*Ventilation '85*, edited by H.D. Goodfellow, 1986
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

# TRACER GASES AS A VENTILATION TOOL: METHODS AND INSTRUMENTATION

J.-P. FARANT[1], D.L. MCKINNON[2], and T.A. MCKENNA[3]

[1]School of Occupational Health, McGill University, Montreal, Quebec, Canada

[2]Dept. of Environmental Technology, Noranda Research Centre, Pointe Claire, Quebec, Canada

[3]Occupational Health Unit, Medical Services Branch, Health and Welfare Canada, Ottawa, Ontario, Canada

## ABSTRACT

Tracer gas techniques, used for routine ventilation checks or trouble shooting are outlined with emphasis on their applicability in a variety of situations. These include methods of determining volumetric flow rates in closed conduits and finding ventilation rates at work stations. Other uses of tracer gases are also dealt with.

Investigations have been performed on the use of occupant generated carbon dioxide ($CO_2$) as an indicator of ventilation rates. Results comparing the simultaneous decay of $CO_2$ and sulfur hexafluoride ($SF_6$) are presented showing the former to be a potentially useful ventilation tool.

Presently, tracer gas studies are limited by available sampling and analytical equipment. Recent developments in the technology used for tracer gas testing and the research being performed on sampling and analytical techniques are outlined. Several different sampling methods are considered ranging from passive to pump operated bag sampling.

$SF_6$ has received wide acceptance as a tracer gas. However, investigations have shown that while it has most of the desirable tracer gas characteristics, it also has some shortcomings. The physical, chemical, and toxicological properties of alternative gases were reviewed for this reason and their relative usefulness as tracer gases is presented.

## INTRODUCTION

Early use of tracer gases concentrated on pollution migration and plume tracking and considerable emphasis has been given to determining air leakage and infiltration in buildings. Tracer gases have also proven to be useful in underground mine ventilation studies where very low air velocities, leakage, and recirculation need to be investigated. Presently, it is generally accepted that tracer gases can be effective ventilation tools.

Tracer gas techniques are essentially based on dilution. Depending on the application, the gas is released into an environment and it's concentration is measured over a period of time or instantaneously. Because release and sampling methods and the timing of these depend entirely on the information desired, an investigator must first define the objectives of the study and have a thorough knowledge of tracer gas techniques to effectively use the technology.

*No single tracer gas has been identified as ideal and as a result, a variety of gases and analytical methods have been utilized. The choice of tracer gas usually depends on the inherent characteristics of the measurements being performed, the familiarity of the investigator with a variety of analytical techniques, and the availability of the required instrumentation. As such, there is no standardized procedure for the use of tracer gases, especially with regards to ventilation investigations where different techniques can be used to gather the same information.*

*This paper outlines three versatile tracer gas techniques and their application with emphasis on their reliability.*

## TRACER GAS METHODS

*The rate of decay, equilibrium concentration, and transfer index tracer gas methods all have considerable application in ventilation studies. These can be used to determine ventilation rates, volumetric flow rates in ducting, hood collection efficiencies, and to quantify air movement. Table 1 outlines the release and sampling requirements and the uses of these methods.*

TABLE 1

Tracer gas methods, associate techniques and uses.

| Method | Release | Sampling | Use |
|---|---|---|---|
| Rate of Decay | -release of a known volume over a short time period to obtain a uniform concentration | -several grab or short term integrated samples<br>-continuous monitoring at individual sites | -ventilation rates (ACPH)<br>-air infiltration<br>-identification of stagnant zones |
| Equilibrium Concentration | -continuous release at a known rate to obtain a stable concentration in the system | -one sample obtained after equilibrium is achieved | -ventilation rates ($m^3/s$)<br>-volumetric flow rates in ducting<br>-pollution tracking |
| Transfer Index | -instantaneous release of a known volume | -continuous monitoring or several grab samples to obtain concentration integral | -ventilation rates ($m^3/s$)<br>-volumetric flow rates in ducting<br>-pollution tracking |

## The rate of decay method

The rate of decay method has been the tracer gas technique most extensively used to determine ventilation rates. The gas is released to achieve a nearly uniform concentration throughout the area of concern and to minimize the effects of diffusion. Proper mixing and the desired initial conditions can be ensured by releasing the gas via the ventilation system with all doors between rooms open (Ref. 1). Other techniques, especially point releases, may require some mechanical mixing. Once the uniform concentration has been achieved, the decay of the gas is monitored.

