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EVALUATION OF THE CLIMATE AND AIRFLOW IN A FLOOD LEACHING STOPE

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OCTOBER 1986

MINING RESEARCH LABORATORIES
DIVISION REPORT MRL 87-68 (TR) c.2

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ABSTRACT

The underground environment research group of the Elliot Lake Mining Research Laboratory has performed a study of a flood leaching stope. The investigation sought to evaluate the efficiency of aerating the stope and re-oxygenating a muck pile to sustain the bacterial leaching activity.

The airflow was evaluated by a tracer gas technique and anemometry. The tracer gas was SF_6 and was released as a continuous injection. Airflow analyses showed a compressed air aeration system to be at least 85% efficient, with a distribution, be it uneven, throughout most of the stope's length. The system was shown to have a residence time of 33 h, and a clearance time of 100 h at an airflow of 0.026 m^3/s.

The stopes interval climate, assessed by psychrometry, was found to be independent of ambient fluctuations. Analysis of the exhausted air of the aeration system showed the bacterial oxygen consumption to be independent of airflow.

This investigation demonstrated the viability of a tracer gas technique to evaluate the integrity of a totally enclosed ventilation system in a flood stope.

Key words: Ventilation; Tracer gas; Flood leaching.

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ÉVALUATION DU CLIMAT ET DU DÉBIT D'AIR DANS UNE CHAMBRE DE LIXIVIATION PAR INONDATION

par

S.G. Hardcastle* et K.C. Butler **

RÉSUMÉ

Le groupe de recherche sur l'environnement souterrain du Laboratoire de recherche minière d'Elliot Lake a fait une étude sur une chambre de lixiviation par inondation. Cette étude avait pour but d'évaluer dans quelle mesure il était efficace d'aérer la chambre et de réoxygéner les déblais afin de maintenir la lixiviation bactérienne.

Le débit d'air a été mesuré à l'aide d'une technique au gaz traceur et d'un anémomètre. Le gaz traceur, le SF_6, a été libéré à un jet continu. Des analyses du débit d'air ont montré qu'un système d'aérage à air comprimé avait une efficacité d'au moins 85 % et que l'air était distribué, que ce soit de façon inégale, sur presque toute la longueur de la chambre. Selon les résultats, le système avait un temps de séjour de 33 h et un temps de dégagement de 100 h à un débit de 0,026 m^3/s.

Le climat par intervalle dans la chambre, évalué par psychrométrie, était indépendant des fluctuations ambiantes. Une analyse de l'air échappé du système d'aérage a montré que la consommation d'oxygène par les bactéries était indépendante du débit d'air.

La présente étude a démontré la viabilité d'un gaz traceur pour évaluer l'intégrité d'un système de ventilation fermé dans une chambre de lixiviation par inondation.

MOTS-CLÉS : ventilation, gaz traceur, lixiviation par inondation.

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INTRODUCTION

At the request of Denison Mines, the Elliot Lake Mining Research Laboratory was asked to define the airflow through a flood leaching stope. This investigation was performed during May/June 1986, and used the tracer gas/gas chromatography facility of the laboratory. This work continues the laboratories interest in residence time studies initiated at Rio Algom Mines Ltd. (1,2).

The location provided for the study consisted of two interconnected parallel stopes (No. 40142, 40143). The average dimensions of the stopes are 70 m long, 12 m wide and 3 m high. Both stopes are sealed with bulkheads and no internal access is possible (Figure 1). Ventilation is provided solely by a compressed air system; from a single air line at one end of the stopes, three 12.7 mm (1/2 in) ID pipes enter the stope. The pipes, which are perforated every 15 cm with 3 mm (1/8 in) ID holes, run below the muck pile in the stopes. After aerating the muck pile the air exits each stope via a 10 cm (4 in) ID hole.

From discussions with mining personnel, the primary objective of the study was defined as determining the efficiency of the sub-muck pile aeration system with respect to providing an even distribution of air through the muck pile, and equating the oxygen consumption of the system and assessing the minimum ventilation requirements of the system. These form two distinct elements for the study.

In association with this investigation, radiation levels were also monitored in the stope. However, the results are presented elsewhere (3).

DEFINING THE AIRFLOW THROUGH THE MUCK PILE AND STOPE

An idealized schematic of the flow paths through the stope is given in Figure 2. To equate the airflow and its distribution in the flood leaching stopes, conventional anemometry techniques alone would not have been

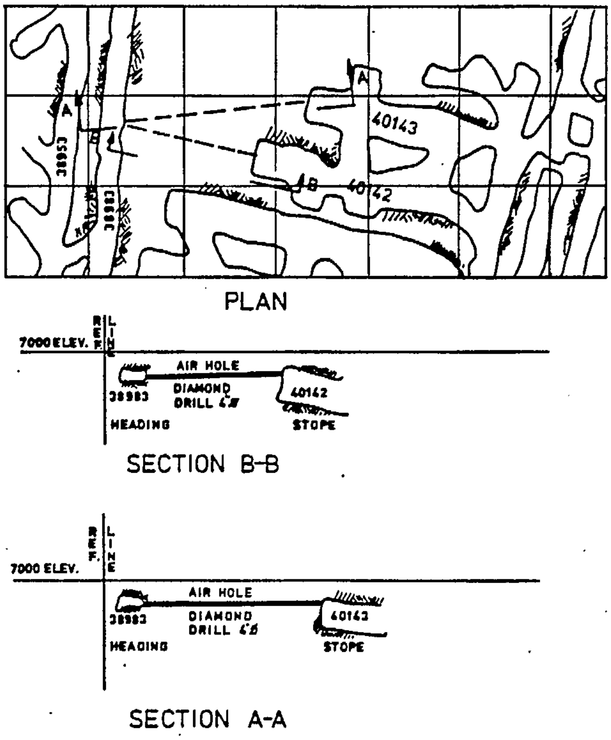
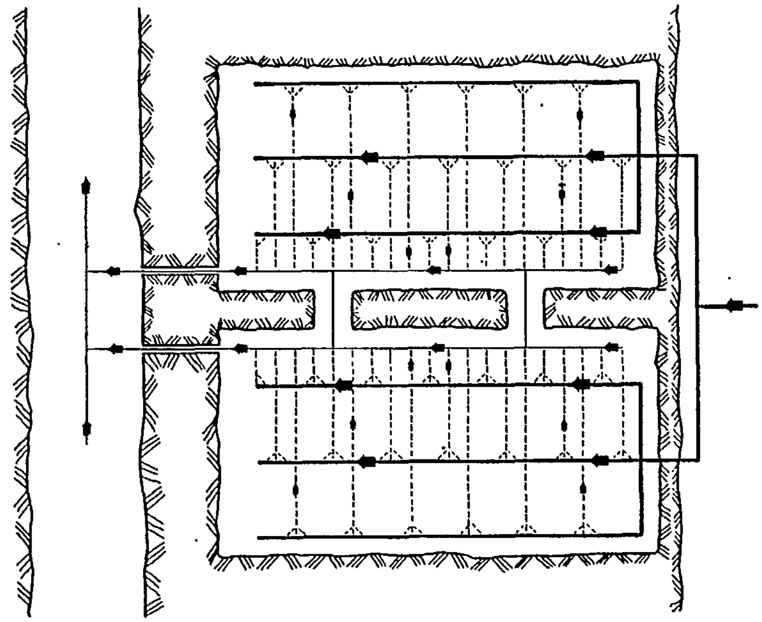


Fig. 1 - Test stopes 40142 and 40143.



—— C/A Line ---- Muck pile —— Open air path

Fig. 2 - Idealized schematic of layout and air paths of the aerations network.

sufficient. Such measurements would have only provided the quantity of air flowing through the system.

Therefore, in association with conventional anemometry a tracer gas technique was used to provide more qualitative information including the air residence time of the system, total air clearance time, and an indication of any major leakage path through the system.

The Elliot Lake Laboratory has a laboratory gas chromatograph maximized for the measurement of sulphur hexafluoride (SF_6) tracer gas. This unit is best suited for the analysis of grab-samples.

In order to determine the optimum tracer gas injection method, it is necessary to estimate the airflow and volume of the system. The mine provided the following information

i) Estimated stope volume, $\hat{U}$, equivalent to 700,000 gallons of water $\approx 3150\ m^3$;

ii) Estimated compressed air flow rate, $\hat{Q}$, $0.0625\ m^3/s \approx 130$ cfm.

To reduce compressed air line flow/pressure fluctuations, the flow was regulated down; two flows of approximately 50 and 75% of maximum were chosen for the study, of which the former would be used for the tracer gas evaluation.

At $0.0312\ m^3/s$ (0.5×0.0625) an estimate of the average air residence time, t_{50}, can be obtained from Equation 1.

$$t_{50} = \hat{U}/\hat{Q} \qquad \text{Eq 1}$$

$$= \frac{3150}{0.0312} = 1.01 \times 10^5 s$$

$$= 28.04 \text{ hours}$$

Depending on the air mixing ratio within the stope the maximum residence time could be up to two times the average, i.e., 56 hours.

Therefore, to use a tracer gas technique, grab-samples would have to be taken during this period of time, with the airflow kept constant.

As the sampling time is so long, either a pulse injection, or a continuous injection would be suitable to analyze the airflow. Previous descriptions of the two techniques (4,1) show that generally a greater number of samples need to be taken in a shorter interval for pulse injection. As no facility for sampling during blasting/shift change was available, which with travel time could create four hour gaps in sampling, a continuous injection mode was selected.

A continuous injection mode is easily provided by a gas bottle of tracer gas with a regulator and restricting orifice (a length of 0.76 mm (0.03 in ID)) capiliary tubing. The ideal delivery duty, V_i, of the tracer gas system can be found using Equation 2.

$$V_i = \hat{Q}.C_i \; . \; 10^{-9} \qquad \text{Eq 2}$$

where C_i = ideal maximum concentration of SF_6 for the gas chromatograph to analyze.

The ideal maximum concentration of the chromatograph, as determined by available calibration standards, is 100 ppb, i.e., 100×10^{-9}. For the estimated flow rate Q = 0.0312 m^3/s:

$$\begin{aligned} V_i = 0.0312 \times 100 \times 10^{-9} &= 3.12 \times 10^{-9} \ m^3/s \\ &= 0.00312 \ mL/s \\ &= 0.187 \ mL/min. \end{aligned}$$

This is a very small flow rate of SF_6 tracer gas, therefore a 1% SF_6 mixture in air was used to provide a more measurable/controllable flow from the delivery system of 18.7 mL/min.

From calibrations against a bubble tube of the delivery system (5), prior to the study (and re-checked after), the system had the following flow equation:

$$\text{Flow (mL/min)} = 3.58 \times \text{Regulator Pressure (psi)} - 6.26 \qquad \text{Eq 3}$$

Therefore, the operating regulator pressure should be:

$$(18.7 + 6.26)/3.58 = 6.97 \approx 7 \text{ psi}$$

This 7 psi is in addition to the compressed air line pressure. Both the air line pressure and regulator pressure were monitored during the injection.

With a continuous injection mode the outlet SF_6 concentration steadily increases to a steady state concentration, at which time mixing of air in the stope with the air/gas mixture enetering the stope have reached equilibrium. This process was expected to last approximately 50-60 hours. A similar time would be expected on the decay. Sixty sampling bags were available to characterize both a build-up and a decay. Allowing for analysis and flushing of sampling bags, it was estimated that a maximum of 13 samples a day could be taken. In the operating schedule of the mine this would provide seven hourly samples on the day shift and six hourly samples on the night shift.

