Chapter 29

RESOLVING COMPLEX MINE VENTILATION PROBLEMS WITH MULTIPLE TRACER GASES

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ABSTRACT

Sulphur hexafluoride (SF_6) has become an accepted standard in the field of mine ventilation tracer gas studies. It has a wide variety of uses for defining mine ventilation flows that cannot be adequately described using conventional instruments such as anemometers and smoke tubes.

The Cape Breton Coal Research Laboratory (CBCRL), Energy, Mines and Resources Canada, has been using SF_6 for the past 4 years and has developed numerous release and sampling systems to increase its versatility. The CBCRL has also completed a successful field trial of an automated rapid sequential SF_6 analyzer (which gives a pseudo real-time readout) that can be used underground. In doing this work, the authors recognised the potential of being able to use more than one tracer gas simultaneously in an underground study.

Two alternative tracer gases (Freon-13B1 and Freon-12) have already been used by CBCRL in some of their underground work. These gases can be measured by gas chromatography utilising an electron capture detector in a similar manner to SF_6. A description of these gases, the methods for their handling, release and sampling are given in this paper together with a brief outline of the analytical system used to measure them. Their suitability to mining applications is compared with SF_6.

A study in which these three gases were used together is discussed and the results and conclusions given.

Some of the additional uses for multiple tracer gases to assist the mine ventilation engineer in resolving problems and improving his day-to-day monitoring are discussed.

Finally, a brief analysis of developments which can be expected in the near future is outlined.

INTRODUCTION

In recent years, tracer gases have become increasingly popular for analyzing ventilation systems, both in buildings and in underground mines. One gas in particular, sulphur hexafluoride (SF_6), has gained popularity as a mine ventilation tracer. In fact to some extent it can be considered the standard in the field of tracer gas studies. It is ideally suited to the demands of mine ventilation systems because only relatively small volumes are required to dope large ventilating airflows. It can be accurately measured in concentrations as low as a few parts per trillion by a gas chromatograph utilising an electron capture detector.

Researchers have used gases such as nitrous oxide and helium as mine ventilation tracers (Shuttleworth, 1958; Wann et al., 1977). However, due to their lower detectability, large volumes of these gases are needed to be released into the airstream. This resulted in problems of their underground transportation and achieving stable flows.

In addition to a low detection limit, SF_6 has a number of other desirable properties: it is non-toxic, odourless, colourless, chemically and thermally stable and it is not found to occur naturally in the environment (Thimons et al., 1974).

Researchers at the Cape Breton Coal Research Laboratory (CBCRL) have been using SF_6 in their mine ventilation studies for the past 4 years. During this time they have refined many of the existing release and sampling systems used with SF_6 and, when required, developed new ones (Stokes et al., 1987). During this refinement period several surveys were conducted which would have benefited by using one or two other tracer gases in conjunction with SF_6. Multiple tracer gas releases could, it was realised, add flexibility to a field survey in many ways.

An additional tracer gas would provide a means to monitor baseline ventilation conditions whilst SF_6 was being used to measure parameters associated with a zone under investigation. Similarly, several tracer gases could be released at different points inside a zone under investigation to provide many times the number of data points for a fixed number of air samples collected during a survey. Presently, when a survey is required with more than one release point inside an investigation zone, a number of unique SF_6 surveys are done in as short a space of time as is physically possible. This approach obviously suffers from changes in the ventilation conditions between surveys which can distort the results. A survey which requires several gas injections into large areas of the mine with relatively small airflows might have to be spread over a period of several days in order to give the tracer sufficient time to disperse from the test zone between injections. Such was the case in a CBCRL study where a series of injections were made into the caved waste area behind an advancing longwall face. Day-to-day variations in the air quantities entering the longwall regularly exceeded 10%.

With the potential benefit of multiple tracer gas capability in mind, CBCRL undertook a program to identify other gases which could be used in conjunction with SF_6. This paper documents the search and trials of alternative gases, the development of a suitable analytical method and two field tests of two of the more promising gases.

