CONTROLLED RECIRCULATION OF MINE VENTILATION AIR: ITS EFFECT ON BLAST CONTAMINANT DISSIPATION

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A project report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I, Nicholas Anthony Alexander, declare that this project report is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

30th day of August 1988

ABSTRACT

A series of tests was undertaken on a recirculation scheme in a deep level gold mine to establish the effect of controlled recirculation of the mine ventilation air on blast contaminant dissipation. Clarification was needed as to whether the existing re-entry interval of three hours would have to be extended with the introduction of controlled recirculation. The re-entry interval is a time interval, after blasting, stipulated by the Inspector of Mines during which the workings are being cleared of blast contaminants and during which time no persons are permitted to enter the workings.

The fresh and recirculated air flow rates were varied and their effects on blast contaminant dissipation measured. Gas concentrations of the oxides of nitrogen (NO_x) and carbon monoxide were monitored continuously in the return air. Dust levels were monitored in the return air from two hours before the blast to four hours after the blast.

Two gas models (mixed-volume and plug-flow) and residence time analysis were used to analyse the data.

In all the tests, the critical blast contaminant for determining the re-entry interval was found to be NO_x. In addition, the following parameters affected the re-entry interval: the amount of explosives ignited daily, the volume of the workings into which the NO_x is dissipated by the ventilating air, the time taken for air to complete one circuit (the cycle time), leakage and short circuiting of air, and the fresh air flow rate. The recirculated air flow rate was found to have negligible effect on the re-entry interval.

To my friend Dave Unsted

Thanks for sharing your knowledge and experience

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NOMENCLATURE

Symbol	Quantity	Units
A	Area under the NO_x trace from time of blast to 12 hours after the blast ($A = \int_0^{12} C(t)\,dt$)	ppm-h
C	Total volume of NO_x released from blast ($C = Q_F A$)	m^3
C(t)	Return air gas concentration taken from gas trace	ppm
$\hat{c}$	Peak concentration of contaminant released by the blast	ppm
c_f	Fresh air contaminant concentration	ppm
c_ℓ	Legal limit of contaminant	ppm
c_r	Recirculated air contaminant concentration	ppm
c_t	Mixed air contaminant concentration	ppm
E(t)	Probability that a particular unit of air will leave the recirculation circuit between time t and t+dt, and is a probability density function ($E(t) = C(t)/A$ where $\int_0^\infty E(t)\,dt = 1$)	
M	Daily mass of explosive ignited	kg
L	Face length blasted daily	m
NO_x	Oxides of nitrogen found in underground atmosphere after blasting ($NO_x = NO + NO_2$)	
Q_F	Fresh air flow rate	m^3/s
Q_R	Recirculated air flow rate	m^3/s
Q_T	Total (mixed) air flow rate ($Q_T = Q_R + Q_F$)	m^3/s
R	Recirculation fraction ($R = Q_R/(Q_R + Q_F)$)	
R*	Recirculation ratio ($R^* = Q_R/Q_F$)	
T	Cycle time of air flowing round recirculation circuit ($T = 2\,844/Q_T$)	min
t*	Re-entry interval given by the time interval from the blast to when the critical contaminant has dissipated to its legal limit (legal limit of NO_x = 5 ppm)	h

τ	Mean residence time which is the average time that a parcel of air remains in the recirculation circuit ($\tau = \int_0^{12} E(t)t\,dt$)	h
TLV-TWA	Threshold Limit Value - Time Weighted Average is the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect. (ACGIH, 1984).	
V	Volume of recirculation circuit through which air is moving	m^3

CHAPTER 1 INTRODUCTION

1.1 Background

Controlled recirculation of mine ventilation air offers considerable practical and financial benefits when used as a means of controlling temperatures in deep, hot mines, in that it can be used as a means of distributing refrigeration. However, recirculation cannot be used for the dilution of blast contaminants and their timeous removal during the re-entry interval. Indeed, there is some concern as to whether recirculation adversely affects the re-entry interval, and this is the objective of this examination.

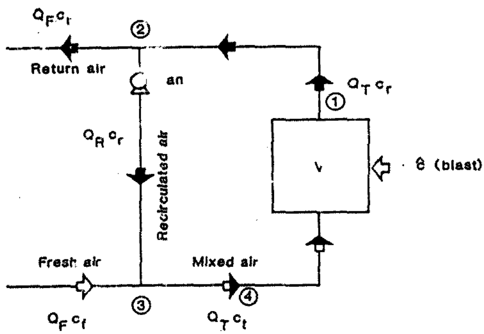

Figure 1.1 Schematic representation of recirculation

A schematic of a controlled recirculation system is shown in Figure 1.1. 'Fresh' air flows to point 3 with a flow rate of Q_F and a contaminant concentration of c_f, where it mixes with a portion of the recirculated air which has a flow rate of Q_R and a contaminant concentration of c_r. This mixed total flow passes through the workings with a flow rate of Q_T. At point 2 this flow is split by the action of the recirculation fan, with a portion travelling to point 3. The rest travels out of the recirculation circuit with a flow rate equal to the incoming fresh air Q_F (air density at inlet assumed equal to air density at outlet) and a contaminant concentration equal to that in the recirculated air c_r.

A field trial (Burton et al. (1984)) at Loraine Gold Mines Limited, demonstrated some of the advantages of controlled recirculation for deep South African gold mines. This practice is increasingly being considered in the mining industry The recirculation circuit at Loraine gold mine was positioned around a number of parallel stopes where scattered mining was practised. It was found that the recirculated air flow rate had little effect on the removal of the contaminants after the blast, and hence on the re-entry interval. In spite of these findings, it was felt necessary to examine the effects of controlled recirculation on the blast contaminant dissipation and the re-entry interval at a longwall mining site. The ventilation system of controlled recirculation at a longwall differs from that of a scattered mining situation and thus an examination at a longwall site could yield results different from those obtained at Loraine gold mine. A test site was selected at Western Deep Levels where longwall mining is practised.

This work has been summarized in a paper by the authors (Alexander, Unsted and Benecke, 1987). A copy of this paper has been included in Appendix A in support of this project report.

1.2 Legislation

The Mines and Works Act and Regulations of the Republic of South Africa (1956) limits the amount of carbon monoxide in the general body of the underground air to 100 ppm, and the oxides of nitrogen (NO_x) to 5 ppm. The NO_x level is the sum of concentrations of all oxides of nitrogen. For mines this is taken as being the sum of the nitric oxide and nitrogen dioxide concentrations, since these are the only two oxides of nitrogen normally found. The concentration of dust shall not exceed such standard as may from time to time be specified by the Government Mining Engineer. A concentration as measured by particle count by the konimeter of less than 200 particles per millilitre is acceptable. No legislation exists for dust concentration measured on a mass basis, although the Threshold Limit Value - Time Weighted Average (TLV-TWA) for mass concentrations is defined by the American Conference of Governmental Industrial Hygienists (ACGIH, 1984). This is an accepted standard, and is dependent on the silicon dioxide (SiO_2) content of the dust collected.

A the Western Deep Levels recirculation site the SiO_2 fraction of the respirable dust collected was found to be about 25 per cent, giving a TLV of 0,4 mg/m^3.

1.3 Aims and Outline of Study

1.3.1 Aims

Shortly after a blast, permissible concentrations of NO_x, CO and dust levels in the working zone are usually exceeded. However, the continuous passage of fresh ventilating air through the workings eventually reduces these contaminant concentrations to safe levels. The re-entry interval depends upon the time from the blast to the time when all the contaminants (NO_x, CO and dust) have returned to below the legal limits. The main concern in this study is to determine whether the recirculation of a fraction of the contaminated return air adversely affects the existing re-entry interval of three hours.

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1.3.2 Outline of study

The effects of recirculation on the re-entry interval were examined by regulating the fresh and recirculated air flow rates for each test. The fresh air flow rate was varied from 17 to 46 m^3/s and the recirculated air flow rate from 14 to 27 m^3/s. For each set of air flow conditions the gas (NO_x and CO) concentrations were measured in the return air continuously. The dust levels were monitored in terms of particle count and mass concentration from 2 hours before the blast to 4 hours after the blast.

Two distinctive flow models, a mixed-volume and a plug-flow model, and residence time theory were used to analyse the data.

(i) Mixed-volume model. This model was derived from work conducted by Burton et al. (1984). This establishes the relevance of the volume of the workings, the amount of explosives used, and the fresh air flow rate on the re-entry interval.

(ii) Plug-flow model. This model assumes that the contaminant flows around the recirculation circuit in a discrete plug with a determined cycle time. The cycle time is the time it takes for the plug to pass completely around the recirculation circuit. It was possible to show relationships between the re-entry interval and varying fresh air flow rates, peak gas concentrations (a function of the amount of explosives used), fresh air contaminant concentrations, and the cycle time. Although not directly measured, it was possible to take account of the effects of leakage, which significantly increased the peak concentration of contaminants. This caused a lengthening of the re-entry interval.

(iii) Residence time analysis. This is a useful technique for analysing transient changes in the contaminant concentrations, especially in the case of an impulse of contaminant due to a blast. The recirculation path was both long and complex. Due to leakage and short circuiting of air, the recirculation path varied from test to test. The residence time calculated is the average time a parcel of air remains in the recirculation circuit. This is indicative of the efficiency of the system in purging the blast contaminants. Logically, one would expect a relationship between the mean residence time and the re-entry interval and it is possible to show that a relationship does exist. This technique established the relevance of the fresh air flow rate.

1.3.3 Limitations

The long and complex recirculation circuit led to many opportunities for leakage and short circuiting of the ventilating air, and difficulties were experienced in regulating the fresh and recirculated air flow rates to desired levels. It was difficult in some cases to estimate the time period for the NO_x concentration to reduce to the legal limit of 5 ppm, from inspection of the traces. This was because the NO_x concentration traces approached the 5 ppm line asymptotically. It should be noted that any interactive and cumulative effect (synergy) that may exist between the blast contaminants or any other contaminants in the recirculation circuit are not considered.

In the analysis two distinctive models, mixed-volume and plug-flow, are developed which are used in isolation. A model which consists of a combination of these two models may be more suitable, but is not included in this report.

CHAPTER 2 FORMULATION OF PROBLEM

A considerable number of technical papers on controlled recirculation have been written. However, the majority are concerned with small-scale recirculation systems in British collieries. Allan (1983) gives a comprehensive review of the development of small-scale controlled recirculation systems in British collieries. He shows the need to control heat, gases and dust. Burton et al. (1984) show that controlled recirculation can be used as a means of controlling temperatures in deep, hot mines. Nevertheless, it was noted in this paper that recirculation cannot be used to accelerate the dilution and timeous removal of gases and dust produced by blasting during the re-entry interval.

2.1 Legislation for South African Mines and Identification of Parameters

Four sections of Chapter 10 (Ventilation, gases and dust) of the Mines and Works Act and Regulations of the Republic of South Africa (1956) are relevant to the timeous removal of blast contaminants during the re-entry interval.

2.1.1 'Fresh' ventilating air

Intake air to be clean
10.6.1 As far as practicable the ventilating air entering a mine shall be free from dust, smoke or other impurity.

Activity in the shaft area and fresh air intakes during the re-entry interval does introduce contaminants into the intake air which then enter the recirculation circuit.

Ventilation of workings

10.6.2 The workings of every part of a mine where persons are required to travel or work shall be properly ventilated to maintain safe and healthy environmental conditions for the workmen, and the ventilating air shall be such that it will dilute and render harmless any inflammable or noxious gases and dust in the ambient air.

Only the fresh air fraction entering the recirculation circuit can 'dilute and render harmless any noxious gas and dust in the ambient air' by removing a portion of the contaminant produced in the return air.

2.1.2 The total air flow rate in the working area

Quantity and velocity of air - metalliferous and diamond mines

10.7 In every controlled metalliferous or controlled diamond mine unless exempted in writing by the Inspector of Mines-

10.7.1 the velocity of the air current along the working face of any stope shall average not less than 0,25 metre per second over the working height; and

10.7.2 the quantity of air supplied at the working face of every development end such as a tunnel, drive, cross-cut, raise or winze which is being advanced and at the bottom of any shaft in the course of being sunk shall not be less than 150 cubic decimetres per second (0,15 m^3/s) for each square metre of the average cross-sectional area of the excavation.

Superimposing recirculation onto the intake air flow increases the air flow into the working area, and subsequently the velocity along the working faces and quantity of air at the development ends.

2.1.3 The re-entry interval

Interval before re-entry

10.10.2 after blasting, other than blasting as permitted in terms of regulations 8.10.44, has taken place in any workings no person shall enter or cause or permit any other person to enter such workings until an interval which shall be fixed in writing by the Inspector of Mines for such workings has expired;

10.10.3 blasting procedures shall be so arranged that no person is exposed to harmful dust, smoke, gas or fumes from blasting;

10.10.4 after blasting has taken place in any part of the workings no person shall enter, or cause or permit any other person to enter, such part or any place liable to be contaminated until a sufficient quantity of fresh air has been caused to flow through such part or place to clear it of harmful dust, smoke, gas or fumes from blasting.

Again, the fresh air is emphasized in 10.10.4 'until a sufficient quantity of fresh air has been caused to flow through such part or place to clear it of harmful dust, smoke, gas or fumes from blasting'. Thus the essential criteria upon which the fresh air flow rate required in underground workings can be determined from the permissible quantities of the blast contaminants.

From the above, the re-entry interval, t^*, can be defined as a time interval, after blasting, stipulated by the Inspector of Mines during which the workings are being cleared of blast contaminants and during which time no persons are permitted to enter the workings. For the purposes of this study the re-entry interval is considered to be a variable, and is defined as the time from blasting to when all the blast contaminants have returned to their legal limits.

2.1.4 Legal limits and effects on the removal of blast contaminants

Permissible quantities of gas and dust

10.6.6 In the general body of the air at any place where persons are required to work or travel, under normal working conditions -

(a) the amount of carbon dioxide shall not exceed 5 000 parts per 1 000 000 of air by volume,

(b) the amount of carbon monoxide shall not exceed 100 parts per 1 000 000 of air by volume,

(c) the amount of oxides of nitrogen shall not exceed five parts per 1 000 000 of air by volume,

(d) the amount of hydrogen sulphide shall not exceed 20 parts per 1 000 000 of air by volume,

(e) the amount of inflammable gas shall not exceed one part per hundred by volume, and

(f) the concentration of dust shall not exceed such standard as may from time to time be specified by the Government Mining Engineer.

The phrase 'shall not exceed' requires that these concentrations must never be exceeded when persons are present in the workings. During the re-entry interval persons are not permitted to be in the workings as the concentration of the blast contaminants are likely to be well in excess of their legal limits.

Carbon monoxide, oxides of nitrogen, and dust are identified as the most important contaminants produced by blasting. The first stage in establishing the safe re-entry interval should be aimed at determining which contaminant takes the longest time to dissipate to its legal limit after the blast, and hence, which contaminant dictates the re-entry interval irrespective of recirculation.

2.1.5 Identification of blast contaminants

Carbon Monoxide (CO)

CO is a product of incomplete combustion of explosives and diesel fuel and is always formed with CO_2.

A CO ecolyzer, which is a gas filter correlation analyser, can be used to measure CO concentration in the ventilating air.

Nitrogen Dioxide and Nitric Oxide (NO_2+NO=NO_x)

Oxides of nitrogen are produced by the ignition of explosives and combustion of diesel fuel. For mines the concentration of oxides of nitrogen is taken as being the sum of the nitric oxide and nitrogen dioxide concentrations, since these are the only two oxides of nitrogen normally present.

Greig (1982) has indicated that the oxides of nitrogen in diesel emissions are very important from the standpoint of toxicity and quantities produced. He also discusses the gaseous products of blasting, and in Table 2.1 he shows the volume of various gases produced per kg of different explosives ignited. The permissible level of NO and NO_2 (collectively known as NO_x) is twenty times less than that of CO. With this in mind, a comparison of the volumes produced indicates that NO_x is more critical.

The greater the volume of gas produced the greater the strength of the explosive. In this study, Ammon dynamite cartridges with Dynagel primers were used to advance the stope face, and for the development ends, Dynagel was used. Approximately 60 per cent of the total mass of explosive ignited was Ammon dynamite which an inspection of the Table will show to be weak. For the same mass of Ammon dynamite, ANFO will produce 75 per cent more NO_x, which would substantially increase the re-entry interval. Thus, in any study of this nature, the strengths and proportions of the various types of explosives used should be noted.

Table 2.1 Volume of gas produced per kg explosive (m^3 at 0°C and 101 kPa) (Greig, 1982)

Type of explosives	Gas			
	CO	NO & NO_2	CO_2	NH_3
Ammon dynamites	0,03	0,004	0,06	0,003
Ammon gelignites	0,05	0,006	0,07	0,003
ANFO	0,03	0,007	0,05	0,009
Dynagel	0,03	0,005	0,07	0,003
Water Gel Explosives	0,009	0,002	0,05	-

A chemiluminescent NO_x analyser can be used to measure NO_x concentrations in the ventilating air.

Dust

Allowable or acceptable respirable dust levels are not stipulated in the regulations, but may from time to time be specified by the Government Mining Engineer. At present, a concentration of 200 particles per millilitre of particle size less than 5 micrometer (as measured by the konimeter), is taken as being acceptable.

Thus it is necessary to use a konimeter to measure dust levels in the return air after the blast. A gravimetric dust sampling technique can also be used where the level is expressed in mg/m^3. In this case the acceptable level is given by the Threshold Limit Value - Time Weighted Average, TLV-TWA. This is defined by the American Conference of Governmental Industrial Hygienists (ACGIH, 1985) as

$$TLV - TWA = \frac{10}{\%SiO_2+2}$$

Where $\%SiO_2$ = the percentage of silica in the respirable fraction

Two methods for measuring dust levels gravimetrically can be used, namely:

- Dupont personal gravimetric sampler, which gives an average level of dust less than 8 micrometer for a measured time period, and the sample collected can be analysed to give the per cent SiO_2 and
- Hund tyndallometer which gives a set of readings at 32-second intervals of dust less than 8 mi-.ometer.