Decay will occur according to:

$$C_t = C_o e^{-VRt} \qquad (1)$$

where $C_t$ is the measured concentration, $C_o$ is the initial concentration, t is time, and VR is the ventilation rate(ACPH). Solving this equation for VR gives:

$$VR = 1/t \ln C_o/C_t \qquad (2).$$

Assuming that perfect mixing is achieved, a plot of 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 does not exist, the function may not be linear. In such instances, phenomena like recirculation and short circuiting should be investigated. If an entire floor in a building is being studied, multi-point sampling for the decay of a tracer gas can yield the ventilation rate for each sampling site as well as the overall ventilation rate for the floor.

This type of investigation was performed in a multi-storied office tower on a floor by floor basis. Each floor was individually flooded with $SF_6$, using the ventilation system to distribute the gas. After approximately an hour, the decay of the gas was monitored during a 2-hour period. The assumption that $SF_6$ decayed exponentially appears to be valid and the standard errors associated with the determination of ventilation rates are relatively insignificant (Table 2). This was also reflected by reasonably good regression correlation coefficients which were preponderantly in excess of 0.80.

## The equilibrium concentration method

According to the principle underlying the equilibrium concentration method, the release of a gas at a continuous rate results in an equilibrium concentration throughout a ventilation system. The equilibrium concentration achieved is related to the amount of ventilating air by the equation:

$$Q = R_r/C_{eq} \qquad (3)$$

where $R_r$ is the rate of emission ($m^3/s$) and $C_{eq}$ is the equilibrium concentration. If measurements are made throughout the area being evaluated, ventilation rates Q ($m^3/s$) can be determined.

*TABLE 2*

*Standard error associated with the determination of ventilation rates at various sites in a multi-storied building.*

| Tower | Floor | Standard errors at various sampling sites | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | NI* | NP | EI | EP | SI | SP | WI | WP |
| $East_1$ | 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 | |
| $East_2$ | 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 | C.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 |

* Sampling sites: N = north, S = south, E = east, W = west
I = interior, P = perimeter

Perhaps the most promising application of the equilibrium concentration method is the balancing and trouble shooting of local ventilation systems. By nature, these systems are under negative pressure and therefore, releasing a tracer gas at the extremities of the system and measuring along the duct network allows the determination of volumetric flow rates throughout. At the same time, hood collection efficiencies can be found by collecting a time-weighted average sample in the duct, just beyond the hood, and comparing the total amount of gas collected to that released (Ref. 2).

A laboratory study of a model local ventilation system was performed to establish the applicability of the equilibrium concentration method to this type of situation. Twenty-seven data points were gathered and tracer gas results were compared to results found with a hot wire anemometer. On average, these agreed within 9.6% of one another, and tracer gas techniques afforded greater precision (Table 3).

## The transfer index method

The transfer index method defines the transfer of air from one location to another and involves the release of a known amount of tracer gas and the measurement of the time integral concentration at points throughout the system being studied. The transfer index (TI) is expressed as:

$$TI = 1/Q_R \int C_t \partial t \quad (4)$$

where $Q_R$ is the amount of gas released ($m^3$). The ventilation rate ($m^3/s$) is given by the reciprocal of the TI. Equation 4 can be reduced to:

$$Q = Q_R / C_{avg.}\ t \quad (5)$$

for finding volumetric flow rates in duct networks. Unlike the equilibrium concentration method, the transfer index method can be used in duct networks under positive pressure as well as in those under negative pressure, and therefore has wider applications in building ventilation studies. With automated sampling systems, this technique could be used to find the air distribution throughout an entire building complex.

