SF_6 was allowed to equilibrate for at least two minutes. Bag samples were then collected at an approximate rate of 1.67×10^{-5} m^3/s for two minute intervals. Each test spanned 16 minutes and samples were collected at ports one, two, and three from:

- 0 to 2 minutes,
- 7 to 9 minutes,

- 14 to 16 minutes.

This was repeated three times and between each test, the samples were analyzed and the bags flushed with zero air. Room air samples were collected occasionally throughout the testing to ensure that there was no SF_6 contamination. At the end of the tracer gas testing, the anemometer was again used for five-point traverses.

This procedure gave air velocities before and after testing and 27 volumetric flow rate measurements (nine at each location). The air velocity measurements were easily converted to flow volumes by multiplying by the cross sectional area of the duct. The equilibrium concentration method was used to determine the volumetric flow rate (m^3/s) at each sample location by the equation:

$$Q = R_r \cdot \frac{C_{standard}}{C_{measured}} \tag{4.1}$$

which is a modified form of Equation 3.3. The volumetric flow rate at location four could be found by simply subtracting the flow volume at two from that at position one.

4.2 OFFICE COMPLEX STUDY

The office complex investigated consists of three office towers and a hotel. A promenade occupies the first two floors of the office towers. The complex is hermetically sealed for energy effeciency and is made of concrete with prefabricated insulated external walls and a brick facade (63). The towers are referred to as east, central, and north (Figure 15). The east tower can be divided into two parts, with the centre acting as the northern wing of the southernmost part. The north tower has 28 floors of office space, the central tower seven, the east tower 18. Because of the terraced nature of the complex, floor plans change with respect to height.

The HVAC system is variable air volume (VAV) which means that the amount of ventilating air supplied to an area is a function of the ambient temperature in that area. As the temperature rises, a thermal sensing unit opens a linear air diffuser, allowing in more cooling air. This occurs in both summer and winter, even though outside air is heated in the winter and cooled in the summer. Each floor is divided into a perimeter and an interior zone. Originally, the perimeter zone was designed so that the diffusers would always operate at some 40% of their total capacity to minimize the effects of heat transfer across windows, whereas the interior diffusers would shut completely when the ambient temperatures reached acceptable levels. This has been reportedly changed and all diffusers remain at least 40% open (63).

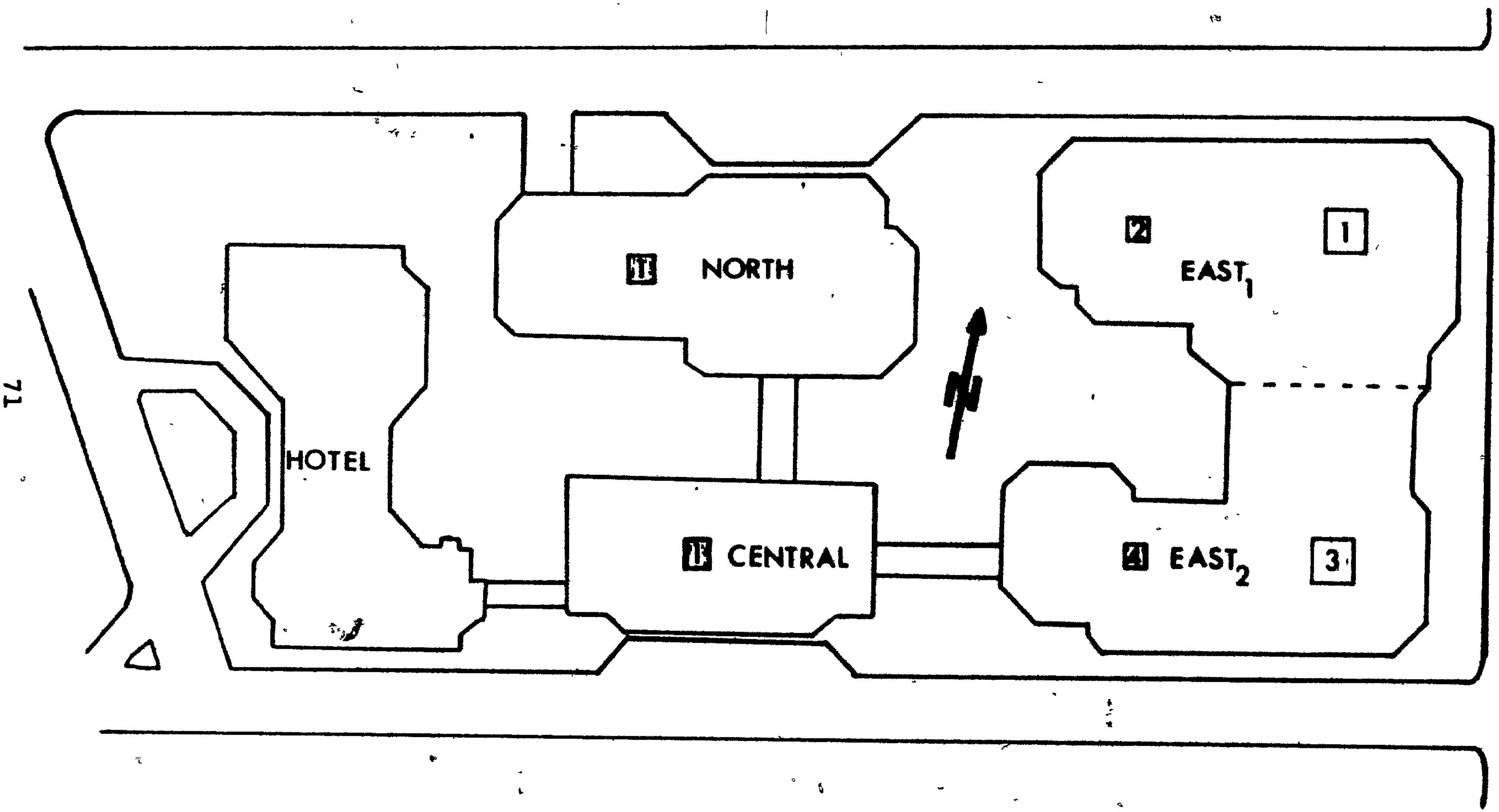


FIGURE 15: PLAN VIEW OF OFFICE COMPLEX

Fresh air handling systems are located in the penthouses of the north and east towers and in the basement of the central tower. Two auxiliary handling units exist on the 10th and 14th floors respectively in towers east 1 and east 2. The outside air, once conditioned, is supplied to mechanical rooms on each floor where it is combined with recirculated air and redistributed to the workplaces. A typical room is shown in Figure 16. The floors of the north and central towers are served by one mechanical room each, whereas on the lower, larger floors of the east towers, two mechanical rooms are used. These ventilation cores are also indicated in Figure 16.

The fresh air handling systems are designed to supply 7.1×10^{-5} m^3/s (0.15 cfm) of outside air per 9.3×10^{-2} m^2 (one ft^2) of occupied floor space. This is equivalent to 7.1×10^{-3} m^3/s (15 cfm) of outside air per person if the occupant density is one person per 9.3 m^2 (100 ft^2). This should provide more than one ACPH of outside air throughout the offices. At the same time, at least 3.2×10^{-4} m^3/s (0.67 cfm) of recirculated air per 9.3×10^{-2} m^2 of office area is also being supplied. More air is supplied to the perimeter zone than to the interior zone with an average of 3.9×10^{-4} m^3/s (0.82 cfm) of air per 9.3×10^{-2} m^2 of office area circulating through the mechanical rooms to the occupied areas. The system is designed to deliver more than five ACPH of total ventilating or primary air.

Workroom and general exhaust air is exhausted through

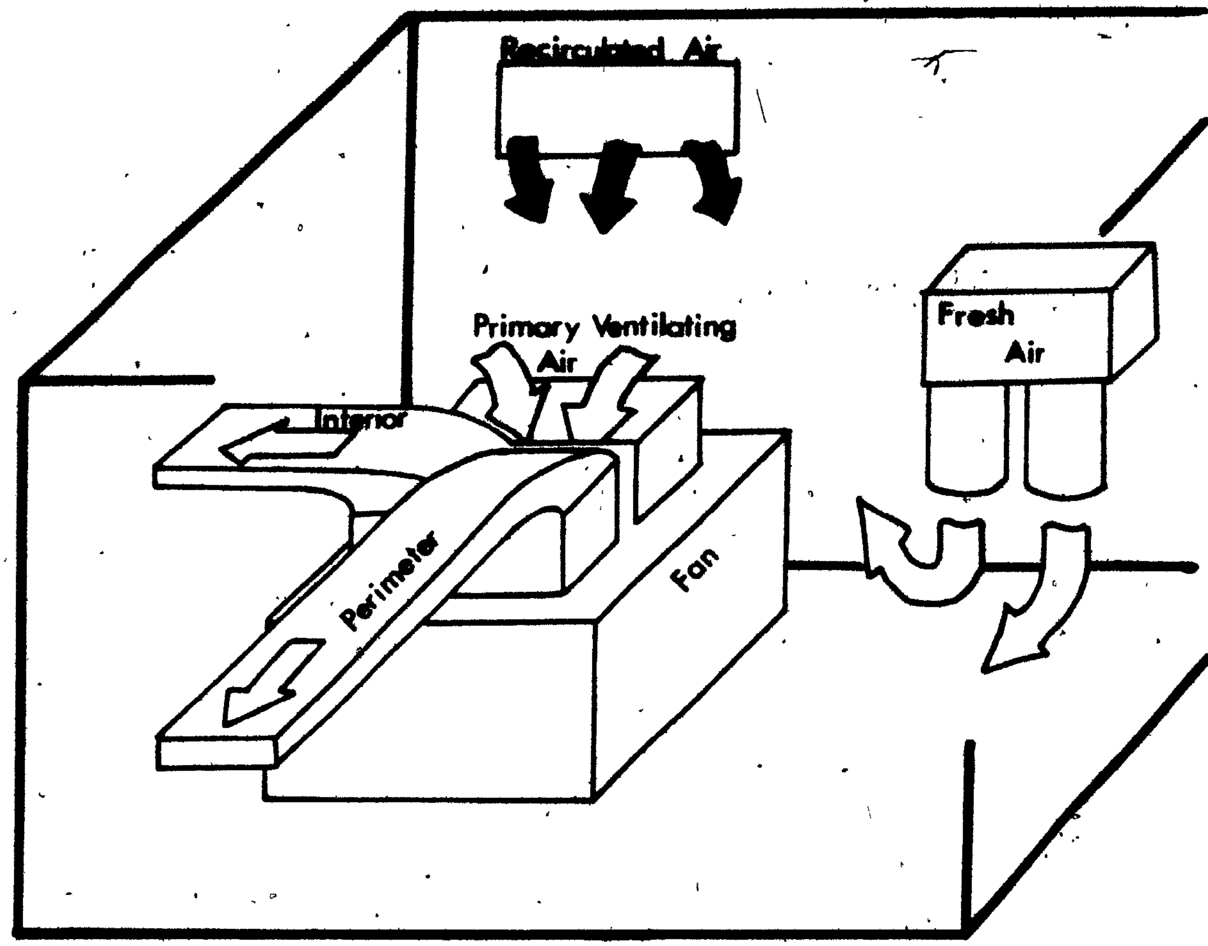


FIGURE 16: MECHANICAL ROOM SCHEMATIC

Z-duct heat exchange units to recover some of its heat before discharging it outdoors. In the summer, this may serve to cool incoming air of temperatures in excess of 30 °C. The Z-duct system included by-pass dampers which allowed the mixing of general and washroom exhaust with incoming air under extreme winter conditions to prevent freezing of the unit. A previous investigation of the ventilation system showed leakage here, and the dampers were sealed shut to prevent re-entry of exhaust air (63).

4.2.1 PRELIMINARY TESTING

Preliminary testing was carried out on nine floors throughout the office complex as listed Appendix V. The objective of these tests were two-fold: firstly, to find decay rates with the rate of decay tracer gas method so that floors could be ranked on relative basis as a part of a much larger study; and secondly, to investigate release and sampling parameters so that a procedure could be developed for ventilation performance evaluation.

To find effective ventilation rates with the rate of decay method, SF_6 was released over a one or two minute period through the ventilation system on a given floor. The decay of the gas was monitored over a four hour period at several sites in the workplaces.

The investigation of sampling and release parameters, so that a tracer gas test could be developed for performance evaluation of ventilation, included: sample timing, methods, and periods and release mechanisms. These sampling parameters are important in tracer gas studies because these have to be used to provide the most information possible. Different approaches to sampling yielded the optimum technique for the available equipment. A variety of release methods were studied for use with the equilibrium concentration and transfer index techniques to determine fresh and primary air supply rates.

4.2.1.1 EQUIPMENT

For the release of the tracer gas, different equipment can be used. A gas cylinder of SF_6 along with a flow meter can be used for large, non-specific releases, but for more precise work flow metering valves should be used. These were tested.

Sampling was carried out using personal air sampling pumps outfitted with a sampling manifold. The manifold incorporated solenoid valves which were activated by a Durant 6450 programmable timer. The timer was located centrally and transmission cable ran to each sample site. Plastic bags were used to collect air samples.