2.2 Further Identification of .arameters

The concentration of the various contaminants produced within the workings after blasting will depend primarily on the face length, L, and number of development ends blasted. It can be related to the mass, E, of explosives ignited and the fresh air flow rate.

The total air flow ($Q_T=Q_R+Q_F$) passing the newly blasted rock will dilute the blast contaminants. The resultant levels measured in the return air-way will reach a peak value, $\dot{c}$, and this parameter is considered to have a strong influence on the re-entry interval. However, not all of the available air, Q_T, passes along the advancing faces or into the development ends, as leakage of air always occurs depending on the prevailing ventilation standards. Thus, less air will be available to dilute the contaminants, and shortly after the blast the peak concentrations of contaminants will increase for the same mass of explosives ignited and total air flow rate.

The portion of the contaminated recirculated air stream with an air flow rate of Q_R, which is continuously re-introduced into the working area, would not have the same effect as fresh air in decreasing the rate of contaminant removal from this area. The rate at which these contaminants are then removed will then depend on the residence time of the air in the recirculation circuit or on the cycle time, T, of the air to complete one circuit. These parameters are dependent on the total air flow rate, the length and size of the excavations in the recirculation circuit and the effects of leakage.

It should be noted that any interactive and cumulative effect (synergy) that may exist between the blast contaminants or any other substances in the recirculation circuit is not considered. If this were the case, then the concentration level set to which the blast contaminants would have to reduce to after the blast in order to determine the re-entry interval could be less than their legal limits. Thus, this could result in a longer re-entry interval.

2.3 Methods of Analysis

Many factors influence the dissipation of contaminants in a recirculation path in the underground workings of a mine. The factors considered include:

(i) the amount of blast contaminant released (C) which is derived from the face length blasted daily (L), or the daily mass of explosive ignited (M),
(ii) the volume of the recirculation circuit through which air is moving (V) or the length of the recirculation path and hence the time taken for air to travel around this path, the cycle time (T),
(iii) the amount of fresh air supplied to the recirculation circuit (Q_F),
(iv) the recirculated air flow rate (Q_R),
(v) the total amount of air coursing through the workings of the recirculation path (this flow rate, Q_T, is equal to the sum of the flow rates of the fresh air and the recirculated air ($Q_T=Q_R+Q_F$)),
(vi) internal leakage paths within the recirculation system, and
(vii) the presence of contaminants in the fresh air supply (C_f).

These factors interact to affect contamination levels at any point in the recirculation path.

Any model of a recirculation circuit should incorporate the inter-relationship of these factors. Three approaches are now considered, namely:

2.3.1 Mixed-volume model

A mixed-volume model assumes that the working zone of volume, V, has a uniform concentration of the contaminant immediately after the blast. In other words, there is an instantaneous, perfect mixing between the contaminant and the air in the working zone. This model was used with some success to analyse data obtained at Loraine Gold Mines Limited by Burton et al. (1984). This sec'ion of work, **Recirculation during blasting**, is given in Appendix

The model can be summarized by the following equation:

$$c_r = c_f + \Delta c \exp[-Q_F t / V] \qquad \text{ppm} \qquad (2.1)$$

where Δc = the instantaneous increase in contaminant concentration due to blasting, ppm
and t = time, s

Solving this equation (2.1) for the re-entry time, which is the time required for c_r to decay to c_ℓ (where c_ℓ is the legal limit for a particular contaminant), gives the following equation:

$$t^* = \frac{V}{Q_F} \ln[\Delta c / [c_\ell - c_f]] \qquad \text{s}$$

Since c_f = 0 (in the present study there is no NO_x in the fresh air intake) and

$\Delta c = \hat{c}$ which can be measured from the NO_x gas trace

then $$t^* = \frac{V}{Q_F} \ln[\hat{c}/c_\ell] \qquad \text{s} \qquad (2.2)$$

Also $\hat{c} = C/V$ ppm

where C = the total volume of NO_x released from the blast

and $C = Q_F \int_0^{12} C(t)\, dt$ m³ of NO_x

or C can be calculated from the daily mass of explosive consumed by

$$C = 0{,}005M$$

then $$t^* = \frac{V}{Q_F} \ln \frac{C/V}{c_\ell} \quad s \qquad (2.3)$$

2.3.2 *Plug-flow model*

The plug-flow model (Unsted, 1987) assumes that the contaminants do not gradually disperse within the blasting zone but rather travel around the circuit in the form of a discrete plug, which reduces step-wise each time the plug passes around the recirculation circuit. Evidence for its validity would be the presence of humps in the profile of the gas traces (see Figure 4.1), and hence the model should reflect the situation at the recirculation site.

A sketch of a recirculation circuit is shown in Figure 2.1.

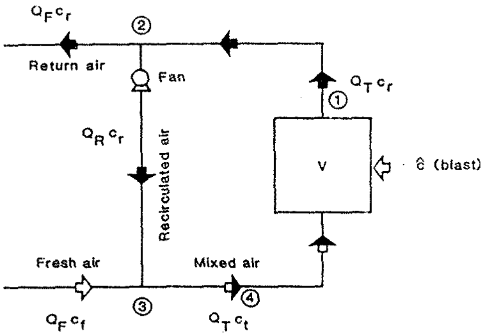

Figure 2.1 Schematic representation of recirculation

Contaminant mass balance of mixed air

By mass balance at point 3:

$$Q_T c_t = Q_F c_f + Q_R c_r \quad \text{parts of contaminant per second}$$

and hence $c_t = \dfrac{Q_F c_f + Q_R c_r}{Q_T}$

where $c_f < c_\ell$ and c_f is assumed to have a constant value

Since $Q_T = Q_F + Q_R$

$$c_t = \frac{Q_F c_f + Q_R c_r}{Q_F + Q_R} \quad \text{ppm} \qquad (2.4)$$

$$c_{t\ \text{loop1}} = \frac{Q_F c_f + Q_R \hat{c}}{Q_F + Q_R} \quad \text{ppm}$$

$$c_{t\ \text{loop2}} = \frac{Q_F c_f + Q_R c_{t\ \text{loop1}}}{Q_F + Q_R} \quad \text{ppm}$$

and after n loops

$$c_{t\ loop\,n} = \frac{Q_F c_f + Q_R c_{t\ loop(n-1)}}{Q_F + Q_R} \quad \text{ppm}$$

Before the blast

Under steady state conditions, and with no addition of contaminant at any place within the recirculation circuit, but especially at point 1 (Figure 2.1)

$$c_r = c_t = c_f \quad \text{ppm}$$

After the blast

After the blast a mixed plug of contaminant starts travelling around the circuit

$$c_r = c_t + \dot{c}$$

The plug of contaminant travels from point 1 to point 2 where it splits, and some contaminant (Q_F c_r) is carried out of the circuit.

The remainder of the contaminant (Q_R c_r) travels to point 3 where it mixes with the fresh air and is diluted, as shown in Equation (2.4).

At point 4 the fresh air and recirculated air is considered to be fully mixed.

The plug then travels through the workings and back to point 1 where no further contaminant is added. From point 1 the plug repeats its cycle with a concentration reduction each time the plug is mixed with fresh air.

After the plug of contaminant has passed any given observation point the concentration at this point will revert to its original value, i.e. the value it had before the blast (c_f). This process is shown graphically in Figure 2.2.

Provided that no additional contaminant is generated in the recirculation circuit, the plug will loop around the circuit with its contaminant concentration successively diminishing at the point where mixing with fresh air takes place. At some time after the blast the contaminant concentration of the plug will closely approach the pre-blast level.

The re-entry interval (uncorrected)

The uncorrected re-entry interval is

$t^*_{uncorrected}$ = No. of loops (uncorrected) x Cycle time h (2.5)

where the No. of loops is equal to the No. of loops to when c_t is 6 ppm plus a fraction of a loop to when c_t is 5 ppm and is calculated by linear interpolation, and cycle time calculated in hours ($T = 47{,}4/Q_T$) is a functiuon of the total air flow rate (Q_T) and the length and size of the excavations in the recirculation circuit at the test site (factor = 47,4).

The re-entry interval (corrected)

The uncorrected re-entry interval does not make allowance for:

(i) the time interval from the time of the blast to peak concentration (see shaded section of Figure 2.3),
(ii) the time it takes the air to travel from point 4 to point 2,
(iii) leakage paths within the recirculation circuit which decrease the amount of air available at the face to dilute the blast contaminants which subsequently cause an increase in the re-entry interval.

To take account of (i) and (ii) the measured No. of loops (t^* measured/T) was plotted against the uncorrected No. of loops and a relationship derived (see Appendix E) such that

No. of loops (corrected) = 2,82 (No. of loops (uncorrected))^{0,593}

To take account of (iii) a new total air flow rate is calculated by considering a leakage factor which is best illustrated with an example.

Given Q_T = 50 m³/s and leakage = 20 per cent

then $Q_{T\ new} = (Q_T + [\frac{100\text{-Leakage}}{100}]\ Q_T)/2 = \frac{50 + 40}{2} = 45$ m³/s

This new value for the total air flow rate is input into equation (2.4).

Thus t* = No. of loops (corrected) x Cycle time. (2.6)

It is possible to input into the plug-flow model the daily mass of explosive consumed, instead of the peak concentration of contaminant (measured from the trace).

Since $\hat{c} = \frac{C}{V}$ ppm

where C = the total volume of NO_x released from the blast

and C = 0,005M m³ of NO_x

and V = (60)(T x Q_T) m³

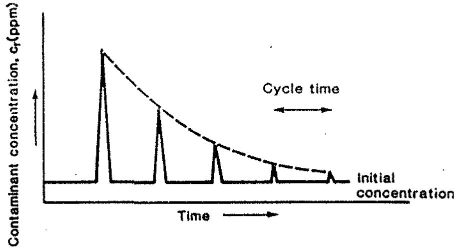

Figure 2.2 Plug-flow model

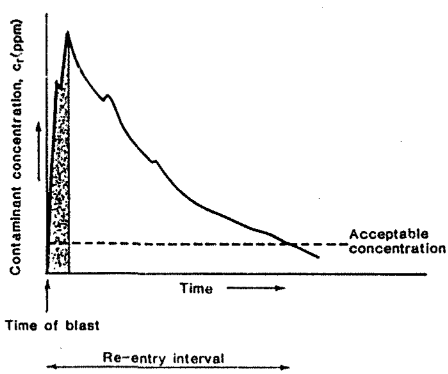

Figure 2.3 Typical profile of return air NO_x concentration after the blast

Using the plug-flow model in a recirculation path that closely resembles the one investigated at Western Deep Levels, changes in different critical parameters can be simulated.

Since NO_x is taken as the critical contaminant (see Section 4.1) after the blast, it is used as the contaminant in the simulations.

Changes in the fresh air flow rate, the amount of contaminant released by the blast, the amount of contaminant in the fresh air, the air cycle time and the recirculated air flow rate can be simulated. An example in the use of this model is given in Appendix E.

Although the plug-flow theory is a simplification of the real situation, it is easy to understand and use.

2.3.3 Residence time analysis

The mixed-volume and plug-flow models have very distinctive flow patterns.

With mixed-volume the profile of the blast contaminants from the peak concentration to the legal limit follows a first order decay function. On the other hand, with plug-flow, the blast concentrations are represented by pulses at regular intervals. The true situation lies somewhere between these two situations. With residence time analysis a model is not derived. Residence time analysis gives a method whereby a mean residence time can be derived for each blast using the data from the contaminant profile after the blast in the return airway. The mean residence time is the average time a parcel of air remains in the recirculation circuit, and logically one would expect a relationship between this and the re-entry interval.

The underground mine environment is continually exposed to transient changes in the contaminant concentrations, and especially in the case of an impulse of contaminant due to a blast. The profile from the peak concentration to the legal limit of the blast contaminants is found experimentally not to follow a true exponential curve. The peak contaminant level depends upon the mass of explosives ignited and the total air flow rate. The mass of explosives vary widely from day to day. In order to normalize this variation, and compare the experimental results from different days, residence time analysis can be used (Levenspiel, 1972). The concentrations of the oxides of nitrogen and carbon monoxide were continuously monitored in the return airway. Figure 4.1 shows a typical trace of blast concentrations in the return airway after the blast.

By residence time analysis, a probability density function E(t) can be derived for each trace and is given by,

$$E(t) = \frac{C(t)}{A}$$

where C(t) = The concentration of the tracer (e.g. NO_x) in the ventilating air at the outlet of the recirculation system, at time t and A = Area under the NO_x or CO trace from time of blast to 12 hours after the blast, when most of the contaminant has been removed and the concentration is near zero,

i.e. $A = \int_0^{12} C(t)\,dt$ ppm-h

which can be conveniently calculated using Simpson's rule and the trapezoidal rule for numerical integration.

A tracer is defined to be a substance which behaves in every way like the ventilating air, but is distinguishable from the fluid by some measuring technique. $E(t)dt$ is defined as that fraction of the air that leaves the recirculation circuit in the time between t and $t + dt$.

Thus the varying amounts of explosives consumed can be normalized and the average residence time which is the time that a parcel of air remains in the recirculation path, τ, is given by

$$\tau = \frac{\int_0^{12} E(t)t\,dt}{\int_0^{12} E(t)\,dt} \qquad h$$

and since $\int_0^{12} E(t)\,dt = \int_0^{\infty} E(t)dt = 1$

Thus $$\tau = \int_0^{12} E(t)t\,dt \qquad h \qquad (2.7)$$

This parameter is independent of the concentration of blast contaminants in the recirculation circuit. It is dependent on air flow rates Q_R and Q_F, the geometry of the recirculation circuit, and leakage and short circuiting of air. Thus, the mean residence time calculated for a particular day is indicative of the efficiency of the ventilation system to purge itself of contaminants.
A calculation of the mean residence time for a test is shown in Appendix F.

CHAPTER 3 RECIRCULATION FIELD TRIAL

3.1 Field Trial Investigation

The effects of recirculation on the re-entry interval were examined by varying the fresh and recirculated air flow rates and measuring the gas contaminants (NO_x and CO) in the return air stream continuously. The dust levels were monitored for a period of 2 hours before the blast to 4 hours after the blast.

The first stage of the investigation was aimed at determining which of the contaminant levels took the longest to reduce to its legal limit after the blast, and hence, which contaminant dictated the re-entry interval. (It will be seen later that this was NO_x).

Having determined that NO_x was the critical contaminant, further analyses were aimed at determining which parameters most affected its dissipation rate and their inter-relationships.

The fresh air flow rate was varied from 17 to 46 m^3/s and the recirculated air flow rate from 14 to 27 m^3/s, giving a recirculation fraction from 0 to 0,6.

It would have been highly desirable to vary each of the parameters separately, while keeping the other parameters fixed; however, under actual mining conditions this was not possible.

3.2 Underground Site and Instrumentation

The test site was at the No. 3 Shaft, Western Deep Levels Limited, in the 91/73 East longwall. The total length of the recirculation path was about 4 km. The longwall is located in the Upper Carbon Leader zone between depths of 2 531 m and 2 760 m. The stope face dips at 30 degrees for about 500 m with a stoping width of 1 m. Figure 3.1 shows a plan of the site and Figure 3.2 is a schematic depicting the ventilation layout. Typical information on mining and environmental conditions in the stope is presented in Table 3.1. The longwall extends from 83 to 91 levels. Fresh air intakes are on the 91 and 87 levels with some air entering the system through the old workings. Approximately 45 per cent of the intake air is fed from 91 level, about 20 per cent from the intake on 87 level and the remainder leaks into the area through the old workings. The return airway is on 83 level. A 75 kW fan situated on 83 level was used to recirculate air from 83 level back to the longwall via a service incline. The recirculated air is fed back into the workings from the service incline through intakes on 85, 87, 88 and 90 levels. About 20 per cent of the recirculated air is fed to the bottom of the longwall.