In association with the tracer gas injection it was also necessary to measure the consistency of the air flow through the stopes. This is possible with continuous anemometry at the borehole outlet of the stopes.

The borehole of one stope was extended with piping to house two anemometers, Figure 3, a continuous reading vane anemometer and a pitot-tube/manometer arrangement. The vane anemometer would be monitored by a data logger every 100 minutes, to provide a continuous record, but as it is not ideally suited to measurements in a pipe, calibration was necessary. This was provided by the pitot tube which is better suited but not ideal, for measurements in small areas. The battery powered pitot-tube/manometer were not suitable for monitoring continuously beyond a 3 h period.

To assess the distribution of flow between the two stopes, anemometer readings were simultaneously obtained for both boreholes regularly throughout the study. The continuous anemometer with data logger was calibrated in situ (5).

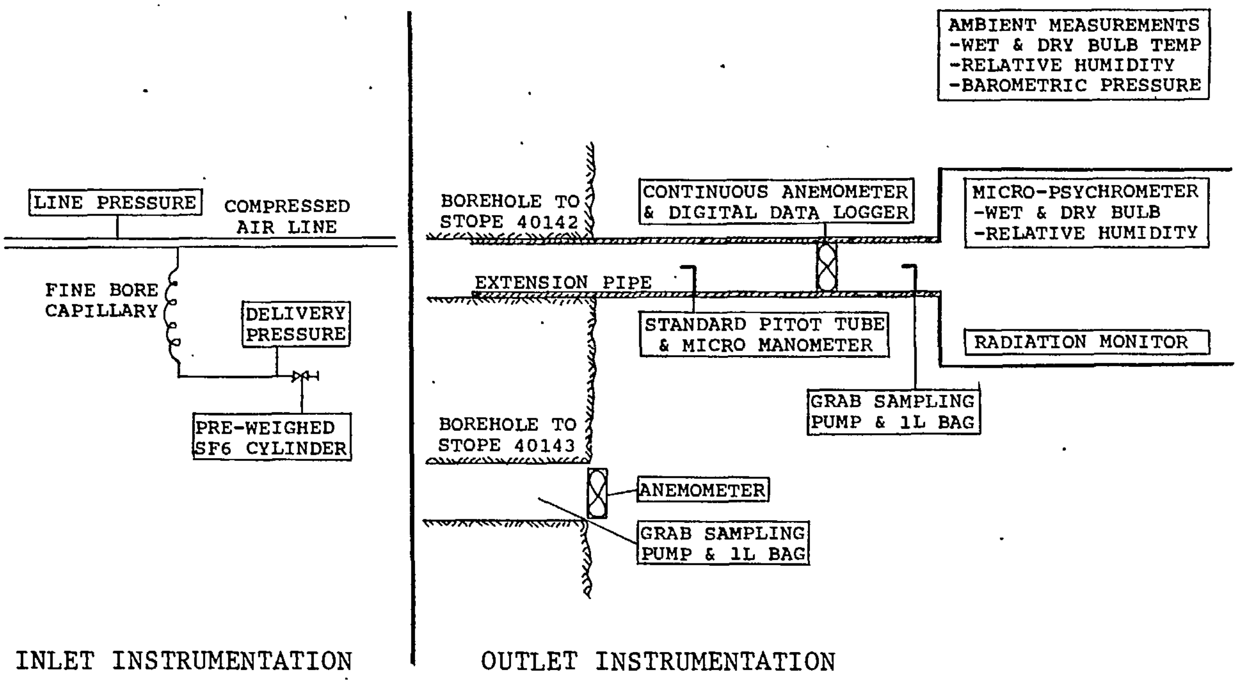


Fig. 3 - Schematic of instrumentation and measurements taken to evaluate the aeration of a flood leaching stope.

Prior to, during, and after the study, the gas chromatograph was constantly calibrated. The calibration was in two parts: an inter-scale calibration to allow rationalization of gas chromatograph response and a standards calibration using four laboratory standards of 1.01, 12.5, 73.7 and 107 ppb. Constant calibration checks are necessary to detect any contamination of the gas chromatograph. Contamination of the chromatograph column was apparent during this study as the sensitivity of the instrument changed considerably on changing the column and re-analyzing standards and samples. Re-analysis of grab-samples was also standard procedure to check all sample bags for leaks. Figure 3 shows all the airflow analysis associated measurements taken during the study.

DEFINING THE OXYGEN CONSUMPTION OF THE BACTERIAL LEACHING PROCESS

The leaching study investigated employed bacteria to help reoxidize the ore of the muck pile with oxygen from the air supply. The performance of the bacteria is dependent on psychrometric properties of the air and the amount of available oxygen (6). These could be determined using a psychrometer, a barometer and analyzing grab-samples for oxygen with a gas chromatograph. The latter analysis was performed on a daily sample by the Cape Breton Coal Research Laboratory.

Figure 3 shows all the psychometric and oxygen measurements taken during the investigation.

AIRFLOW ANALYSIS RESULTS

The airflow analysis was divided into two parts, the tracer gas evaluation, and the anemometry measurements.

ANALYSIS OF CONTINUOUS TRACER GAS INJECTION RESULTS

The tracer gas injection was to be evaluated using grab-samples. During the build-up to a steady state concentration of SF_6 in the leaching stope a total of 37 samples were scheduled over 3.0 days. A further 2.5 days (including a weekend) were allowed for stabilization of the steady state, with 7 scheduled samples before the SF_6 tracer gas was turned off. The decay was then monitored over 4 days with 52 scheduled samples. The total number of scheduled samples during the investigation was 96; the resulting number of samples that came from the study is given in Table 1. In the overall study there was a 66% success in obtaining good samples. This is a low efficiency; the worst part of the study was the build-up which was plagued with sample problems and had only 59% success, (the steady state is not a critical part of the curve).

Most of the air samples were taken in 1 litre bags, of which 67 were evaluated for SF_6 concentration in a first analysis, and 43 were re-evaluated in a second analysis. Under each analysis a minimum of three samples, up to a maximum of 12 samples, were drawn from each bag to be analyzed for SF_6 by the gas chromatograph with erroneous results being rejected. The primary results from the two analyses (5) have been composited, and are represented graphically in Figure 4.

Figure 4 shows the distinct lack of data points throughout a major part of the build-up curve, and it would therefore be extremely tenuous to draw any conclusions from this part of the curve. Much greater detail was obtained for the decay of SF_6 concentration and this will be subject to further analysis.

DETERMINATION OF THE STOPE AIRFLOW FROM TRACER GAS AND ANEMOMETRY RESULTS

The air flow through the stope can be calculated using Equation 4:

Table 1 - Breakdown of gas samples collected and analyzed during injection

	Build-Up	Steady-State	Decay	Total Study
Samples:				
Scheduled Samples	37	7	52	96
Extra Samples O_2 Analysis	2	1	4	7
Total Possible Samples	39	8	56	103
Losses:				
i) No Night shift samples	6	0	6	12
ii) Delayed Start	2	1	1	4
iii) Leaking Samples	4	2	9	15
iv) Chromatograph Malfunction	4	0	0	4
Total Losses:	16	3	16	35
Final No. of Samples (1st Anal)	23	5	40	68
Percentage	(59)	(62.5)	(71.5)	(66)
Samples Retained (2nd Anal)	12	3	28	43

Total No. of sample bags used = 60; 43 bags were recycled.

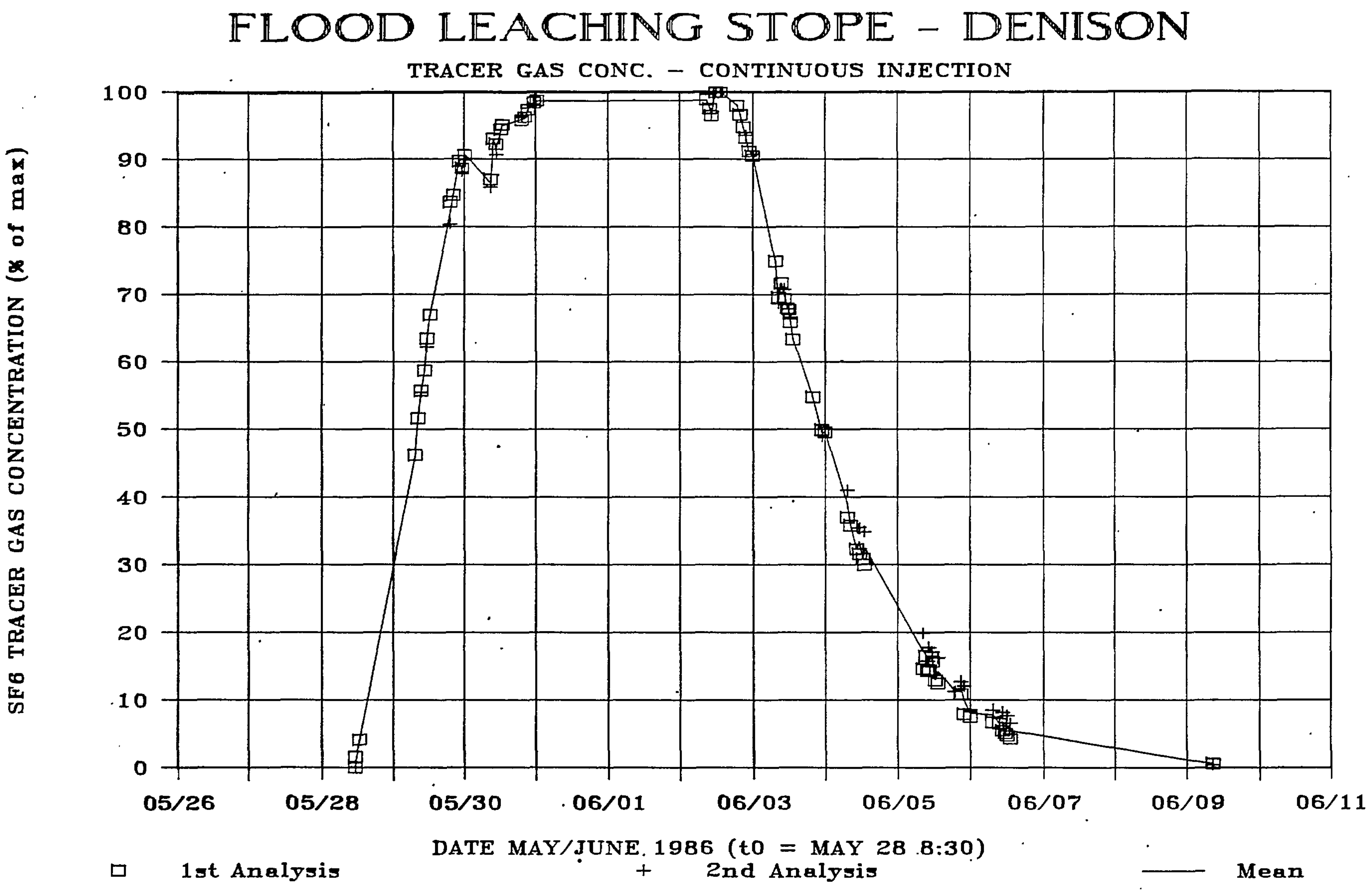


Fig. 4 - Tracer gas concentration - continuous injection.

$$Q = \frac{\dot{V}}{C} \cdot 10^9 \qquad \text{Eq 4}$$

where, Q is the stope airflow (m^3/s)

$\dot{V}$ is the flow of SF_6 (m^3/s)

C is the steady state concentration of SF_6 measured at the exhaust of the stope.