TABLE 3

Volumetric flow rates in a laboratory duct system.

| 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 | 3.20 ± 0.09 | 3.3 ± 0.5 | 3 |
| 2 | 1.63 ± 0.07 | 1.9 ± 0.3 | 15 |
| 3 | 0.72 ± 0.04 | 0.8 ± 0.2 | 11 |
| | | Total average difference: | 9.6% |

* Average of nine measurements

** Average of three traverses

TRACER GASES

An ideal tracer gas should:

- not be a normal constituent of the environment to be investigated;
- be easily measurable and allow an accurate determination of concentration differences between release and sampling points;
- be non-toxic and non-allergenic to permit its use in occupied spaces;
- be non-reactive and non-flammable so that its movement is easily traced;
- be economical to use.

No single tracer gas fulfills all the requirements mentioned. A wide variety of gases have been employed and have usually been chosen to exploit a specific characteristic. Of all the gases used as tracers, those receiving the most widespread use include nitrous oxide, carbon dioxide, sulfur hexafluoride and the freons (see Table 4).

*TABLE 4*

*Characteristics of commonly used tracer gases.*

| Gas | TLV (ppm) | Analytical Method | Detection Range (ppm) | Comments |
|---|---|---|---|---|
| Carbon Dioxide | 5,000 | Infrared | 0.05-2000 | Variable background |
| Nitrous Oxide | 25 | Infrared | 0.05-2000 | Low TLV |
| Sulfur Hexa-fluoride | 1,000 | Infrared<br>GC-ECD | 0.05-1000<br>$0.02 \times 10^{-3}$ to 0.5 | Possible toxic agents at 500°C |
| Freons | 1,000 | Infrared<br>GC-ECD | 0.05-2000<br>$1 \times 10^{-3}$ to 0.05 | Possible background levels |

Nitrous oxide can be measured at the parts per million (ppm) range using infrared techniques. However, its potential toxicity has somewhat limited its use.

Carbon dioxide can also be measured at the ppm level, has a background level of approximately 350 ppm and is generated by the occupants of the buildings. It has proven useful as a tracer. The following advantages can be attributed to the use of occupant generated $CO_2$ for ventilation rate determination using the rate of decay method:

- no need to introduce foreign gases into the test environment;
- readily detectable by relatively affordable, reliable IR monitors;
- initial mixing is ensured.

However, there are limitations. These include:

- occupants must be absent during the test and, as such, tests must be conducted after working hours;
- the operation of the ventilation system should be independent of heat loads, and operated in the same manner if testing is performed after hours.

The results of a study comparing the simultaneous decay of occupant generated $CO_2$ and $SF_6$ has been performed in an office tower in Montreal. The results shown in Figure 1 and Table 5 clearly demonstrate the similarity in results obtained with both these gases.

Halogenated tracer gases such as $SF_6$ and the freons are most promising. In addition to their relative non-toxicity, they have low background levels. They can also be measured at ppm concentrations by infrared analysis. However, their distinct advantage arises from their analysis by gas chromatography using an electron capture detector (GC-ECD). This analytical method permits detection of