The main measuring station was in the return airway on 83 level (station 1) and was used to monitor the return air contaminant levels as well as the recirculated air flow rate and the reject air flow rate. From these measurements the total flow rate through the longwall was determined and the total intake air flow rate deduced (this will equal the reject air flow rate). The other measuring points were in the intake on 91 level (station 2), the intake on 87 level (station 4) and the return air at the stope outlet (station 3) at the top of the longwall. The gas analysis equipment was situated on 91 level in fresh air, and samples of air were drawn from the main measuring station in the return airway on 83 level to the instruments via a sniffer tube of 4 mm diameter which was installed in the service incline. The length of the tube was about 750 m and it was estimated that it took the gas sample approximately 5 minutes to travel through this tube from the return airway to the gas analysis equipment. The NO_x levels were measured by chemiluminescent analyser and CO levels by a gas filter correlation analyser. The information was recorded continuously on a

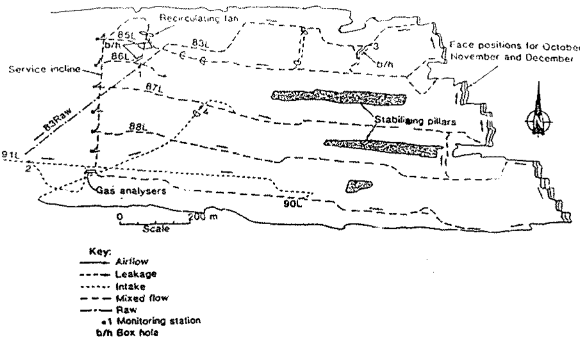

Figure 3.1 Plan of field trial site (Alexander et al. (1987))

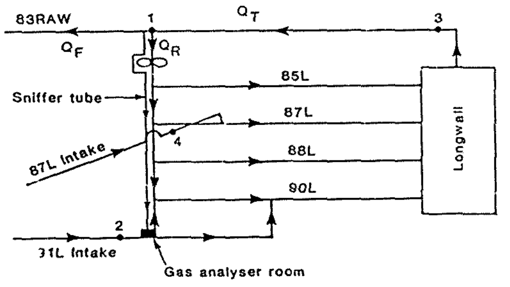

Figure 3.2 Schematic of test site (Alexander et al. (1987))

Table 3.1 Typical values for mining and environmental parameters in test longwall (Alexander et al. (1987))

Rock production tons (waste and reef) centares nominal face advance	13661 - 17783 3310 - 4646 8 m
Face length No. of Panels Stope Width Dip Advance per blast	486 m 26 1 m 30° 0,7 m
Depth below surface 83L/91L Virgin rock temperature Rock density	2531 m/2760 m 43 °C 2700 kg/m³
Average ventilation air flow rates - Fresh air m³/s per kton per month Fresh air Recirculated air Recirculation fraction Standard face velocity Air density - Intake on 91L Intake on 87L Return on 83L	 2 - 2,5 35 m³/s 25 m³/s 0,42 1,5 m/s 1,21 kg/m³ 1,21 kg/m³ 1,16 kg/m³
Cooling supplied (rated, 11 cooling cars x 300 kW(R))	 3 300 kW(R)
Water consumption	2,3 tons/ton
Barometric pressure - Intake on 91L Intake on 87L Return on 83L Air temperatures - Intake on 91L (WB/DB) Intake on 87L (WB/DB) Return on 83L (WB/DB)	 106,4 kPa 106,0 kPa 103,4 kPa 27/29 °C 24,5/29,5 °C 30/32 °C
Recirculation Fan details - Type Rated Power Pressure Air flow rate Revs	 Axial Flow 75 kW 1,15 kPa 30 m³/s 1475 rpm
Explosive details - Type : Cartridge - Face - End	 Ammon Dynamite Dynagel

chart recorder. (See Figure C1 of Appendix C for the NO_x and CO measurement layout, and see Appendix B for the gas (NO_x and CO) concentration traces as recorded by the chart recorder.)

The NO_x and CO levels in the intake airway on 91 level were also monitored and found to be close to zero, since diesel vehicles were not used in the area.

The air flow rates were varied by adjusting a regulator situated in the return airway, and by controlling a bypass around the recirculation fan. The regulator consisted of a steel grill erected in the return airway, which was covered with plastic sheeting. The recirculated and the reject air flow rates were monitored at the main measuring station (Point 1 in Figures 3.1 and 3.2). Calibrated vortex anemometers giving a 4 to 20 mA output signal were used and the data stored on a battery-powered 'Squirrel' data logger.

Although a difference in air density between intake and return conditions was found, it was of the order of only four per cent and was ignored in the analyses. The variation in flow rates for any one day was small and thus average values of air flow rates were assigned to each test. (See Appendix B for typical variation in air flow for one particular test day).

Dust levels in the return air were measured throughout the test period. Both mass concentration and particle count measurements were recorded. An automated konimeter was used to determine the particle counts. (A conventional konimeter fitted with a plunger activated by a piston driven by a small electric motor, which also rotated the slide to coincide with the 59 slide positions.) The sampling interval could be varied between five and ten minutes. Dust concentrations on a mass basis were measured continuously, using Hund Tyndallometers. These instruments make use of the light-scattering properties of the airborne dust and store the data every 32 seconds in an in-built data logger. Hund Tyndallometer gravimetric dust measurements were taken continuously in the intake on 91 level and the return on 83 level. These measurements were used as an indication of the dust load in the intake air system which is present, irrespective of recirculation. By comparing similarities in the traces from the Tyndallometers on 91 level with that on 83 level, the cycle time could be estimated for a particular set of fresh and recirculated air flow rates. (See Appendix E for traces of the Tyndalliometers showing similarities in the dust concentration profiles).

A Dupont personal gravimetric sampler was used to provide a check on the average dust concentrations given by the Hund Tyndallometer over the test period. It makes use of a screening cyclone which separates and discards all particles greater than 8 micrometres. The dust collected by this sampler was also used to determine the silicon dioxide content. The average content of SiO_2 was about 25 per cent.

Spot measurements of temperature and barometric pressure were taken, using hand-held instruments. (See Table C1 of Appendix C which gives a schedule of instrumentation details).

CHAPTER 4 RESULTS AND DISCUSSION

4.1 The Critical Contaminant

Plots of the measured concentrations of the three contaminants (NO_x, CO and dust) after the blast for a test where the fresh and recirculated air flow rates were 24 m^3/s and 26 m^3/s respectively, with a recirculation fraction of 0,52, are shown in Figure 4.1. In order to assist the reader, the vertical axes for the different contaminants have been arranged so that the legal limits of NO_x and CO, together with the recommended limits for dust, all coincide.

The contaminant profiles for this test are typical, with the NO_x concentration taking the longest time to reach the legal limit of 5 ppm. Therefore NO_x dictates the re-entry time, which in this case can be seen to be 5,0 hours. The CO concentration for this test did not exceed the legal limit of 100 ppm; in tests when it did exceed the limit, the time for it to drop back to 100 ppm was considerably less than that for NO_x to reach 5 ppm. The dust concentration measured by particle count (Konimeter) took longer to reduce to the legal limit than the dust concentration measured on a mass basis. It is believed that this is because the heavier dust particles drop out of the air stream before the lighter particles, and hence have a greater effect on the rate of reduction of dust levels when measured on a mass basis. The average dust concentration values measured with a Dupont personal gravimetric sampler throughout the test period compared well with those measured by the Hund Tyndallometer.

The NO_x concentration in the ventilation air took the longest time period to reduce to the legal limit in all the tests, and hence in further analysis was the only contaminant used to determine the re-entry interval. Note that the TLV-TWA of NO_x as given by the ACGIH (1985) is 3 ppm. If the legal limit was taken as 3 ppm then this would adversely increase the re-entry interval.

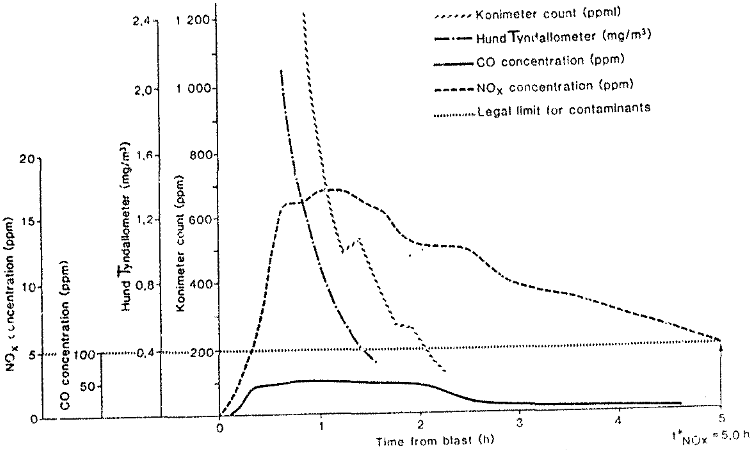

Figure 4.1 Typical set of contaminant profiles after blast in return airway (Alexander et al. (1987))

4.2 Treuds Indicated by Inspection of Data

It would have been highly desirable to vary only one of the parameters at a time, while keeping the others fixed. However, under practical mining conditions, this was not possible. For this reason no one parameter could be studied in isolation and only trends in the relationships of the parameters can be indicated in the discussion that follows.

The results of the tests are presented in Table 4.1 which is arranged in increasing order of mean residence time. Some correlation appears to exist between the mean residence time and the re-entry interval. The mean residence time depends on the fresh and recirculated air flow rates and the geometry of the recirculation circuit through which the total air (Q_R + Q_F) flows. It is not dependent on the mass of explosive ignited daily. Relationships between any one of the parameters and the re-entry interval are not obvious. This is due to the inter-relationship between the parameters and the influence of leakage and short circuiting of the ventilating air within the recirculation circuit.

Leakage and short circuiting of air within the recirculation circuit have a marked effect on the re-entry interval. A reduced air flow rate in the workings results in a higher peak concentration of NO_x than should be the case. The higher concentration would then take longer to reduce to the allowable level of 5 ppm. Inspection of Table 4.1, a comparison of the results of tests five and sixteen, shows that for the same face length blasted the peak concentration increases with decreasing total air flow rate. The re-entry interval increases accordingly. Note that the fresh air flow rate in test sixteen is almost half that of test five, and this fact also certainly results in a greater re-entry interval in test sixteen. It can be seen that the mean residence time of test sixteen is greater. This contributes to a greater re-entry interval. The effects of leakage for tests five and sixteen are minimal, but these effects become apparent when comparing test six with test nine. The total air flow rates and face length blasted were similar. The peak concentration for test six was very high and resulted in an extended re-entry interval. This is in spite of the greater fresh air flow rate on day six, which should have

Table 4.1 Summary of Results (Alexander et al. (1987))

Test No.	Fresh Air Flow Q_F (m^3/s)	Recirculated Air Flow Q_R (m^3/s)	Total Air Flow ($Q_R + Q_F$) Q_T (m^3/s)	Recirculation Ratio (Q_R/Q_F) R'	Recirculation Fraction $Q_R/(Q_R+Q_F)$ R	Face Length Blasted L (m)	Explosive Charge (4L+450) E (kg)	Area Under Gas Trace A (ppm-h)	Peak NO_x Conc. $\hat{c}$ (ppm)	Cycle Time T (minutes)	Mean Residence Time t (h)	Re-Entry Interval for NO_x t' (h)
1	39,0	14,7	53,7	0,38	0,27	170	1 130	37,5	37,5	53	1,90	2,65
2	43,2	20,7	63,9	0,48	0,32	170	1 130	30,0	16,5	44	2,05	2,10
3	45,5	[illegible]	60,6	0,33	0,25	200	1 250	46,3	28,0	47	2,12	3,10
4	30,8	25,2	56,0	0,82	0,45	240	1 410	50,6	29,5	51	2,31	3,00
5	30,3	19,7	50,0	0,65	0,39	180	1 170	46,6	26,5	57	2,49	3,00
6	34,8	18,6	53,4	0,53	0,35	300	1 650	106,1	63,0	53	2,79	5,90
7	29,8	25,3	55,1	0,85	0,46	230	1 370	46,8	22,0	51	2,84	3,00
8	35,0	24,7	59,7	0,71	0,41	230	1 370	55,7	23,5	47	2,86	4,20
9	28,4	22,3	50,7	0,79	0,44	280	1 570	68,0	24,8	56	2,94	5,00
10	21,1	20,9	42,0	0,99	0,50	140	1 010	72,4	24,5	67	2,95	4,75
11	21,1	19,2	40,3	0,91	0,48	230	1 370	72,7	29,5	70	2,95	5,00
12	24,2	25,6	49,8	1,06	0,51	200	1 250	69,5	24,3	57	3,13	4,63
13	25,0	25,8	50,8	1,03	0,51	330	1 770	133,8	38,5	56	3,25	6,75
14	22,8	17,6	40,4	0,77	0,44	240	1 410	91,9	23,0	70	3,30	6,00
15	23,9	26,0	49,9	1,09	0,52	370	1 930	68,4	20,0	57	3,38	5,00
16	17,5	26,7	44,2	1,53	0,60	180	1 170	72,8	32,5	64	3,56	4,40
17	19,4	25,5	44,9	1,31	0,57	270	1 530	88,8	32,0	63	3,7[illegible]	5,60

resulted in a reduced re-entry interval, approximating to that of day nine. Thus, if a smaller proportion of air reaches the working faces due to leakage, the resultant decreased flow rate in this zone will give rise to a higher peak concentration and an extended re-entry interval.

When investigating the main parameters which affect the re-entry interval and the mean residence time, the absolute values of air flow rates Q_F, Q_R and Q_T had to be used rather than any ratio of these flows. This is due to the fact that a given value of ratio (e.g. Q_R/Q_F) can be obtained from various combinations of values of the relevant air flows. This ratio would give a different re-entry interval and mean residence time. In other words, Q_R/Q_F cannot be considered as an independent parameter.

It is evident that the length of face blasted, and hence the mass of explosives ignited daily, has a strong influence on the re-entry interval. The relationship between the length of face blasted and the re-entry interval is shown in Figure 4.2. Broad zones of total air flow rates were grouped together to show the trends in this relationship. For the trial period, the average face length blasted daily was only 224 m, or 46 per cent of the total face length.

The cycle time for the recirculation circuit was established by tracing a significant sudden increase in dust concentration at an intake monitoring station through to the monitoring station in the return airway for one particular test. This was based on output from continuous reading gravimetric samplers (Hund) and was found to be 57 minutes (test fifteen). The cycle time thus obtained was used as standard, and is taken as being inversely proportional to the total air flow rate. The time varies between 44 and 70 minutes over the range of the tests. In Figure 4.3 a plot of the re-entry interval against cycle time, is shown. Broad zones of face length blasted were grouped together to show the trends in this relationship. In this recirculation circuit, the airway in which the recirculated air was coursed from the return airway back to the intake air was sited about one kilometre from the workings. As a result of this feature the cycle time was long (typically one hour). A reduction of the path length, which can be achieved by siting the recirculation fan closer to the workings, will reduce the cycle time and thus the re-entry interval.

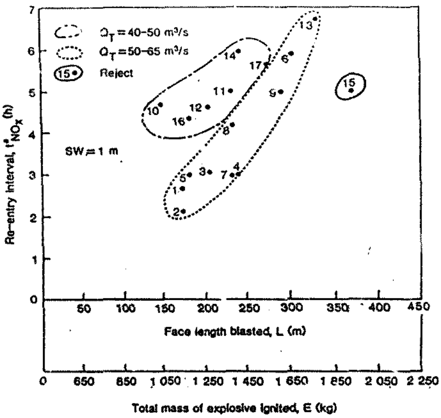

Figure 4.2 Comparison of re-entry interval and face length blasted

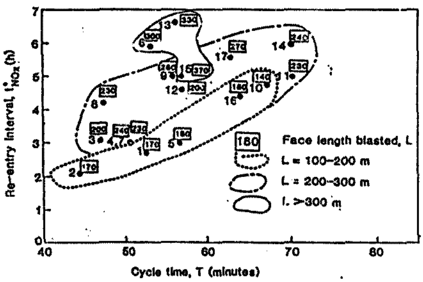

Figure 4.3 Comparison of re-entry interval and cycle time

Some trends are evident in that the re-entry interval is a function of the fresh air flow rate, the total air flow rate, the face length blasted, and the cycle time. More detailed analysis is needed to establish the effect of the recirculated air flow rate on the re-entry interval. However, it would appear that the re-entry interval is not significantly affected by recirculation. Greater clarification is also needed to establish the effects of both leakage and an increase in the fresh air contaminant concentration on the re-entry interval.

Some of the measured re-entry times shown in Table 4.1 are clearly unacceptable under normal circumstances. It should be emphasized that these were obtained when the fresh air flow rate was deliberately reduced for experimental purposes.

4.3 Mixed-Volume Model

The relationship between the estimated explosive charge and the measured volume of NO_x (C) released from the blast is shown in Figure 4.4, together with the theoretical prediction by Greig (1982) (C = 0,005M (see Table 4.1)). The correlation is reasonable, considering the approximate manner for determining the explosive charge. Thus, it is possible to input into the mixed-volume model the daily mass of explosive consumed, instead of the peak concentration of contaminant (measured from the trace) (equation 2.3).

The measured re-entry interval and the times predicted using the mixed-volume model (equations 2.2 and 2.3) are shown in Figure 4.5. For an estimated working volume of 260 000 m^3 a good correlation exists. Analysis showed that a slightly smaller value for the working volume would have provided a better correlation.

The scatter in Figure 4.4 is believed to be due to the numerous leakage paths within the workings, the location and extent of which varied from test to test.

Clearly, within the limits of experimental errors, the mixed-volume model is well supported by the data. This means that the re-entry *interval given by this approach is not dependent on the recirculated*

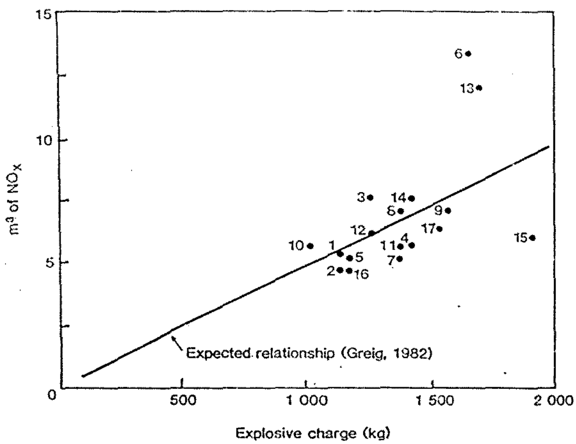

Figure 4.4 Comparison of volume of NO_x produced and explosive charge (Alexander et al. (1987))

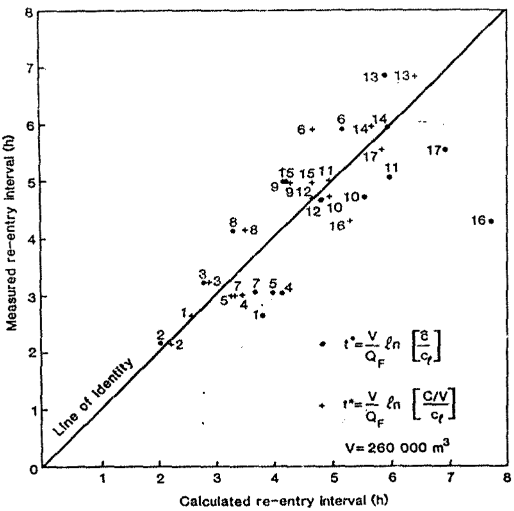

Figure 4.5 Comparison of measured re-entry interval against that predicted by mixed-volume model

air flow rate, but only upon the fresh air flow rate, the explosive charge and the volume of the recirculation circuit.

