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Fluctuations in barometric pressure as a contributory factor to gas explosions in South African mines

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Synopsis

The main purpose of the paper is to determine the contribution of fluctuations in barometric pressure to flammable-gas explosions in South African mines. For this purpose, the barometric-pressure patterns preceding each of the 59 major explosions in South African gold and coal mines over the past 20 years were analysed.

It is concluded that diurnal fluctuations in pressure do not have a major influence on the accumulation of gas in the underground workings, but that pressure drops associated with cyclonic weather systems moving across the country over a number of days are the major factor contributing to gas explosions in mines.

To illustrate some of the points made in the paper, the Hlobane Colliery explosion of September 1983 is used as a case study.

In the final section, several general conclusions are drawn and recommendations put forward as to how mines should recognize and react to meteorological phenomena that may lead to an increased probability of gas explosions in underground workings.

Samevatting

Die hoofdoel van hierdie referaat is om die bydrae van barometriese drukveranderinge tot gasontploffings in Suid-Afrikaanse myne vas te stel. Vir hierdie doel word barometriese drukpatrone wat elk van die 59 groot ontploffings in Suid-Afrikaanse goud- en steenkoolmyne die afgelope 20 jaar vooraf gegaan het, ontleed.

Daar word tot die gevolgtrekking gekom dat daaglikse skommelinge in druk nie 'n groot invloed het op die opbou van gas in ondergrondse werkplekke nie, maar dat drukvalle as gevolg van sikloniese weerstelsels wat oor die land beweeg oor 'n tydperk van 'n paar dae die grootste faktor is wat 'n bydrae lewer tot gasontploffings in myne.

Om sommige van die punte in die referaat te illustreer word die gasontploffing in die Hlobane Steenkoolmyn in September 1983 gebruik as gevallestudie.

In die laaste afdeling word sekere gevolgtrekkings gemaak en word aanbevelings aan die hand gedoen na aanleiding waarvan myne meteorologiese verskynsels wat die waarskynlikheid van ondergrondse gasontploffings verhoog, kan herken en daarop kan reageer.

INTRODUCTION

Gas explosions in mines are not new. In South Africa, gas explosions can be traced back to the turn of the century[1], and have occurred ever since with uncomfortable regularity.

Similarly, the idea that changes in barometric pressure have played a role in many major explosions world-wide is far from new. More than a century ago, two British engineers, H. Robert Scott and William Galloway, asserted that 'in the course of the 3 years 1868 to 1870, 525 firedamp explosions occurred in English coal mines: 49% of these after rapid and considerable drops in pressure, 22% can be associated with abnormally hot periods of time'. According to these engineers, almost three out of every four explosions in the Yorkshire mines were thus related to meteorological anomalies[2].

In 1964, Boyer[3] took a long-term and broad look at coal-mine disasters, and came to the conclusion that the 'peak for major disasters is ascribed to the effect of barometric minima on the methane content of mine air'.

Against this background, it is surprising to find a dearth of well-researched literature on a phenomenon that seems to have been clearly recognized for so long. The South African mining industry is no exception: although many explosions have occurred and still occur in our mines, there has been very little attempt to quantify the relationship between fluctuations in barometric pressure and the build-up of flammable gas in underground workings. This paper will attempt to

- assess the situation in South Africa in recent years
- quantify some of the parameters that may influence the inflow of gas into underground workings induced by barometric pressure
- propose some theories on the causal relationship between fluctuations in barometric pressure and gas explosions
- provide broad guidelines to mines as to how to recognize the danger signals associated with fluctuations in barometric pressure, and how to react to such signals.

Many of these findings, obtained deductively from a macro-analysis of South African meteorological and explosion data, are not fully conclusive and, for this reason, the final purpose of the paper is to indicate the need for, and possible direction of, further research in this regard.

RECENT GAS EXPLOSIONS IN SOUTH AFRICA

The main purpose of the paper is not to provide a full historical review of all explosions in South Africa but rather to investigate the underlying principles. To this

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effect, information was obtained from various inspectorates across the country on gas explosions reported to them in terms of the requirements of the Mines and Works Act and Regulations (Regulations 25.1 and 25.6(d)(iv))[4]. The information requested was limited to the following:

- explosions that resulted in fatal or serious injury to one or more persons, as well as explosions that resulted in extensive damage to underground workings; that is, minor explosions were excluded
- explosions that occurred during the past two decades, i.e. since 1970; the reason for this restriction was to ensure that the explosions had occurred under mining conditions representative of current-day operations
- data from the ten inspectorates that cover the bulk of gold and coal mining in South Africa; platinum and base-mineral mining areas were excluded since these mines do not have a history of major gas explosions.

A total of 59 explosions, 33 in gold mines and 26 in coal mines, fell into this classification. Several general conclusions about gas explosions in South African mines emerged from a statistical analysis of these data.

(1) Although comparison in quantifiable terms is difficult, it seems that there is no material difference between the probability of an explosion on the average coal mine and the average gold mine in South Africa. From Table I it can be seen that, in the 20-year period under consideration, 26 explosions occurred in collieries and 33 in gold mines. It is accepted that the relative risk can be quantified properly only if the number of mines, total production output, number of people employed, etc. are brought into consideration. However, for the purpose of this paper it is sufficient to note that both gold and coal mines in South Africa have a history of gas explosions.

(2) In gas explosions, the number of persons fatally injured is generally much higher than the number of injured because of the catastrophic nature of such incidents. This is unlike most other types of accidents in the mining industry, where the injury rate is generally an order of magnitude greater than the fatality rate. For example, in 1989 the fatality rate and reportable injury rate for mines that are members of the Chamber of Mines were as shown in Table II.

On the other hand, it can be seen from Table I that the fatality rate in respect of explosions is almost double the injury rate. Over the 20-year period under consideration, 351 people died in gas explosions while 208 were injured.

Table I

Explosions in South African mines—incidents per mining area 1970–1989

Mining area	No. of explosions	No. of fatalities	No. of injuries	Fatalities per explosion	Injuries per explosion
Natal coalfields*	10	106	32	10,60	3,20
Eastern Transvaal coalfield	7	53	22	7,57	3,14
South Rand coalfield	4	2	13	0,50	3,25
Highveld coalfield	4	34	24	8,50	6,00
Witbank coalfield	1	13	1	13,00	1,00
Total—coal mines	26	208	92	8,00	3,54
Klerksdorp goldfield	7	21	48	3,00	6,86
OFS goldfield	13	106	27	8,15	2,08
West Wits Line	12	13	41	1,08	3,42
West Rand goldfield	1	3	0	3,00	0,00
Total—gold mines	33	143	116	4,33	3,52
Total—all mines	59	351	208	5,95	3,53

* *Natal coalfields* includes Kliprivier, Utrecht, and Vryheid Coalfields

Table II

Fatalities and injuries on mines that are members of the Chamber of Mines of South Africa[5]

Type of mine	Fatality rate*	Reportable injury rate*
Gold	1,16	20,05
Coal	0,46	4,84
Other minerals	0,58	7,69
All mines	1,01	16,88

* Per 1000 employees at work per annum

(3) Explosions in collieries tend to be more severe and extensive than explosions in gold mines, as is evident from the average number of fatalities per explosion shown in Table I, i.e. 8,0 fatalities per explosion in coal mines versus 4,3 fatalities per explosion in gold mines. This is a very broad conclusion encompassing the net effect of a number of factors, such as the following:

- the areal extent of the gas emission into the workings, which is a function of, amongst others, the mine lay-out, the permeability of the surrounding strata, and the gas content of the seam
- the presence, frequency, and effect of geological disturbances, such as faults, dykes, and joints
- the concentration of workmen in the working places.

(4) Geographically, most coal-mine explosions occur in the coalfields of Natal and the Eastern Transvaal while, in the gold industry, the OFS goldfield, the West Wits line, and the Klerksdorp goldfield are the main problem areas (Table I). This is based on a very cursory look at the matter. An in-depth assessment of the extent of the hazard in each area would require an analysis of the number of explosions relative to the number of mines in each area, the tonnage produced in that area, etc.

(5) An analysis of the trend in the frequency of explosions over time reveals no obvious upward or downward trend in the number of incidents per annum (Figure 1). There is an apparent peak in the number of incidents in the early eighties, followed by a downward trend since then, but this peak and subsequent downward trend are not statistically significant.

(6) Similarly, there is no obvious trend in the number of fatalities over time (Figure 2). Some very high peaks occurred in years where one or two explosions resulted in major disasters, such as the Hlobane Colliery explosion in 1983 and the St Helena Gold Mine explosion in 1987. In this case, as in (5) above, no attempt was made to relate the incidents to tonnage production or to the number of persons employed underground but, given the very high variability in the figures, it is doubted whether a statistically significant

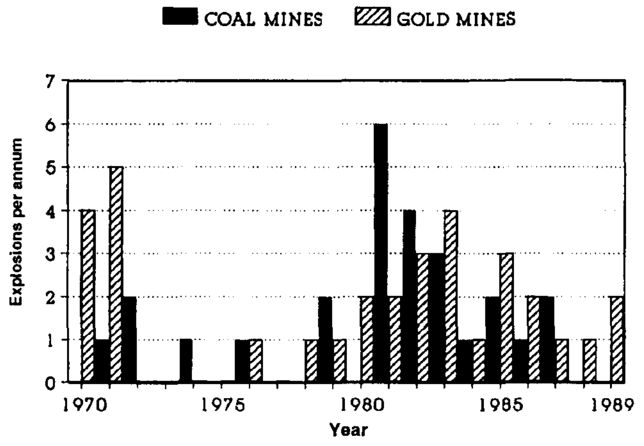

Figure 1—Annual frequency of gas explosions in South African mines, 1970–1989

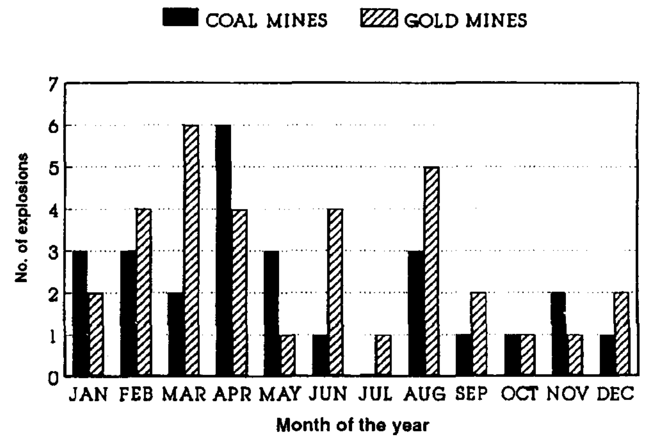

Figure 3—Frequency distribution of gas explosions in South African mines per month of the year, 1970–1989

trend would be present over the 20 years. Over a very long period of time (say since 1900), there is an observable downward trend in the number of explosions per million run-of-mine tons produced[1]. This, however, is largely the result of improvements in technology and mining practice over many decades—effects not easily observable over 20 years, particularly as mining technology had not changed materially during this latter period.