A portable Analytical Instrument Development (AID), Inc. gas chromatograph 511-60, an ECD and a 0.5 nm molecular sieve column outfitted with a Hewlett Packard 3390A integrator, were used for analysis of SF_6. Samples were drawn through a 1.0 x 10^{-6} m^3 (ml) gas sampling valve or injected manually. Both methods gave similar results (outlined in Section 5.3.2. A Metronics Dynacalibrator 340 with SF_6 permeation devices was used to generate gas standards.

4.2.1.2 PROCEDURE AND INTERPRETATION

Procedures varied from test to test and are specifically outlined in Appendix V. After attempts to quantify fresh and primary air supply rates were performed, floors were flooded with SF_6 to a nearly uniform ambient concentration. This was achieved by releasing the gas into the mechanical room and waiting long enough for the concentration to peak in the occupied areas. The release had to be repeated in all cores ~~supplying a particular~~ floor. The volume of gas released in a given core depended on the volume of the floor influenced by the core. This ensured uniform initial conditions. The decay of the gas was then monitored at eight sample locations (four interior and four perimeter zone). When the measured SF_6 concentrations were plotted as a function of time on semi-logarithmic graph paper, the slope of the line gave the effective ventilation rate (Section 3.3.1).

Fresh air and recirculation rates testing was also attempted in this part of the investigation, but results were erratic. To find these rates, the equilibrium concentration method was used most often. Pure SF_6 was released in the fresh air supply duct and samples were collected downstream in these ducts to reflect the amount of fresh air being supplied, and on the opposite side of the fan supplying air to work areas, to reflect the amount of recirculated air, which is the difference of the primary and fresh air supply volumes (see Figure 16). Sampling was done first to find recirculation rates so that the SF_6 did not have time to re-enter the mechanical room with the recirculated floor air. This can lead to erroneous results (discussed in Section 5.2). Occasionally, a similar procedure was employed to find recirculation rates with the transfer index method, the only difference being that a known volume of SF_6 was instantaneously released in the mechanical room. In these instances, this testing preceded the testing to determine fresh air supply rates.

4.2.2 TESTING OF THE ADOPTED TRACER GAS PROCEDURE

The 28th floor in the north tower was chosen for the testing of the finalized procedure described in Section 5.1. The floor is approximately 27.9 by 42.5 m (92 x 140 ft) and is about 3.5 m (11.5 ft) high, including the plenum above the false ceiling. The occupancy space is equal to about 920 m^2 (9900 ft^2). Total design ventilating air to the perimeter zone is 3.0 m^3/s (6350 cfm), or 5.2×10^{-5} m^3/s (1.1 cfm) per 9.3×10^{-2} m^2 (one ft^2) of occupied space, and to the interior zone is 1.8 m^3/s (3730 cfm) or 4.2×10^{-4} m^3/s (0.9 cfm) per 9.3×10^{-2} m^2 of occupied space.

A plan view of the floor (Figure 17) shows the types of offices present and the sample locations.

The objective of the tests performed was to show that the procedure adopted as a result of the preliminary work can be used to determine:

- effective ventilation rates using the rate of decay method,
- overall ventilation rates using the average of the above,
- the primary air supply rate using the transfer index technique,
- the amount of fresh air supplied to the floor using the equilibrium concentration method.
- the percentage of recirculation using the last two results.

Fresh air supply rates were also found by the conventional pitot tube traverse technique. Because of the construction of the fresh air supply ducts, it was necessary to use only the effective area of the ducts as determined by the pressure measurements. For example, results found behind baffles were often zero and therefore, those were discarded along with their zone of influence in subsequent calculations. No corrections for temperature and humidity were made because the additional uncertainty introduced into the results is minimal compared to the uncertainties introduced due to the position of the

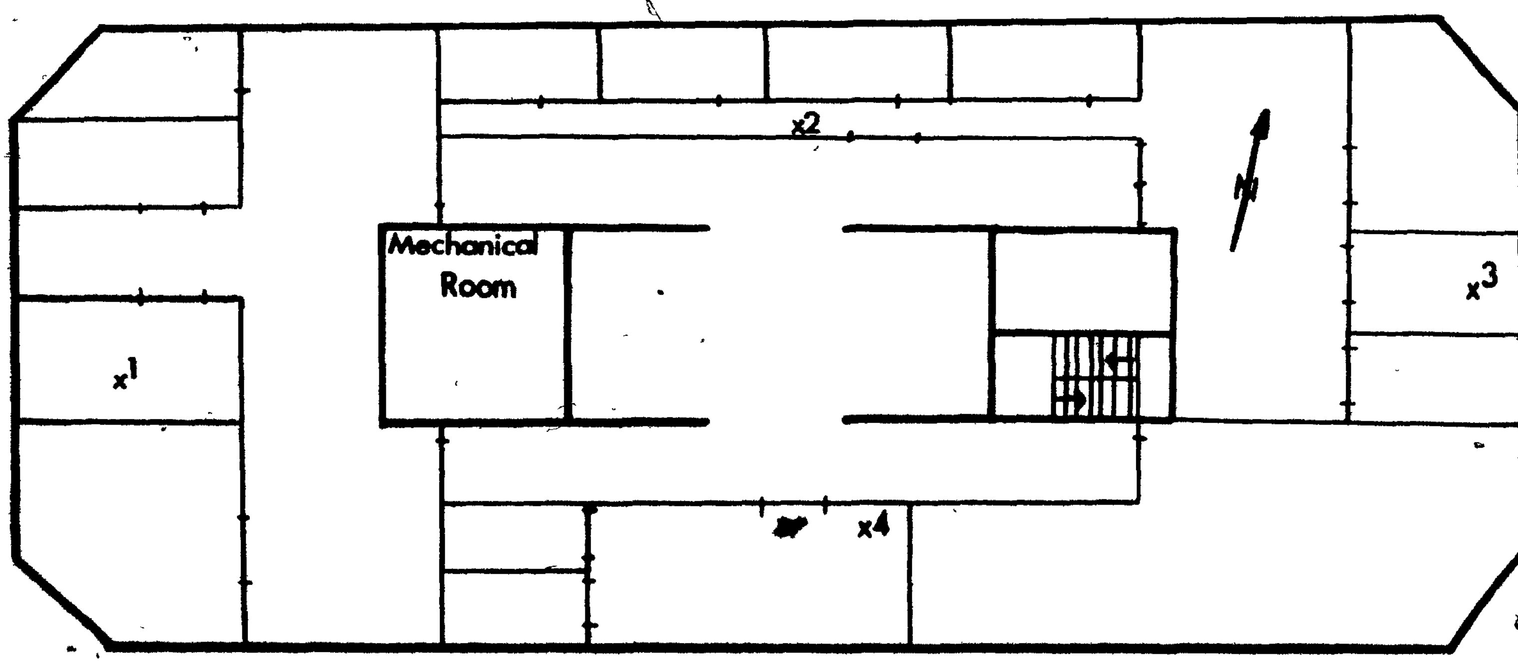


FIGURE 17: PLAN VIEW OF THE 28th FLOOR

traverses.

4.2.2.1 EQUIPMENT

The analytical chemistry equipment employed was the same as that mentioned in Section 4.2.1.1. Tracer gas release was achieved in three ways. For fresh air supply rate calculations, a 9100 ppm gas standard was released into the two ducts with a Devilbiss electric pump. Known volumes of SF_6 were released with a plastic 5.0×10^{-6} (50 ml) syringe to determine both effective ventilation and primary air supply rates. Furthermore in some instances, SF_6 was released from a gas cylinder through a two stage regulator with an in line flow metering valve to initially flood the floor with the gas to find effective ventilation rates.

Bag samples were collected when finding the fresh air supply rates and syringe samples were used for primary air calculations. Both these techniques were employed in the rate of decay method after a comparison of the two proved favorable.

4.2.2.2 PROCEDURE AND INTERPRETATION

The procedure to determine volumetric flow rates of the outside air/ the amount of recirculated air and the effective ventilation rates at selected sample locations was in three parts, excluding analytical work (Appendices III and IV).

It was first necessary to prepare a 1.0×10^{-2} m^3

(10 l) bag standard to be used for outside air supply rate measurements. The concentration of the standard was determined by the expected volumetric flow rate in the outside air supply ducts and the linear range of the GC to be used. For example, a system handling 4.7 m^3/s (10 000 cfm) at 20% outside air would require a 2832 ppm (0.28%) standard of SF_6 to be released at 1.67×10^{-5} m^3/s (one lpm) into the supply ducts, if the perimeter and interior zones were supplied separately and equally, to result in a concentration of 100 ppb in the ducts as determined by Equation 4.1. Once this and analytical preparatory work was completed, the first step was to release a known volume of SF_6 into the mixing room close to the fresh air supply ducts and to sample on the supply side of the floor fan to find the primary air supply rate. Timing of the samples was very important and had to be done as quickly and as often as possible after the release to ensure that the effects of recirculation could be pinpointed. The initial volume released again depends on the linear range of the GC and the amount of primary air ventilating the office space. As reflected by Equation 3.6, the amount of gas released, Q_R, had to ensure that the average concentration was composed of no single sample concentration above the linear range.

Next, using the equilibrium concentration method, the amount of fresh air entering the mixing room was determined. Recirculated SF_6 had no bearing on this aspect of the study unless it recirculated back into the building through the fresh air handling unit. Therefore, background samples were taken as a check. A similar procedure for volumetric flow rate determination with the equilibrium concentration method has already been thoroughly outlined in Section 4.1.

At this stage, the amount of primary air supplied by the mechanical room and the amount of fresh air supplied have been determined with the transfer index and equilibrium concentration methods respectively, using Equations 3.6 and 4.1. The difference between the two represented the quantity of recirculated air.

The next release was used to flood the work areas with SF_6 so that decay rates could be calculated. This was achieved by releasing pure SF_6 through a two-stage regulator and a flow metering valve or by releasing syringes full of the gas in the mechanical room. The gas was released throughout the room to ensure that equal distribution between the perimeter and interior zones occurred. The volume released was calculated as a function of the volume of the floor including the return air plenum. The ratio of the two volumes should not excede the capabilities of the GC but should be high enough to account for the inherent error related to gas chromatographic techniques (Section 5.2.2).

To define the decay of the tracer gas, four sampling sites were selected (Figure 17) and samples were gathered every half hour after a one hour equilibration period. Initially, two minute bag samples were collected but during the last three days of testing, grab syringe samples at the same intervals were taken. As outlined in Sections 3.3.1 and 4.2.1.2, effective ventilation rates were found by plotting the natural logarithm of sample concentrations with respect to time. The slope of this line gave the number of ACPH found at the sample location.

5.0 RESULTS AND DISCUSSION

The primary aim of this research was to develop a method to evaluate some of the performance characteristics of a HVAC system using a tracer gas (SF_6). Hence, building ventilation systems were studied on a floor by floor basis to determine effective ventilation rates, the fresh air supply rate and the percentage of recirculation, all of which have a bearing on the quality of the work environment. The equilibrium concentration, transfer index, and rate of decay methods, outlined in Section 3.4, were used. The procedure was divided into three stages: SF_6 release, sampling, and analysis. Each plays an important role in the resulting accuracy of the evaluation and consequently, deserve attention.

The results from both laboratory and field investigations show that SF_6 or another tracer gas can be used to quantify some of the operating parameters of a building HVAC system. In fact, tracer gas measurements substitute for pitot tube velocity measurements and can be readily used to find effective ventilation rates at several locations on a floor.

5.1 A TRACER GAS METHOD FOR VENTILATION PERFORMANCE EVALUATION

Although the exact procedure outlined in Section 4.2.3.2 is specific to the 28th floor of the complex studied, the generalized steps outlined in Figure 18 can be adopted for use in any building. The three principal ventilation performance characteristics ascertainable by this procedure are: primary and fresh air supply and effective ventilation rates. From these, the amount or percentage of recirculation and the overall ventilation rate for a given floor can be found.

