Coal self-heating and explosibility

by M.J. Gouws* and T.P. Knoetze†

Synopsis

The spontaneous combustion of coal and the explosion of coal dust are two phenomena that were identified by the South African mining industry as requiring investigation. Research contracts were awarded to the G.P. Badenhorst Research Facility of the CSIR and the Department of Mining Engineering of the University of the Witwatersrand by the now defunct National Energy Council. Both projects entailed tests on numerous coal samples in specially designed apparatus. Since the completion of the project, attempts have been made to predict experimental results without incurring the cost of performing experiments. This paper describes predictive indices, based on routine laboratory tests, that were developed by the

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Introduction

Early coal-miners believed underground fires and explosions to be caused by supernatural agencies, and it was not until the early 1600s that scientists began to investigate these phenomena. A great deal has since been written about the spontaneous combustion of coal and the explosibility of gases and coal dust, but there is still a great deal to learn. The fact that most major coal-mining countries still have active research programmes in these fields indicates the undiminished seriousness that these problems are accorded.

This paper discusses elements of two South African research programmes that were completed recently. One programme investigated the explosibility of coal dust, while the second investigated the relative propensity of coal to self-heat. Both programmes investigated the use of indices, based on routine coal analyses, to predict the results of laboratory experiments.

This paper compares these predictive indices, and discusses the results obtained by testing samples from collieries where incidents of spontaneous combustion or coal-dust explosions have occurred.

South African statistics

The causes of underground fires in South African collieries during the period 1970 to 1990[1] are shown in Figure 1. The spontaneous combustion of coal was found to be the major cause of fires, being responsible for more than a third of the 254 fires reported during this period. This represents an average of 4,3 incidents of spontaneous combustion per year. Flammable gases caused just over 21 per cent of the fires.

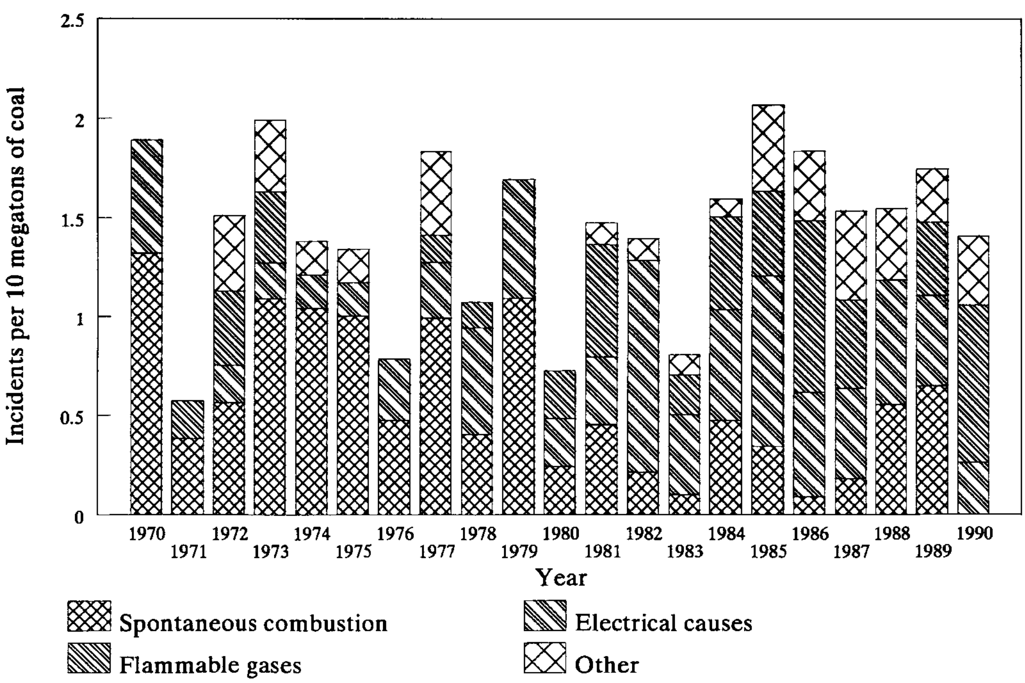

Figure 1—Causes of fires in South African collieries, 1970–1990

different research teams for their particular projects. A comparison of the results obtained by applying the spontaneous combustion liability index and the explosibility index to common coal samples indicates that, in general, propensity to spontaneous combustion and explosibility exhibit an inverse relationship. A brief overview is given of some major South African coal-mine disasters.