(7) Figure 3 shows the occurrence of explosions per month of the year. While there is some peaking in March/April and August, these peaks are not statistically significant at the 5 per cent level of confidence, which leads to the conclusion that the explosions in South African mines tend to occur at random throughout the year. This is in contrast to, for example, the findings by Boyer[3] in respect of coal-mine disasters in the USA, which seem to peak during the winter months.

(8) An analysis of explosions relative to the day of the week on which they occurred shows an interesting trend (Figure 4). The number of explosions on Sundays is low, as one would expect from the comparative absence of ignition sources on non-production days. However, during the week for both gold and coal mines, there is a gradual increase in the number of incidents from Monday to Wednesday and a decrease thereafter. Although these results appear interesting, from a purely statistical point of view they do not show a significant deviation (at the 5 per cent level of confidence) from the uniform distribution of explosions across week days.

(9) From Figure 5 it is evident that the time of day during which explosions occur is largely related to the main activity periods of the mines, when ignition sources are most likely to be present. The difference between coal- and gold-mining operations is evident from these figures: gold-mining operations generally peak between 06h00 and 16h00 (main production shift) with some, but greatly reduced, activity from about 20h00 to 06h00 (night-shift cleaning). As can be seen from Figure 5, more than 80 per cent of all explosions in gold mines occur between 06h00 and 16h00. Collieries, on the other hand, work two (or sometimes three) identical production shifts. The more popular two-shift system generally runs from about 06h00 (start of the day shift) to about 24h00 (end of the afternoon shift). From Figure 5 it is evident that 95 per cent of the explosions occur in this period, and are more or less evenly spread over time during the period.

The figures analysed thus far really represent the

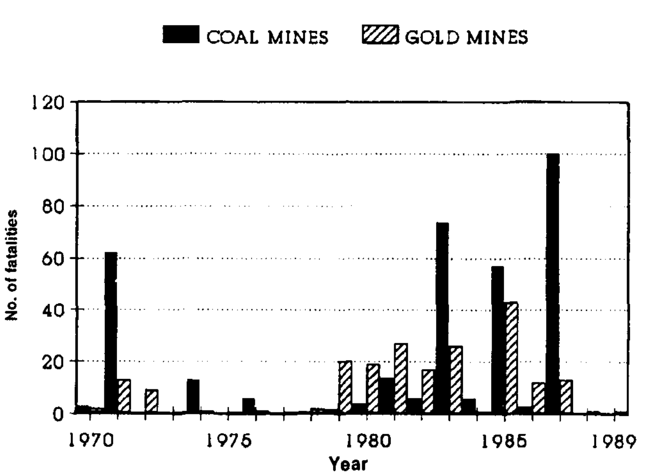

Figure 2—Fatalities per annum resulting from gas explosions in South African mines, 1970–1989

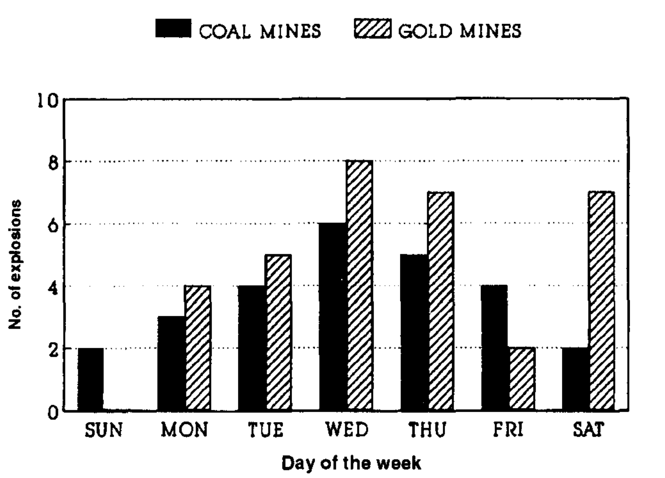

Figure 4—Frequency distribution of gas explosions in South African mines per day of the week, 1970–1989

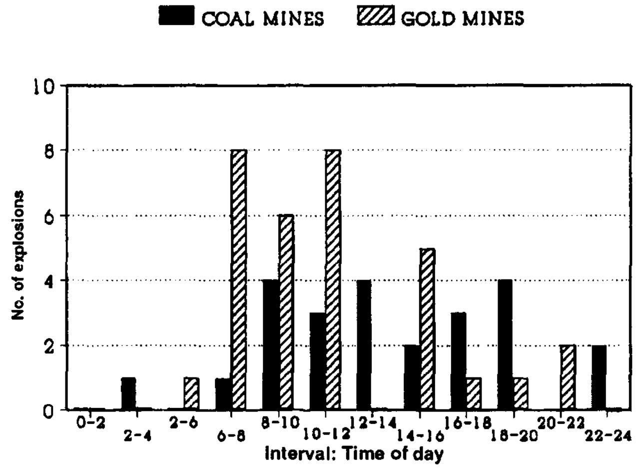

Figure 5—Time of occurrence of gas explosions in South African mines, 1970–1989

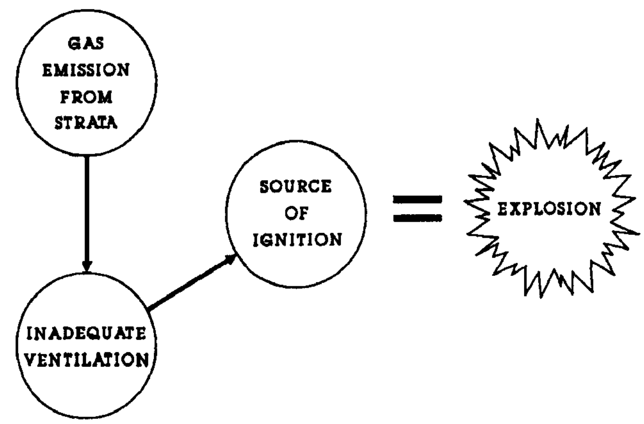

Figure 6—Essential conditions for a gas explosion

proverbial horse that has bolted inasmuch as these are explosions that have occurred. What remains to be analysed is the possible relationship between explosions and physical phenomena that can be monitored and/or predicted so that such knowledge can be used in the identification of potential danger situations when, or preferably before, they develop.

IGNITION OF FLAMMABLE GAS

Although, as was stated at the outset, the main purpose of this paper is to assess the contribution of fluctuations in barometric pressure to gas explosions in mines, it should be kept in mind that, for a gas explosion to occur, three essential conditions must be met:

- a substantial quantity of gas must be emitted from the surrounding strata into the underground workings over a period of time
- ventilation conditions in a specific area must be inadequate (not necessarily below accepted or statutory norms) to remove that gas from the workings, thus allowing it to accumulate to levels above the lower explosibility limit (but below the upper explosibility limit) of the gas–air mixture, i.e. between roughly 5 and 15 per cent for mixtures of methane and air
- an ignition source must emit a spark of sufficient energy to ignite the mixture, thus initiating an explosion.

This concept is illustrated diagrammatically in Figure 6. From this diagram, it is clear that the ignition source is the last, yet important, link in the chain of events leading to an explosion. It is therefore essential to be aware of the most likely sources of ignition in mines since the elimination or control of such sources could prevent accumulations of gas from becoming gas explosions.

The sources of ignition of the 59 explosions analysed are shown in Figures 7 and 8 for coal and gold mines respectively. Most of these sources are self-explanatory but a few require some elaboration.

(a) All explosions caused by lightning occurred in the eastern Transvaal coalfield in the Ermelo district. Generally, coal mines in South Africa are relatively shallow, and many conductors exist along which current from lightning can penetrate the underground workings to cause a spark and hence an explosion, e.g. shaft steelwork, borehole casings. Furthermore, violent electrical storms are normally accompanied by a rapid drop in barometric pressure which, as will be discussed later, could contribute to an enhanced outflow of methane into the underground workings. One final point in this regard: the Ermelo area has a very high incidence of lightning strikes, with a lightning density of some 9 to 10 flashes per square kilometre per annum[16]. The high frequency of explosions caused by lightning in this district is therefore not entirely unexpected.

(b) All coal-mine explosions initiated by blasting operations, except one, occurred in the Natal coalfields. This is probably attributable to
   - the higher gas content of many of the Natal coal seams compared with most other coal seams in South Africa
   - the more difficult ventilation of workings under the generally thinner seam conditions prevailing in Natal
   - the paucity of non-explosive mechanized mining in Natal compared with the Transvaal, where a significant portion of the tonnage comes from non-explosive mining methods such as continuous miners and longwall operations.