It is important that the steps be performed in the order indicated in Figure 18 for a couple of reasons. Firstly, when using the transfer index technique to find primary air supply rates, the possibility of SF_6 re-entering the mechanical room from the work places has to be minimized or at least postponed until well into the test when it can be easily detected. Performing other tests before this necessitates sampling for residual SF_6 that can overwhelm the subtle changes in concentration that must be detected for the primary air measurement. Secondly, monitoring for the decay of SF_6 to find effective ventilation rates is not possible if while the gas is decaying, an investigator contributes to its concentration by performing other tests in the mechanical room. These two facts require that the equilibrium concentration method to find fresh air supply rates be performed in between the other two tests. Fortunately, it is ideally

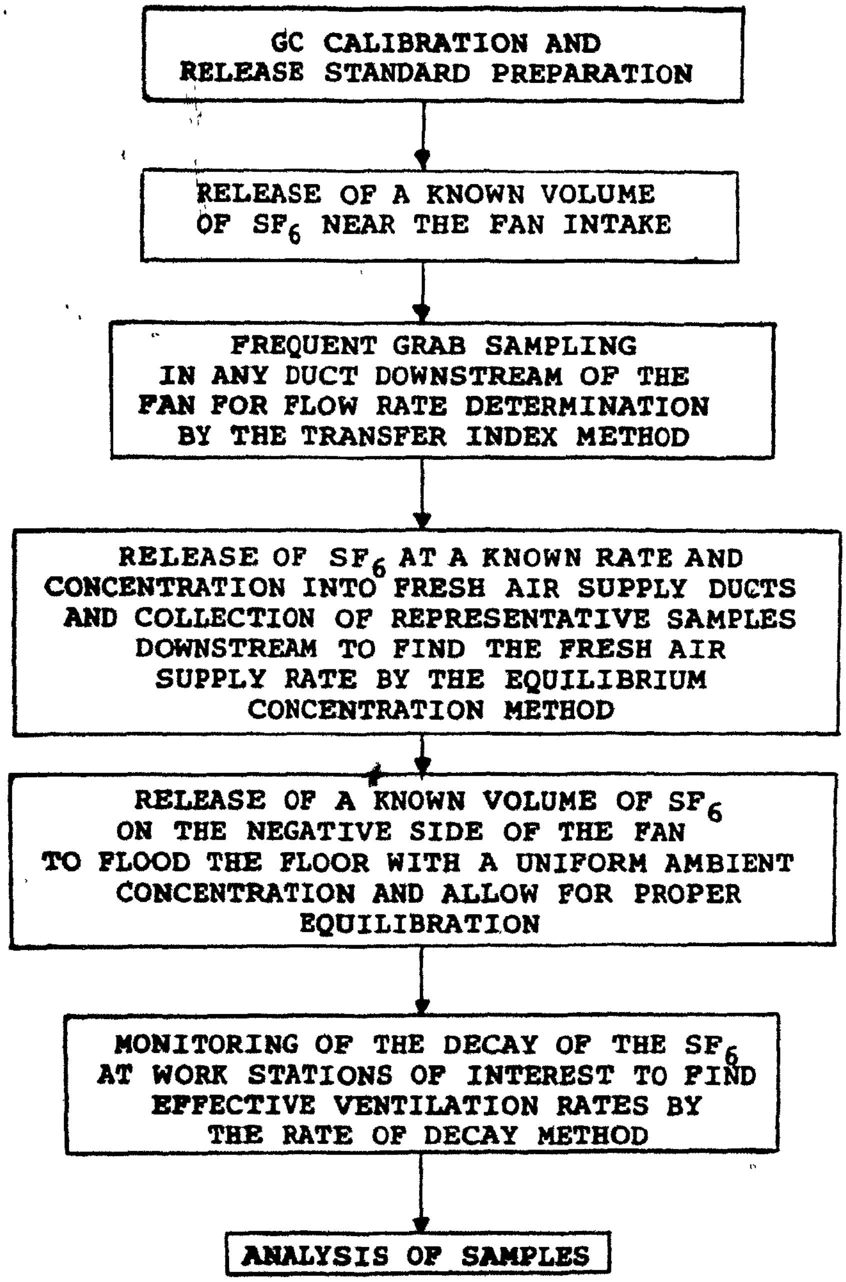


FIGURE 18: FLOW CHART OF TRACER GAS PROCEDURE TO BE USED IN VENTILATION PERFORMANCE EVALUATION

suited to this sequence. Because this test is performed in the fresh air supply duct, residual SF_6 will not affect the testing, although if there is some chance of SF_6 recirculating into the penthouse fresh air handling unit, which can sometimes occur, a background sample should be taken to identify its effect on the measurement. In most instances, the contamination will be negligible, as is attested to by the results presented in Section 5.1.1. Finally, even though both the equilibrium concentration and transfer index tests result in an ambient concentration of tracer gas in the work places, it is normally quite minimal and can be easily accounted for in the final release used to flood the work places with SF_6 to ensure that the GC's capabilities are not surpassed.

To quantify the amount of SF_6 needed to flood the work places, the volume of floor; excluding elevator, stair, mechanical, and electrical cores but including the plenum; must be used. The volume to volume ratio (SF_6: volume of floor) should be as high as possible without exceeding the upper detection limit of the GC. Tests found that releasing the tracer gas through the mechanical ventilating system distributes it uniformly to work places. In situations where this does not happen, auxiliary mixing may be required. This can be achieved with portable fans.

The linear range of the GC also has to be considered when making preliminary calculations for tracer gas releases used in volumetric flow rate measurements, as mentioned in

Section 4.2.2.2. The release gas concentration and the anticipated volumetric flow rate in the duct determine the release rate or volume when using either the equilibrium concentration or transfer index techniques. It is advised that anticipated sample concentrations, once an approximate duct flow rate has been assumed, fall in the middle of the GC's linear range. This lends a degree of tolerance to preliminary calculations and minimizes the chances of test failure. Figure 19, which can be used in these preliminary calculations, shows the expected sample concentration as a function of release standard concentration for a duct volumetric flow rate of 0.59 m^3/s (1000 cfm) at a release rate of 1.67×10^{-5} m^3/s (one lpm). This may seem quite specific but is in fact quite versatile. If the anticipated volumetric flow rate is doubled, the sample concentration is halved. If the release rate is halved, so is the sample concentration, and so on.

The steps outlined in Figure 18 can be slightly modified to facilitate the testing of an entire building complex for multi-floor investigations. It is conceivable that air flow measurements could be made to balance a ventilation system and that effective ventilation rates could be obtained for a variety of work stations throughout a building. Care would have to be exercised in locating and timing of releases and samples, and a thorough prior knowledge of the ventilation system of interest would be of utmost importance.

In a positively pressurized ventilation system with

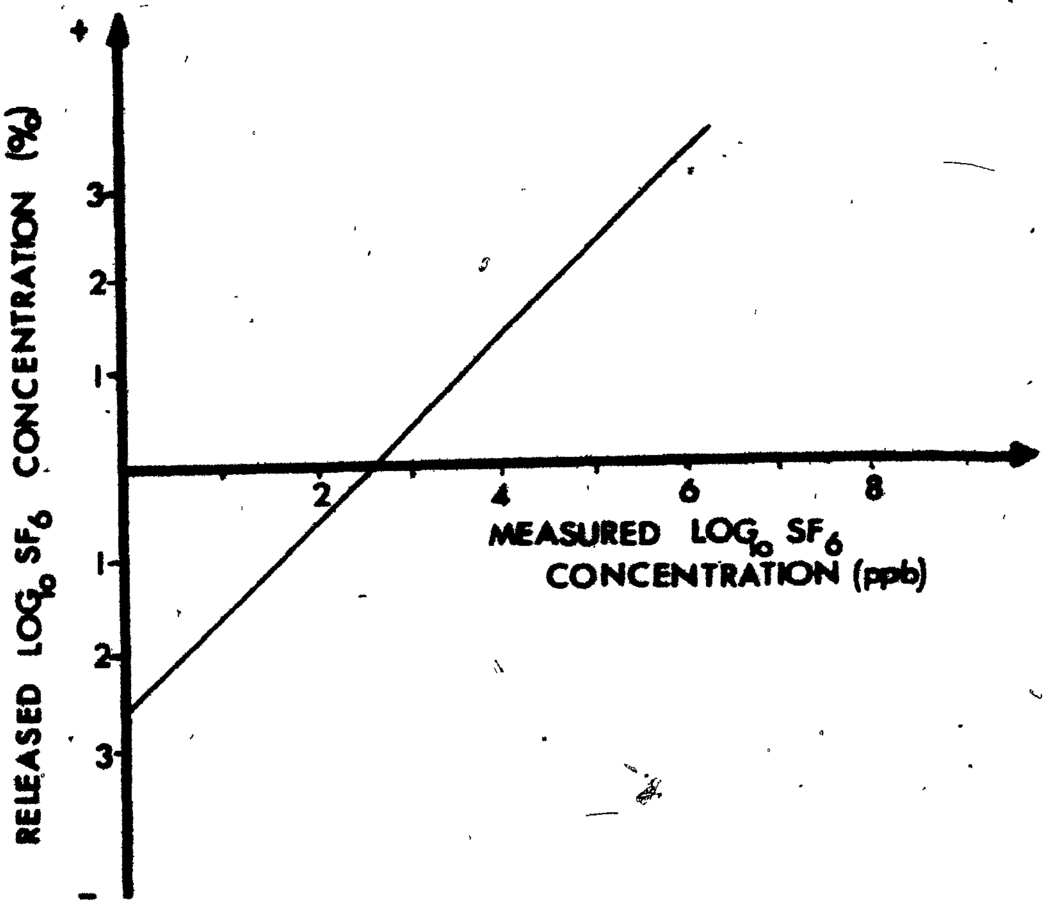


FIGURE 19. Expected Sample Concentration in a Duct as a Function of Release Rate and Concentration
($\dot{Q}$ = 0.59 m^3/s, Rr = 1.67 x 10^{-5} m^3/s)

many branches such as the one investigated in Hull, Quebec, the transfer index technique could be used to calculate how much primary air is going to the interior and perimeter zones or even through each duct in the context of a single test, assuming proper sampling instrumentation was available. If this is not available, the equilibrium concentration technique can be used for these measurements, although testing would have to be done one duct at a time.

In an exhausting ventilation system such as the one used in the laboratory, the equilibrium concentration method can be easily used to determine flow rates in ducts. Releasing the tracer gas at the extremities of given branches would allow an investigator to balance and check such systems. Time is not a factor as is the case with the transfer index technique and measurements need not be taken simultaneously. Sequential sampling while the gas is continuously released will give all the necessary information.

5.1.1 DETERMINATION OF FRESH AND PRIMARY AIR SUPPLY RATES AND PERCENTAGE RECIRCULATION

Volumetric flow measurements in closed conduits using the equilibrium concentration method were successfully made in laboratory and field studies. However, attempts to find the amount of primary air supplied to a particular floor with this method proved unsuccessful, probably due to the openness of the mechanical room and recirculation. The transfer index technique was used instead with promising results.

In the laboratory, the equilibrium concentration method was used to determine volumetric flow rates in the local exhaust system described in Section 4.1.1. The results are tabulated in Table 9 and the average difference between these and results found with a hot wire anemometer was an acceptable 9.6%. Using this method for volumetric flow rate determination in the field also provided very encouraging results (Table 10). The average variations between the designed flow rates and those found with the tracer gas technique were 7% and 14% for the two ducts tested. This difference was also noticed when using the pitot tube traverse method; therefore, either technique can be used for the measurement. It is assumed that any discrepencies between the two methods were due to inaccuracies encountered in the pitot tube traverse results because traverses could not be performed seven duct diameters downstream as recommended. Furthermore, laboratory testing supports the reliability of the tracer gas results.

POSITION	FLOW AS DETERMINED BY SF_6 ($m^3/s \times 10^{-2}$)	FLOW AS DETERMINED BY ANEMOMETER* ($m^3/s \times 10^{-2}$)	AVERAGE DIFFERENCE (%)
1	3.2 3.2 3.2 3.2 3.2 3.0 3.3 3.2 3.3	3.3	3
2	1.7 1.5 1.7 1.6 1.6 1.7 1.7 1.6 1.6	1.9	15
3	0.7 0.7 0.7 0.7 0.8 0.8 0.7 0.7 0.7	0.8	11
		TOTAL AVERAGE DIFFERENCE: 9.6%	

* Average of Three Traverses

TABLE 9: VOLUMETRIC FLOW RATES IN LABORATORY DUCT SYSTEM

VOLUMETRIC FLOW RATES FOUND WITH SF_6 (m^3/s)		DESIGNED RATES (m^3/s)	
$DUCT_1$	$DUCT_2$	$DUCT_1$	$DUCT_2$
0.50	0.50		
0.52	0.52	0.50	0.53
0.58	0.67		

TABLE 10: VOLUMETRIC FLOW RATES IN TWO FRESH AIR SUPPLY DUCTS

The transfer index technique was used successfully to quantify the amount of primary air being fed to the 28^{th} floor. Although pitot tube traverses could not be performed for comparison's sake, the calculated flow of 4.91 m^3/s (10,400 cfm) was only 3.2% greater than the design value. It was sometimes difficult to interpret results when using transfer indices because of the characteristic recirculation of the ventilation system. Collecting syringe samples at specific intervals and using the average concentration for the calculation of the flow rate had the advantage that the recirculation became apparent as a secondary peak (Figure 20). Taking the average of all values before this peak yielded the correct result. This would be the same as using the equivalent curve shown.

Using the transfer index to find the quantity of primary air and the equilibrium concentration method to find the amount of outside air supplied allows the determination of recirculation rates. The difference between the two values gives the volumetric flow rate of recirculated air.