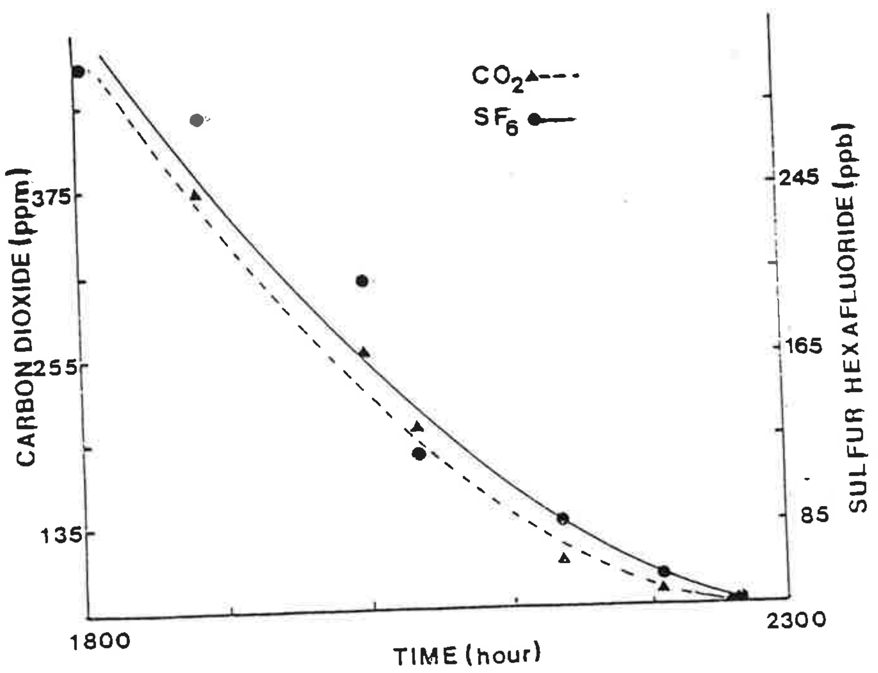


*Fig 1. Comparison of carbon dioxide and sulfur hexafluoride decay rates.*

*TABLE 5*

*Comparison of ventilation rates (ACPH) obtained with sulfur hexafluoride and carbon dioxide at several sites on one floor of a building complex.*

| Site | Ventilation rate (ACPH) | |
|---|---|---|
| | Carbon dioxide | Sulfur hexafluoride |
| 1 | 0.46 | 0.44 |
| 2 | 0.46 | 0.49 |
| 3 | 0.61 | 0.53 |
| 4 | 0.50 | 0.42 |
| 5 | 0.49 | 0.44 |
| 6 | 0.43 | 0.47 |
| 7 | 0.50 | 0.42 |
| 8 | 0.62 | 0.53 |
| 9 | 0.42 | 0.42 |
| 10 | 0.44 | 0.45 |
| Average | 0.49 ± 0.07 | 0.46 ± 0.04 |

concentrations down to the parts per billion (ppb) to parts per trillion (ppt) level. This minimizes the volume of tracer gas needed to test a large system.

Sampling methods

For ventilation tests using tracer gas techniques, the choice of a sampling method is dependent on:

- the tracer gas method;
- the tracer gas employed; and
- the analytical instrumentation.

A continuous record of tracer gas concentrations at the sampling sites provides an overall view of tracer dilution under a specific set of conditions. This approach facilitates the interpretation of results no matter which tracer gas method is used. A continuous record can be obtained as follows:

- a continuous monitor output to a recorder;
- sequential time integrated samples;
- several short-term or grab samples.

Continuous monitoring can be performed using both GC-ECD and infrared techniques. However, as an instrument is required at each sampling site, the cost of instrumentation usually prohibits simultaneous sampling at several sites. Therefore, collection of sequential, time-integrated samples or several short-term (grab) samples is commonly done. Samples can be collected in a number of ways: bags, adsorbents and evacuated containers being a few examples of these.

During the testing of a ventilation system in an office tower by a McGill team, a programmable, remote sampling system capable of collecting eight bag samples at eight different locations was used (Fig. 2). This system consisted of a programmable timer, used to activate and deactivate solenoid valves, thus sequentially filling eight bag samples per site. Normally closed solenoid valves, situated on a manifold connected to an air sampling pump, were programmed to open for predetermined intervals. This provided data for the determination of ventilation rates through the use of the rate of decay method.