No diesel vehicles were used at the recirculation site or in the fresh air intakes to the site, and consequently the NO_x concentration in the intake air is zero. However it is important to consider the potential concentration of NO_x in the intake (c_f) if diesel vehicles were to be used. Since the NO_x trace is seen to approach its legal limit asymptotically, any slight increase in intake levels, say a constant level of 1 ppm of NO_x, will increase the re-entry interval. Use can be made of the mixed-volume model. For the same volume of the workings and fresh air flow rate, and with the intake level set at a constant 1 ppm instead of a zero concentration, the re-entry interval will increase by approximately 10 per cent. (See Appendix D).

4.4 Plug-Flow Model

The measured re-entry interval and the corrected times predicted using the plug-flow model are shown in Figure 4.6. The effect of changes in the fresh air flow rate, the peak concentration of contaminant released after the blast, the amount of contaminant in the fresh air, the air cycle time and the recirculated air flow rate on the re-entry interval have been simulated using the plug-flow model. The results of these simulations are shown in Figure 4.7. Note that there is no volume (V) term in the plug-flow equation since this term is variable from day to day and difficult to determine. Account is taken of the volume of the workings through which air flows by the inclusion of the cycle time in the calculations.

Again, the influence due to changes in intake NO_x levels (c_f) has been simulated and is shown in Figure 4.7.

From exercise A through to exercise F the levels of Q_f, $\hat{c}$, c_f and cycle time (in case of E) have been set, and tend to give a progressive decrease in the re-entry interval with changes in the recirculated air flow rate.

It can be seen that in all the exercises, the recirculated air flow rate has only a minimal effect on the re-entry interval (see Figure 4.7). In some cases the re-entry interval tends to decrease with increasing recirculation rate.

Inspection of the change in the values assigned to Q_F, $\dot{c}$, c_f and cycle time with each exercise, reveals the significance of these parameters, namely the re-entry interval is proportional to:

(i) the mass of explosives ignited daily ($\dot{c}$),
(ii) the concentration of the contaminant in the fresh air supply,
(iii) the cycle time of the plug of contaminant in the recirculation circuit, and

the entry interval is inversely proportional to the fresh air flow rate.

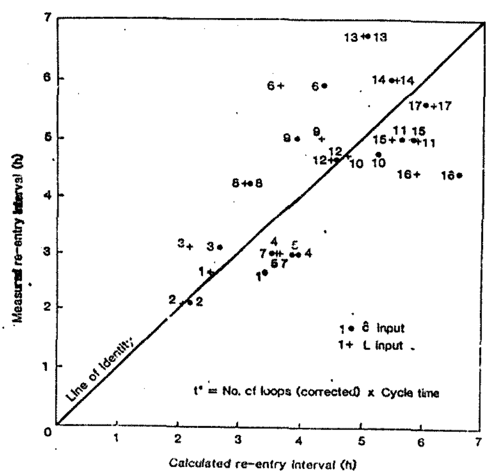

Figure 4.6 Comparison of measured re-entry interval against that predicted by plug-flow model

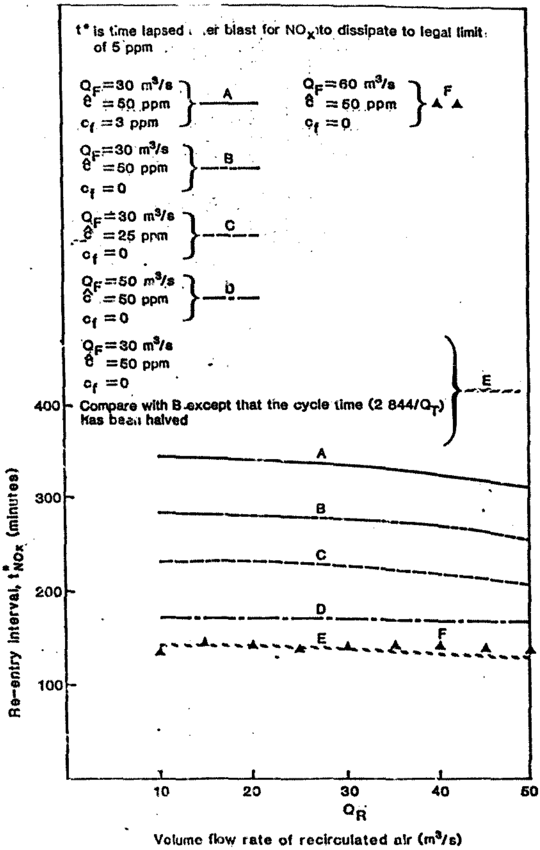

Figure 4.7 Curves showing the influence of various parameters on the re-entry interval

4.5 Residence Time Analysis

The mean residence time is the average time that a parcel of air remains in the recirculation circuit.

The value of the mean residence time varied between 1,8 and 3,7 times the cycle time. Thus no correlation is shown by the cycle time and mean residence time, although a relationship has been shown to exist between cycle time and re-entry interval.

The mean residence time is a measure of the efficiency of the system in purging itself of contaminants. Intuitively it was expected that a shorter mean residence time should result in a reduced re-entry interval, all other factors being equal. This relationship is shown in Figure 4.8. Correlation is not good, but clearly the trend exists.

A strong relationship also exists between mean residence time and fresh air flow rate, and thus this parameter is very important as is clearly evident from the analysis in terms of the two models. This relationship is shown in Figure 4.9.

Since NO_x is not a perfect tracer gas, it is suggested that the mean residence time could be calculated by using a perfect tracer gas, sulphur hexafluoride (SF_6). Instead of a sudden impulse of NO_x from blasting being monitored, an impulse of SF_6 could be released at a position just before the recirculation fan. Samples of air could be collected at suitable intervals in the return airway and a profile of SF_6 concentration drawn with time. From this profile the mean residence time is calculated as described in Section 2.3.3. The SF_6 can also be released into the mine atmosphere during the shift when men are present, and thus the experiments would not have to be conducted during re-entry interval.

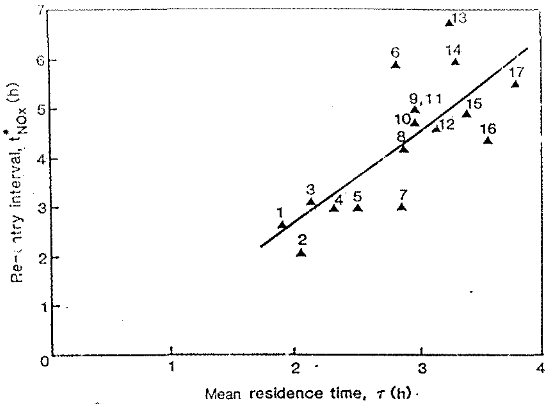

Figure 4.8 Comparison of re-entry interval and mean residence time

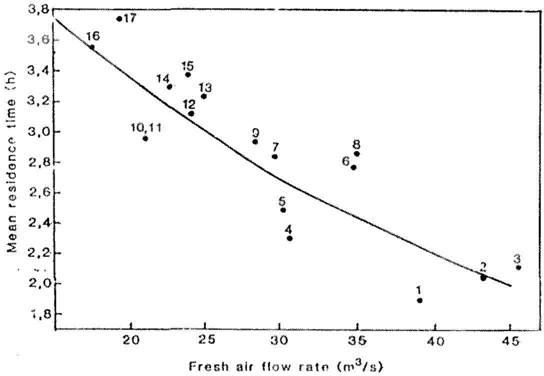

Figure 4.9 Comparison of mean residence time and fresh air flow rate (Alexander et al. (1987))

4.6 Comparison of the Mixed-Volume and Plug-Flow Models and Residence Time Analysis

A comparison of the mixed-volume and plug-flow models is given in Table 4.2.

From the comparison in Table 4.2 it is evident that the most suitable model should:

(i) include the parameters $\hat{c}$, c_f, c_1, c_r, c_t, T, Q_f, Q_R, Q_T and although no NO_x filtration exists it would be desirable to have a term for filtration, and
(ii) be able to simulate the effects of leakage.

The volume of the workings is very difficult to establish from day to day. Either the mean residence time or the cycle time used with the plug-flow model will take account of the volume of the recirculation circuit.

In summary, the numerous leakage paths at the test-site and the difficulty of being able to investigate the effects of each parameter in isolation made it difficult to analyse the data. However, two very different single models have been used and which show, within experimental accuracy, that the recirculated air flow rate had little effect on the re-entry interval.

It is suggested that, instead of using these models in isolation, a sophisticated hybrid model, with mixed flow and plug-flow volumes placed in series and parallel within the recirculation circuit, and with the inclusion of the mean residence time parameter, may prove to be more suitable.

Table 4.2 Comparison of mixed-volume and plug-flow models

	Mixed-Volume Model	Plug-flow Model
Assumptions	· After blasting working zone (including access ways) of Volume V, m^3, has a uniform, instantaneous concentration of noxious contaminant.	· A discrete plug of contaminant is produced after the blast which decreases in concentration each time it loops around the circuit by removal of a portion of the plug to the reject airway and dilution by the intake fresh air.
Parameters	V, Q_F, C, $\hat{c}$, $c_1(c_f = 0)$	$\hat{c}$, c_f, c_1, c_r, c_t, T, Q_F, Q_R, Q_T
Conclusions	· Q_R does not affect t^*. · t^* is proportional to V, *ℓn of mass of explosives ignited daily and is* inversely proportional to Q_F	· Q_R does not significantly affect t^*. · t^* is proportional to $\hat{c}$ *(or mass of explosives* ignited daily), c_f, and T and is inversely proportional to Q_F.
Limitations	. The assigned value of V is taken as being constant for tests. . If c_f greater than zero then not strictly true to use this model due to time taken for air to travel from outlet of working zone to mixing point of recirculated air with freash air. · Cannot take account of leakage which has been shown to be a significant factor. · Does not account for time interval from time of blast to time at peak concentration i.e. Re-entry only *calculated from peak concen*tration to legal limit.	· Knowledge of the cycle times (being dependent on the total air flow rate) from test to test is needed. · Have to calculate time from blast to $\hat{c}$ and add this time to time derived from model to give t^*.
Further Comments	· Cannot be used to simulate variations in leakage and filtration.	· Can be used to investigate effects of leakage and filtration. · An easy to understand and easy to use model.

CHAPTER 5 CONCLUSIONS

1. NO_x was found to be the critical contaminant in calculating the re-entry interval, irrespective of recirculation.

2. As a first-order approximation, the re-entry interval is proportional to:

   - the length of face blasted and hence the amount of explosives consumed daily,

   - the volume of the recirculation circuit and the time taken for air to complete one circuit (the cycle time),

   and is inversely proportional to:

   - the fresh air flow rate.

   There are daily fluctuations in the face length blasted and the fresh air flow rate is fixed, which makes it difficult to control the re-entry interval by varying these parameters. However, the re-entry interval can be controlled by reducing the volume of the recirculation circuit especially in the case when backfill is used.

3. Irrespective of the effect of all other parameters on the re-entry interval, the amount of recirculated air was found to have little effect. However, if controlled recirculation were to be used to substitute some fresh air with recirculated air, the re-entry interval would then be extended.

4. Leakage and short circuiting of air within the recirculation circuit reduce the amount of air available at the working faces. For a given amount of explosives used, this reduced air flow yields a higher maximum concentration of contaminant and consequently a longer re-entry interval.

5. Diesel vehicles were not used in the fresh air intakes to the test area, and thus NO_x concentrations in the fresh air supply were close to zero. If diesel machinery were to be used, the potential increase in NO_x levels in the fresh air could increase the re-entry interval. However this would be independent of the recirculated air flow rate.

The above conclusions relate to a specific longwall system. However, it is believed that the general trends would apply to other recirculation schemes where the actual results might differ depending upon the mine layout.

APPENDIX A

ANCILLARY WORK

Controlled Recirculation: Its Effect on Blast Contaminant Decay

This paper is included in support of the project report. It makes use of the mixed-volume model and residence time analysis. The same conclusions are reached with both the paper and the project report. However, with the project report, greater use is made of the plug-flow model and residence time analysis, and a comparison of these analysis techniques is given.

There are some differences, in that with the project report:

(i) The test numbers 1 4 (Q_R = 0) and point 7 are not used,
(ii) the test points have been renumbered in terms of increasing mean residence time, instead of increasing recirculation ratio,
(iii) there are differences in the re-entry intervals due to the difficulty in establishing the intercept point of the trace with the legal limit line of NO_x (5 ppm) as they approach each other asymptotically,
(iv) the mixed-volume model was modified in that the fresh air contaminant concentration, c_f, was taken as zero, and
(v) the peak NO_x concentration of point 15 reads 20 and not 53 as reported for the same point 20 in the paper.

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CONTENTS

CONTROLLED RECIRCULATION:

ITS EFFECT ON BLAST CONTAMINANT DECAY

N.A. Alexander*, A.D. Unsted*, and K.C. Benecke†

SYNOPSIS

A series of tests was undertaken on a recirculation scheme at a longwall site at Western Deep Levels Limited to establish the effect of controlled recirculation on the re-entry period. The fresh and recirculated air flow rates were varied and their effects on blast contaminant decay measured. Gas concentrations of the oxides of nitrogen (NO_x) and carbon monoxide were monitored continuously, while dust levels were monitored in the return air from 2 hours before the blast to 4 hours after the blast.

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The fresh air flow rate was varied from 20 to 40 m³/s and the recirculation fraction from 0 to 0.6. Over the full range of tests, the critical contaminant for determining the safe re-entry period was found to be NO$_x$. The amount of explosives used and the fresh air flow rate affected the re-entry period, while the amount of recirculated air was found to have a negligible effect. This is in keeping with the findings from a scattered stoping situation[1].

INTRODUCTION

A recent field trial[1] at Loraine Gold Mines Limited demonstrated some of the advantages of controlled recirculation for deep South African gold mines and this practice is being introduced increasingly in the mining industry. The recirculation circuit at Loraine Gold Mines was positioned around a number of parallel panels where scattered mining was taking place. It was found that the recirculated air flow rate had no effect on the removal of the contaminants after the blast and hence the re-entry time. In spite of these findings, it was felt necessary to examine the effects of controlled recirculation on the blast contaminant decay and the re-entry time at a longwall mining site. The selected area was at No. 3 Shaft, Western Deep Levels, Limited, where it was possible to vary the fresh and recirculated air flow rates independently and carefully monitor the contaminant levels in the return air.

Some of the advantages of controlled recirculation have been demonstrated for deep gold mines and this practice is being introduced increasingly.

Legislation[2] limits the maximum concentration of carbon monoxide to 100 ppm and the NO$_x$ concentration to 5 ppm in the underground workings. The NO$_x$ level is the sum of the concentration of all oxides of nitrogen. For mines this is taken as being the sum of the nitric oxide and nitrogen dioxide concentrations since these are the only two oxides of nitrogen normally present. In the case of dust the Threshold Limit Value (TLV) depends on the silicon dioxide content[3]. At the Western Deep Levels recirculation site the SiO_2 fraction was found to be about 25 per cent giving a TLV of 0,4 mg/m³. The maximum acceptable level of dust when measured by particle count is normally taken to be 200 particles per millilitre.

Shortly after a blast the legal limits for the maximum allowable NO$_x$, CO and dust levels in the working zone are exceeded. However, the continual passage of fresh ventilation air through the workings eventually reduces the contaminant concentrations. The re-entry period depends upon the time from the blast to the time when all three contaminants (NO$_x$, CO and dust) have returned to below the legal limits. The main concern in this field trial was to determine whether the re-circulation of a fraction of the contaminated return air would adversely affect the existing re-entry period.

FIELD TRIAL INVESTIGATION

The effects of recirculation on the re-entry period were examined by varying the degrees of recirculation and measuring the gas contaminants (NO$_x$ and CO) in the return air stream continuously. The dust levels were monitored for a period of 2 hours before the blast to [illegible] hours after the blast.

The first stage of the investigation was aimed at determining which of the contaminant levels took the longest to decay to its legal limit after the blast and hence which contaminant dictated the length of the re-entry period. (It will be seen later that this was NO$_x$).

Having determined that NO$_x$ was the critical contaminant, further analyses were aimed at determining those parameters which affected its decay time. The approach here was to examine the effects of the amount of explosives used, the fresh air flow rate and the recirculated air flow rate, the cycle time and the mean residence time. The cycle time is the time for a unit of air to travel once around the entire circuit (workings plus recirculation path). The mean residence time is the average time for a unit of air to remain within the recirculation circuit and was determined from measurements (by means of a gas concentration — time trace) and standard statistical procedures[4].

The fresh air flow rate was varied from 20 to 40 m³/s and that of the recirculated air from 20 to 30 m³/s.

It would have been highly desirable to vary each of the parameters separately while keeping the other parameters fixed; however, under actual mining conditions this was not possible.

UNDERGROUND SITE AND INSTRUMENTATION

The test site was at the No. 3 Shaft, Western Deep Levels Limited in the 91/73 East longwall. The total recirculation path was about 4 km. The longwall is located in the upper Carbon Leader zone between depths of 2 530 m and 2 760 m. The stope face dips at 30 degrees for about 500 m with a stoping width of 1 m. Figure 1

NOMENCLATURE

- c_i Intake air gas concentration m³/m³
- c_l Legal limit of gas concentration (for NO$_x$, $c_l = 5 \times 10^{-6}$), m³/m³
- c_{max} Peak gas concentration after blast m³/m³
- c_r Return air gas concentration m³/m³
- C Total volume of NO$_x$ released from blast, m³
- Q_f Fresh air flow rate (equal to reject air flow), m³/s
- Q_r Recirculated air flow rate, m³/s
- R Recirculation fraction ($Q_r/(Q_r + Q_f)$)
- t Time from blast, s or h
- t* Re-entry period, s or h
- V Approximate volume of working zone including recirculation airway, m³
- Δc Maximum increase in contaminant concentration due to blast m³/m³

shows a plan of the s ... e 2 is a schematic depicting the ventilati ... cal information on mining and environ ... n the stope are presented in Table 1 ... ds from 83 to 91 levels. Fresh air in ... and 87 levels with some air entering ... n through the old workings. Approximately 45 ... nt of the intake air is fed from 91 level, about 20 per cent from the intake on 87 level and the remainder leaks into the area. The return airway is on 83 level. A 75 kW fan situated on 83 level was used to recirculate air from 83 level back to the longwall via a service incline. The recirculated air is fed back into the workings from the service incline through intakes on 85, 87, 88 and 90 levels. Less than ... r cent of the recirculated air reaches the bottom of the longwall.