5.1.2 DETERMINATION OF EFFECTIVE VENTILATION RATES

To properly apply decay rates to determine effective ventilation rates, a nearly uniform ambient concentration is required throughout the floor being investigated. This assures that the effects of diffusion as described in Section 5.2.4 are minimal. A number of investigators (6,7,51) have used artificial mechanical mixing means to achieve this, whereas

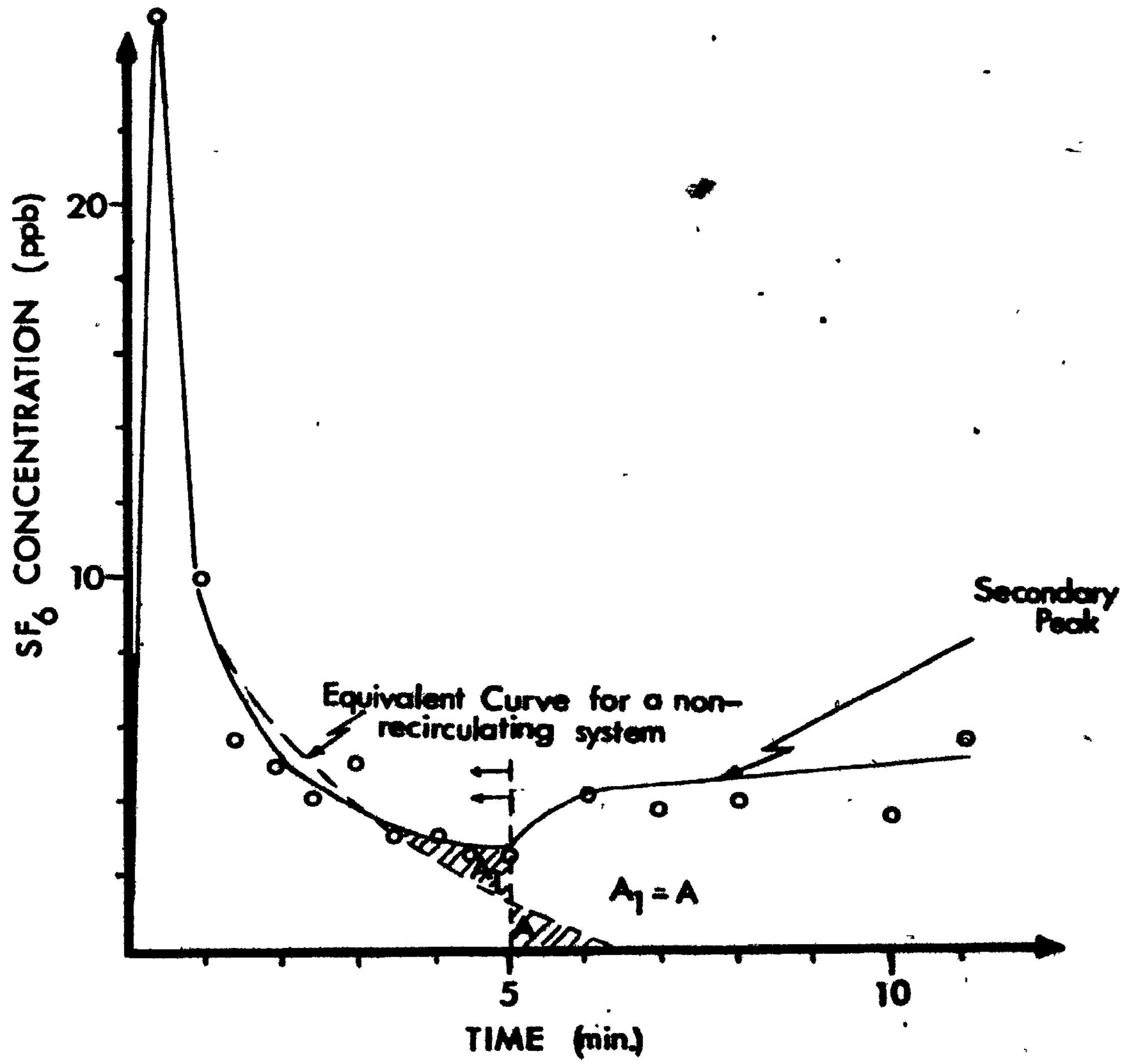


FIGURE 20: MEASURED CONCENTRATIONS WITH RESPECT TO TIME USING THE TRANSFER INDEX TECHNIQUE FOR PRIMARY AIR SUPPLY RATES

Kallioski et al. (50) suggest that the ventilation system itself can be used to attain a uniform initial concentration. The latter method was used in the investigations and worked reasonably well as indicated in Table 11. During the equilibration period doors were left open where possible to enhance mixing.

Table 12 outlines the effective ventilation rates found on the 28th floor by four tests along with the regression coefficient found for each analysis. Linear regression was applied to the logarithms of the measured concentration versus time with six degrees of freedom in all but one case where two samples were lost. The high correlation coefficients indicated that a decay did take place and that it fit an exponential curve well. Therefore, a high degree of confidence could be put on the results. The results found on the fourth day of testing were relatively low, perhaps due to the lower initial concentrations accruing from the release. The errors attributable to gas chromatography (Section 5.3.2) may have acted to increase sample concentrations at the end of the test period, thereby decreasing the rate of decay and effective ventilation rate. Otherwise, initial concentrations were high enough to reduce this error to acceptable levels and hence, these results could be considered more reliable.

Even in preliminary testing, the rate of decay method worked exceptionally well, as attested to by the standard errors for the results found at the sites sampled (Table 13).

TEST NUMBER	INITIAL CONCENTRATION (ppb)				COEFFICIENT OF VARIATION (%)
	LOCATION 1	2	3	4	
1	38.6	37.7	34.3	35.0	5.7
2	34.2	34.1	31.7	31.6	4.4
3	25.6	25.6	25.6	23.5	4.2
4	12.8	11.5	10.6	12.1	7.9
5	37.0	32.8	30.9	33.2	7.6

TABLE 11: INITIAL AMBIENT CONCENTRATIONS MEASURED BEFORE MONITORING THE RATE OF DECAY AT SAMPLE LOCATIONS DURING FINAL TESTING

TEST #	EFFECTIVE VENTILATION RATE (ACPH)				AVERAGE REGRESSION COEFFICIENT	OVERALL VENTILATION RATE (ACPH)
	LOCATION 1	2	3	4		
1	0.28	0.33	0.32	0.30	0.98	0.31
2	0.84	0.80	0.94	0.85	0.99	0.86
4	0.11	0.21	0.26	0.20	0.96	0.20
5	0.72	0.69	0.58	0.60	0.95	0.63

TABLE 12: - EFFECTIVE VENTILATION RATES FOUND DURING FINAL TESTING

TOWER	FLOOR	STANDARD ERRORS OF EFFECTIVE VENTILATION RATES (ACPH)							
		NI 1I	NP 1P	EI 2I	EP 2P	SI 3I	SP 3P	WI 4I	WP 4P
$EAST_1$	12	0.05	0.00*	0.00*	N/A	N/A	N/A	0.01	0.04
	14	0.22	0.02	0.02	0.06	0.03	0.04	0.03	0.04
	15	0.01	0.01	0.02	0.01	0.01	0.24	0.02	N/A
$EAST_2$	9	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.07
	10	0.04	0.04	0.02	0.02	0.02	0.02	0.01	0.02
	18	0.03	0.01	0.05	0.00	0.05	0.06	0.05	0.04
CENTRAL	7	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
NORTH	10	0.05	0.06	0.16	0.08	0.04	0.07	0.08	0.06
	28	0.14	0.03	0.01	0.01	0.03	0.08	0.03	0.26

* BASED ON A TWO PT. REGRESSION

TABLE 13: STANDARD ERRORS OF EFFECTIVE VENTILATION RATE DETERMINATIONS DURING PRELIMINARY FIELD TESTING

5.2 PARAMETERS AFFECTING PERFORMANCE EVALUATION

In order for SF_6 to be used effectively in evaluating a HVAC system's performance, it was necessary to minimize the errors associated with its release, sampling, and analysis. Many difficulties and intricacies related to SF_6 testing were encountered in both laboratory and field investigations. In order to develop the procedure outlined in Section 5.1, release and sampling parameters had to be researched so that appropriate techniques could be employed. During these investigations, many of the possible errors and parameters affecting the interpretation of tracer gas results became evident. These are presented below to inform other investigators of their possible effects.

5.2.1 SULPHUR HEXAFLUORIDE RELEASE

The type and location of release are determined by the characteristic of the ventilation system being evaluated and therefore, by the tracer gas method used. For example, to find the amount of outside air supplied to a floor, the equilibrium concentration method and consequently, a continuous release is needed, whereas an instantaneous release of a known volume of SF_6 is required when using the transfer index technique to determine primary air supply rates. Both types of release can be used with the rate of decay method; However, a continuous release to flood a floor with SF_6 should span a relatively short period of time to shorten the subsequent equilibration period. Furthermore, SF_6 release must take place in the duct of concern when using the equilibrium concentration method to find volumetric flow rates but is performed in the mechanical room for the other two tests.

No problems were encountered with the release in either the rate of decay or transfer index studies; however, problems relating to release velocities and control were witnessed when using the equilibrium concentration method.

In essence, two types of release which can be used with the equilibrium concentration method were investigated during laboratory and field work. Pure SF_6 was released directly from a gas cylinder through a two-stage regulator with an in line flow metering value, and a standard concentration of SF_6 was released with an air pump. Both methods were used with differing degrees of success.

5.2.1.1 RELEASE OF PURE SF_6

In preliminary investigations, SF_6 was released in the outdoor air supply duct to find the amount of outside air entering the floor being studied. To do this, SF_6 was released directly from a gas cylinder outfitted with a two stage regulator with the second stage regulated at 68950 N/m^2 (10 psig). The flow was governed by a pre-calibrated flow metering valve. Initially, SF_6 was used at flow rates as low as 1.7 x 10^{-8} m^3/s (one ml/min) to ensure that sample concentrations were detectable by the GC. These low flow rates caused a problem because of the time required for the gas to travel from the cylinder through the tubing to the duct. This lag is a function of the length of tubing used and must be properly accounted for during testing. To overcome this delay, a second cylinder of air was added to the release apparatus to act as a carrier gas (Figure 21). A second flow metering valve was used to govern the flow rate of the zero air at about 1.67 x 10^{-5} m^3/s (one lpm) which ensured a minimal time lag. The error introduced by the extra air entering the duct was 0.004% and can be considered negligible.

Table 14 outlines the results obtained and compares them to design specifications for fresh air supply rates. Although some results agreed better than others with the design values, the majority differed considerably. The variation between the two was considered to be caused by the release method rather than the operation of the system. This was validated in the laboratory where one of the flow metering valves was calibrated at 1.3 x 10^{-8} m^3/s (0.80 + 2% ml/min) and subsequently turned off and reset 10 consecutive times. The flow was measured each time and the coefficient of variation was + 25% as indicated in Table 15. This had a direct influence on results found by the equilibrium concentration method and could not be tolerated. The variation was probably not caused by the setting of the valve itself, but rather a result of setting the regulator. Another contributing factor to error found in these investigations is the low 0.0005 m/s release velocity of the

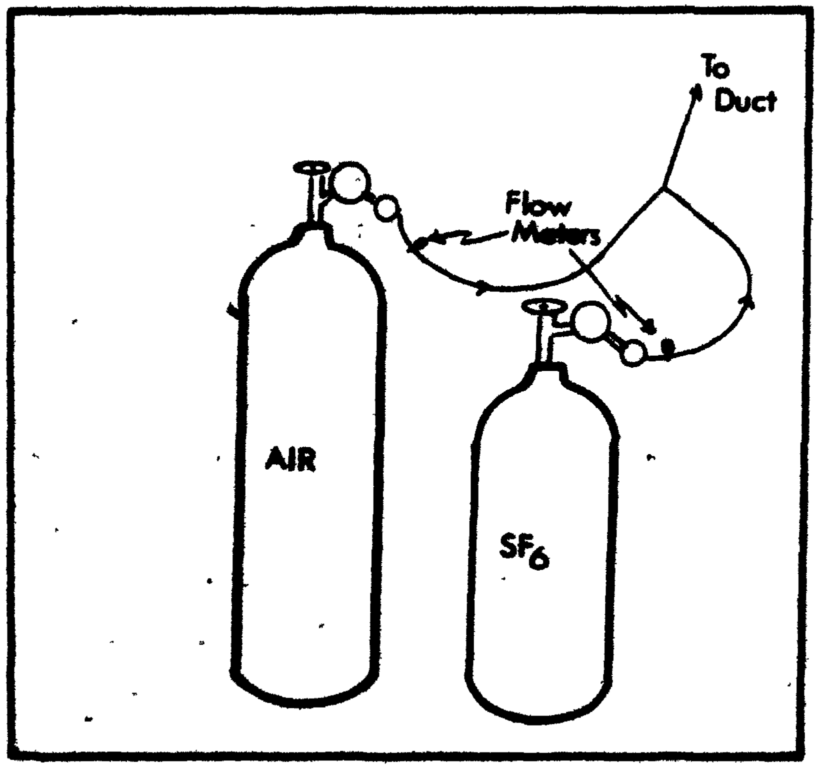


FIGURE 21: RELEASE APPARATUS

LOCATION TOWER	FLOOR	CORE	TRACER GAS RESULTS (m^3/s)	DESIGN SETTING (m^3/s)	DIFFERENCE (%)
$East_1$	15	1	0.84	0.58	45
		2	12.03	0.93	100
	14	1	1.72	0.58	100
		2	1.81	0.93	95
	9	3	0.41	1.84	78
		4	0.35	0.46	24
$East_2$	18	3	0.46	0.77	40
North	10	1	0.94	0.71	32
Central	7	1	0.21	0.88	76

TABLE 14: PRELIMINARY RESULTS FOR FRESH AIR SUPPLY RATES

TEST	TIME TO TRAVEL 0.5×10^{-6} m^3 (s)	RESULTANT FLOW (m^3/min $\times 10^{-6}$)
1	21.8	1.38
2	35.4	0.85
3	28.9	1.04
4	26.1	1.15
5	22.8	1.32
6	25.3	1.19
7	62.6	0.48
8	21.5	1.40
9	21.5	1.40
10	23.9	1.26
	AVERAGE:	1.15
	COEFFICIENT OF VARIATION:	+ 25%

TABLE 15: COEFFICIENT OF VARIATION ASSOCIATED WITH RESTARTING THE RELEASE APPARATUS

air/SF_6 mixture as outlined in Section 5.2.1.3.