(c) Explosions caused by 'machine operation' in coal mines were all caused by frictional heat from the picks of continuous miners or coal cutters.

(d) The incidence of explosions in gold mines caused by smoking (6) is disturbingly high. These can be eliminated only by strict management control and education of the workforce.

(e) In gold mines, the number of incidents falling in the 'unknown' category is unfortunately very high: for more than one-third of all gold-mine explosions, the source of ignition is unknown. This high incidence of unknown causes makes the causal analysis difficult and rather inconclusive.

Closely linked to the source of ignition is the type of working place in which explosions occur since this can give an indication of whether certain areas of the mine are more vulnerable than others. Summaries of working places in which explosions occur most frequently are shown in Figures 9 and 10 for coal and gold mines respectively.

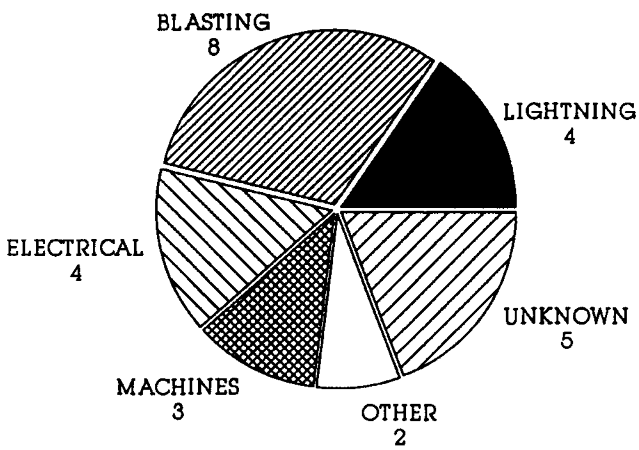

Figure 7—Sources of ignition of gas explosions in South African coal mines, 1970–1989

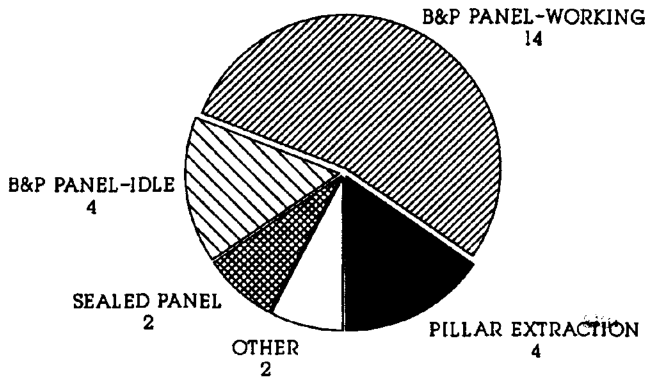

Figure 9—Gas explosions in South African coal mines: occurrence per type of working place

These figures are largely self-explanatory and require only a few supplementary comments.

(i) As one would expect, most explosions occur in the active ore-producing areas of mines because this is where the ignition sources are most likely to occur. Furthermore, the process of winning the ore in itself leads to an imbalance between the atmospheric pressure in the workings and the gas pressure of the methane in the strata at the new air–rock interface, the latter being higher than the former. This leads to an immediate inflow of gas from the strata into the workings as the ore is blasted or cut[13].

(ii) The preponderance of explosions in bord-and-pillar workings in coal mines is largely a reflection of the predominance of this mining method in South Africa.

(iii) It is interesting to note that, although the output from longwall operations in coal mines has grown substantially over the past 20 years, no major explosion has as yet been associated with this mining method.

(iv) In gold mines, as can be expected, almost half the explosions occur in development ends. This underscores the good sense of prohibiting contraband beyond the point of last through ventilation.

THE NATURE OF FLUCTUATIONS IN BAROMETRIC PRESSURE

Before the contributory role of fluctuations in barometric pressure to the occurrence of gas explosions in mines is analysed, it is necessary to understand the nature of such fluctuations from a mining-engineering point of view. Barometric pressure at any point above sea level is not an absolute constant for that point, but is subject to fluctuations over time[15]. These fluctuations fall into two broad categories:

(1) diurnal variations, which follow a fairly consistent pattern from day to day

(2) medium- to long-term upward or downward trends in barometric pressure, which take place over several days and which are 'superimposed' on the diurnal fluctuations.

Diurnal variations in barometric pressure are largely the result of the differential heating and cooling of the surface of the earth. In South Africa, which lies at a mean latitude of approximately 27°S, the solar radiation at the top of the atmosphere amounts to approximately 360 W/m^2. Of this energy, roughly 65 per cent reaches the surface of the earth, heating it during the day[7]. At night, the opposite happens when heat is radiated from the surface. The exact

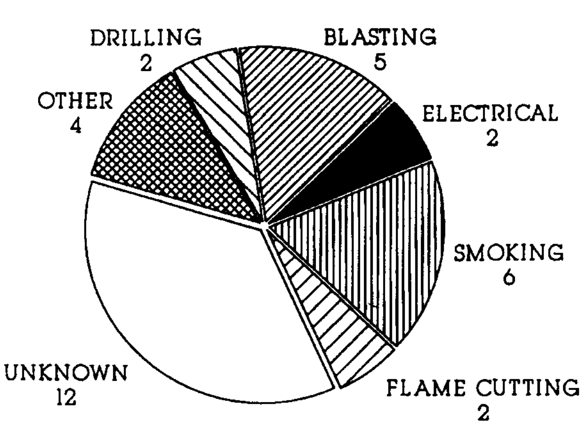

Figure 8—Sources of ignition of gas explosions in South African gold mines, 1970–1989

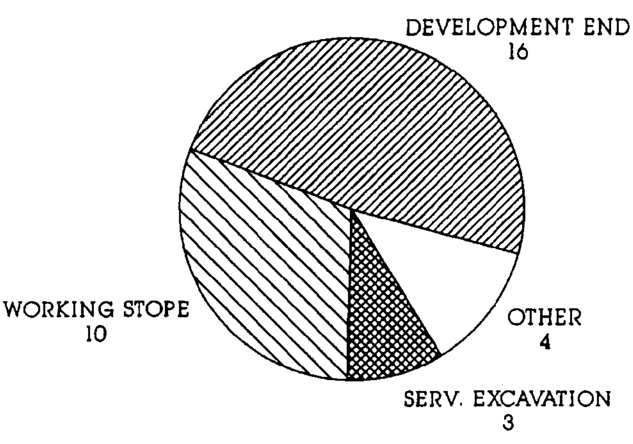

Figure 10—Gas explosions in South African gold mines: occurrence per type of working place

relationship between this radiation energy and fluctuations in barometric pressure is not fully understood but, for the purpose of this discussion, it is probably sufficient to accept that the increase in temperature of the surface of the earth causes the air above it to heat up, expand, become less dense, and rise, thus causing a drop in pressure. Conversely, when heat is radiated from the surface, the air above it ultimately cools down and an increase in barometric pressure is observed. Figure 11 shows a typical diurnal pattern of barometric pressure measured at Jan Smuts Airport over a 24-hour period during the month of April.

The explanation for the medium- to longer-term upward or downward trends in pressure can be found in the features of the general circulation of the atmosphere. South Africa is situated within a high-pressure belt skirted to the south by the circumpolar westerly airstream. This high-pressure belt, centred approximately 30°S, is not homogeneous but is broken up into several cells of high pressure. The country is almost entirely under the influence of this westerly circulation, and weather changes are largely dominated by these disturbances in the circulation of the southern hemisphere, which on the surface appears as a succession of cyclones (low-pressure systems[8]) or anticyclones (high-pressure systems) moving around the coast or across the country from west to east[7].

The net result of these phenomena is a medium-term downward trend in barometric pressure when a cyclonic system moves across the country, and an upward trend in pressure when an anticyclonic system moves across the country. Figure 12 gives an example of these effects over a period of several days (measured at Jan Smuts Airport in late November).

These weather disturbances maintain more or less the same general pattern of a succession of cyclones and anticyclones progressing from west to east across the country[7]. However, individually the systems are of infinite variety as regards their

- position relative to the country
- direction of motion
- rate of travel
- intensity
- state of development or disintegration.

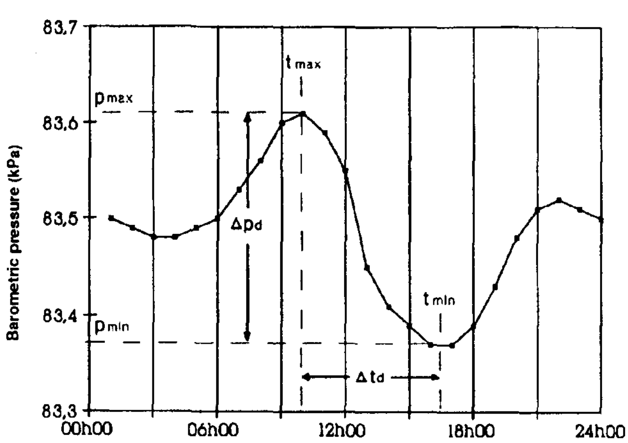

Figure 11—Typical diurnal pattern of barometric pressure

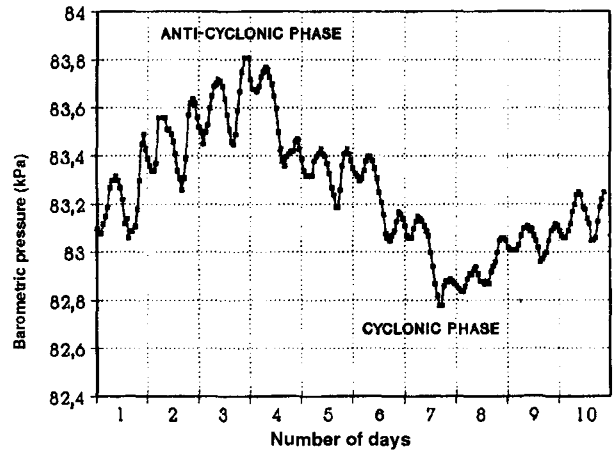

Figure 12—Typical anti-cyclonic and cyclonic patterns of barometric pressure

As a result, many different trends are observed in practice and, as will be discussed later in the paper, certain of these medium-term trends have a definite bearing on gas explosions in gold mines and collieries.