The main measuring station was in the return airway on 83 level and was used to monitor the return air contaminant levels as well as the recirculated air flow rate and the reject air flow rate. From these measurements the total flow rate through the longwall was determined and the total intake air flow rate deduced (this

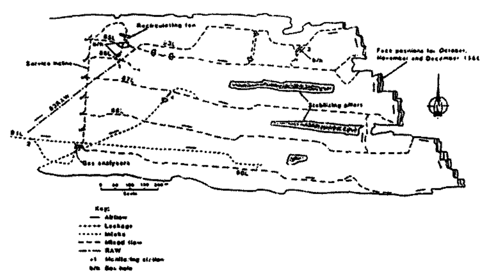

Figure 1: Plan of field trial site

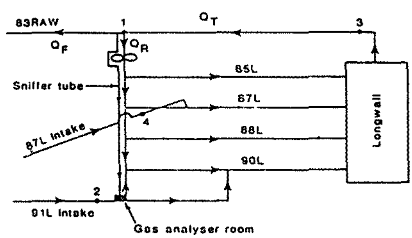

Figure 2: Schematic of test site

will equal the reject air flow rate). The other measuring points were in the intake on 91 level, the intake on 87 level and the return air at the stope outlet. The gas analysis equipment was situated on 91 level and samples of air were drawn from the main measuring station in the return airway on 83 level to the instruments via a sniffer tube of 4 mm internal diameter which was installed in the service incline. The length of the tube was about 750 m. The NO_x levels were measured by chemiluminescent analyser and the CO levels by a gas filter correlation analyser. The information was recorded continuously on a chart recorder.

The NO_x and CO levels in the intake airway on 91 level were also continuously monitored. Diesel vehicles were not used in the area and hence the intake NO_x concentrations were low.

The air flow rates were varied by adjusting a regulator situated in the return airway and by controlling a bypass around the recirculation fan. The regulator consisted of bratticing covered with plastic sheeting. The recirculated and the reject air flow rates were monitored at the main measuring station (Point 1 in Figures 1 and 2). Calibrated vortex anemometers giving a 4 to 20 mA output

Table 1 TYPICAL VALUES FOR MINING AND ENVIRONMENTAL PARAMETERS IN TEST LONGWALL

Rock production per month	tons (waste and reef)	13661 — 17783
	centares	3310 — 4646
	nominal face advance	8 m
Face length		486 m
No. of Panels		16
Stope Width		1 m
Dip		30°
Advance per blast		0,7 m
Depth below surface 83L 91L		2531m - 2760m
Virgin rock temperature		43 °C
Average ventilation air flow rates —		
Fresh air m³/s per kton per month		2 — 2,5
Fresh air		35 m³/s
Recirculated air		25 m³/s
Recirculation fraction		0,42
Face velocity		1,5 m/s
Barometric pressure —		
Intake on 91L		106,4 kPa
Intake on 87L		106,0 kPa
Return on 83L		103,4 kPa
Air temperatures —		
Intake on 91L (WB DB)		27,0 - 29,0 °C
Intake on 87L (WB DB)		24,5 - 29,5 °C
Return on 83L (WB-DB)		30,0 - 32,0 °C
Recirculation Fan details —		
Type		Axial Flow
Rated Power		75 kW
Pressure		1,15 kPa
Air flow rate		30 m³/s
Explosive details —		
Type : Cartridge — Face		Ammon Dynamite
— End		Dynagel

signal were used and the data stored on a battery powered "Squirrel" data logger.

Dust levels in the return air were measured throughout the test period. Both mass concentration and particle count measurements were recorded. An automated konimeter was used to determine the particle counts (A conventional konimeter fitted with a plunger activated by a piston driven by a small electric motor; which also rotated the slide to coincide with the 59 slide positions.) The sampling interval could be varied between five and ten minutes. Dust concentrations on a mass basis were measured continuously using Tyndallometers. These instruments make use of the light-scattering properties of the airborne dust and store the data every 32 seconds in an in-built data logger.

Tyndallometer gravimetric dust measurements were also taken continuously in the intake on 91 level. These measurements were used as an indication of the dust load in the intake air system which is present irrespective of recirculation.

A personal gravimetric sampler was used to provide a check on the average dust concentrations given by the Tyndallometer over the test period. It makes use of a screening cyclone which separates and discards all particles greater than 8 micrometres. The dust collected by this sampler was also used to determine the silicon dioxide content (the average content of SiO_2 was about 25 per cent).

The heavier dust particles drop out of the air stream before the lighter particles and hence have a greater effect on the decay as measured on a mass basis.

Spot measurements of temperature and barometric pressure were taken using hand-held instruments.

RESULTS AND DISCUSSION

Plots of the measured concentrations of the three contaminants (NO_x, CO and dust) after the blast for a test where the fresh air flow rate was 24 m³/s and the recirculation fraction was 0,5 (Test 20 in Table 2) are shown in Figure 3. In order to assist the reader, the vertical axes for the different contaminants have been arranged so that the maximum legal limits of NO_x and CO together with the recommended limits for dust, all coincide.

The decay patterns for this test are typical, with the NO_x concentration taking the longest time to reach the legal limit of 5 ppm. Therefore the decay of NO_x concentration dictates the re-entry time, which in this case can be seen to be 5,4 hours. The CO concentration for this test did not reach the maximum legal limit of 100 ppm: in tests when it did exceed the limit, the time for it to drop back to 100 ppm was considerably less than that for

NO_x to reach 5 ppm. The dust concentration measured by particle count (Konimeter) took longer to reduce to the legal limit than the dust concentration measured on a mass basis. It is believed that this is because the heavier dust particles drop out of the air stream before the lighter particles and hence have a greater effect on the decay as measured on a mass basis.

The average dust concentration values measured with a personal gravimetric sampler throughout the test period compared well with the values measured by the Tyndallometer.

The results of all the tests are presented in Table 2. Tests 1 — 4 refer to the days when there was no recirculation. Tests 5 — 22 are arranged in increasing order of recirculation fraction. The recirculation fraction is the recirculated air flow rate divided by the total air flow rate and can only vary between 0 and 1. The NO_x concentration in the ventilation air took the longest time period to reduce to the legal limit in all the tests and hence in further analysis was the only contaminant used to determine the re-entry period.

Over the test period the length of face blasted on any particular day varied between 100 and about 400 m (Column 7, Table 2). This determined the amount of explosives used and hence the amount of NO_x released. The amount of explosives used was not measured directly but has been estimated on the basis of the typical drilling pattern and the face length blasted with allowance being made for development blasting which took place within the area. The estimated amount of explosive blasted on each day is given in Column 8, Table 2. Approximately 60 per cent of this was Ammon Dynamite and the remainder was Dynagel. The total amount of NO_x released at each blast (Column 11 in Table 2) was calculated by the product of the area under the NO_x — time trace and the air flow rate leaving the recirculation loop. The relationship between the estimated explosive charge and the measured volume of NO_x released from the blast is shown in Figure 4, together with the theoretical prediction. The agreement is reasonable considering the approximate manner for determining the explosive charge.

The peak concentration of the NO_x which occurred just after the blast was deduced from the NO_x gas traces for each test and is given in Column 9, Table 2.

The cycle time which is the time for a unit of air to travel once around the entire circuit (workings plus recirculation path), is given in Column 12, Table 2. The cycle time was determined by measuring the time for a dust concentration peak to travel around the recirculation loop. The value varies between 0,7 and 1,2 hours over the range of the tests. As shown in Figure 5 the cycle time is directly related to the total air flow rate.

The mean residence time, which is the statistical average for a unit of air to remain within the recirculation circuit, is given in Column 13, Table 2. The value of the mean residence time varies between 1,8 and 3,7 times the cycle time. Figure 6 shows a correlation between the mean residence time and the fresh air flow quantity.

It was difficult in some cases to estimate the time period for the NO_x concentration to reduce to the legal limit of 5 ppm. This was because the NO_x concentration traces approached the 5 ppm line very flatly. Estimates were made by careful examination of the traces and these are given in Column 14, Table 2. (Estimated uncertainty values which were typically 6 per cent with a maximum of 10 per cent are also included).

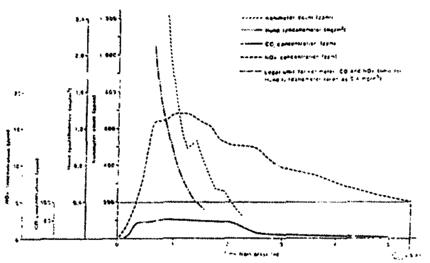

Figure 3: Typical set of contaminant profiles after blast in return airway

1	0,00	0,00	30,1	0,0	30,1	170	1 130	19,0	1,0	4,2	-	-	7,0 ± 0,1
2	0,00	0,00	33,0	0,0	33,0	140	1 010	33,0	0,5	4,9	-	-	8,0 ± 0,1
3	0,00	0,00	33,0	0,0	33,0	390	1 330	36,4	0,0	4,5	-	-	2,5 ± 0,1
4	0,00	0,00	35,0	0,0	35,0	310	1 750	40,0	1,5	10,2	-	-	5,5 ± 0,1
5	0,33	0,25	45,5	15,1	60,6	700	1 350	30,0	1,0	3,6	0,70	3,13	3,0 ± 0,2
6	0,30	0,27	39,6	14,1	53,7	170	1 130	37,5	1,0	1,2	0,88	1,90	3,2 ± 0,2
7	0,44	0,31	31,4	13,9	45,4	200	850	10,0	1,2	3,7	1,03	1,90	3,3 ± 0,3
8	0,48	0,32	43,3	20,3	63,9	170	1 150	16,5	5,0	4,7	0,75	2,08	3,7 ± 0,3
9	0,43	0,31	74,6	10,4	83,4	300	1 490	63,0	1,5	13,3	0,88	2,79	6,4 ± 0,1
10	0,61	0,39	30,3	19,7	50,0	180	1 170	34,5	1,2	6,1	0,5[illegible]	2,49	3,5 ± 0,1
11	0,71	0,41	35,0	24,7	59,7	330	1 370	33,5	1,7	7,0	0,78	2,64	4,0 ± 0,2
12	0,77	0,44	33,0	17,4	60,4	340	1 410	33,0	1,4	7,9	1,17	2,30	7,0 ± 0,4
13	0,79	0,44	28,4	22,3	50,7	280	1 570	24,0	0,5	7,0	0,93	3,04	5,0 ± 0,5
14	0,83	0,45	30,8	25,2	56,0	240	1 410	29,5	6,0	9,4	0,85	3,31	3,0 ± 0,2
15	0,86	0,46	30,0	25,1	55,4	330	1 370	32,0	1,5	5,5	0,85	3,04	3,6 ± 0,1
16	0,91	0,48	31,3	15,2	40,3	330	1 370	29,5	1,3	5,3	1,17	2,05	5,0 ± 0,3
17	0,99	0,50	21,1	20,9	42,0	140	1 010	34,5	0,5	5,9	1,13	2,05	4,9 ± 0,3
18	1,02	0,51	25,0	25,8	50,6	330	1 790	30,5	1,3	12,0	0,93	3,05	6,0 ± 0,2
19	1,06	0,51	24,3	25,6	49,8	300	1 350	34,3	0,0	6,1	0,95	3,13	4,8 ± 0,3
20	1,09	0,52	23,9	26,0	49,5	370	1 930	33,0	0,0	5,5	0,95	3,38	5,4 ± 0,1
21	1,21	0,57	20,4	25,5	44,9	270	1 530	32,0	1,5	6,3	1,05	3,75	6,6 ± 0,3
22	1,33	0,60	17,5	26,7	44,2	160	1 170	32,5	1,4	6,6	1,07	3,54	6,2 ± 0,4

Table 2: Summary of results

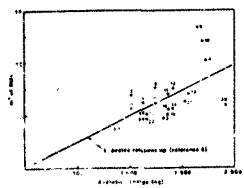

Figure 4: Comparison of volume of NO, leaving site during re-entry period and explosives used.

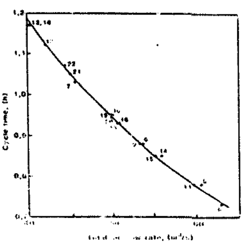

Figure 5: Comparison of cycle time and vital air flow rate.

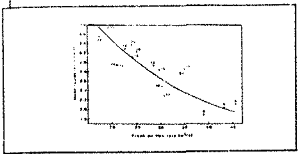

Figure 6: Comparison of mean residence time and fresh air flow rate

Some of the measured re-entry times shown in Table 2 are clearly unacceptable under normal circumstances. It should be emphasised that these were obtained when the fresh air flow rate was deliberately reduced for experimental purposes. Diesel vehicles are not used in the test area and hence NO_x concentrations in the fresh air supply area are close to zero, (Column 10 in Table 2). However, if diesel machinery were used in the intake airways it could lead to an increase in intake NO_x concentrations which would increase the re-entry period.

ANALYSIS

A superficial examination of Table 2 does not reveal any obvious correlations between the re-entry period and the parameters such as recirculation fraction, fresh air flow rate and explosive charge. A correlation exercise between the measured re-entry times and recirculation fractions revealed no specific dependence on recirculation fraction. On the contrary, it indicated that the fresh air quantity and the amount of explosive charge were the dominant parameters affecting the NO_x re-entry period.

In order to determine the combined effects of the parameters two simple models were applied to experimental data. The first is a 'plug-flow' model which assumes that the contaminants do not gradually disperse within the blasting zone but rather travel around the circuit in the form of a plug which reduces step-wise each time the plug passes around the recirculation cycle. This model indicates a slight dependence on the recirculation fraction and evidence for its validity would be the presence of 'spikes' in the gas traces. However, examination of the gas traces did not reveal any definite evidence of such 'spikes' and hence the model did not accurately reflect the situation at the recirculation site.

The second model is a 'mixed-volume' model which assumes that the working zone of volume, V, has a uniform concentration of the contaminant immediately after the blast. In other words, there is perfect mixing between the contaminant and the air in the working zone. This model was used with some success to analyse data obtained at Loraine Gold Mines by Burton et al[4].

The model can be summarized by the following equation:

$$c_t = c_s + \Delta c \exp\{-Q_f t / V\} \qquad (1)$$

Solving this equation for the re-entry time, which is the time required for c_t to decay to c_l (where c_l is the legal limit for a particular contaminant), gives the following equation:

$$t^* = V/Q_f \ln[\Delta c / (c_l - c_s)] \qquad (2)$$

The value of Δc in Equation 2 was assessed in two ways: firstly, by using the total amount of NO_x released (Column 11, Table 2), and secondly, by equating Δc to the difference between the return-air contaminant concentrations just prior to and just after the blast.

For the first case, Equation 2 becomes:

$$t^* = V/Q_f \ln[(C/V) / (c_l - c_s)] \qquad (3)$$

The measured re-entry times and the times predicted by Equation 3 are shown in Figure 7. A best-fit procedure was used to estimate the value of the volume of the working zone, V; which was found to be 260 000 m^3 and corresponds approximately to the geometry of the workings at Western Deep Levels Limited recirculation site. A similar analysis of the data gathered at Loraine Gold Mines[4] showed a smaller volume which corresponded to the geometry at that recirculation site. The data in Figure 7 closely follow the line of identity and hence support the second model.

It indicated that the fresh air quantity and the amount of explosive charge were the dominant parameters affecting the NO_x re-entry period.

For the second case, Equation 2 becomes:

$$t^* = V/Q_f \ln[(c_{max} - c_s) / (c_l - c_s)] \qquad (4)$$

The measured re-entry times and the times predicted by Equation 4 are shown in Figure 8. For the working volume of 260 000 m^3 estimated above, Equation 4 correlates well with the measured re-entry times. Analysis showed that a slightly smaller value for the working volume would have provided a better correlation with Equation 4.

The scatter in Figures 7 and 8 is believed to be due to the numerous leakage paths within the workings, the location and extent of which varied between those tests with recirculation and those without. However, the good overall correlation indicates that the model is relatively insensitive to these effects.

Clearly, within the estimated experimental errors, the 'mixed-volume' model is very well supported by the data. This means that the re-entry time is not dependent on the recirculation fraction but only upon the fresh air flow rate, the explosive charge and the size, or volume, of the working zone (including all airways within the recirculation circuit).

CONCLUSIONS

1. NO_x was found to be the critical contaminant in establishing the re-entry period, irrespective of recirculation.
2. If the fresh air flow rate and the rock production (hence the total amount of blast contaminants) remains constant, then the introduction of recirculated

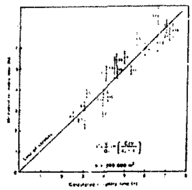

Figure 7: Comparison of measured re-entry time against that predicted by Equation 3.

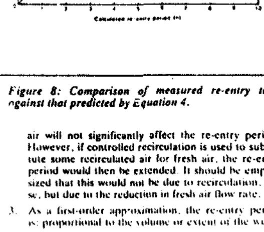

Figure 8: Comparison of measured re-entry time against that predicted by Equation 4.

air will not significantly affect the re-entry period. However, if controlled recirculation is used to substitute some recirculated air for fresh air, the re-entry period would then be extended. It should be emphasized that this would not be due to recirculation, per se, but due to the reduction in fresh air flow rate.