The frequency of reported ignitions and explosions for the period 1982 to 1993[2] is shown in Figure 2. There were an average of 3,8 ignitions and 1,5 explosions per year over the twelve-year period. Four people were injured in incidents involving ignitions, and there were no fatalities. Explosions, on the other hand, caused 93 injuries and 218 deaths. Figure 3 shows the average number of injuries and deaths per explosion over this period. Major incidents occurred in 1983 (Hlobane), 1985 (Middelbult), 1987 (Ermelo) and 1993 (Middelbult). These four incidents make up 22 per cent of the total number of explosions that occurred, yet account for 28 per cent of the injuries and 87,2 per cent of the fatalities.

The gathering of data on the number of incidents of spontaneous combustion and coal-dust explosions is fraught with difficulty. Incidents of self-heating can often be treated by loading out the hot coal before a fire occurs. It is possible, then, that statistics on incidents of spontaneous combustion record only those incidents that progressed to a stage that necessitated them being reported to the Inspector of Mines. The statistics also reflect only incidents at underground collieries, and do not indicate the magnitude of the problem as regards strip mines, dumps, stockpiles, abandoned mines, or ships.

Isolating incidents of coal-dust explosions also has its difficulties. Statistics are normally available for reported ignitions *and* explosions, or fires caused by flammable gases. It would appear that, in the majority of cases, methane is responsible for the incident. Only in particularly violent incidents is the mechanism of the incident extensively researched, and in those cases a secondary coal-dust explosion is usually suspected.

From the above discussion, it can be seen that the decision to research these two phenomena was correct. Spontaneous combustion is the major cause of underground fires, and a coal-dust explosion has the potential to turn an ignition or explosion incident into a major catastrophe.

Research contracts were awarded to the G.P. Badenhorst Research Facility of the Council for Scientific and Industrial Research (CSIR) and the Department of Mining Engineering of the University of the Witwatersrand, in an effort to characterize the explosive and self-heating potential of South African coals. The research was funded by the coal-mining industry via the National Energy Council. Both projects involved the design, construction, and refining of apparatus and techniques, and have since been completed. Recent interest in that work has led to attempts to predict the explosibility and self-heating potential without actually having to perform experimental work.

