A TRACER GAS TECHNIQUE FOR THE MEASUREMENT OF AIRFLOW IN HEADINGS

By J. HIGGINS, B.Sc., and SHEILA E. H. SHUTTLEWORTH, M.A.*

This article describes a novel method of measuring the airflow in a heading using nitrous oxide as a tracer gas, the concentration being determined by means of an infra-red analyser

A need exists for a reliably accurate method of measuring the quantity of air flowing through underground roadways, the accuracy of which is independent of the variation in velocity of the airstream across the cross-section of the roadway and also of the fluctuations in velocity at any point due to normal degrees of turbulence present in the flow. The method in current use is to measure the mean velocity of the air by traversing a vane anemometer over the cross-section: the cross-sectional area is also measured and the quantity of air flowing is obtained as the product of the mean velocity and cross-sectional area. For general routine work by colliery officials the repeatability of this method is sufficient to indicate any marked change in the airflow, although its accuracy and the information it provides concerning the velocity distribution is limited. It has been found[1] that vane anemometers are subject to errors of up to 20 per cent. under conditions different from those in which they are calibrated. When it is required to know the quantity of air flowing in a mine roadway with a high degree of accuracy, the technique of measurement must not only be independent of the normal degrees of turbulence present in the airflow and of the irregular cross-sectional area of the roadway; it should not use an instrument calibrated under an entirely different set of conditions, as is the case with anemometers, and it should be capable of use in low air velocities (below 30 ft. per min.).

A tracer technique offers important advantages in that the quantity of air flowing, and not the velocity, is measured directly and the cross-sectional area of the roadway does not need to be known. Also, varying degrees of turbulence in the airstream do not introduce errors as is the case with anemometers.

The tracer technique

When applied to the measurement of airflow underground the technique consists of releasing into a mine airway a quantity of tracer gas either instantaneously or over a period of several minutes. As the tracer is carried downstream from the release point it gradually diffuses into the airstream, the process being aided by the general turbulent nature of the flow. A stage is ultimately reached when the tracer is uniformly mixed with the airstream across the whole cross-section of the airway. At a point in the airway where the tracer is known to be completely mixed with the airstream, samples of the air are taken and analysed for their tracer content. Knowing the tracer concentration and the rate of release of the tracer (or the total quantity released), it is possible to determine the airflow directly.

A radioactive tracer was not adopted as it requires the Ministry's permission for use underground. The alternative of using a stable isotope as the tracer and then irradiating it was rejected on the grounds of inconvenience and expense. For underground use most available chemical tracers had also to be rejected for reasons of toxicity, explosion hazard, or difficulties associated with the detection of concentrations of the tracer in air, or for the fact that the chemical was already present in mine airs in unknown and varying amounts.

Nitrous oxide is the most suitable tracer, and, with an infra-red gas analyser, it is possible to determine concentrations of this gas in air of the order of 100 p.p.m. to an accuracy of $\pm$ 1 per cent. It is easy to obtain, fairly cheap and non-toxic.

Two methods of measuring the airflow were examined. In the first method, here called the Steady Release Method, the tracer is released continuously at a constant known volume rate q. As the tracer-air mixture reaches and passes the sampling point, the concentration of tracer in the airstream at this point builds up to a value which remains constant. The time of build up may vary from a fraction of a second to several minutes according to the turbulence of the airstream and the distance between release and sampling points. At any time after the build up a sample is taken and the concentration, c, of the tracer in the airstream at the sampling point is determined. Since steady conditions prevail and the tracer is uniformly mixed across the whole cross-section of the airway containing the sampling point (N.B. this fact should be ascertained by two or three test samples), and assuming that there is no loss of tracer gas between release and sampling point, the volume rate of airflow, Q, through the airway is calculated from the relation $\frac{q}{Q} = c$.