3. As a first-order approximation, the re-entry period is proportional to the volume or extent of the workings (including all airways within the recirculation circuit); proportional to the log of the amount of explosives used, and inversely proportional to the fresh air flow rate.

ACKNOWLEDGEMENT

The study described in this paper was carried out as part of the research programme of the Research Organization of the Chamber of Mines of South Africa. The work was carried out in close collaboration with the management and staff of the Environmental Engineering Department of Western Deep Levels Limited.

11. REFERENCES

1. BURTON, R.C., PLENDERLEITH, W., STEWART, J.M., PRETORIUS, B.C.B. and HOLDING, W. Recirculation of Air in the Ventilation and Cooling of Deep Gold Mines. In: Proceedings of the Third International Mine Ventilation Congress, Harrogate, England. The Institution of Mining and Metallurgy and The Institution of Mining Engineers. 1984. pp 291-299.
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5. GREIG, J.D. Gases Encountered in Mines. In: Environmental Engineering in South African Mines, ed. J. Burrows et al. The Mine Ventilation Society of South Africa. Cape Town, Cape and Transvaal Printers, 1982. pp. 723-723

NEWS FROM COM'S RESEARCH ORGANIZATION

Mr. John Sheer, formerly director of the Environmental Engineering Laboratory has been appointed senior director of the Chamber of Mines Research Organization with responsibility for all work embracing the environmental problem area.

Mr. Steven Bluhm succeeds Mr. Sheer as director of the Environmental Engineering Laboratory (EEL).

Following the formation of a hazardous materials unit Dr. Jack Greig has been appointed head of this unit.

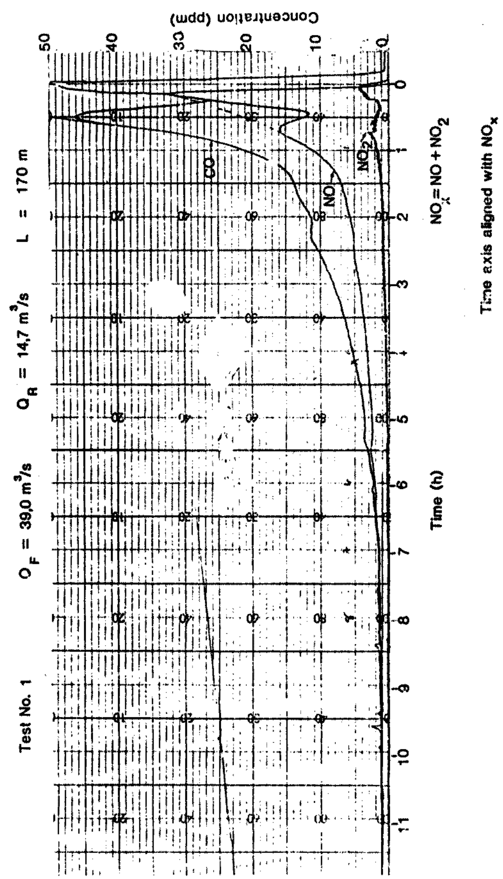
APPENDIX B

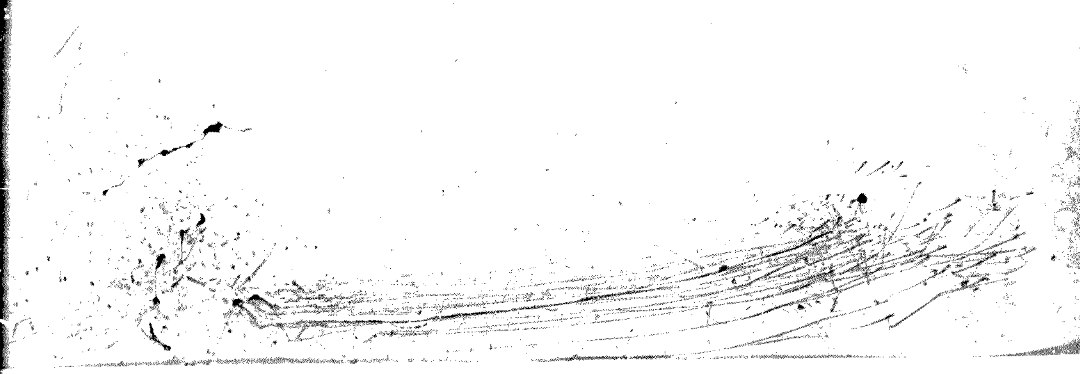
DATA

Information gathered at the test site include:

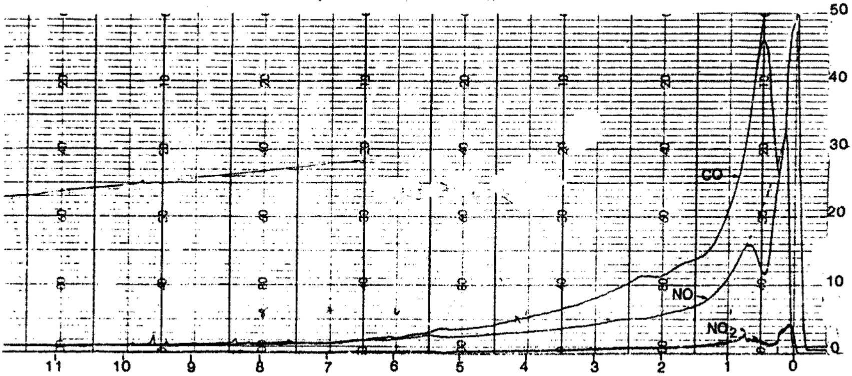
(i) Gas concentration traces (NO_x and CO) for all the test days,
(ii) airflow data (Q_R and Q_F) - measurements made by the vortex anemometers and recorded by a 'Squirrel' data logger showing the typical variation in air flow rates during the re-entry interval on a particular test-day, and
(iii) the variation in inlet (91 level and 87 level) and outlet (83 level) air density.

Gas Concentration Traces (NO_x and CO)





Test No. 1 Q_F = 39,0 m^3/s Q_R = 14,7 m^3/s L = 170 m

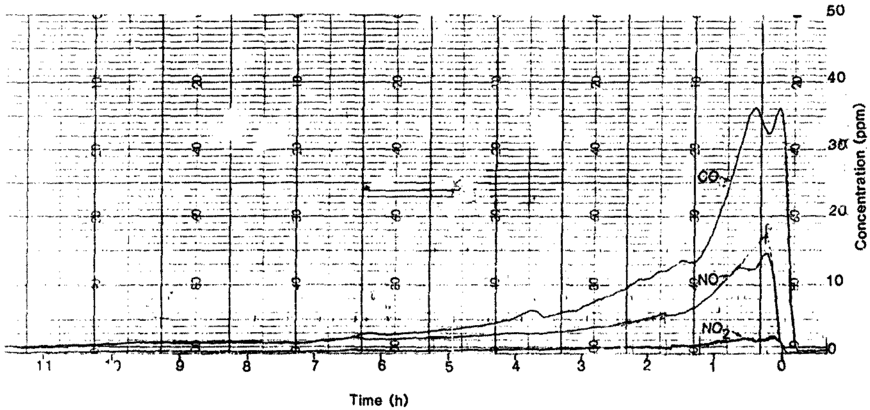


$NO_x = NO + NO_2$

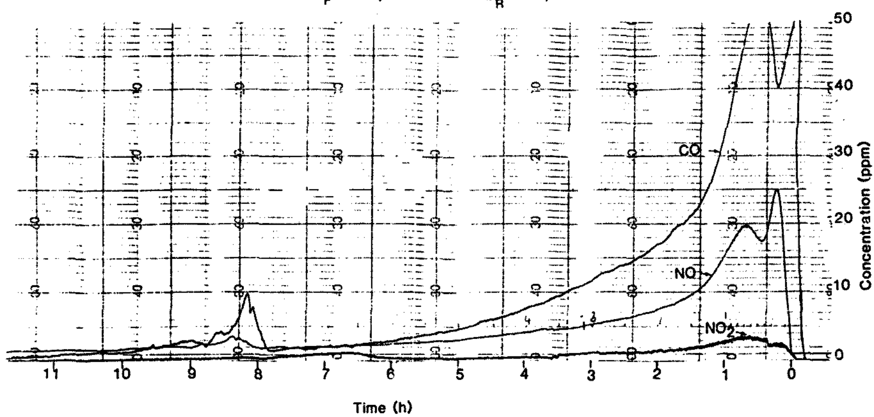
Time axis aligned with NO_x

Gas Concentration Traces (NO_x and CO)

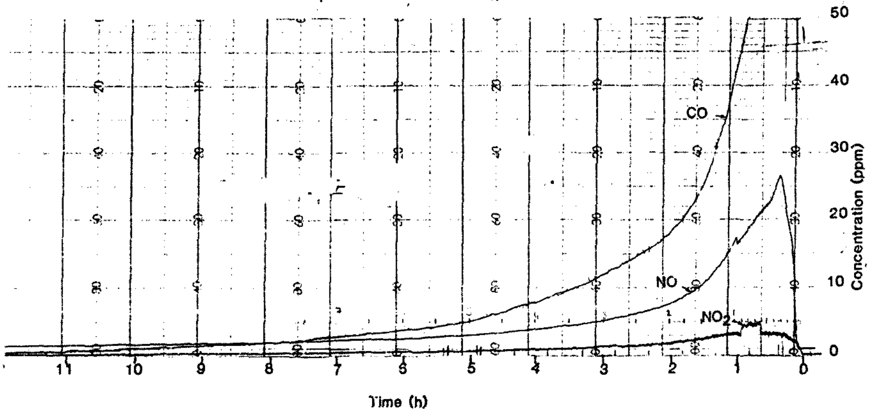
Test No. 2 Q_F = 43,2 m^3/s Q_R = 20,7 m^3/s L = 170 m

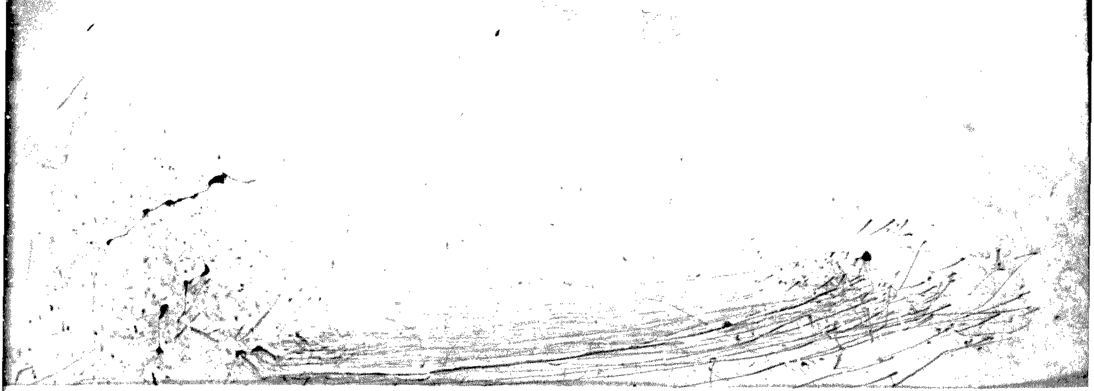


Test No. 3 $Q_F = 45{,}5\ m^3/s$ $Q_R = 15{,}1\ m^3/s$ L = 200 m

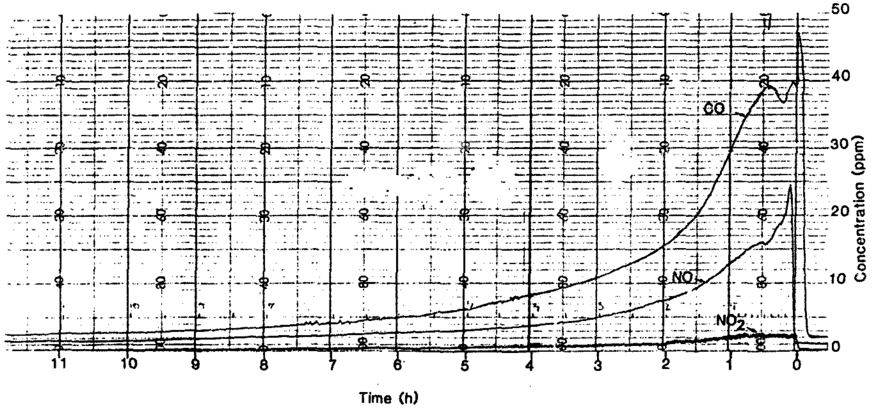


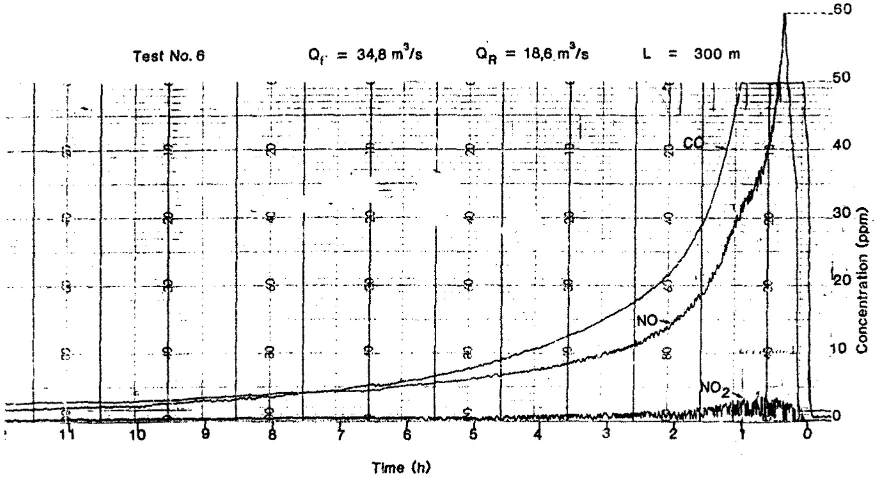
Test No. 4 Q_F = 30,8 m^3/s Q_R = 25,2 m^3/s L = 240 m

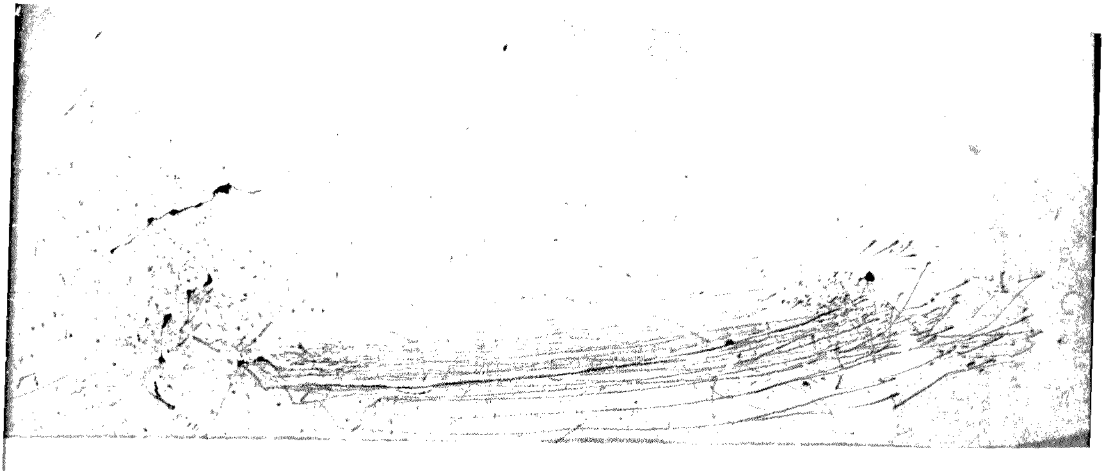


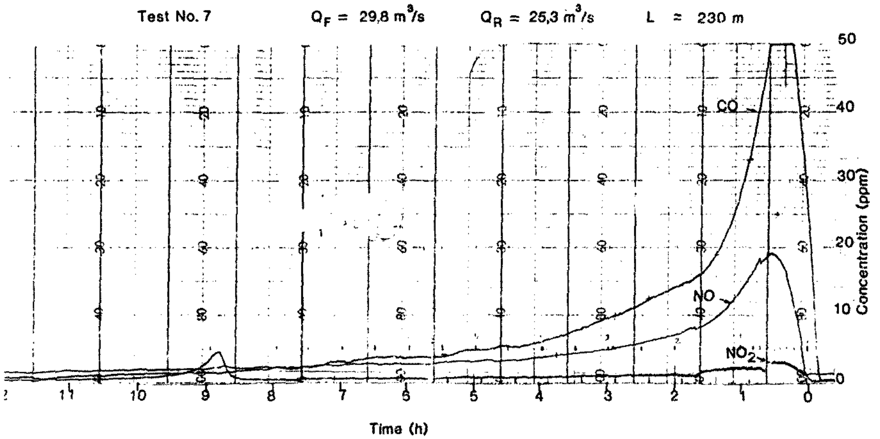


Test No. 5 $Q_F = 30{,}3\ m^3/s$ $Q_R = 19{,}7\ m^3/s$ $L = 180\ m$

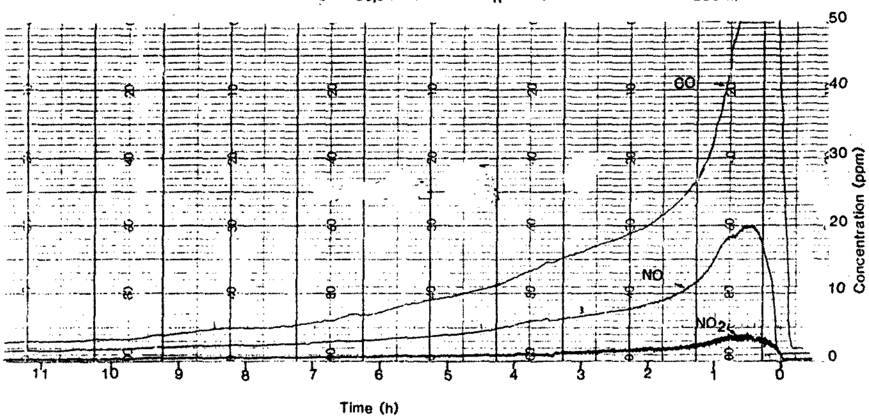


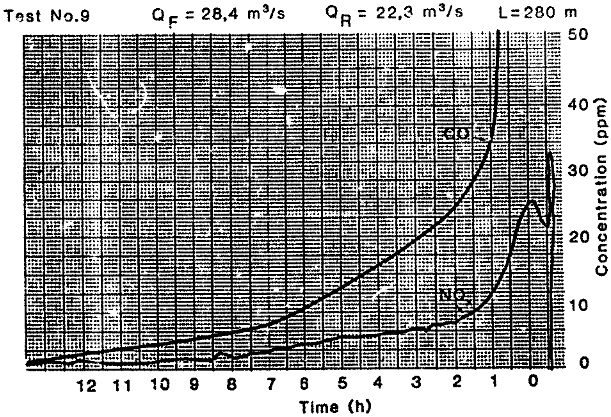

Test No. 6
Q_f = 34,8 m³/s
Q_R = 18,6 m³/s
L = 300 m
CO
NO
NO_2
Concentration (ppm)
0
10
20
30
40
50
60
Time (h)
11
10
9
8
7
6
5
4
3
2
1
0