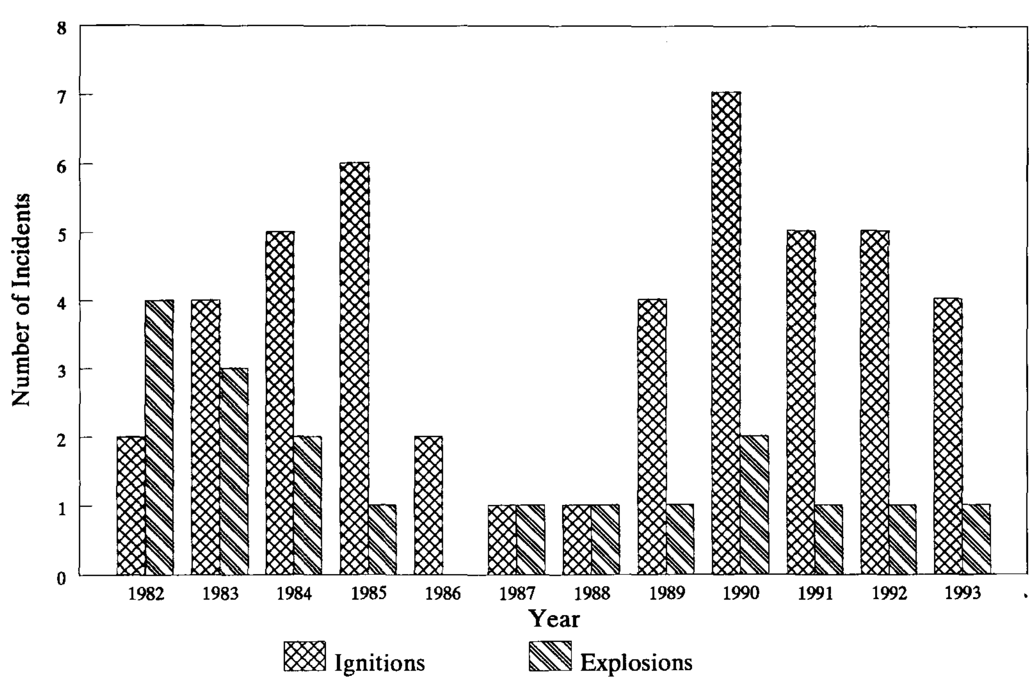

Figure 2—Ignitions and explosions in South African collieries, 1982–1993

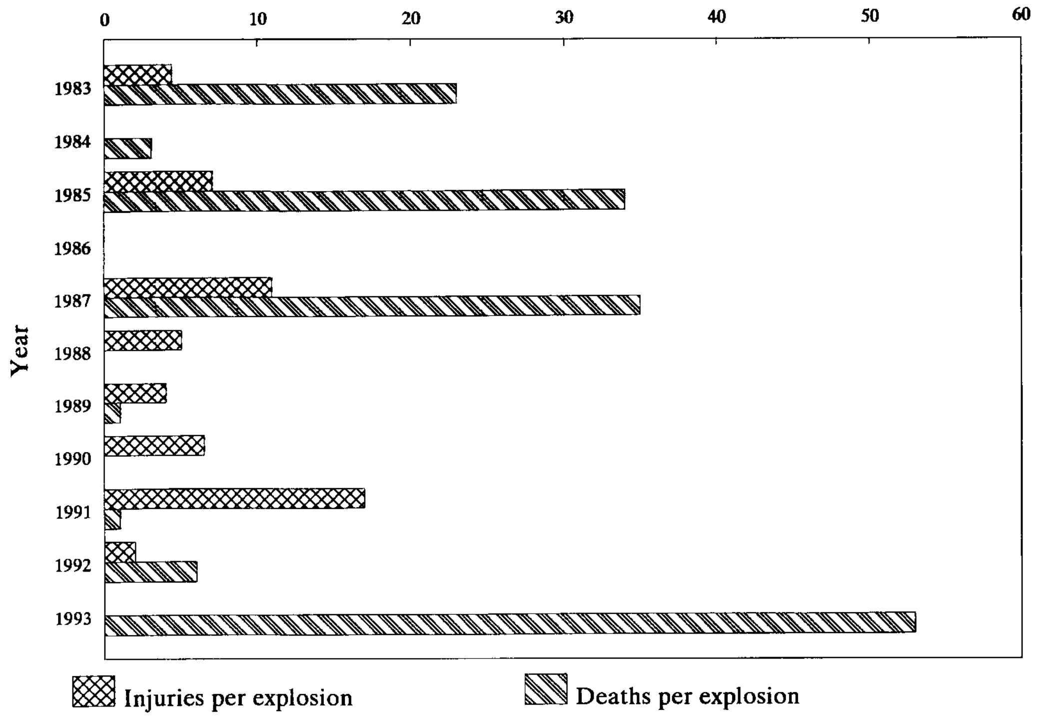

Figure 3—Injuries and fatalities in methane and coal-dust explosions, 1983–1993

Self-heating liability and explosibility

Explosibility predictive index

The explosibility of coal dust can be expressed in terms of an experimentally determined explosibility index (K_{ex}). The apparatus used to determine the K_{ex} value of a coal dust is a 40-litre explosion vessel (Figure 4). The coal dust is blown into the vessel with compressed air, and the resulting cloud is then ignited. The gas pressure resulting from the ignition is plotted versus time, and the K_{ex} value is calculated from this curve. Coals with a K_{ex} value of less than 70 bar/s are considered to be non-explosive, while a K_{ex} value of more than 90 bar/s indicates a coal dust that will propagate an explosion in an underground coal mine. Repeatability is a problem for dusts with a K_{ex} value of less than 90 bar/s in tests using the explosion vessel, and an explosion gallery is recommended for the further evaluation of coals with K_{ex} values of between 70 and 95 bar/s.

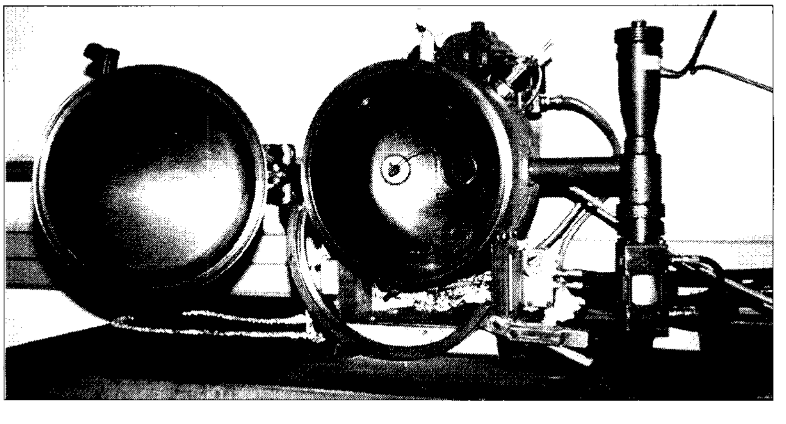

Figure 4—The 40-litre explosive vessel used to determine the explosibility index (K_{ex}) of coal dusts