To determine the average volume flow rate of SF_6 it is necessary to know its concentration as released from the gas bottle and the flow rate from the gas bottle, and use the following relationship.

$$\dot{V} = \frac{\dot{q}}{60} \times \frac{\dot{C}}{100} \times 10^{-6} \qquad \text{Eq 5}$$

where, $\dot{q}$ is the gas bottle delivery rate of SF_6 and air (mL/min)

$\dot{C}$ is the concentration of SF_6 in air in the bottle (%).

During the injection of SF_6 gas/air mixture, which lasted 125 h, the compressed air line and regulator delivery pressure were regularly monitored (Figure 2).

A time-weighted average pressure drop across the delivery system, Figure 3, was obtained from the observed daily averaged pressures. Any drift in pressure was corrected after each observation.. Ideally a pressure drop of 7 psi (as obtained with Equation 5) was created and maintained across the delivery system. Table 2 lists the observed pressures on the delivery system.

The time-weighted average pressure at 6.9 psi was slightly below design (7 psi) and using Equation 3, gave a SF_6/air flow of 18.44 mL/min. The nominal concentration of SF6 in air as supplied by Canadian Liquid Air, Montreal was 0.95%. The volume flow rate of pure SF_6 was obtained using Equation 5.

$$\dot{V} = \frac{18.44}{60} \times \frac{0.95}{100} \times 10^{-6}$$

Table 2 - Average pressures measured at the delivery system.

	Duration (h)	Gauge Pressure (psi)	C/A Line Pressure (psi)	Delivery System Pressure Drop (psi)
May 28/29	24	17.5	10.75	6.75
May 29/30	24	19.0	11.25	7.75
May 30/June 2	72	18.5	11.75	6.75
June 2	4	18.0	12.5	5.5
	Time weighted average:			6.90

$$= 2.92 \times 10^{-9}\ m^3/s$$

The steady state (maximum) concentration of SF_6 at the stope exhaust was 110.2 and 115.3 ppb under the first and second analyses, respectively, with an average of 112.8 ppb.

Using Equation 4 to calculate the airflow:

$$Q = \frac{2.92 \times 10^{-9}}{112.8 \times 10^{-9}}$$

$$=0.026\ m^3/s\ (55cfm)$$

This is the total flow through the system. Side by side anemometry measurements at the borehole exhausts of the two stopes exhibited a 63:37% division of the compressed air flow. Therefore, the flow through the monitored borehole would be 0.016 m^3/s.

FLOW VARIATIONS DURING THE GAS INJECTION AND ITS DECAY

The borehole flow rate of 0.016 m^3/s, calculated above, was compared with anemometer values for the borehole. The continuously recording vane anemometer measurements were corrected with respect to the reference pitot tube/anemometer arrangement and converted into a quantity flow. For the duration of SF_6 being in the stope the average quantity flow from the anemometers through the borehole was 0.02 m^3/s, which shows an over-estimation of 25%. The flows have been corrected appropriately to give the true borehole quantity and also the combined flow of two stopes. These results now show the variation of flow during the injection of SF_6 and its decay. The flows are presented in graphical formats in Figures 5 and 6.

Figure 5 shows a result by result trace of the airflow for the monitored borehole and corrected for the two stopes. It is apparent that the flow fluctuates. In Figure 6 both traces have been reduced to daily averages. Here it is evident that the flow gradually increased during the injection. The major increase, after the injection and decay of SF_6 tracer gas in the stope, was deliberate.

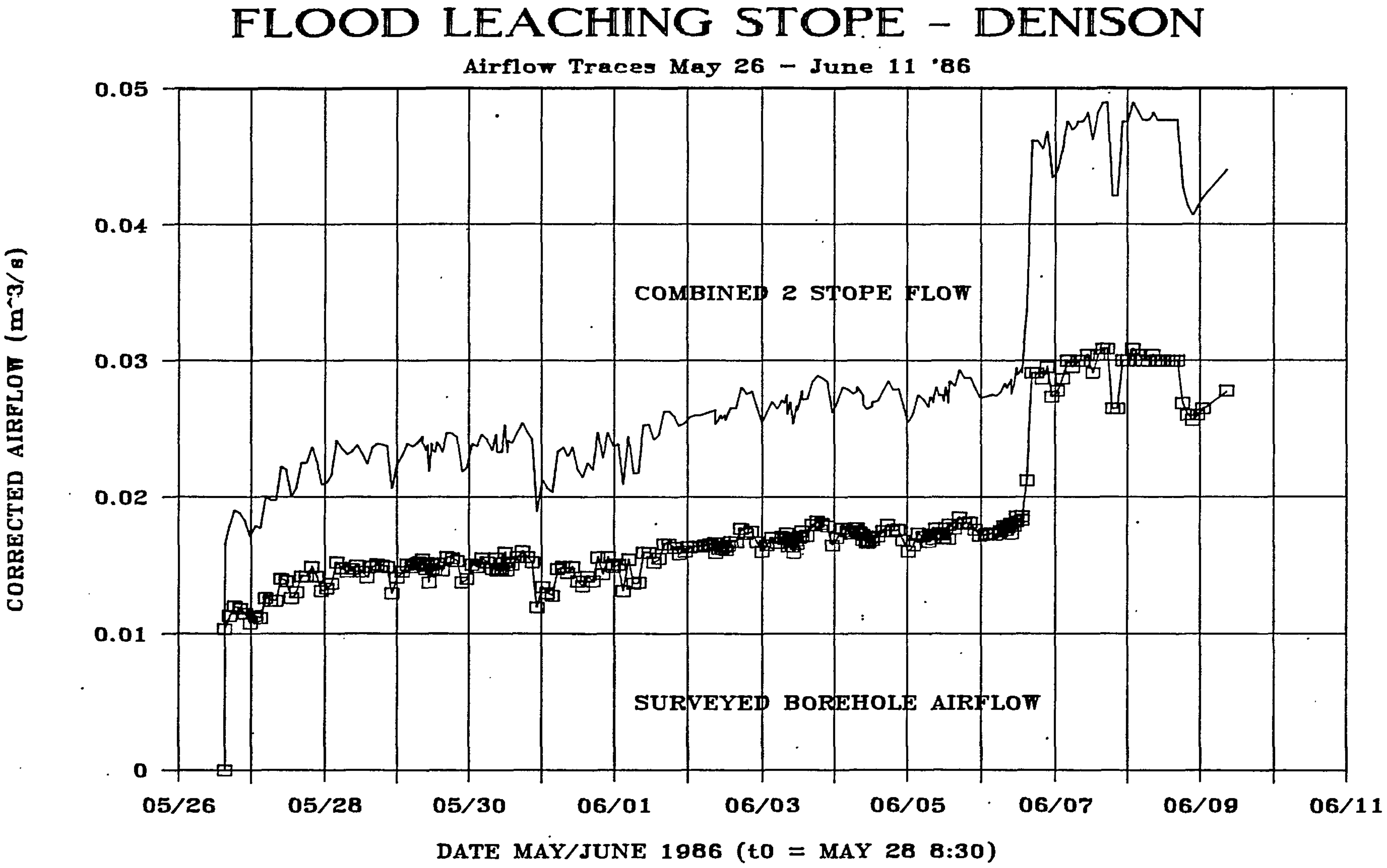


Fig. 5 - Airflow traces May 26 - June 11, 1986.

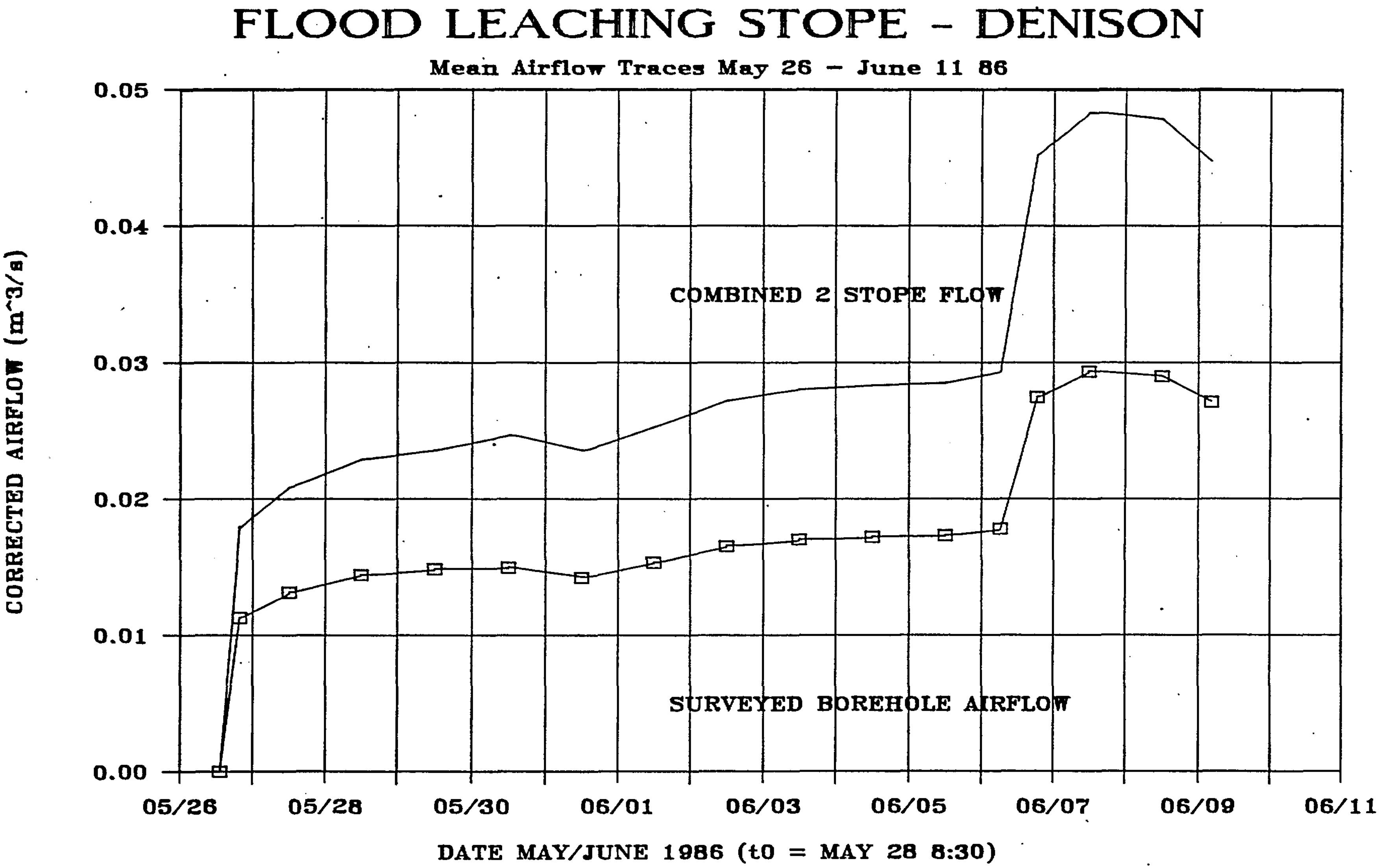


Fig. 6 - Mean airflow traces May 26 - June 11, 1986.

THE AVERAGE RESIDENCE TIME

The average residence time of the air through the compressed air lines and stope may be found from the t_{50} percentile time of Figure 4 (7). Because of the lack of data, the t_{50} value has only been taken from the decay curve, and is the time taken from turning off the gas supply until the exhaust concentration has decayed to 50% of the steady state concentration. From the curve a value of 33.5 h may be obtained.