Recent work studying the passive adsorption of various tracer gases on adsorbent materials, particularly charcoal cloth, has proven promising. This adsorbent's ability to passively sample $SF_6$ in the 1-150 ppb range during a relatively short sampling period (30 seconds) is shown in Figure 3.

ANALYSIS OF DIFFERENT TRACER GASES

The analysis of tracer gases is usually achieved by infrared spectroscopy or gas chromatography (Table 4). An infrared spectrometer, using a single distinctive band associated with the chosen tracer gas, can be used to analyse most tracer gases and especially carbon dioxide and nitrous oxide. Halogenated tracer gases are best analysed with a gas chromatograph equipped with an electron capture detector. In this manner, levels of tracer gas in the ppb and ppt range can be measured.

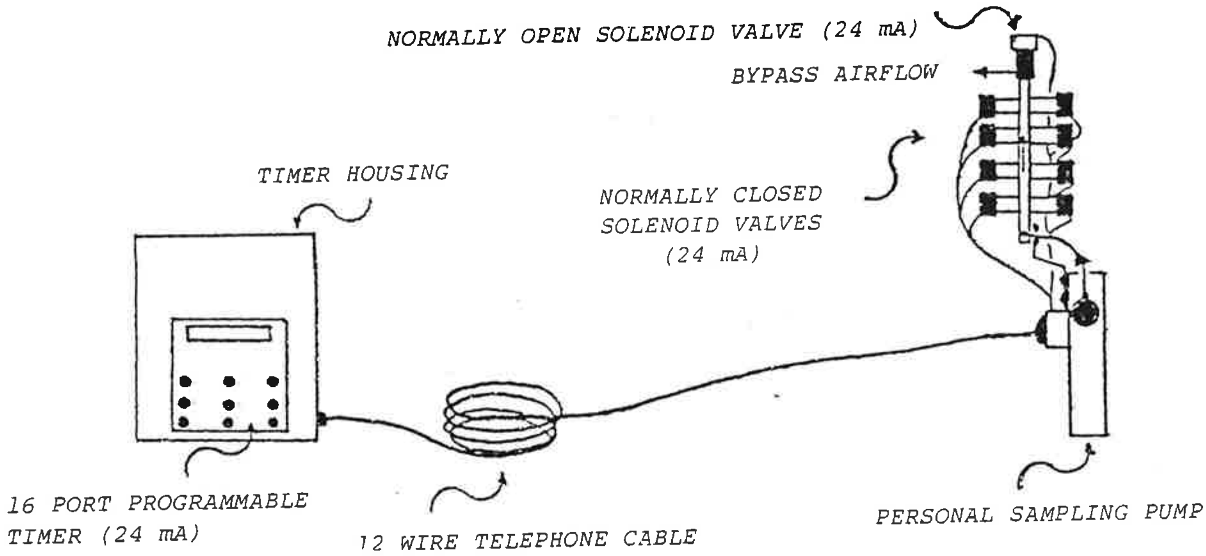


Fig. 2. Programmable, remote sampling system.