Unlike European coals, South African coals do not exhibit a good relationship between the K_{ex} value and volatile matter content. In an effort to predict the K_{ex} value from routine coal tests, therefore, it was decided to investigate the relationship between explosibility and the *energy* released by the combustion of volatiles in the coal[3].

The calorific value (CV) of the volatiles in the coal can be determined by subtracting the energy released by the combustion of the fixed carbon portion of the coal from the CV of the coal. It is assumed that the inorganic component of the coal does not contribute to the volatile content of the coal. If it is also assumed that the amount of energy liberated by the combustion of a given quantity of fixed carbon is the same as that which would be liberated from a similar quantity of graphite, the following relationship can be used:

$$\text{CV of total volatile material} = (100 \times \text{CV of the coal} - 32{,}8 \times \text{FC})/100 \qquad [1]$$

where :

CV is the calorific value (MJ/kg)
32,8 is the calorific value of graphite (MJ/kg)
FC is the fixed carbon content (%).

Forty-six different coals were tested[4] in order to investigate the relationship between K_{ex} and the volatile matter content of the coal, the dry ash-free volatile matter content of the coal, and the CV of the volatile matter portion of the coal.

Most of the coals tested in the 40-litre apparatus yielded K_{ex} values well in excess of 90 bar/s. Statistical analysis showed that the best predictor of the K_{ex} value was the CV of the volatiles.