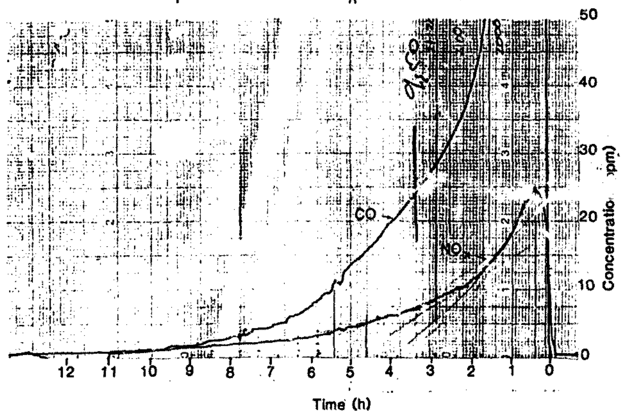

Test No. 7
Q_F = 29,8 m³/s
Q_R = 25,3 m³/s
L = 230 m
CO
NO
NO2
Concentration (ppm)
50
40
30
20
10
0
11
10
9
8
7
6
5
4
3
2
1
0
Time (h)

Test No. 8 Q_S = 35,0 m^3/s Q_R = 24,7 m^3/s L = 230 m

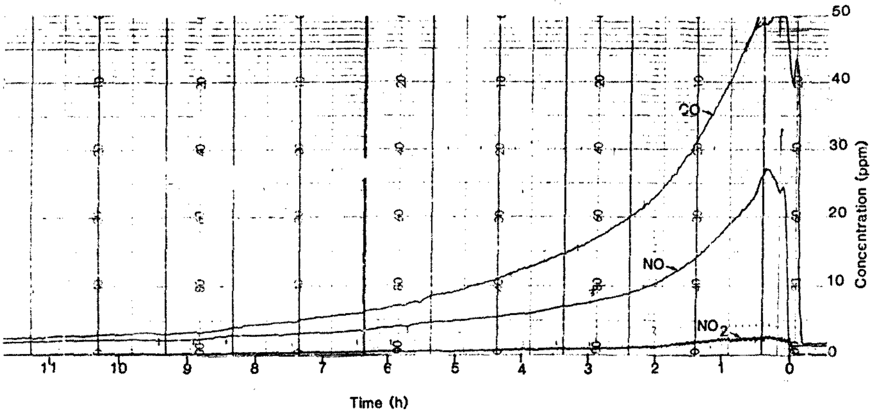



Test No.9
Q_F = 28,4 m³/s
Q_R = 22,3 m³/s
L=280 m
CO
NO_x
50
40
30
20
10
0
Concentration (ppm)
12
11
10
9
8
7
6
5
4
3
2
1
0
Time (h)

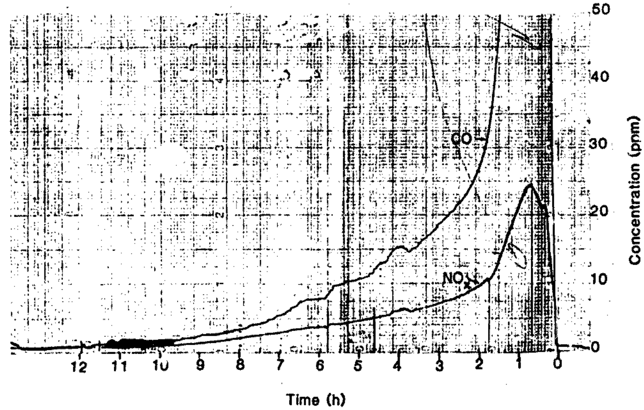
Test No. 10 $Q_F = 21{,}1\ m^3/s$ $Q_R = 20{,}9\ m^3/s$ L = 140 m



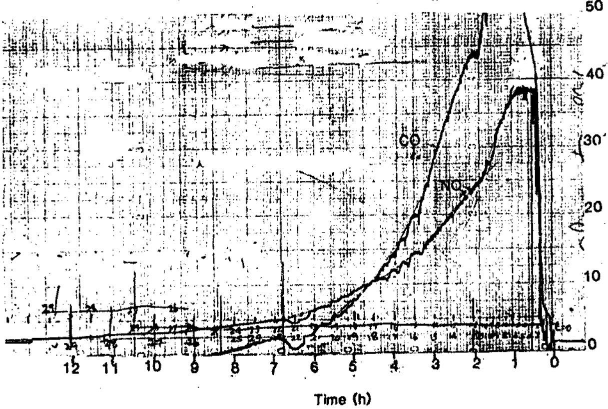
Test No. 11 Q_F = 21,1 m^3/s Q_R = 19,2 m^3/s L = 230 m



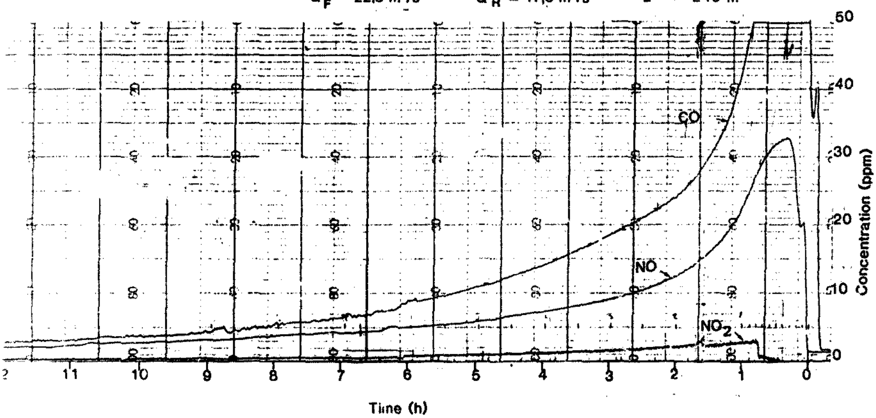
Test No. 12 Q_F = 24,2 m^3/s Q_R = 25,6 m^3/s L = 200 m



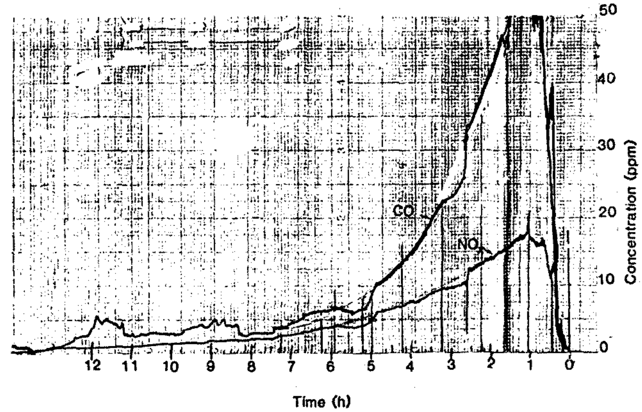
Test No. 13 Q_F = 25,0 m^3/s Q_R = 25,8 m^3/s L = 330 m



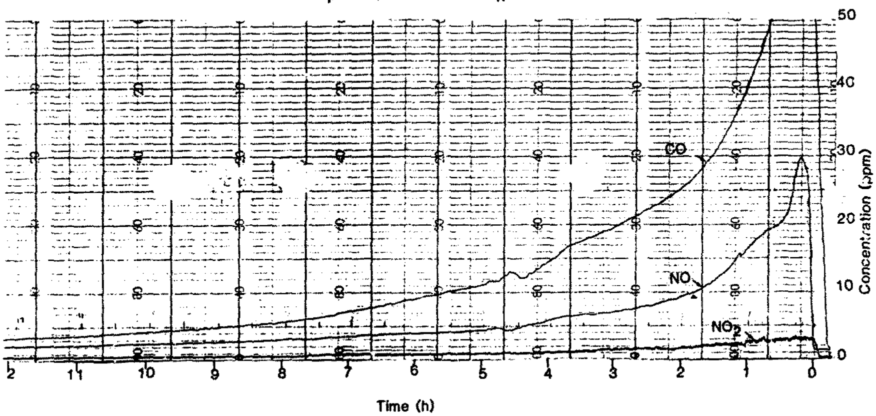
Test No. 14 $Q_F = 22{,}8\ m^3/s$ $Q_R = 17{,}6\ m^3/s$ L = 240 m



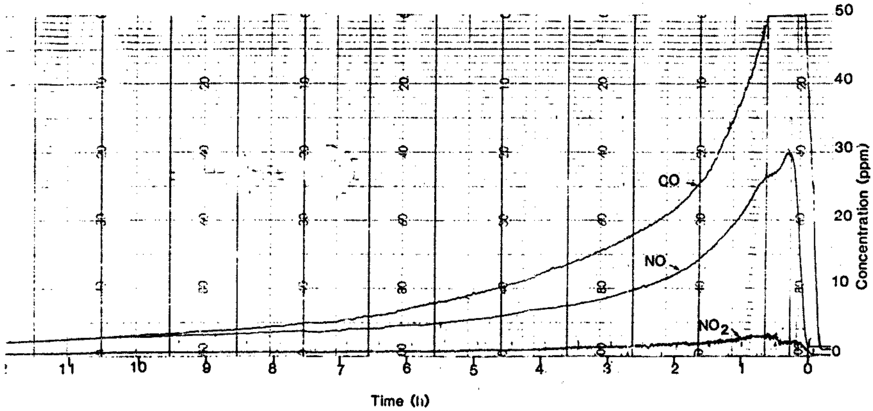
Test No. 15 $Q_F = 23{,}9\ m^3/s$ $Q_R = 26{,}0\ m^3/s$ $L = 370\ m$



Test No. 16 $Q_F = 17{,}5\ m^3/s$ $Q_R = 26{,}7\ m^3/s$ $L = 180\ m$



Test No. 17 Q_F = 19,4 m^3/s Q_R = 25,5 m^3/s L = 270 m



Variation in air flow rate during re-entry interval

The variation in air flow during the re-entry interval on a particular test day (Test No. 12) is given below. The signal from the vortex anemometer was recorded every two minutes, and, since the fresh and recirculated air flow rates were steady, only every fifteenth recording (half-hourly) was used.

$Q_F (m^3/s)$			$Q_R (m^3/s)$		
Time (h)	mA	Q_F	Time (h)	mA	Q_R
0	7,52	24,67	0	7,04	26,04
0,5	7,44	24,20	0,5	6,88	25,55
1,0	7,20	22,81	1,0	6,72	25,05
1,5	7,36	23,74	1,5	6,96	25,80
2,0	7,28	23,27	2,0	6,80	25,30
2,5	7,44	24,20	2,5	6,80	25,30
3,0	7,52	24,67	3,0	6,96	25,80
3,5	7,52	24,67	3,5	7,20	26,54
4,0	7,44	24,20	4,0	7,04	26,04
4,5	7,44	24,20	4,5	6,48	24,31
5,0	7,36	23,74	5,0	6,64	24,80
5,5	7,60	25,13	5,5	6,96	25,80
6,0	7,44	24,20	6,0	6,96	25,80
6,5	7,68	25,59	6,5	6,80	25,30
7,0	7,44	24,20	7,0	6,96	25,80
mean =	7,45 mA =	$24,2\ m^3/s$	mean =	6,88 mA =	$25,6\ m^3/s$

Standard deviation = $0,69\ m^3/s$ Standard deviation = $0,55\ m^3/s$

Note: $Q_F = 5,80\ mA - 18,95$ and $Q_R = 3,10\ mA + 4,22$

Since the standard deviation in re[illegible]on to the mean of each test is small it is justifiable to use the mean values of the fresh and recirculated air flow rates in the analysis.

Variation in Inlet and Outlet Air Density

The air density on 91 level and 87 level fresh air intakes and 83 level return airway was determined from psychrometric data as follows:

91 level

B.P. (kPa)	WB (°C)	DB (°C)	Density kg/m^3
106,4	27,0	29,0	1,21

87 level

B.P. (kPa)	WB (°C)	DB (°C)	Density kg/m^3
106,0	24,5	29,5	1,21

83 level

B.P. (kPa)	WB (°C)	DB (°C)	Density kg/m^3
103,4	30,0	32,0	1,16

Thus, the percentage difference in air density of the inlet and outlet is

$$\text{Percentage difference} = \frac{1,21 - 1,16}{1,16} \times 100\ \%$$

$$= 4,3\ \%$$

which is considered to be insignificant.

APPENDIX C

INSTRUMENTATION

Figure C1 shows the NO_x and CO measurement layout. Note that the gas analysis equipment had to be sited in fresh air in a sub-station at the bottom of the service incline some distance (750 m) from the sampling point in the 83 level return airway.

Table C1 gives a schedule of instrumentation details.
The 'Squirrel' data logger proved to be most useful for this type of work. During the re-entry interval it operated successfully in hot, humid and dusty conditions in the 83 level return airway. It was quick and easy to install and easy to convey to and from the test site. However, although Western Deep Levels Limited is classified as a non-fiery mine, the 'Squirrel' data logger used at the test site did not carry the Government Mining Engineer's stamp of approval (intrinsic safety) for use in fiery mines. This factor drastically limits the use of this data logger in South African mines as a large number of mines are classified as being fiery.

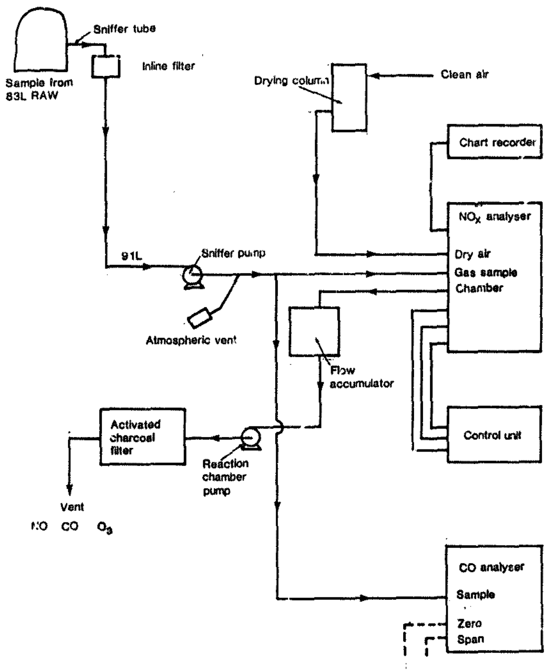


Figure C.1 NO_x and CO measurement Layout

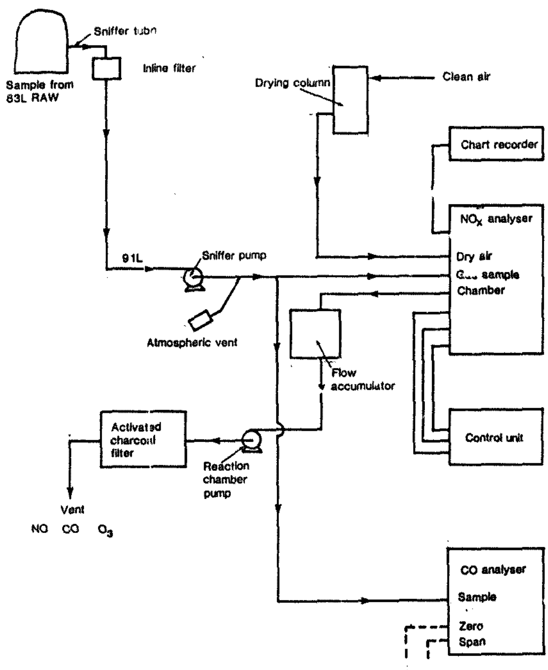


Figure C.1 NO_x and CO measurement Layout

Table C.1 SCHEDULE OF INSTRUMENTATION DETAILS

INSTRUMENT	OUTPUT	UNIT
Barometer	Analogue	Bar
Whirling Hygrometer	WB/DB	°C
Vane Anemometer Vortex Anemometer Calibration Curve	Analogue 4 - 20mA	m/s m/s
Tyndallometer Automated Konimeter Personal gravimetric sampler	Digital, data logger Particle count - less than 5 micron Mass, SiO_2% - less than 5 micron	mg/m^3 p/ml mg;SiO_2% (TLV)
NO_x Analyser and CO Analyser linked to 3 pen strip chart recorder	0 - 1V chart recorder 0 - 10V chart recorder	ppm ppm

APPENDIX D

MIXED-VOLUME MODEL

ANCILLARY WORK

Recirculation of air in the ventilation and cooling of deep gold mines

The following extract, **Recirculation during blasting**, from the paper by Burton <u>et al</u>. (1984) is pertinent to this project report. The mixed-volume model given by Equation 2.2 or Equation 2.3 in Section 2.3.1 has been derived from Equation 13 below.