In summary, the variability associated with the release of a tracer gas with flow metering valves is unacceptably high for use with the equilibrium concentration method in volumetric flow rate determination. However, it can be used to initially flood a floor with SF_6 in the rate of decay technique where a fair degree of tolerance to this type of variation exists.

5.2.1.2 RELEASE OF A STANDARD CONCENTRATION OF SF_6

A standard concentration of SF_6 was released into the laboratory duct system with a personal air sampling pump to find volumetric flow rates by the equilibrium concentration method. The consistency of results, as outlined in Table 9, reflects a steady release rate even though the tests were performed at different times. The reproducible release rate in this instance is largely due to the flow compensating nature of the pump. As the resistance to flow increases, the pump maintains a constant flow rate by increasing motor speed.

Further confidence in the results is attributable to the relative ease of calibration at release rates considerably higher than those mentioned in the previous section. Calibration was found to have less than a 2.2% error associated with it at these rates.

The major disadvantages of this method are associated with the preparation of gas standards. Errors are introduced into the volumetric flow rate calculation, as described in Section 5.3.1, unless a gas standard has been purchased. Purchasing standard concentrations limits studies to a small range of duct flows because of limitations associated with the analysis, e.g. the linear range of the GC, and release pumps. For example, a good personal sampling pump can be calibrated from about 3.3×10^{-7} m^3/s (20 ml/min) to 5.8×10^{-5} m^3/s (3500 ml/min). Hence, for versatility, preparing standards is recommended if it can be done accurately.

While a personal air sampling pump was also used in the field, a more powerful electric pump was tested in an attempt to overcome the problem of low release velocities described in the next section. Although this pump has a larger flow range, the errors and limitations remain the same.

5.2.1.3 RELEASE VELOCITY

Knoepke (9) states that turbulent flow serves to enhance flow measurements made with tracer gases, whereas it reduces the accuracy of pitot tube measurements. However, situations exist when turbulence alone will not ensure thorough mixing and tracer gas tests become inaccurate. Here, a high release velocity is needed. At the office complex studied, the outside air was supplied to the mechanical room at high velocities through relatively short ducts (- 1 m in length). Preliminary estimates of the fresh air supply rate found by the equilibrium concentration method either under or over estimated these rates because sample concentrations found were too low or high. These concentrations resulted from low release velocities. The SF_6 mixture would leave the duct before being thoroughly mixed as depicted in Figure 22 and therefore, results were influenced by which part of the duct samples were collected at. Increasing the release velocity by reducing the release outlet size to a few μm alleviates this problem. With high enough velocities, the SF_6 mixture behaved similar to a jet stream and resulted in more thorough mixing, giving a more representative sample. A comparison of results found using both high and low velocity releases is made in Table 16. The ducts have been designed to supply 0.50 m^3/s (1050 cfm) and 0.53 m^3/s (1125 cfm) respectively. In the high velocity case, results agreed reasonably well with these values and there was a marked improvement over the results found with lower release velocities.

5.2.2 SAMPLING

Many different sampling techniques are available for SF_6 sampling: evacuated containers, syringes, bags, portable sniffers, and infrared analyzers, to mention a few. The two techniques that were available for the studies performed were bag and syringe sampling. A comparison of the two types was performed for applications with the rate of decay, the equilibrium concentration, and the transfer index techniques.

Syringe sampling is quick, cheap, and reliable. Bag sampling requires a pump but is also reliable. The major

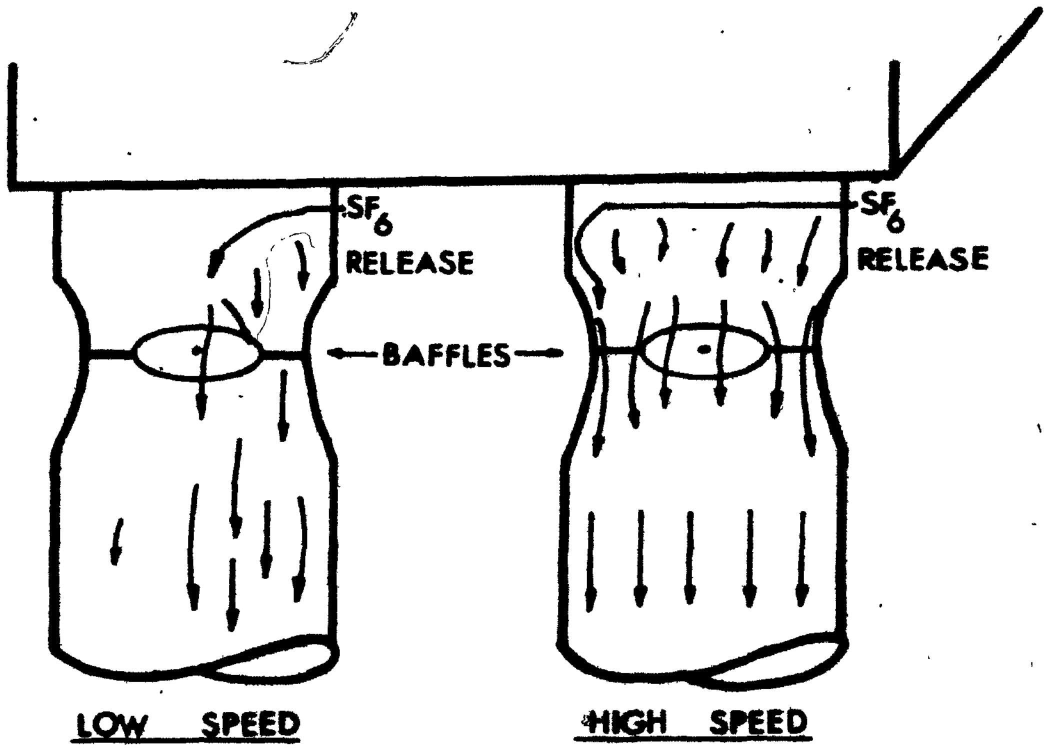


FIGURE 22: CROSS SECTIONAL DISTRIBUTION OF SF_6 FOR BOTH HIGH AND LOW VELOCITY RELEASES

RELEASE VELOCITY	VOLUMETRIC FLOW RATES FOUND (m^3/s) DUCT$_1$	DUCT$_2$	DESIGNED RATES (m^3/s) DUCT$_1$	DUCT$_2$
low	2.33	0.95	0.50	0.53
low	3.57	1.37		
high	0.50	0.50	0.50	0.53
high	0.52	0.52		
high	0.58	0.67		

TABLE 16: VOLUMETRIC FLOW RATES IN FRESH AIR SUPPLY DUCTS FOR HIGH AND LOW VELOCITY RELEASE

difference between the two techniques is that syringe samples are short term, whereas bags can be used for either short or long term time weighted samples. This makes bag sampling more versatile and particularly well suited to the transfer index method where a time integral concentration may be required. A major disadvantage of bag sampling is that the bags themselves are bulky and consequently, awkward.

During investigations, particularily when using the transfer index method, both sample length and timing became critical. The length of sample period is important when short term flow fluctuations characterize a ventilation system. Syringe sampling showed a high degree of variability in laboratory experiments (Table 17) where the grab samples were collected approximately once every minute, whereas good precision was shown for two minute, time weighted bag samples collected at five minute intervals. The results found with the bag samples further agree well with those found with an anemometer as discussed in Section 5.1. Therefore, if short term systemic variations are anticipated in the system under study, time weighted samples should be used to determine volumetric flow rates in the ducting.

Finding effective ventilation rates with the rate of decay method can be performed using either grab samples collected with syringes or two minute, time weighted bag samples. The two methods were compared in rate of decay tests and the results found by each method agreed closely at all four

POSITION	TEST #	TIME WEIGHTED CONCENTRATION (ppb)	C.V. (%)	GRAB SAMPLE CONCENTRATION (ppb)	C.V. (%)
1	1	6.5		8.4	
	2	6.5		8.9	
	3	6.2		8.4	
	4	---	3	9.0	4
	5	---		8.7	
	6	---		9.3	
	7	---		8.4	
	8	---		---	
2	1	12.4		13.5	
	2	12.3		20.8	
	3	12.2		20.1	
	4	----	1	16.0	20
	5	----		16.0	
	6	----		19.5	
	7	----		10.9	
	8	----		18.1	
3	1	28.5		34.7	
	2	26.1		31.5	
	3	27.5		49.8	
	4	----	4	42.9	26
	5	----		35.4	
	6	----		34.2	
	7	----		40.2	
	8	----		33.6	

TABLE 17: VARIABILITY OF SYRINGE SAMPLES IN LABORATORY EXPERIMENTS

sample sites (Table 18). The grab samples were gathered at the middle of the bag sampling period. The interchangeability of sampling techniques in this instance was a consequence of decay being a stable, long term process when associated with a ventilation system.

It is mandatory to wait for the tracer gas to equilibrate throughout a floor before sampling begins in effective ventilation rate studies. Allotting an insufficient equilibration period accrues the loss of initial samples for the calculation because the decay has not yet begun. This is shown in Figure 23 where sampling began approximately 15 minutes after the release. In this instance, it took about an hour and a half for the SF_6 concentration to peak; however, this was not typical and a one hour period was normally enough.

Investigations also found that longer term bag samples (15, 30, or 60 minutes) yielded results that were close to those found with shorter two minute sampling periods for the rate of decay method. The 28th floor of the office complex was studied twice using five time weighted average samples sequenced for 15, 15, 30, 30, and 60 minutes intervals, and the average effective ventilation rates were 0.68 and 0.59 ACPH, compared to an average of 0.58 ACPH for two tests where two minute samples were collected.

It was very difficult to find proper sampling times and periods to properly evaluate the amount of primary air on a floor with the transfer index technique because of the openness

SAMPLE LOCATION	TYPE	TIME AFTER EQUILIBRATION PERIOD (min.) 0-2	30-32	60-62	90-92	120-122	150-152
1	Bag	38.6	30.8	26.1	23.2	20.4	18.9
	Syringe	41.5	33.2	27.3	24.9	21.2	20.8
2	Bag	37.7	32.4	23.9	22.9	20.7	18.7
	Syringe	39.8	31.4	30.0	21.5	19.7	17.3
3	Bag	39.3	28.1	26.5	21.9	19.5	17.0
	Syringe	40.5	29.2	23.3	21.8	18.7	17.7
4	Bag	35.0	30.6	lost	lost	19.7	18.1
	Syringe	38.2	32.4	27.2	22.5	21.0	18.2

TABLE 18: A COMPARISON OF SYRINGE AND BAG SAMPLING TECHNIQUES IN RATE OF DECAY INVESTIGATIONS

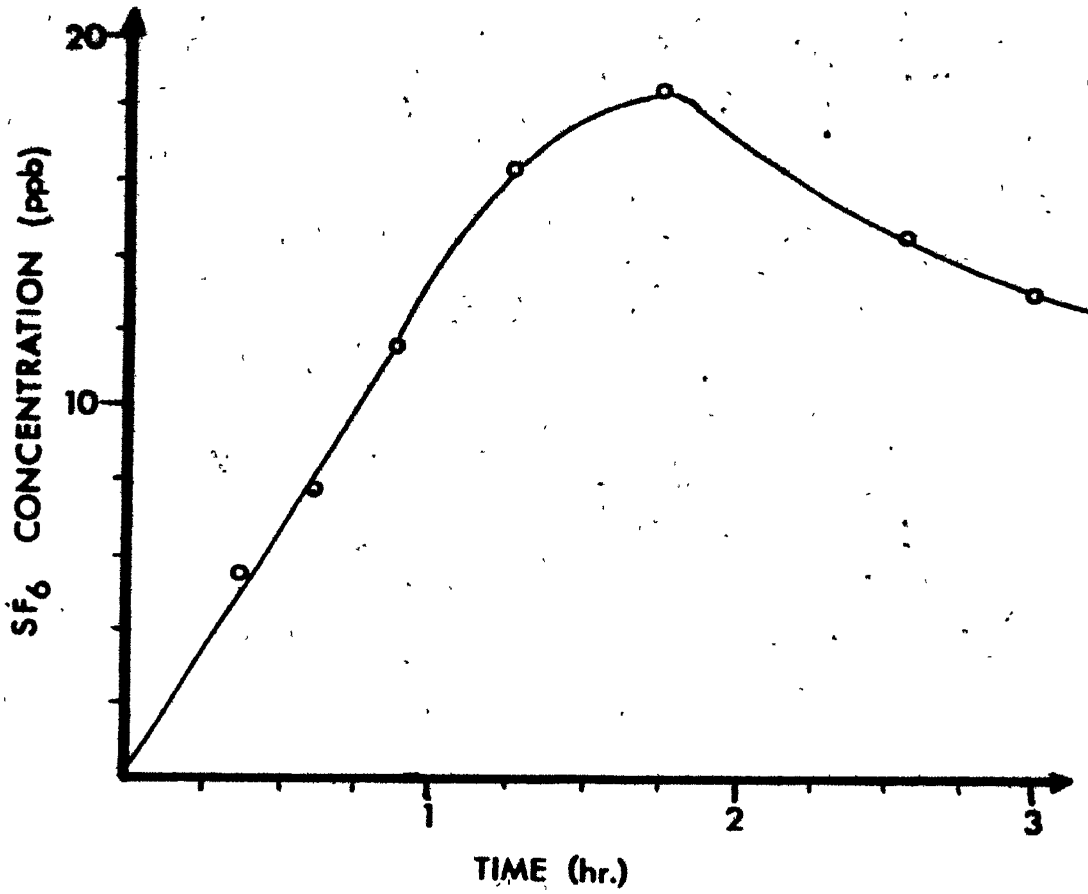


FIGURE 23: SF_6 CONCENTRATION WITH RESPECT TO TIME AFTER FLOODING THE WORK PLACES

of the mechanical room. The use of time weighted bag samples proved inadequate because of recirculation. Syringe samples were tried at one minute intervals so that more information about concentration peaks indicating recirculation could be obtained. Again, little success was obtained, with no outstanding peaks evident. Finally, syringe samples at half minute intervals for the first five minutes, one minute intervals for the next three minutes, and two minute intervals for the last four minutes were used with success as described in Section 5.1. It is evident that the timing of samples was very important in this situation.