The following relationship was determined:

$$K_{ex} = 15{,}81\ (\text{CV of volatiles}) - 6{,}35. \qquad [2]$$

This equation is valid for K_{ex} values between 90 and 120 bar/s, and relates K_{ex} and the CV of the volatiles with a correlation coefficient of 0,87. The complete form of the equation, obtained by substituting equation [1] into equation [2], is given by:

$$K_{ex} = 0{,}1581\ (100 \times \text{CV of coal} - 32{,}8 \times \text{FC}) - 6{,}35. \qquad [3]$$

Predictive indices of spontaneous combustion

Two experimental techniques have been used to determine the propensity of a coal to self-heat. Ignition temperature tests (crossing-point temperature tests and differential thermal analysis) were used during the initial phases of the research programme, while adiabatic calorimetry was used in later tests[5]. Results obtained from ignition temperature tests were plotted on a differential thermal analysis (DTA) thermogram, and the characteristics of the curve were used to determine the propensity of the coal to spontaneously combust according to the WITS-EHAC liability index[6]. A coal with an index value of more than five had a high propensity to self-heat, while a sample with an index value of less than three was regarded as having a low tendency to self-heat. A coal sample with an index value of between three and five was regarded as having a medium risk of undergoing spontaneous heating. More than 100 coals were tested using the ignition temperature apparatus.

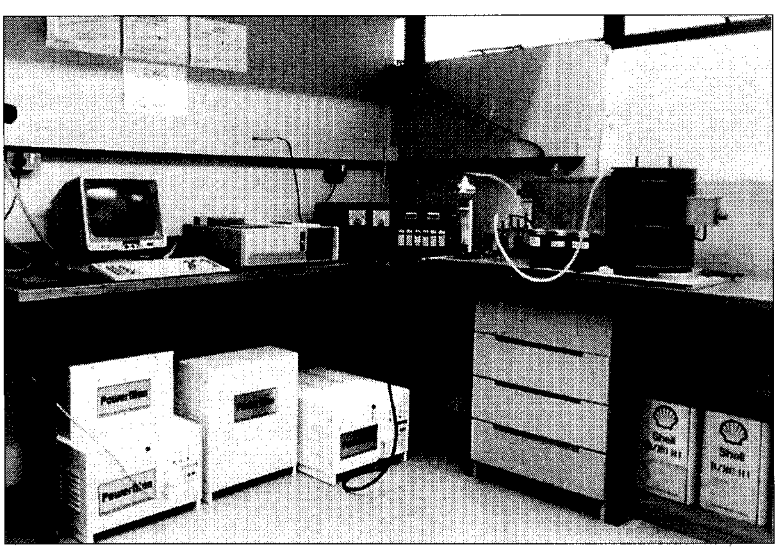

Figure 5—The adiabatic calorimeter and controlling and recording apparatus for determining the spontaneous combustion liability of coal

During a later phase of the research programme, an adiabatic calorimeter was designed and constructed[5,7] (Figure 5). The calorimeter was operated in a mode that simulated the ignition temperature apparatus used in the first phase of the programme. Duplicate samples of coals tested in the ignition temperature apparatus were tested in the calorimeter, and the results were compared. A calorimeter index was developed to replace the WITS-EHAC liability index. The calorimeter greatly simplified the laboratory work that was required, but the apparatus was de-commissioned at the end of the research programme. However, the continued demand for inexpensive tests led to a search for a characteristic that would predict the self-heating risk. The development of a predictive index began with a comparison being made between the calorimeter index values of coal samples and the results of proximate, ultimate, and petrographic tests.

From Table I, it can be seen that there is a significant relationship between the calorimeter index and rank-related qualities such as the reflectance of vitrinite, moisture content, oxygen content, and carbon content. The best correlation coefficients (about 80 per cent) were, however, obtained for a multiplicative regression against the oxygen-to-carbon ratio; and an exponential regression against the dry ash-free (daf) oxygen content. Two predictive formulae were proposed[8]; these were:

$$\text{daf oxygen index} = e^{(0{,}907 + 0{,}126 \times \text{daf oxygen})} \qquad [4]$$

and

$$^{O}/_{C}\ \text{ratio index} = 28{,}8 \times (^{O}/_{C}\ \text{ratio})^{0{,}492} \qquad [5]$$

Both the daf oxygen index and the O/C ratio index compared well with the calorimeter index, and identified the same high-risk coals. A calorimeter index value of greater than six is considered to indicate a high-risk coal, and corresponds to a value of greater than ten for the two predictive indices. The self-heating potential of coals can be ranked as shown in Table II.