Requirements for Alternative Tracer Gases

Any gas which is going to be used as a tracer in conjunction with SF_6 should fulfill the following requirements:

i) The gas should have the following desirable properties and attributes:

- non-toxic
- non-corrosive
- non-radioactive
- chemically stable
- thermally stable
- odourless
- colourless
- readily obtainable
- inexpensive
- no exotic storage requirements
- easily transportable
- gas at mine temperatures and pressures
- measurable in trace concentrations (<ppb)
- not found naturally occurring in the environment

ii) The gas should be compatible with the existing release and sampling systems which have been developed for SF_6 (i.e. does not permeate through the walls of the gas bags used in grab sampling).

iii) The gas should be measurable by the same, or a slightly modified version of, the analytical train presently being used for SF_6.

IDENTIFICATION AND TESTING OF THE CANDIDATE GASES

From the criteria which were identified in the previous section, it was decided that the most probable group of gases to investigate would be the Freons.

The six Freons which were selected as the most promising candidate gases were Freon-12, Freon-13, Freon-13B1, Freon-22, Freon-23 and Freon-116. All of these gases satisfied most of the requirements identified in section (i) above. The next stage of the screening process was therefore to determine the detectability of these gases using the electron capture detector. From a series of experiments, it was found that none of them produced as good a response from the electron capture detector as SF_6. Only Freon-12 and Freon-13B1 were within two decades of the sensitivity of SF_6. The other four gases were several orders of magnitude less sensitive. For this reason they were discarded.

The full and proper names of Freon-12 and Freon-13B1 are Dichlorodifluoromethane and Bromotrifluoromethane respectively. Table 1 outlines some of the chemical and physical properties of these gases together with SF_6.

Table No. 1

Properties of SF_6, Freon-13B1 and Freon-12

Sulphur Hexafluoride (Formula: SF_6)

Molecular Weight	146.054
Specific Volume @21.1°C, 101.3 kPa	156.1 cc/g
Vapor Pressure @21.1°C	2308 kPa
Relative Density @20°C, 101.3 kPa (Air=1)	5.114
Threshold Limit Value (1986 ACGIH)	1000 ppm

Bromotrifluoromethane (Formula: $CBrF_3$)
Synonyms: Trifluoromethyl Bromide; Freon-13B1 ®

Molecular Weight	148.910
Specific Volume @21.1°C, 101.3 kPa	162.3 cc/g
Vapor Pressure @21.1°C	1411.3 kPa
Relative Density @25°C, 101.3 kPa (Air=1)	5.31
Threshold Limit Value (1986 ACGIH)	1000 ppm

Dichlorodifluoromethane (Formula: CCl_2F_2)
Synonyms: Freon-12 ® ; Genetron-12 ® ;
Isotron-12 ® ; Ucon-12 ®

Molecular Weight	120.914
Specific Volume @21.1°C, 101.3 kPa	195.4 cc/g
Vapor Pressure @21.1°C	585 kPa
Relative Density @20°C, 101.3 kPa (Air=1)	4.2
Threshold Limit Value (1986 ACGIH)	1000 ppm

ANALYTICAL METHOD

A Perkin-Elmer Sigma 2000 gas chromatograph equipped with an electron capture detector is used for analyzing the tracer gas samples. SF_6 and Freon-13B1 are determined using a molecular sieve 5A column. Freon-12 is measured on a Porapak Type P column. A switching valve, located in the gas chromatograph's oven, allows each column in turn to be placed on stream with the detector.

Analysis time for SF_6 and Freon-13B1 is two minutes per sample while Freon-12 takes three minutes to elute from the Porapak column. A detailed description of the analytical method is given elsewhere (Kennedy, 1987).

TESTING OF RELEASE AND SAMPLING SYSTEMS

A number of different systems have been developed for releasing SF_6 into the airstream. Of all these, the one most commonly used by CBCRL in their field studies is the constant steady flow from a restricted lecture bottle. This consists of a lecture bottle of SF_6 with a regulator to maintain a constant outlet pressure. Attached to this is a long length of 0.1 mm I.D. stainless steel capillary tubing. This provides a large resistance to the flow of gas from the bottle and hence maintains a steady flow. The desired flow rate can be achieved by varying the gas pressure with the regulator and changing the length of the capillary tubing. A variation of this release system uses a critical orifice made from sapphire instead of the capillary tubing with a differential pressure regulator to maintain a constant pressure across it. Both these systems are described in more detail elsewhere (Stokes et al., 1987).