In summary, either bag or syringe samples over a long or shorter period can be used with the rate of decay method for determining effective ventilation rates. Sampling became more critical for the transfer index technique to measure volumetric flow rates in a recirculating ventilation system. The best approach, in this instance, is to collect short term samples as often as possible so that concentration fluctuations can be pinpointed. If the tracer gas is properly released (Section 5.2.1), sampling is not a crucial aspect of studies involving the equilibrium concentration technique.

5.2.3 THE DENSITY OF SF_6

Sulphur hexafluoride is about five times more dense than air at STP. Hemeon (64) indicates that this is often believed to have a considerable effect on its behavior in air but that this is incorrect. It is the SF_6/air mixture's density that is important as it determines behavioural differences with respect to normal air. With SF_6 in the 35 parts per billion range, the mixture's density is only negligibly different than that of air and does not change normal airflow patterns when performing ventilation studies.

Collins et al. (30) state that heavy gases do not mix well in air. This phenomenon did not present problems in the studies performed. The initial concentrations obtained during rate of decay investigations (Table 11) show that the method of releasing the tracer gas through the ventilation system overwhelms the effects of its density on mixing.

5.2.4 DIFFUSION

Diffusional effects of a tracer gas are only of concern when using the rate of decay method. It is to minimize these effects that a uniform ambient SF_6 concentration is required at the beginning of a test. Typically, the concentration gradients found by the initial conditions witnessed during investigations were approximately 0.02 ppb per metre; therefore, the diffusional velocity of SF_6 in air is only 1×10^{-6} m/s (Appendix VI). With such low diffusional velocities, the ambient conditions generated by the ventilation system will overwhelm any diffusion and subsequent decay rates reflect the action of the system itself.

5.3 POSSIBLE SOURCES OF ERROR

The possible sources of error that can be encountered when performing tracer gas ventilation studies include:

- release velocity, calibration, and method;
- sample biasing, frequency, positioning, and contamination;
- the density and purity of the gas used;
- standards preparation;
- and gas chromatography.

Assuming all the parameters listed and discussed in Section 5.2 have been incorporated into the proper development of a testing procedure, many of these errors can be minimized or eliminated. This involves the selection of good release mechanisms and techniques, proper sample timing and positioning, and ensuring the use of a pure gas and that its density and diffusional properties do not significantly affect results. Sample contamination can be eliminated if sampling equipment is thoroughly cleaned with air between tests. Sample biasing is only of concern when finding overall ventilation rates by averaging effective ventilation rates and is minimized by increasing the number of samples collected. This leaves both standards preparation and gas chromatographic techniques as the major sources of unavoidable errors in tracer gas investigations.

5.3.1 STANDARD PREPARATION

Two standard preparation techniques were used for SF_6 release and calibration of the GC. When generating standards with a gas generator like the Metronics Dynacalibrator used, SF_6 concentrations are produced by heating gas permeation devices. These devices are factory calibrated at a certified rate within 2% at 30 °C. To produce higher standard concentrations (0.2 to 12 ppm), the oven temperature can be increased and extra permeation devices added. The increase in temperature changes the permeation rate with an accuracy of 5% for a 10 °C shift in temperature (66). Consequently, when generating high standard concentrations, a compounded error results from the use of extra permeation devices and the temperature shift.

Although the gas generator is outfitted with pre-calibrated rotameter scales, more accuracy can be achieved if a bubble flow meter is used to measure the outlet stream flow rate used in Appendix IV. In making volumetric measurements, the effect of water vapour may be taken into account. However, the error introduced by humidity is normally quite small and was therefore not used in data reduction. Another error related to the use of a bubble meter arises from the actual timing, but the resulting error is in the region of only 1% (67).

For even higher SF_6 concentration (e.g. 1%), a flow meter which combines two separate, individually calibrated flows (air and SF_6), was used. Rather than relying on supplied calibration curves, a bubble meter was used to measure the flows. Again, the anticipated error can be minimized to 1%.

In summary, the largest error encountered as a result of gas standards preparation occurred while performing the laboratory duct experiment where two permeation devices were used at 50 °C. This error was as high as 10.5%. Otherwise, errors were much lower.

5.3.2 GAS CHROMATOGRAPHY

The errors associated with gas chromatography result from sample injection, concentration, volume, and detection. Table 19 is a summary of various tests performed in order to quantify a coefficient of variation (C.V.) when using different GC injection techniques on both high and low concentrations.

The most obvious conclusion to be drawn from these studies is that syringe injection of relatively small volumes from a large gas tight syringe is an unacceptable practice. This results in a C.V. of about 62%. The tests indicated that on two occasions the sample did not even enter the column. Although more reasonable precision was obtained when injecting 5×10^{-5} m^3 (50 μl) from a 1×10^{-4} m^3 (100 μl) syringe, a marked difference was seen in the C.V.'s of high and low concentrations. This results from the fact that the standard deviation of the combined effects of injection and detection was

TEST #	RESULTS WHEN USING 5.2 ppb STANDARD			RESULTS WHEN USING 35.9 ppb STANDARD	
	INJECTION TECHNIQUE			INJECTION TECHNIQUE	
	1/2 SYRINGE	1/10 SYRINGE	GAS SAMPLING LOOP	1/2 SYRINGE	GAS SAMPLING LOOP
1	5.2	5.2	3.8	35.9	35.9
2	5.8	7.4	3.5	35.9	35.6
3	5.6	2.8	3.5	35.0	35.0
4	5.5	0.0	3.6	35.7	34.9
5	4.8	0.0	3.6	34.8	34.8
6	4.7	3.4	3.3	35.0	35.2
7	3.6	6.2	3.5	35.1	34.2
8	5.1	4.7	4.1	35.2	35.0
9	4.3	6.3	---	34.0	34.6
10	4.2	5.6	---	33.9	34.7
C.V.: (%)	15	62	7	2	1

AVERAGE STANDARD DEVIATIONS
FOR COLUMNS 1 AND 4: 0.71 ppb
3 AND 5: 0.38 ppb

TABLE 19: VARIATION OF DIFFERENT INJECTION TECHNIQUES USING GAS STANDARDS

about 0.71 ppb which inherently results in more error at lower concentrations. This same phenomenon was present for gas sampling valve injections; however, the standard deviation was somewhat decreased to 0.38 ppb. This would indicate a deviation of about 0.3 ppb attributable to the syringe injection technique, because most of the deviation found for the gas sampling valve technique was a result of detection rather than injection.

Even though syringe injection techniques seemed to give a more reliable estimate of the standard concentration used, this is a result of the GC calibration and should be ignored. The experiment was designed to test the precision of the different techniques only.

To minimize the errors associated with gas chromatography, either proper syringe injection or a gas sampling valve should be used with relatively high sample concentrations.

5.3.3 SUMMARY ERRORS

In performing a tracer gas study, anticipated errors are as outlined above if no consideration is given to sample biasing, operator induced and other procedural errors that can be minimized with experimental control and care. Using a sum of the squares approach and adding all expected errors as a result of standard generation, release pump calibration, and analysis, errors of less than 12% can be anticipated if a gas sampling loop and relatively high concentrations are being used, regardless of the gas standard preparation technique. This error can be decreased to about 2% using flow meter generated standards. These figures assume proper release pump calibration which has an associated error of 1% (67).

5.4 A COMPARISON OF TRACER GAS AND CONVENTIONAL METHODS OF VENTILATION ANALYSIS

Previously presented results show that tracer gas techniques can be effectively used to perform volumetric flow and effective ventilation rate measurements in ventilation studies. The major advantage of using tracer gases rather than conventional tools is that more information about air flow patterns in the workplaces can be obtained. Lagus (51) refers to the fact that conventional air infiltration studies can not be performed in large open areas like factories because fan capacities do not sufficiently pressurize the structure. The rate of decay technique can be used in this instance. Furthermore, effective ventilation rates can be found by this technique in air tight structures, whereas these can not be found with conventional tools. Both air infiltration and effective ventilation rates are measures of air flow patterns.

The rate of decay method for ventilation rate measurement has several advantages over the conventional methods described in Section 3.3.2. It is an experimental measure of effective ventilation rates rather than a theoretical calculation of overall ventilation rates. Often, effective ventilation rates are of more concern. These reflect how well a ventilation system is working at different locations rather than assuming that the average rate is representative of all sites and can be directly compared to ASHRAE's most recent standards. The only way to determine effective ventilation rates by conventional methods in hermetically sealed buidings is to measure the amount of fresh air entering the system and apply the resulting overall rate to work locations. This type of measurement is subject to the limitations of conventional air velocity measuring devices.

Using conventional tools for ventilation evaluation requires that velocity measurements be made at least seven duct diameters downstream from any obstruction to air flow (15). Building and ventilation design do not necessarily take this into account and consequently, as in the building studied, measurements have to be made wherever possible, jeopordizing the accuracy of results. The turbulence created by obstructions and geometric changes in ducting serve to mix the SF_6 with the air, whereas it acts to reduce the accuracy of pitot tubes or other air velocity measuring devices. The mixing of the tracer gas enhances the subsequent volumetric measurement because it is essentially based on dilution. Furthermore, only velocities in excess of 3.05 m/s can be accurately measured with a pitot tube (15), while tracer gas techniques lend themselves to the measurement of any volumetric flow rate whether it be characterized by high or low velocity.

With the sampling and analytical equipment available for the research, volumetric flow rates in closed conduits can be determined by either the tracer gas method outlined or conventional air velocity measurement techniques in approximately equivalent amounts of time. No corrections or extraneous readings such as temperature and humidity have to be gathered for tracer gas methods, which are based on actual volumetric measurements rather than velocity measurements. However, a background sample is sometimes required for other tracer gases which have naturally occurring ambient concentrations, like CO_2, so that it can be accounted for in subsequent calculations. If automated sampling methods were available, SF_6 could be used to give flow rates in a number of ducts in much less time than that required for pitot tube traverses. The transfer index method can be used for flow rates in positive pressure ventilation systems and the equilibrium concentration method can be used in negative pressure systems.

Another advantage of tracer gas over conventional methods is that the procedures to perform volumetric flow and effective ventilation rate measurements can be incorporated into one study. This does not apply to conventional techniques where both are separate entities.

The main disadvantages of ventilation studies using SF_6 are associated with the analytical chemistry required. To properly analyze samples, expertise is needed. This makes the technique somewhat inaccessible to engineers, but with further research into automated sampling and analysis this could be overcome. If care is not exercised in standard preparation and equipment calibration, large errors can result. This is not true of conventional techniques.

6.0 SUMMARY AND CONCLUSIONS

The research conducted indicates that SF_6 can be used effectively as a ventilation evaluation tool. Volumetric flow measurements, recirculation and effective and overall ventilation rates can be determined using the methods described in this paper. Presently the procedure is somewhat cumbersome, requiring manual sampling and analysis which renders it as time consuming as conventional methods of ventilation analysis. However, with more research and development, tracer gas techniques can become an attractive alternative to flow measurement and ventilation assessment techniques currently being used.

Volumetric flow measurements made in a laboratory local exhaust system by the equilibrium concentration method agreed within about 9% of measurements made with a hot wire anemometer. This indicates that this method is ideally suited to the balancing of local exhaust systems of all sorts. The technique can also be used to find holes in ducting. This would be reflected by a decrease in gas concentration from one end of a branch to another, and the actual volume of air leaking into the system could be determined. However, this technique can not be used to find flow rates in blowing ventilation systems that subsequently branch. The flow in the duct where the SF_6 is released can be determined but the flow in subsequent branches can not be found because the concentration will remain constant throughout the system. Leakage can not be quantified either.