Also from this trace it is evident that the concentration takes 95 to 100 h to totally decay away; thus a total air exchange also takes place during this time. It should be noted that the airflow was deregulated at 98 h to its normal flow.

CONVERSION OF CONTINUOUS INJECTION TRACE TO AN EQUIVALENT PULSE INJECTION CURVE

This conversion is necessary to evaluate the integrity of the flow inside the stopes. This service and some of the subsequent analysis was supplied by the Cape Breton Coal Research Laboratory (8). A concentration/ time trace, as in Figure 4 has been processed on computer (9). The profile after being digitized was then differentiated to obtain the equivalent profiles that would have been obtained from a pulse injection of tracer gas. Insufficient data are available to produce an equivalent curve for the build-up, of any confidence, and has been omitted from the results. The histogram generated for the decay is given in Figure 7, and a curve of averaged values (5 either side) is also included to show the general trend of the injection. From interpretation of this figure it is possible to infer the flow regimes in this stope.

Initially, it can be seen again that approximately 100 h are required to totally clear the stope even including a change of airflow.

Flow Times Through the Compressed Air Lines

To interpret Figure 7, it is initially necessary to determine the

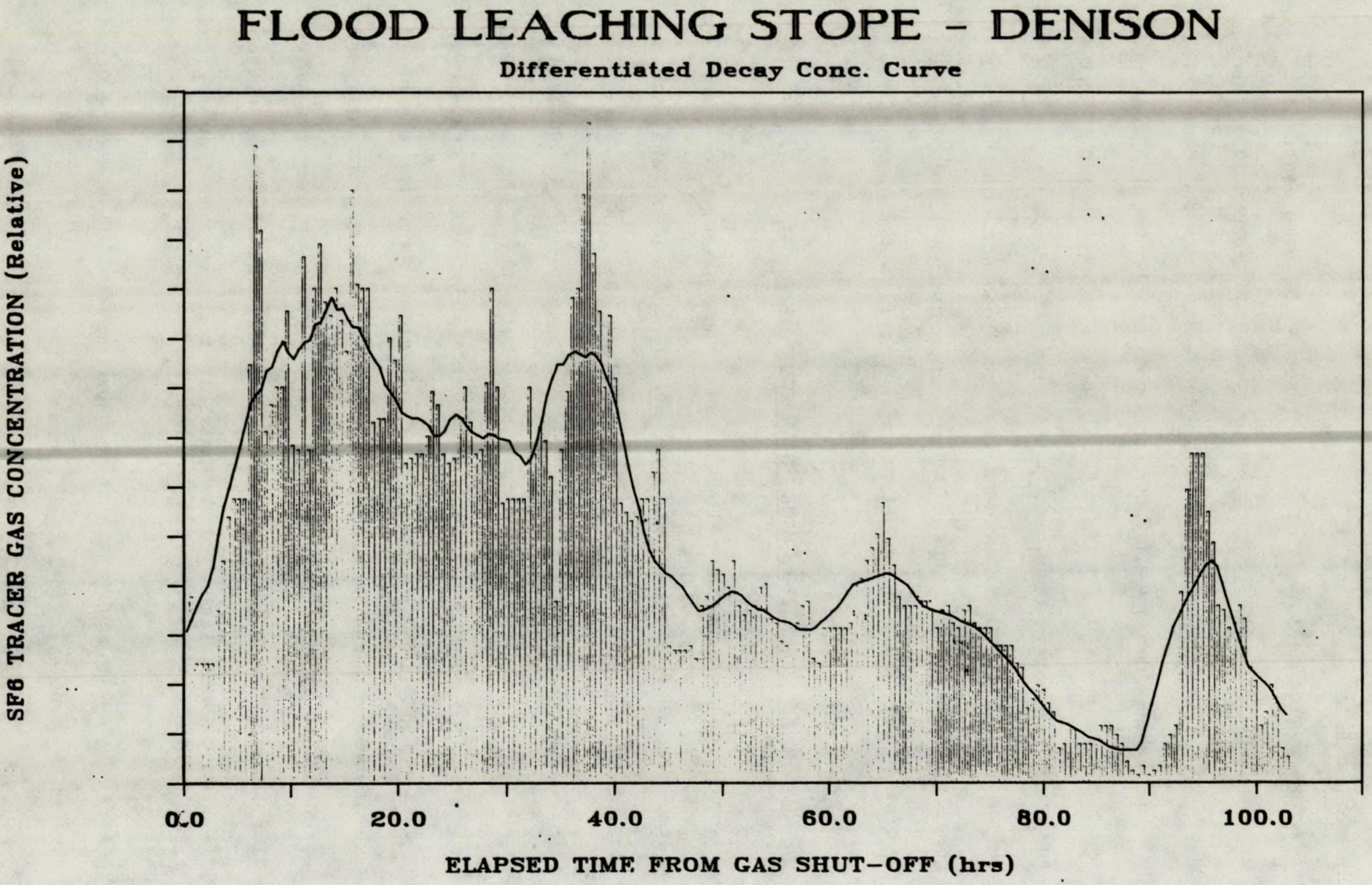


Fig. 7 - Differentiated decay concentration curve.

average travel time through the compressed air lines which run through the stopes. A volume of 0.026 m^3/s was being fed into six 1/2 in diameter pipes, three in each of the parallel stopes. If even leakage is assumed along the length of these pipes, then the average flow would be 0.013 m^3/s, and using Equation 6 it provides the average velocity in the compressed air lines.

$$\bar{V}_p = \frac{\bar{Q}}{\Sigma Ap} \qquad \text{Eq 6}$$

where, $\bar{V}_p$ is the average velocity in the pipe lines (m/s)

$\bar{Q}$ is the average volume flow fate (m^3/s)

ΣAp is the summated pipe's cross-sectional area (m^2)

$$\bar{V}_p = \frac{0.013}{6(\Pi \times 0.0127^2)/4}$$

$$= 17.0 \text{ m/s}$$

Therefore, for the pipelines in a stope 70 m long, assuming 10% extra pipe for deviations from straight, the average time for the gas to be introduced into the muck pile can be determined from Equation 7.

$$\bar{t}_i = \frac{l_p}{\bar{V}_p} \qquad \text{Eq 7}$$

where, $\bar{t}_i$ is the average introduction time (s), and

l_p is the length of the pipe line (m).

$$\bar{t}_i = \frac{70 \times 1.1}{17.0}$$

$$\bar{t}_i = 4.5 \text{ s}$$

This demonstrates that the average travel time purely within the compressed air lines is less than 5 seconds. An uneven distribution would not create a maximum travel time many magnitudes greater. Therefore, when considering the average residence time and total clearance/single air exchange time, 33.5 and ≈100 hours, respectively, the time spent in the compressed air lines is insignificant. It can thus be assumed for the purpose of this analysis that the tracer gas is introduced to all points within the stope simultaneously.

Flow Requirements in the Stope

The differentation of the decay as a histogram, Figure 7, gives the peaks that a real-time concentration profile would produce for a pulse injection. In this diagram there is no single significant peak that dominates the profile, rather there is a rapid rise in concentration followed by a slow decay with a number of smaller peaks superimposed onto it. This indicates that the air was released along virtually the whole length of the pipes in the stope. There is, however, a single distinct peak which arrives at the outlet at approximately 96 h, which is after the main body of gas. This peak demonstrates that a substantial volume of air vacated the compressed air lines close to the stope inlet after which little or no air was released for a significant distance. If this were not the case, the peak would have become merged with the main body of gas. The area under this peak compared with under the rest of the curve shows that less than 10% of the total air volume was released at this point from the pipes. The size of this peak would have been compressed by a change in airflow at 98 h.

Because of the nature of the release of gas into the stope and the overall air distribution system it is impossible to calculate for certain whether all parts of the muck pile are being aerated from the compressed air line. However, the trace does indicate that the gas was released virtually throughout its length.

The Volume of the Air Path

The volume of the air path can be obtained from the average air flow and the transit time of the last peak/first release in the stope.

The anemometry analysis shows that there is a 63:37 division ratio between the exhaust air flow of the two stopes.

If this division is also present at the entry to the stopes and assuming that the air is released roughly evenly along the length of the pipes into the stope (even after the leak at the beginning of the line), then the average flow rate in the stope would be half of that entering the stope, namely:

$$\text{Average air flow} = 0.026 \times 0.63 \times 0.5$$
$$= 0.008\ \text{m}^3/\text{s}.$$

Thus, using a 96 hour transit time for the last peak gives a stope volume of 2790 m^3. The quoted volume by the mine was 3150 m^3, a difference of 13%. This lower value is indicative of non-linear release with a larger proportion of the gas being released closer to the stope inlet.

RESISTANCE OF THE SYSTEM TO AIR FLOW

Inside the stope two distinct types of flow exist, turbulent and laminar, which are categorized by Reynold's Number.

Reynold's Number and Flow Type

Figure 6 depicts two flow rates to the stopes with averages, 0.026 and 0.046 m^3/s. For each of these the Reynold's Number in the compressed air line, the holes in the line, through the stopes and out through the boreholes have been calculated. Average values of air quantity have been used for each section. In total there are 6 compressed air lines with a maximum of 500 perforations each. Reynold's Number is given using the following relationship:

$$Re = \frac{\rho d v}{\mu} \qquad \text{Eq 8}$$

where, ρ is the density (kg/m^3)

d is the diameter of pipe (m)

v is the air velocity (m/s)

μ is the air viscosity (kg/ms)

In the compressed air line the air density is given by:

$$\rho = \frac{P_a}{R_g T} \qquad \text{Eq 9}$$

where, P_a is the absolute pressure in the line (Pa)

R_g is the gas constant = 287 (J/kgK)

T is the absolute temperature (K)

In the stope the hydraulic mean diameter is given by:

$$dn = \frac{4A}{O} \qquad \text{Eq 10}$$

where, A is the cross-sectional area (m^2)

O is the perimeter (m).

The following assumed values have been used: for normal air the density is 1.2 kg/m^3 and air viscosity is 1.8×10^{-5} kg/ms. The average absolute temperature and pressures in the compressed air lines taken from survey measurements are:

i) $T = (273 + 10) = 283$ K

ii) $P_1 = (104 + \frac{79.2}{2}) \times 10^3 = 143.6$ kPa

iii) $P_2 = (104 + \frac{206.8}{2}) \times 10^3 = 207.4$ kPa

Table 3 gives the calculated Reynold Numbers for the flow paths in the stopes. Flows through the muck pile have been omitted as its cross-sectional area is indeterminate, although normally this flow tends to be laminar, i.e., below Re = 2000. Fully turbulent flow occurs for Reynold's Numbers >3200. The perforations of the compressed air line although made with a 1/8 in (0.0032 m) punch/nail would be smaller due to the elasticity of the pipe, 1/16 in (0.0159 m) has been used.

It is doubtful whether the air is distributed throughout the length of the compressed air lines so values of Reynold's Number are also included for 1/2, and 1/4 of its length.

From Table 3, it can be seen that the compressed air line and borehole flow, on average are fully turbulent, flow through the stope is laminar and through the air line perforations tending towards fully

Table 3 - Reynold numbers in the stope.