The two systems most commonly used by CBCRL for collecting grap samples of tracer gas from underground are plastic syringes and TEDLAR gas sampling bags. These systems and their use are discussed in more detail elsewhere (Stokes et al., 1987). Both systems were given an extensive laboratory test to determine their suitability for use with Freon-12 and Freon-13B1.

A cylinder of compressed air was prepared as a standard by doping it with small amounts of SF_6, Freon-12 and Freon-13B1. This produced a mixture containing 101 ppb of SF_6, 181 ppb of Freon-12 and 205 ppb of Freon-13B1. These concentrations are in the approximate range that they would be used underground. Six syringes and six TEDLAR gas bags were then filled with this gas mixture. They were then left to sit for 24 hours (the typical time between collection and analysis in a field survey) and then analysed for their tracer gas content. Results showed that providing the gas bags were in good condition, there was no detectable degradation of the gas sample during the 24 hours. The gas held in the syringes however did show a significant reduction in the concentration of all three tracer gases. SF_6 showed a loss of between 0.5% and 1%, Freon-13B1 showed a loss of between 2.5% and 3% and Freon-12 showed a loss of around 6%. The syringes were therefore emptied and refilled with the standard gas, left for a further 24 hours and tested again for their tracer gas content.

The loss of tracer gas after the second filling of the syringes was approximately half that after the first. This leads to the conclusion that at least some of this loss was due to adsorption of the tracer gas onto the internal parts of the syringes and not all permeation through the walls or leaks past the seals. The reason the loss after the second filling was less is explained by the internal parts of the syringes already being coated with tracer gas molecules. Whatever the cause of these losses however one thing is clear; that although a 1% loss of SF_6 and a 3% loss of Freon-13B1 after 24 hours may be acceptable for some surveys, the loss of 6% of Freon-12 is not. So until more suitable types of syringes could be found all further tests with Freon-12 should be done collecting grab samples in TEDLAR bags or other suitable containers.

FIELD TESTS OF THE GASES

Having satisfied ourselves that the release and sampling systems would perform adequately, two trials were devised to test the tracer gases when used together under field conditions.

Field Test No. 1

The objective of the first field test was to monitor the three tracer gases when released together into an airstream to check that they behaved in a similar manner (i.e. compare their diffusion rates into the airstream and their adsorption onto the roadway walls etc.).

For this test, three lecture bottles of the tracer gases were taken to an actively working advancing longwall district in a coal mine and positioned approximately 60 m from the return end of the face. The outlet tubes from the bottles were bundled together and hung from the canopy of one of the face supports. This ensured that the gases would be released into the same part of the airstream. The valves on all three bottles were opened and given sufficient time for their flows to stabilise. The gas flows were measured using a 100 ml soap bubble flow meter. Flows from the bottles were as follows: SF_6 - 2.02 cc/s, Freon-13B1 - 3.68 cc/s, Freon-12 - 3.76 cc/s. These flows were checked at the end of the test and were all within 1% of their original values.

Once the tracer gases had had sufficient time to reach steady state conditions along the entire length of the return gateroad, grab samples were gathered from along its length at approximately 50 m intervals. These samples were collected using a steady flow pump and a sampling wand to draw air into TEDLAR gas sampling bags. Once the roadway had been traversed, a second set of air samples were gathered from the same sampling points using a similar sampling technique except the samples were stored in 60 ml plastic syringes.

All the air samples were analysed the following day. The graphs in Figure 1 show the resultant concentrations of the three gases measured in the gas bags and those in Figure 2 show the SF_6 and Freon-13B1 concentrations in the syringe samples.

The tracer gas concentrations marked onto Figures 1 and 2 have been joined together to form lines (one for each gas). The SF_6 has been drawn to a different scale to the other two Freons (twice the scale) to make the profiles easier to compare.