Nonetheless, blowing ventilation systems can be balanced using the transfer index technique. This method was employed in the office complex studied to find the amount of primary air being supplied to a floor and the results were within a few percent of the designed rate.

The office complex investigations also indicate that the rate of decay method can be used to find effective ventilation rates. In all cases, the measured decay was nearly exponential which is attested to by the high regression coefficient obtained for linear regression of the natural logarithms of measured concentrations. Hitchin and Wilson (18) list that perfect mixing of ventilating air is required to properly use this method to find ventilation rates as a drawback. However, this was not witnessed during testing. Initial preparation assured that the diffusional effects of SF_6 were overwhelmed by the ventilation itself, and even though perfect mixing did not exist, as is indicated by different effective ventilation rates, a high degree of confidence can be put in the results. Although ventilation systems are designed to distribute air somewhat uniformly, misbalancing may negate this and therefore, it is important to know effective ventilation rates. The average of the effective rates found can then be applied as an overall rate.

The variability of the effective ventilation rates found for a given floor seems to indicate that interior floor space utilization (office types and positioning) affects the uniformity of air distribution. The HVAC system studied was designed to distribute ventilating air based on the heat requirements; however, testing was performed at night when the only source of heat would have been lighting. This would have resulted in a uniform heat load accompanied by uniform air distribution as reflected by consistent effective ventilation rates. However, this was not found and consequently, the architectural interior layout of the floors seemed to disrupt air flow patterns. A high degree of confidence can not yet be put in this conclusion because of the limited number of tests performed.

Laboratory experiments are characterized by a fair degree of experimental control but often this type of control is not easily achieved in the field. Results of the office complex studies show that this control was achieved but it was not a simple task. Many preliminary results had to be discarded because of errors introduced by a lack of experimental control. Discrepancies of hundreds of percent were present. This serves as a caution to other investigators. Even though SF_6 can be used effectively to evaluate performance characteristics of ventilation systems, errors can easily become apparent and therefore, some standardization is in order.

A major drawback of this technique is the analytical chemistry presently needed to interpret results. This is obviously not practical if the method is to replace the procedures now used. Considerable simplification of these requirements will be needed if tracer gas techniques are to be made available to the engineers or technicians who will be making air flow measurements and quantifying air flow patterns. Research has to be performed to find easier and simpler sampling methods. Analysers, which give an answer automatically after taking the sample from the collection device, would be a desirable development.

It is questionable whether SF_6 is the best gas to use as a tracer. Its detectability proved to be a problem in field testing where contamination of sampling equipment was evident.

The potential of tracer gas studies in the performance evaluation of ventilation systems are enormous and can encompass assessments of entire building, mine, or factory systems, as well as local ventilation.

6.1 FURTHER WORK

Tracer gas ventilation studies could only be performed on a floor by floor basis and the number of volumetric flow measurements possible in ducting under positive pressure were few. In both cases, these limitations were due to the available sampling techniques. Whether these were bag or syringe type, manual samples had to be gathered. This can be cumbersome at times and does not allow for complete study of the ventilation system in question. Research into some form of automatic, remote sampling would allow more intricate measurements to be made throughout an entire complex. This could greatly reduce the time involved for an evaluation of a ventilation system.

To make tracer gas studies more accessible to those who perform the tests, an automatic analyzer should be developed. It seems most reasonable to anticipate a portable analyzer which pulls the sample from the sample container and gives a digital read-out.

Further refinement of release methods is also in order. High velocity release is best and a more elegant solution to the assembly used in this testing is required. A powerful pump with a critical orifice would be best.

Different gases should be investigated to be used in ventilation evaluation. SF_6 has many advantages and admirable characteristics but contamination is a source of difficulties. Tubes and sampling equipment have to be thoroughly cleaned and if pure SF_6 has been in contact with equipment, cleaning can be very difficult because of its stability.

Finally, the effect of interior office space design on air distribution should be investigated more thoroughly. It is expected that more consideration should be given to the office types and placement of these and partitions with regards to their compatibility with the ventilation system.

APPENDIX I

THE EQUIVALENT LENGTH METHOD

In ventilation design, energy losses as a result of air flowing through junctions, elbows, contractions, and expansions are normally included as a part of the system's resistance by the equivalent length method. The losses incurred are expressed as an equivalent loss that would result from the air flowing through a length of straight ducting. Hence, the air distribution network can be considered to consist of straight pipe only and Equations 2.14 and 2.15 can be used to calculate losses. This greatly facilitates ventilation design.

The ACGIH (15) outlines expected losses for commonly found duct geometries. These are found in Tables A1 to A4 and are expressed as a fraction of the duct velocity pressure on the upstream side of the geometric change as determined by the equivalent length method.

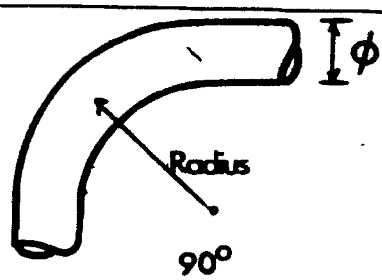
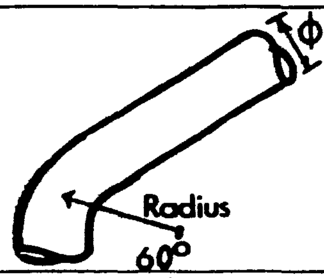
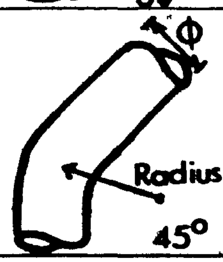
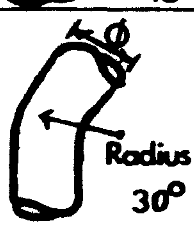
SCHEMATIC	RADIUS (no. of ϕ)	LOSS FRACTION OF VP
	2.75	0.26
	2.50	0.22
	2.25	0.26
	2.00	0.27
	1.75	0.32
	1.50	0.39
	1.25	0.55
	2.75	0.17
	2.50	0.15
	2.25	0.17
	2.00	0.18
	1.75	0.21
	1.50	0.26
	1.25	0.37
	2.75	0.13
	2.50	0.11
	2.25	0.13
	2.00	0.14
	1.75	0.16
	1.50	0.20
	1.25	0.28
	2.75	0.09
	2.50	0.07
	2.25	0.09
	2.00	0.09
	1.75	0.11
	1.50	0.13
	1.25	0.18

TABLE A1: EXPECTED PRESSURE LOSS THROUGH ROUND ELBOWS

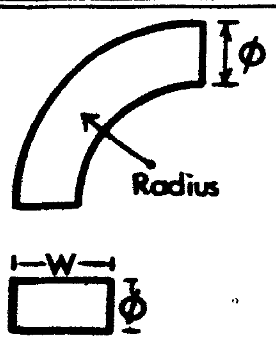
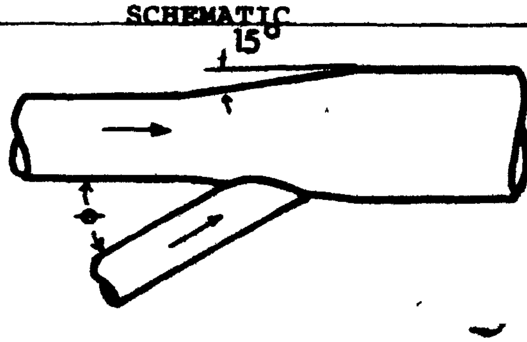
SCHEMATIC	RADIUS (ϕ)	LOSS FRACTION OF VP ASPECT RATIO (W/ϕ) 0.25	0.50	1.00	2.00	3.00	4.00
	0.0	1.50	1.32	1.15	1.04	0.92	0.86
	0.5	1.36	1.21	1.05	0.95	0.84	0.79
	1.0	0.45	0.28	0.21	0.21	0.20	0.19
	1.5	0.28	0.18	0.13	0.13	0.12	0.12
	2.0	0.24	0.15	0.11	0.11	0.10	0.10
	3.0	0.24	0.15	0.11	0.11	0.10	0.10

TABLE A2: EXPECTED PRESSURE LOSS THROUGH SQUARE AND RECTANGULAR DUCTING

SCHEMATIC



ANGLE (θ)	LOSS FRACTION OF VP IN MAIN BRANCH
10	0.06
15	0.09
20	0.12
25	0.15
30	0.18
35	0.21
40	0.25
45	0.28
50	0.32
60	0.44
90	1.00

TABLE A3: EXPECTED PRESSURE LOSS THROUGH BRANCHES IN CIRCULAR DUCTING

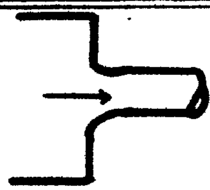
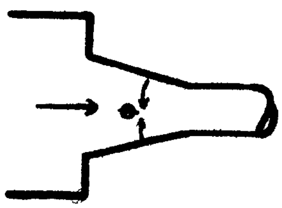
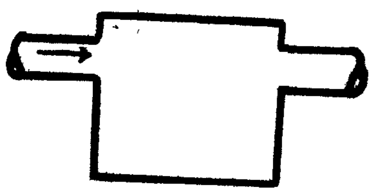
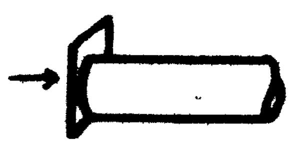
SCHEMATIC	LOSS FRACTION OF VP		
	0.6 TO 0.1		
	ANGLE (θ)	ROUND DUCTING	RECTANGULAR DUCTING
	15	0.15	0.25
	30	0.08	0.16
	45	0.06	0.15
	60	0.08	0.17
	90	0.15	0.25
	120	0.26	0.35
	150	0.40	0.48
	1.5		
	0.93		
	0.49		

TABLE A4: EXPECTED PRESSURE LOSS THROUGH OTHER DUCT GEOMETRIES

APPENDIX II

FAN LAWS

The operation of a fan is not only dependant on the resistance of the system it is serving but also on fan speed (v) and diameter (ϕ) and air density (ρ). These parameters have an effect on the volumetric flow rate delivered (Q), the fan's SP, power, and efficiency. These can be expressed as:

SPEED CHANGE:

$$\frac{Q_2}{Q_1} = \frac{v_2}{v_1} \qquad \frac{SP_2}{SP_1} = \left(\frac{v_2}{v_1}\right)^2$$

$$\frac{power_2}{power_1} = \left(\frac{v_2}{v_1}\right)^2$$

Efficiency remains constant

FAN DIAMETER:

$$\frac{Q_2}{Q_1} = \left(\frac{\phi_2}{\phi_1}\right)^2 \qquad \frac{power_2}{power_1} = \left(\frac{\phi_2}{\phi_1}\right)^2$$

Efficiency and SP remain constant

AIR DENSITY:

$$\frac{SP_2}{SP_1} = \frac{\rho_2}{\rho_1} \qquad \frac{power_2}{power_1} = \frac{\rho_2}{\rho_1}$$

Efficiency and volumetric flow rate remain constant

APPENDIX III

STANDARD PREPARATION

Proper calibration of analytical equipment is of utmost importance in any study involving their use. Without proper standards, it is impossible to get satisfactory results. Standard gas concentrations can be obtained with a standard generator for a variety of gases. A standard is prepared by putting a permeation device into a chamber at a controlled temperature and allowing the device to equilibrate. Once equilibrated, the flow from the chamber is diluted with a known volume of clean air. This is controlled on the front of the generator.

The permeation devices are certified for different mass flow rates at different temperatures. The equation governing the use of a standard generator is:

$$Q_d = \frac{R_p K}{C} - Q_c$$

where: Q_d is the dilution flow (ml/min), R_p is the device mass permeation rate (ng/min), K is a molecular constant, Q_c is the carrier flow (ml/min). Three of the five parameters, R_p, K_m, and Q_c are predetermined; therefore, the only two variables are the desired concentration and the dilution flow rate. The permeation rate is a function of the chamber temperature and can be calculated knowing the permeation rate R_{po}, and the temperature, T_o, for which it is certified, by the equation:

$$\log R_p = \log R_{po} + 0.034(T - T_o)$$

This results in an accuracy of $\pm$ 5% for a 10 ^{o}C shift in temperature.

The effect of changing dilution flow rates and temperature enables the generation of a wide range of standard concentrations. For example, with two SF_6 permeation devices available, one can generate standards ranging from a few ppb up to about 10 ppm which is a 10,000 fold range.

Although standard generators are outfitted with calibrated rotameters in most instances, it is advised that total flow rates be measured for more accurate standards. This can be done by putting a bubble meter in line with the stream outlet to determine Q_T which is the sum of the dilution and carrier flows.

APPENDIX IV

GAS CHROMATOGRAPHY FOR SF_6

Gas chromatography involves the separation of gases through a stationary phase. To detect SF_6, a molecular sieve column and electron capture detector can be used. The SF_6 is carried by a carrier gas which must be inert to detection, dry, and pure. Often, nitrogen or an argon methane mixture is used. Figure A1 schematically represents the entire GC process.