Recirculation model for gaseous contaminants

Nomenclature

Q_i Quantity of intake air, m³/s
Q_r Quantity of recirculated air, m³/s
c_i Intake-air contaminant concentration, mg/m³
c_r Return-air contaminant concentration, mg/m³
c_m Mixed-intake contaminant concentration, mg/m³
C Contaminant produced in working area, mg/s

Recirculation during blasting

Assume that, as a result of blasting, a working zone of volume V, m³, has a uniform, instantaneous concentration of a noxious contaminant, c_n, mg/m³. At some time, t, s, the rate of decay of noxious contaminant from the working area must equal the rate of removal in the return air. Using the nomenclature given earlier, the following can be stated:

$$V\frac{dc_n}{dt} = Q_i(c_i - c_r) \qquad (12)$$

It can be seen that the recirculated quantity does not appear in equation 12. The reason is shown in Fig. 2, where, for any given concentration in the return air, the amount of contaminant removed by the recirculated air is immediately returned to the

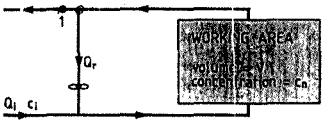


Fig. 2 Schematic of blast-contaminant decay

area. In this respect, therefore, recirculation will have no effect on the rate of removal of contaminant from the recirculation system (at point 1, Fig. 2). The concentration in the return air, c_r may, however, be dependent on the recirculated quantity. If the air within the working area is perfectly mixed, c_r will equal c_n. If the air is less than perfectly mixed, c_r is likely to be less than c_n. The recirculated air quantity may well create better mixing.

If it is assumed that there is perfect mixing, c_r can be substituted for c_n in equation 12. Upon integration, the concentration in the return air (and, hence, in the working area) would be given by

$$c_r = (c_r - c_i)_0 \exp\left(-\frac{Q_i t}{V}\right) + c_i \qquad (13)$$

where $(c_r - c_i)_0 = (c_r - c_i)$ at time $t = 0$.

Although c_i would normally be small for most blast contaminants, it is included in the above analysis to allow for the presence of, for example, carbon monoxide produced by diesel locomotives in the intake air.

The effect of the fresh air contaminant concentration on the re-entry interval

The sensitivity of the fresh air contaminant concentratiuon, c_f, on the re-entry interval can be established using the mixed-volume model.

Given that

$$t^* = \frac{V}{Q_F} \ln [\Delta c / (c_\ell - c_f)]$$

$$= \frac{V}{Q_F} \ln \frac{(\hat{c}-c_f)}{(c_\ell-c_f)}$$

If $\quad x = \ln \frac{(\hat{c}-c_f)}{(c_\ell-c_f)} \quad$ then $t^* = \frac{Vx}{Q_F}$

and $\quad c_\ell = 5$ ppm (NO_x)

For the same volume of the workings and fresh air flow rate, and for $\hat{c}$ = 50 ppm and 30 ppm two sets of exercises can be performed to give the percentage increase in the re-entry interval for various selected values of c_f.

$\hat{c}$ = 50 ppm

c_f	x	percentage increase
0	2,30	0
1	2,51	9
2	2,77	20
3	3,16	37

$\hat{c}$ = 30 ppm

c_f	x	percentage increase
0	1,79	0
1	1,98	11
2	2,23	25
3	2,60	45

APPENDIX E

PLUG-FLOW MODEL

Example in the use of the model

Given that Q_F = 30 m³/s; $\hat{c}$ = 50 ppm; c_f = 3 ppm; Q_R = 30 m³/s and leakage = 0 %. The critical contaminant is NO_x with c_ℓ = 5 ppm.

The re-entry interval is derived using the plug-flow model as follows:

$\hat{c}$ input

No. of loops uncorrected

By mass balance at point 3 (Figure 2.1)

$$c_t \text{ loop1} = \frac{Q_F c_f + Q_R \hat{c}}{Q_F + Q_R} \quad (1)$$

$$= \frac{(30)(3) + (30)(50)}{30 + 30}$$

$$= 26,5 \text{ ppm}$$

$$c_t \text{ loop2} = \frac{(30)(3) + (30)(26,5)}{30 + 30}$$

$$= 14,75 \text{ ppm}$$

$$c_t \text{ loop3} = \frac{(30)(3) + (30)(14,75)}{30 + 30}$$

$$= 8,88 \text{ ppm}$$

$$c_t \text{ loop4} = \frac{(30)(3) + (30)(8,88)}{30 + 30}$$

$$= 5,94 \text{ ppm}$$

$$c_t \text{ loop5} = \frac{(30)(3) + (30)(5,94)}{30 + 30}$$

$$= 4,47 \text{ ppm}$$

Thus it takes between 4 and 5 loops for the NO_x concentration to reduce to 5 ppm.

By Linear interpolation

$$\text{No. of loops (uncorrected)} = 4 + \frac{(5{,}94 - 5)(1)}{(5{,}94 - 4{,}47)}$$

$$= 4{,}64$$

For the test site

$$\text{No. of loops (corrected)} = 2{,}82\ (\text{No. of loops (uncorrected)})^{0{,}593}$$

$$= (2{,}82)\ (4{,}64)^{0{,}593}$$

$$= 7{,}01$$

Now Cycle time, T, for the test site is given by:

$$T = 2\ 844/Q_T \quad \text{mins}$$

$$Q_T = Q_F + Q_K$$

$$= 30 + 30$$

$$= 60$$

$$\therefore \quad T = (2\ 844)/(60)$$

$$= 47{,}4 \quad \text{mins}$$

$$\therefore \quad t^* = \text{No. of loops (corrected)} \times \text{Cycle time}$$

$$= (7{,}01)\ (4{,}74)$$

$$= 332 \quad \text{mins}$$

$$= 5{,}54 \quad \text{h}$$

M input

Suppose 905 kg of explosive were consumed

$$\text{Since } \dot{c} = C/V = \frac{0{,}005\ M}{(60)(T \times Q_T)}$$

$$\therefore\ \dot{c} = \frac{(0{,}005)(905)}{(60)(47{,}4)(60)}$$

$$= 26{,}5 \times 10^{-6}\ \frac{m^3{}_{NO_x}}{m^3{}_{Air}}$$

$$= 26{,}5 \text{ ppm by volume}$$

This $\dot{c}$ is then input into (1) to give the same t* as calculated above.

The No. of Loops (corrected)

The No. of loops (corrected) is established by correlating the measured (correct) No. of loops (t* measured/T) with the uncorrected No. of loops such that

No. of loops (corrected) = 2,82 (No. of loops (uncorrected))$^{0{,}593}$

This relationship is shown in the following Figure E.1.

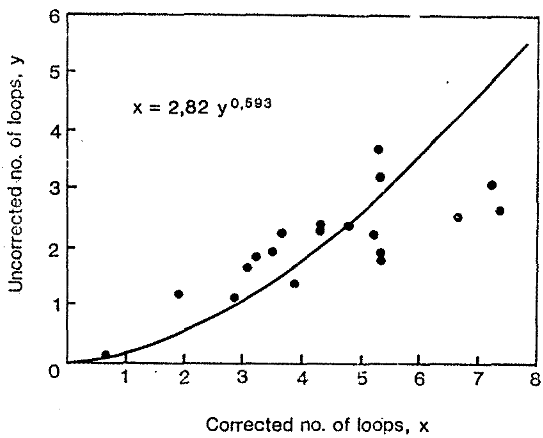


Figure E.1 Curve showing the relationship between the corrected no. of loops and the uncorrected no. of loops made by the plug of NC_X

Cycle time

The Cycle time (T), being the time for the air to complete one circuit, is dependent on the path length of the recirculation circuit and the total air flow rate (Q_T).

The relationship between T and Q_T for test No. 15 was established by comparing the similarities in the traces from two Hund Tyndallometers operating simultaneously in the intake and return airways at the test site. Hund 1 was sited at control point 1 on 83 level and Hund 2 was sited at control point 2 on 91 level (see Figures 3.1 and 3.2).

Figure E.2 shows the similarities in the dust traces. The shift in the dust profiles for a plug of dust represents the time it took this plug of dust to travel from control point 2 to control point 1 ($\Delta t = 49$ mins). To this time an estimate (8 mins) was added for the time it took the air to travel from 83 level to 91 level via the service incline and thus complete the circuit.

Thus $T = 49 + 8 = 57$ mins for $Q_T = 49{,}9\ m^3/s$

Since $T \propto \frac{1}{Q_T}$

Then $57 \propto \frac{1}{49{,}9}$

or $\frac{T}{57} = \frac{49{,}9}{Q_T}$

$$T = \frac{(49{,}9)(57)}{Q_T}$$

$$\therefore \quad T = \frac{2\ 844}{Q_T} \quad \text{mins}$$

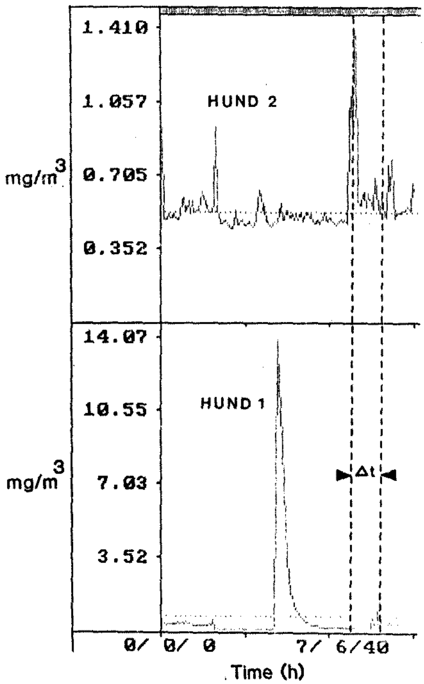


Figure E.2 Traces of Tyndallometers showing similarities in the dust concentration profiles

APPENDIX F

RESIDENCE TIME ANALYSIS

An example of the calculation of the mean residence time by Equation 2.7 for a particular test day is given in two steps as follows:

STEP 1 - Establish the area (A) under the NO_x trace for 12 hours after the blast ($\int_0^{12} C(t)dt$) using Simpson's Rule and the Trapezoidal Rule for numerical integration.

Point No.	C(t) ppm	Coefficient	Coefficient x C(t)		delta t(h)
1	1,25	1	1,25		0,167
2	5,25	4	21,00		
3	12,50	2	25,00		
4	51,75	4	207,00		
5	37,00	2	74,00		
6	38,50	4	154,00		
7	37,50	2	75,00		
8	35,00	4	140,00		
9	32,50	2	65,00		
10	28,00	4	112,00		
11	26,50	2	53,00		
12	24,50	4	98,00		
13	23,50	1	23,50		
		Simpson's Rule-integral	58,26	(a)	
13	23,50	1	23,50		0,5
14	20,00	4	80,00		
15	16,70	2	33,40		
16	14,30	4	57,20		
17	12,00	2	24,00		
18	10,50	4	42,00		
19	9,00	2	18,00		
20	7,50	4	30,00		
21	6,20	2	12,40		
22	4,50	4	18,00		
23	4,80	2	9,60		
24	4,50	4	18,00		
25	4,20	1	4,20		
		Simpson's Rule-integral	61,72	(b)	
25	4,20	1	4,20		4,0
26	2,70	1	2,70		
		Trapezoidal Rule-integral	13,80	(c)	

Total Area, A = (a) + (b) + (c)

∴ <u>A = 133,78 ppm-h</u>

STEP 2 - Compute E(t) for each point (C(t)/A), multiply this by the time (E(t) x time) and again use Simpson's Rule and the Trapezoidal Rule for numerical integration to give the mean residence time ($\int_0^{12} E(t)t\,dt$).

Point No.	E(t) ppm	time, t(h)	Coefficient	E(t) x time x Coefficient		delta t(h)
1	0,009	0,000	1	0,000		0,167
2	0,039	0,167	4	0,026		
3	0,093	0,333	2	0,062		
4	0,387	0,500	4	0,774		
5	0,277	0,667	2	0,369		
6	0,288	0,833	4	0,959		
7	0,280	1.000	2	0,561		
8	0,262	1,167	4	1,221		
9	0,243	1,333	2	1.648		
10	0,209	1,500	4	1,256		
11	0,198	1,667	2	0,660		
12	0,183	1,833	4	1,343		
13	0,176	2,000	1	0,351		
		Simpson's Rule-integral		0,457	(d)	
13	0,176	2,0	1	0,351		0,5
14	0,149	2,5	4	1,495		
15	0,125	3,0	2	0,749		
16	0,107	3,5	4	1,496		
17	0,090	4,0	2	0,718		
18	0,078	4,5	4	1,413		
19	0,067	5,0	2	0,673		
20	0,056	5,5	4	1,233		
21	0,046	6,0	2	0,556		
22	0,034	6,5	4	0,875		
23	0,036	7,0	2	0,502		
24	0,034	7,5	4	1,009		
25	0,031	8,0	1	0,251		
		Simpson's Rule-integral		1,887	(e)	
25	0,031	8,0	1	0,251		4,0
26	0,020	12,0	1	0,202		
		Trapezoidal Rule-integral		0,906	(f)	

Mean Residence Time, τ = (d) + (e) + (f)

$\therefore$ $\underline{\tau = 3,25\ h}$

LITERATURE REVIEW

A considerable number of technical papers on controlled recirculation have been written. However, the majority are concerned with small-scale recirculation systems in British collieries (Allan (1983)). Very few deal with recirculation systems in deep level gold mines. Most of the papers written address particular aspects of controlled recirculation. Allan (1983) shows that controlled recirculation can be used to help control methane layering, dust and temperature levels. The only paper which covers most aspects of controlled recirculation in a deep level gold mine is by Burton et al. (1984). This paper is also the first paper which considers recirculation during blasting and develops a model which analyses the effects of controlled recirculation on blast contaminant decay. Subsequent to this, Alexander et al. (1987) developed this model and made use of residence time analysis as described in the chapter on non-ideal flow by Levenspiel (1972), in order to analyse the effect of controlled recirculation in a deep level gold mine.

Re-entry interval

The re-entry interval is a time interval stipulated by the Inspector of Mines (Mines and Works Act and Regulations (1956)) during which time the workings are being cleared of blast contaminants and during which time no persons are permitted to enter the workings. For the purposes of this study the re-entry interval is considered to be a variable and is defined as the time from blasting to the point when all the blast contaminants have returned to their legal limits. The legal limits are stipulated by the relevant sections in Chapter 10 of the Mines and Works Act and Regulations (1956). Recommended safe limits are also given by the American Conference of Governmental Industrial Hygienists (1984).

Critical contaminant

The blast contaminants dissipate to below their legal limits at various rates. The contaminant that takes the longest to reach its legal limit is then termed the critical contaminant. Greig (1982) has shown that a mass of explosives will generate specific volumes of e gas depending on which type of explosive is used. It can further be shown that the oxides of nitrogen produced by the ignition of explosives is critical when considering the volumes of each gas produced and their relative toxicities. Alexander et al. (1987) have shown that of the various blast contaminants, namely oxides of nitrogen (NO_x), carbon monoxide and dust, the critical contaminant in all cases was NO_x.

Methods of analysis

a. Ideal flow

Burton et al. (1984) assume that after a blast the whole volume of the workings is instantaneously filled with blast contaminant and that the decay of the contaminant from the peak level to its legal limit assumes a perfect first order decay function. For a series of tests the time constants, being the time for the return air contaminant level to decay to half of its peak concentration, were measured. When plotted against the corresponding fresh air flow rates, the time constants had an inverse linear relationship. A formula was derived which shows the relationship between the concentration of contaminant in the return airway after a time for a particular fresh air flow rate, the volume of the workings and the intake air contaminant concentration. It was shown that the rate of removal of contaminant in the return airway was independent of the recirculated air flow rate. Using this work, Alexander et al. (1987) developed a mixed-volume model and also showed that the re-entry interval was independent of the recirculated air flow rate. The mixed-volume model assumes perfect mixing of the contaminant in the ventilation air, but in reality this does not happen. Another approach is to assume that after the blast the contaminant travels around the recirculation circuit as a discrete parcel or plug. A plug flow model (Unsted, 1987) is developed and tested with some success in the present study. The true situation is probably a combination of the mixed-volume and plug flow models. The present study does not attempt to develop such a combined model.

b. Non-ideal flow

Levenspiel (1972) suggests that we should not restrict ourselves to the use of the mixed-volume and plug flow models only as these can be too idealized. Levenspiel (1972) also suggests that scale-up of the reactor, which in context of this study is a recirculation circuit, could cause deviation from these idealized flow patterns, since all the major variables should be controlled. Hence the findings as reviewed by Allan (1983) of small-scale recirculation systems in British collieries is not strictly applicable to a large recirculation system such as has been investigated in this study. The long and complex recirculation circuit in deep level gold mines can lead to many opportunities for leakage and short-circuiting of the ventilating air, and difficulties can be experienced at a test site when regulating the major variables of the fresh and recirculated air flow rates to desired levels as experienced both by Burton et al. (1984) and Alexander et al. (1987). The underground mine environment is continually exposed to transient changes in the contaminant concentration; especially in the case of an impulse of contaminant due to a blast. For this reason, and due to leakage and short-circuiting of air in the recirculation circuit, residence time analysis has been used (Levenspiel (1972)). This technique also normalises the varying amounts of explosives that are consumed daily. NO_x is assumed to be a tracer gas and the profile of the return air contaminant concentration during the re-entry interval is used to calculate the mean residence time. This is the average time that a parcel of air remains in the recirculation circuit. The mean residence time calculated for a particular day is indicative of the efficiency of the ventilation system in purging itself of contaminants. The fresh air flow rate was found to be inversely proportional to the mean residence time. It is also postulated that the greater the mean residence time, the less efficient the ventilation system, in which case the re-entry interval is likely to be extended.

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