In the second method, the Pulse Release Method, a

* National Coal Board, Mining Research Establishment, Isleworth

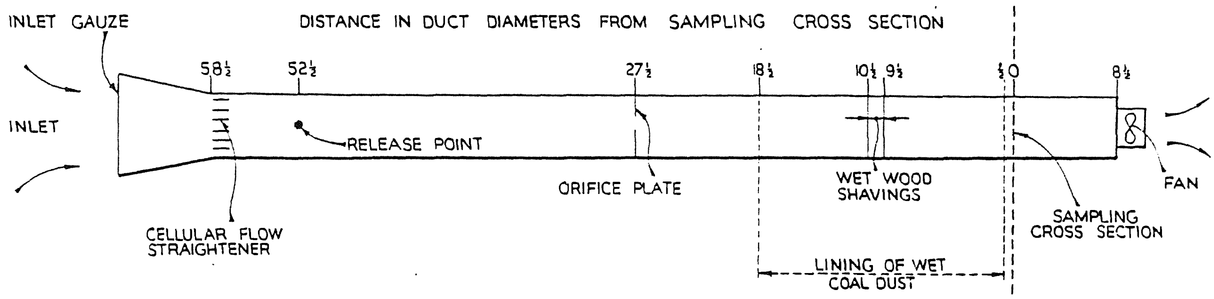

Fig. 1. The duct assembly for the accuracy and absorption tests

known mass, m, of the tracer is continuously released, but the rate of release need not be constant. Throughout the period of passage of the pulse of tracer-air mixture past the sampling point, samples are taken as frequently as is practically possible until the concentration of tracer gas becomes immeasurably small. A concentration-time curve is then drawn up and the area under this curve, A, is evaluated. The volume rate of airflow, Q, through the airway is determined as follows:—

Let c be the concentration of tracer at the sampling point at time t during the passage of the pulse past the point.

Let m, ρ be the mass and density respectively of nitrous oxide used.

At time t, the volume rate of flow of tracer past the sampling cross-section is cQ. Hence, the volume of tracer contained in the whole of the pulse passing the cross-section is $\int_0^\infty cQdt$ where the time of commencement of the passage of the pulse is taken as zero. Assuming no loss of tracer between release and sampling points and an airflow which is constant, then

$$\frac{m}{\rho} = Q\int_0^\infty cdt = QA$$

$$\therefore Q = \frac{m/\rho}{A}$$

A laboratory study of the accuracy of the tracer technique

Before taking the tracer technique underground it was necessary to examine the accuracy of the Steady Release Method in the laboratory. The airflow given by this method in a ventilation duct was compared with that given by an orifice plate inserted in the duct. The laboratory experiments also included a study of absorption of nitrous oxide by water and carbon in order to determine what quantities of tracer, if any, would be lost by absorption underground.

The airflow was measured in a straight length of circular rigid ducting 67 ft. long and 12 in. diameter. The orifice plate was 4·37 in. in diameter with D and $\frac{D}{2}$ pressure tappings and was placed in the duct as shown in Fig. 1. The differential pressure between the tappings was recorded by a ring balance manometer, thus giving a continuous record of the airflow. The orifice plate readings gave the airflow to within 1 per cent. of further measurements with pitot tube traverses.

From some earlier studies on the nature of diffusion of nitrous oxide within the duct it was possible to determine the distance required between the release point and the sampling cross-section. In cases where there was no obstruction to the flow (such as an orifice plate), this distance was greater than the length of ducting available. The insertion of an orifice plate not only enabled a continuous record of the airflow to be taken, but also assisted considerably the diffusion process.

The effect of any absorption by water upon the accuracy of the tracer method was tested by passing the nitrous oxide through a 12 in. length of wood-shavings saturated with water and placed across the duct in between the release and sampling points. The effect of any absorption by carbon (and also water) was tested by suspending in the duct an irregular lining 18 diameters long covered with a wetted coal dust (Linby Main). The positions of the various devices when in use are shown in Fig. 1.

The nitrous oxide was released continuously from a point on the axis of the duct at a known rate (q) measured by a rotameter calibrated for nitrous oxide in the range 0·002 to 0·02 cu. ft. per min. At the sampling point, the tracer-air mixture was drawn out of the duct through a tube facing upstream and then through an infra-red gas analyser by means of a small pump. The analyser used was fitted with nitrous oxide condensers and calibrated for nitrous oxide. The sensitivity was set to give a maximum scale reading of approximately 130 p.p.m.