The daf oxygen index is in agreement with an index proposed by the US Bureau of Mines[9], and will be used to compare self-heating propensity and explosibility of coal in the remainder of this paper.

Table I

Correlation coefficients from regressions of the calorimeter index against coal qualities (after Gouws[8])

Variable	Linear $y = a + bx$	Multiplicative $y = ab^b$	Exponential $y = e^{(a + bx)}$	Reciprocal $^1/_y = a + bx$
Moisture content	68,39	+71,46*	68,43	65,01
Fixed carbon	58,89	57,59	–60,10*	58,26
Elemental carbon	50,30	51,15	–51,97*	50,77
Dry ash-free oxygen content	78,06	79,84	+80,19*	78,10
Oxygen-to-carbon ratio	76,39	+80,07*	77,58	74,62
Reflectance of vitrinite	60,46	–66,14*	63,86	65,08

* The sign of the correlation coefficient is shown only for the best regression model

Table II

Self-heating potential of coal, as indicated by liability indices

Self-heating potential	Self-heating liability index			
	WITS-EHAC	Calorimeter	daf oxygen	O/C ratio
High risk	>5	>6	>10	>10
Medium risk	3 – 5	3 – 6	5 – 10	7 – 10
Low risk	<3	<3	<5	<7

Comparison of predictive indices

All the data required to predict self-heating potential and explosibility, from equations [3] and [4], were available for coal samples tested in the spontaneous combustion laboratory at the University of the Witwatersrand. The calculated self-heating potential and explosibility of 43 South African coals are compared in Figure 6.

Figure 6 suggests that there is an inverse relationship between self-heating liability and explosibilty. Coal from Springfield Colliery is known to have a high self-heating risk, and is seen to have a K_{ex} value of less than 70 bar/s. Samples from the three collieries that have been the site of explosions with the most fatalities since 1982 are also indicated in Figure 6. Both Ermelo (1987) and Hlobane (1983) have samples with high K_{ex} values and do not have a high self-heating potential. Middelbult Colliery, however, is shown to have a high self-heating risk and a low K_{ex} value. This colliery was the site of major explosions in 1985 and 1993 (the latter explosion is *sub judice,* and will not be discussed further).

Major disasters

Spontaneous combustion

Although no deaths or reportable injuries have been attributed to spontaneous combustion for more than 20 years, the potential for serious accidents still exists, as this phenomenon has been the major cause of fires in South African collieries during the same period. The loss of production and the cost of treating an incident are the effects most noticed by an active colliery, but there are other consequences that can easily become national disasters.

As an example, a fire caused by spontaneous combustion led to the loss of about two million tons of coking coal at Northfield Colliery in November 1951.