In order to have norms against which to measure and analyse fluctuations in barometric pressure prior to explosions, one must have a quantitative appreciation of the 'normal' diurnal variation in barometric pressure. To assess this, a stratified random sample of 720 days, consisting of 60 sample-days for each month of the year, was drawn from the meteorological data for Jan Smuts Airport for the period 1970 to 1989.

As the drop in barometric pressure was expected to be the main factor in explosions, it was considered necessary to get a feel for the magnitude and variation of the daytime pressure drop on the diurnal pattern, which is by far the most significant feature of the pattern over any 24-hour period. For each of the sample-days, the following information was determined, the associated terminology being illustrated in Figure 11:

(i) the time of day when the barometric pressure reaches a maximum (mid-morning), t_{max}

(ii) the time of day when the pressure reaches a minimum point on its quasi-sinusoidal trough (late afternoon), t_{min}

(iii) the maximum barometric pressure immediately prior to the daytime drop in pressure, p_{max}

(iii) the minimum barometric pressure at the end of the daytime drop in pressure, p_{min}

(iv) the total drop in pressure, Δp_d, where

$$\Delta p_d = p_{max} - p_{min}$$

(v) the duration of the pressure drop, Δt_d, where

$$\Delta t_d = t_{min} - t_{max}$$

(vi) the rate of pressure drop, R_d, where

$$R_d = \Delta p_d / \Delta t_d.$$

Frequency distributions, drawn up for the parameters listed above, showed that the data in all instances had essentially normal distributions. The averages, standard deviations, and ranges were therefore calculated for each parameter for each month of the year and aggregated for the year as a whole. Some of the more important results are shown graphically in Figures 13 to 17 (monthly figures) and in Table III (aggregated figures).

Table III

Statistical estimates of various parameters related to variations in barometric pressure over the full year

Parameter*	Arithmetic mean	Standard deviation	Range	
			Minimum	Maximum
Daytime pressure drop, Δp_d (Pa)	270,4	79,21	60	650
Time of daytime maximum, t_{max}	09h31	54,5 min	06h00	12h30
Time of daytime minimum, t_{min}	16h23	57,4 min	13h00	19h00
Duration of pressure drop, Δt_d (h)	6,9	1,51	2,0	12,0
Rate of pressure drop, R_d (Pa/h)	39,8	9,67	9,3	72,7

* These parameters are illustrated graphically in Figure 11

From these figures, the following features of the diurnal variations in barometric pressure can be noted.

(a) Over the year, the average daytime barometric pressure drop is 270 Pa. However, this figure is not static but varies with the season, ranging from an average of 328 Pa in November to 239 Pa in July (Figure 13). This is not unexpected since both the length of day and the average daytime temperature are higher in the summer than in the winter.

(b) During the day, the barometric pressure on average reaches a maximum at 09h31 in the morning. This average, like the magnitude of the pressure drop, is not constant but, as shown in Figure 14, ranges from as early as 08h44 in the summer (November) to as late as 10h18 in the winter (July).

(c) The barometric pressure reaches a minimum point on its quasi-sinusoidal diurnal pattern on average at 16h23 in the afternoon, ranging from as early as 15h44 in May to as late as 17h16 in January/February (Figure 15).

(d) The net effect of the time ranges outlined in (b) and (c) above is that the duration of the pressure drop varies quite markedly over the year. Over the year, the average duration of this pressure drop is 6 hours 54 minutes, but, as shown in Figure 16, it ranges from an average of only 5 hours 37 minutes in mid-winter (July) to 8 hours 14 minutes in mid-summer (January).

(e) Finally, the total pressure drop, in conjunction with the duration of the pressure drop outlined above, results in an average rate of pressure drop of 39,8 Pa/h, ranging from a low of 34,0 Pa/h in January to a high of 44,1 Pa/h in June (Figure 17). It is interesting to note that, while the total pressure drop is much higher in summer than in winter (as indicated in (a) above), the rate of pressure drop is higher in winter than in summer. This is the result of the total pressure drop taking place over a much longer period in summer than in winter. The effect of this longer duration is large enough to override the effect of the higher total pressure drop.

THE ROLE OF FLUCTUATIONS IN BAROMETRIC PRESSURE IN GAS EXPLOSIONS

In an assessment of the role that fluctuations in barometric pressure may have played in the gas explosions that have occurred in South African mines, barometric-

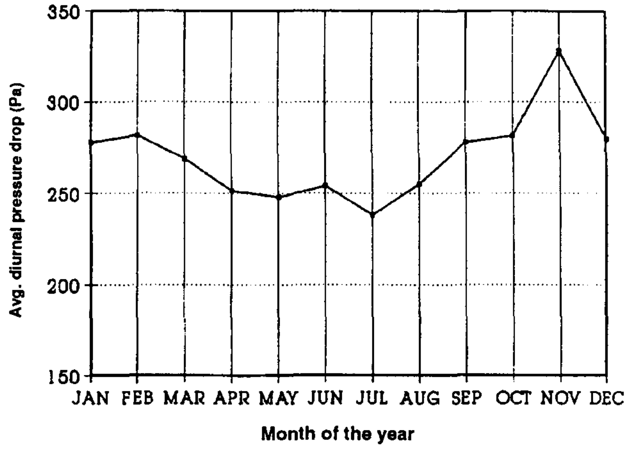

Figure 13—Variation of the average diurnal pressure drop throughout the year

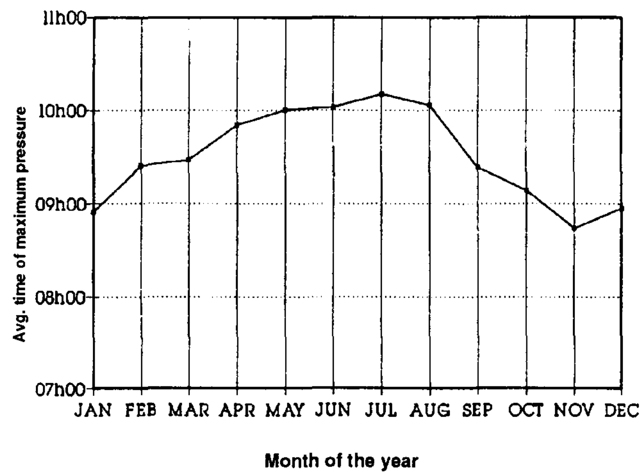

Figure 14—Variation over the year of the average time of day at which the diurnal pattern of barometric pressure reaches its daytime maximum

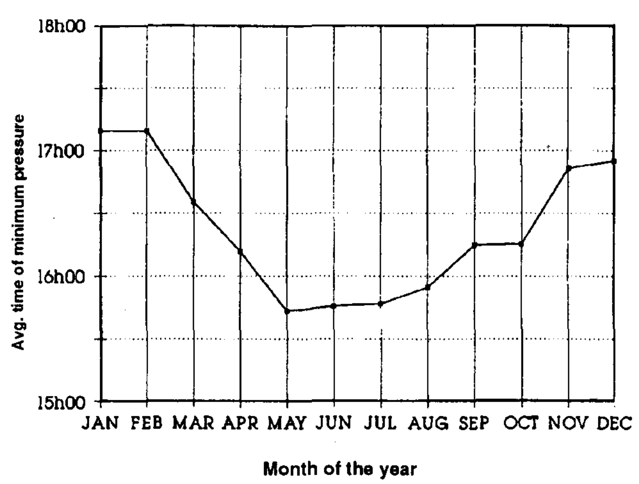

Figure 15—Variation over the year of the average time of day at which barometric pressure reaches its daytime minimum

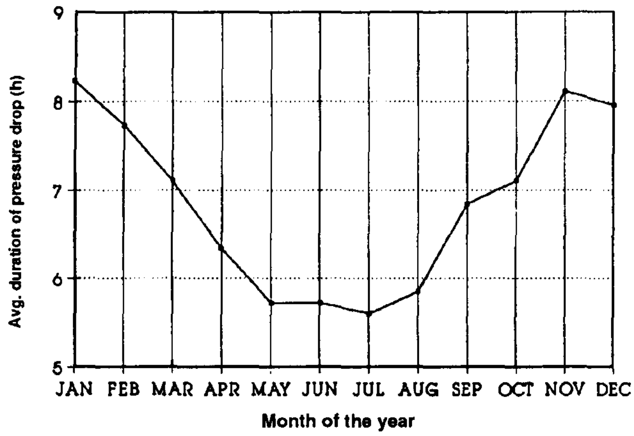

Figure 16—Variation over the year of the average duration of the daytime diurnal drop in barometric pressure

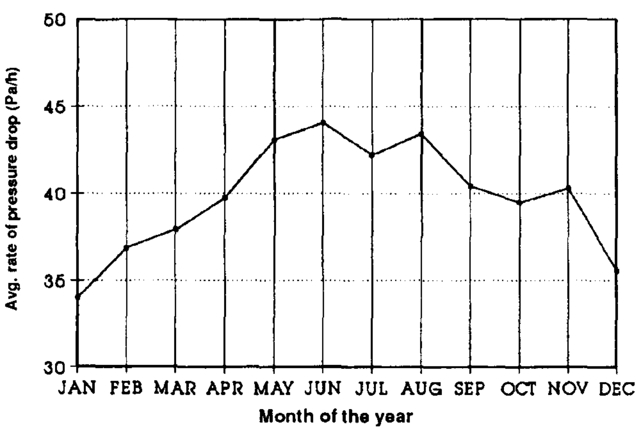

Figure 17—Variation over the year of the daytime rate of pressure drop

pressure patterns over a number of days immediately prior to each of the 59 explosions were analysed. In each case, hourly pressure data for the seven days preceding the explosion were plotted and the trends analysed. Pressure data from three weather stations were used: Newcastle (for the Natal coalfields), J.B.M. Hertzog Airport, Bloemfontein (for the OFS goldfields), and Jan Smuts Airport (for all the other mining areas). The data could be applied with confidence to all the mines analysed since barometric-pressure patterns remain relatively stable over fairly wide areas in South Africa, with a reasonably high degree of correlation between measuring stations[9-11] (with coefficients of correlation generally greater than 0,9). Similarly, the application of surface barometric-pressure data to the underground situation is totally acceptable since the correlation between surface and underground barometric pressure is very high[12], with coefficients of correlation ranging from 0,94 to 0,99 for a typical deep coal mine[9].