Flow Path Section	Average Total Flow (m^3/s)	Average Section Flow (m^3s)	Air Density (kg/m^3)	Section Diameter (m)	Average Air Velocity (m/s)	Average Reynolds Number	Average Flow Type
C/A Line	0.026	$2.2x10^{-3}$	1.77	0.013	17.03	21200	Turbulent
	0.046	$3.8x10^{-3}$	2.55	0.013	30.31	54600	"
Perforations (500)	0.026	$0.9x10^{-5}$	1.77	$1.6x10^{-3}$	4.33	700	Laminar
	0.046	$1.5x10^{-5}$	2.55	$1.6x10^{-3}$	7.75	1700	"
Perforations (250)	0.026	$1.7x10^{-5}$	1.77	$1.6x10^{-3}$	8.56	1300	Laminar
	0.046	$3.1x10^{-5}$	2.55	$1.6x10^{-3}$	15.61	3500	Turbulent
Perforations (125)	0.026	$3.5x10^{-5}$	1.77	$1.6x10^{-3}$	17.63	2700	Transition
	0.046	$6.1x10^{-5}$	2.55	$1.6x10^{-3}$	30.72	6900	Turbulent
Stope	0.026	0.006	1.20	4.80	$3.6x10^{-4}$	200	Laminar
	0.046	0.011	1.20	4.80	$6.4x10^{-4}$	400	"
Borehole	0.026	0.013	1.20	0.10	1.60	10800	Turbulent
		0.023	1.20	0.10	2.84	10200	"

turbulent.

Observed Resistance of the Ventilation System

For fully turbulent flow the frictional pressure drop is directly proportional to the quantity of air squared, and for laminar flow it is directly proportional to the quantity. Equating the flows and frictional pressure drop of the two flows will give indication of the index and whether it tends towards 1 or 2.

The flow index, n, is given by Equation 11:

$$n = \log (P_1/P_2) \;/\; \log (Q_1/Q_2) \qquad \text{Eq 11}$$

where ,P_1 and P_2 are pressure drops across the system (kPa)

Q_1 and Q_2 are the corresponding flow rates (m^3/s)

The average compressed air line gauge pressures at the two flow rates were 79.2 and 206.3 kPa, including these gives:

$$n = \log \left(\frac{79.2}{206.8} \right) \Big/ \log \left(\frac{0.026}{0.046} \right)$$

$$= 1.66$$

This value shows a predominantly turbulent flow, but is reduced by the laminar flow through the muck pile, the laminar flow in the stope and some laminar flows through the perforations of, and within, the compressed air line.

Now using Equation 12, the system resistance can be determined:

$$P = RQ^n \text{ or } R = P/Q^n \qquad \text{Eq 12}$$

$$R = 79.2 \times 10^3/(0.026)^{1.66}$$

$$= 3.5 \times 10^7 \ Ns^2/m^8$$

Theoretical Resistance of the System

From theoretical relationships it is also possible to calculate the approximate system resistance. This requires the determination of individual resistances of the delivery manifold, the perforated compressed air line per elemental length, i.e., between perforations, the resistance of the perforation and the resistance of the exhaust borehole. In all these sections predominantly turbulent flow will exist and an index of 2 has been used. The resistance of the muck pile and stope have been omitted as the laminar flow through them gives a small resistance that is negligible when summated in series with the holes of the compressed air line.

Resistances may be combined with two equations depending on whether they are in series or in parallel using the following relationships:

i) For series resistances:

$$R_T = R_1 + R_2 + R_3 \ldots + R_n \qquad \text{Eq 13}$$

ii) For parallel resistances:

$$\frac{1}{\sqrt{R_T}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} + \frac{1}{\sqrt{R_3}} \cdots + \frac{1}{\sqrt{R_n}} \qquad \text{Eq 14}$$

where, R_1 - R_n are the branch resistances (Ns^2/m^8), and

R_T is the equivalent resistance of a single branch (Ns^2/m^8)..

The resistance of the compressed air delivery manifold is obtained using Equations 15, 16 and 9 (10).

$$R = \frac{RfL}{\rho} \qquad \text{Eq 15}$$

where, L is the unit length (m)

Rf is the resistance factor derived from Equation 16 (m^{-5})

ρ is the air density from Equation 9 (kg/m^3).

$$Rf = 10^{13.83}/(d \times 10^3)^{5.28} \qquad \text{Eq 16}$$

For the 1 inch delivery manifold: d = 0.0254 m, thus $Rf = 2.6 \times 10^6$ m^{-5}; at line gauge pressure 79.2 kPa, $\rho = 2.254$ kg/m^2; and at line pressure 206.8 kPa, $\rho = 3.800$; L = 6.096 m.

Therefore, the delivery manifold resistance, $R_d = 8.1 \times 10^6$ Ns^2/m^8 at the lower flow, $R_d = 4.1 \times 10^6$ Ns^2/m^8 at the higher flow. This resistance, R_d, is provided by each manifold to both stopes.

Using the same equations as above, the elemental resistance between perforations of the 6 x 1/2 inch air distribution lines may also be calculated.

For the 1/2 inch air line: $d = 0.0127$ m, thus $Rf = 101.9 \times 10^6\ m^{-5}$; at line gauge pressure 79.2/2 kPa, $\rho = 1.77\ kg/m^3$; at line pressure 206.8/2 kPa, $\rho = 2.553\ kg/m^3$; $L = 0.15$ m (6 inch spacing). Therefore, the air line resistance $R_a = 8.8 \times 10^6\ Ns^2/m^8$ at the lower flow; and $R_a = 6.1 \times 10^6\ Ns^2/m^8$ at the higher flow.

The perforations in the air line can be treated as an orifice for which the generalized flow equation (10):

$$Q = A_2C\left(\frac{2P}{\rho(1-\left(\frac{A_2}{A_1}\right)^2)}\right)^{0.5} \qquad \text{Eq 17}$$

where, A_2 is the area of the orifice (m^2)

C is the discharge coefficient

A_1 is the area of the pipe (m^2).

Rearranging gives:

$$P = \left(\frac{Q}{A_2C}\right)^2 \frac{\rho(1 - \left(\frac{A_2}{A_1}\right)^2)}{2}$$

Substituting this in Equation 12 with an index of 2 gives:

$$R = \frac{\rho(1 - \left(\frac{A_2}{A_1}\right)^2)}{2(A_2C)^2} \qquad \text{Eq 18}$$

The area of the pipe has been calculated using Equation 10 for the plane at right angles to flow through the orifice/perforation.

From standard tables (11) the coefficient of discharge was given as 0.6. The term $\left(1 - (A_2/A_1)^2\right)$ tends to unity for the diameter 0.0032 m hole and hydraulic diameter 0.023 m pipe. The cross-sectional area of the hole was 0.0000079 m^2. The air density was 1.77 and 2.55 kg/m^3 dependent on the flow.

Therefore, the orifice resistance was:

$$R_o = \frac{1.767 \times 1}{2(7.92 \times 10^{-6} \times 0.6)^2} = 3.91 \times 10^{10} \text{ Ns/m}^8 \text{ at low flow}$$

and, $R_o = 5.65 \times 10^{10}$ Ns^2/m^8 at high flow.

For the entire length of 1/2 inch line there are approximately 500 perforations and elemental lengths of pipe. These have been reduced to an equivalent resistance in a computer program using Equations 13 and 14.

For the low flow the total time resistance, R_L, reduces to 8.7×10^7 Ns^2/m^8. For the high flow the resistance R_L reduces to 7.75×10^7 Ns^2/m^8. Again using Equation 14 the resistance for the three parallel lines can be derived:

$$\frac{1}{\sqrt{R_{3L}}} = \frac{3}{\sqrt{8.4 \times 10^7}}$$

$R_{3L} = 9.7 \times 10^6$ Ns^2/m^8 at low flow

$R_{3L} = 8.6 \times 10^6$ Ns^2/m^8 at high flow.

The above two values when summed with their respective resistance for the manifold, R_d, provide the total resistance of the stope, R_s, excepting the boreholes.

$R_s = (9.7 + 8.1) \times 10^6 = 17.8 \times 10^7$ Ns^2/m^8 at low flow

$R_s = (8.6 + 4.1) \times 10^6 = 12.7 \times 10^7$ Ns^2/m^8 at high flow.

Reducing these for the two stopes in series provides the resistance:

$R_{2S} = 4.45 \times 10^7$ Ns^2/m^8 at low flow

$R_{2S} = 3.2 \times 10^7$ Ns^2/m^8 at high flow.

The final resistance is provided by the boreholes, and this resistance is given by the following relationship:

$$R = \frac{kOL}{\rho A^3} \qquad \text{Eq 19}$$

where, k is the Atkinson friction factor (Ns^2/m^4).

For rough unlined airways $k = 0.01$ Ns^2/m^4, thus for a 40 ft x 4 in diameter borehole: the perimeter, $O = 0.319$ m, the area, $A = 5.3 \times 10^{-7}$ m^2 with the length, $L = 12.19$ m, and at standard density $\rho = 1.2$ kg/m^3:

$$R_B = 6.1 \times 10^4 \ Ns^2/m^8$$

Combining the two boreholes in parallel reduces the resistance to:

$$R_{2B} = 1.6 \times 10^4 \ Ns^2/m^8$$

This should be added to the stope resistance to provide the total resistance but is virtually negligible. Thus, the theoretical resistance of the system is 3.2 to 4.4 x 10^7 Ns^2/m^8. These values compare well with the observed resistance 3.5 x 10^7 Ns^2/m^8.

THE LEACHING ENVIRONMENT

Describing the environment within the stope forms the second part of this study, the preceding airflow analysis being the first.

PSYCHROMETRIC EVALUATION OF THE LEACHING ENVIRONMENT

Figure 3 shows the psychrometric measurements taken during the study. These were only observed during the day shift at each sample time.

Measurements taken included barometric pressure at the sample station, wet and dry bulb air temperature, and relative humidity of the ambient air and that exhausted from the stope. The ambient barometric pressure was also logged on surface.

From the observed values the moisture content, density and relative humidity were calculated using standard psychrometric equations (12). The calculated values of humidity were used in preference to observed values as the unit did not compensate for pressure, which, however, proved to be negligible.

The calculated conditions inside the stope used the airway barometric pressure and were not corrected for the frictional loss of 15-50 Pa in the borehole depending on flow rate.

The observed and calculated psychrometric results from the duration of the study are graphically presented in Figures 8 to 13.

Figures 8 and 9 show the wet and dry bulb temperatures of the stope and ambient air. The ambient traces are extremely variable and probably reflect the surface environment, whereas the traces of the stope show little outside influence and stay constant within 1°C. The only exception is at the start of the monitoring period where the stope had been closed, therefore, with no air flow, the dry bulb would tend towards virgin strata temperature. The initial dry bulb temperature was 15.8°C (60.4°F).

The pressure traces, Figure 10, again show that the barometric pressure at the measuring station reflects the ambient surface trace. Variations inside the stope away from that at the station would have been minimal.

The relative humidity, moisture content and air density traces, Figures 11 to 13, similarly show that the condition of the ambient air can change excessively, again probably reflecting the surface atmosphere. However, inside the stope minimal fluctuations are observed except for air density. In this, using the air pressure inside the stope could be more critical.

Generally, all the psychrometric traces show that the conditions inside the stope are independent of the outside atmosphere. Therefore, they may be expected to remain relatively constant with the only influences being virgin strata temperature, the airflow rate through the system and the presence of adequate water for evaporation.

For the conditions during the study the average psychrometric conditions were as follows for a flow of 0.02584 m^3/s.