There are two methods of injection available to the user; syringe injection or a gas sampling loop. The former is characterized by more operator induced error than the latter. In the gas sampling loop technique, the sample is pumped through a small loop which fills. A switch then opens a valve which allows the sample volume to enter the column where separation takes place. Hence, the sample volume is always the same. Different sizes of loops are available and are selected according to the sensitivity of the detector. A gas like SF_6, which is extremely detectable, is best analyzed with about a 50 l loop.

Once injected, the sample enters the column, which is normally at an elevated temperature and pressure. A molecular sieve column separates gases on the basis of molecular size. Smaller molecules travel a longer path through the column and consequently, are eluted later. This is illustrated in the chromatogram shown in Figure A2. As shown, the oxygen is eluted after the larger SF_6 molecule.

The sample travels through the column to an ECD where radiation is continuously emitted, resulting in a continuum of

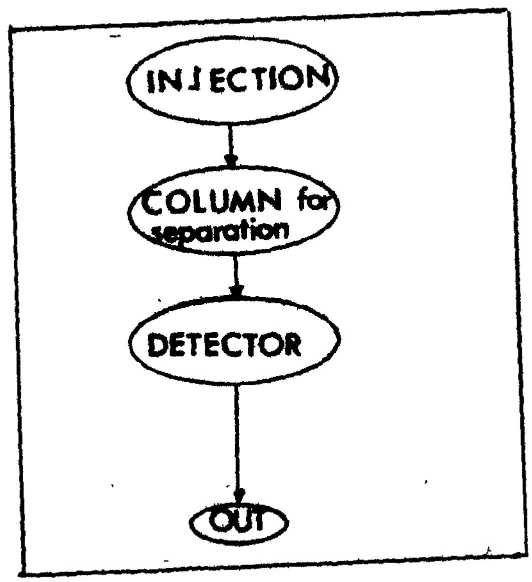


FIGURE A1: THE GAS CHROMATOGRAPHY PROCESS

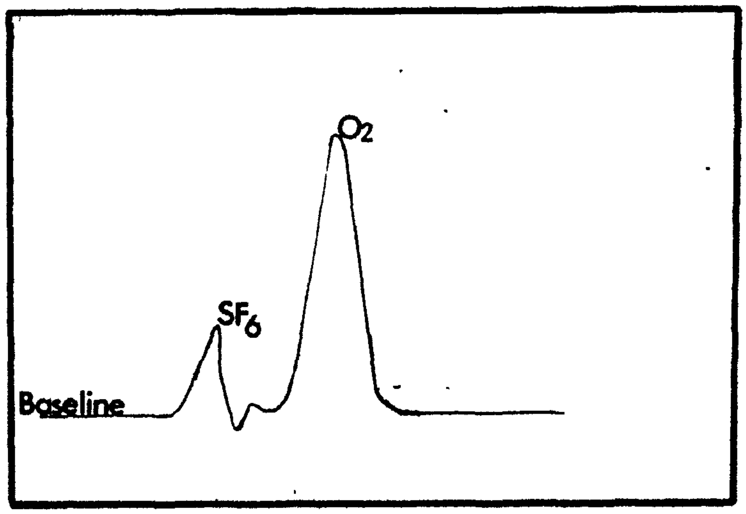


FIGURE A2: A GAS CHROMATOGRAM.

electrons between the source and detector. As electronegative gases pass through the arc between the cathode and anode negative ions are formed. This causes a decrease in the voltage reading which can be converted to a concentration reading once the instrument is calibrated.

CALIBRATION OF A GC FOR SF_6

The response of an ECD is a decreased voltage as the result of an electronegative gas like SF_6 capturing electrons created by a radiating source. This voltage drop can be converted to a concentration reading on a peak height or area basis. A strip chart recorder can be used to plot the changes in voltage and consequently, will show a peak relative to the baseline reading as SF_6 passes.

To calibrate the GC strip chart recorder, standards are prepared as outlined in Appendix III. The standards are injected into the GC and the peaks formed are then used as a reference peaks. Hence, a peak whose height or area is doubled, depending on the mode of operation, is twice the concentration of the standard, assuming operation is within the linear range of the detector. The linear range is defined up to the concentration where detector saturation begins. Multiple standard concentrations are used to find a calibration curve (Figure A3). This curve is then used to define sample concentrations.

For samples containing more than one electronegative gas, the retention time of the gases in the column must be

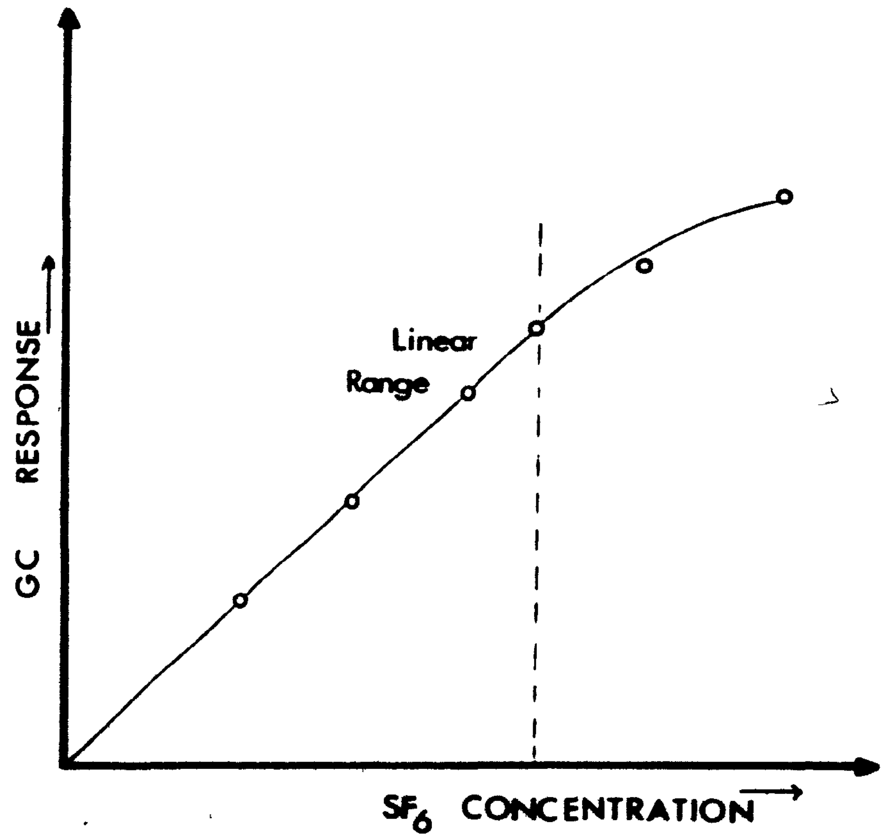


FIGURE A3: A CALIBRATION CURVE FOR GAS CHROMATOGRAPHY

noted. For example, SF_6 elutes before oxygen. The calibration only applies to the calibration gas and therefore, one must know when the gas is eluted.

An integrator like the Hewlett Packard 3390A used in the testing much simplifies the analysis and calibration of a GC. It automatically records peak height or area and resolves those relative to standards to give the resultant concentration.

APPENDIX V

ACTUAL PROCEDURES USED FOR PRELIMINARY TESTING

7^{th} FLOOR, CENTRAL TOWER

1) Release 9.7×10^{-8} m^3/s of SF_6 using air as a carrier gas into the fresh air supply system and sample the air being supplied to the interior and perimeter zones after waiting 40 s. Sample duration is one minute.

2) Sequentially release 1.8×10^{-8} m^3/s with air as a carrier in each fresh air supply duct and collect one minute samples further downstream after 30 s has elapsed.

3) Release 1.3×10^{-7} m^3/s with air as a carrier for one minute uniformly throughout the mechanical room. Wait one hour and then monitor the decay in the work places.

10^{th} FLOOR, $EAST_2$ TOWER

Core 3:

1) Sequentially release 9.3×10^{-8} m^3/s in each fresh air supply duct and measure downstream after allowing for equilibration.

2) Take a sample in the mechanical room to check for SF_6 contamination.

3) Release 9.3×10^{-8} m^3/s in the fresh air supply system and wait one minute and then sample the perimeter and interior zone supplies.

Core 4

1) Repeat the above procedure.

2) Release 9.3 x 10^{-8} m^3/s for one minute throughout the mechanical room.

Core 3

Release 1.7 x 10^{-7} m^3/s for one minute throughout the mechanical room.

Cores 1 and 2

1) Release 1.7 x 10^{-7} m^3/s for one minute throughout the mechanical rooms.

2) Return to tower $East_2$ and wait one hour and then monitor the decay in the work places.

10th FLOOR, NORTH TOWER

1) Sequentially release 5.0 x 10^{-8} m^3/s with air as a carrier gas in the fresh air supply ducts and wait one minute and sample further downstream.

2) Release 1.5 x 10^{-7} m^3/s with air as a carrier gas in the fresh air supply system and sample on the downstream side of the floor supply fan after one minute.

3) Increase the release rate to 6.5 x 10^{-5} m^3/s and release throughout the mechanical room for one minute.

4) Wait one hour and then monitor the decay in the work places.

12th FLOOR, $EAST_1$ TOWER

Core 2

1) Release 9.7×10^{-7} m^3/s in the fresh air supply system and sample both the interior and perimeter zones supply after waiting two minutes.

2) Release 1.7×10^{-8} m^3/s into the fresh air supply ducts and sample further downstream.

Core 2

1) Repeat the above procedure.
2) Release 1.8×10^{-7} m^3/s throughout the mechanical room for one minute.

Cores 1 and 2

1) Repeat the step in each core and wait half an hour before monitoring the decay in the work places of $East_1$ tower.

14th FLOOR, $EAST_1$ TOWER

1) Same procedure as outlined for the 12th floor except the final releases in the mechanical rooms should be increased to 3.2×10^{-7} m^3/s and the decay should be monitored after waiting a full hour.

15^{th} FLOOR, $EAST_1$ TOWER

1) The same procedure as the 14^{th} however, the final release rate should be increased to 3.8×10^{-7} m^3/s.

9^{th} FLOOR, $EAST_2$ TOWER

1) Release 1.7×10^{-8} m^3/s into the fresh air supply system and sample the perimeter and interior zones supply after one minute.

2) Sequentially release the same amount into the fresh air supply ducts and sample further downstream.

Core 3

1) Repeat the above.

Core 4

1) Release 1.4×10^{-6} m^3/s for one minute throughout the mechanical room and then return to core 3, and release 7.0×10^{-7} m^3/s for one minute throughout the core. Wait one hour before monitoring the decay in the work places.

18^{th} FLOOR, $EAST_2$ TOWER

1) Release 14.7×10^{-8} m^3/s with air as a carrier gas sequentially into the fresh air supply ducts and sample downstream.

downstream.

2) Repeat this release in the fresh air supply system and after one minute, sample the perimeter and interior zone supplies.

3) Release the same way throughout both cores for one minute and after 15 minutes monitor the decay in the work places of $East_2$.

28th FLOOR, NORTH TOWER

Not available.

APPENDIX VI

DIFFUSIONAL VELOCITY OF SF_6 DURING TESTING

Diffusional effects of a tracer gas are only of concern when using the rate of decay method in ventilation studies. It is to minimize its effects that a uniform initial concentration is required in the area being monitored. Fick's law:

$$C \frac{\partial x}{\partial t} = -D \frac{\partial C}{\partial x}$$

where; $\partial x/\partial t$ is the diffusive velocity (cm/s), D is the diffusion coefficient (cm^2/s), and C is a concentration given as mass per unit volume, governs diffusion in air.

Assuming the SF_6 molecule to be spherical, the diffusion coefficient can be found by Hirschfelder's Equation:

$$D = bT^{3/2} \sqrt{\frac{1/MW_{air} + 1/MW_{SF_6}}{P\phi_{12}^2 I_d}}$$

where in ventilation studies: D is in (cm^2/s), b = (10.7 - 2.46($1/m_{air} + 1/m_{SF_6}$) x 10^4, MW is molecular weight, P is in ATM., ϕ_{12} is the collision diameter (A°), I_D is the collision integral for diffusion which is a function of kT/ε_{12}, k is Boltsman's Constant (erg/°K) and ε_{12} is the energy of molecular interaction (ergs). Furthermore; kT/ε_{12} is equal to 28.2/ T_b where T_b is the temperature of component boiling point (°K). The collision diameter of SF_6 in air is given by:

$$\phi_{12}^{2} = \left(\frac{3.62 + 1.18V^{1/3}}{2}\right)^2$$

where V is the atomic volume of SF_6 whose bonds are approximately 1.35 A^o as outlined by Cotton and Wilkinson [65]. Therefore, the diffusion coefficient is 0.5413 cm^2/s. Substituting this value in to Hirschfelder's equation and knowing that 35 ppb on a volume to volume basis is equivalent to 209 ppb on a mass to volume basis at room temperature and standard pressure and that $\partial c/\partial x$ is typically about 0.02 ppb per metre, the velocity of SF_6 in air is only 0.0001 cm/s.

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