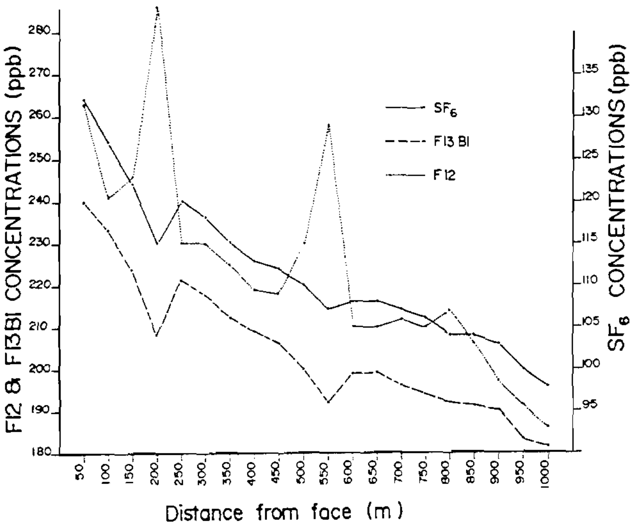

FIGURE 1. Gas concentrations versus outbye distance from the face (gas bag air samples).

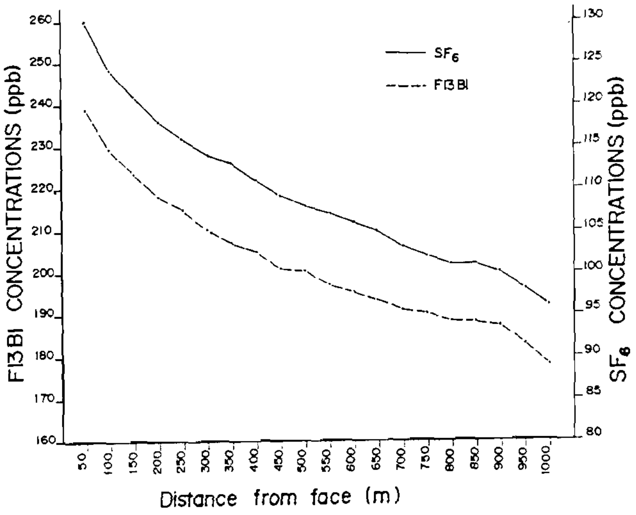

FIGURE 2. Gas concentrations versus outbye distance from the face (plastic syringe air samples).

From the profiles shown in Figure 1, it is obvious that there is an abnormality with the results. As all three gases were released at the same point it is fair to assume that they were affected by the same variables and as such it could be expected that variations in the concentration profiles are very similar and in terms of relative accuracy agree to better than 1%. However, the trace for the Freon-12 shows significant differences to the other two. When compared to the trace which would have been expected from this type of survey, it can be seen that there are three distinct peaks superimposed onto the Freon-12 profile. These are located approximately 200, 550 and 800 m back from the face. Furthermore, these peaks are mirrored about the expected profile line by smaller troughs in the other two profiles. Clearly something had adversely affected the results.

The samples contained in the syringes were gathered from along the same roadway less than an hour after the bag samples. Yet the tracer gas profiles shown in Figure 2 do not contain these same large deviations. This suggests that the peaks and troughs seen in Figure 1 were caused by an external source. Background samples collected prior to the start of the test showed that there were no detectable amounts of any of the three tracer gases or any other contaminant gases that could be detected by the analytical train. This external influence was therefore intermittent.

Although it is not known for certain what this influence was, certain types of spray paints which are used by the surveyors in the mine have propellants containing Freons. Although this survey was conducted on a Sunday, it is possible that maintenance crews in the mine might have been using this type of paint or some other type of aerosol propellant.

Close examination of the SF$_6$ and Freon-13B1 profiles in Figure 2 show excellent agreement. For any one sample, the ratio of their concentrations should be the same as the ratio of their volumetric release rates. If the profiles are adjusted for the adsorption of tracer gases onto the internal surfaces of the syringes, these ratios are within 2% of what they should be. Both profiles show the same characteristic features caused by the dilution of the tracers by uncontaminated air short-circuiting the face through the caved waste area. This shows that both gases behave in a similar manner with regard to diffusion, adsorption, etc.