Dry Bulb Temperature	13.6°C (56.5°F)
Wet Bulb Temperature	13.1°C (55.6°F)
Relative Humidity	95.3%
Air Density	1.26 kg/m^3
Moisture Content	0.009 kg H_2O/kg Air

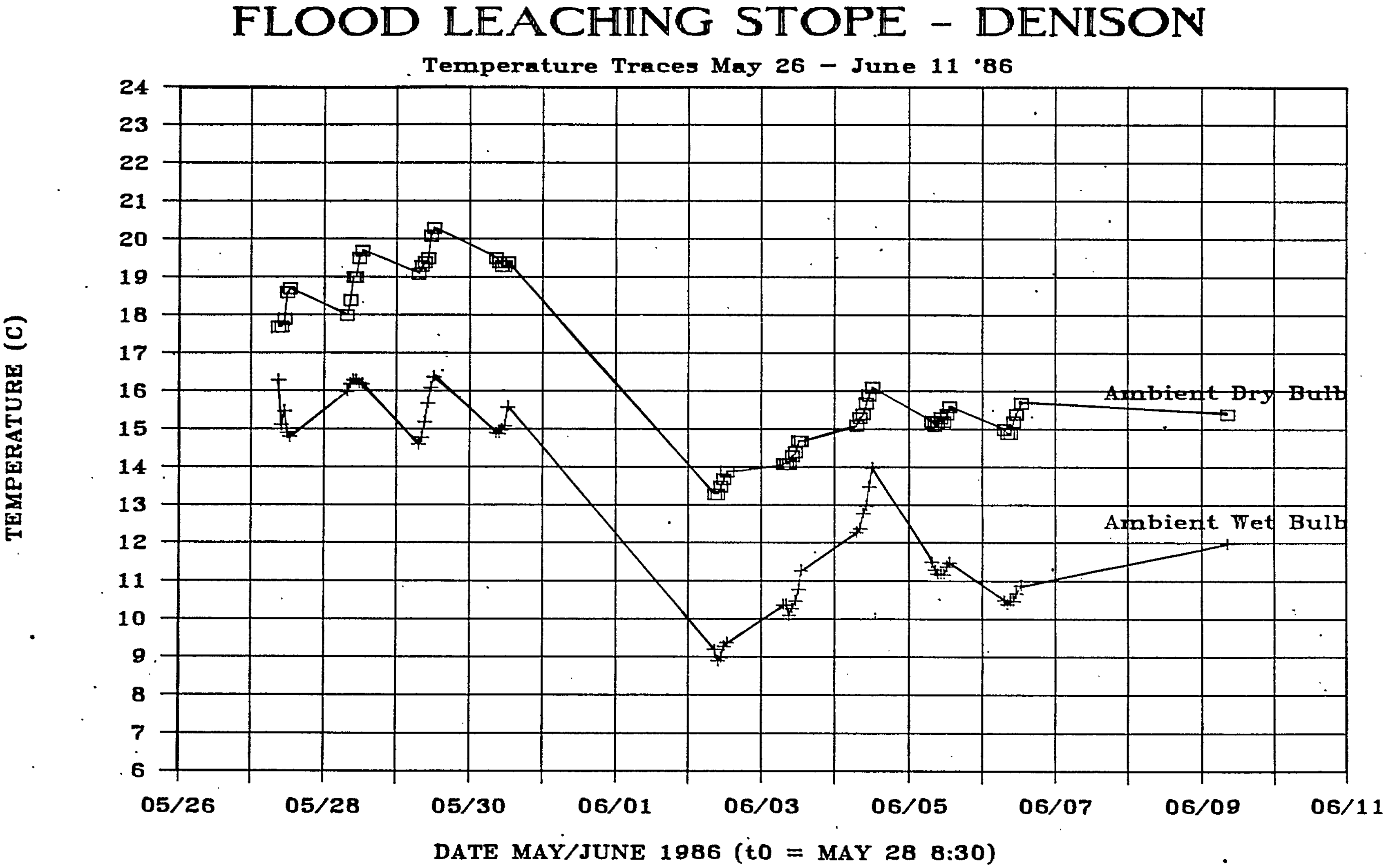


Fig. 8 - Temperature traces May 26 - June 11, 1986.

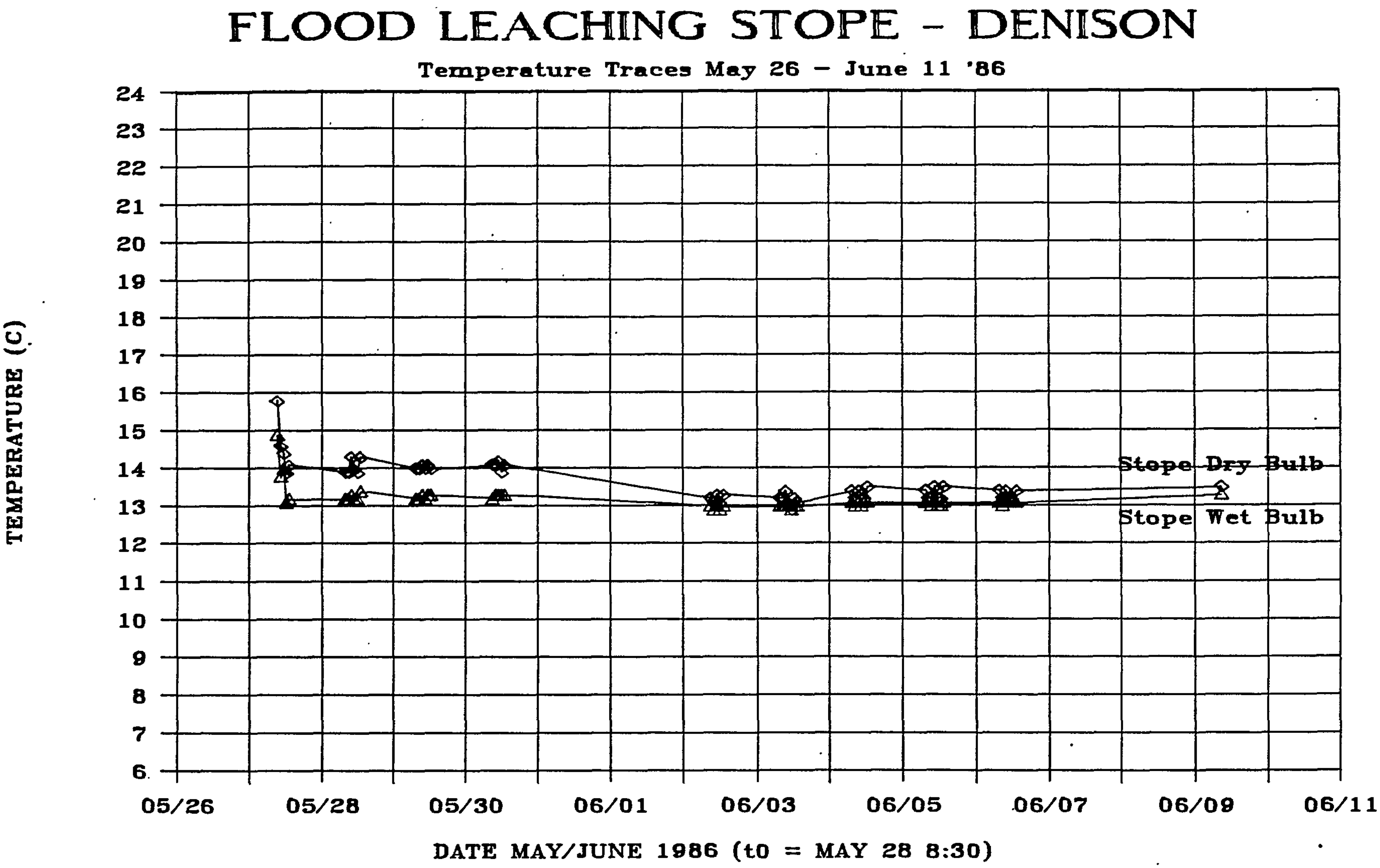


Fig. 9 - Temperature traces May 26 - June 11, 1986.

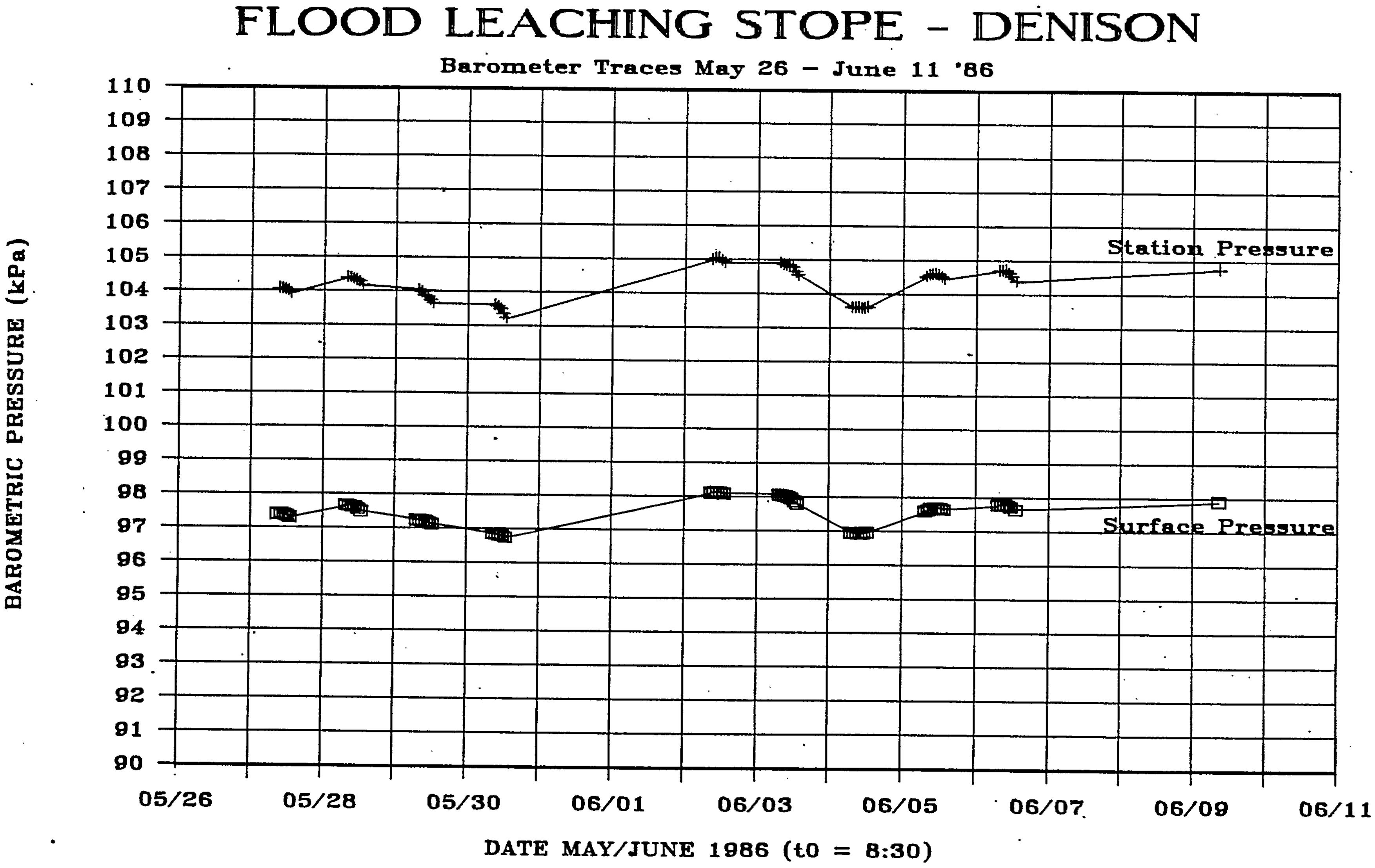


Fig. 10 - Barometer traces May 26 - June 11, 1986.