For each test, five samples evenly spread along a diameter were taken, and since the tracer over the whole of the sampling cross-section was uniformly mixed with the airstream, the concentration (c) was taken as the arithmetic mean of the samples. The volume rate of airflow (Q) in each test was then determined from the relation $Q = \frac{q}{c}$ and was compared with that obtained from the orifice plate.

A group of accuracy tests and a further three groups of absorption tests with either the wet wood-shavings (groups (1) and (2)) or the wetted coal dust (group (3)) in the duct were carried out at airspeeds between 135 and 240 ft. per min. For each individual test the airflow measured by the Steady Release Method, Q_s, was expressed as a percentage of the airflow measured by the orifice plate, Q_o. Comparisons of the tests within a particular group were made and these results are shown in Tables I and II.

Table I shows a very good agreement between the tracer gas technique and the orifice plate and this close agreement is maintained in Table II. Hence, not only was there no absorption of gas by either

TABLE I—TESTS OF THE ACCURACY OF THE NITROUS OXIDE TECHNIQUE

Number of Tests n	Mean Airflow by Orifice Plate $\frac{\Sigma Qo}{n}$ (cu. ft./min.)	$\frac{\Sigma \frac{Qs}{Qo} \times 100}{n}$	Standard Deviation of $\frac{Qs}{Qo} \times 100$
7	187·7	99·7	1·6

TABLE II—EXAMINATION OF THE ABSORPTION OF NITROUS OXIDE IN WATER AND CARBON

Group	Number of Tests n	Mean Airflow by Orifice Plate $\frac{\Sigma Qo}{n}$ (cu.ft./min.)	$\frac{\Sigma \frac{Qs}{Qo} \times 100}{n}$	Standard Deviation of $\frac{Qs}{Qo} \times 100$
(1) Water	8	108·4	99·7	0·9
(2) Water	5	123·8	99·1	0·7
(3) Carbon and Water	6	182·5	99·8	1·1

water or carbon, but without exception, the agreement between the tracer technique and the orifice plate in each individual test was very satisfactory.

The measurement of airflow in an underground heading

In order to examine the nitrous oxide tracer technique underground a site was required in which the airflow could also be measured by means other than the tracer technique. A heading with a forcing ventilation system offered the most suitable conditions as the air entering the heading could be metered accurately by means of an orifice plate placed in the duct. A level, straight heading at Snowdown Colliery which was driven through solid ground and had a cross-sectional area of approximately 140 sq. ft. was used. The forced ventilation was supplied at the rate of about 6,400 cu. ft. per min. An orifice plate was inserted into the 24 in. diameter duct 63 yards from the discharge end and the pressure tappings, of the D, $\frac{D}{2}$ type, were connected to a sensitive inclined manometer. The straight pipe requirements for the orifice were met adeqately and the tolerance for the installation was calculated as $\pm$ 1 per cent. (Flow Measurement B.S. 1042: 1943).

In addition to testing the performance of the tracer technique under actual underground conditions, opportunity was taken to test the performance underground of the Centre Factor Method[2] for measuring duct airflows. This method consists of holding a vane anemometer centrally against the discharge end of the duct and measuring the central velocity. The mean velocity in the duct is then calculated by multiplying the reading obtained by a factor, previously determined experimentally. From the mean velocity and the cross-sectional area of the duct the volume rate of airflow is determined.

The performance of both the Steady Release and Pulse Release tracer methods was examined. The nitrous oxide was released into the ventilation duct at a steady rate at a point 8 ft. upstream of the orifice plate. From theoretical calculations[3], 55 yards of unobstructed duct length (less if the duct were obstructed) were necessary for uniform mixing of the tracer with the airstream. Hence, with the orifice plate inserted downstream of the release point in order to assist mixing, a discharge of a uniform mixture of tracer gas and air into the heading was ensured. For each experiment the time of release was of the order of 20 min. The rate of flow was approximately 0·8 cu. ft. per min., so that the total amount of nitrous oxide used in each case was about 16 cu. ft. The rate was selected to give a concentration under steady conditions of the order of 120 p.p.m. which was a concentration that could be measured by the gas analyser to an accuracy of $\pm$ 1 per cent. The rotameter used in the experiments was calibrated in the laboratory for nitrous oxide and corrections determined for temperature effects due to the vaporization of the nitrous oxide in the pressurised gas cylinder. For the purpose of examining the performance of the Pulse Release Method, the gas cylinders were also weighed before and after each experiment in order to determine the mass of gas used.