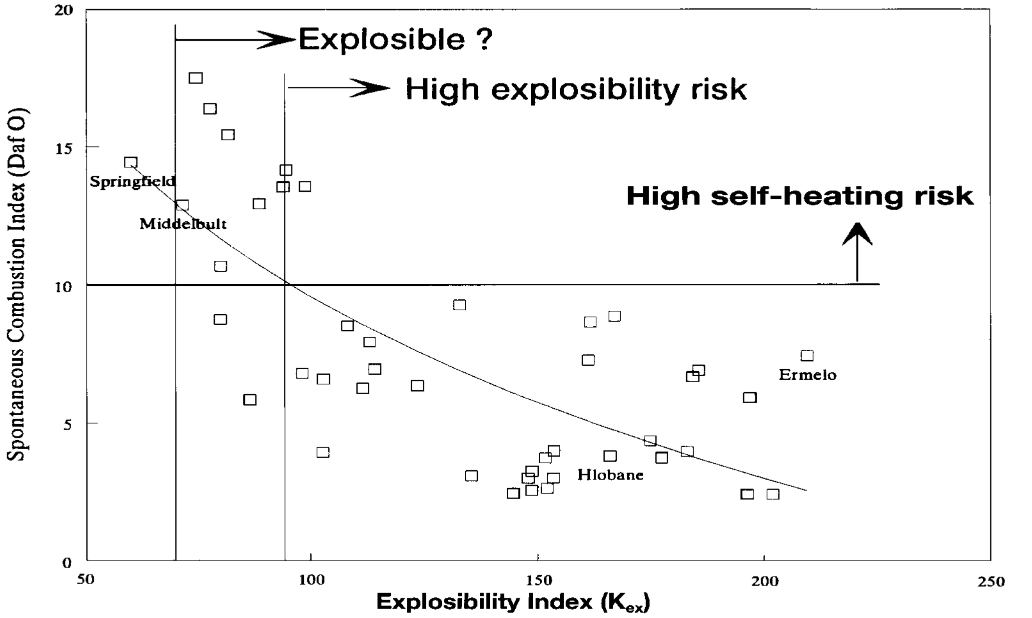

Figure 6—The calculated spontaneous combustion propensity and explosibility of 43 South African coals

Underground fires, probably caused by spontaneous combustion, have been raging in some abandoned mines for many years. These fires cause subsidence of the surface, either by collapse of pillars (seen as a subsidence basin on surface) or by the collapse of the bords (seen as sinkholes or chimneys), making the land unsuitable for residential or farming use. An area of 550 ha adjacent to an industrial centre in Witbank is an example of chimney-type subsidence causing land to be unsuitable for development. An underground fire also threatened the safety of the rail link between South Africa and Mozambique recently.

Subsidence at shallow abandoned mines often results in cracks through to the surface, allowing the ingress of air and water. The air enables the coal to self-heat, or feeds a fire if one is present, and the water manifests itself as acid mine drainage. An area plagued by underground fires was declared a national disaster area in 1990, when the streets of a residential area were flooded with acid mine drainage and raw sewage. The sewage had been allowed to flow into the underground workings after a pipe had burst, because it was believed that it would help to control the underground fire. Spontaneous combustion has also been responsible for excessive air pollution in some areas of Southern Africa.

From the above discussion it is clear that spontaneous combustion not only affects mine safety, but can also have a major impact on the environment. It is important, therefore, to give due consideration to this phenomenon when drawing up an environmental management programme or negotiating a closure certificate.

Explosions

In the Hlobane explosion of 12 September 1983, 68 miners were killed and eight were injured. The source of the ignition was found to be a silicon-controlled rectifier panel of a battery driven scooptram[10]. A conductor had been caught between the flanges of the flameproof enclosure of the control panel during a repair operation, and the resulting gap allowed the propagation of a flame. The explosion took place shortly after work commenced on a Monday morning. It is believed that methane accumulated in the section during the weekend, after mining operations in another section had disrupted the ventilation on the Saturday. A low-pressure system (storm) that had passed over the colliery on the Sunday is also suspected of contributing to the release of methane from the coal seam.

The Middelbult explosion of 12 August 1985 occurred close to a bord and pillar section while workers were constructing an air crossing[2]. It is believed that methane emanated from a borehole that was intersected during normal mining operations, and accumulated in the roof cavity that was created for the air crossing. It is suspected that the ignition occurred as a result of blasting operations in the roof. Thirty-four miners were killed, and another seven were injured.

The explosion of 9 April 1987 at Ermelo Mine Services occurred after a new section was opened on the main development, opposite the section it was replacing[2]. The redirection of ventilation from the old section to the new section is believed to have allowed methane layering to occur in the old section. Although the ignition source was not determined, the explosion is believed to have taken place while the old area was being inspected and one miner was waiting at a transformer in the old section. Thirty-five miners were killed, and eleven were injured. Four of the fatalities resulted from carbon monoxide poisoning.