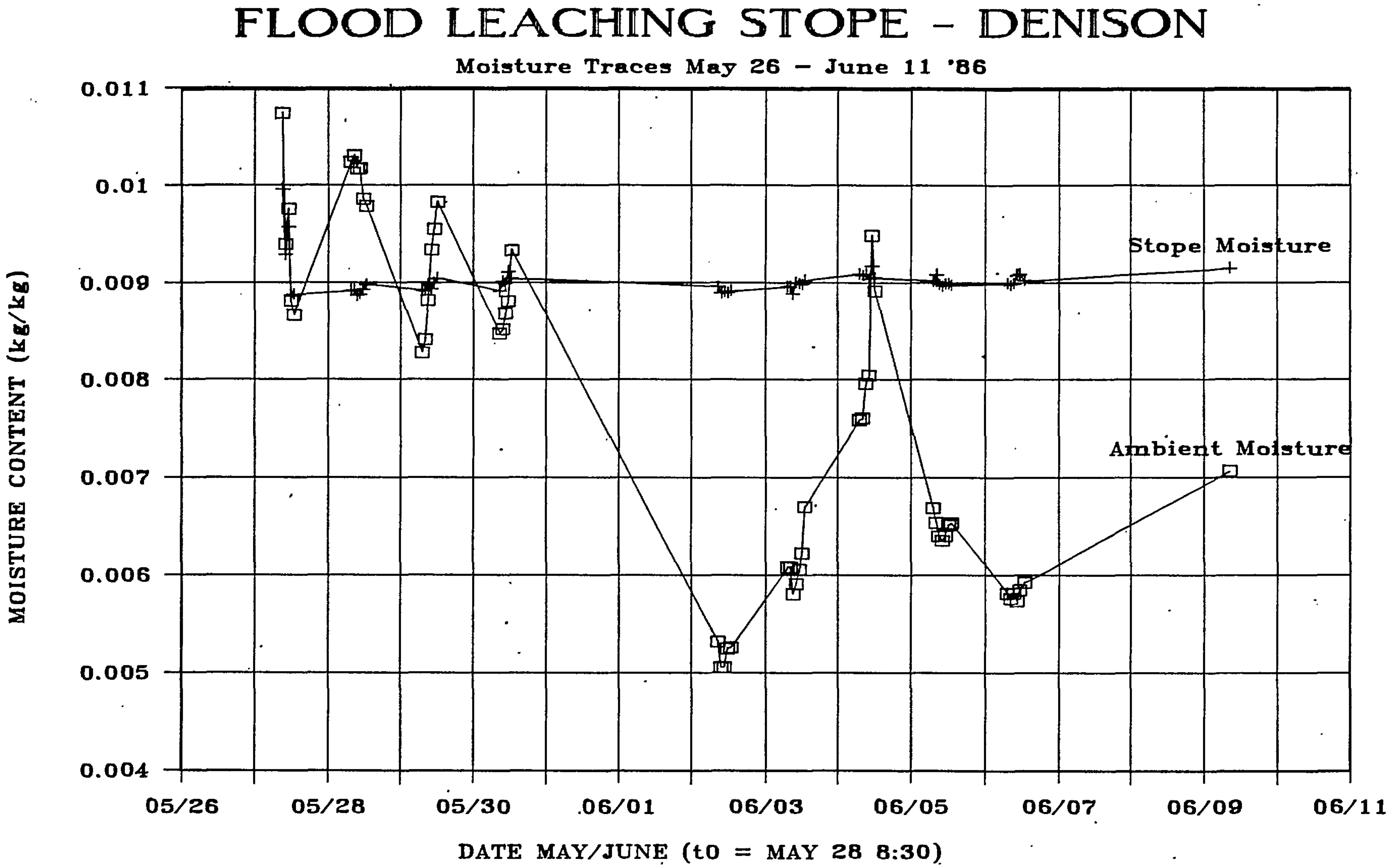


Fig. 11 - Moisture traces May 26 - June 11, 1986.

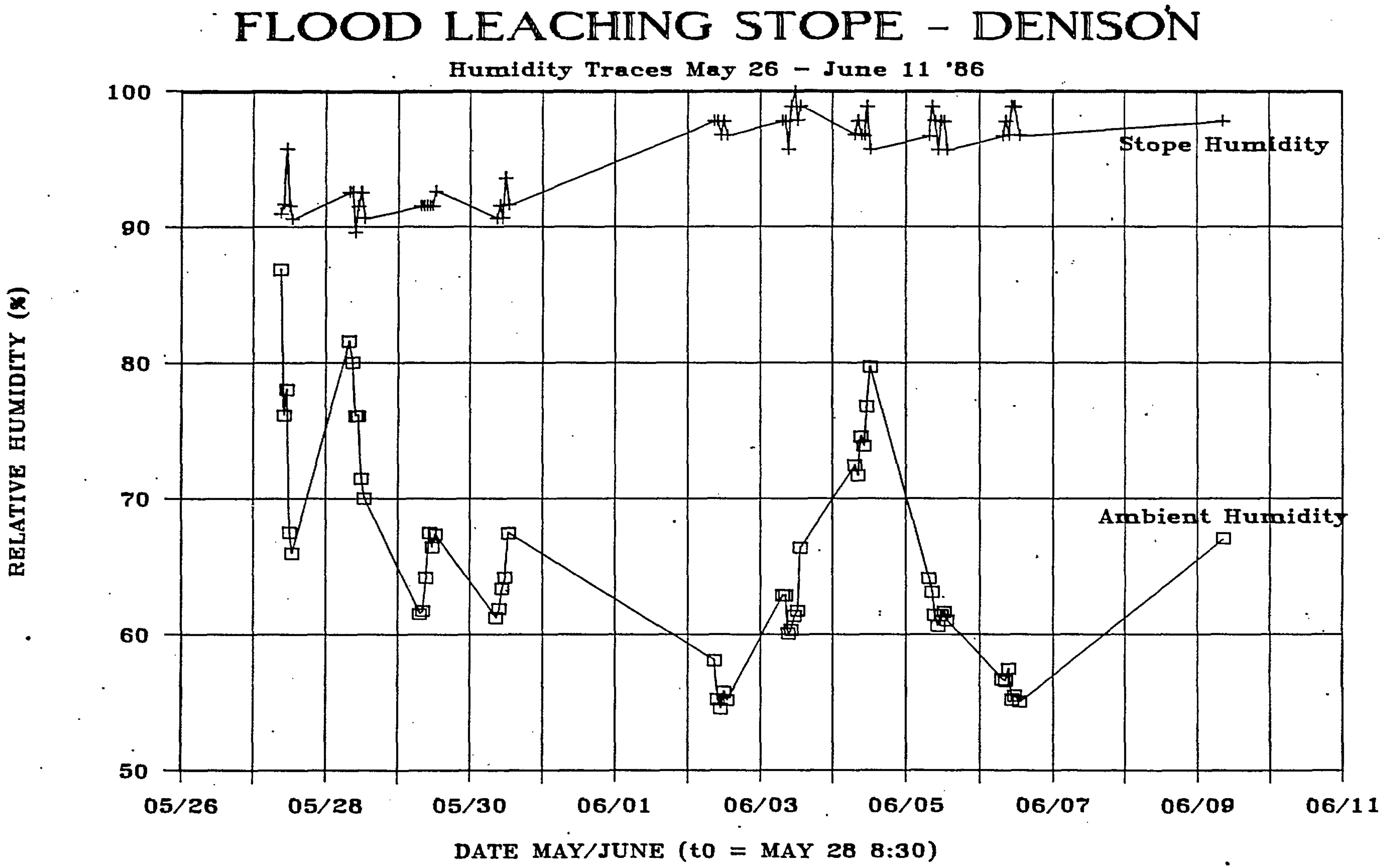


Fig. 12 - Humidity traces May 26 - June 11, 1986.

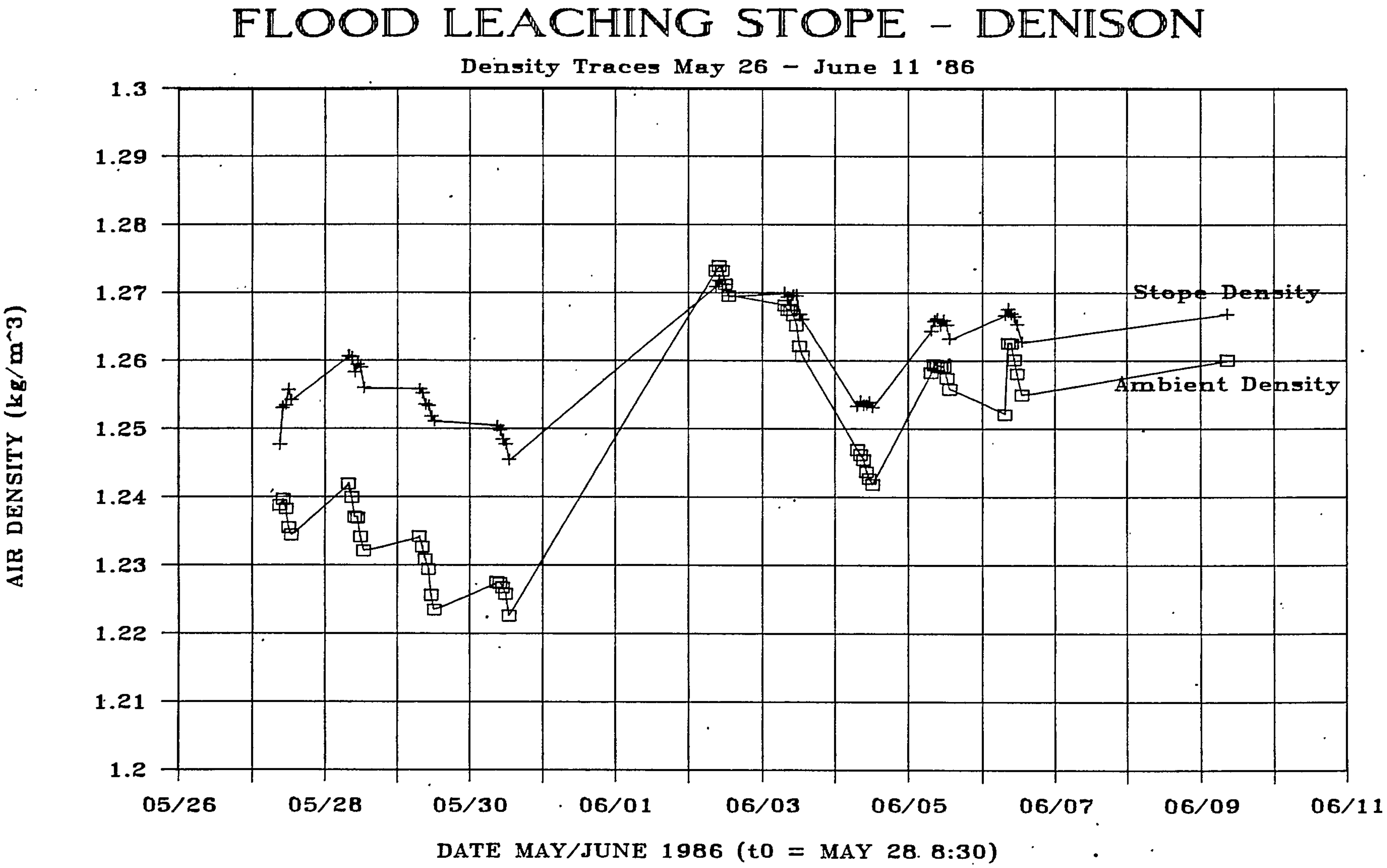


Fig. 13 - Density traces May 26 - June 11, 1986.