During the analysis, it became apparent that the pressure patterns preceding the explosions could be classified into four broad categories.

Type Al A substantial drop in pressure over a number of days continuing right up to the time of the explosion. An example of this type of pattern is shown in Figure 18.

Type A2 A substantial drop in pressure, followed by a short-term (less than 24-hour) rise in pressure immediately prior to the explosion. Figure 19 shows an example of this type of pattern.

Type A3 A substantial drop in pressure over a number of days, followed by a definite reversal into an upward trend, indicative of the start of an anticyclonic pattern. However, at the time of the explosion, the barometric pressure is still lower than the previous anticyclonic maximum. This pattern is illustrated in Figure 20.

Type B A definite strong upward trend in pressure prior to the explosion so that the pressure at the time of the explosion is substantially higher than the previous anticyclonic maximum. An example of this type of pattern is shown in Figure 21.

It should be noted that, where the pressure was rising immediately prior to the explosion as a result of the normal diurnal fluctuations, but the overall trend was still downward owing to the influence of a cyclonic pattern, the pressure pattern was classified as an Al type. This situation is illustrated in Figure 22.

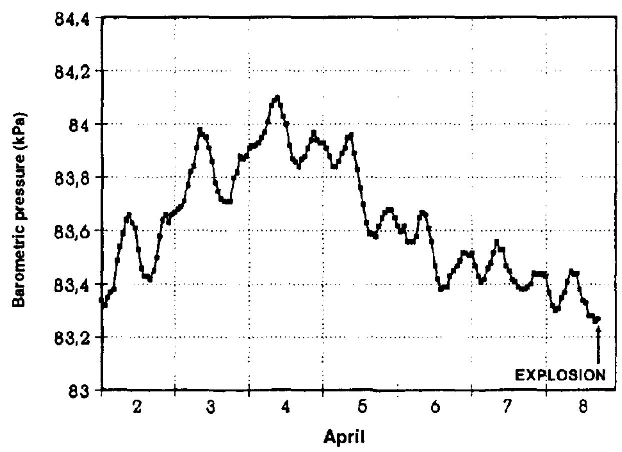

Figure 18—Example of a type Al pressure pattern

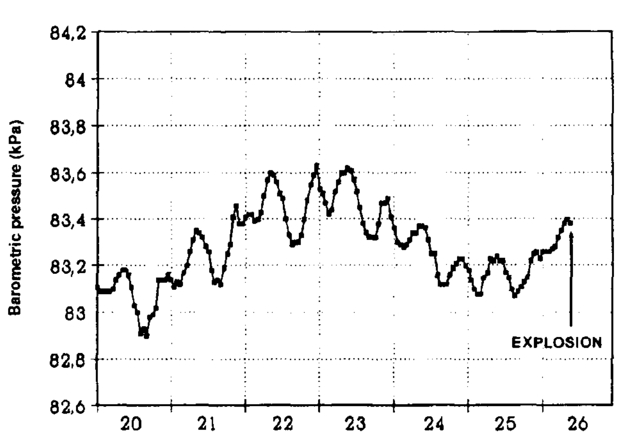

Figure 19—Example of a type A2.pressure pattern

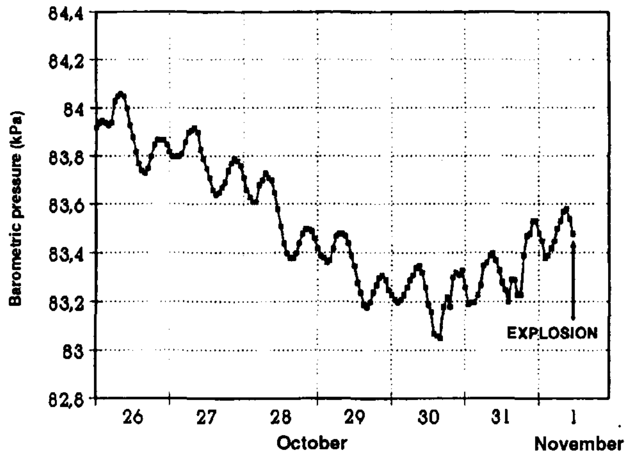

Figure 20—Example of a type A3 pressure pattern

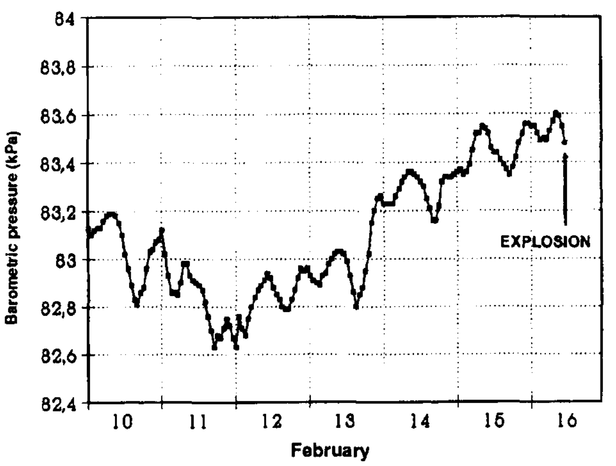

Figure 21—Example of a type B pressure pattern

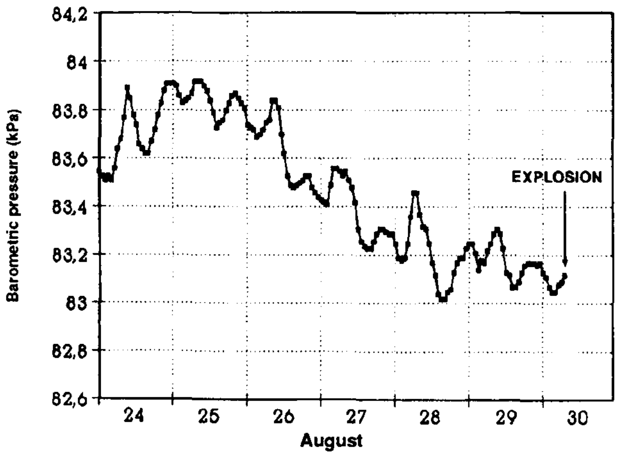

Figure 22—Example of a type A1 pressure pattern with diurnal upturn

The pressure patterns prior to all the explosions were analysed in an attempt to determine

- the possible influence of cyclonic minima on the build-up of flammable gas in the underground workings
- the possible influence of short-term (diurnal) drops in pressure on the build-up of gas in the underground workings
- the order of magnitude of the pressure differentials (both long-term and short-term) that would constitute a hazard if this were determinable from the available data.

In order to quantify the pressure differentials prior to explosions, the following terminology was introduced and is illustrated in Figure 23.

Δp_m The maximum pressure drop between an anticyclonic maximum and a cyclonic minimum immediately prior to the explosion (Pa)

Δt_m The time period over which Δp_m took place (h)

Δp_e The pressure differential between the last anticyclonic maximum prior to the explosion and the actual barometric pressure prevailing at the time of the explosion (Pa)

Δt_e The time period over which Δp_e took place (h)

Δp_i The increase in pressure between the cyclonic minimum immediately prior to the explosion and the actual pressure at the time of the explosion, where such an increase is present (Pa)

Δt_i The time period over which the pressure increase Δp_i took place (h)

Δp_s A short-term (less than 24 hours) pressure drop immediately prior to the explosion (Pa)

Δt_s The time period associated with Δp_s (h).

From the above definitions, it follows that

(i) $\Delta p_e = \Delta p_m - \Delta p_i$

(ii) $\Delta t_e = \Delta t_m + \Delta t_i$

(iii) $\Delta t_s < 24$.

By use of the above definitions, all 59 explosions were categorized, and the pressure differentials and time intervals were quantified. The results are shown in Tables IV and V for coal and gold mines respectively, and are summarized in Table VI according to the type of pressure pattern. It should be noted that the 'averages' shown in these tables are arithmetic means excluding the data of type B pressure patterns. For example,

$$\Delta \bar{p}_m \,(\text{coal}) = \sum_{j=1}^{22} \Delta p_{mj}$$

$$\Delta \bar{p}_m \,(\text{gold}) = \sum_{j=1}^{29} \Delta p_{mj} \,.$$

The reason for these exclusions will become apparent in the discussions that follow.

From these results, the following conclusions were drawn.