Field Test No. 2

A second field test was done to clarify the results of the first and to demonstrate a simple application of the multiple tracer gas technique.

The advancing longwall used in the first test was selected again for this one. The test was conducted one week later so ventilation conditions in the district had changed slightly.

In this experiment, the same three bottles of tracer gas were used. This time however bottles were positioned approximately 10 m from either end of the face line and near the middle of it. The objective of this multiple release was to identify the areas of the face line from which most air leakage occurs. How this is done is described later. The schematic in Figure 3 shows the locations of each of the tracer gas release systems and the expected face airflow patterns.

The release rates for the three gases were as follows: SF$_6$ - 2.05 cc/s, Freon-13B1 - 3.70 cc/s and Freon-12 - 3.79 cc/s. After allowing sufficient time for equilibrium to occur, gas samples

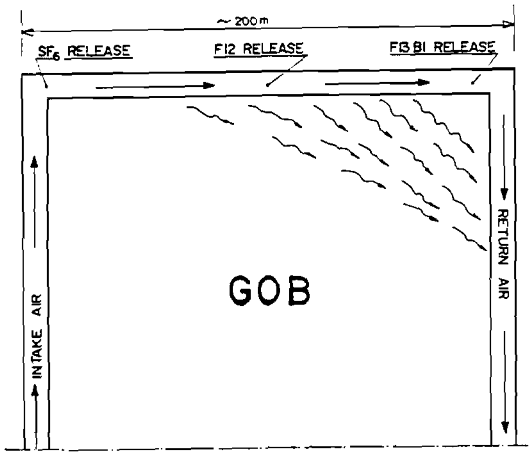

FIGURE 3. Schematic plan of 10 East showing locations of the tracer gas release systems and expected airflow patterns.

were gathered from the return roadway in TEDLAR gas sampling bags using the technique previously described. Samples were collected from the return gateroad every 25 m for 450 m beginning at the return end of the face. These were analysed the following day. Figure 4 shows the concentrations measured in the bag samples versus the distance from the face that they were taken.

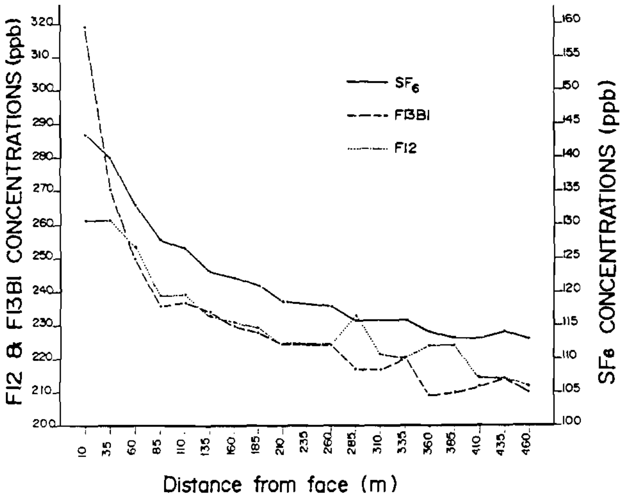

FIGURE 4. Gas concentrations versus outbye distance from the face (gas bag air samples).

The sample collected 235 m behind the face line was disregarded since the bag was found to be damaged. The points on these graphs have been connected to form profiles for the individual gases. The SF$_6$ concentration has been drawn to a different scale to the other two Freons (twice the scale) to make the features of the three profiles easier to compare.

Generally, the three concentration profiles show good agreement. However, as in the first test, some superimposition of two sets of peaks and troughs can be identified on the profile lines. These occurred in the samples collected close to 285 m and 385 m back from the face. As before, the Freon-12 profile has peaks superimposed onto its profile with corresponding smaller troughs onto the other two. It is important to note that these abnormalities were measured at different sampling locations than those measured in the first test and that different sampling bags were used for this survey. This effectively discounts two other potential sources for the abnormalities and to some extent strengthens the hypothesis that they are caused by some other influence in the airstream.