Air Pressure 104.3 kPa

GASEOUS MAKE-UP OF THE LEACHING ENVIRONMENT

Selected grab-samples collected in gas bags were available and subjected for standard gas analysis subsequent to being evaluated for SF_6 content. Cape Breton Coal Research Laboratory performed a dry air analysis with a gas chromatograph and provided oxygen and nitrogen concentrations in the samples.

The gas chromatograph performed a dry air analysis, that is air samples were drawn through a drying column, as water vapour will contaminate the gas chromatograph and affect the analysis.

The true wet air values can be obtained using the vapour pressure of the samples from standard tables for vapour pressure (13), and Equations 20 and 21.

The water content is given by:

$$\text{Water Content (\%)} = \frac{P_v}{P_a} \times 100 \qquad \text{Eq 20}$$

where, P_v is the vapour pressure (Pa).

The correction back to wet air composition is given by:

$$\text{Wet Analysis (\%)} = \text{Dry Analysis (\%)} / \left(1 + \frac{(\text{Water Content (\%)})}{100}\right) \qquad \text{Eq 21}$$

These corrected oxygen and nitrogen results are presented graphically in Figure 14. From the figure it is evident that both the oxygen and nitrogen are relatively constant for the air flow of 0.026 m^3/s, but change when the flow is increased to 0.046 m^3/s; i.e., beyond 12:00, June 6.

The average dry concentration of nitrogen and oxygen at the two flows are:

i) at 0.026 m^3/s, N = 81.2% ; O_2 = 17.9%

ii) at 0.046 m^3/s N = 79.9% ; O_2 = 19.2%.

In order to compare these values with a standard atmosphere where the

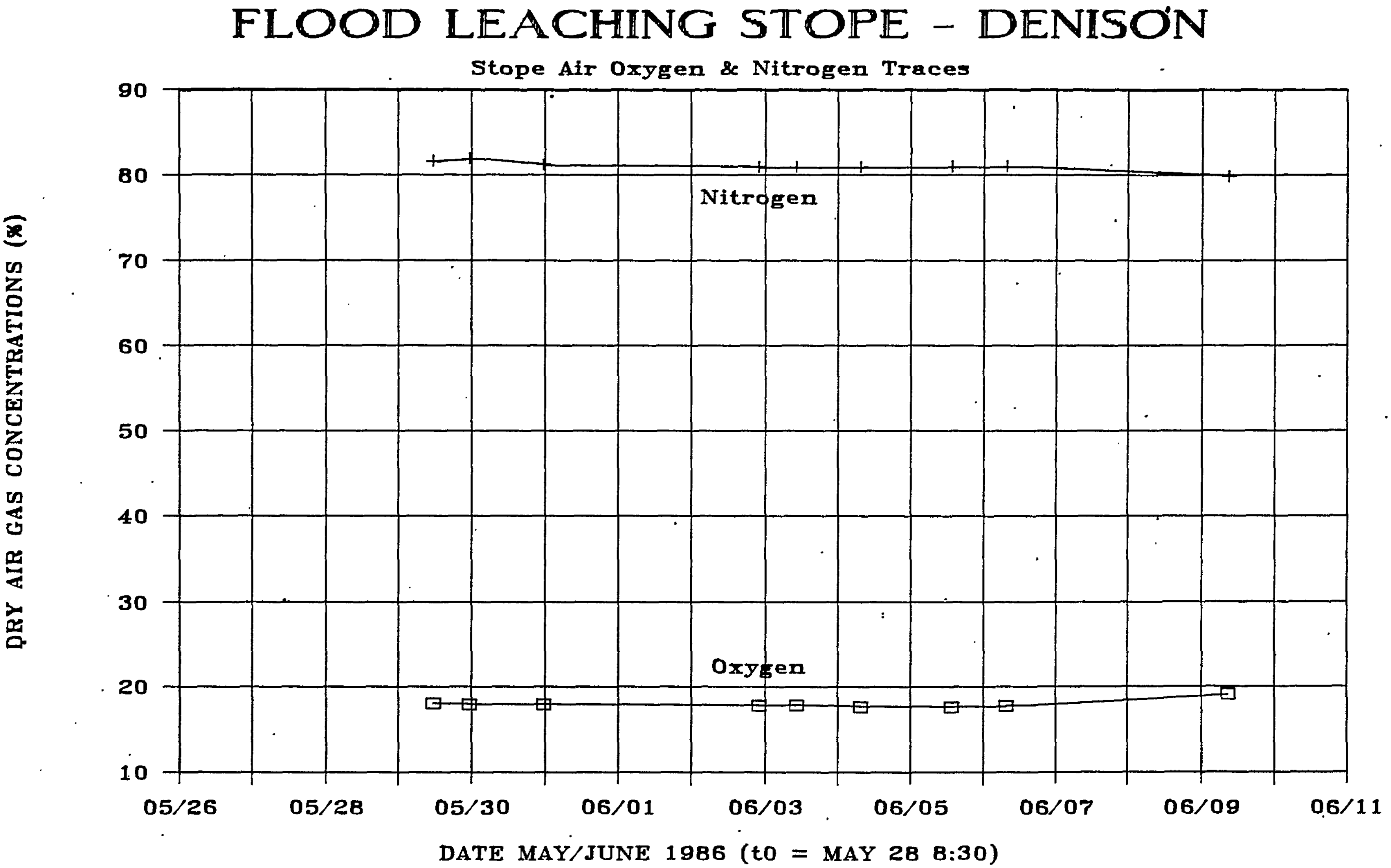


Fig. 14 - Stope air oxygen and nitrogen traces.

dry composition is 78.1% nitrogen and 21.0% oxygen, both have to be corrected for relative changes in proportion purely due to the removal of oxygen. The physical amount of nitrogen in the system has not changed, thus if χ is the percentage change in volume:

$$\frac{(100 - \chi)}{100} \times 81.2 = 78.1$$

Therefore, $\chi = 3.85\%$.

Similarly, for oxygen:

$$\frac{(100 - 3.85)}{100} \times 17.9 = \text{original oxygen concentration}$$

$$= 17.2\%.$$

For the second flow rate, $\chi = 2.33\%$, and the original oxygen concentration prior to volume correction was 18.8%. These corrected concentrations show that 3.8 and 2.2% oxygen were depleted from the air at the low and high air flows, respectively. For both flows this equates to a depletion rate of 0.0001 m^3/s oxygen.

DISCUSSION OF LEACHING STUDY RESULTS

The tracer gas technique used was a continuous injection. This produced a steady build-up of SF_6 within the stope to steady state concentration and was then allowed to decay.

Differentiation of the SF_6 concentration versus time curve produced an equivalent pulse injection curve. This latter curve showed that the majority of the air used to aerate the muck pile was passing through the muck pile and stope prior to being exhausted. Excepting one independent flow path near the beginning of the stope, it was evident that air was being released throughout the stope length from the compressed air lines. Greater detail of flow paths in the stope would have been obtained if:

i) more samples and/or a pulse injection mode was used;

ii) both exhausts were monitored continuously; and

iii) if the air exchange between the two stopes could have been evaluated.

The air flow obtained by the tracer gas technique was 0.026 m^3/s for both stopes combined. This was 26% higher than that given by conventional anemometry.

The tracer gas data for the above flow rate also exhibited that the average residence time of the whole system was 33.5 hours, and the total clearance time was approximately 100 hours. The volume of the air path was also equated at 2790 m^3 as compared with 3150 m^3 from the survey plans. This lower value indicates a non-linear release weighted towards the inlet which would be expected as the resistance of the system increases and the pressure differential drops towards the exhaust.

In the stopes and ventilation system both laminar and turbulent flow can exist. This is supported by the index of the general airflow equation $P = RQ^n$ being 1.7; it is unity for laminar flow and 2 for turbulent flow.

The resistance of the whole system from observed results was 3.5×10^7 Ns^2/m^8. This compares favourably with theoretically derived values of $3.2 - 4.4 \times 10^7$ Ns^2/m^8. Virtually all this resistance is provided by the compressed air lines and their perforations

A lower system resistance would be obtained with larger diameter distribution lines and possibly increasing the size of the holes in the line towards the stope outlet. Alternatively, the system could be fed from both ends; this method has now been adopted in other stopes. Any of these suggestions would also improve the air distribution throughout the stope.

The climate within and outside the stope was extensively monitored. The results demonstrate that the climate inside the stope was independent of the external atmosphere and probably purely a function of strata temperature, air flow and an excess of water in the stope.

Gas samples taken from the stope also provided the oxygen concentrations of the exhaust air and the relative oxygen consumption of the system. For an air flow of 0.026 m^3/s there remained 17.9% oxygen and this equated to a consumption rate of 0.001 m^3/s oxygen. At a higher air flow the concentration was 19.2% oxygen, but the consumption rate had remained the same. This indicates that the oxygen consumption of the bacteria was independent of air flow for the range investigated. The air flow would have to be approximately 0.005 m^3/s for all available oxygen to be consumed.

The oxygen consumption rate of the bacteria would change if their number changed, or if the climate and specifically the temperature within the stope was changed. The temperature, however, has been shown to be relatively constant.

The average climate in the stope during this investigation, as measured at the exhaust was:

Dry Bulb Temperature	13.6°C
Wet Bulb Temperature	13.1°C
Relative Humidity	95.3%
Air Density	1.26 kg/m^3
Air Pressure	104.3 kPa.

Further work is necessary if it is desired to quantify the air distribution within the stope. This would comprise repeating the study using one or more pulse injections and extensive simulation tests on a computer.

CONCLUSIONS

A study was designed to investigate the air flow and monitor the atmospheric conditions within the totally enclosed environment of a flood leaching stope. Air was introduced to the stope via a perforated manifold under the leach muck pile.

A tracer gas technique was successfully used to accurately determine the overall air flow in the stope. The technique used a continuous flow of SF_6 to produce a build-up to a steady state concentration and then decay. The steady state concentration gave a combined airflow of 0.026 m^3/s.

Differentiation of the concentration/time curve was used to provide an equivalent pulse injection curve. This indicated that the majority of the air, 85-90% was passing through the muck pile.

For the above flow the average residence time was 33.5 h, and the total clearance time approximately 100 h. The indicated volume of the air path was 2790 m^3, this is lower than that from survey plans and indicates a non-linear release weighted towards the inlet of the manifold.

The observed resistance of the system to airflow was 3.5×10^7 Ns^2/m^3, while theoretical values were $3.2 - 4.4 \times 10^7$ Ns^2/m^8. Virtually all this resistance is provided by the sub-muck pile air distribution system.

The climate within and outside the stope were extensively monitored. The climate inside the stope proved to be independent of the external atmosphere and purely a function of strata temperature, air flow and water content of the stope.

Gaseous analysis of the exhaust air from the stope showed an oxygen consumption rate of 0.001 m^3/s, but this value is individual to the stope as it is a function of bacteria number and temperature.

The investigation has been successful in evaluating the stope climate and airflow, however, further work is necessary to accurately quantify the air distribution of the stope.

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