(i) 51 of the 59 explosions, i.e. 86 per cent, were associated with a net drop in barometric pressure after an anticyclonic maximum, i.e. $\Delta p_e > 0$ (pressure

Table IV
Pressure differentials prior to gas explosions in coal mines

Explosion code	Pressure type	Pressure differential, Pa				Time period, h			
		Δp_m	Δp_e	Δp_i	Δp_s	Δt_m	Δt_e	Δt_i	Δt_s
El	Al	720	720	0	270	79	79	0	7
E2	Al	370	210	160	140	43	48	5	13
E3	Al	380	380	0	130	27	27	0	2
E4	Al	460	400	60	210	55	58	3	10
H3	Al	240	240	0	120	28	28	0	3
H6	Al*	280	90	190	0	29	47	18	0
H7	Al	370	370	0	270	29	29	0	6
H9	Al	470	470	0	0	109	109	0	0
D2	Al	630	460	0	0	104	110	0	0
D4	Al	700	700	0	260	79	79	3	8
D5	Al*	330	110	220	0	27	37	10	0
D6	Al	360	360	0	210	53	53	0	7
D9	Al	830	820	0	180	104	105	1	9
D10	Al	1330	1290	40	210	54	56	2	8
H4	A2	570	350	220	0	84	100	16	0
D7	A2	720	480	240	0	54	75	21	0
D8	A2*	600	390	210	0	56	75	19	0
E5	A3	410	170	240	160	79	123	44	5
E6	A3	410	90	320	170	66	154	88	10
H1	A3	570	360	210	330	66	153	87	7
H5	A3*	290	140	250	300	30	82	52	11
WB1	A3	650	60	590	0	104	155	41	0
H2	B	?	(430)	430†	90	?	?	130	21
H8	B	440	(10)	450	0	43	90	47	0
D1	B	400	(440)	840	0	32	73	41	0
D3	B	730	(90)	820	0	52	146	94	0
Averages†		531,4	393,6		211,4	61,8	81,0		7,6

* Difficult to classify, but judged to be in that category
† Excluding type B pressure patterns

patterns of types A1, A2, and A3), leading to the conclusion that medium-term decreases in barometric pressure as a result of cyclonic weather patterns definitely contribute to the risk of gas explosions in mines.

(ii) In 60 per cent of the cases (type Al and A2 pressure patterns), the evidence is very strong that these medium-term downward trends in pressure played a major role in creating pressure differentials of sufficient magnitude (and duration), between the atmospheric pressure in the underground workings and the gas pressure in the surrounding strata, to cause an enhanced outflow of gas into the workings.

(iii) In the case of only 14 per cent of the explosions analysed (namely, all the type B explosions), is there evidence that medium-term fluctuations in barometric pressure probably did not play a role in the gas accumulations that were present prior to these explosions. This is the proverbial exception that proves the rule: fluctuations in barometric pressure may be the major contributory factor to an enhanced outflow of gas into underground workings, but it is not the only factor. Other factors, mainly the mining operation itself, also contribute to an outflow of gas into the workings. It is therefore necessary to stress that the normal precautions against flammable gas, i.e. good ventilation, routine testing, etc., should always remain in force, even when the barometer indicates no 'abnormality' in the weather pattern. For the purpose of further quantitative analyses, these explosions were excluded from the data.

(iv) In 30 of the 59 explosions (51 per cent), there were

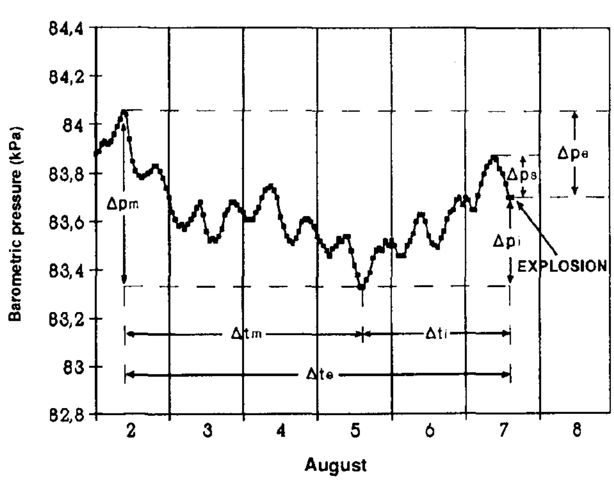

Figure 23—Notation used in the analyses

Table V

Pressure differentials prior to gas explosions in gold mines

Explosion code	Pressure type	Pressure differential, Pa				Time period, h			
		Δp_m	Δp_e	Δp_i	Δp_s	Δt_m	Δt_e	Δt_i	Δt_s
KL1	A1	770	770	0	410	32	32	0	7
KL3	A1	470	370	100	0	31	37	6	0
KL5	A1	620	470	150	0	78	86	8	0
W1	A1	860	830	30	0	115	118	3	0
W5	A1	370	370	0	130	131	131	0	14
W6	A1	850	850	0	280	150	150	0	7
W7	A1	370	270	100	0	19	25	6	0
V2	A1	730	710	20	360	80	83	3	11
V4	A1	1 290	1 220	70	170	81	84	3	12
V6	A1*	360	350	10	290	31	33	2	9
J1	A1	520	520	0	190	29	29	0	5
C1	A1	870	830	40	260	115	117	2	18
C2	A1	840	840	0	310	90	90	0	18
C3	A1*	280	50	230	0	8	26	18	0
C4	A1	530	470	60	0	43	45	2	0
C5	A1	460	460	0	0	60	60	0	0
C6	A1	860	760	100	280	55	59	4	23
KR1	A1*	230	160	70	0	18	20	0	0
KL7	A2	570	190	380	0	102	119	17	0
V1	A2	560	250	310	0	64	82	18	0
V3	A2	1 230	630	600	0	125	144	19	0
KR4	A2	490	150	340	0	57	74	17	0
KL2	A3	790	260	530	0	66	129	63	0
KL6	A3	560	130	430	240	103	150	47	6
V5	A3	500	310	190	260	57	103	46	7
J2	A3	1 010	580	430	100	105	148	43	2
C7	A3	720	260	460	150	78	141	63	21
KR2	A3	710	310	400	180	54	119	65	18
KR3	A3	630	80	550	80	92	136	44	4
KL4	B	520	(180)	700	0	54	95	41	0
W2	B	?	(630)	630†	0	?	?	152	0
W3	B	560	(290)	850	0	34	146	112	0
W4	B	?	(650)	650†	0	?	?	0	0
Averages†		656,9	463,8		168,8	71,3	88,6		13,0
Averages—gold and coal		602,7	433,5		130,4	67,2	85,3		5,6

* Difficult to classify, but judged to be in that category
† Excluding type B pressure patterns

Table VI

Classification of explosions according to the type of pressure pattern preceding the explosion

Type of pressure pattern	Number and percentage of explosions					
	Coal		Gold		Total	
	No.	%	No.	%	No.	%
A1	14	54	18	55	32	54
A2	3	11	4	12	7	12
A3	5	19	7	21	12	20
B	4	15	4	12	8	14
Total	26	100	33	100	59	100

short-term (less than 24-hour) downward movements in barometric pressure immediately prior to the explosions. These short-term downward movements were generally associated with normal downturns on the diurnal curve. The question must be asked whether these diurnal downturns could have contributed to an enhanced outflow of gas into the workings. If one considers that the normal diurnal pattern of barometric pressure is in an upward phase for roughly half the day and in a downward phase for the other half (Figure 11), then clearly the statistical probability of an explosion occurring during a diurnal downturn in pressure is 0,5. The fact that 51 per cent of the explosions occurred during a diurnal downturn must therefore be interpreted as purely a random occurrence. There is no reason to believe that diurnal downtrends have a significant influence on the build-up of gas in the underground workings in South African mines. This is to some extent in contrast to, for example, coal mines in the UK, where the diurnal fluctuations are considered to have an important bearing on the outflow of gas into the workings. However, from a theoretical point of view, these diurnal downturns cannot be ignored completely in the South African context, particularly when the diurnal pressure drop is abnormally large.

Having established that downtrends in barometric pressure over a number of days play an important role in the outflow of flammable gas into underground workings, the next step was to try to establish whether critical values in terms of pressure drop, and/or the times over which these occur, could be determined. In other words, are there certain pressure differentials which, if exceeded, should be regarded as constituting a hazard to mines, particularly if sustained over an extended period of time?

From Tables IV and V the following general conclusions were drawn.

(a) Pressure drops associated with cyclonic low-pressure systems moving across the country, which result in gas accumulations large enough to cause major explosions, are generally substantially greater than the 'normal' pressure drops associated with diurnal fluctuations in pressure. For example, the arithmetic mean of the maximum pressure drop ($\Delta\bar{p}_m$) prior to the gas explosions analysed is 603 Pa compared with the mean diurnal drop in pressure ($\Delta\bar{p}_d$) of 270 Pa. It should, however, be noted that the values of Δp_m range from 230 to 1330 Pa.

(b) Similarly, the mean residual pressure differential ($\Delta\bar{p}_e$) between the maximum pressure at the peak of the anticyclonic pattern and the actual pressure prevailing at the time of the explosion (434 Pa) is significantly higher than the mean diurnal variation in pressure (270 Pa). Here, again, there is a substantial variation in the values of Δp_e ranging from as low as 50 Pa to as high as 1290 Pa.

(c) As will be postulated in the next section, the low permeability of the strata and geological structures in South African mines, and the resultant high resistance to the flow of gas, require high pressure differentials between the gas in the strata and the atmosphere inside the workings to be maintained for substantial periods of time before gas in sufficient quantities will flow into the workings to constitute a potential hazard. The duration of pressure drops prior to explosions therefore needs to be considered. From Tables IV and V it is evident that the mean duration of medium-term downtrends in pressure from anticyclonic maxima to cyclonic minima (i.e. $\Delta\bar{t}_m$) prior to major explosions was of the order of 67 hours, while the mean duration from anticyclonic maxima to the time of the explosions (i.e. $\Delta\bar{t}_e$) was of the order of 85 hours. The actual values of Δt_m ranged from 8 hours to 150 hours, while Δt_e ranged from 20 hours to 155 hours.