Sampling was carried out using the standard equipment developed for the purpose of mine air analysis[4]. It consists of a pump by means of which the sample is compressed into a metal sampling bottle. This system of sampling is convenient and large numbers of samples can be carried easily and safely. There was however a time delay between sampling and analysing, but with the metal bottles samples could be kept for at least two days with no measurable effect. Each bottle was filled by ten strokes of the pump immediately before the sample was taken; the contents were then discharged and the bottle refilled by another ten strokes. The final correction to be applied for the initial volume of air in the bottle was thus reduced to less than 1 per cent.

The procedure during each experiment was as follows. Observers were stationed at the positions A and C shown in Fig. 2. Position A was at the discharge end of the duct, and position C was at the centre of the cross-section of the roadway 63 yds. outbye from the discharge end of the duct. At position C it was immaterial where the sampling position was within the cross-section as the concentration was the same, but for convenience the centre of the roadway was selected in each case. Samples of the air were collected at both these positions at frequent intervals over a period of about 40 min. This period, starting one minute before the nitrous oxide was turned on, completely covered the time during which the tracer content of the airstream at positions A and C was significant. The length of time necessary for this was determined by preliminary observations. The uniformity of concentration of the tracer across the cross-section of the roadway at position C was also checked in one of these preliminary observations. The observer at A, in addition to taking samples of the air, took anemometer readings of the axial velocity at the discharge end of the duct for the purpose of testing the Centre Factor Method. The manometer reading for the orifice plate was noted by a third observer at several times during the experiment.

Fig. 3 shows the type of concentration-time curve obtained from the analysis of the samples taken at position C. The two curves are the results of two