Apart from the disturbances, the three profiles show excellent agreement. One hundred metres behind the rear of the face most of the tracer gases seem to have entered the return gateroad from the gob. From this point back (neglecting the interferences) the three tracer gas profile lines follow an almost identical path. This fact tends to confirm that the three gases do behave in a similar manner and none of them display a tendency to be more readily adsorbed than any other (from these results it appears there is little adsorption occurring at all).

Figure 5 shows plots of the indicated airflow profiles derived from the profiles in Figure 4 using the following relationship:

$$Q = \frac{v}{c} \times 1000 \qquad (1)$$

where Q is the indicated airflow (m^3/s)
v is the volume flow rate of the tracer gas (cc/s)
and c is the tracer gas concentration measured in the sample (ppb)

These plots show the amount of leakage of ventilation air from the face and where it leaks from. Due to the mining method, face air leakage patterns change constantly.

During this particular survey there was little or no leakage from the bottom half of the face. This is evidenced by the similarity between the SF$_6$ and Freon-12 profiles in the return gateroad immediately behind the face. Ten metres behind the face the Freon-13B1 airflow profile is some 3 m^3/s less than the other. This represents the volume of air that leaked from the face between the Freon-12 and Freon-13B1 release points. The Freon-13B1 airflow profile then rises rapidly to the same level as the other two between 60 and 85 m behind the face. This represents the face leakage air rejoining the main airstream in the return gateroad. This pattern of airflow is typical with what has been previously measured in similar longwall layouts (Stokes, 1985).

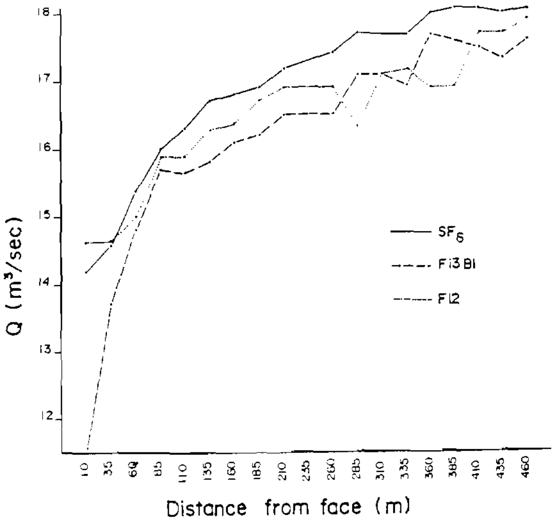

FIGURE 5. Indicated return gateroad airflow profiles as derived from the three tracer gases.

ERRORS ASSOCIATED WITH MULTIPLE TRACER GAS SURVEYS

The results of the field tests showed a good agreement in terms of absolute accuracy between the detected concentrations of the three tracer gases. The differences that were seen can be explained by the following sources of error:

1) error in measuring the tracer gas release rate (±0.5%)
2) analytical error (±2%)
3) adsorption of tracer onto roadway walls etc. (unknown error)
4) difference in elevation between tracer release points (1% per 100 m difference in elevation)
5) sampling error (±1%)

It should be noted that the relative error in a series of samples is less than the absolute error for each measurement. The relative error involves instrument stability and could be as low as 0.5%. The absolute error involves comparing the gas sample with a known standard and could be as high as 5%.

EVALUATION OF FREON-12 AND FREON-13B1 AS TRACER GASES

Preliminary evaluations indicate that Freon-12 and Freon-13B1 perform well as mine ventilation tracer gases. In the tests done so far, both gases displayed the same mixing and adsorption characteristics as SF_6.

Since Freon-12 is used as a refrigerant and as a propellant in aerosols, background samples should be taken to ensure that it is not present in the ventilation network under investigation. The importance of taking background samples in a tracer gas survey cannot be over emphasized. This is the only way one can be certain that interfering gases or the tracer gases used are not present in the ventilation network.

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