An analysis of the frequency distributions of the duration of pressure drops showed that the values were almost uniformly distributed over the range 25 to 155 hours for both Δt_m and Δt_e. Therefore, it would seem that a pressure drop with a duration in excess of 24 hours (i.e. a medium-term drop), if substantial, constitutes a hazard irrespective of whether the duration is one day or more than one day. This should be seen in contrast to the finding that pressure drops of very short duration (i.e. less than 24 hours) do not materially contribute to the explosion hazard in South African mines.

(d) In a conceptual sense, one would expect the product of pressure drop and the duration of the drop to be a possible yardstick by which to gauge the extent of a hazard. However, such a simple measure is likely to have important shortcomings that render it unsuitable for practical application. For example, the same result is obtained from a large drop in pressure over a short period of time as from a small drop in pressure over a long period of time. In practice, the small pressure drop over a long period of time (say a week) is more likely to allow the ventilation system in the underground workings to remove the gas from the workings since the flow of gas from the strata is likely to be slow and gradual. If, on the other hand, a large pressure differential is sustained over a comparatively short period of time (say one or two days), this may lead to an enhanced outflow of gas that the ventilation system may not be able to handle. Obviously, the most dangerous situation would prevail when a large pressure differential is maintained over a fairly long period of time, say a number of days. With this in mind, an analysis was made of the product of pressure drop and time for each explosion, i.e. $\Delta p_e \times \Delta t_e$, but no obvious trend or critical values could be detected .

(e) From the argument outlined above, it was concluded that the rate of pressure drop in itself was not a criterion governing the outflow of gas from the strata into underground workings. It was only of relevance if linked to some meteorological anomaly that causes a large drop in pressure to occur and be maintained over a substantial period of time.

(f) Finally, it is interesting to note that pressure differentials prior to explosions in gold mines are generally higher than the equivalent figures for coal mines. For example,

$\Delta\bar{p}_m$ (coal) = 531 Pa
$\Delta\bar{p}_m$ (gold) = 657 Pa

$\Delta\bar{p}_e$ (coal) = 394 Pa
$\Delta\bar{p}_e$ (gold) = 464 Pa.

Although there is no significant difference between the mean residual pressure differentials prior to explosions ($\Delta\bar{p}_e$) for gold and coal, the mean value of the maximum pressure drop prior to explosions ($\Delta\bar{p}_m$) is significantly higher for gold mines than for coal mines at the 5 per cent level of confidence. This could imply that the mechanism by which gas flows through the strata into the workings in gold mines has a generally higher resistance to the flow of gas than the equivalent mechanism in coal mines. Alternatively, the gas content of the strata/structures in gold mines could be less in volume per equivalent unit of exposed surface than in coal mines. Both of these postulates would imply that a higher pressure differential is required to move a given quantity of gas into the underground workings in gold mines than in coal mines. This, in turn, would mean that coal mines are more sensitive to changes in barometric pressure than gold mines, which would imply that coal mines on average could build up given quantities of gas at smaller pressure drops than gold mines. However, the point is only of academic interest since the basic thesis remains that both gold and coal mines can expect enhanced outflows of flammable gas into underground workings during medium-term cyclonic downturns in barometric pressure, particularly if the resultant pressure differentials are substantial.

GAS EMISSION INTO UNDERGROUND WORKINGS

To understand the outflow of gas into underground workings and to find some explanation for the relationship between medium-term barometric pressure drops and gas explosions in South African mines, it is useful for one to think in terms of a simplified conceptual model of gas flow from the strata surrounding underground excavations into such workings.

It is postulated that this mechanism of gas flow from the strata into the workings of, for example a coal mine, could be as follows.

(a) Assume that there is equilibrium between the gas pressure (say P_{g1}) in the strata at the coal–air interface and the barometric pressure in the atmosphere (say P_{b1}) prior to the face being blasted. (For the sake of simplicity, assume for the moment a static atmospheric pressure.) As soon as the face is blasted, the gas pressure at the interface instantaneously increases to, say, P_{g2} as a result of the face advancing. As P_{g2} will be greater than P_{b1} because the face is advancing towards virgin gas pressure, the gas starts to flow into the underground workings in an attempt to reach equilibrium between P_{g2} and P_{b1}. If P_{b1} remains constant, equilibrium will once again be achieved when sufficient gas has flowed from the strata into the underground workings, i.e. at the coal–air interface, P_{g2} reduces to $P_{g1} = P_{b1}$.

(b) Assume that no further blasting takes place and that the barometric pressure now increases to, say, P_{b3} which is substantially higher than P_{g1}. Pressure equalization will now take place by some air from the excavation marginally penetrating the coal, and by methane from deeper inside the strata flowing into the fracture zone immediately around the excavation, albeit at a slow rate. As a result, the gas pressure at the coal–air interface will increase until $P_{b3} = P_{g3}$. During this anticyclonic phase, there is obviously no outflow of gas into the underground workings.

(c) Finally, assume that the barometric pressure now drops substantially, to say, P_{b4} as a result of a cyclonic low pressure system. There will again be a substantial pressure differential at the coal–air interface with $P_{g3} > P_{b4}$. In order to attain pressure equalization, methane gas will again start flowing into the underground workings.

In view of the results obtained from earlier analyses, the question arises as to why short-term fluctuations in pressure do not result in substantial inflows of gas into the underground workings since the model described above essentially centres on the existence of pressure differentials. The answer lies in the high resistance to the flow of gas through strata. This high flow resistance means that pressure equalization is a fairly slow process, and a substantial time lag is bound to exist between the relatively rapid changes in atmospheric pressure in the workings and the gas pressure inside the strata. A practical illustration of this concept occurred in some experimental work by the author with sealed panels in collieries, where it was found that there were time lags of some 1 to 3 hours between changes in barometric pressure outbye of the seals of sealed panels and the barometric pressure inside such panels[11] (Figure 24). If it is accepted that the strata surrounding sealed roadways in collieries are normally highly fractured, it is evident that pressure equalization between the atmosphere of the workings and the gas at a given point in the strata is likely to be much greater than 3 hours, which would explain the apparent lack of influence exerted by short-term fluctuations in barometric pressure on the gasflow.

A CASE HISTORY: THE HLOBANE COLLIERY EXPLOSION

Hlobane Colliery, of the Vryheid (Natal) Railway Coal and Iron Company Ltd, is a coal mine in the magisterial district of Vryheid, Natal, producing coal from three economic seams in the Ecca Group: the Dundas, Gus, and Alfred seams. These seams are mined for their coking properties.

On Monday, 12th September, 1983, at about 08h00, an explosion of methane occurred in sections 5 and 10 of the Boomlager No. 3 area of the mine, in which 64 persons were killed and 12 persons seriously injured; 4 of the injured died subsequently as a result of their injuries, bringing the total death toll to 68 persons[14].

The sections in which the explosion occurred were being mined on the bord-and-pillar system, using a suite of equipment consisting of a coal cutter, hand-held electric coal drills, and battery-driven scooptrams (low-profile

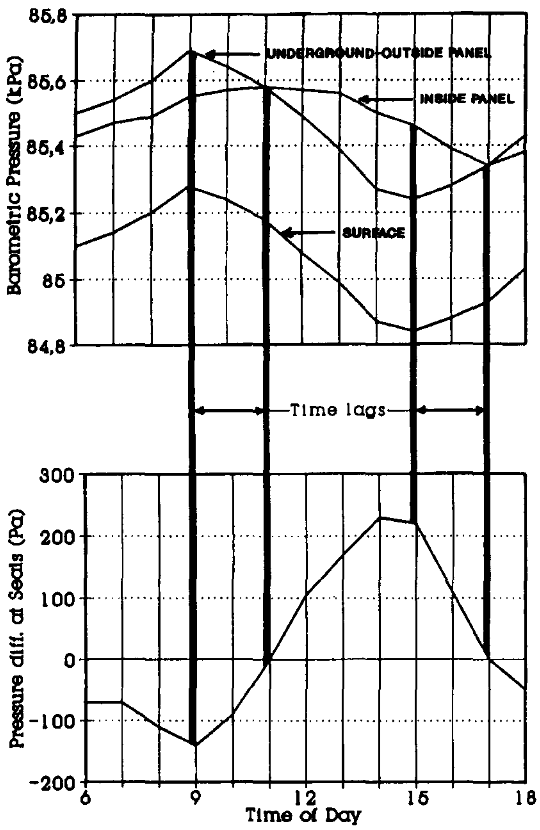

Figure 24—Example of time lags in pressure equalization

load–haul–dump machines).

Up to the time of the explosion, Hlobane was not regarded as a very gassy mine in the sense that detectable quantities of gas were not found on a regular basis. This fact in itself was probably the reason for the apparent lack of appreciation prior to the explosion of the need to have ventilation systems in perfect working condition at all times.

This case study is cited because it was one of the most extensively investigated explosions in the history of the South African mining industry, and it clearly illustrates how all the pre-conditions for a gas explosion developed over a number of days and ultimately combined to result in the most devastating explosion in the recent mining history of this country.

These pre-conditions were as follows:

- a change in the weather pattern, leading to an enhanced outflow of methane into the underground workings
- a disruption of the ventilation system in the sections where the explosion occurred, thus allowing the gas to accumulate
- failure to detect the accumulation of gas
- a ready source of ignition in the form of the electrical system of a production machine that had been rendered non-flameproof as a result of faulty workmanship.

Each of these factors will be described briefly.