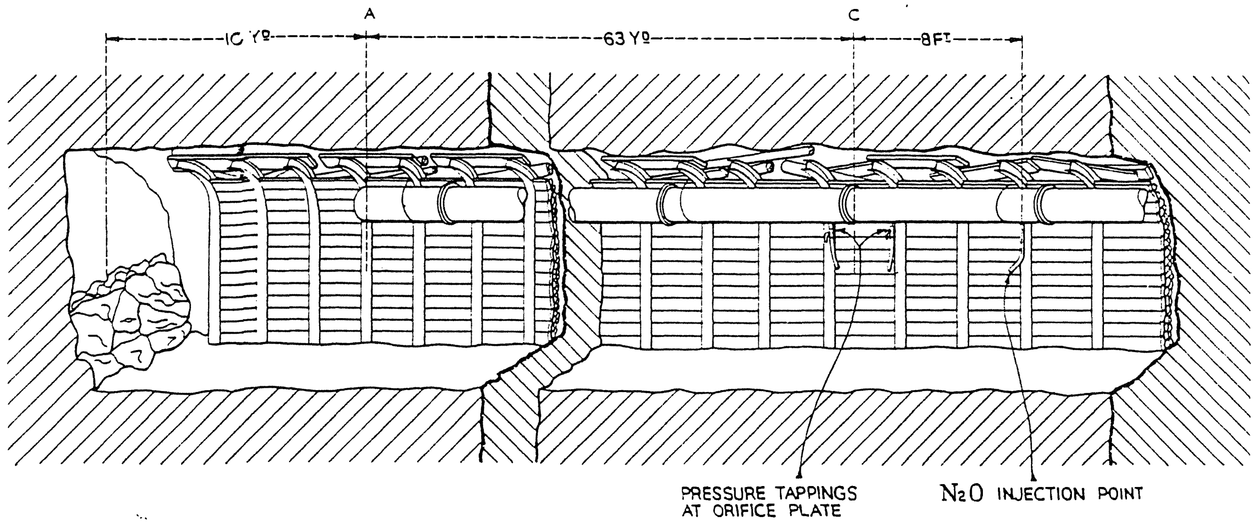

Fig. 2. Section of the heading

identical experiments on different days. It should be noted that work was in progress in the heading while the experiments were being carried out and that the positions of tubs, drilling rigs, etc., were constantly changing. The effect of these changes upon the longitudinal dispersion of the nitrous oxide in the airstream can be seen in the marked difference in the shapes of the curves.

For each experiment, values of the airflow, Q_s, were determined at positions A and C by both the Steady and Pulse Release Methods. Further values of the airflow, Q_o and Q_a, were determined from the orifice plate readings and from the anemometer readings at the discharge end of the duct respectively. The results are shown in Table III.

Apart from the Steady Release Method at position C, there is close agreement with the orifice plate in all four methods. At position C (where the velocity of the airstream was low, being only about 45 ft. per min), it was concluded that owing to the longitudinal dispersion of the nitrous oxide, the time of build up there was so stretched out that the steady state was not quite reached within the release time available. This accounts for the positive error in the results. The Pulse Release Method is independent of build up times and consequently the results by this method at position C agree more closely with the others. At

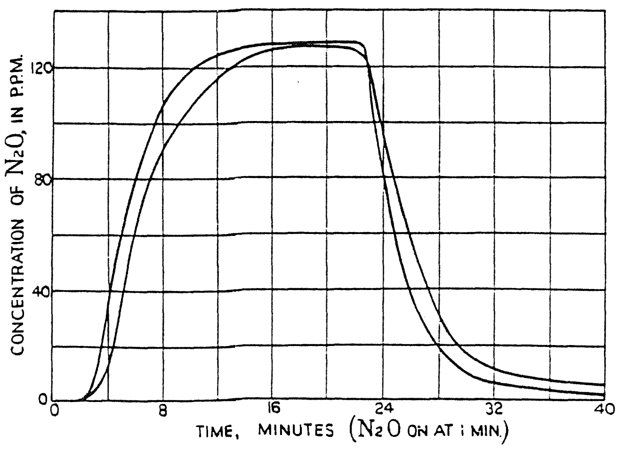

Fig. 3. Variation of concentration with time at the same position on different occasions

position A, where the times of build up and decay were almost immediate owing to the high velocity of discharge from the duct and the relative nearness to the release point, the steady state was well established and the results of the Steady Release Method here agree favourably with the orifice plate. It would appear therefore that in cases of low velocity, additional turbulence due to the presence of working apparatus, or large distances between release and sampling points, the Pulse Release Method would be preferable.

The centre factors used for the evaluation of the airflow by the Centre Factor Method had been determined previously in the laboratory[2]. The results of the underground experiments by this method amply justify the use of these centre factors, the deviation being well within the permissible limits prescribed in the laboratory.

Replacement of air at the face of heading

It is essential that exposed strata surfaces underground are efficiently scoured by air in order to ensure adequate dilution of any methane that is emitted. During the course of the aforementioned trials opportunity was taken to carry out a few preliminary studies on the rate of change of air at the face of the heading by means of the tracer technique. Nitrous oxide was released into the duct airstream at a fixed rate for about 20 min. and during the period of release of gas, samples of the air at several positions at the face of the heading were taken. As the air present at the face before the experiment was gradually replaced by the fresh, tracer laden air from the duct, the time taken to do so was recorded by the increase in concentration of the tracer in the samples taken. It was possible to study these times for two distances of the duct exit from the face, 15 yards and 26 yards, the airflow rate and positioning of the duct remaining unchanged. Five sampling positions were selected and these are shown in the inset to Fig. 4. Fig. 4 itself shows the results of the experiments at sampling positions X and Y which were the positions giving the two extremes with the duct 15 yards from the face. For a given duct distance the time taken to change the air completely was observed to vary with position on the face, but the most significant fact observed was the effect of