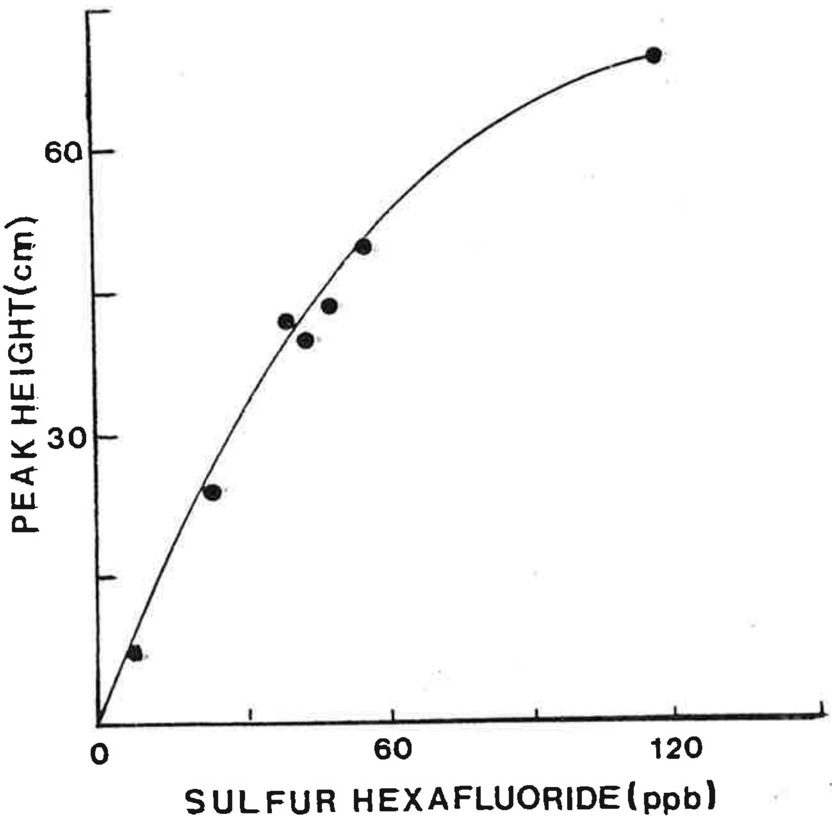


Fig. 3. Adsorption of sulfur hexafluoride by charcoal cloth exposed to the tracer for 30 seconds.

*DISCUSSION*

*The three tracer gas methods presented in this paper can be used in a variety of situations. However, all three, the rate of decay, the equilibrium concentration, and the transfer index methods can also be used interchangeably. The selection of one technique over another depends on the investigator's familiarity with the individual techniques and various other technical considerations such as available instrumentation, the amount of gas required, the desired units of the measurement (ACPH or $m^3/s$), personal preference and others.*

*Following the selection of a particular tracer gas method, consideration should be given to the choice of tracer, as it influences all of the analytical parameters. Thereafter, the interdependencies of the analytical method, and sampling and release techniques must be examined. These choices are illustrated in Figure 4.*

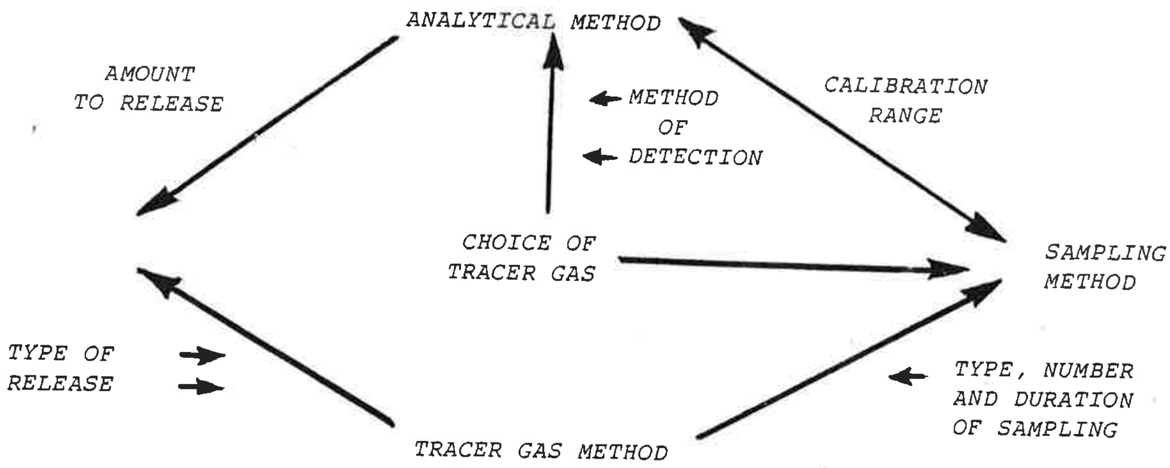


*Figure 4. Interdependencies of the tracer gas method.*

*Once the tracer gas has been chosen, the analysis of the gas should be reviewed since it can affect the selection of a sampling method, the amount of gas to be released, and the method of release. The calibration range of the analytical instrumentation defines the amount of tracer gas which can be released. A wide range is desirable as it reduces analytical manipulations such as dilution of* samples and allows for greater variability in the measured concentration.