The report on the Hlobane explosion stated that coal dust played a part in the explosion. It was argued, however, that the extent to which it was involved in the explosion was pure speculation, and that no benefit would be gained by pursuing this aspect of the investigation[10]. This approach was also adopted in investigations of later incidents. The Hlobane report did, however, stress that precautions against a coal-dust explosion must be taken at all times.

Conclusion

Experimental techniques and apparatus have been used by the G.P. Badenhorst Research Facility (CSIR) and the Department of Mining Engineering (University of the Witwatersrand) to effectively predict the self-heating liability and explosibility of coal. The WITS-EHAC liability index and the calorimeter index have been used to determine spontaneous combustion propensity, while an explosibility index (K_{ex}) has been used to assess explosion risk. Both research projects also attempted to predict experimental results from routine coal analysis. Explosibility was found to be related to the calorific value of the volatiles in the coal, while the self-heating propensity was found to be related to the dry ash-free oxygen content and the oxygen-to-carbon ratio of the coal.

By comparing the explosibility and spontaneous combustion propensity of 43 coal samples, it was shown that, in general, there is an inverse relationship between these two characteristics for South African coals.

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In a review of some major disasters, spontaneous combustion was identified as being the major cause of fires in South African collieries. This phenomenon was shown to be important not only in the field of mine safety, but also in the formulation of environmental management programmes and applications of closure certificates.

Four major coal-mine explosions were identified. One incident is still *sub judice,* but the remaining incidents were examined, and it was shown that all were methane explosions. All incidents occurred after an event that led to the disruption of the normal ventilation system, or an increase in the rate of methane emanation. Reports indicated that coal dust played a part in these incidents, but the extent of its role was never quantified. ◆

Brandspruit Colliery becomes 'double millionaire'

Sasol Coal's Brandspruit Colliery at Secunda has reached the 2-million fatality-free manshifts mark—becoming the first mine at Secunda Collieries to do so and one of only a handful of coal mines in South Africa to attain this impressive safety achievement.

It took three years, one month and eight days to reach the target, which was passed on October 10.

This achievement comes after a string of other safety milestones by Brandspruit—the latest was winning the National Occupational Safety Association's 1993 international mining safety competition, announced recently.

Frik Grobbelaar, Brandspruit's manager, said the mine's success in reaching the 2-million fatality-free manshifts mark was proof of the effectiveness of various programmes aimed at making underground conditions safe on a continuous basis. 'A major part of this is achieved through awareness and communication, involving the entire workforce at all levels,' he said.

Brandspruit is on track to win NOSA's highest honour this year, as Noscar award, for which it is required to maintain an injury incidence rate of less than 1 per cent of the workforce and a NOSA audit grading over 95 per cent.

Brandspruit's sister collieries Sigma Collieries at Sasolburg and Middelbult Colliery at Secunda are the only underground collieries in the country that have won Noscar awards so far—in 1990 and 1991 respectively.

The programmes which have contributed greatly to the maintenance of high safety levels at Brandspruit include a recent series of intensive three-day consultation sessions organised away from the mine environment for each of the mine's 18 working groups during the first half of this year.

In this programme all workers in each section attended a series of talk-and-listen meetings known as an 'izwana', where they were encouraged to raise questions and discuss problems about all aspects of the work, including safety.

Short indabas with workers, to maintain communication and keep tabs on problems raised at the izwanas, are held every five weeks.

Grobbelaar said that in recent years a change in the approach by supervisors and safety and environmental inspectors towards workers from the traditional prescriptive approach to a supportive approach had done much to improve safety as well as increasing productivity. 'All employees now readily participate in decision-making, making suggestions or bringing problems to our attention. We are in close liaison with the unions in encouraging a sense of ownership among employees and keeping them constantly informed about everything that is going on,' he said.

He added that the full-time literacy training provided by Sasol Coal had helped to boost the participative process. So far 257 Brandspruit employees have completed the full-time in-house course, which includes instruction in life skills. Many of them have gone on to attend technical courses, also provided by Sasol Coal, to improve their knowledge and skills. ◆

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