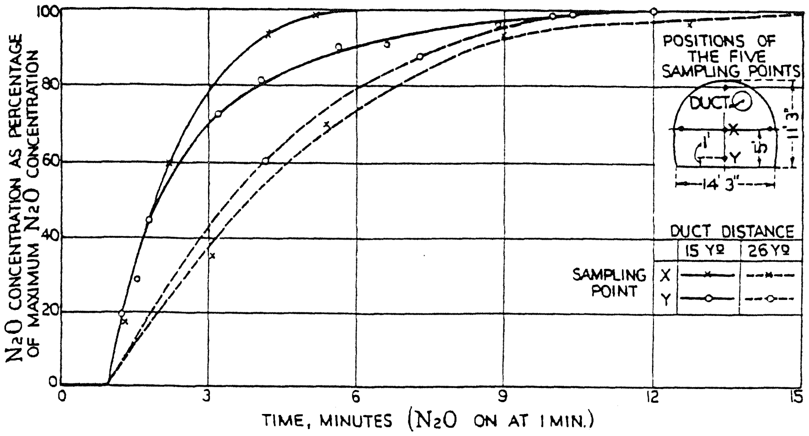

Fig. 4. Build up of concentration at the face for two distances of the duct exit from the face

altering the duct distance upon the rate at which the air at the face was changed. The general manner in which the air at the face was replaced with the duct exit 26 yards away was in general at a much slower rate and of a different pattern to the replacement with the duct exit 15 yards away. In both cases it was noted that more than 10 min. could elapse before the air at the face was completely replaced.

Table III—Comparison of Airflow Measurements in the Underground Experiments

(Orifice Plate Method taken as Standard)

Orifice Plate Method Qo cu. ft./min.	Vane Anemometer Centre Factor Method at at position A $\frac{Qa}{Qo} \times 100$	Tracer Technique $\frac{Qs}{Qo} \times 100$			
		Pulse Release		Steady Release	
		Position A	Position C	Position A	Position C
6,400	—	101·7	103·0	101·7	105·9
6,410	—	102·6	102·0	103·4	104·4
6,430	97·0	103·9	101·9	103·3	103·7
6,310	—	105·5	104·4	105·9	105·4
6,330	97·3	—	103·1	—	107·3
6,310	98·9	102·8	104·7	100·8	107·4
Mean	97·7	103·3	103·2	103·0	105·7
Standard Deviation	0·8	1·3	1·1	1·7	1·4

Conclusions

(1) The tracer technique of measuring the quantity of air returning through underground headings by means of a steady release or pulse release of nitrous oxide is found to be both reliable and accurate to within 5 per cent.

(2) If the time of release of the tracer has to be limited or there is significant longitudinal diffusion the Pulse Release Method is preferable.

(3) In a working area where the positions of tubs and other mining equipment are constantly changing, thereby causing unusual degrees of turbulence, the accuracy of the tracer technique is not impaired.

(4) The tracer technique is especially valuable in the measurement of small quantities of air where the velocities are too low to be measured by vane anemometers.

(5) From both the laboratory experiments and the underground trials it is concluded that none of the materials present in an underground roadway is likely to absorb any nitrous oxide in its passage down-stream during the period of a measurement (which may be up to 25 min.).

(6) The nitrous oxide tracer technique can be used to determine the times required to replace air at any particular position in a heading. Several minutes can elapse before a concentration of gas, fumes or dust at that position is diluted even to half its initial value. To clear the face completely, for the conditions existing in the heading at Snowdown, requires up to 11 minutes with the duct exit 15 yards from the face.

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Electronic computers

Experimental installations of electronic computers are being made in three of the National Coal Board's Areas. These are part of a planned investigation into the application of electronic data processing to all aspects of wages accounting in the coal industry. Each of the installations, designed primarily for labour costing and pay-bill work for an Area will, as a first step, absorb this processing work for a number of collieries in the Areas concerned. The economics of the systems and other advantages can then be assessed, and the systems and equipment compared.

The calculation of earnings was chosen as the first subject for examination because the data processing involved is so complex.