Another aspect of a tracer gas investigation which needs to be considered is the sampling method. The tracer gas technique selected defines the type, number, and duration of samples which must be collected to furnish the necessary data. The absolute amount of gas collected must coincide with the analytical method's capability.

Finally, the release method should be examined with regards to type, duration, and the amount of gas to be liberated. The type of release may be continuous or instantaneous depending on the tracer gas method. The amount to be released must take into account the sampling and analytical techniques and the amount of ventilation anticipated.

Some of the potential errors associated with tracer gas techniques for ventilation evaluation include:

- release velocity, and method;
- sample biasing, location, frequency, calibration and contamination;
- purity of the gas used;
- standards preparation; and
- the analytical technique.

Many of the errors associated with these sources can be eliminated through the selection of suitable, well calibrated release mechanisms and techniques; proper sample timing, positioning, and calibration; ensuring the use of a pure gas; and flushing sample equipment with air between tests. Sample biasing is of concern during the determination of an overall ventilation rate obtained by averaging a number of ventilation rates. However, it can be minimized by increasing the number of samples collected. This leaves both standards preparation and sample analysis as the major sources of error.

To quantify the error expected when $SF_6$ is used in ventilation studies, an error analysis for GC-ECD, standard preparation with a Metronics Dynacalibrator, bag sampling, and pump calibration, was performed using a sum of the squares approach. In the worst instance, generating relatively concentrated standards (12 ppm) and with sample concentrations being in the low end of the linear range of the GC, an error of about 16% was found with 10.5% being attributed to standards preparation, 4% to GC-ECD, and 1% to pump calibration (Ref. 3). This was reduced to 5% with lower standard and higher sample concentrations. Errors of this magnitude can also be expected for conventional tools and probably, for other tracer gases.

Trouble shooting, balancing and quantifying airflow through a ventilation system is done to compare the data obtained to design or recommended values, to pinpoint a misbalanced state, inherent defficiencies, and to assist in identifying their probable causes. Conventional ventilation measurement tools (pitot tubes, anemometers) have these shortcomings:

- *can't afford a direct measure of ventilation rates at work locations;*
- *can't actually monitor air movement and airflow patterns;*
- *turbulence acts to reduce the accuracy of the measurements.*

*Tracer gas techniques represent an alternative means of ventilation analysis which is not hampered by these shortcomings.*

*In summary, recent developments in associate tracer gas methodologies indicate that, in the near future, ventilation specialists will be provided with easy to use, flexible, econonical and accurate instrumentation and procedures to study ventilation systems. It is anticipated that these novel methodologies will either supplement or complement existing techniques and procedures used to study ventilation systems.*

*REFERENCES*

1 P. Kallioski, R. Niemela and J. Salmivaara, The Tracer Gas Technique - A Useful Tool for Industrial Hygiene, Scand. J. Work Environ. Health, 6 (1980) 120-130.

2 C. Bruffey, P. Clarke, T. Clark, M. Phillips and T.O. Bruckle, Evaluation of an Air Curtain Hooding System for a Primary Copper Converter, EPA-600/S2-84-042, Project Summary, April, 1984.

3 G.O. Nelson, Controlled Atmospheres, Ann Arbor Science Publishers, Inc., 2nd printing, U.S.A. (1972), p. 28.

*ACKNOWLEDGEMENTS*

*The authors wish to acknowledge the financial support received from Treasur Board Canada, CANMET, IRSST. The second author would further like to acknowledg the encouragement given by the management of Noranda Research Centre in the preparation of this paper.*