Drop in Barometric Pressure

Figure 25 shows the pattern of barometric pressure for a number of days immediately prior to the explosion[14]. On Sunday, 11th September, 1983, a storm passed over the mine that was associated with a very substantial drop in pressure. In fact, the pressure drop of 1010 Pa from 23h00 on Saturday, 10th September, to 21h00 on Sunday, 11th September, is the highest pressure drop the author has seen in any 24-hour period.

From Figure 25 it can be seen that some instability in the weather pattern already started developing on Thursday, 8th September, when the pressure started increasing. At the same time, there was a marked increase in the amplitude of the diurnal fluctuations. For example, on Friday, 9th September, the diurnal drop in pressure was some 450 Pa, compared with the statistical mean of 270 Pa for August, while the diurnal increase in pressure on the same day amounted to 570 Pa.

The pressure pattern peaked at 01h00 on Saturday, 10th September, and started to drop almost immediately, with a major drop recorded the following day. The maximum drop in pressure from the anticyclonic maximum to the cyclonic minimum (i.e. ΔP_m) eventually amounted to 1330 Pa, with a residual pressure (ΔP_c) of 1290 Pa remaining at the time of the explosion. This substantial drop in pressure, which took place over 56 hours (Δt_e), must have caused a major inflow of methane gas into the underground workings. In other words, the first pre-condition for an explosion was firmly in place.

Disruption of the Ventilation

On Saturday, 10th September, a holing was effected between two roadways in Section 10, which disrupted the ventilation to these two sections as a whole, with the supply of air to Section 5 being reduced by some 60 per cent. Although this fact was reported by the miner, no action to rectify the situation was taken prior to the weekend. The scene was thus set for a substantial accumulation of gas in this area, and the second pre-condition for an explosion was in place.

Non-detection

From the enquiry, it emerged that the miner in charge of

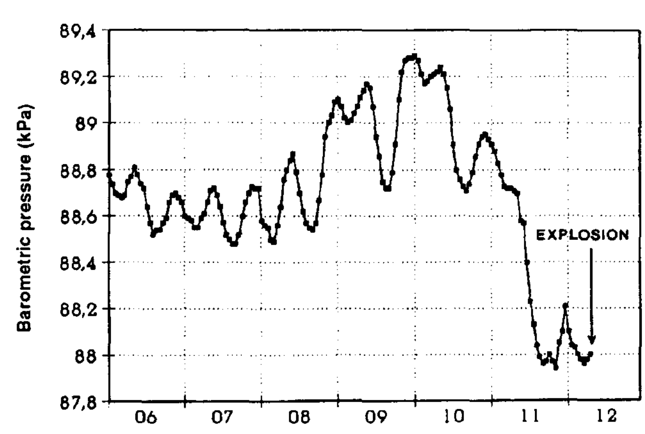

Figure 25—Barometric pressure pattern prior to the Hlobane explosion

Section 5 had apparently failed to carry out the statutory tests for gas during his early examination of the workings. Had this been done, he would certainly have detected the gas since the seam height was only 1,2 m. The massive build-up of gas thus remained undetected prior to the start-up of operations.

The Source of Ignition

During the enquiry into the explosion, it was established beyond a doubt that the source of ignition was the control panel of a battery-driven scooptram. The section electrician had worked on the panel three days earlier, and the cover of the flameproof enclosure had been replaced in such a way that a conductor wire was caught between the machined flanges of the cover and the box, resulting in a gap of some 10 mm. This gap was more than adequate for the propagation of flame, which must have been initiated by sparking inside the enclosure. Thus, the final pre-condition for an explosion was met, resulting in a major explosion and the loss of 68 lives.

CONCLUSIONS AND RECOMMENDATIONS

As was said at the outset, many of the findings in this paper, by the very nature of the investigation and the source data, must be regarded as not fully conclusive. However, it is felt that the investigation broke some new ground that could form the basis for further research.

To summarize, the main conclusions that emerged from this investigation are the following.

(1) In South African gold and coal mines, medium-term (longer than one-day) downward trends in barometric pressure, rather than short-term (diurnal) variations in pressure, are the main contributory factor to explosions of flammable gas in underground workings.

(2) At this stage, the total drop in pressure following an anti-cyclonic maximum is regarded as an appropriate measure by which mines should judge the extent of the potential hazard, particularly where such a drop in pressure is maintained for longer than 24 hours.

(3) The absolute values of pressure drop and/or duration that should be regarded as critical from a hazard-development point of view are not easily determinable since they are influenced by many factors. As a general rule, however, it seems that a pressure drop in excess of the mean diurnal variation in pressure (i.e. 270 Pa) should be regarded as a potential danger, particularly where such a pressure differential is part of a definite cyclonic downturn in pressure and is maintained for a significant period of time (more than 24 hours).

(4) The rate of pressure drop, measured in pascals per hour, in itself is not an important criterion by which to judge the extent of a hazard. The only significance it may have is the fact that a very large total pressure differential may develop as a result of a rapid drop in pressure associated with, for example, the onset of bad weather (e.g. the Hlobane explosion).

With apologies to Mark Twain, it can be said that everyone talks about the influence of the weather on gas explosions, but can anything be done about it? From the findings of this investigation, it would seem that the following recommendations could be put to the mines.

(i) In view of the demonstrated role of barometric-pressure fluctuations in major gas èxplosions, each mine should have ready access to a sensitive barometer. Such a barometer need not necessarily be on the mine or shaft itself since regional barometric data can be used with a large degree of confidence. However, communications with the centre where a barometer is located should be good enough for 'gas alerts' to be received timeously. If a gas alert is given, it is preferable that it be issued prior to the workforce going on shift to ensure that every underground worker is aware of it.

(ii) As the Weather Bureau is able to predict the movement of cyclonic systems with a high degree of confidence, it may be worth while establishing a communication system with them by which mines can be alerted if major disturbances in weather conditions (such as was the case with the Hlobane explosion) are expected.

(iii) Workers responsible for gas testing in mines should be educated to understand and appreciate the influence of fluctuations in barometric pressure on gas emissions in mines. They should also understand that a 'gas alert' means that the probability of finding gas in the workings is likely to increase—nothing more, nothing less. For this reason, a 'gas alert' requires that they should
- adhere strictly to the testing procedures required by the Mines and Works Act and Regulations (as they should do as a matter of routine)
- test for gas at more frequent intervals than called for in the Regulations; (in this regard, it may be helpful to specify such greater frequency in the Mine Standards issued by the Manager in terms of Section 13 of the Act)
- ensure that all ventilation appliances are in perfect working order.

(iv) A 'gas alert' should be given when the barometer starts dropping in a pattern consistent with the onset of a cyclonic low-pressure system. As a rule of thumb in the absence of any better scientific information, it is suggested that a pressure drop of more than 200 Pa, if maintained for more than 24 hours, should trigger such an alert. Such a mechanistic trigger point has its shortcomings, and it is submitted that an intelligent interpretation of the pattern as being in a cyclonic downphase would be more important and effective than a single trigger point.

(v) Once a 'gas alert' has been given, it should not be lifted until the onset of a further anticyclonic system has increased the pressure to a point where the differential between the actual pressure and the previous anti-cyclonic maximum is less than, say, 50 Pa, and remains at that level or less, or becomes negative for at least 24 hours.

(vi) Although it is contended that medium-term cyclonic downturns in barometric pressure are the major contributing factor to an enhanced build-up of gas in underground mine workings, it is by no means the only factor. The normal precautions against a build-up of flammable gas should therefore always be adhered to even when no 'gas alert' is in force.

(vii) Mines that do not have a history of methane gas occurrences in their underground workings are not immune to gas explosions, as the Hlobane disaster so starkly proved. Normal precautions against gas accumulations and statutory testing for gas should be strictly enforced at all times.

(viii) Mines that do have a history of substantial gas emissions into the underground workings, e.g. gold mines in the OFS, coal mines near Ermelo and in Natal, should consider investing in continuous methane-monitoring systems with sufficient sensor heads to monitor all the major production areas. Such devices should be coupled to, for example, a PC-based early-warning system, which should be manned on a 24-hour basis. Such mines should also consider equipping the cap lamps of all workers with continuous methane-monitoring devices that could provide early warning of a gas build-up if a major change in barometric pressure takes place undetected by other early-warning systems.

(ix) Finally, the analyses on which this paper are based are not fully conclusive and many questions remain unanswered. It is suggested that this subject matter needs further in-depth scientific investigation and research. The following investigations could possibly be undertaken to improve the body of knowledge in this regard.

- The statistical base of the investigation could be improved by the addition of further explosion data, e.g. taking into consideration all explosions and not just major explosions; going back to 1960 instead of 1970 with the database, etc.
- Medium-term cyclonic downturns in pressure should be analysed statistically to determine, for example,
  - the mean duration of such pressure drops (Δt_m) as well as the range of pressure drops
  - the mean values and variation of the maximum pressure drops (Δp_m) that may be encountered over the year, etc.
- The maximum and minimum values of anticyclonic peaks and cyclonic troughs respectively were used in this study to quantify pressure drop, duration, etc. However, as a result of both the substantial diurnal variation in pressure and the time lags associated with pressure equalization between the atmosphere in the workings and the gas in the strata, a study of pressure drops prior to explosions would be more meaningful if based on fairly sophisticated trend analyses.
- The most reliable scientific evidence would obviously be obtained if several mines, or sections of mines, with a history of gas accumulations could be instrumented with sensitive continuous methane-monitoring systems and continuous recording barometers to allow increases in methane content in the underground workings to be directly correlated with changes in barometric pressure over an extended period of time, say 12 months. This would obviously be an extensive study requiring substantial resources, but it would provide some answers to questions that, for the moment, remain unanswered. It is hoped that the industry will see its way clear to undertake a study of this nature in the not-too-distant future.

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